RECONNAISSANCE SURVEYS OF CONTEMPORARY PERMAFROST ENVIRONMENTS IN CENTRAL ICELAND USING GEOELECTRICAL METHODS: IMPLICATIONS FOR PERMAFROST DEGRADATION AND SEDIMENT FLUXES

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ABSTRACT. Four different sites in the highlands of central Iceland have been investigated for permafrost occurrence using two-dimensional resistivity imaging. The results of the surveys indicate the presence of shallow permafrost of low to medium resistivity. The distribution pattern is spatially heterogeneous which is consistent with permafrost at the fringe of seasonal frost. These sites are likely to react rapidly to changes of the environmental boundary conditions, therefore future research should include monitoring for detecting the early impact of climate change on permafrost degradation. The extent to which periglacial morphodynamics and sediment fluxes are influenced by permafrost and/or seasonal frost and potential permafrost degradation is hard to determine. Hence, long-term monitoring approaches for both permafrost and sediment dynamics are essential.

Key words: permafrost environments, central Iceland, heterogeneous permafrost distribution, palsa, seasonal frost, two-dimensional resistivity imaging

Introduction

Iceland is well known for its volcanic activity and high geothermal heat flux. However, there is geomorphological evidence that suggests the ground thermal regime is also influenced by permafrost which occurs in different mountain environments around the island (e.g. Thorarinsson 1951; Frideman *et al.* 1971; Schunke 1975). To date, most of the permafrost-related research in Iceland has been concentrated in the north, on Tröllaskagi peninsula, where Martin and Whalley (1987) and Whalley and Martin (1994) described rock glaciers related to temperate glacier ice. More recently Wangensteen *et al.* (2006) measured surface displacement rates on debris-covered glaciers and rock glaciers using digital photogrammetry. The analysis of the flow dynamics indicates a mixture of glacial flow and additional creep taking place in the surface of the debris-covered glacier and the glacier-derived rock glaciers. Further permafrost investigations were conducted by Etzelmüller *et al.* (2006) also in Tröllaskagi and eastern Iceland, borehole temperature measurements and geoelectrical surveys indicate warm (above –1°C), thin mountain permafrost occurrences at altitudes above 850 to 900 m a.s.l. in wind-blown areas in the highlands of eastern Iceland.

In the central highlands of Iceland only one study into the seasonal and annual dynamics of frozen ground and palsas has been undertaken in the area south of Hofsjökull (Thórhallsdóttir 1996). In recent years the Natural Research Centre of North-western Iceland and the Agricultural University of Iceland have carried out studies on the palsa site at Orravatnsrústir, north of the Hofsjökull glacier. These studies have focused on the origin and size distribution of the palsas, and the thickness of the active layer.

In July 2005, systematic permafrost investigations were started at four sites in the highlands south of the Skagafjörður fjord in central Iceland (Kneisel *et al.* 2006). The sites were selected to represent different periglacial environments, with and without obvious geomorphological evidence of the presence of permafrost. These included a flat mountainous periglacial area, a mountainous envi-

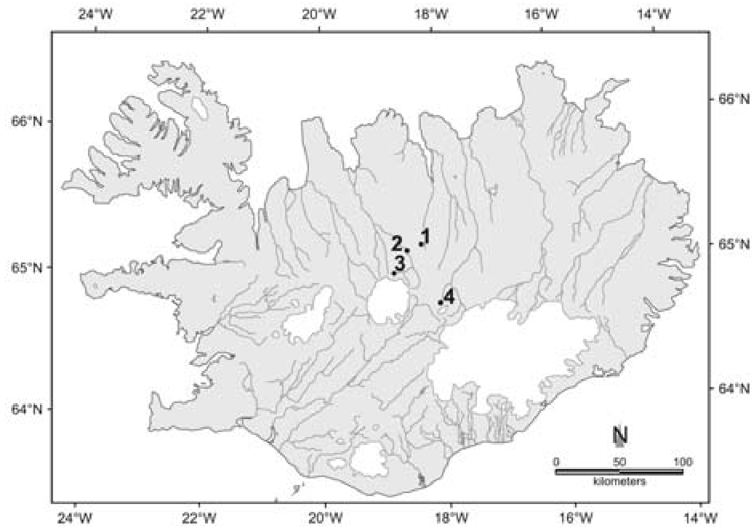

Fig. 1. Map of the location of the study areas: 1, the Nýjabæjarfjall Mountain site; 2, the Orravatnsrústir palsa site: 3, the Krókafell Mountain site; 4, the Sprengisandur site

