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L A N D F O R M E V O L U T I O N I N M O U N T A I N A R E A S

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GLACIAL ICE AND PERMAFROST DISTRIBUTION IN THE MEDENA KOTLINA (SLOVAK TATRAS): MAPPED WITH APPLICATION OF GPR AND GST MEASUREMENTS

Abstract. The paper presents results of Ground Penetrating Radar (GPR) surveys and Ground Surface Temperature (GST) monitoring at the largest Tatra's glacieret and the adjacent debris slope, where in the period 2002–2003, the only outcrop of buried massive ice in the whole Carpathian-Balcanian region was exposed. The aim of these investigations were to determine the ice limit in the debris substratum and its relation to the contemporary glacieret. This made it possible to verify the results of the earlier DC resistivity and electromagnetic soundings, and to better detect the glacieret bed. The new data confirm the existence of a buried glacial ice both in the floor of the contemporary glacieret and in the debris slope of the Medena kotlina. The range of this ice is however smaller than it had been assumed in earlier investigations. Within the debris slope, it contributes to creation of an isolated patch of contemporary permafrost containing mainly interstitial ice. Its occurrence is influenced by orographic conditions.

Key words: glacieret, buried ice, permafrost, Ground Penetrating Radar, Ground Surface Temperature, the Tatra Mountains

INTRODUCTION

During the last twenty years, in the highest zones of unglaciated mountains in middle latitudes, the possibility of permafrost occurrence was stated or suggested (Urdea 1992; King and Ackerman 1993; Ishikawa et al. 2003; Dobiński 2005). The presence of permafrost in the Tatras was first reported by W. Dobiński (1997) based on the results of climatological and geophysical investigations. According to W. Dobiński thawing and freezing indices provide evidence that sporadic discontinuous permafrost may occur at an elevation of 1,700 m a.s.l. with continuous permafrost occurring above 2,500 m a.s.l. Contemporary permafrost likely occurs above 1,930 m a.s.l. on north-facing slopes and above 2,050 m a.s.l. on south-facing slopes. W. Dobiński (2004) calculated also the time necessary for complete decay of Pleistocene freezing of ground in the Tatra Mountains and submited a thesis that it might have been preserved until present time. Moreover, basing on the results of BTS, DC resistivity and shallow electromagnetic soundings, he showed that both contemporary and relic permafrost may exist even within the summit of Kasprowy Wierch at the height of 1986 m a.s.l. (Dobiński et al. 2006). However, permafrost mapping using BTS, DC resistivity, infrared imagine and georadar methods in the Kozia Dolinka (1,940–2,020 m a.s.l.) revealed only the occurrence of isolated patches of permafrost in lens-like form on the north facing slopes (Mościcki and Kędzia 2001; Kędzia 2004; Lamparski and Kędzia 2007). The results of two-year monitoring of ground surface temperature in this hanging cirque evidence that contemporary permafrost in the alpine zone of the Tatra Mountains develops in some north facing slopes both under a thick and a thin snow cover, and its existence may be more related to local circulation of cold air over the surface and low solar irradiation (low summer ground heat storage) than to altitude and snow cover development (Gądek and Kędzia 2008). On the other hand, in the Medena Kotlina, a several-year long negative mass balance and the recession of the largest Tatra's glacieret caused redeposition of debris material at its foreland which uncovered massive ice in the period 2002–2003 (Gądek and Kotyrba 2003). Moreover, the first georadar data on the internal structure of this glacieret indicate the occurrence of fossil ice in its frontal part (Gądek and Kotyrba 2003, 2007). In order to determine the limit of this ice in the ground, DC resistivity and deep electromagnetic soundings were applied (Gądek and Żogała 2005; Gądek et al. 2006). The obtained results evidence that in the debris substratum of the Medena kotlina, the buried ice forms the eastern non-active part of the contemporary glacieret. It may be therefore assumed, that the modern periglacial environment of this hanging cirque favours the occurrence of permafrost. This gives bases to formulate new views on functioning and Holocene evolution of cryosphere and the whole natural environment of the periglacial zone of the Tatra Mountains. However, morphodynamic features of debris slopes in the Medena kotlina do not evidence the presence of buried ice (Rączkowska 2004, 2005). Therefore, in order to verify the interpretation of electroresistivity and electromagnetic data, the Ground Penetrating Radar (GPR) and Ground Surface Temperature (GST) measurements were carried out, which included the whole area of previous investigations. GST method is excellent for mapping the internal structure and subsurface geometries of ice bodies because ice has low energy dissipation (Arcone et al. 2002; Brandt et al. 2007). On the other hand, GST monitoring makes it possible to determine the ground thermal state (Hoelzle et al. 1999; Ishikawa 2003; Lewkowicz and Ednie 2004).

