PERMAFROST OCCURRENCE IN KOZIA DOLINKA (HIGH TATRA MOUNTAINS) IN LIGHT OF GROUND PENETRATING RADAR INVESTIGATIONS

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Piotr Lamparski, Stanisław Kędzia: Permafrost occurrence in Kozia Dolinka (High Tatra Mountains) in light of ground penetrating radar investigations. Geomorphologia Slovaca et Bohemica, 7, 2007,1, 5 Figs., 1 Tab., 13 Refs.

The investigations on permafrost occurrence in Kozia Dolinka valley in Polish part of High Tatra Mountains have been carried out since the mid 1990s with the application of different investigation methods (BTS – bottom temperature of the winter snow cover, DC resistivity soundings, infrared imaging). In September 2005, the next investigations were carried out in Kozia Dolinka with the application of georadar soundings, which had not been used before in this area. The results of these soundings were then compared with other results of investigations which had been carried out in Kozia Dolinka. Despite difficult high-mountain conditions (the investigations were carried out at the altitude of 1.900-2.000 m a.s.l.) this method appeared very useful for this kind of investigations. The obtained results are very similar to the results obtained from other earlier used methods. This considerable consistence of results from different geophysical investigations, which were carried out in different time, evidences the stability of permafrost, suitable selection of research methods and their comparability. Georadar soundings carried out in Kozia Dolinka confirmed the occurrence of permafrost within the slopes facing north and lack of permafrost within sun (south) facing slopes and in the valley bottom. Non of the studied profiles showed the resistance typical for glacier ice, as it took place in Medená kotlina in Slovakian Tatra Mountains. The obtained results suggest the occurrence of permafrost in form of frozen debris and soil.

Key words: High Tatras Mts, permafrost, ground penetrating radar

1 INTRODUCTION

Investigations on the occurrence of permafrost in Kozia Dolinka Valley in the Polish part of High Tatras have been carried out since the mid 1990s using different research methods (KĘDZIA et al., 1998, KĘDZIA 2004, MOŚCICKI and KĘDZIA 2001). So far the following methods were applied:

- BTS (bottom temperature of the winter snow cover) including both reconnaissance measurements and continuous registration with the use of loggers,
- DC resistivity soundings carried out in spring and autumn,
- infrared imaging with the use of thermovision camera and pirometer,
- measurement of water temperature flowing out from the valley,
- trial pit in the scree.

This work shows the results of investigations with the use of ground penetrating radar (GPR) which were carried out at the end of September 2005 and which aimed to investigate the occurrence of permafrost in Kozia Dolinka Valley. The results of these soundings were then compared with the results of other investigations which had been earlier carried out in this area.

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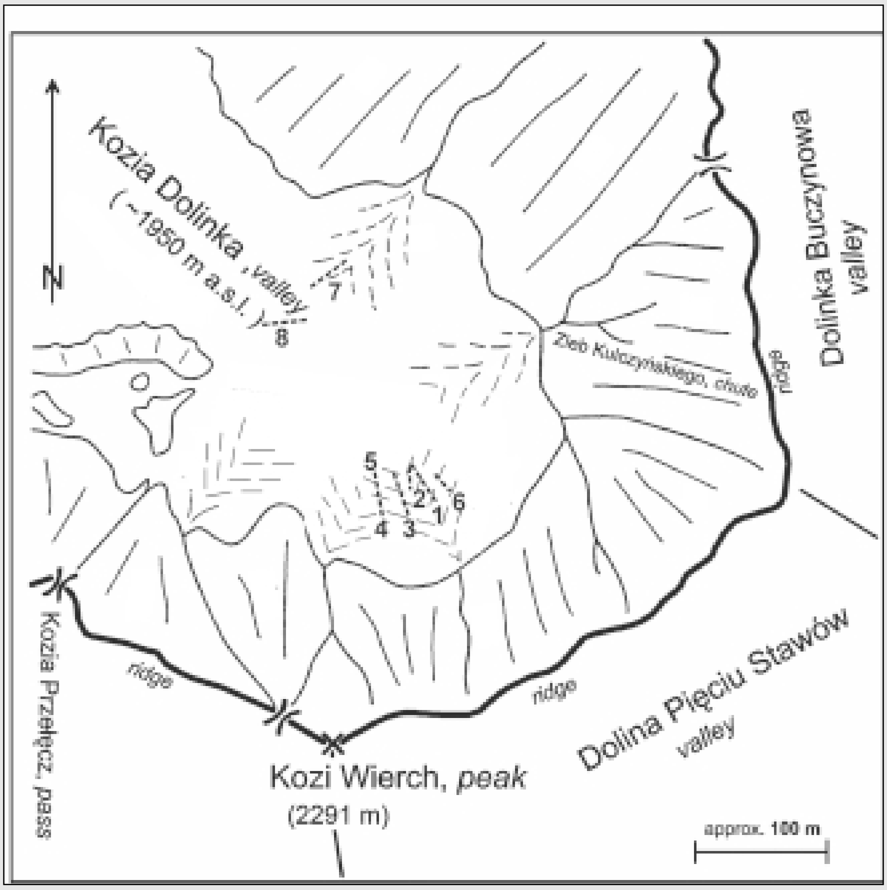


