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Geophysical methods in research of permafrost in the Tatra Mountains and northern Scandinavia

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Abstract: A set of geophysical methods were implemented in the research conducted on permafrost of the Tatra Mountains and the Abisko area, Northern Sweden. Results of geophysical surveys show evidence of permafrost in both areas. Comparative studies on the occurrence of permafrost in the Tatras and in the Abisko area indicate that contemporary active as well as fossil permafrost might occur in both locations. Results of the electric resistivity, electromagnetic, shallow refraction seismic, and ground penetrating radar methods reveal similar results and might be successfully used in indirect research on permafrost in the mountainous regions.

Key words: permafrost, geophysics, Tatras, northern Scandinavia

Introduction

Permafrost is a pure termophysical phenomenon because its definition describes it as a thermal state of a rock or ground. Ice can, but does not have to, occur in it (Washburn, 1973; van Everdigen, 1998). The direct evidence of permafrost's presence is ground temperature equal or below 0°C.

Indirect, not based on ground temperature measurement, geophysical methods have been used in geological surveys for years. Since the 1960s, they have been systematically introduced into glaciological surveys and the ones of permafrost occurrence. The first, more synthetic, description of the methodology used in permafrost was given by Scott (Scott *et al*., 1979). Since then, geophysical methods have been more and more widely employed in glaciology and permafrost science. The BTS (bottom temperature of the winter snow cover), which is a geophysical method specifically dedicated to detecting and mapping of near surface permafrost, has been developed (Haeberli, 1973). The use of geophysical surveys in permafrost research became more extensive in the 1980s and 1990s, when they covered the environment of high mountains at various latitudes (King, 1984; Vonder Mühll, 1993; Hauck, 2001), which is almost inaccessible for direct surveys, generating high costs (e.g. drilling) in such an environment. As a result, a certain set of methods, which sufficiently meet the needs of research into permafrost and, when combined, can give a full and fairly certain view of permafrost occurrence in the Alpine environment of high mountains (Vonder Mühll *et al*., 2001), has been adopted.

Undertaking the research of permafrost occurrence in the Tatra Mts. in 1993 was based on the methodology, which was successfully used in the Alps and later in other European mountains (Dobiński, 1995, 1996a, b; Urdea, 1992). In this way, the extent and likely thickness of permafrost in the Tatra Mts. were determined (Dobiński, 1998a, b, 2004). The study on permafrost in the Alpine zone of the High Tatra Mts., initiated in the Department of Geomorphology, Faculty of Earth Sciences at the University of Silesia, has been continued for 16 years now. The research on the Tatra Mts.' permafrost has been carried out by scientists from other research centres, as well (Kędzia *et al*., 1998; Kędzia, 1999; Gądek & Kotyrba, 2007; Gądek *et al*., 2006). In the last years almost all of geophysical methods were applied in the comparative study of mountainous permafrost in the Abisko area, Northern Sweden (Fig.

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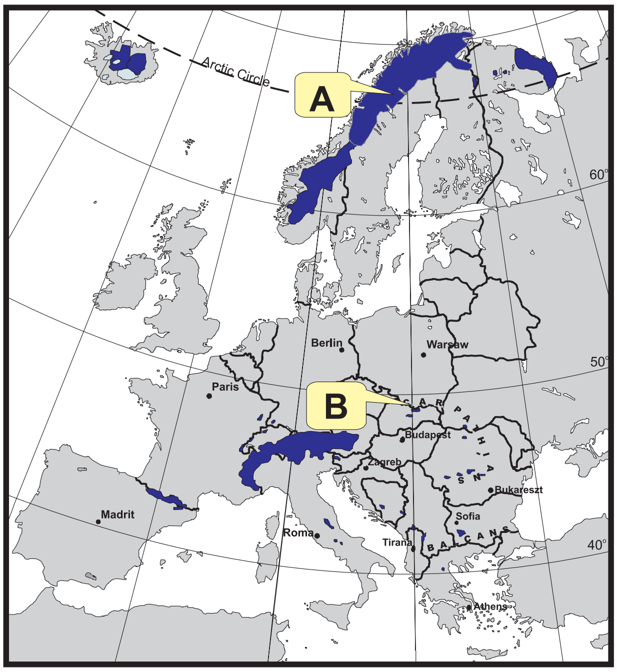

Fig. 1. General map of the permafrost in Europe with location of the research areas (after Brown *et al.*, 1997) . A – Abisko area, B – Tatra Mts.