STUDY AREA

The Medena Kotlina is located in the eastern fringe of the High Tatras in the upper part of the Kežmarska Biela voda valley (Fig. 1). It represents a poorly developed hanging glacial cirque sloping the north, located in the temperate cold climatic zone (1,850–2,200 m a.s.l.), where MAAT = 0÷–2°C (Hess 1996) and periglacial processes are still active (e.g. Kotarba 1992; Rączkowska 2004). From the east, south and west rocky walls of the surrounding summits, which are over 2,500 m a.s.l., shade the cirque. The Medeny glacieret, nourished mainly by snow avalanches, covers the western part of the cirque (Photo 1). It is the largest firn-ice body in the Tatras (Jania 1997). In the autumn 2007, its area reached about 2.4 ha (Gądek, unpublished materials). It created two ramparts of frontal-lateral moraines, the older of which developed during the Little Ice Age (Rączkowska 2004). In 2002, at the slope of nival-fluvioglacial channel below the glacieret front, outcrops of massive ice became exposed from the below of debris cover (Gądek and Kotyrba 2003). The eastern part of the Medena kotlina bottom is covered by talus and alluvial cones. Alluvial cones are cut across by channels of debris flows and the

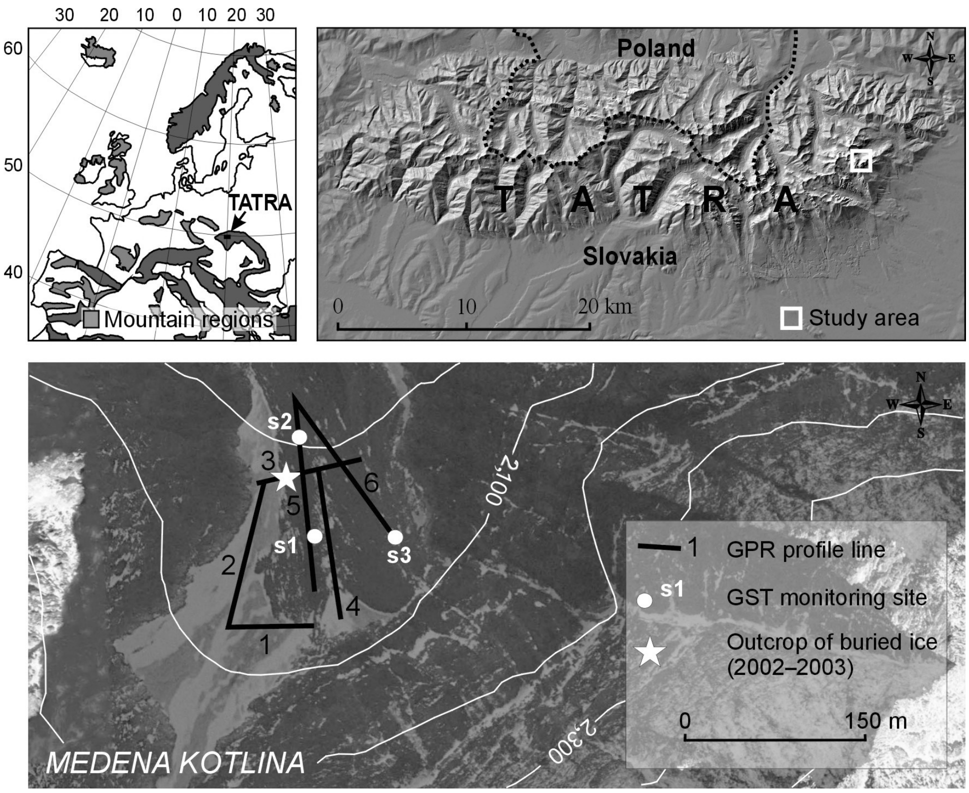

Fig. 1. Location of the study area, GPR profile lines and GST monitoring sites

Photo 1. The Medeny glacieret in July 2007 (Photo by T. Budzik)

largest of them have rocky bottoms (Rączkowska 2004). In the upper part of the nival niche, between a frontal-lateral moraine and a talus cone, a firn-ice patch is usually present. In the whole area forms of active structural soils occur and effects of intensive frost activity are visible (Rączkowska 2005).

METHODS

GPR SURVEYS

The GPR method is used to detect electrical discontinuities in the ground. It accomplishes by transmission of a high-frequency electromagnetic pulses, reception of their reflections from subsurface inhomogenities/layer boundaries and the travel-time measurement. The velocity of radar pulse propagation depends on electrical properties of experiences substrates (Neal 2004).

