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Geophysical characteristics of permafrost in the Abisko area, northern Sweden

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Abstract: Research on permafrost in the Abisko area of northern Sweden date from the 1950s. A mean annual air temperature of -3 °C in the Abisko mountains (*i.e.* 1000 m a.s.l.) and -1 °C beyond the mountain area at an altitude of around 400 m suggests that both mountain and arctic permafrost occur there. Several geophysical surveys were performed by means of resistivity tomography (ERT) and electromagnetic mapping (EM). Wherever possible the geophysical survey results were calibrated by digging tests pits. The results show that permafrost occurs extensively in the mountain areas, especially those above 900 m a.s.l. and also sporadically at lower altitudes. At 400 m a.s.l. permafrost may be up to 30 m thick. Its thickness and extent are determined largely by the very variable local rock and soil conditions. Fossil permafrost is also likely to occur in this area.

Key words: Arctic, Abisko, permafrost, geophysics.

Introduction

Since the 1980s, there has been an increasing interest in researches concerning the occurrence of permafrost in mountain environment. It is attributed to several factors, one more being putative climate warming, which leads to permafrost degradation (Haeberli 1990; Anisimov and Nelson 1996; Serreze *et al*. 2000) and an increasing threat of such features as debris flows and avalanches in intensively cultivated mountain areas (Haeberli 1992). A number of research projects carried out in Europe, such as the installation of monitoring of mountain permafrost temperature in boreholes sunk specifically for the purpose (Isaksen *et al.* 2001), have led to a better understanding of permafrost occurrence in the mountain environment. However, to date, little has been done to fill the gap in our knowledge concerning the form, the age, the properties, and the lower limit of permafrost occurrence in a mountain environment at different latitudes in Europe. The aim of this work is to try fill in one of these gaps by reporting on mountain permafrost developments in northern Sweden in particular their geophysical characteristics. The paper also discusses permafrost origin and evolution.

Previous work

Although the Scandinavian mountains form one of the largest ranges in Europe and span the polar circle, there has been little intensive research on permafrost here until recently (King and Seppälä 1988). Rapp (1960, 1982) and Østrem (1964) were pioneers in this field and after *c.* 20 years or so their work is now being extended (Darmody *et al*. 2000; Baumgart-Kotarba *et al*. 2001; Beylich *et al.* 2004). However, the first publications giving details of permafrost occurrence in the mountain area of Abisko date back to the beginning of the XX century. Ekman's (1957) descriptions of the water resources of the Abisko area is an important study from this early period. He presented indirect evidence of permafrost occurrence in northern Scandinavia by using a climatic method. He also gave a detailed description of a borehole which was sunk to prospect for groundwater in the Abisko area in 1941. Another place where 20-m thick permafrost occurs is the Moskogaisa mine, in the Lyngen area in Norway, at the altitude of 750 m a.s.l. Until mid-1980s, little was known on permafrost occurrence apart from the information contained in Ekman's publications, except such specific landforms where it was present in palsa and peat bogs (Svensson 1986). A review of a research conducted in that period is presented by Jeckel (1988).

Research on permafrost was then limited to the one on palsa-relief forms which were once considered the only indication of permafrost occurrence (Seppälä 1982; Åkerman and Malmstrom 1986). Significant progress in research on permafrost is attributed to King (1984, 1986), who like Østrem (1964), used geophysical methods to try to understand the nature of the periglacial environment. However, both King and later workers concentrated almost entirely on the southern parts of the Scandinavian range and in the Tarfala area (Ødegård *et al.* 1992, 1996; Etzelmüller *et al.* 1998).

In those times – 1980s, about 80% of publications about the Abisko area concerned the biological sciences – indeed it is probable, that this proportion has not changed. In the last 3 decades, certainly, several works have been published, where permafrost presence is discussed not only incidentaly but as the main topic of research. The same is true of the use of geophysical methods in the mountain area of Abisko. Those works which describe geophysical survey have refer to mainly geological and geomorphological features such as the extent of glacial erosion, identification and thickness estimation of glacial sediments *etc.* (Baumgart-Kotarba *et al*. 2001; Beylich *et al*. 2004; Mościcki *et al.* 2006).

Recently, researchers, involved in the PACE program (Harris *et al.* 2001), have contributed greatly to the recognition and description of permafrost in Scandinavia. Boreholes in the Tarfala and Juvvashøe area are a part of this research program which will hopefully enable the determinion of the permafrost extent and evolution. The two boreholes were drilled in the areas where the mean annual air temperature (MAAT) is -3.9 and *c.* -4.5°C respectively, *i.e.* much above the lower limit of permafrost occurrence in this area (Isaksen *et al.* 2001). Consequently, they will not allow for direct (thermal) characteristic of permafrost nearby the altitudinal limit of its occurrence. It may be possible for contemporary permafrost present in the Dovrefjell area, where 11 shallow boreholes, 9-metre-deep, were drilled (Sollid *et al.* 2003). Deeper thermal recognition was made by indirect geophysical methods (Hauck 2001). Nowadays observations of active-layer thickness from nine sites with up to 29 years of gridded measurements located in the Torneträsk region were examined in relation to climatic trends by Åkerman and Johansson (2008). Because of warming of climate, active layers at all sites have become thicker at rates ranging from 0.7 to 1.3 cm per year.