Fig. 1 Map of location of GPR profiles in Kozia Dolinka Valley.

2 STUDY REGION

Kozia Dolinka Valley represents the uppermost glacial cirque which belongs to Czarny Staw Gąsienicowy Valley. It is built from granites of crystalline core (BAC-MOSZASZWILI and GĄSIENICA-SZOSTAK 1990) and it is cut through by faults and fissures of NE-SW and NW-SE strike (GROCHOCKA-PIOTROWSKA 1970). It is circle-shaped and open towards the NW, falling down with a polished threshold of the height of about 140 m (**Fig. 1** and **2**) to the main valley. Kozia Dolinka Valley is about 800 m long and 350 m wide. Its flat bottom covered by weathering material and moraines is located at the height from 1930 m to 1950 m a.s.l. The valley is surrounded from three sides by rocky steep slopes and walls up to 350 m high, cut up in their lower parts and usually glacially polished. The rocky slopes and walls are cut along by deep gullies connected with faulting and fissuring. At the gullies' mouths, large but poorly dismembered scree cones developed (KLIMASZEWSKI 1988). The last glacier in Kozia Dolinka Valley probably melted in Holocene at the end of a cold period called Venediger in the Alps, about 8.3 ka BP (BAUMGART-KOTARBA and KOTARBA 2001a and b). A frontal moraine deposited at the rocky threshold at the valley's mouth comes probably from that period.

Kozia DolinkaValley, due to its location, size and shape (high rocky walls especially from the S), shows different climate than other large convex geomorphological forms located at similar altitude, e.g. Kasprowy Wierch. Undoubtedly, shading considerably influenced an individual character of microclimate of this area. Shading and accumulation of large volume of snow (the observed maximum thickness of snow cover both at the bottom and on the slope was about 6 m) cause that snow cover usually melts in the first part of June, whereas in the area of meteorological station at Hala Gąsienicowa (1.520 m a.s.l.) the snow cover melts in the beginning of May. Small snow patches, on the other hand, which are located at the foot of rocky walls of Kozi Wierch and Kozie Czuby sometimes do not melt for many years (KĘDZIA 2004).

3 METHODOLOGY

During investigations 9 GPR images were conducted of a total length of over 250 m, which make 8 profile lines (**Fig. 1, 3** and **4**, **Tab. 1**). The profiles started in the upper part of the slope, if not (profile No. 2) – they were inverted during the interpretation. The range of sounding was assumed to 120 ns (profile no. 5-150 ns), which corresponds with about 6 m (7.5 m respectively) thick layer of rocky debris with small voids filled with air (vertical scale – 20 ns/m). In valuation of vertical scale it was assumed that a dielectric constant for wet granite is 7, for air 1, and for weathering material abo-

Fig. 2 The view of Kozia Dolinka Valley from Kościelec (Photo J. Mościcki)

ut 15. In case of profiles no. 7 and 8 the upper layer represented probably a thick layer of grass. For organic deposits dielectric constant was, depending on the content of water, from 35 to 55. In that case a mean value of about 45 was accepted. For such value of dielectric constant, the vertical scale was 45-50ns/m.