ronment with solifluction slopes of different exposure, and a site with well developed palsas as an obvious geomorphological indicator of sporadic or isolated permafrost. This paper presents the preliminary data from the initial monitoring of these sites in central Iceland. The sites are thought to be characterized by sporadic mountain permafrost, and are at the fringe of permafrost existence. The sites have been selected as excellent locations for future monitoring of the impact of climate change on permafrost aggradation / degradation and related changes of sediment fluxes within the ESF SEDIFLUX and IAG/AIG SEDIBUD programmes (Beylich *et al*. 2006). This contribution provides first results of reconnaissance surveys of contemporary permafrost environments in central Iceland using two-dimensional electrical resistivity imaging with the main focus on the detection and the characterization of mountain permafrost being at the fringe of permafrost existence. Knowledge of the permafrost distribution and characteristics is of fundamental importance for the assessment of possible future permafrost and sediment dynamics.

Site locations and settings

The study areas include two periglacial sites, Nýjabæjarfjall Mountain (1000 m a.s.l.) and the Sprengisandur area (800 m a.s.l.), one site with well developed palsas, at the Orravatnsrústir palsa area (700 m a.s.l.), and one proglacial site at Krókafell Mountain on the northern margin of the Hofsjökull glacier (800 m a.s.l.).

Prior to this study most of these sites have been given little or no attention. One privately owned automatic weather station is located close to the Sprengisandur site, measuring only wind speed and air temperature. The climatic data given below are taken from the Meteorological Office database, giving annual values over temperature and precipitation from 1961 to 1990 (www.vedur.is). Only in the Orravatnsrústir site have mapping of vegetation and study on the palsa formation been carried out (Hirakawa 1986).

Nýjabæjarfjall Mountain

Nýjabæjarfjall Mountain is located in the southernmost part of the Tröllaskagi Mountain massif, between the Eyjafjörður and Skagafjörður valleys in central north Iceland (Fig. 1). Nýjabæjarfjall Mountain is an extensive mountain region, with several high peaks reaching up to 1000–1200 m a.s.l. Bedrock in the area belongs to the Tertiary basaltic formation, around 6–10 million years old. It is mainly composed of jointed basaltic lava flows, erupted subaerially. Individual flows vary in thickness from 2 to 30 m and are usually separated by lithified sedimentary horizons varying in thickness from a few centimetres to a few metres.

The surface of the mountain is boulder-rich, with little or no vegetation (Fig. 2a). The mean annual precipitation at Nýjabæjarfjall Mountain is estimated to be from 1200 to 1999 mm, which is slightly higher than for the surrounding areas, at lower elevations. The mean annual temperature is between

