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Application of DC resistivity soundings and geomorphological surveys in studies of modern Arctic glacier marginal zones, Petuniabukta, Spitsbergen

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Abstract: DC resistivity soundings and geomorphological surveys have been carried out in the marginal zones and adjacent outwash plains of two glaciers in central Spitsbergen, Norwegian Arctic: Ebbabreen and Hörbyebreen. The study has revealed complex relationships between landforms, buried glacier ice and permafrost. From this work it is possible to distinguish between moraine ridges which are ice-cored and those which are not. The latter occur in areas which have possibly been affected by glacier surge. The active layer thickness was found to be 0.4 to 2.5 m for diamicton deposits (moraines) and 0.3 to 1.6 m in outwash glacifluvial sediments. The sediment infill thickness in valleys was determined to be as much as 20 m, thereby demonstrating that sandurs have important role in sediment storage in a glacial system. Typical resistivity values for sediment types in both the active layer and in permafrost were also determined.

Key words: Arctic, Spitsbergen, DC resistivity sounding, permafrost, glacial geomorphology.

Introduction

Geomorphological and depositional effects of modern glaciers action in Spitsbergen (Svalbard, Norwegian Artic) have been a subject of numerous studies (*e.g.* Karczewski 1982; Hagen *et al.* 1993; Glasser *et al.* 1998; Sørbel *et al.* 2001). However, existing knowledge is based almost entirely on morphological evidence and the nature of surface sediments. Consequently, prediction of reactions to changing environmental conditions cannot be made with any degree of confidence. Also, as in much as modern Arctic glaciers have been used as models for former ice sheets (*e.g.* Boulton 1972a), a fuller understanding of recent glacial activity might help to explain the behavior of the former glaciers. A 3D view of modern marginal zones, which would permit the study of the vertical variability of glacial sediments, as well as demonstrating the existence of glacier ice under a debris cover, is obviously desirable. However, owing to a general lack of appropriate outcrops in frozen ground conditions, this situation is infrequent. Normally the thickness of the glacial and glacifluvial sediments can only be surmised. An alternative source of information may be geophysical survey. In recent years, several geophysical methods were developed to study ground characteristics of permafrost regions in both polar and mountain areas (Vonder Mühll *et al.* 2001). The most common are: refraction seismics (*e.g.* Wagner 1996; Kneisel and Hauck 2003), DC resistivity soundings (*e.g.* Fisch *et al.* 1977; King *et al.* 1987; Evin *et al.* 1997; Everest and Bradwell 2003), ground penetrating radar (*e.g.* Lehmann *et al*. 1997; Isaksen *et al*. 2000) and electromagnetic induction (*e.g.* Hauck *et al.* 2001).

The present study has been carried out in marginal zones and adjacent outwash plains of two glaciers in central Spitsbergen. Our investigation aimed to ascertain the geological structure of landforms; whether glacier ice and permafrost are present beneath debris cover in modern glacial marginal zones and to asses the thickness of sediments in the proglacial zones. The study included geomorphological survey and DC resistivity soundings. The latter method uses direct current to investigate the electrical resistivity of the subsurface. Interpretation of the soundings may lead to identification of the number of layers present in the investigated medium (in vertical direction), their resistivities and approximate thicknesses. The method is particularly valuable when layers with contrasting resistivity values are present. For instance, it can normally identify between clastic sediments and ice, the latter having resistivities which are one to two orders of magnitude higher (Østrem 1959; Hoelzle 1993; Guglielmin *et al.* 1997; Everest and Bradwell 2003; Etzelmüller *et al.* 2003).

Most of the land-terminating glaciers on Spitsbergen have moraine ridges, which are generally believed to have been ice-cored and to have been generated either during the Little Ice Age maximum or during glacier surges (Kozarski 1982; Hagen *et al.* 1993; Hambrey *et al.* 1996; Bennett *et al.* 1999). Whether or not the moraines are ice-cored is of considerable importance for interpreting their genesis and for forecasting the evolution of landscape consequent on future ice core melting. The latter is largely controlled by the distribution of the permafrost, which may also be successfully examined by DC resistivity soundings (*e.g.* Evin and Fabre 1990). Also, it may be possible, in certain cases, to distinguish clastic sediments from bedrock on the basis of variation in the resistivity values (Vonder Mühll *et al.* 2001). The information about the amount of sediments stored in valleys may offer new insights into aspects of their sediment storage potential.