Study area

The mountains are the result of Cenozoic uplift. The rock forming the mountains were deformed during the Caledonian Orogeny. The Torneträsk area in northern Sweden is shown in Fig. 1. The range is built from igneous and metamor-

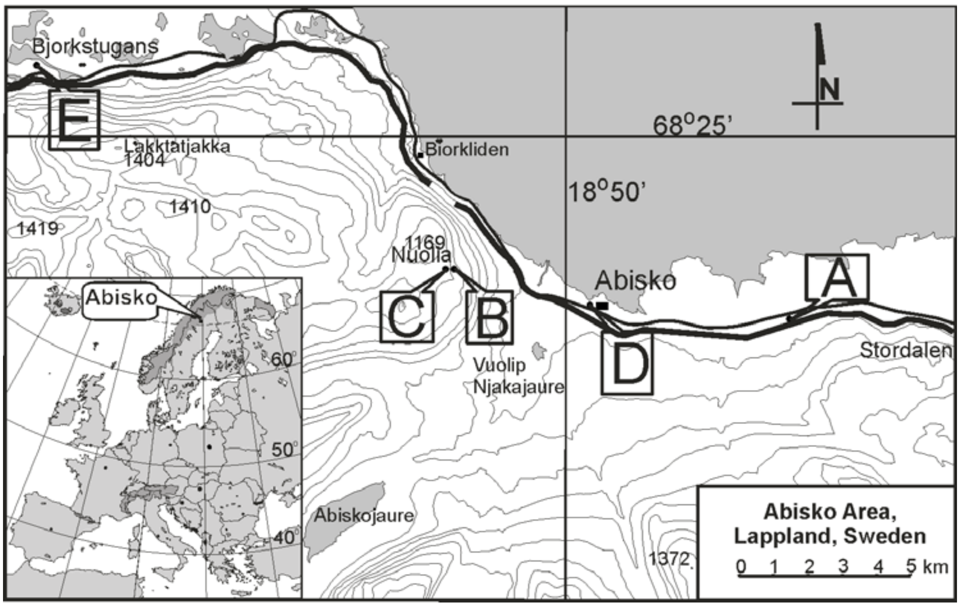

Fig. 1. Locations of the permafrost research on a map of the Abisko area. A – Storflaket mire; B, C – Mt. Nuolia, slope and above hanging valley, respectively; D – vegetated blocky surface near Abisko Scientific Station; E – granitic *roche moutonée*, with blocky cover and vegetation, at the Björkstugans site.

Table 1

Average air temperature and precipitation at different elevations in the Abisko area compilled after Ridefeld and Boelhouwers (2006) and Jonasson (1991)

Station	Altitude (m a.s.l.)	Air temp (°C)	Precipitation (mm)
Bjorkliden	360	-	848
Abisko	388	-0.6	304
Torneträsk	393	-1.0	428
Riksgränsen	508	-1.5	940
Katterjåkk	515	-1.7	807
Karkevagge 3	700	-1.1	–
Karkevagge 2	720	-2.0	–
Karkevagge 1	750	-1.6	–
Rakkaslahku	830	-1.3	–
Låktatjåkka valley	830	-2.1	–
Gohpascorru	840	-2.3	–
Njulla 2	920	-2.7	–
Latnajaure	990	-4.0	–
Njulla 1	1050	-3.1	–
Låktatjåkko	1220	–	1750
Latnjacorru	1350	-4.5	–

phic rocks. Granites and gneiss are both common and quartzite and phyllites and, nearby Nuolia, mica schists and marbles are also present and outcrop. Till sediments are common in the valleys surrounded area. Weathered *in situ* rocks developes blocky covers, which are common on slopes, and also on convex forms of terrain. The upper limit of forest grown – a sub-alpine birchwood belt – lies at 600 m a.s.l. (Barenkow and Sandgren 2001). Above this lies a narrow belt of willow shrub (salix) and above a middle-alpine belt consisting of meadow with herbs, fresh heath, dry heath (>500 m), extreme dry heath (>960) and grass heath (>1020) (Rune 1965). Peat bogs and mires are common in the depressions. Permafrost was identified in some of those localities (Jeckel 1988).

For period 1913–2006, the climate in the survey area is characterized by a sub-zero mean annual air temperature ranging from -4.5 °C at an altitude of about 1350 m a.s.l. in Latnajaure to -0.6 °C at Abisko Scientific Research Station (388 m a.s.l.) (Åkerman and Johansson 2008). A notable feature of this area is the variability of the rainfall in the area. It is 940 mm at Riksgränsen but only 304 mm at Abisko, 40 km away (Jonasson 1991; Ridefeld and Boelhouwers 2006; Åkerman and Johansson 2008) (Table 1).

Methods

The survey areas were selected so as to achieve the greatest possible spatial and altitudinal variety of surveys, land-surface cover and medium in which permafrost occurs, within the resources aviable (Fig. 1). With respect to previous work and keeping in mind the comparative character of this study – the fact that in similar climatic and geological conditions in the Tatras fossil permafrost is likely to exist (Dobiński 2004), it was decided that deeper than 10–20 m soundings should be performed in the Abisko area as well.