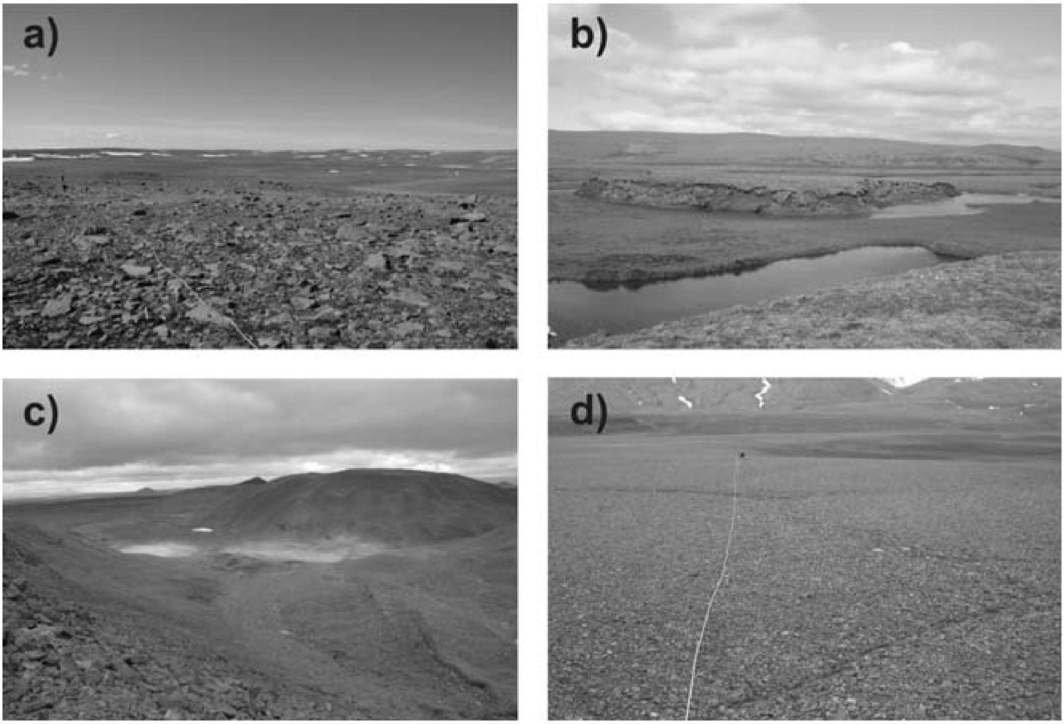

Fig. 2. (a) Nýjabæjarfjall plateau and multi-electrode cable. (b) Orravatnsrústir palsa site. (c) View from the slope of Krókafell Mountain towards Tvifell and ice-cored terminal moraine. (d) Resistivity survey layout, multi-electrode cable across frost-crack polygons at the Sprengisandur site

–4 and –6°C, with a mean July temperature of 2 to 4°C and mean December temperatures of –8 to –10°C (www.vedur.is).

The Orravatnsrústir palsa site

The Orravatnsrústir palsa site is located in the Hofsafrétt area north of the Hofsjökull glacier at approximately 710–715 m a.s.l. The site is characterized by well developed palsas surrounded by small lakes and ponds (Fig. 2b). The site is one of the best developed palsa sites in Iceland. In the northern part of the area the palsas are often around 40–60 cm high and up to 2000 m^2 in area. On the southern side the palsas are larger, 150–200 cm high and up to 2500 m^2 in area. The area is to a great extent vegetated, which is rather uncommon at this high altitude in Iceland.

The active layer depth at this site has been monitored since 2001 using a stainless steel rod which is pushed through the upper soil layers down to the permafrost table. Data were collected both in the northern and southern part of the area, along fixed transects across selected palsas. All the measurements were carried out in late summer, around the middle of September.

The mean annual precipitation at the Orravatnsrústir site is estimated to be 600 to 1199 mm, which might be partly explained by a rainshadow effect from the Hofsjökull glacier. The mean annual temperature is –2 to –4°C, with a mean July temperature of 4 to 6°C and mean December temperatures of –6 to –8°C (www.vedur.is).

Krókafell Mountain

Krókafell Mountain is located close to the northern margin of the Hofsjökull glacier (Fig. 1). The area is characterized by small hills or mountain ridges, 100–150 m high. The study site is located between Krókafell Mountain (966 m a.s.l.) in the west and Tvífell Mountain (1006 m a.s.l.) in the east (Fig. 2c). The bedrock in the area constists largely of Late Quaternary formations (younger than 800 000 years), mainly composed of hyaloclastic volcanic rocks erupted subglacially. A few postglacial lavas also occur in the area, e.g. the Lambahraun lava which is estimated to be around 3700 ^{14}C years in age (Hjartarson 2003).

The Hofsjökull glacier is an active central volcano with an ice-filled caldera. The glacier is the third largest glacier in Iceland (923 km^2) and the highest peak reaches 1800 m a.s.l. (Björnsson 1988). Since 1950, measurements on fluctuation of the northern margin of the Hofsjökull glacier have been carried out, just east of the Krókafell Mountain. Over the past 56 years the ice margin has retreated more than 600 m, at an average rate of approximately 11–12 m a^{-1}. This rate has varied over the years and during the last few years the average retreat rate has been 20–25 m a^{-1} (Sigurdsson 2000; Sigurdsson pers. comm).

The mean annual precipitation at Krókafell Mountain site is estimated to be 600 to 1199 mm, which might be partly explained by a rainshadow effect from the Hofsjökull glacier. The mean annual temperature is –2 to –4°C, with a mean July temperature of 4 to 6°C and mean December temperatures of –6 to –8°C (www.vedur.is).

The Sprengisandur site

The Sprengisandur site is located in the middle part of the Sprengisandur proglacial area between the Hofsjökull and Vatnajökull glaciers in central Iceland. The site is located close to the Tungnafellsjökull glacier at around 700–800 m a.s.l. (Fig 1.). The Sprengisandur proglacial area is approximately 70 km long from north to south and 30 km wide from east to west. The area is poorly vegetated and the surface shows indications of extensive wind erosion (Fig. 2d). The bedrock in the area is mainly composed of Late Quaternary formations (younger than 800 000 years), predominantly hyaloclastic volcanic rocks erupted subglacially during glacial periods and subaerial lava flows erupted during interglacial periods.