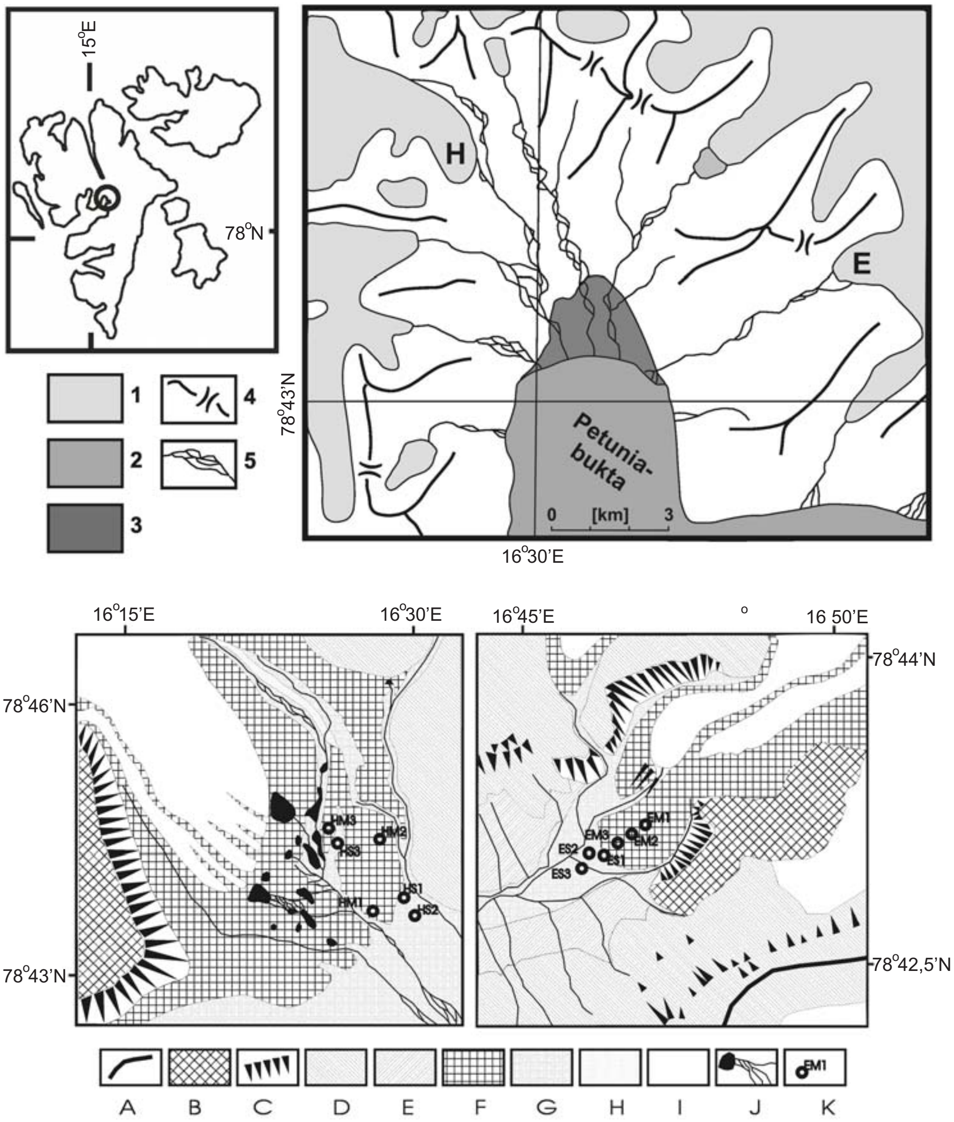

Fig. 1. The study site and location of measurement profiles in marginal zones of Hörbyebreen (H) and Ebbabreen (E). Modern glacier limits are marked on the basis of own GPS survey. 1 – glaciers; 2 – sea water; 3 – tidal flat; 4 – mountain ridges and passes; 5 – hydrographic network; A – mountain ridges; B – weathering covers; C – steep rocky walls; D – slope deposits; E – fluvial-fan deposits; F – morainic deposits; G – sandur deposits; H – crevasse-filling deposits; I – glacier ice; J – lakes and streams; K – measurement points.

The main aims of the research were threefold:

- description of modern glacier marginal zones, focussing on buried ice and permafrost features in relation to glacier dynamics;

Fig. 2. Oblique photograph of Ebbabreen marginal zone and adjacent sandur. Note the distance of ice front retreat from the maximum extent in the Little Ice Age (LIA).
Photo taken by G. Rachlewicz, July 2003.

- estimation of clastic sediment thickness, to assess whether modern Arctic valleys serve as a source, sink or transfer zone for sediments; and
- to assess the applicability of DC resistivity soundings in the investigation of polar region landforms.

Study area

The surveys were carried out in the marginal zones of two glaciers: Ebbabreen and Hörbyebreen, and their adjacent sandurs. The glaciers are located at Petuniabukta, in the central part of Spitsbergen, Norwegian Arctic (Fig. 1). Both glaciers are polythermal (naled ice was observed in their forefields during the study period 2000–2003). The Ebbabreen represents a complex outlet glacier with an area of c. 24.6 km^2. Hörbyebreen is a valley glacier system comprising two main ice streams and four small tributary glaciers, the total area of which is c. 21.7 km^2. Both glaciers were in recession during the last hundred years. The average ice front retreat rate for the last 44 years was between 15 and 28 m y^{-1} for Ebbabreen and Hörbyebreen, respectively (Rachlewicz and Szczuciński 2002). The decrease in

Fig. 3. Oblique photograph of Hörbyebreen marginal zone and adjacent sandur. Note the distance of ice front retreat from the maximum extent in the Little Ice Age (LIA) and the disturbed shape of medial moraines (used by Karczewski (1989) as the surge evidence).
Photo taken by G. Rachlewicz, July 2003.

the area covered by ice is of 0.4 km^2 for Ebbabreen (Fig. 2) and 1.6 km^2 for Hörbyebreen (Fig. 3).

The bedrock geology is dominated by dislocations along the Billefjorden Fault Zone. The longitudinally-oriented faulting has brought a wide variety of rock types to outcrop in the study area. The Ebbabreen catchment is floored mainly by metamorphic rocks: amphibolites, schists and marbles, which are partly covered by carbonates with intercalations of anhydrite and siliclastic rocks. The Hörbyebreen drainage area is floored by similar sediments, although mudstones and coal seams are more prominent in the succession here (Dallmann *et al.* 1994).