The fieldwork was conducted at the end of July 2007. The measurements were performed by using a RAMAC/GPR CUII (manufactured by *Mala GeoScience).* The unshielded antennae (transmitter and receiver) with center frequency of 200 MHz and with antennae separation of 0.6 m were applied. Because of a large inclination of the area (to 40°), four persons took part in measurements, who were responsible for manual moving of antennae (2 persons), operation/transport of the central unit and computer (1 person) and rope safeguard (1 person). The measurements were performed along 6 profile lines of a total length of 650 m (Fig. 1). They were located on the glacieret (1, 2 i 3), nival niche (4), frontal-lateral moraine (5), alluvial cone (6) and slope modelled by avalanche (3, 4, 5, 6). Measurement lines 1 and 3 cut across the places where the maximum thickness of the glacieret (1) and the outcrop of buried massive ice (3) had been earlier determined (Gądek and Kotyrba 2003, 2007). The beginning and end of each of the profile were marked by reference points which co-ordinates were determined from the ortophotomap at a scale 1:5,000 (Gądek et al. 2004). More precise positioning of measurement points with the use of GPS receiver was not possible to obtain because the horizon was shaded by rock walls. Depending on the speed of the antennae motion a real coverage of surveyed section by radar signal traces (amplitude — time series of radar reflections coming back to receiving antennae) ranged from 15 to 35 for 1 m. Time windows of data collection were selected for 286 ns and 501 ns. The RadExplorer v. 1.4 software (*DECO-Geophysical Ltd.*) was used for data processing and interpretation. In most cases, DC removal, time-zero adjustment, background removal, amplitude correction, trace edit and radio-wave velocity models were applied. The values of relative permittivity and the velocities of radar pulses propagation in each layer of the explored ground were calculated basing on opening angle of the recorded hyperbolic diffractions and their location using interactive functions of the software. In the qualitative interpretation of the GPR sections of the Medeny glacieret, the results of photogrammetric monitoring of its fluctuations and development of its internal structure in the period 1998–2007 were also used (Gądek, unpublished materials).

GST MONITORING

GTS monitoring was carried out at 3 soil-free sites located: between the bottom of nival niche and the ridge of frontal-lateral moraine (s1), at the slope modelled by avalanche (s2) and at the alluvial cone (s3) in the altitude zone from 1,990 to 2,070 m a.s.l. (Fig. 1). The GST measurements in the Medena Kotlina were carried out from 1.10.2005 to 30.09.2006. Miniature data loggers Onset Hobo Pro were applied, which contained thermistors with a temperature range from –30°C to +50°C, a resolution of 0.02°C and with an accuracy given by manufacturer of better than ±0.4°C. All the equipment was installed before the first snow falls. During the measurement period, thermistors were covered by 3 cm thick debris layer in order to protect them from direct solar radiation and to secure good thermal conductivity with the ground surface. GST values were recorded every hour. Mean annual ground surface temperature (MAGST) values were calculated, and stable values of March bottom temperature of snow cover (BTS) were recorded — when snow cover thickness exceeded 0.8 m (lack of short-term fluctuations of GST) and before a spring thawing started. It was assumed that negative values of MAGST and BTS < –3°C indicate the presence of contemporary permafrost (Haeberli 1973; Hoelzle et al. 1993; Lewkowicz and Ednie 2004).

