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COMMENTS AND OBSERVATIONS ON THE APPLICATION OF RESISTIVITY SOUNDING IN THE RESEARCH OF PERMAFROST

Abstract

When the method of resistivity soundings is applied in the research of permafrost number of problems with interpretation arise. This paper shows some theoretical and experimental results concerning the changes in shape of sounding curves for simplified models of permafrost. Properties of frozen rock material in relation to field resistivity data are discussed, too. Two examples of resistivity soundinds performed in different geological and geographical conditions are presented and analysed.

INTRODUCTION

Permafrost has been subject both to scientific and utilitarian examinations. The former type aims at identifying and explaining characteristic features of this phenomenon (ŁOZIŃSKI 1909; TUMIEL 1946; DYLIKOWA, OLCHOWIK 1954; DYLIK 1962; TRICART 1967; JAHN 1970; WASHBURN 1979; DANIŁOW 1990; FRENCH 1996), while the latter deals with the issues of construction, communication and the protection of underground infrastructure in the far north of America, Asia and Scandinavia (FERRIANS, KACHADORIAN, GREEN 1969; JOHNSTON 1981; PÉWÉ 1983). Such investigations involve, to a large extent, non-destructive geophysical exminations, in particular, the method of resistivity sounding. HAEBERLI (1985), FISCH, FISCH, HAEBERLI (1977); KING, FISCH, HAEBERLI, WAECHTER (1987) and KING (1982, 1984); KING, GORBUNOV, EVIN (1992) have largely focused on this method and their work provides vital information in this respect.

In Poland the problem of permafrost is basically non-existent. The only area where certain forms of permafrost may occur is the High Tatra Mountains. However, in the relevant specialist literature one can find opinions that modern permafrost also exists in the Sudety Mountains

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(CZUDEK 1986). In the early 1990's in the Polish part of the Tatra Mountains W. DOBIŃSKI was the first to look for permafrost using the method of resistivity soundings (DOBIŃSKI, GĄDEK, ŻOGAŁA, 1996). However, the obtained curves of soundings were hard to interpret in quantitative terms, which must have resulted from the extreme conditions in which the soundings were performed. In mid–1990's S. KĘDZIA (1999) started to look for permafrost in the Kozia Dolinka Valley. Geothermal examinations using the BTS method were performed, followed by resistivity soundings and the use of a thermovision camera (KĘDZIA, MOŚCICKI, WRÓBEL, 1998). These examinations are still being carried out and other methods of investigation have been used as well. Meanwhile, in 1998, for comparative purposes measurements of temperature and resistivity soundings were carried out in the vicinity of Abisko, Sweden (GAŁAŚ, KĘDZIA, MOŚCICKI, 1999).

In this article we will focus on a number of problems with interpretation which arise when the method of resistivity soundings is applied in the research of permafrost.

GENESIS OF PERMAFROST – SIMPLE GEOPHYSICAL MODEL

Permafrost occurs when favourable thermal conditions are locally present in the ground. A simplified model of this phenomenon is presented below.

Let us analyse the following situation. Let us assume that a rock medium is homogeneous (with a thermal diffusivity of α) and has a flat surface and sinusoidal fluctuations of temperature occur within the period P and amplitude T_0 on this surface. Let us also assume that the annual average temperature on the surface of the medium (MAST) is known, and that temperature rises according to the adopted value of the G geothermic gradient with increasing depth.

The desired temperature distribution in the medium in the function of depth *z* and time *t* is presented by the Fourier one-dimensional equation (INGERSOLL, 1948). The solution to the equation, given the above assumptions, can be obtained as follows:

$$T(z,t) = T_0 \cdot \exp(-z\sqrt{\pi/\alpha \cdot P}) \cdot \sin(t \cdot 2\pi/P - z \cdot \sqrt{\pi/\alpha \cdot P}) + MAST + G \cdot z$$

Fig.1 represents a graph (envelope) of extreme temperatures calculated for the assumed parameters characterising the medium (given in the table T_0, α and *G* correspond to the average values assumed for the lithosphere). We can see that depending on the time of year down to a depth of 8 m the temperature of the ground can be either above or below 0°C. Below this level, to a depth of over 40 m, the temperature of the medium is al-