The climate of the region is strongly modified by the warm West Spitsbergen Current (the northernmost extension of the Norwegian Atlantic Current), which makes it surprisingly mild, considering its northern latitude. The average annual temperature is about –6°C. The warmest month is July (5 to 6°C on average), and the coldest period is January – March (about –15°C). Precipitation is relatively low, annually about 400 mm (Førland and Hanssen-Bauer 2003; Hagen *et al.* 1993). On Spitsbergen, permafrost is continuous (with taliks under polythermal glaciers) and its thickness ranges from less than 100 m near the coasts to more than

500 m in the highlands (Humlum *et al.* 2003). The thaw zone reaches at maximum depth of more than 2 m, and depends on a range of factors: sediment/rock type, altitude, exposition, plant cover *etc.* (Grześ 1988).

The glaciers and their forefields have been mapped at scale of 1:40 000 (Karczewski *et al.* 1990) and several detailed studies of their geomorphology and glacial geology have also been carried out (Kłysz 1985; Karczewski 1989; Karczewski and Rygielski 1989; Stankowski *et al.* 1989). The present study hopes to extend these earlier efforts.

Methods

Detailed topographical mapping of the study area was based on a differential GPS survey. The studied sediments (from the land surface, natural outcrops and ditches dug to *c.* 1m – to the permafrost level) were described macroscopically, sampled and analyzed for basic properties (grain size, carbonate content, clast petrography).

Owing to the fact that different rock layers have different physical properties, it is possible to identify vertical changes in geological structure from variations of electrical resistivity. In areas of permafrost, a particularly strong contrast in resistivity exists between: water (~10–100 Ωm) and water saturated deposits, ground ice (10^3–10^6 Ωm) and glacier ice (10^6–>10^7 Ωm) (*e.g.* Etzelmüller *et al.* 2003). However, the exact values of the resistivity depend on several factors including rock/sediment type, water or ice content and temperature (*e.g.* Haeberli and Vonder Mühll 1996).

In general, a uniformly layered structure can fully be determined from DC resistivity sounding, but in practice there are some limitations. Therefore, certain assumptions must be established (Mussett and Aftab Khan 2000). Firstly, the ideal geological cross-section should consist of flat, parallel strata without any lateral variations or anisotropy, *i.e.* resistivity is expected to vary only in a vertical direction. Secondly, a sharp, easy-to-measure contrast between strata must be present. Often, it is quite difficult to maintain such conditions, in which case interpretation of the results may become uncertain.

In the present study, twelve DC resistivity soundings in four settings were carried out (Table 1) using a ABEM *Terrameter* in association with the automatic-multielectrode-sounding system ABEM, *Multimac*. All the electrodes were placed outward from the sounding center symmetrically in opposing directions and were connected by addressable switchers and cables to the main electrical device (*Terrameter*). The electrodes were hammered into ground to a depth of about 15–20 cm. Owing to difficult field conditions, for some soundings the electrode spacing was reduced. The results were calculated using the *Aquaphys* and *Winsev5* computer programs. The purpose of the geophysical interpretation is to fit the ob-

Table 1

Summary of data on measurement points locations, their geomorphological situation, surface deposits and the measurement parameters.

Sign Points	GPS position of the centre of each resistivity soundings	The spacing of the electrod AB/2 [m]	Geomorphological situation	Surface deposits
EM1	78°43.14'N 16°46.80'E	27	Ice-cored moraine	diamicton
EM2	78°43.13'N 16°46.58'E	27	Ice-cored moraine	diamicton
EM3	78°43.10'N 16°46.39'E	27	Ice-cored moraine	diamicton
ES1	78°43.02'N 16°46.19'E	38.9	Sandur	gravel, sand
ES2	78°43.03'N 16°45.31'E	38.9	Sandur	gravel, sand
ES3	78°42.95'N 16°44.93'E	27	Sandur	gravel, sand
HM1	78°44.49'N 16°27.39'E	18.7	Moraine	diamicton
HM2	78°44.48'N 16°27.60'E	13	Moraine	diamicton
HM3	78°44.57'N 16°26.46'E	27	Moraine ridge	diamicton
HS1	78°44.18'N 16°28.33'E	56.2	Sandur	sand, gravel
HS2	78°43.95'N 16°29.21'E	117	Sandur	sand, gravel
HS3	78°43.48'N 16°26.60'E	38.9	Sandur	sand, gravel

tained field data to the theoretical master curves and, consequently, to achieve the geoelectrical parameters (resistivity and thickness) of particular strata. On the basis of the results, 12 plots of apparent resistivity were made. The interpreted curves refer to two, three and four-layer models. The measurements were conducted in the middle of summer season, when the permafrost active layer was well developed.