In order to determine the extend and properties of permafrost in a mountain environment, geophysical methods have been employed in the research. Those methods are widely and successfully implemented in permafrost research since long time in the Alps, in Scandinavia (Haeberli 1985; Vonder Mühll 1993; Ødegård *et al.* 1996; Hauck and Vonder Mühll 1999; Hauck *et al.* 2000, 2001; Hauck 2001; Vonder Mühll *et al.* 2001; Kneisel 2006) as well as in smaller mountain ranges – the Tatras, south Poland (Dobiński 2004; Dobiński *et al.* 2006).

Two geophysical methods were used to detect permafrost in the survey area: electroresistivity tomography (ERT) and shallow and deep electromagnetic soundings (EM). Wherever possible, test pits were excavated near to the survey line. On the mires, the depth of an active layer was determined precisely by means of a steel rod. The results of bottom temperature of the winter snow cover (BTS) conducted by Förster (2005), zonal and polyzonal permafrost landforms (Harris 1988) and available climatic data were also taken into consideration in respect to permafrost occurrence.

In order to properly interpret the results of electro-resistivity soundings in the works on permafrost, it is important to clearly differentiate between resistivity values characteristic of frozen and unfrozen environments. It is generally understood that when temperature of a certain material falls below 0 °C, its resistivity increases by a several orders of magnitude (Hoekstra and McNeill 1973). The greater the fall in temperature, the greater the increase. Furthermore, empirical studies, both in the field and in laboratory have enabled us to determine the range of resistivity values for frozen and unfrozen rocks of various types (Hauck 2001).

However, ice resistivity values differ greatly depending on the environment where the ice occurs. Hochstein (1967) stated that in temperate glaciers resistivity, a temperature of 0 °C is higher than 10 MΩm, while in cold glaciers and in ice fields it is only 0.1 MΩm at a temperature of -10 °C. Röthlisberger (1967) compared the results of soundings made in mountain glaciers and polar areas, finding differences of a few orders of magnitude between ice in these environments (Table 2). The decrease in resistivity is usually attributed to a saline content, especially in polar ice, which leads to a decrease in phase transformation temperature. Thus, the results of electroresistivity soundings often differ significantly, depending on whether they are made on permafrost containing ice or on polar ice of high latitudes (Table 2). Although this phenomenon has yet to be investigated thoroughly, it is known that apparent resistivity of mountain permafrost tends to be much higher (by as much as 1 MΩm) than that of Arctic permafrost (1–10 kΩm) (Röthlisberger 1967; Ruotoistenmäki and Lehtimäki 1997; Hauck *et al.* 2001). The latest publications show that

Table 2

Values of resistivity of different kind of ice according to certain authors

Author	Object	Material	Resistivity (kΩm)
Röthlisberger 1967	Steingletscher, Switzerland	Mountain glacier	10000–14000
	Glacier de St. Sorlin, France	Mountain glacier	87500–170000
	Jungfraujoh ice tunnel	Mountain glacier	17000–75000
	Athabasca Glacier	Mountain glacier	3500–22000
	Thule Air Base, Greenland	Polar ice	100
Röthlisberger and Vögtli 1967	Unteraargletscher, Grosser Aletschgletscher	Mountain glaciers	20000–120000
Vögtli 1967	Devon Island	Polar ice	20–700 (4000)
Clark, Key and Pert 1969	Paris Glacier, Greenland	Polar ice	65–85
Bentley 1977	Ross Ice shelf	Polar ice	70
Reynolds 1982	George VI Ice Shelf	Polar ice	48–70
Reynolds and Paren 1984	George VI Ice Shelf	Polar ice	50–150 (80)
Hochstein 1967	"Station Centrale" Greenland	Polar ice	30–750

low resistivity values (2000 Ωm) in permafrost are also registered in a continental environment at lower latitude (Etzelmüller *et al.* 2006).

In the Abisko area, the results of electroresistivity soundings which have sought depict the occurrence of permafrost in the form of underground ice or permanently frozen ground differ significantly from one another. Kneisel (2006) states the values from about 480 kΩm to about 13 kΩm are characteristic of permafrost in that region. This illustrates that when interpreting the results of electroresistivity soundings in the research on permafrost detection, the contrast of resistivity values between frozen and unfrozen layers is as important as values of resistivity itself. Obviously, electroresistivity sounding, which is an indirect method, is not solely sufficent to identify permafrost presence in a survey area. If one is searching for permafrost one is obliged to employ several methods (Vonder Mühll *et al.* 2001).

In my surveys, the electromagnetic methods which are normally used in Arctic permafrost research were employed (Hoekstra and McNeill 1973; Sartorelli and French 1982). The conductometer EM 31 has been introduced as a tool for research on mountain permafrost (Hauck and Vonder Mühll 1999; Hauck et al. 2001; Kneisel and Hauck 2003) but has already proved to be a very useful instrument in the mapping of permafrost occurrence, particularly when combined with electroresistivity instruments (ERT). EM 31 employs an electromagnetic field at the fixed frequency of 19.8 kHz and employs fixed transmitter-receiver spacing of 3.7 m to induce an electrical current in the ground. The depth, to which reliable results are available, reaches 6 m. The conductometer EM-34 which can be used with variable transmitter – receiver spacing, enables us to survey to a depth of *c.* 60 m, allowing reaching the depth of about 60 m under the ground surface.