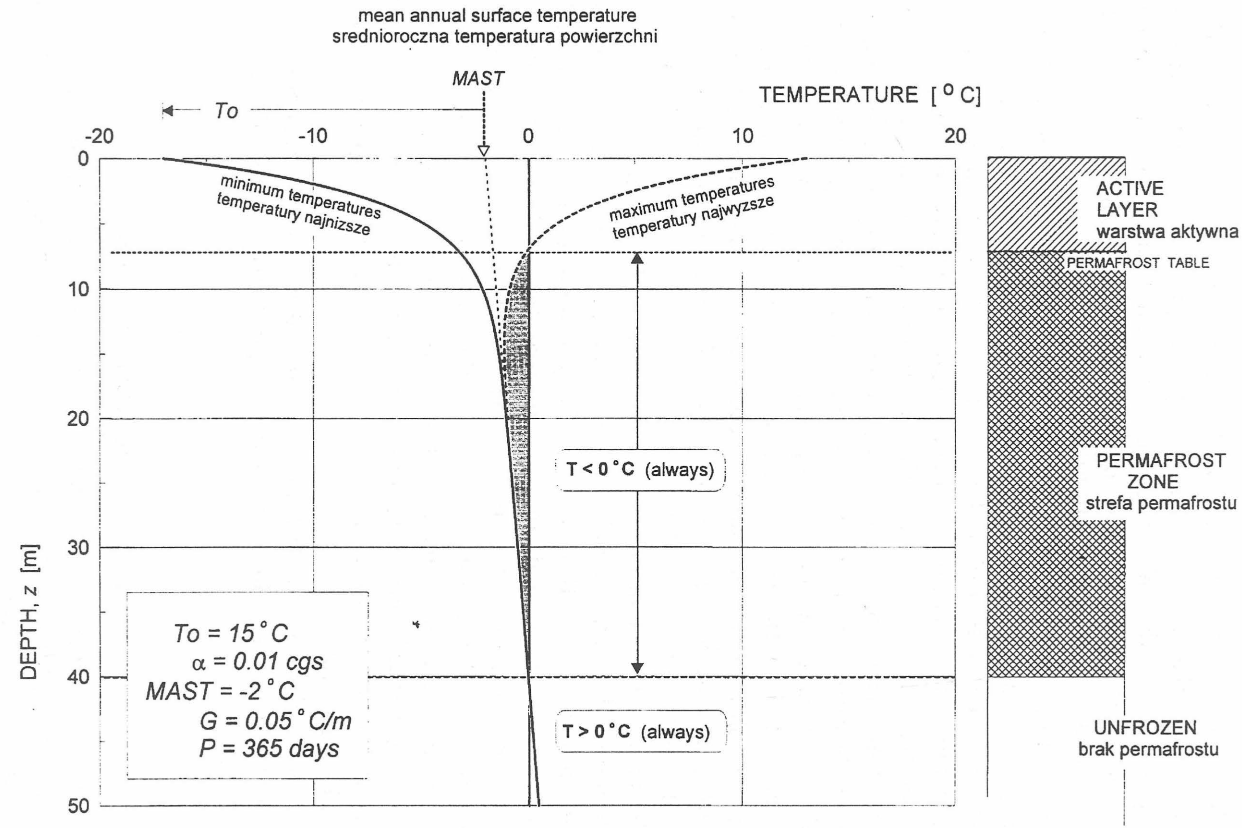

Fig. 1. Simplified 1D model of continuous permafrost

ways below 0°C. These are ideal conditions for permafrost to develop. In summer sub-surface temperatures can rise above 0°C, which will enable partial defrosting of the medium and push the permafrost level down. This simplified situation is presented in the right-hand section of Fig. 1. The model of permafrost has a "sandwich" three-layer structure with the particular layers displaying different physical properties. This situation – the flat, parallel "sandwich" structure of the medium – can effectively be examined with the use of the non-destructive geophysical method of resistivity soundings (Koefoed, 1979).