Results

Ebbabreen marginal zone. — The marginal zone of Ebbabreen (Fig. 2) is composed of two parts. A prominent terminal moraine complex, known to be ice-cored, and believed to originate from the Little Ice Age maximum (end of the

Fig. 4. Ice core in the Ebbabreen marginal zone, exposed below a 1.5 m thick glacial diamicton cover in the marginal part of a moraine ridge. *Photo taken by G. Rachlewicz, July 2003.*

19th century), lies in its southern part. The ice core is visible in several sections cut by meltwater erosion or as a result of mass movement, and is probably linked with the modern glacier ice body (Fig. 4). The debris cover thickness in available places varies between 0.2 and 1.8 m. It is composed of material delivered mainly from supraglacial sources and has been transported to its terminal position partly via a medial moraine which descends from a prominent nunatak in the central part of the glacier basin. The dominant lithofacies are represented by different types of diamictons with large limestone boulders up to 5 m in diameter. They are poorly sorted and are composed of sub-rounded clasts. The carbonate content of the sediment matrix is < 15%. Their stability is variable owing to different moisture contents. In most cases, the upper part of debris cover is dry, but on slopes it is often wet and subjected to gravity-driven mass movements. Depressions between morainic hillocks are occupied by glacifluvial sediments in the form of crevasse fillings. The marginal zone in the northern part is developed on a bedrock step, and the modern glacier terminates directly at its edge. The main subglacial outflow is located there and meltwater cascades down via a waterfall which is several decameters high. No deposits from direct glacial sedimentation are preserved and, below this step, only glacifluvial sediments are present. A more detailed description of the marginal zone was given by Kłysz (1985).

Table 2

Measurement results – values of resistivity and thickness (thick.) of strata as well as their geological interpretation for locations in the Ebba valley.

EM1			EM2			EM3		
Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation
130	0.4	diamicton	1200	0.5	diamicton	145	0.4	diamicton
7000	1	diamicton in permafrost	5500	2	diamicton in permafrost	15 000	1	diamicton in permafrost
100000		glacier ice	10 0000		glacier ice	10 0000		glacier ice

ES1			ES2			ES3		
Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation
1050	1.6	dry sand/gravel	1470	1.6	dry sand/gravel	1250	0.3	dry sand/gravel
630	1	sand/gravel	650	0.9	sand/gravel	560	2	sand/gravel
11500		sand/gravel in permafrost	25 000		sand/gravel in permafrost	17 800		sand/gravel in permafrost

Three soundings at locations EM1, EM2, EM3, with short electrode spacing, (see Table 1) were surveyed on the moraine which was presumed to have an ice core. The interpreted resistivity sounding curves are nearly identical and are of A-type depicting a gradually increasing curve ($\rho_1 < \rho_2 < \rho_3$) (Fig. 5). The values of the resistivity increase with depth up to about 100 kΩm (Table 2). The layers distinguished in the models are of only limited thickness. RMS (root means square) errors of fitting the results to the master curves are below 10%.

Ebbabreen proglacial sandur. — In the upper part of the Ebba valley, braided stream systems from Ebbabreen and the adjacent glacier, Bertrambreen, have created a wide sandur plain. This is composed mainly of poorly-sorted coarse glacifluvial sediments and remnants of washed older till deposits. With distance from the glacier edge, progressive fining of the sediment fraction was noted, from the coarse gravel and boulder fraction in the most proximal part to medium sand fraction distally. Calcium carbonate contents vary between 5.3 and 9.0%. Meltwater reworking had small impact on larger clast roundness, however, small particles show much variability of surface abrasion levels.

The measurement points ES1, ES2, ES3 were situated on the broad outwash plain adjacent to the moraine ridge (Fig. 1). Although the area is relatively flat and without vegetation, investigations were difficult owing to the coarse-grained character of the deposits. Three-layer models are interpreted from the sounding results.