1). The methods and first results of this comparison are presented below.

BTS

At first, the BTS method (Haeberli, 1973) was employed in the study as it allows for a relatively fast, although very rough, determination of permafrost occurrence, which exists at a depth of no more than 6 m below the ground surface, in the area covered with coarse blocky debris extending above the upper limit of the timberline. The method involves measuring temperature in the bottom of snow cover deposited for at least a few weeks. In this period of time, when its thickness exceeds 0.8 m, its isolating impact on the terrain surface causes the measured temperature to be connected with the flow of geothermal heat, and not with the temperature changes taking place on the surface. Haeberli (1973) determined the following BTS temperature ranges with reference to permafrost occurrence: the temperature below –3°C indicates the probability of permafrost occurrence, the temperature between –3°C and –2°C shows that permafrost occurrence is possible (the range of uncertainty), whereas the temperature above –2°C means that permafrost occurrence is unlikely. The lowest BTS temperatures registered in the Tatra Mts. stand at below –10°C (the Kozia valley – Kozia Dolinka) (Kędzia, 1999). In the Dolina Pięciu Stawów Polskich (the Five Polish Lakes Valley) the lowest registered temperature was –5°C (Dobiński, 1997). In order to check the method, measurements were also made on the frozen lake.

VES-ERT

The other methods used in the Tatra Mts. and in northern Sweden were the VES – vertical electroresistivity sounding and the ERT – electroresistivity tomography. Following the publications from other mountain areas, an assumption was made that resistivity value of frozen rock is higher by 2–3 orders of magnitude than its resistivity in a non-frozen state (Vonder Mühll, 1993; Hauck, 2001). The resistivity of weathered material with ice content (cemented by ice) can be even higher and reach hundreds of kilo-ohmometres. However, not only resistivity values were taken into consideration, but the contrast between high-resistivity and low-resistivity layers as well. Figure 2 shows the results of permafrost research made on the mire near Abisko, Sweedish Lappland. On the graph, two ERT profiles and direct active layer measurements are presented.

A similar, very high, resistivity is also generated by air-filled spaces in coarse blocky cover, which is common in the surveyed area of high mountains. Therefore, an analysis of results which is not supported by additional field observations, and ideally by the use of another method, can be unreliable. In order to check and calibrate the method and verify the results of the resistivity soundings in the Tatra Mts., resistivity measurement was conducted on a perennial snow patch. The results show resistivity values in mega-ohmometres (Dobiński, 1997). The VES-ERT methods give very good results in the surveys of permafrost, hence they are willingly and commonly used by researchers dealing with the problem of permafrost mapping and research. The ERT method was applied in both places (Fig. 3).

The results show that in different mountainous locations the resistivity values can vary significantly. In the coarse blocky cover, the resistivity of permafrost reaches tenths of kilo-ohmometres, whereas in the peat-bog, palsa areas the results confirmed by direct outcrop show ca. 5 kΩm and less, as a border value for the permafrost level.