The mean annual precipitation at the Sprengisandur site is estimated to be 600 to 1199 mm, which might be partly explained by a rainshadow effect from the Vatnajökull glacier. The mean annual temperature is –2 to –4°C, with a mean July temperature of 4 to 6°C and mean December temperatures of –6 to –8°C (www.vedur.is).

Methods

Two-dimensional resistivity imaging was used to detect and characterize the permafrost and ground ice. This non-destructive geophysical tool yields comparatively quick and inexpensive results about the structure and stratigraphy of the subsurface. Knowledge of the permafrost conditions is useful in assessing slope stability, hydrology, sediment fluxes and other geomorphological processes (Haeberli *et al*. 1997; Harris *et al*. 2001; Kneisel 2005).

Electrical resistivity imaging

DC resistivity sounding is a traditional geophysical method that has been applied in permafrost research to confirm and characterize mountain permafrost (e.g. Hauck and Vonder Mühll 2003; Ishikawa *et al*. 2001; Kneisel and Hauck 2003; Kneisel 2006). Since a marked increase of electrical resistivity occurs at the freezing point, the method is expected to be most suitable to detect and characterize structures containing frozen material.

Resistivity surveys are conducted by injecting a direct electrical current (I) into the ground via two current electrodes (A and B). The resulting voltage difference (ΔV) is measured at two potential electrodes (M and N). The overall purpose of resistivity measurements is to determine the subsurface resistivity distribution. From the current (I) and voltage difference values (ΔV) the resistivity ρ is calculated:

$$\rho_\alpha = K \frac{\Delta V}{I} \qquad (1)$$

where K is a geometric factor which depends on the arrangement of the four electrodes. The calculated resistivity value is not the true resistivity of the subsurface, but a so-called 'apparent resistivity' ρ_a, which equals the true (or specific) resistivity only for a homogeneous subsurface. For heterogeneous resistivity distributions in the ground the resistivity can be derived from the measured apparent resistivity values using inversion methods implemented during post-processing of the data. The basic principle for the successful application of geoelectrical methods in geomorphology and Quaternary geology is based on the varying electrical conductivity of minerals, solid bedrock, sediments, air and water and consequently their varying electrical resistivity. The resistivity of rock, for example, depends on the degree of water saturation, chemical properties of pore water, structure of pore volume and temperature. The large variability in resistivity values for most materials is due to varying water content. Similarly, resistivity values of frozen ground can vary over a wide range of values (from 1–5 kΩ m

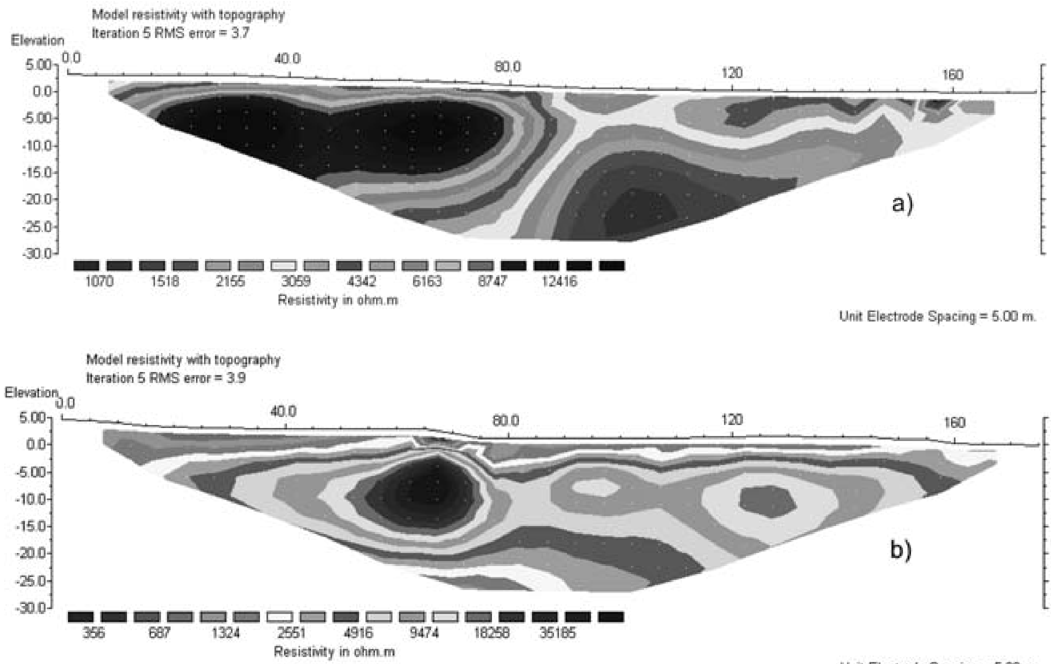

Fig. 3. Resistivity tomograms of two Wenner surveys across two different small solifluction terraces at the Nýjabæjarfjall site. Orientation of the profiles is SE–NW