Results

Storflaket mire. — Mires represents this kind of ground surface where permafrost is most common in the area of research. Storflaket mire gives relatively easy access and was located close to the main road. It gives the opportunity to use complete set of geophysical methods. Research was carried out in an area close to the location, where active layer changes were previously noted by Åkerman and Johansson (2008). The permafrost thickness having been measured by drilling in this mire in the 1980s. The permafrost thickness was then 15 m. The aim was to determine characteristic resistivity values at a place where permafrost occurrence was known and where ground temperature has been measured for many years. Shallow ground temperature monitoring in the active layer was conducted by the author in the period 8 August 2007 – 10 August 2008. The location of the geophysical works is presented in Fig.1, location 1A. Studies have included ERT, electromagnetic soundings, as well as steel rod measurements of the active layer and test pitting.

An electrode spacing of 0.3 to 5.0 m was used in 4 ERT profiles so profiles obtained by the application of RES2DINV software gathered meaningful data between depths of 5 to 40 m respectively. The profiles show variable resistivity values ranging from 180 Ωm to *c.* 30 kΩm. The shallowest profile best shows the resistivity gradient values, which increases with depth and shows the change between unfrozen and frozen material (broken line on Fig. 2). A considerable rise in resistivity, from about 540 Ωm, was observed at the depth below 0.5 m. At a depth of *c.* 1.5 m, resistivity values are close to 5000 Ωm. Below, resistivity values level off between 5 to about 10 kΩm were noted.

Deeper soundings show that the increase in depth is accompanied by a significant rise in resistivity values, which, in deeper soundings, takes the form of an anomaly of resistivity value above 40 kΩm. This high-resistivity layer extends from a depth of about 1.5 m to more than 30 m (Fig. 3B) and is interpreted here as a permafrost layer.

In each of the Storflaket profile, the thickness of an active layer of permafrost was measured by means of a steel rod (Fig. 3A). In 2006, it was 50 cm thick in dry sites and > 1m thick in the sites where the terrain is either partially or wholly saturated or where small ponds are present. Based on this measurement and the test pitting (Fig. 4), it is possible precisely to determine the limiting resistivity value of the frozen layer of the ground as *c.* 500 Ωm.

The results of mapping by means of the EM-31 (Fig. 5) match those of the electroresistivity surveys, and permit a wider spatial analysis of the measurement results. Very low values of electromagnetic conductivity (0.5–2 mS/m), indicate the occurrence of permafrost at the depth of 6 m below the ground surface in the whole area (Dobiński *et al.* 2006; Hauck *et al*. 2001). The conductivity variation seems to be associated with the degree to which the ground is saturated. Such a va-

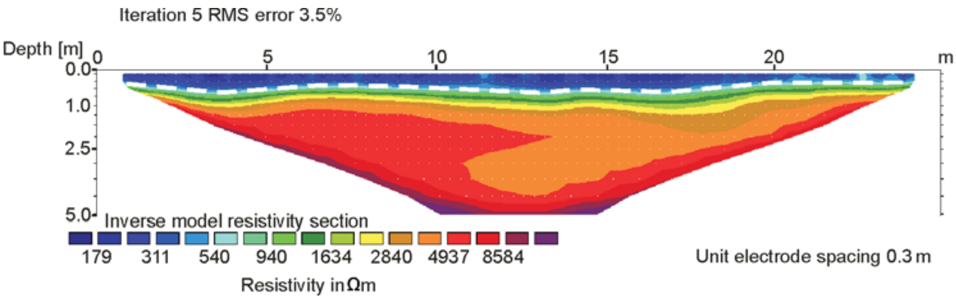

Fig. 2. The results of the shallow ERT surveys profiling on the Storflaket mire near Stordalen. The white broken line shows the depth of the active layer.

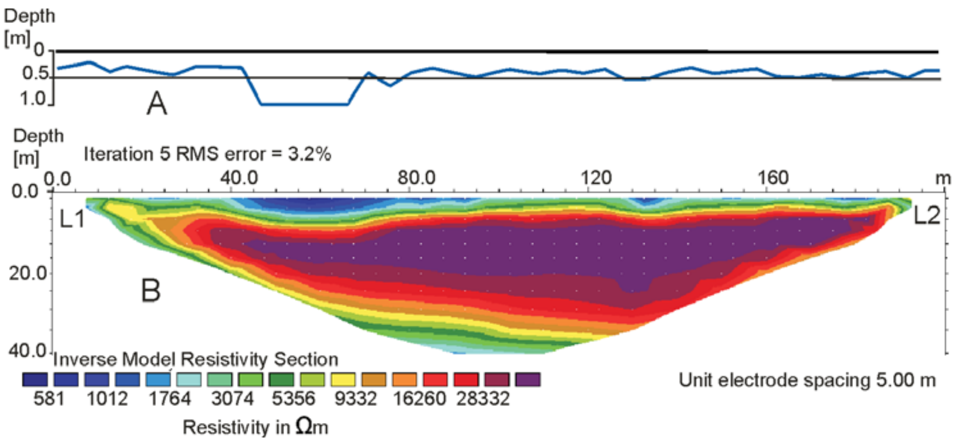

Fig. 3. **A**. Active layer depth as measured by using a steel rod. **B**. Results of the deep ERT-surveys profiling in the same locality as in Fig. 2, with different electrode spacing. The active layer connot be identfied.

riety is also visible in the electroresistivity profile on the distance between 40 m and 80 m (Fig. 3B). It is clear from these results that climatic warming does not necessarily lead to complete degradation of permafrost in the mires, although it may be observed in other places of the region (Christensen *et al*. 2004). Similar results were obtained by Kneisel *et al*. (2007) in surveys carried out in Iceland.