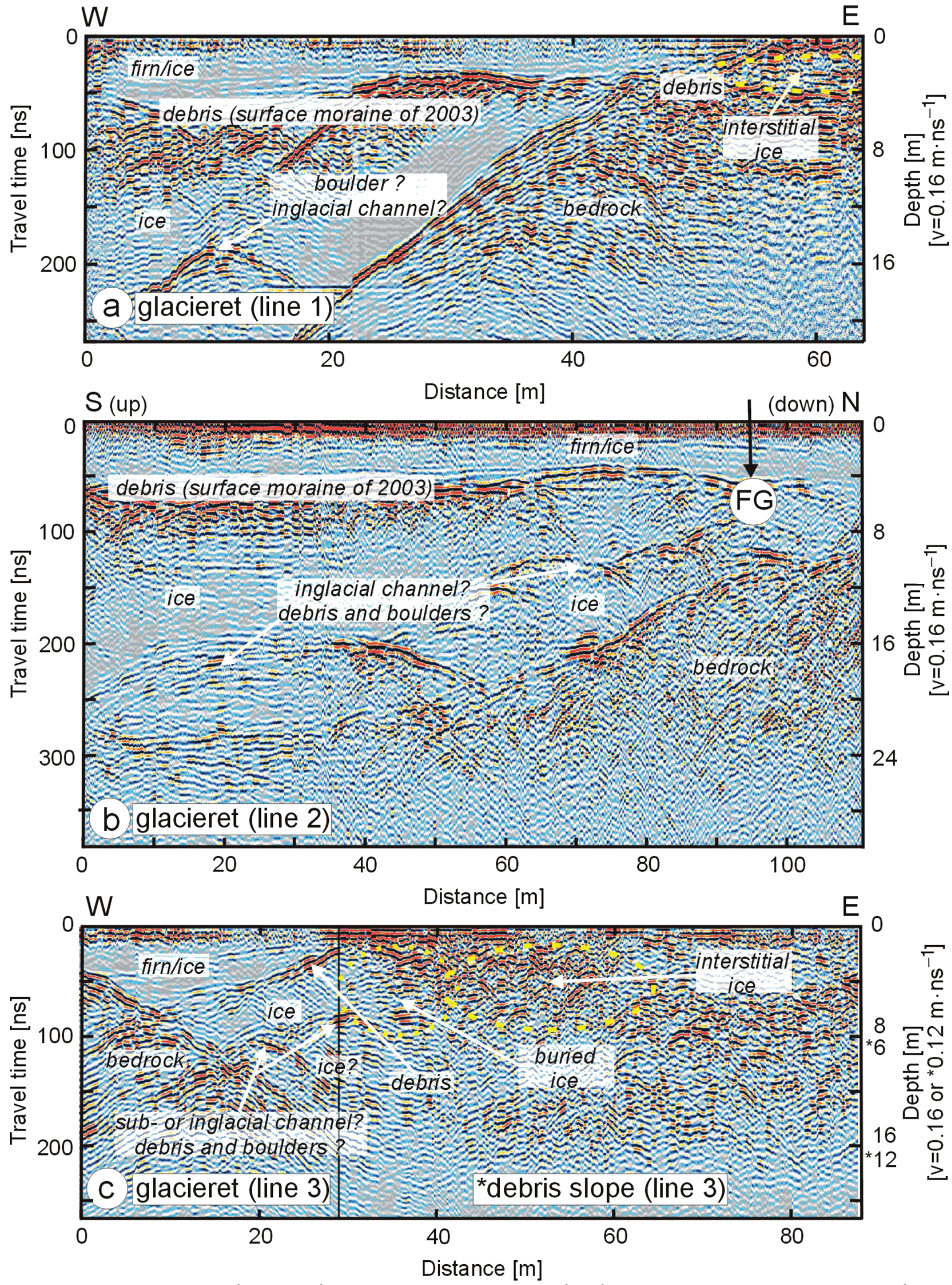

Fig. 2. The GPR sections (200 MHz) of the Medeny glacieret (a–c) and the adjacent debris slope (a and c). Yellow dotted line shows substrates inside the debris forms (a and c), in which velocity of radar pulses propagation was typical for ice (ca. 0.15 m · ns^{-1}). Reflection patterns of these substrates and their relation to the internal structures of the glacieret and debris slope suggest that it is a buried massive ice or sediments containing interstitial ice (explanations in the text). A black arrow shows the location of the glacieret front (FG) in the period 2002–2003

RESULTS AND INTERPRETATION

GPR DATA

Recorded on the radar images reflections from the line and point objects (Figs. 2 and 3) enabled to determine the glacieret internal structure, thickness and approximate volume, its relations with the outcrop of buried massive ice and also interstitial ice distribution in debris slope of the Medena Kotlina. The calculated values of relative permittivity and the velocity of radar pulses propagation in the investigated substrates shows Table 1. The depth limit of the detection ranged from 6 m (in derbis slope) to 30 m (in the glacieret).

Table 1

Relative permittivity and velocity of radar pulses propagation in the investigated substrates

Substrates	Relative permittivity	Radar velocity [$m \cdot ns^{-1}$]
Firn	2.9÷2.5	0.178÷0.188
Ice (glacieret)	4.0÷3.0	0.150÷0.174
Buried ice	3.7	0.156
Permafrost (interstitial ice)	4.6÷3.5	0.140÷0.160
Loose debris/unfrozen sand dry	7.3÷5.0	0.111÷0.134
Compacted/wet debris/sand	27.4÷8.9	0.057÷0.101

Internal structure and volume of the glacieret

The velocity of propagation of electromagnetic impulses inside the glacieret (Fig. 2a–c) was changing from 0.178 $m \cdot ns^{-1}$ to 0.188 m ns^{-1} in the firn and from 0.15 $m \cdot ns^{-1}$ to 0.174 $m \cdot ns^{-1}$ in the ice. The reflection horrizons recorded in GPR sections were generated by debris-boulder layers, inglacial channels and granitoide bedrock. The layer of debris underlying the firn-ice cover was recorded the most distinctly. It was located at the depth of about 4 m and it was from 1 m to over 5 m thick. In 2003, this layer formed a wide surface moraine (Photo 2). The second clear reflection horizon was projected in the floor part of the glacieret. It was composed mainly of broad reflections of hyperbole shape which probably came from the roof of an inglacial channel chamber or large boulders. It started at the bedrock in the beginning of the measurement line 2 and joined the upper layer of the debris at the 95 m of this profile (Fig. 2b), where, in the period 2002–2003 the glacieret front was located (Photo 2). The floor of the exposed at that time nival niche was covered with debris. The ice package about 5 m thick occurring below represents a fossil part of the glacieret. The maximum thickness of its active part (which shows mass circulations features) on the day of measure-