In the natural environment the development, distribution and occurrence of permafrost can be very complex (Jahn, 1970; Washburn, 1979; Daniłow, 1990, French, 1996). This is due to the particular geographical location, geological structure, varying water relations, morphology and altitude, as well as local climactic conditions and their changes over geological time. The simultaneous occurrence of many different physical phenomena, however, with a different and changing degree of intensity, has made all this even more complicated (rainfalls, melting, freezing, filtration etc.). This is the reason why in the natural environment there are many types of permafrost, including continuous and sporadic, with non-homogeneous petrophysical parameters (Black after Lachenbruch, 1968). These forms may intertwine; their extent and features are "alive" and affected by the past and present climatic conditions of the earth.

The mentioned genetic conditioning of permafrost is the reason why the application of the method of resistivity soundings faces a number of problems in terms of methodology and interpretation. The basic indicators used in the interpretation of soundings performed during the examination of permafrost are the absolute values of the measured resistivity of the medium and characteristic shape of the obtained curve. These are not by any means "error-free" indicators, however, their application requires experience and a dose of criticism. Let us now focus on these aspects from the geophysical standpoint.

We will now discuss how the shape of sounding curves depends on the form of permafrost and the impact of temperature on the resistivity of a rock medium.

SHAPE OF SOUNDING CURVES

Fig. 2a shows theoretical, normalized (referring to the parameters of the first layer) sounding curves for three simple cases of a 1D flat-parallel structure of a medium.

A model – the occurrence of continuous permafrost with infinite resistivity (ice is practically an electric insulator) and thickness exceeding the scope of resistivity sounding. The sounding curve rises at an angle of