Mount Nuolia and Abisko Scientific Research Station. — Electroresistivity profiling was carried out, on the east facing slope of Mount Nuolia, near the upper station of the cable car (Fig. 1B) and in the small valley located above (Fig. 1C). Jeckel (1988) had previously measured ground temperatures in two locations here, from which he estimated the thickness of the active layer to be *c.* 2.5 m and the limit of discontinuous permafrost occurrence at an altitude of 880 m a.s.l. Geomorphological mapping of relief forms characteristic of regions where permafrost likely to occure (Rączkowska 1990) and BTS measurements also indicate that permafrost is likely to exist on Mount Nuolia (Förster 2005).

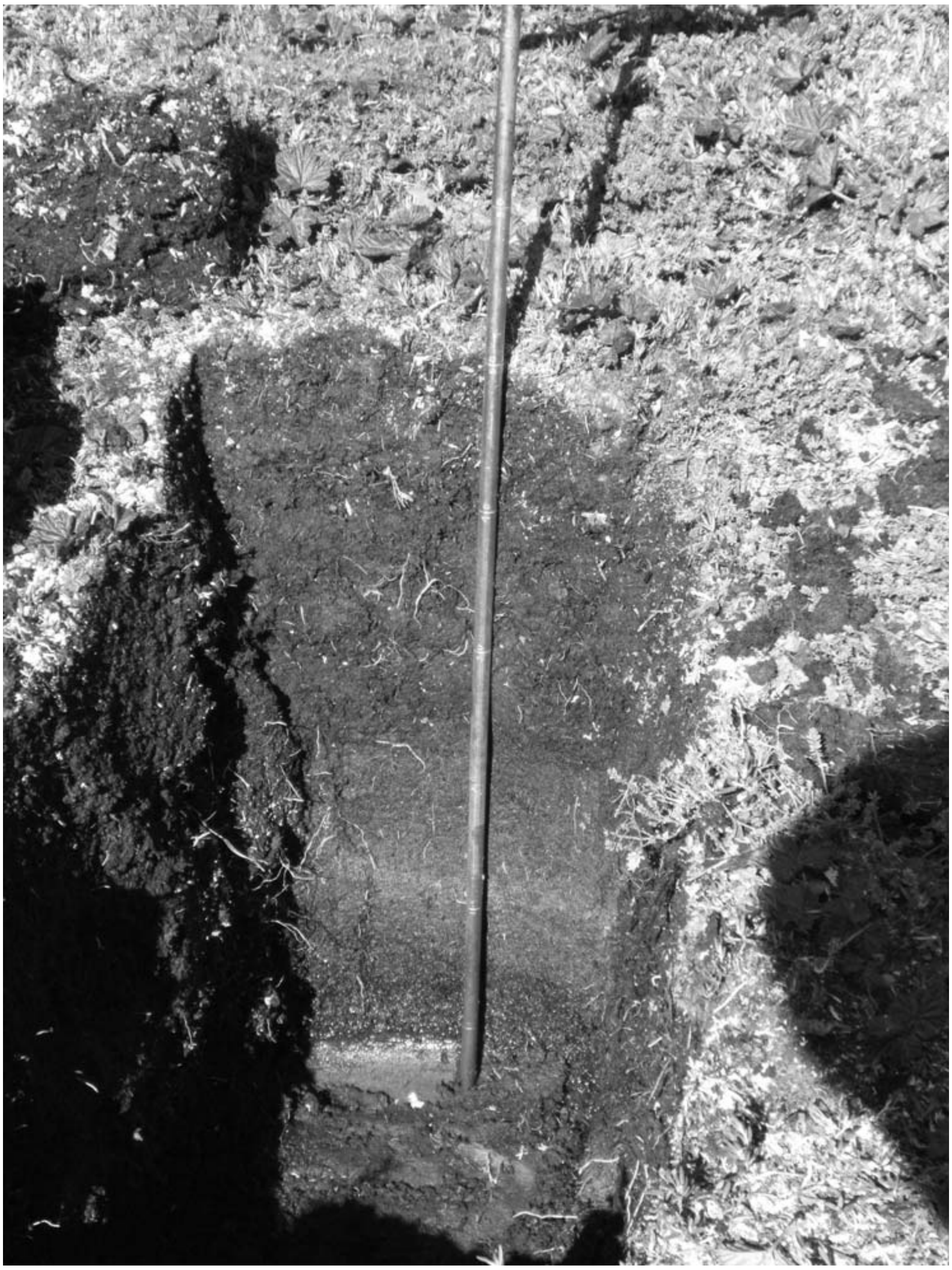

Fig. 4. The excavation made on the Storflaket mire near ERT surveys profile (Fig. 2), showing the base of the active layer at a depth of *c.* 80 cm.