The interpretation of GPR images was based on the assumption that the same parameters of signal amplification were used for all the profiles (**Fig. 1, 5AB**). Therefore a relative resistivity of layers which are penetrated by electromagnetic waves may be a start point to determine the type of a deposit which is penetrated by a radar. According to KNEISEL (2006), REYNOLDS (1997) and TELFORD ET AL. (1990) the values of resistivity for different bodies are as follow: granite – $5x10^{3}$-10^{6} Ω m, frozen deposit in periglacial conditions – $1x10^{6}$-10^{8} Ωm, air – infinite, ground water – 10-300 Ωm. Taking into account their electric features, granite unfortunately is not much different from a frozen deposit. Therefore the distinction of wet granite rocks from the lump of dirty ice or frozen ground is in this case impossible or at least very difficult. The distinction of granite rocks from clean glacier ice would be much easier. It should be also remembered that a scree material contains large boulders between which there are large empty voids filled with air. These voids are objects of the highest resistivity, however the air contained in them is almost transparent for penetrating electromagnetic waves and it does not cause any particular geophysical anomalies which could be observed on the image. The planes surfaces of boulders, on the other hand, are the reason of interference and numerous false anomalies.

Because of the lack of other reliable criteria, the interpretation of all GPR profiles aiming to recognise possible frozen lumps of sediment, consisted in distinguishing places and areas of the highest values of resistivity. Such areas in all radar images are marked in dark grey colour. The additional criterion of distinguishing questionable places were lens-like shapes and large sizes of such anomalies. It should be however remembered that the presence of frozen material within the areas of grey anomalies on radar images is only a hypothesis, not very certain one. This is however the only way to distinguish, using the GPR investigations, areas suspected of the presence of frozen deposit. The lenses of material of the increased resistivity often occur at a similar depth as horizontal geophysical anomalies which run along the whole profiles. The presence of these horizontal (in fact parallel to a scree surface) boundaries seems to evidence that the scree cones developed in several stages. The boundaries probably represent previous scree surfaces covered by successive layers of debris. Single geophysical anomalies of small sizes were placed on GPR images as ellipses. These are probably reflections of planes of large boulders parallel to the radar aerial.

Most of GPR profiles shows that the resistivity of deposit increases at the depth of about 1-1.5 m below the ground surface. This is connected with the increase of water content and increase of finer material filling the voids between the boulders. This horizon is overlaid by dry layer of rocky debris isolated with grass or finer material.

Fig. 3 Location of radar profiles in shaded scree cones under Kozi Wierch.

4 RESULTS

Profiles 1AB and 2 run along a soil patch grown by high-mountain grass (**Fig. 3**). In the upper part of the profile 1AB, the layers of high resistivity (marked in dark grey) occur at the depth 2.5-3 m, and in the lower part at the depth of about 1.5 m (**Fig. 5A**). The obtained course of the occurrence of high-resistivity layers is consistent with the occurrence of permafrost obtained from other geophysical investigations (KĘDZIA et al. 1998; KĘDZIA 2004; MOŚCICKI and KĘDZIA 2001). In the soil patch studied, DC resistivity soundings had been performed several years before the present investigations. The first sounding was carried out in mid September 1997 and the next at the end of June and beginning of October 1999. The sounding from 1997 was located in the upper part of the radar profile 1AB, and the soundings from 1999 were also located in the upper part of the profile, above the sounding from 1997. According to interpretation model of the sounding from 1997, the permafrost occurred at the depth just below 2 m, whereas the subsequent DC resistivity sounding from 1999 made it possible to determine that the permafrost thickness decreases with the scree height, i.e. the permafrost is thinner in the upper part of the scree and thicker in the lower part. The increase of permafrost thickness and simultaneous decrease of the thickness of active layer in the lower part of the scree is also evidenced by the results of ground temperature measurements using thermovision camera and BTS method. Based on BTS measurements and a formula prepared by HAEBERLI and PATZELT (1982), the thickness of active layer in the lower part of the scree was calculated as well as the thickness of active layer in the place where electro-resistivity measurements were performed in 1997. The obtained results are 1.1 m and 2.8 m respectively (KĘDZIA 2004). Comparing these values with the values from GPR profile and the values from DC resistivity soundings, a large consistency is visible despite the fact that these measurements were carried out in different years. This evidences not only the stability of the permafrost but also comparability of results obtained from different geophysical methods used in the investigations.