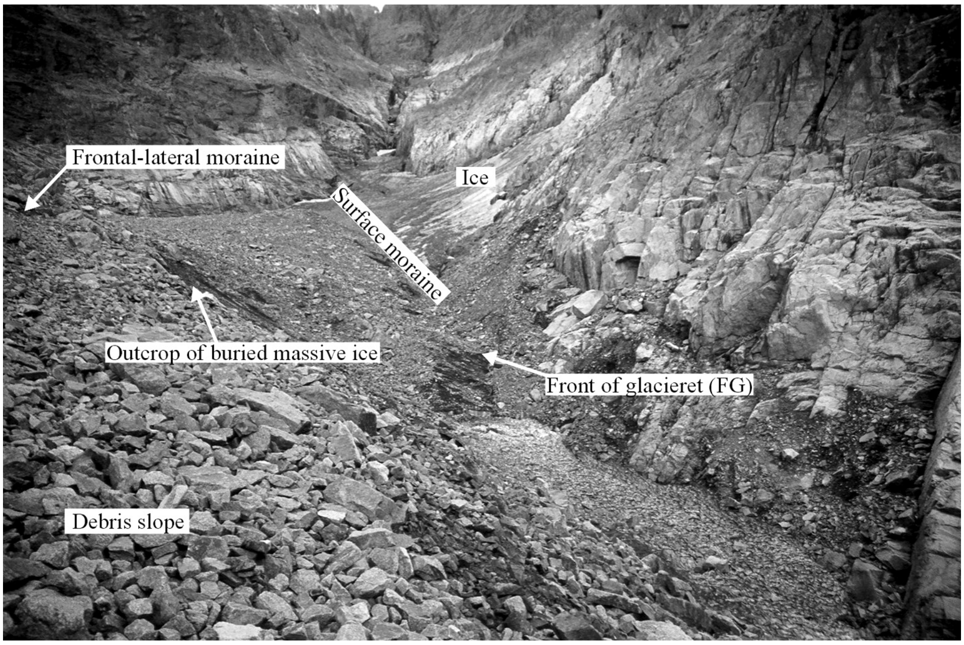

Photo 2. The Medeny glacieret in September 2003. A thick surface moraine visible in the photograph became covered by firn and ice in the period 2004–2007 (Fig. 2a and b). The arrows show the location of the glacieret front (FG) marked in Fig. 2b, and the outcrop of buried massive ice (Photo by B. Gądek)

ments was 22 m. Taking into account changes of ice thickness recorded at all profiles (Fig. 2a–c) and the area of the glacieret, it may be assumed that its volume accounted to about 240,000 m^3, 37% of which represented firn and ice from the period 2004–2007.

Buried massive ice limitation

Figure 2c shows the results of measurements performed along the line which cuts the place where the outcrop of buried massive ice was visible in 2002–2003 (Photo 3). In the period when the outcrop existed, this place was at the foreland of the glacieret (Photo 2), whereas on the day of measurements it was located within its frontal zone built of firn and 4 year old ice. The thickness of this part of the glacieret accounted to 5 m. It was underlain by a thin layer of debris, which, in turn, is underlined by fossil package of ice which thickness increases towards the east from 3 m to 5 m. The velocities of electromagnetic waves in this depth zone accounted to 0.156 $m \cdot ns^{-1}$. This ice occurred also in the debris slope on the eastern part of the glacieret, where it thinned out at the distance of about 10 m. The thickness of debris-sandy material overlying the buried ice accounted to 2–2.5 m.

Photo. 3. The outcrop of buried massive ice in the foreland of the Medeny glacieret in 2003 (Photo by B. Gądek)

The youngest part of the modern glacieret is separated from the buried ice by about 1 m thick debris cover. It developed in summer seasons 2003 and 2004 as a result of sliding of the overlying material on the surface of exposed and melting ice. The substratum of the fossil part of the glacieret in its western part is represented by a solid rock, and in its eastern part a debris-boulder layer, which is probably underlain by lithologies which show the structure of ice-debris body. However, in their inner part no reflections were recorded to determine the velocity of radar waves, which would help to identify the type of the material. Within the debris slope, because of more intensive attenuation of electromagnetic waves, these lithologies were beyond the range of radar determination (Fig. 2c). Hyperbolic shape of the reflections generated on its roof may also evidence the existence of a sub- or inglacial channel. Their location corresponds to the run of the floor reflection horizon inside the contemporary glacieret (Fig. 2b).

Interstitial ice distribution

The velocity of electromagnetic waves in the range 0.14–0.16 m ns^{-1} was measured also inside the nival niche with firn-ice patch, frontal-lateral moraine, and slope modelled by avalanche (Fig. 3a–c). However, very irregular reflection patterns of these layers suggest that it is not a buried glacier ice, but rocky crumbs cemented