Resistivity values obtained by profiling the slope at altitudes between 890 and 950 m a.s.l. are generally low (*c.* 12 kΩm for high resistivity anomalies) (Fig. 6). Second ERT profile was made in the hanging-like valley located in the upper part

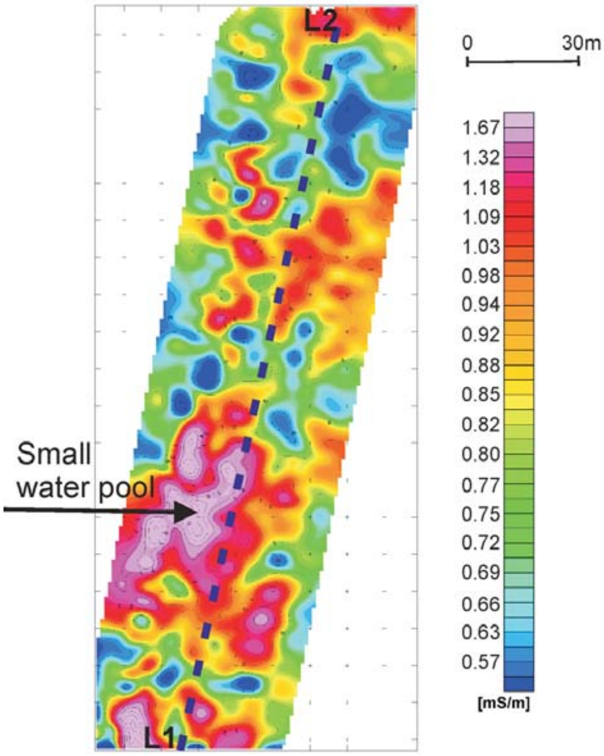

Fig. 5. Map of conductivity variation showing the results of shallow electromagnetic soundings using EM-31 conductivity meter. The broken line L1–L2 shows ERT surveys profile which is shown in Fig. 3.

of the mountain ridge. In the valley floor profile, resistivity values are much higher and exceed 40 kΩm. With respect to the great contrast in resistivity values, it may safely be assumed that, in both cases, discontinuous permafrost is present and that the lower limit of its occurrence lies on the slope. Such results from elswere in the Abisko area are similarly interpreted by Kneisel (2006). The results of the electro-resistivity profiling are confirmed by BTS measurements (Förster 2005) and the measurements of ground temperature (Jeckel 1988) made here also show that in this place the margin of mountain permafrost probably occurs.

Electroresistivity sounding near the Abisko Scientific Research Station (Fig. 7) was performed on vegetated coarse blocky cover, below the upper limit of forest grow (Fig. 1D). Nevertheless, a high resistivity anomaly of 13–20 kΩm was measured in this place as well. Resistivity values obtained there are similar to those obtained in the sounding on the Nuolia slope. If we assume that on Nuolia resistivity values indicate permafrost occurrence, which is confirmed by surveys conducted by other researchers, it seems reasonable to regard the high-resistivity anomaly in the profile near the Abisko station as a locus of sporadic permafrost occurrence. However, this result has yet to be confirmed by means of other methods.

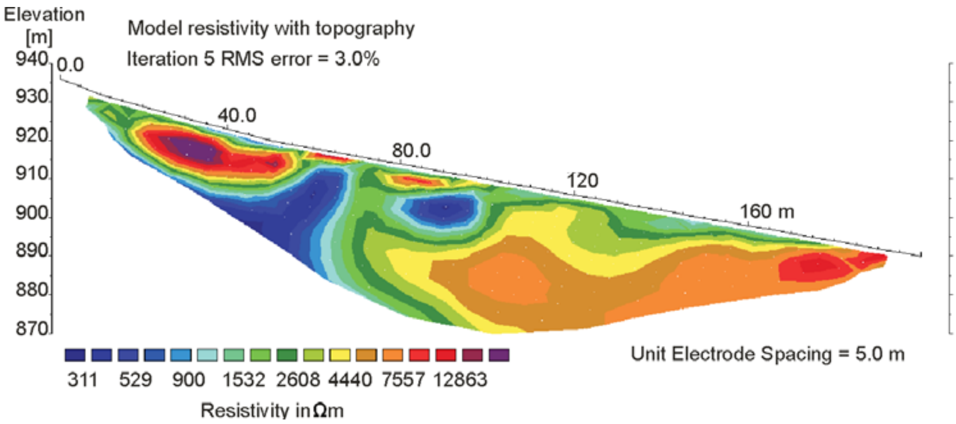

Fig. 6. The results of the ERT surveys profiling on the slope of Mount Nuolia.