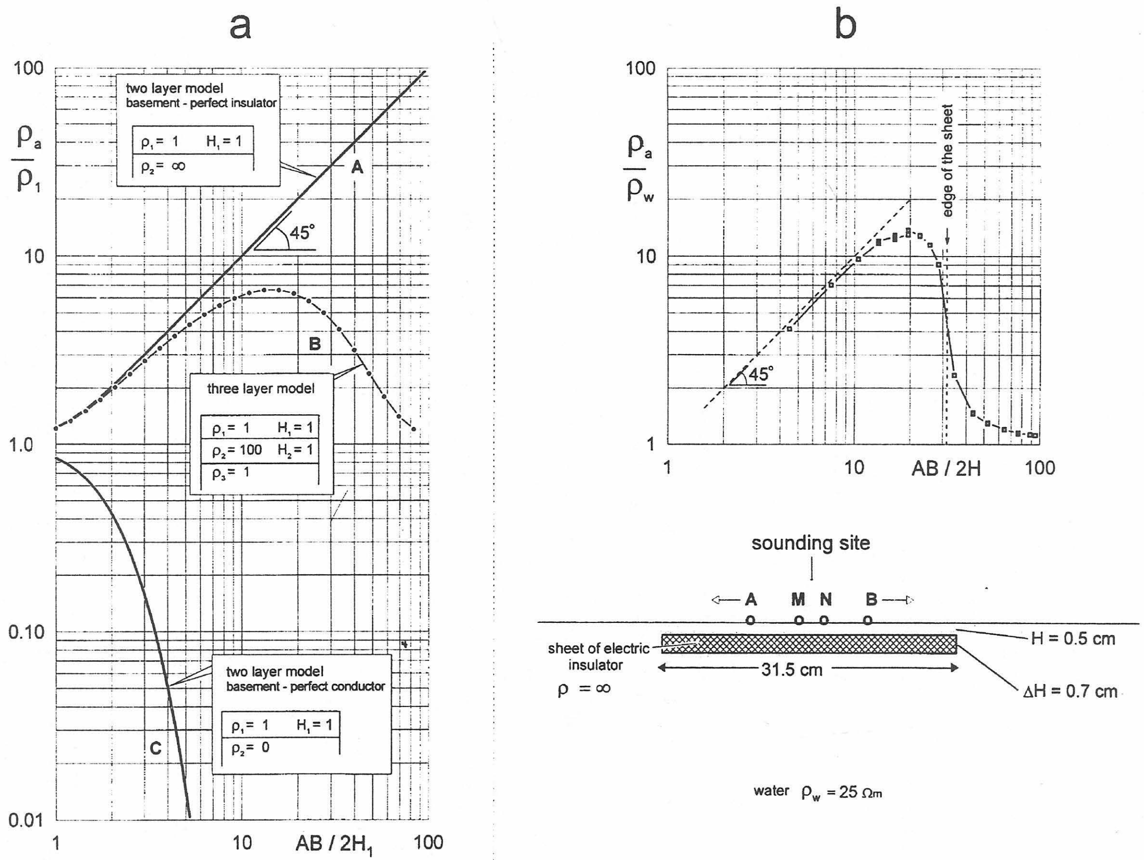

Fig. 2. The shape of resistivity sounding curves for different models

a. theoretical curves for 1D "sandwich" models; b. laboratory curve for 2D model

45° (this is a boundary value and it cannot be exceeded if the structure of a medium is similar to the "sandwich" one – i.e. has flat-parallel boundaries of division) and irrespective of the resistivity of the cap formations, i.e., the active layer. It should be emphasized that the shape of the curve depends on the relative resistivity (and thickness) of particular layers, and not on the absolute values of resistivity (and thickness) (KOEFOED, 1979).

B model – though the occurrence of continuous permafrost with limited thickness and high but finite resistivity. It can be seen that the rising branch of sounding is curve tilted at an angle of less than 45°

C model – this case has no connection whatsoever with continuous permafrost it presents another extreme situation in which the foundation serves a perfect electric conductor.

Fig. 2b shows the results of physical modelling (carried out in the laboratory of the Geophysics Department at the Krakow University of Metallurgy) for the 2D case of discontinuous "isle-like" permafrost. Sounding was conducted over the centre of the model. It can be seen that the initial branch of the curve is practically identical to the **A** curve in Fig. 2a. With more sounding being performed, the spacing of the **AB** measuring array increases and, finally, exceeds the width of the insulator plate (permafrost model). Electric current starts to flow under this model and the "screening" phenomenon occurs, which is accompanied by a collapse of the curve of sounding. The slant of the declining branch is bigger than for the **C** curve in Fig. 2a. One should mention that the results of modelling can be used to describe a "real" situation in the field, if the dimensions of the model are appropriately enlarged and the relative curve of apparent resistivity ρ_a/ρ_w is multiplied by the actual resistivity ρ_w of the medium surrounding permafrost. The same can be done with respect to the theoretical curves in Fig. 2a, however, taking into account the first layer in the calculations.

RESISTIVITY OF PERMAFROST

Resistivity of rocks increases when the temperature drops below 0°C. This is mainly due to the presence of water in the rock pores and freezing.

Monocrystals of ice are characterised by high resistivity (which reaches $10^8 \div 10^{10}$ Ωm) and their inability to practically conduct electric current. With respect to sedimentary rock or clastic formations (e.g. detrital material or talus), a portion of water never freezes, thus the developing ice is polycrystalline in nature and its resistivity may be lower. For example, ice from a glacier may have a resistivity of $10^5 \div 10^6$ Ωm., while underground layered ice may be even lower at $10^4 \div 10^5$ (DORTMAN 1984). This is due to different types of impurities and the chemical composition of water. When dealing with very clean glacial ice, KING (1984) has reported values of apparent resistivity exceeding even 10 MΩm.

In the High Tatra Mountains mainly granite rocks are present. "Healthy", i.e. not weathered, rocks have an actual resistivity of $10^3 \div 10^4$ Ωm. On the other hand, gravel and granite talus may display higher resistivity if the space between stones is filled with air, or lower, if this space is filled with water.

The question is whether the resistivity of a layer of permafrost is different from the resistivity of granite rubble. This has to some extent been answered by laboratory experiments and measurements conducted in the field. They are presented below.