Electromagnetic methods

In the research of permafrost in both areas shallow and deep electromagnetic methods, using EM-31 and EM-34 instruments, were also employed. The former permits observation of changes in electromagnetic conductivity, down to a depth of about 6 m below the ground surface. The latter can reach much more deeply, depending on the medium (e.g., soil, rock) properties. In the Tatra Mts. and in north-

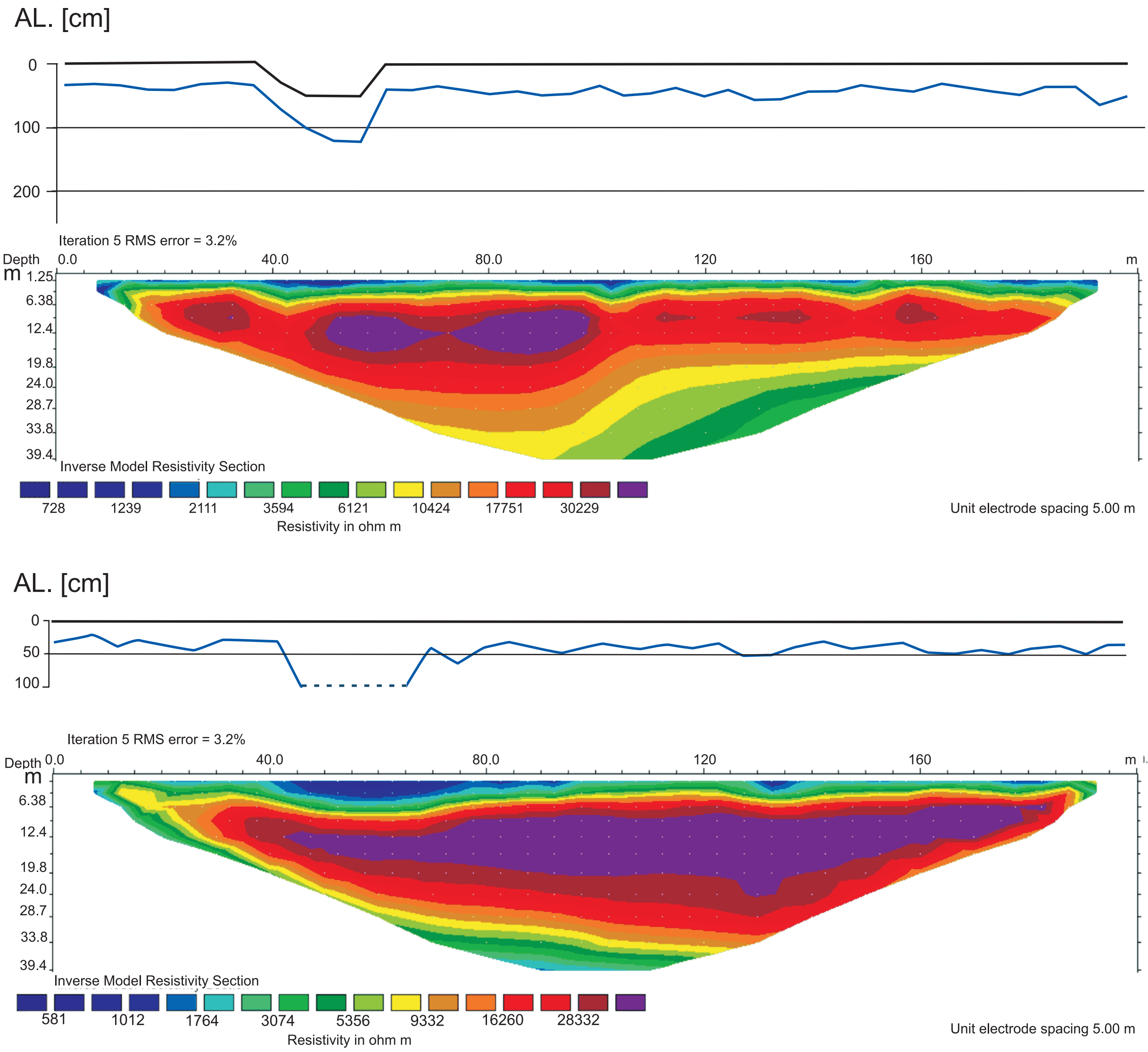

Fig. 2. Results of the two ERT profilings on the mire near Abisko. AL – active layer depth measured by steel rod. Results show that vertical extent of permafrost exceeds ca. 35–40 m. Active layer is not visible, because interpretation of profiles starts from 1.25 m below the ground surface, and all resistivity values indicate frozen state. Increase in resistivity follows the decrease of temperature in the ground. The lowest temperatures are visible at a depth of ca. 12 m