Fig. 4 Location of radar profiles in the valley bottom and insolated slope of Zadni Granat.

Profile No. 3 runs along the neighbouring large snow patch, where BTS measurements and infrared imaging had been performed (**Fig. 3**). On the image from thermovision camera taken in September 1997 (KĘDZIA et al. 1998) the temperature of the surface of this patch is 2-4°C lower than the neighbouring surfaces, similarly to the earlier described soil patch (profile 1AB, 2). This is probably caused by the difference of humidity (including also capacity and thermal conductivity) of scree surfaces covered by soil and screes without soil covers. Different situation occurs in winter. In this case BTS on screes without snow cover is lower than the BTS on screes covered by soil. In both soil patches studied BTS values were very low, which suggests the occurrence of permafrost. Also on GPR profile, numerous light grey lenses are visible which suggest the presence of permafrost (**Fig. 5A**). The analysis of their distribution suggests that the permafrost in this part of the scree is the thickest among all the profiles studied.

Profiles 4 and 5 run along debris flow and they show the largest electric homogeneity, which may be connected with the fact that fine-grained material of the flow filled in the voids which resulted in the increased homogeneity of the deposit in terms of its humidity (**Fig. 3**). The suggested permafrost layer is relatively thin in this place (**Fig. 5AB**). Unfortunately in this place other investigations apart from infrared imaging and GPR measurements were not carried out therefore it is difficult to say something more about the permafrost. Special attention should be paid to distinctive parallel magnetic anomalies which occur in the lower parts of both profiles. They may illustrate a rocky substratum of the cirque, which, in this place, should not be covered with too thick debris layer.

GPR profile No. 6 runs along the surface of the scree composed of loosely packed fine weathering material. It does not show the presence of such large anomalies of resistivity increase as profiles 1-3 (**Fig. 4, 5B**). The image shows boundaries more or less parallel