In an experiment conducted in a laboratory we have examined how in the process of freezing changes the resistivity of granite coarse gravel (obtained from grinding boulders from the Tatra Mountains) with the granulation of 5 ÷ 20 mm completely (100%) saturated with water. The sample was placed in a cylindrical container. A measuring array and a temperature sensor were attached in the axis of the container. The current with an intensity of 0.0625 mA and frequency of 133 Hz was applied. We were interested in the relative changes in resistivity, thus the dimensions of the sample had been randomly selected and the size of the AMNB measuring array was immaterial. The results of the experiment are presented in Fig. 3. We can see that as the temperature was falling (though remaining always above 0°C) the resistivity of the sample was increasing. This is related to a dependence of water resistivity on temperature. In the pores water freezes when the temperature is around 0°C. This is a very long process. During this process the "traffic capacity" of the ways of ionic electric conduction decreases. This results in a slow increase in resistivity (resistivity locally drops after the seventh hour of the experiment, which may have been caused by capacitive effects). When the sample freezes completely, we observe a dramatic increase in resistivity, which soon reaches 10, 100 times, or more higher, than the initial value.

Given the outcomes of the experiment, we may assume that the resistivity of permafrost may be even higher than, for instance, that of granite talus. However, it is practically unfeasible to measure the resistivity of "bare" talus due to the fact that it is difficult to place the electrodes of the measuring array in such a way that they fit the rock well while retaining the right geometry of such an array. However, this task is much simpler with granite gravel and blocks covered with a thin layer of soil. We have examined this type of medium in the Valley of Białka the results of which are given in Fig. 4. The curve of soundings indicates that the gravel and granite blocks buried in this place form a layer, the resistivity of which in the aeration zone is high (yet not exceeding 30 kΩm). Electric current is conducted in these formations due to natural dampness,