ern Sweden the depth of ca. 60 m was reached. The use of the shallow method on the Kasprowy Wierch summit resulted in obtaining conductivity values from 0.2 to 1.7 mS in those places. Very low conductivity of the medium were registered also in Northern Scandinavia in the Abisko mire. Comparison of the results is shown in Figure 4. The results compared with those presented in previous figures show very low conductivity at places where permafrost occurs.

Seismic sounding

Seismic sounding/profiling is a method which registers a different geophysical parameter – seismic wave velocity in a rock or ground. Thus, it is a very good method verifying the results of previous methods. In the Tatra Mts., the seismic method has been used on Hruby Piarg in the Dolina Pięciu Stawów Valley, and on the Kasprowy Wierch summit. The first results indicate the occurrence of permafrost in this place as in the first layer, at the depth of about 8–9 m, velocity ranging between 660 and 900 ms^{-1}, whereas in the second one – between 2,260 and 2,670 ms^{-1}. Such a result supports relatively low BTS values, below – 4°C (Dec & Dobiński, 1998), obtained at this place. The second result, on the Kasprowy Wierch Mt., is presented together with seismic profiling made on the mire near Abisko. In the Abisko area, shallow refraction seismics was applied in the locations where ERT and EM were previously used (Fig. 5).

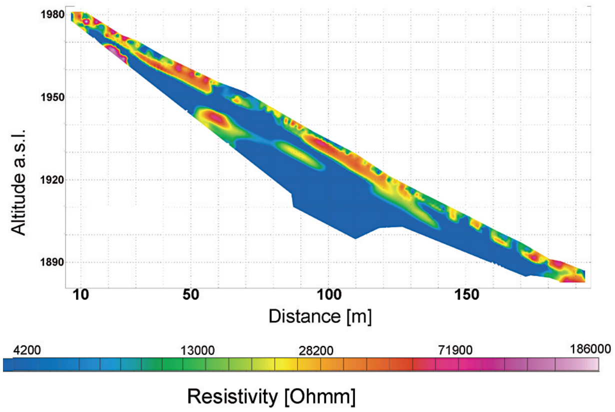

Fig. 3. Results of the ERT profiling on the western slope of the Kasprowy Wierch Mt., Tatra Mts. High resistivity anomalies with values between 20–80 kΩm indicate a frozen layer/lens of ice-filled debris

Ground penetrating radar (GPR)

One of the latest tools used in the surveys of the extent of Quaternary sediments and permafrost is GPR. Its features make it much more suitable for glaciological surveys as it offers a much deeper reach available in pure ice. In the Tatra Mts. (Gądek & Kotyrba, 2007) and in northern Sweden, various instruments with antennas with frequencies of 120, 200, 500 and 800 Mhz have been used. On the georadar picture, an active layer of permafrost can be distinguished, but the structure of the subsurface lithology is much better visible (Fig. 6). The calculated dielectric constant of ε = 2.6 permits identification of the permafrost as well. However, in deeper surveys it does not generate better results than the ones received by means of other methods.