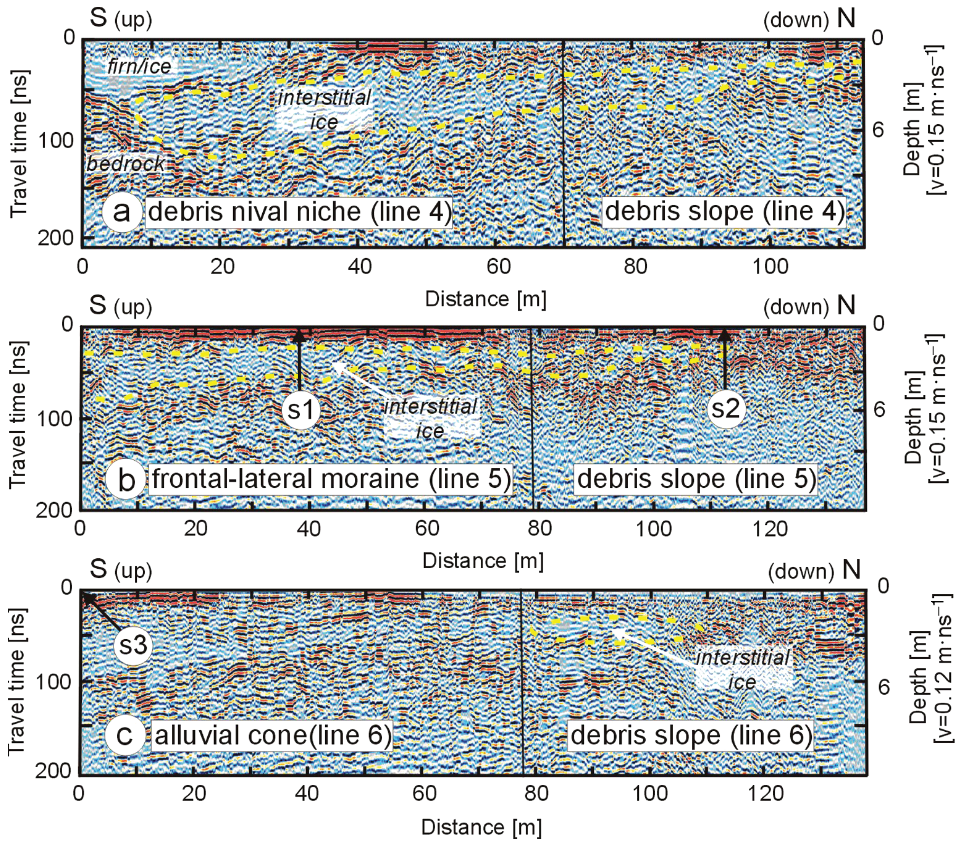

Fig. 3. The GPR sections (200 MHz) of the debris nival niche (a), frontal-lateral moraine (b), alluvial cone (c) and slope modelled by avalanche (a–c). A yellow dotted line shows layers in which velocity of radar pulses propagation was typical for ice (ca. 0.15 m · ns^{-1}). Irregular reflection patterns of these layers and their relation to the other part of the slope suggest that these are sediments containing interstitial ice (explanations in the text). Black arrows show the location of GST monitoring sites (s1, s2 and s3)

probably by interstitial ice — i.e. a typical high mountain permafrost, which originates as a result of water freezing in the ground. In the light of the obtained data, interstitial ice also existed in the debris bed of the 4 year old firn-ice patch (Fig. 3a), where it reached the granitoide bedrock. The thickness of the material overlying these substrates accounted to 2–2.5 m along all the measurement profiles. They formed a patch about 110 m long (Fig. 3a–b) and at least 30 m wide (Fig. 2c). Its thickness decreased with altitude — within the nival niche from 4 m to 1 m (Fig. 3a), and along the frontal-lateral moraine axis and its extension to the slope modelled by avalanche from 3 m to 0.5 m (Fig. 3b). This layer was also recorded in the alluvial cone (Fig. 3c), where velocities of propagation of electromagnetic waves were in the range 0.111–0.134 · m ns^{-1}. This may suggest that material in this part of the slope was not frozen. Within the underlying sediments (probably compacted/wet debris/sand) radar wave velocities were in the range 0.057–0.101 m · ns^{-1}. The lowest limit of the occurrence of contemporary permafrost in the slope modelled by avalanche run at the altitude of about 1,990 m a.s.l.

GST DATA

The recorded values of GTS at individual sites are shown in Figure 4. They reflect different topographic conditions, development of snow cover, and possibility of permafrost development in the site studied (Tab. 2). The obtained data are consistent with the interpretation of the results of GPR surveys.