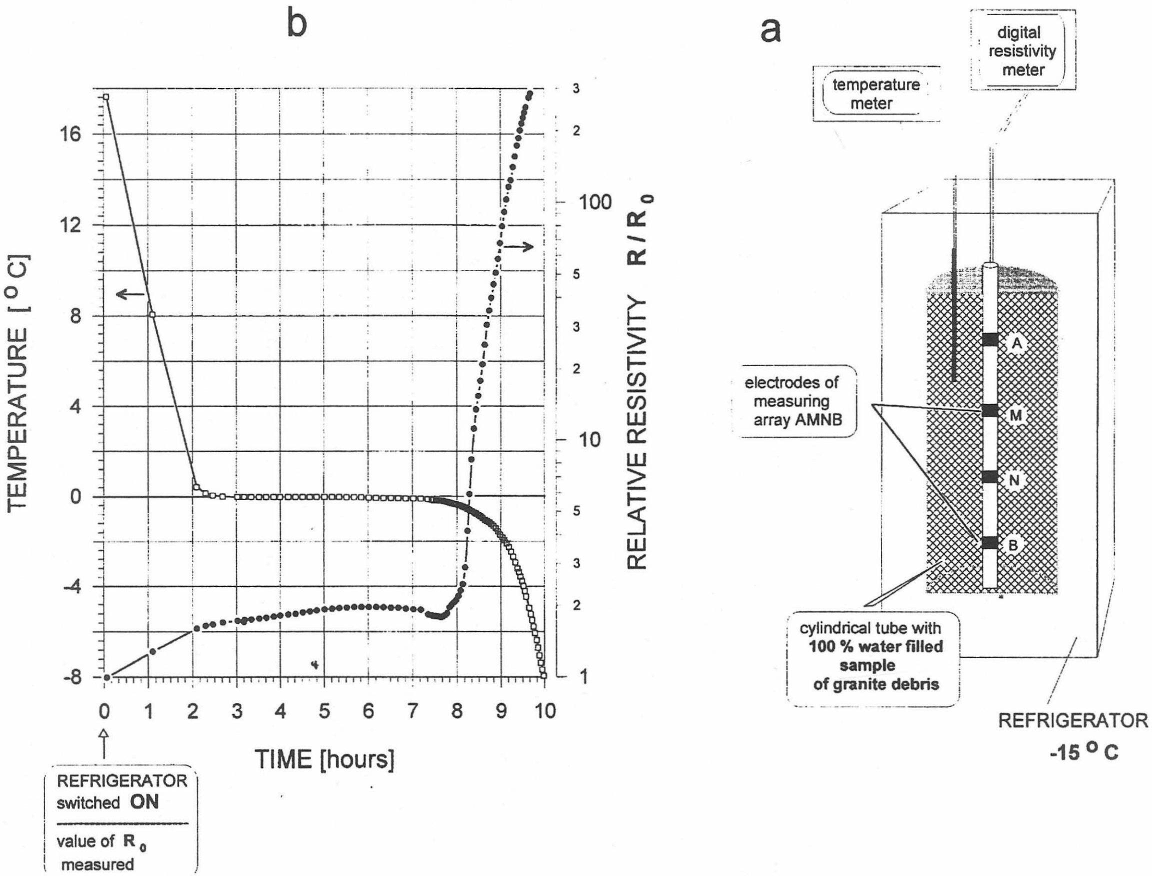

Fig. 3. Relation between temperature and resistivity of the granite debris sample. Results of laboratory experiment

which improves electric contract between boulders at the spots where they touch each other. When these contract spots freeze, resistance may rise considerably and reach hundreds of kΩm. Such values, and even higher, had been recorded earlier during the investigation in the Alps and Scandinavia (KING, 1984).

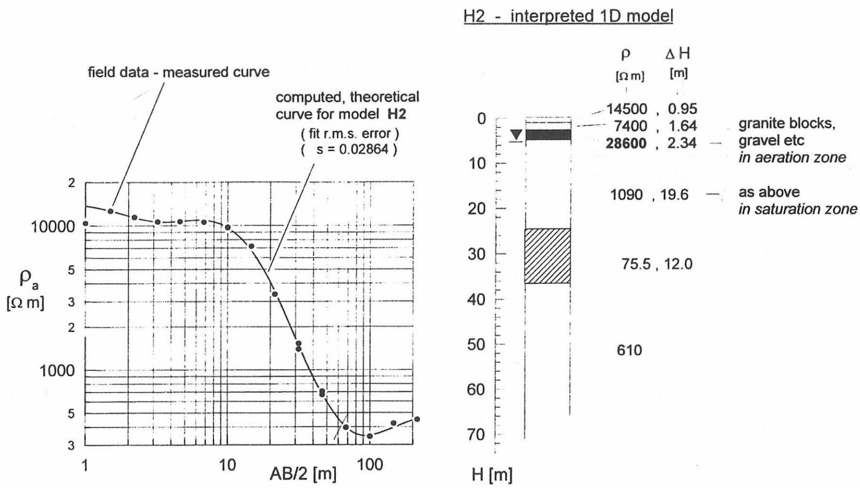

Fig. 4. Interpretation of resistivity sounding no 2/95 sited in the bottom of the Białka Valley, Poland, High Tatras, Białka Valley , 1000 m. a.s.l. (200 m south from Głęboki Źleb ravine outlet)

EXAMPLES OF EXAMINATIONS IN THE FIELD

Fig. 5 presents the results of resistivity soundings performed in the Kozia Dolinka Valley in September, 1997 (KĘDZIA, MOŚCICKI, WRÓBEL, 1999). What implies the occurrence of permafrost in this area are high values of apparent resistivity of granite talus. Moreover, the left branch of sounding rises at an angle of 45° (compare Fig. 2a). Approximate interpretation using the 1D model indicates that here the actual resistivity of permafrost can reach 1 MΩm. Permafrost is irregular and "isle like" here, which is clearly shown in the right branch of the curve (a deviation from the 1D model).