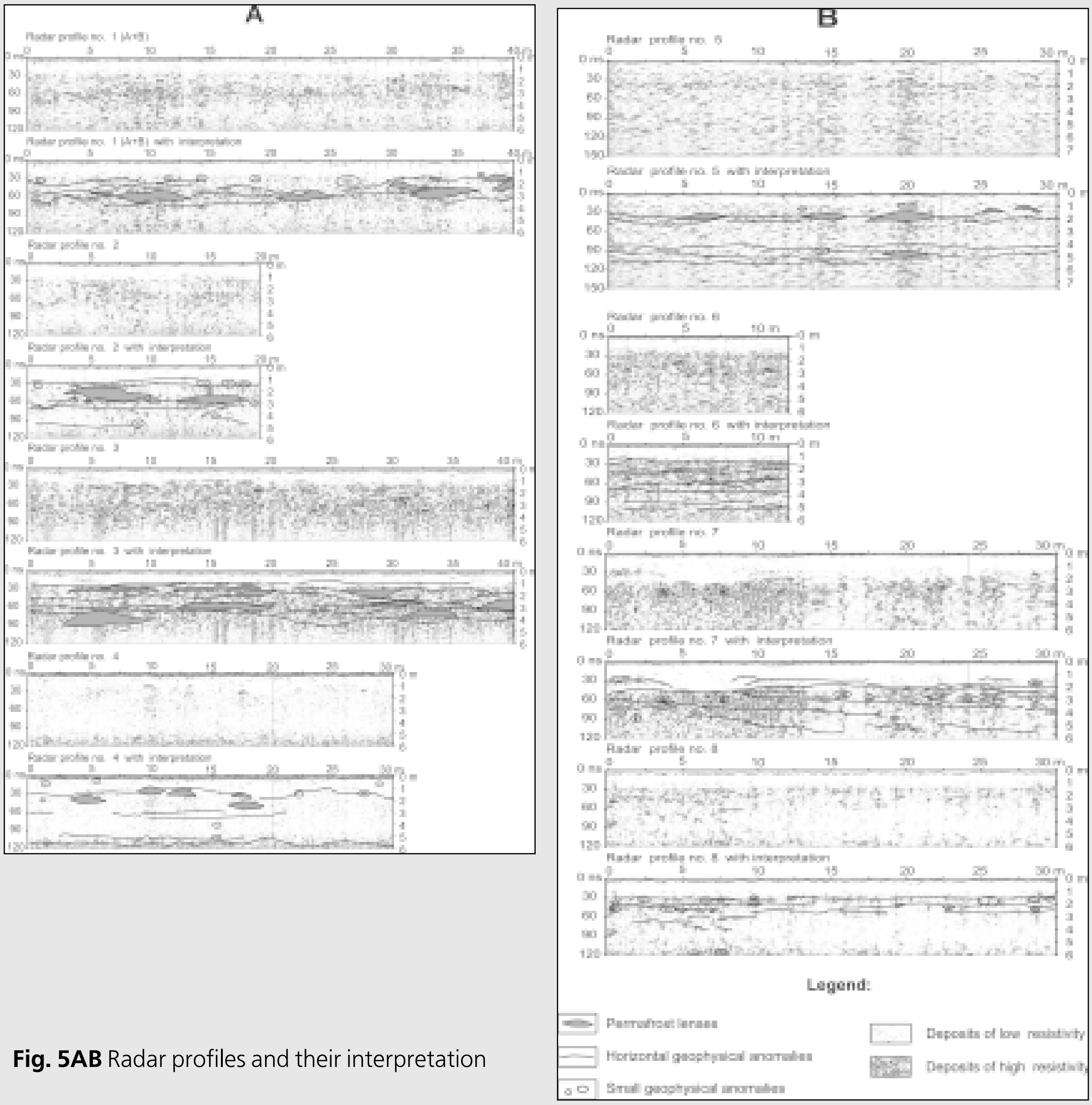


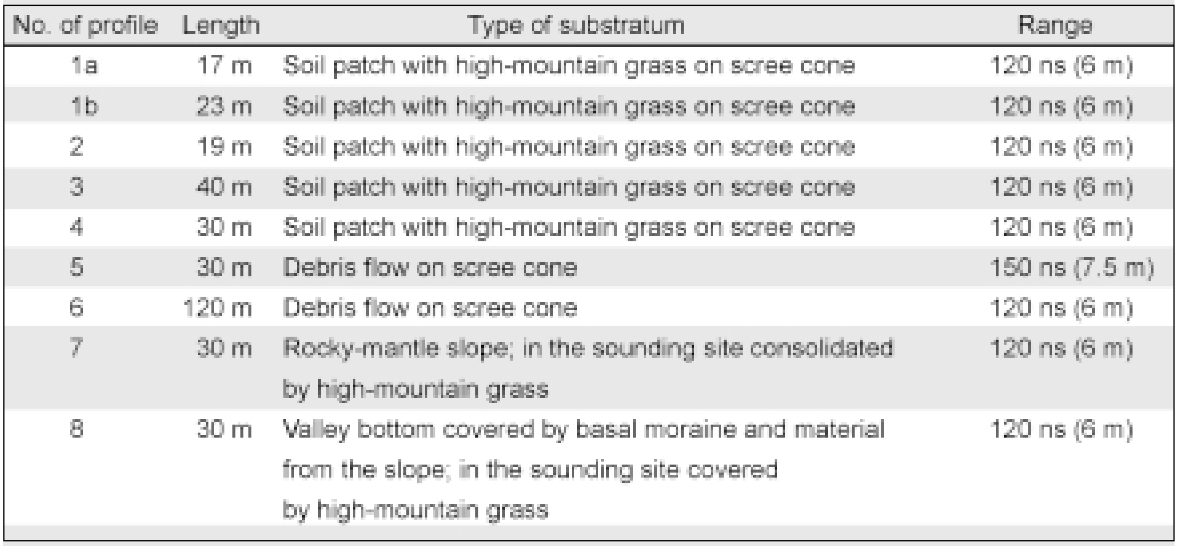
Fig. 5AB Radar profiles and their interpretation