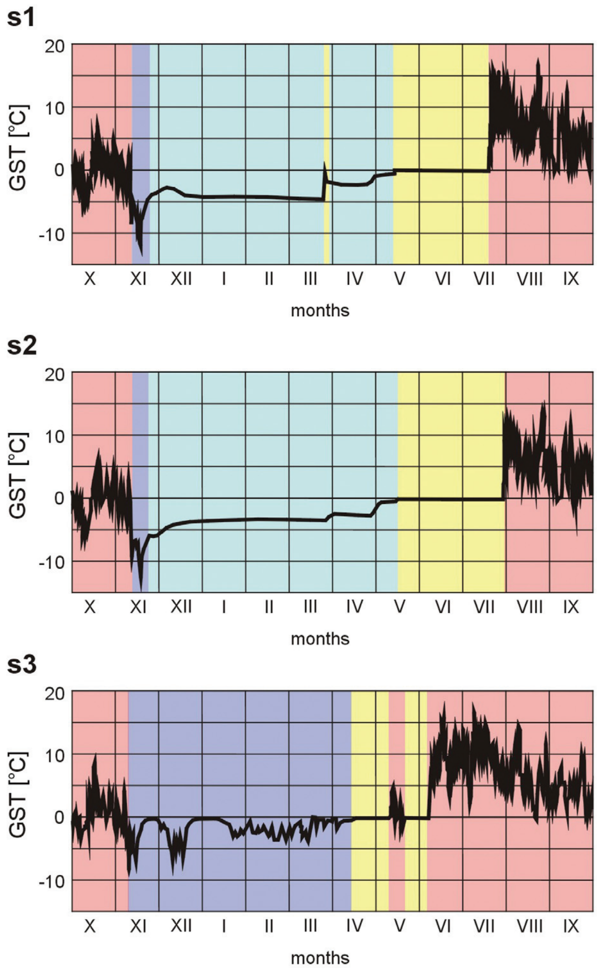

Fig. 4. Variation of GST values and snow cover development during the period from 1.10.2005 to 30.09.2006. The GST monitoring sites were located: between the bottom of nival niche and the ridge of frontal-lateral moraine (s1), at the slope modelled by avalanche (s2) and at the alluvial cone (s3). Background colours indicate the periods without a snow cover (red), with thin (dark blue) or thick (blue) snow cover, and with thawing (yellow)

Table 2

Morphological and thermal attributes of the GST monitoring sites

Site	Altitude [m a.s.l])	Slope exposition	Landform	Type of GST winter regime (snow cover development)	GST values in March [°C]	MAGST [°C]	Possible existence of permafrost
s1	2,045	N	Frontal-lateral moraine /nival niche	Lack of short-term GST fluctuation during the almost whole period of dry snow cover occurrence (thick snow cover)	–4.7	–1	Yes
s2	1,990	N	Debris slope modelled by avalanche	Lack of short-term GST fluctuation during the almost whole period of dry snow cover occurrence (thick snow cover)	–3.5	-0.9	Yes
s3	2,070	N	Alluvial cone	Short-term GST fluctuation during the whole winter (thin snow cover)	–4.5÷0	+1.5	No

Lack of short-term GST fluctuations in the winter season 2005/2006 at the sites located in the zone of avalanche accumulation between the bottom of nival niche and the ridge of frontal-lateral moraine (s1), and also on the slope modelled by avalanche (s2) evidences a rapid increase of snow cover at these sites. A thick snow cover protected the substratum against the impact of short-term air temperature variations. A short-term GST fluctuations were recorded during the whole measurement period at the alluvial cone (s3) and they evidenced that the snow cover at that site was not thick.

In November 2005, a rapid increase of snow cover at the sites s1 and s2 favoured an early stabilization of its bottom temperature. In the period from December 2005 to the thaw in March 2006, GST values at these sites were close to –4.5°C and –3.5°C respectively. Percolation of melting water connected with a warm period caused at both sites rapid increase of temperature at the snow cover bottom to –0.5°C and –2.8°C respectively. On the proceeding days of March its temperature at the site s1 decreased to –2.5°C , and at the site s2 it was stable until the spring thaw. In May 2006 the GST values everywhere increased finally to 0°C. The decay of snow cover took place in the second part of July (Fig. 4).

At the site s3, ground surface temperature in the winter season 2005/2006 was changing in the range from 0°C to –6°C in November and December and from 0°C to –3.5°C in other months. During the period 26.04–15.05.2006, the snow cover in that place melted totally (Fig. 4).

Among the monitored sites, the coldest one was located between the ridge of the frontal-lateral moraine and the bottom of the nival niche (s1). The MAGST and BTS values at that site were close to –1°C and –4.7°C respectively, whereas 30 m below on the slope modelled by avalanche (s2) they accounted to –0.9°C and –3.5°C respectively. This values suggested a negative thermal balance of the subsurface ground layer and possibility of contemporary permafrost development in that part of the slope. Such thermal conditions were not determined at the alluvial cone — which was the highest located measurement site (s3). Mean annual ground surface temperature at that site accounted to +1.5°C.

DISCUSSIONS

The calculated velocities of propagation of electromagnetic waves in the upper layer of the glacieret were typical for firn (Kohler et al. 1997), and in its other part they were typical for glacial ice in the temperature of melting point under pressure (Arcone et al. 2000). Also within the buried part of the glacieret they were typical for ice (Brandt et al. 2007). On the other hand, the velocities of radar waves determined for that part of the debris slope, which was assumed as a zone of interstitial ice occurrence, may suggest both permafrost, and unfrozen, dry debris and debris-sandy material (Daniels 2004; Sass 2007). However, negative MAGST values together with relatively low BTS values in this zone suggest, that it was a frozen layer. This is also confirmed by the decrease of mean velocity of electromagnetic waves by 0.02 m · ns^{-1} beyond the limit of the determined permafrost patch – within a much warmer alluvial cone (Tab. 1).