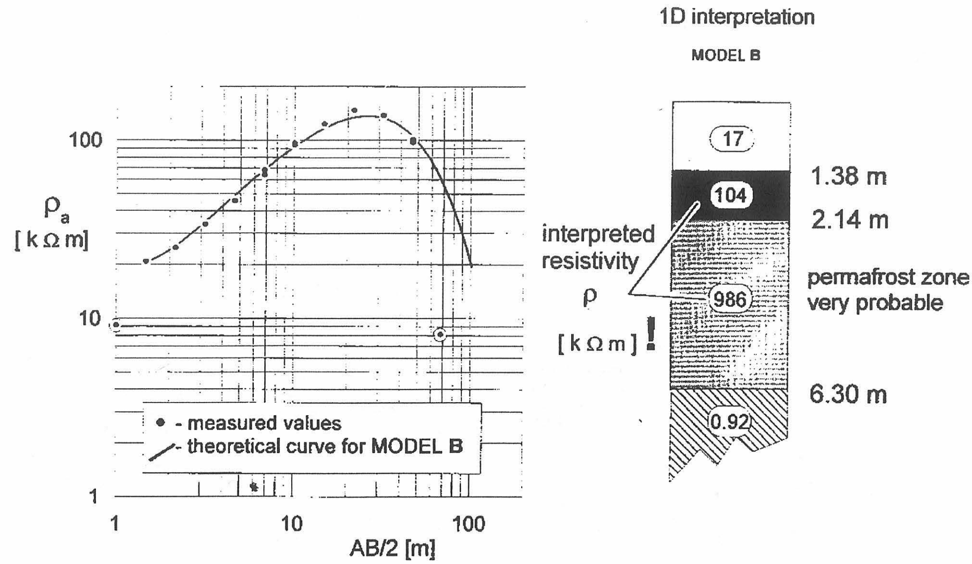

Fig. 5. Interpretation of resistivity sounding no 2/97, Poland, High Tatras, Kozia Dolinka Valley, 1936 m. a.s.l. (southern slope) (Kędzia, Mościcki, Wróbel, 1998)

Fig. 6 shows one of the sounding curve obtained during the research carried out in co-operation with the Research Station of the Swedish Academy of Sciences (Gałaś, Kędzia, Mościcki, 1999). The presented resistivity sounding was performed in the northern Lapland region about 20 km west of Abisko, along the ridge of Vassitjakko (at an altitude of 1200–1230 m above sea level), which is located between the Karkereppe Glacier and Cirque Lake.

The rocks composing the Vassitjakko continental plateau do not bear any resemblance to the Tatra type. These are mainly metamorphic shales where detrital material forms layers containing silty materials characterised by good electric conductivity (silty rock can have a resistivity even 100 times lower than granites and similar magma rocks).

Sounding was performed on a virtually flat surface in an area with patterned ground and numerous sorted circles, indicating that intensive freezing processes have occurred there.

Both lithology and the discontinuous (probably the "isle like") form of permafrost are reflected in the results of soundings. Apparent resistivity is