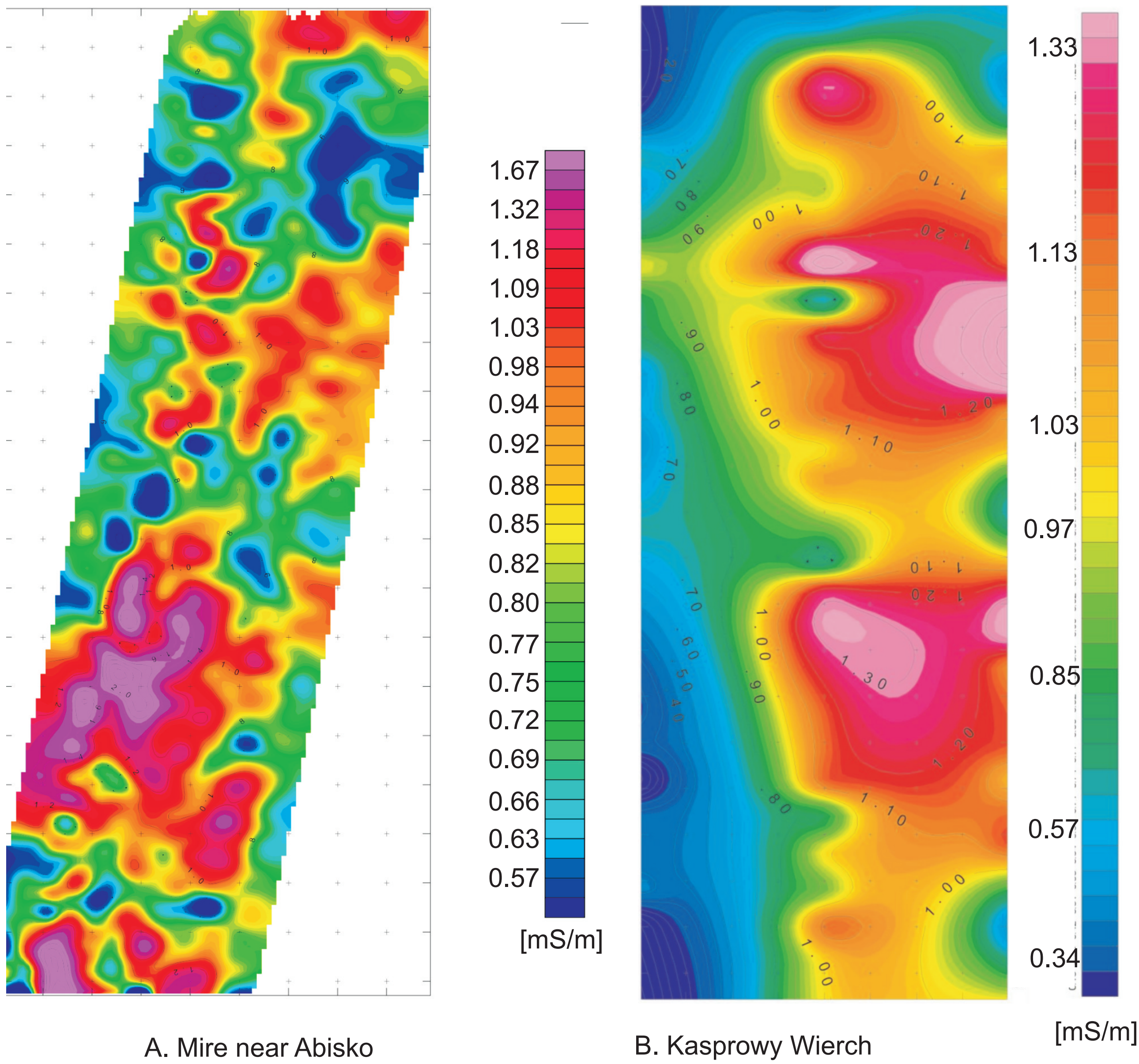

Fig. 4. Results of the shallow, up to 6 m, electromagnetic research made on the mire near Abisko, Sweden (A) and on Kasprowy Wierch, Tatras (B). The very low values of electromagnetic conductivity confirm the results of ERT profiling