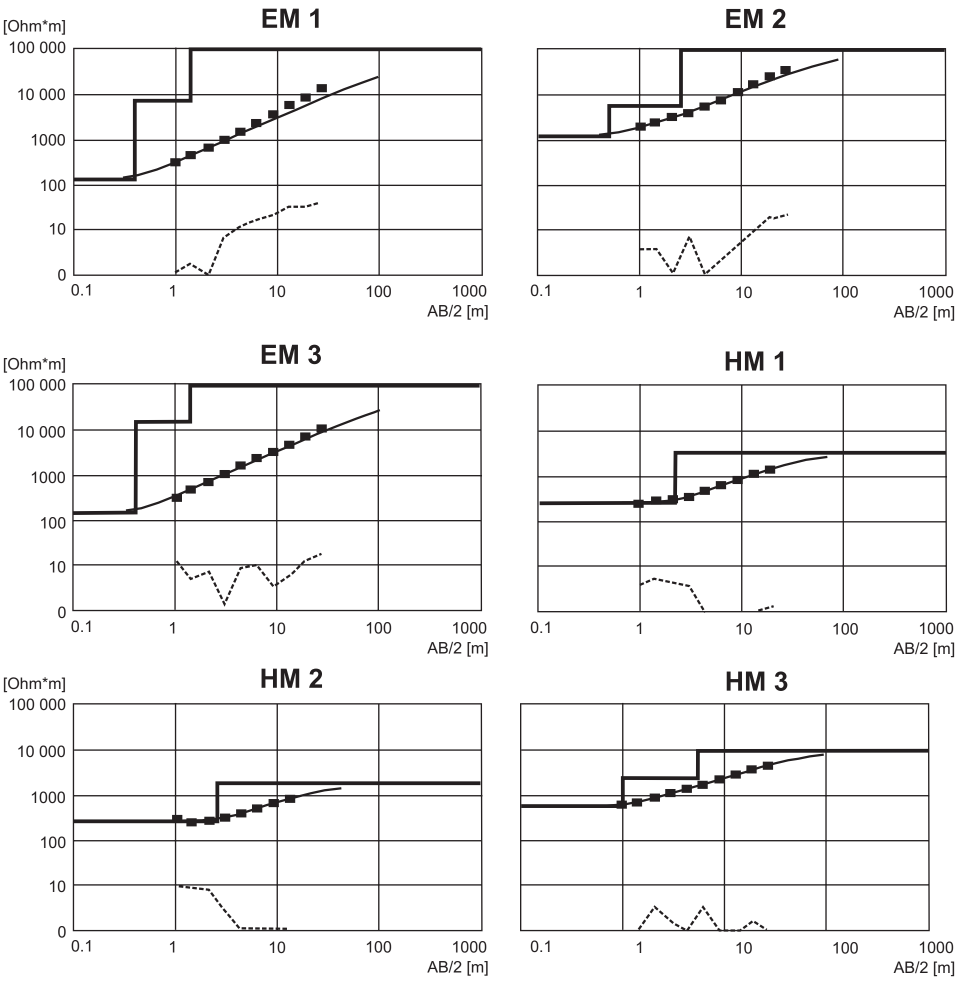

Fig. 5. Resistivity curves and models for sites localized on moraines of Ebbabreen (EM) and Hörbyebreen (HM). Square symbols – measured apparent resistivity values plotted against particular current electrode distance (AB/2) and fitted by synthetic curve resulting from the inversion procedure. Solid line denotes the layer model and the dashed line – the module of relative difference between measured and calculated apparent resistivity for the electrode spacing AB/2.

The resistivity sounding curves have a minimum (H-type) (Fig. 6). Comparing all three obtained models (Table 2) we distinguished: a surface layer of resistivity between 1050–1470 Ωm, a second layer with a lower resistivity about 600 Ωm and a third layer beginning at a depth of about 2.5 meters, which shows higher resistivity values (*e.g.* 25 000 Ωm or 17 800 Ωm). RMS fitting errors are insignificant (less than 3%), suggesting a reasonably good match of the curves to the data points.

Hörbyebreen moraines. — The marginal zone of Hörbyebreen is composed of elevated, ice cored lateral moraines, terminal moraine ridges, a complex belt of

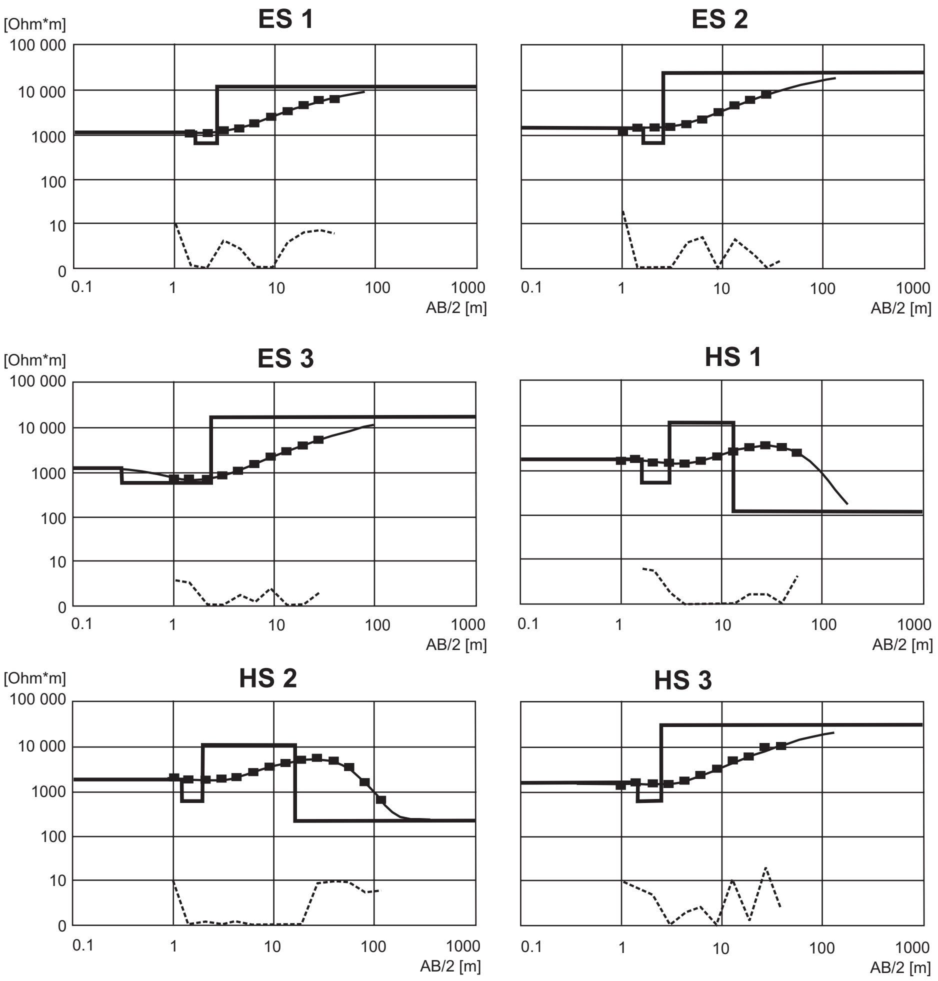

Fig. 6. Resistivity curves and models for sites localized on sandurs in marginal zones of Ebbabreen (ES) and Hörbyebreen (HS). Square symbols are measured apparent resistivity values plotted against particular current electrode distance (AB/2) and fitted by synthetic curve resulting from the inversion procedure. Solid line denotes the layer model and the dashed line – the module of relative difference between measured and calculated apparent resistivity for the electrode spacing AB/2.