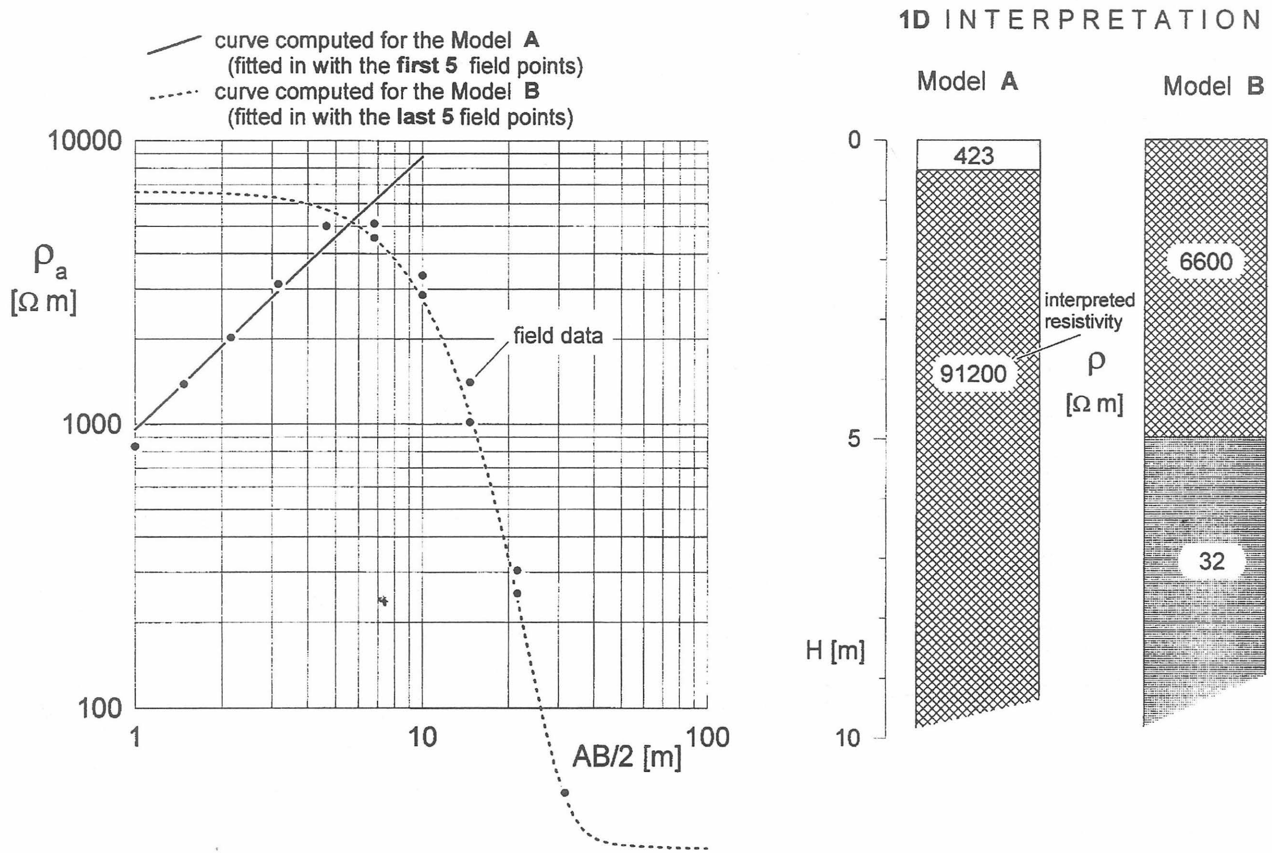

Fig. 6. Analysis of resistivity sounding no VAS01m; Sweden, Kärkevagge Valley – Vassijakko plateau, 1200 m a.s.l.

not high enough to indicate clearly that permafrost occurs. However, this can be assumed by observing the shape of the curve. The steeply rising left section of the graph indicates that there is a big difference between the resistivity of the cap layer and the formations underneath. The curve collapses for AB/2 > 7 m, which means that the whole curve of soundings cannot be interpreted using the categories of the 1D model. Clearly, the rock mass here is not homogeneous and can contain lenticular forms of permafrost; similarity of the curves in Fig. 2b and Fig. 6 is striking. Therefore, only the geoelectric structure has been assessed using a 1D approximation of only some portions of the curve. These analyses show that permafrost may have a 4 m thick, rather compact lenticular form lined with a layer of altered rock of a considerably lower resistivity.

CONCLUSIONS

The observations refer only to an issue of the interpretation of curves of soundings. However, interpretation itself is only the ultimate product of the whole procedure of sounding. An appropriate methodology of taking measurements in the field ensures that the method is effectively applied in the examinations of permafrost. Of paramount importance is the selection of the location. It is also essential that the electrodes of the measuring array fit the medium well and that measurements are verified on a continuous basis during examinations. All this requires considerable experience and skill.

Once these requirements are met, resistivity sounding can effectively be applied as an indirect method of detecting the presence of permafrost in the ground. Depending on geological and geomorphological conditions, the results of measurements may be less (for example examinations in the valley of Kärkevagge, Sweden) or more ambiguous (for example the occurrence of permafrost in the Kozia Dolinka Valley in the Tatra Mountains, also confirmed by other methods).

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