to several hundred kΩ m or even a few MΩ m; Haeberli and Vonder Mühll 1996). Apart from the host material (soil or rock type of the frozen material) the resistivity is mainly dependent on the ice content, the temperature and any impurities which are present. The dependence of resistivity on temperature is closely related to the unfrozen water content. The differentiation between sedimentary ice (typical glacier ice) and congelation ice (typical permafrost ice) is based on the genetic/petrographic classification of Shumskii (1964). Congelation ice (interstitial and segregation ice), which is the predominant form of ground ice, shows much lower resistivities than sedimentary ice which forms by the metamorphosis of snow to firn-ice. Characteristic values for sedimentary ice from temperate alpine firn zones are several MΩ m to more than 100 MΩ m and for congelation ice 10 kΩ m to a few MΩ m.

For the two-dimensional (2D) surveys a SYSCAL Junior Switch system was used together with the Wenner, Wenner-Schlumberger and Dipole-Dipole array types. The data post-processing was performed using the RES2DINV software package. Since the raw data were of good quality, standard settings of the software could be applied for the analyses. The inversion software tries to reduce the difference between the calculated and measured apparent resistivity values by adjusting the resistivity of the model blocks. A measure of this difference is given by the root-mean-square error (RMS). However, the best model from a geomorphological or geological perspective might not be the one with the lowest possible RMS. Thus, it is essential to consider the local geomorphological setting when performing the interpretation. This enables unrealistic images of the subsurface structure to be excluded. Further details on different array geometries are given in Telford *et al*. (1990) and Reynolds (1997), and applications of different arrays to various geomorphological studies are described in Kneisel (2003, 2006).

Results and interpretation

The Nýjabæjarfjall site (1000 m a.s.l.)

For the characterization of the subsurface lithology at this site, 2D resistivity surveys were performed at various places on the mountain plateau. Figure 3 shows the results of two surveys across two small solifluction terraces. The image of re-

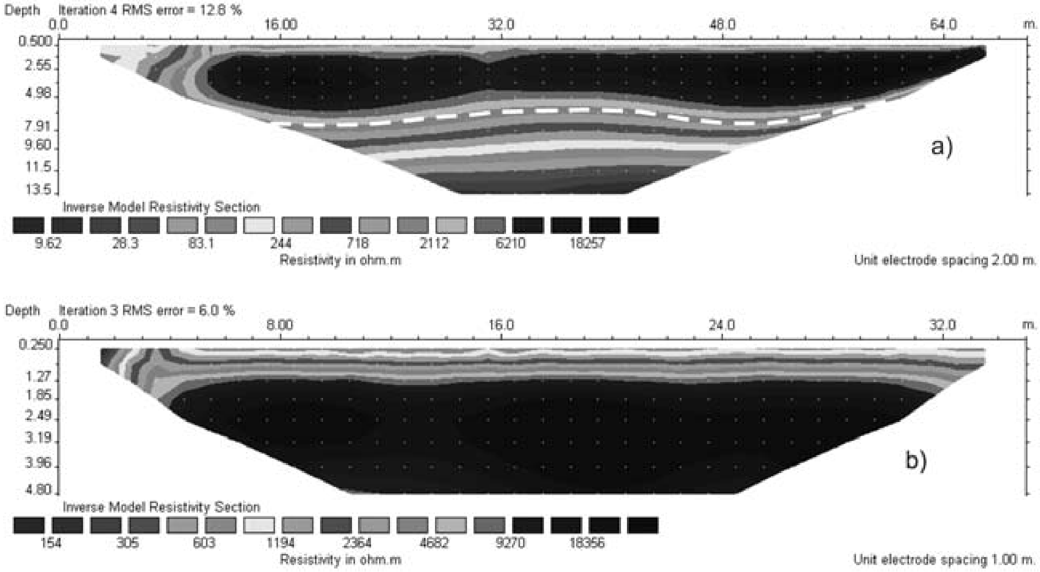

Fig. 4. Resistivity tomograms of two Wenner-Schlumberger surveys across a palsa at the Orravatnsrústir site using 2-m (a) and 1-m (b) spacing

sistivities against depth shows a large anomaly of higher resistivities at the left side of the tomogram, adjacent to an area where the subsurface is markedly more conductive (towards the right of the tomogram). The tomogram in Fig. 3b performed on another solifluction terrace at the same site shows a distinct area of higher resistivities between horizontal distance 45 m and 80 m and a less pronounced area of higher resistivity values between 110 m and 140 m.