moraine ridges originating from medial moraines and undulating areas covered by glacial till. These are interspersed with small inner sandurs, eskers and ice-crevasse fills. The outer part of marginal zone represents a lobe-shaped hill complex typical of ice-advance. The zone is described in detail in several previous works (Karczewski 1989; Karczewski and Rygielski 1989; Wojciechowski 1989). All previous workers have speculated about the existence of ice cores in several of the landforms, but except in the case of lateral moraines no direct evidence of them is present. Also, the date and mechanism of the landform origin have yet to be determined, although Karczewski (1989) hypothesized that they are the products of gla-

Table 3

Measurement results – values of resistivity and thickness (thick.) of strata as well as their geological interpretation for locations in the Hörbye valley.

HM1			HM2			HM3		
Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation
265	2.2	diamicton	265	2.5	diamicton	550	1	diamicton
3400		gravel	1950		gravel	2400	4.5	gravel
						9700		sand/gravel in permafrost

HS1			HS2			HS3		
Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation	Resistivity [Ωm]	Thick. [m]	Interpretation
1800	1.6	dry sand/gravel	2000	1.2	dry sand/gravel	1450	1.5	dry sand/gravel
550	1.4	sand/gravel	565	0.7	sand/gravel	600	1	sand/gravel
12000	10	sand/gravel in permafrost	11 000	14	sand/gravel in permafrost	30 000		sand/gravel in permafrost
120		?	220		?			

cier surge. The moraine ridges are composed of diamicton with a smaller content of boulders than in case of Ebbabreen moraine. The petrography of the eratics is complex – limestones, sandstones and rhyolites prevail. The sediments covering moraine ridges are poorly sorted, with a carbonate content in the range 8–12%. The internal structure of many moraines comprises a thin layer of diamicton, overlying glacifluvial sediments, which continues extensively over the marginal zone. There are no direct traces of ice-cores.

One DC resistivity sounding (HM3) was carried out on a distinct moraine ridge and two (HM1, HM2) on an elevated flat moraine surface of complex origin (Fig. 1). Here, owing to the complex topography, only resistivity soundings with short spacing were carried out (Table 1). The results were interpreted from two-layer models for the points HM1 and HM2 and a three-layer model of A-type for the point HM3 (Fig. 5). The sediments are composed of a relatively thin (< 2.5 m) surface layer, which has low resistivity values, the second and the third layers (only at the point HM3) having much higher resistivity values (several thousands of Ωm) (Table 3). All models have RMS fitting errors at very low level: approximately 2%.

Hörbyebreen sandurs. — An extensive sandur plain was created by braided meltwater streams in front of the morainic complex, which originated from Hörbyebreen and, in lower parts, also from Svenbreen and Ragnarbreen. Small sandurs are also present within this complex of moraines and between modern glacier edge and the morainic belt; these are known as "inner sandurs" (Rachlewicz and Rygielski 1988). The latter and the proximal zone of the major sandur are composed of coarse material, deposited in a high energy braided river environment (Rachlewicz 1989). Distally, the sediments are finer and, at sea level, the sandur becomes a muddy tidal flat. The sediments are usually poorly sorted with some intercalations of well-sorted finer sediments (sand or silt). The petrography of the gravel fraction reflects the source rock composition and is represented by both igneous rocks and sedimentary rocks. The carbonate content is in range 3.4–9.6%. In the river banks the thickness of sediments observed is ≥1.5 m.

Two DC resistivity soundings were carried out on the broad outwash plain in the front of the Hörbyebreen marginal zone (points HS1 and HS2) and on the inner sandur deposits (HS3), between moraine ridges and closer to the modern ice margin (Fig. 1). The measurements on the outwash plain yielded four-layer resistivity sounding curves of HK-type and a three-layer curve of type H on the inner sandur (HS3) (Fig. 6). Interpretation of the DC resistivity sounding curves reveals similar parameters for the interpreted layers (Table 3). Differences might occur in respect of the different distance of electrode spacings (AB/2: 38.9 m for HS3, 56.2 m for HS1 and 117 m for HS2). The RMS fitting error is about 4%. Resistivity values of the first layer vary from 1450 to 2000 Ωm, with similar thicknesses at all locations (c. 1.5 m). The next layer, about 1 m thick, has a resistivity values of about 600 Ωm. The third layer, which is the thickest and has the highest resistivity values, appears below at depth of about 3 m (*i.e.* 11 000 Ωm in HS2 or 30 000 Ωm in HS3). At the points HS1 and HS2, a fourth layer with considerably lower resistivity values in the range of 120–220 Ωm was distinguished.

Interpretation and discussion

The interpretation of DC resistivity soundings (Tables 2 and 3) is based on both electrical resistivity values and direct field survey. Below are presented possible interpretations for the studied cases and their implications.