to the present surface of the scree. The boundaries probably represent its previous surfaces successively covered by deposits. The lack of layers suggesting the occurrence of permafrost along this profile seems strange, as other geophysical investigations carried out in this place and in its neighbourhood had suggest its presence. Possibly it is caused by measurement error or internal structure of the scree in this place.

GPR profile No. 7 runs along the sun-facing slope of the valley, opposite to the other profiles (**Fig. 4**). A characteristic feature is here an upper layer, which is 30-50 ns thick (**Fig. 5B**). It is probably a layer of grass and organic deposits. The insolation favours vegetation and scree bounding by plants. Assuming that this layer is enriched in organic deposits its thickness is estimated to 0.5-0.7 m. Below the low resistivity layer there is a layer of large concentration of high resistivity geophysical anomalies. These anomalies probably illustrate successive layers transported mainly by debris flows. This is evident from quite chaotic not parallel run of these boundaries.

The final profile (No. 8) runs along a flat surface of the valley bottom (**Fig. 4**). Similarly to the profile No. 7 it contains a sub-surface low resistivity layer, connected with its enrichment in organic deposits (**Fig. 5B**). Below it there is a thin layer of increased resistivity. It has a regular character, which suggests that this is a layer of fine debris which were deposited here by flow. In the upper part of this profile, above the flown layer there is probably the front of the scree cone.

Profiles No. 7 and 8 do not show typical for profiles no 1-3 lenses of geophysical anomalies of the increased resistivity. Profile No. 7 contains in fact zones of the increased resistivity, but these are without doubts groups of granite boulders which build the scree cone. BTS measurements carried out in both profiles show, similarly to GPR images, the lack of permafrost.



No. of profile	Length	Type of substratum	Range
1a	17 m	Soil patch with high-mountain grass on scree cone	120 ns (6 m)
1b	23 m	Soil patch with high-mountain grass on scree cone	120 ns (6 m)
2	19 m	Soil patch with high-mountain grass on scree cone	120 ns (6 m)
3	40 m	Soil patch with high-mountain grass on scree cone	120 ns (6 m)
4	30 m	Soil patch with high-mountain grass on scree cone	120 ns (6 m)
5	30 m	Debris flow on scree cone	150 ns (7.5 m)
6	120 m	Debris flow on scree cone	120 ns (6 m)
7	30 m	Rocky-mantle slope; in the sounding site consolidated by high-mountain grass	120 ns (6 m)
8	30 m	Valley bottom covered by basal moraine and material from the slope; in the sounding site covered by high-mountain grass	120 ns (6 m)

Tab. 1 Descriptions of GPR profiles

5 CONCLUSIONS

The presence of lens-like high-resistivity anomalies may suggests the presence of lumps and lenses of frozen deposit, but it is not an univocal evidence for its occurrence. It should be underlined however, that GPR results are very similar to results obtained from other methods. The only exception is profile No. 6. This large consistence of results from different geophysical investigations carried out in different time evidences the stability of permafrost, proper choice of investigation methods and their comparability.

In non of the profiled studied, resistivity values typical for glacier ice were determined, as it was in Medena kotlina valley (GĄDEK et al. 2006) in Slovakian Tatras. The obtained results suggest rather the occurrence of permafrost in form of frozen debris and soil.

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