From the range of resistivities measured, and the fact that the resistivities first increase with depth followed by a decrease below the detected higher resistivity anomalies, it can be concluded that the subsurface consists of shallow permafrost at both sites. The active layer appears to be comparatively thin which is probably due to the fact that the surface has become snow-free only recently. The geomorphological implication of the fact that this plateau and the adjacent slopes are partly underlain by permafrost is that the periglacial morphodynamics are permafrost-related and this will influence processes such as solifluction/gelifluction.

The Orravatnsrústir palsa site (700 m a.s.l.)

Investigations at this palsa site include active layer monitoring using a stainless steel rod, as well as electrical resistivity tomography to infer permafrost depth. The 2D geoelectrical surveys indicate that the permafrost depth varies around 6–8 m, below which very conductive material is detected (Fig. 4a). With a 2-m survey spacing the active layer depth could not be inferred from the resistivity measurements, therefore additional surveys with 1-m spacing were performed. From the results of the survey (Fig. 4b) an active layer thickness of 35 to 75 cm is estimated, which compares well with the direct measurements of between 40 and 50 cm. The comparatively high RMS error of the tomogram in Fig. 4a is due to the fact that some electrodes were placed at the edge of the palsa in wet sediments or even water, hence there are highly conductive zones next to more resistive zones which influence the inversion routine. Results from the five-year period of direct active layer monitoring at this site indicate that considerable variation has occurred in the thickness of the active layer. In 2001 the average thickness of the active layer ranged from 45 to 65 cm. In 2003 the average thickness of the active layer ranged from 65 to 75 cm and in 2006 the thickness ranged from 77 to 81 cm. These measurements suggest the thickness of the active layer is increasing, which can be directly related to higher summer temperatures in the highlands north of the Hofsjökull glacier during the last few years.

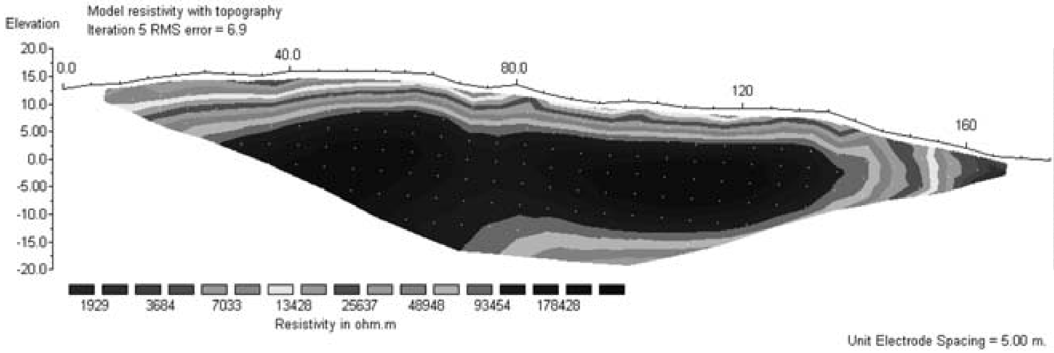

Fig. 5. Resistivity tomogram of a Wenner survey on the ice-cored moraine north of Hofsjökull at the Krókafell site. Orientation of the profile is SE–NW

The Krókafell site (800 m a.s.l.)

In this area north of the Hofsjökull glacier, a survey on a terminal moraine complex was performed in order to determine whether the moraine contained massive ice all over the survey line. Based on the results, the presence of massive ground ice of considerable thickness could be confirmed in the moraine. This is clearly visible in the high resistivities in the tomogram (Fig. 5). During a site visit in summer 2006, exposed massive ice was found on the moraine. Similar profiles have been measured on moraines in the Swiss Alps and northern Sweden (Kneisel 2004, 2006).