Ebbabreen marginal zone. — Three layers of different resistivity were observed in the Ebbabreen marginal zone. These are interpreted as: a superficial layer of coarse grained diamicton deposits which overlie diamicton in a permafrost zone, which, in turn, overlies glacier ice (Table 2). This explanation is not contradicted by field observations – in several places an ice core coated by about 1–2 m of debris cover has been observed. On the basis of differences in resistivity values within the debris cover two zones are distinguished. Because the permafrost conditions increase the values of resistivity, we believe that the resultant geoelectrical model is an effect of both changing thermal conditions and the possible presence of ground ice rather than any variation in sediment type. The very high values of the lowest layer are typical of glacier ice (*e.g.* Evin and Fabre 1990; Evin *et al.* 1997;

Etzelmüller *et al.* 2003 – see Table 4). Presumably, permafrost conditions above the glacier and high resistivity values of glacier ice imply that, currently, the ice is not melting in the places where it is covered by a debris blanket. It also reflects the thermal conditions of this part of glacier, assumed to be cold throughout. In fact, this condition is typical for a model polythermal glacier, where a part of a glacier tongue is frozen and, as such, causes sliding of warmer ice above it. The consequence of this is that subglacial debris is delivered into a supraglacial position and ice-cored moraines are formed (Boulton 1972b; Baranowski 1977). Ice-cored moraines in Svalbard are relatively common but a little is known about their thermal structure or their stability in modern climatic conditions (*e.g.* Araźny and Grześ 2000). In several cases on West Spitsbergen coast, ice cored moraine have been observed to disintegrate by mass movement (Szponar 1975; Bennett *et al.* 2000) as well as by progressive melting of an ice core. For example, Karczewski *et al.* (2002) measured the lowering of ice cored moraine surface in the vicinity of Hansbreen, Hornsund at between 7 to 14 cm yr^{-1} on average with a maximum of 28 cm yr^{-1} in the period 1984–1998. Hence, in respect that the reported form had a similar thickness of debris cover to that studied here, it is reasonable to speculate that central Spitsbergen is characterized by a colder climate, one which provides better conditions for the preservation of ice cored moraines. However, although the average temperature is indeed lower in the central part of the island (Hagen *et al.* 1993), such a conclusion should be treated with some reservation. Without question, more detail investigations are required to confirm such a relationship.

Ebbabreen proglacial sandur. — The results of DC resistivity soundings on the sandur in Ebbadalen best fit a three-layer model for the all measurement locations (Table 2). The surface layer is clearly related to coarse-grained, poorly-sorted braided river deposits which have numerous air-filled pore spaces and low soil-moisture content (the measurements were conducted in profiles, which now lie at some distance from active streams). The second layer has a slightly lower resistivity; we infer that this is represented by gravelly-sandy deposits similar to those of the first layer but which presumably have a higher soil-moisture content and/or a finer sediment. The third layer has the highest resistivity values. We conclude that it is probably a permafrost zone. The stable resistivity values in the permafrost zone suggest that any variability of the nature of the deposits is of minor importance; moreover, they probably represent a contemporary braided river facies. The resistivity values smaller than those expected for crystalline rocks, which are expected to floor the valley, so possibly up to 20 m of modern clastic sediments were deposited in this part of sandur. In turn, this indicates that the valley is important as a contemporary glacifluvial sediment storage zone in the modern polar environment.

Hörbyebreen moraines. — Whereas the resistivity soundings curves obtained from the Hörbyebreen marginal zone are similar to those from Ebbabreen, the resistivity values of certain layers are considerably lower (Table 3). In contrast

Table 4

Examples of resistivity values for deposits in permafrost conditions, after different sources and these in the present paper; units and classification of rock types follow original sources.

Rocks/Deposits		Resistivity values	Source
Active layer (different sediments)		15–25 kΩm	Isaksen *et al.* 2000
		8–15 kΩm	Kneisel and Hauck 2003
		20–40 kΩm	Kneisel 2004
Frozen ground (different sediments)		5×10^{3}–10^{6} Ωm	Kneisel 2004
		1–5-several hundred kΩm or even several kΩm	Hauck and Vonder Mühll 2003
Ground ice		10^{3}–10^{6} Ωm	Etzelmüller *et al.* 2003
Massive ground ice	Massive ice	>1.5 MΩm	Hauck and Vonder Mühll 2003
	Massive ground ice of polygenetic origin	>1 MΩm	Kneisel 2004
	Massive ice within a moraine	>100 kΩm	Hauck and Vonder Mühll 2003
	Massive ground ice	>1 MΩm	Kneisel 2004
Permafrost	Permafrost	about 20 kΩm	Vonder Mühll *et al.* 2001
	Permafrost in extensive boulder fields or blocky ground moraine	~100 kΩm	Etzelmüller *et al.* 2003
	Permafrost lenses	120 kΩm	Kneisel 2004
	Permafrost in non-bedrock areas	>20 kΩm	
	Permafrost	30–90 kΩm	Kneisel and Hauck 2003
		200–600 kΩm	Kneisel 2004
Frozen unconsolidated material		5–70 kΩm	Isaksen *et al.* 2000
		Few kΩm – several hundred kΩm or more	Ishikawa and Hirakawa 2000
Glacial sedimentary ice		10^{6}–>10^{7} Ωm	Etzelmüller *et al.* 2003
		Few MΩm – more than 100 MΩm	Kneisel 2004
Perennially frozen silt, sand, gravel or frozen debris with varying ice content		5 kΩm – several hundred kΩm	Kneisel and Hauck 2003
Unfrozen ground beneath permafrost		2–5 kΩm	Kneisel and Hauck 2003
Unfrozen material; sand and gravel		100–10 kΩm	Ishikawa and Hirakawa 2000
Cover of rock glacier (about 75% of ice content)		100–900 kΩm	Isaksen *et al.* 2000
Glacier ice		100 000 Ωm	this paper
Diamicton in permafrost zone		7000–15 000 Ωm	this paper
Unfrozen diamicton		130–1200 Ωm	this paper
Cobbles, gravel and sand in permafrost		11 000–30 000 Ωm	this paper
Sand and gravel		1050–2000 Ωm	this paper
Anhydrite (?)		120–220 Ωm	this paper