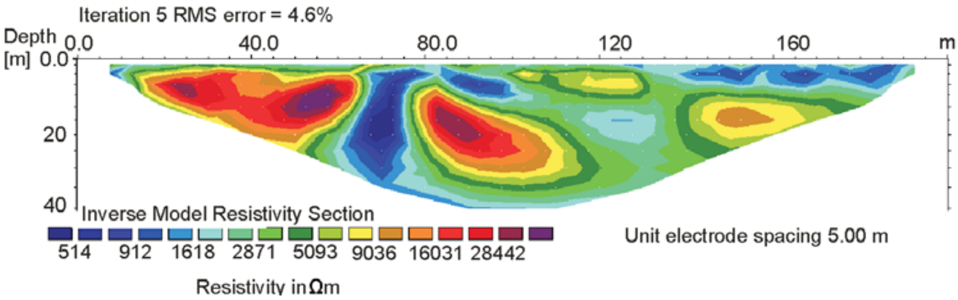

Fig. 7. The results of the ERT surveys profiling near the Abisko Scientific Station.

Björkstugans site. — This is a relatively small *roche moutonnée* moulded on granite, situated a few hundred meters to the north of the road Narvik-Kiruna, near Björkstugans (Fig. 1E). Its surface is fractured and covered with coarse blocky sediment which was partly deposited by glaciers and partly created in periglacial conditions prevailing there since the retreat of glacier. Some initial periglacial processes *e.g.* frost sorting was encountered. Two ERT profiles and EM 34 electromagnetic soundings were performed there. The E-W oriented profiling was 200 m long, thereby enabling interpretation of resistivity values at a depth of *c.* 40 m. The second was carried transversely and was 400 m in length. The two profiles intersecting in the middle.

The first profile shows a relatively homogenous structure dominated by very high resistivity values (20–30 kΩm) at depths below 5 m. Closer to the surface, resistivity values are more variable. A very characteristic image was obtained in a deeper sounding (Fig. 8). In this profile, at depth between *c.* 5–15 m, discontinuous high-resistivity anomalies (30–50 kΩm) are registered and a clear high-resistivity layer of a similar resistivity value is present at a depth of *c.* 30–60 m.

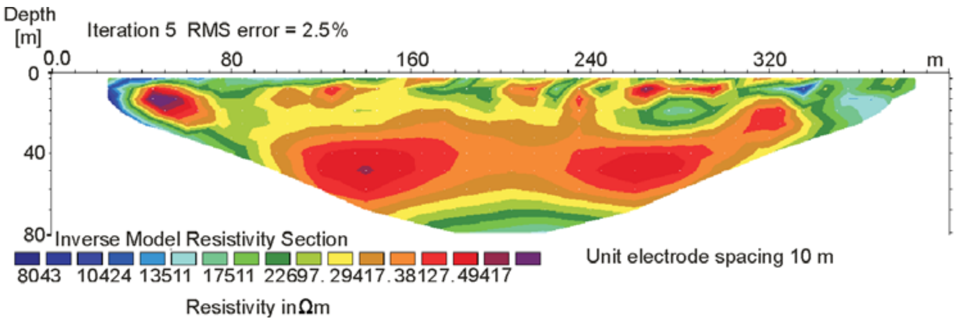

Fig. 8. The results of the ERT surveys profiling near the Björkstugans site.

These observations are supported by deep electromagnetic soundings, which indicate a distinct variation in electromagnetic conductivity at different depths. The map of electromagnetic conductivity drawn up for the depth of 15 m shows only a slight variation in value ranging from 3.2 to 4.0 mSm. At the depth of 30 m, conductivity decreases to 1.7–2.1 but rises again to 8.4–11.0 mSm at a depth of 60 m.

Discussion

By providing new data, the results of geophysical surveys on permafrost in the Abisko area reported here allow a broader look at the problems of identification of permafrost development than has been possible so far. Resistivity values, which have been interpreted by the author as characteristic of permafrost, vary greatly. In the palsa mire environment, resistivity values of frozen material may be as low as 500 Ωm, as it is confirmed by direct measurements of the active layer and excavation. Such low values result, among others, from the fact that an active layer existing over the permafrost table is often partially saturated with groundwater, and sometimes completely wet. Below this, particularly in a zone under the permafrost table, which is several decimeters thick, there is probably a rapid fall of temperature from 0 °C at the contact point with the active layer (and warm permafrost) to, probably, much lower temperatures at depths of between *c.* 1.5 and 5 m. Certainly, this is marked by a considerable increase in resistivity values at this depth. Depending on location (Figs 3, 6), below 5 m to depth of 20–30 m, the temperature within a permafrost layer probably stabilizes, just as resistivity value. Below, there is a steady increase in temperature, but its gradient is not as steep as in the case of the permafrost interface with the active layer. The greater degradation of permafrost here may be caused by small water reservoirs, which locally increase the depth of the active layer above 1 m.

The permafrost which occurs in the survey area is not always accompanied by ground ice. It is indicated by the surveys conducted on the *roche moutonnée* near

Björkstugans. Here high-resistivity anomalies can be observed both near the surface and at depth (Fig. 8). As in other places, the shallower anomalies can be interpreted as an active permafrost associated with contemporary climate. As it is probable that the geological structure in the survey areas is homogeneous, the changes in resistivity and electromagnetic conductivity values are doubt to be attributed to other than permafrost physical factors. Deep fracture system in the bedrock ought to be penetrated by water of meteoric origin, and such change should theoretically lead to a decrease in resistivity. However, the opposite is registered – resistivity is shown by these survey to rise. Perhaps then the high resistivity anomaly occurring here at a depth are better interpreted as dry, probably relict permafrost layer.