Additional surveys were performed on adjacent slopes in an area of solifluction lobes and terracettes (west-exposed and east-exposed slopes). The image of resistivities against depth shows a general decrease in resistivity with depth at the west-exposed slope (Fig. 6). The high resistivities at the lower end of this profile might be due to bad coupling of the electrodes to the ground. Nevertheless, the results are interpreted as a shallow permafrost occurrence at the fringe of the permafrost distribution. The small but widespread solifluction phenomena at this site are thought to have originated due to the presence of underlying permafrost. The survey at the east-exposed slope was performed across a solifluction terracette and shows a distinct high-resistivity anomaly in the central part (Fig. 7a). To obtain a more reliable interpretation, a second perpendicular profile was carried out (Fig. 7b). The active layer appears to be comparatively thin which is again due to the fact that the surface has become snow-free only recently. The results of the two surveys are consistent, leading to the geomorphological interpretation that this slope is underlain by permafrost and that the morphodynamics are related to the presence of active permafrost resulting in gelifluction and the formation of solifluction terraces.

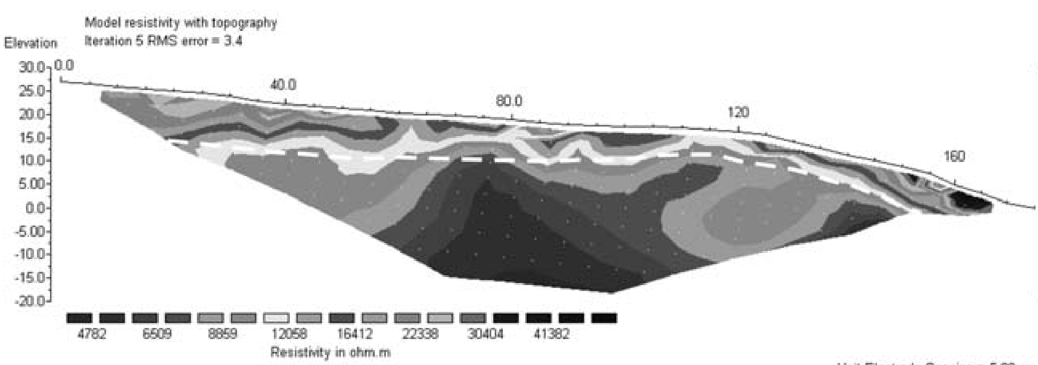

Fig. 6. Resistivity tomogram of a Wenner-Schlumberger survey across a solifluction slope at the Krókafell site. Orientation of the profile is N–S