to the very coarse-grained diamicton deposits which cover the Ebbabreen ice cored moraine, the surface sediments in the Hörbyebreen marginal zone are much finer – probably to be due to the presence of several different bedrock types in the source area. Mudstones, siltstones and sandstones may reasonably be expected to supply finer debris than the hard crystalline rocks present in the Ebbabreen basin. The higher resistivity values in the deeper layer seem likely to be related to permafrost conditions though, certainly, the values are much lower than for glacial ice, therefore the possibility that an ice core is present here can be excluded. Also, there was no evidence of an ice core in the existing outcrops. This has important implications for its genesis. It was probably formed as a push moraine in conditions where the ice front remained unfrozen (in contrast to the Ebbabreen situation). Such conditions are met during glacier surge (*e.g.* Bennett *et al.* 1999) and our data, together with previous geomorphological indicators (the looped medial moraines, Karczewski 1989), suggest strongly this is likely. However, in respect that it must have happened before 1936 (on the evidence of air photography) there are no data on the timing of this event.

Hörbyebreen sandurs. — The structure of the sandur (inner and outer) in the forefield of Hörbyebreen, is very similar to that postulated for the sandur in Ebbadalen (Tables 2 and 3). The surface layer is composed of gravel and sand, and is underlain by a stratum which has slightly lower resistivity (lower resistivity in respect that it has a higher soil moisture and/or of finer fraction content). Both layers are 2–3 m thick and cover thick layers, which have a much higher resistivity value, interpreted here as clastic sediments in a permafrost zone. The the third layer is 10–14 m thick, again indicating that modern Arctic valleys are important as repositories for glacifluvial sediment storage. The lowest layer identified on the outer sandur (locations HS1 and HS2) is characterized by significantly lower resistivity values. It is not possible to make a positive identification of this layer. We consider it is probably bedrock, locally composed of anhydrite or gypsum (and possibly with a highly mineralised pore water content); however, it may also simply denote the lower limit of the permafrost. It is also possible that the lowermost layer is an effect of the model used, which assumes, for example, that the layers are horizontal. Uncertainties in interpretation, where sudden falls in resistivity are observed under a thick, high resistivity layer, were discussed for example by Kędzia *et al.* (1998).

Resistivity values. — Analysis of all the DC resistivity soundings enable us to list the ranges of electrical resistivity values for certain rock types (Table 4). The highest values are presented by glacier ice and sediments in the permafrost zone and the lowest for moist, fine-grain sediments and saline rocks (*e.g.* anhydrite). In Table 4 are also listed results of resistivity measurements of other types of sediments, also in permafrost. The comparison shows that the values obtained in this study are in the range of previously reported. The resistivities of sediments in the permafrost zone are smaller than for the similar sediments with high content of ground ice, so we conclude that there is little ice in the permafrost zone studied. This presumably reflects the generally dry climatic conditions of the study region. We believe that the DC resistivity sounding is a method of considerable value for identification of ice occurrence in the sediments (in a permafrost zone or as ice cores). However, the most effective approach would be as suggested in previous works (Vonder Mühll *et al.* 2001), the application of several geophysical methods at the same location – hopefully to omit mistakes generated by the method limitations. DC resistivity soundings could usefully be associated with seismic or electromagnetic induction methods. Also, the application of 2D resistivity imaging would significantly improve data quality (Hauck and Vonder Mühll 2003).

Conclusion

Our results reveal that DC resistivity sounding is a helpful tool in the study of modern glacier marginal zones in permafrost regions. Our data on the marginal zones show two contrasting examples of moraine ridges – those with ice cores and those without. The origin of the first type is related to the presence of cold ice in the marginal part of the glacier tongue; the second reflects rather more temperate conditions. In turn, this may indicate that the latter type (as at Hörbyebreen) was formed during recent surge activity. The presence of ice cores has important implications for future landscape development. If global warming is taking place (*e.g.* Førland and Hanssen-Bauer 2003) the ice cores will progressively melt away and the modern landforms will change significantly. However, in contemporary conditions, the whole ice core in the Ebbabreen moraine probably lies in the permafrost zone. Also resistivity data on the sediments in the permafrost zone suggests that they may contain a small amount of ground ice, which, in the context of possible future permafrost degradation, suggest smaller surface topography changes than in areas rich in ground ice. The significant thickness of glacifluvial deposits in the sandurs (at least 10 m) shows that valley floors serve not only as a sediment transfer zone but are also important as a sediment storage zone.

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