Such interpretation was applied by the author in similar terrain conditions in the Tatra Mts (Dobiński *et al.* 2006). Certainly, most of the world's permafrost developments resulted from Pleistocene cooling. In particular, this is true of the deeper developments. Ekman (1957) acknowledged the existence of permafrost, at least 70 m thick, near Låkktatjåkka, located few kilometers to the west from Mount Nuolia in the same mountains. Combination of relict and active permafrost are also distinguished in the same area in northern Sweden by King (1984, p. 36, table 6), who estimated that the depth of the active layer of relict permafrost is *c.* 400 cm and its thickness at 50–100 m. A similar situation is also registered in Tatras (Dobiński *et al.* 2006). In the 100 m deep borehole, near the Tarfala Research Station, located in the Kebnekaise Massif, south of Abisko, a temperature of -2.8 °C was registered at the bottom of the hole which suggests a permafrost thickness of *c.* 350 m in this place (Isaksen *et al*. 2001). It is clearly not possible for permafrost of such thickness to be solely an effect of current climatic impact.

The above assumptions are supported by an analysis of climate evolution in northern Scandinavia after deglaciation. A long-term climatic history of northern Scandinavia since deglaciation and tree limit changes in the Holocene were described mainly by Karlén (1976, 1979, 1981, 1993). The deglaciation of the Torneträsk area took place around 9000 ^{14}C years BP (Karlén 1979), and birch forest was established at the beginning of the Holocene. In the period 9000–7000 ^{14}C, climate was undergoing periodical fluctuations, reaching a thermal maximum *c.* 8000 ^{14}C years BP. The climatic optimum in that area lasted from *c.* 7000 to 3900 ^{14}C years BP, with noticeable cooling since *c.* 4500 ^{14}C years BP. The last 3900 ^{14}C years are characterised by alternations of cooler and warmer periods. The glaciers, which disappeared during the early Holocene, were reformed around 2000–3000 ^{14}C BP (Karlén 1981, 1993). According to whom, in that period, a maximum rise of about 200 m in the upper limit of forest growth took place in the Abisko area. Barenkow and Sandgren (2001) stated that, during the early and mid-Holocene, tree-line denoted by *Betula pubescens* was 300–400 m higher than today according to the macrofossil record from Lake Njulla.

Surely, the upper limit of forest is not an indicator that absolutely define the lower limit of permafrost development. Nevrtheless, it is often proposed as a reliable indicator of the MAAT (Hess 1965), and certainly permafrost requires a sub-zero MAAT to develop, actually below -1 °C (Jahn 1975; Haeberli 1985). Without doubt, permafrost can also develop sporadically below the tree line, but only in particularly conducive microclimatic and topographic conditions. If Haeberli's assumption concerning the time required for permafrost degradation is accepted (Haeberli 1985, p. 47), the location of the upper limit of birch forest can be used as an indicator of above-zero MAAT temperature. Accordingly, it may be suggested that in northern Scandinavia, where contemporary MAAT is *c.* -1 °C at *c.* 400 m a.s.l., climatic conditions that would allow a complete degradation of permafrost did not prevail long enough during the Holocene.

Conclusions

The geophysical surveys conducted in the Abisko area reported here yielded results which contribute new information concerning permafrost development and their geophysical properties. The lowest resistivity value in permafrost (in palsa mires), as confirmed by excavation, is *c.* 500 Ωm. The thickness of the permafrost layer varies greatly over short distances. In the mountain environment, near lower limit of permafrost, resistivity values reache about 12 kΩm, whereas dry permafrost in crystalline rock probably has resistivity value of *c.* 50 kΩm.

The author concludes that, in the Abisko area, two types of permafrost may be identified: a mountain permafrost, associated with a decrease in air temperature at altitudes above 500 m a.s.l. (Gorbunov 1988) and an arctic permafrost, associated with the cold climates typical of high latitudes, which occurs below the mountain environment at altitudes of *c.* 400 m a.s.l. Both types of permafrost are of an active character, and of discontinuous or sporadic form, and are associated with current climate. Evidentely, the Abisko area is a place where the two types of permafrost, latitudinal and altitudinal, meet. The results described here, *i.e.* that discontinuous/sporadic permafrost can exists at a MAAT of *c.* -1 °C, show that much milder climatic conditions than it is believed might be the cause of permafrost occurence at present.

Geophysical data and the analysis of climate evolution in the Holocene lead to the conclusion that in the lowland area of the Abisko area, depth *c.* 30 m, permafrost developments are associated with an earlier cool period, probably the Little Ice Age. In the tomographic profile of the Björkstugans area, two separate climate periods were probably registered during the Holocene. The older created a more deeply-located permafrost layer, which was not completely degraded during the intervening warm period, and a much younger, discontinuous form, relating to the contemporary climate. A similar occurrence of permafrost is also registered in the Tatra Mts of south Poland (Dobiński 2004). It cannot be excluded probably in other mountain ranges as well. Such an hypothesis could best be verified in a direct way, by means of temperature measurements in a drill hole.

The employment of geophysical methods in the research into permafrost should not be limited to detection of active permafrost, *i.e.* that associated with the present climate. The possibility of fossil permafrost occurrence, at much greater depths, should also be taken into consideration.

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