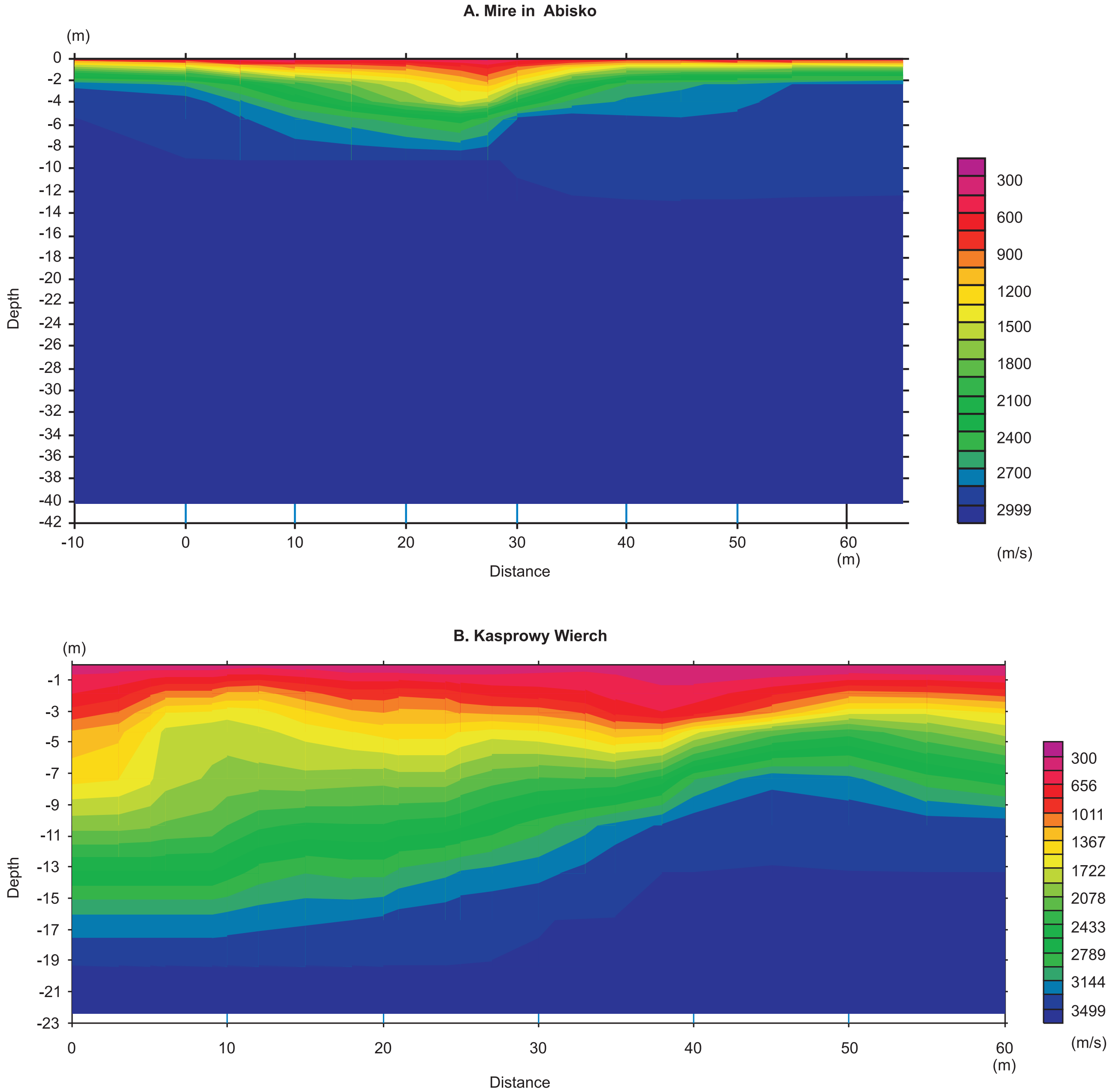

Fig. 5. Results of the shallow seismic profiling made on the mire near Abisko (A) and on Kasprowy Wierch (B). On the mire, very thin active layer is visible. On Kasprowy Wierch, values of wave-speed correspond well with the thickness of weathered material. Wave speed for ice-reach permafrost starts with the value of ca. 2,000–2,500 m/s