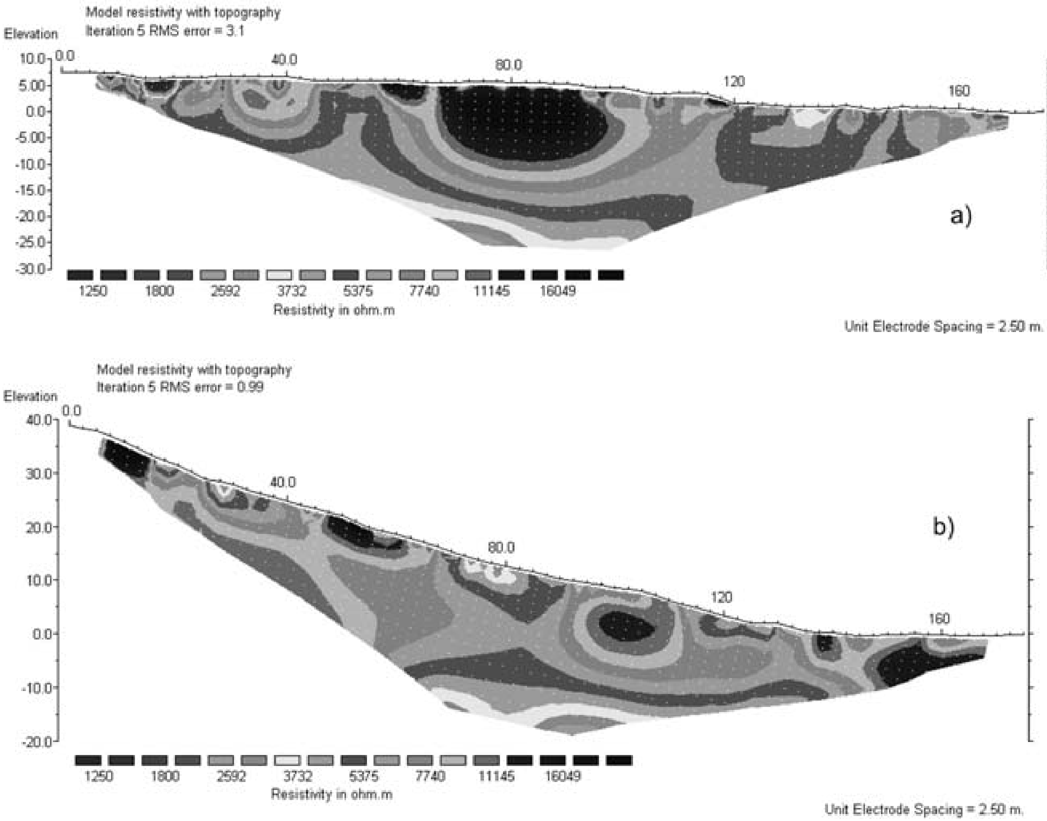

Fig. 7. Resistivity tomogram of two Wenner surveys across a solifluction slope at the Krókafell site: (a) across the slope; (b) downslope. Orientation of the profiles is SE-NW (a) and SW–NE (b)

The Sprengisandur site (800 m a.s.l.)

At the Sprengisandur site several geoelectrical surveys using the Wenner-Schlumberger configuration with 2-m spacing have been performed across frost-crack polygon fields (Fig. 2d). The tomogram in Fig. 8 shows a general decrease in resistivity with depth. Below an approximately 5-m deep surface layer of higher resistivities, the subsurface shows greater conductivity at depth. This resistivity structure could be due to a subsurface layer of higher moisture content below a dryer surface layer. The top layer below about 1 m depth might also consist of still frozen fine-grained sediments causing the higher resistivity values. This site is thought to be at the boundary between possible sporadic permafrost occurrence and seasonal frost. The site could represent seasonal frost-crack polygons which occur in areas with discontinuous permafrost or seasonal frost and little snow cover. Alternatively, the opening of the several-metres-long cracks might be due to desiccation cracking in a colder period during the 'Little Ice Age' (c.f. French 1996). Direct monitoring of the crack systems or deep probing / drilling would be necessary to test these hypotheses. Miniature temperature loggers were placed in July 2006 in order to monitor the ground thermal regime at this site.

Conclusions and perspectives

The results of these reconnaissance geophysical surveys indicate mostly shallow permafrost occurrences consisting of low to medium resistivity permafrost showing a heterogeneous distribution pattern. The comparatively low resistivities could point to 'warm' permafrost containing a certain amount of unfrozen water causing the better conductivity, similar to results of geoelectrical surveys on mountain permafrost in northern Sweden and

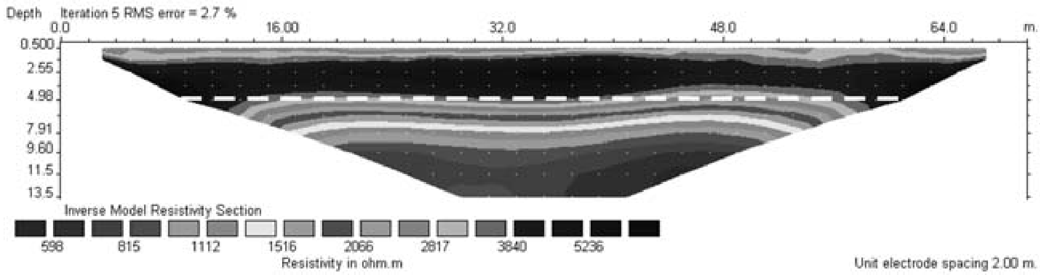

Fig. 8. Resistivity tomogram obtained on the frost-crack polygon field at the Sprengisandur site shown in Fig. 2d. Orientation of the profile is NW–SE

Switzerland. This assumption is supported by findings from Etzelmüller *et al*. (2006) from borehole temperature measurements and geoelectrical surveys in the highlands of eastern Iceland.

The dynamics of permafrost and seasonal frozen ground are of particular interest close to its limits, since the marginal zones are most sensitive to environmental change. Since the investigated permafrost environments in Iceland will possibly react rapidly to potential changes of the environmental boundary conditions, future research should include a combined approach consisting of geoelectrical monitoring at selected sites in conjunction with ground surface and subsurface temperature monitoring. Near-surface ground temperature monitoring was started in summer 2006 at the Krókafell site, the Sprengisandur site and the Orravatnsrústir palsa site using miniature temperature loggers. A major focus should be on monitoring the effects of changes in permafrost on surface sediment fluxes because these have the greatest potential to cause adverse environmental effects (Beylich *et al*. 2006).

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