Conclusions

In the Polish permafrost research in the Tatra Mts. and in northern Sweden, as well as in other survey areas, almost all geophysical methods developed and implemented for this purpose have been used successfully. They have permitted determination of the extent of permafrost occurrence, its thickness and also some of its physical qualities, such as border resistivity values for frozen and unfrozen material in subarctic peat, specific refraction wave velocity for frozen and unfrozen material, as well as electromagnetic properties and ice content. Ground penetrating radar provides an opportunity of an insight into the structure of the medium rather than in permafrost extent in the research areas, however, its restricted use for permafrost research can be useful.

A comparison of the results from the Tatras and northern Scandinavia shows similarity visible in seismic wave velocity and electromagnetic conductivity in the permafrost of both areas. Differences, for instance significantly different border values of the resistivity in frozen peat in the Abisko area and frozen debris in the Tatras, are also clearly visible. The results of the applied methods allow for a better understanding of the extent of permafrost in both places.

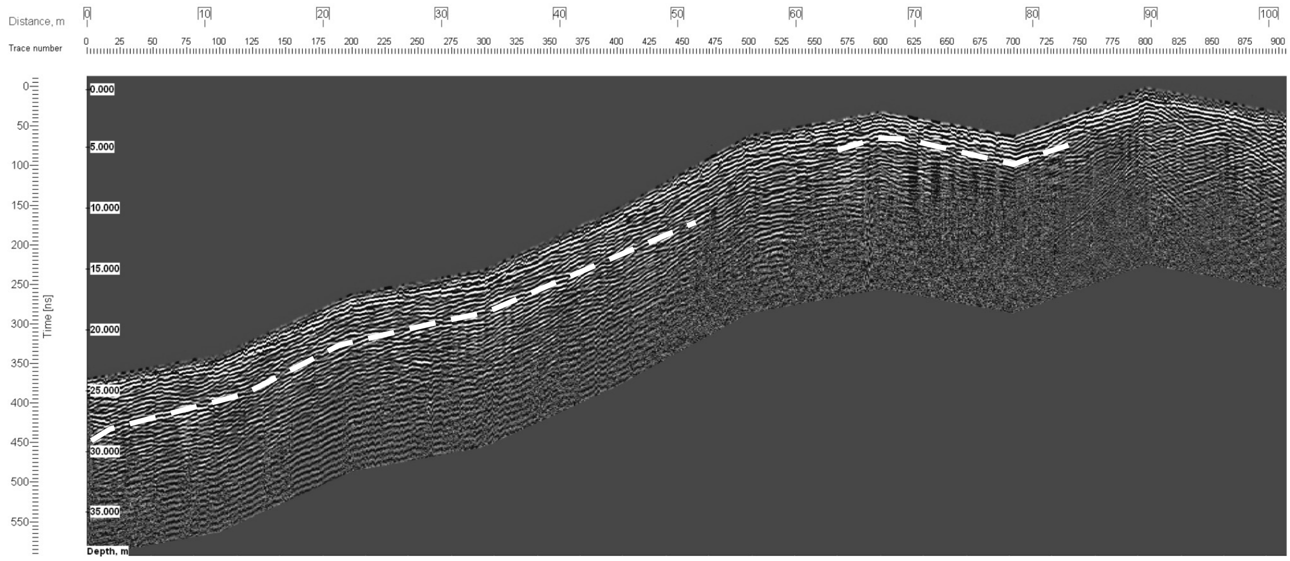

Fig. 6. Results of the Ground Penetrating Radar survey made on the Kasprowy Wierch summit

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