The comparison of the obtained GPR section of the glacieret with an analogical image recorded 5 years earlier (Gądek and Kotyrba 2007) makes it possible to study mass circulation dynamics and mechanism of this perennial ice form. The increase of the glacieret volume in the period 2002–2007 by over 1/3, undisturbed location of the surface moraine of 2003 covered by firn-ice layer, and lack of noticeable differences in reflection horizon between the active and probable fossil parts of the glacieret, evidence a considerable dynamics of changes of its dimensions, as well as a small role of rotation movement in the process of its mass exchange. This is connected with the possibility of preservation of a very old ice in the floor part of the glacieret. The reflection horizon generated by the layer of the surface moraine from before 4 years is the only one of this type inside the glacieret. It may be assumed therefore that in 2003 the dimensions of the glacieret were extremely small. Probably the massive buried ice in the debris slope, supported before by the glacieret, became exposed for the first time.

The obtained data make it possible to verify the interpretations of the results of the previous measurements of DC-resistivity and deep electromagnetic soundings, which had suggested the possibility of buried ice existence in the whole investigated part of the Medena kotlina (Gądek et al. 2006). The new GPR data evidence that the range of buried ice is limited to about ten meters long transition zone between the rampart of frontal-lateral moraine and the slope modelled by avalanche. Only in that zone they also confirm the possibility of existence of two packages of fossil ice in the floor of the contemporary glacieret (Gądek and Kotyrba 2007). The main reason of the first divergence was the assumption that the layers showing electric resistivity typical for a dry part of a glacieret (several MOhmm) consist of massive ice (Gądek and Żogała 2005), whereas new data indicate that they consist of interstitial ice. They do not include however the zone of debris substratum located below the depth of 6 m. A larger range of the layer showing reflection patterns typical for fossil ice, visible in GPR section of the glacieret of 2002 may result from: a) larger distance of the former measurement line from the western rock wall, or b) false interpretation of the image in the zone of considerable attenuation of electromagnetic waves (the determination depth was at that time smaller because 500 Mhz antennae was applied).

The overburden thickness of both buried massive ice and interstitial ice was determined exclusively basing on the changes of reflection patterns of the subsurface ground layer in the middle of summer. It may be assumed however that the thickness of active layer is larger than 2 m, which is consistent with the results of DC resistivity soundings carried out in the autumn (Gądek and Żogała 2005).

The obtained GPR and GST data are complementary to each other. They indicate a contemporary development of permafrost inside the frontal-lateral moraine, nival niche, and at their extension within the slope modelled by avalanche, both below a thin and thick snow cover. They evidence, that in places of small resources of heat in the ground, a thick and long occurring snow cover represents only a thermal buffer and may not be able to protect its substratum against a cooling influence of the atmosphere. In the light of these results, also the roof of the buried massive metamorphic ice (of glacial origin) is located below the active layer and represents a form of contemporary permafrost. Simultaneously, they indicate the lack of permafrost in the analogical depth zone within the alluvial cone, even in higher located places of the same slope exposure. They confirm therefore the view, that the occurrence of contemporary permafrost in the alpine zone of the Tatras may be more related to local circulation of cold air over the terrain surface, than with the altitude and snow cover development (Gądek and Kędzia 2008). Higher temperature of the ground and considerably faster decay of snow cover in the upper part of the alluvial cone may additionally be connected with winter ascending air circulation throughout debris slope (eg. Delaloye and Lambiel 2005). Thermal state of the ground reflected in the GST values at the edge of the permafrost patch in the Medena Kotlina (site s2) may be assumed as a limit for the development of contemporary permafrost in the alpine zone of the Tatra Mountains.

CONCLUSION

The obtained data confirm the existence of buried glacial ice both in the floor of contemporary glacieret and in the debris slope of the Medena Kotlina, and they reveal the existence of contemporary permafrost patch containing interstatial ice. The massive metamorphic ice buried in debris slope contacts with interstitial ice — so it also represents a form of contemporary permafrost. But its range is limited only to a transition zone between the frontal-lateral moraine and the slope modelled by avalanche. The ice buried in the glacieret bed represents its fossil part of the temperature close to melting point under pressure.

The existence of both the glacieret and the permafrost in the Medena Kotlina is conditioned by orography. The existence of the glacieret is connected with avalanche accumulation of large amount of snow, and the patch of contemporary permafrost is connected with ground cooling as a result of local circulation of cold air. In both cases, a considerable shading of the area is another essential factor. Smaller solar irradiation influences possibility of both positive mass balance of the glacieret, and negative heat budget of ground. In the light of the obtained data it may be assumed that in the alpine zone of the Tatras only isolated patches of contemporary permafrost may occur.

In case it is not possible to make boreholes, the existence of permafrost should be determined applying several complementary geophysical methods like DC resistivity, GST and GPR measurements.

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STRESZCZENIE

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LÓD LODOWCOWY I WIELOLETNIA ZMARZLINA W MIEDZIANEJ KOTLINIE (TATRY SŁOWACKIE) W ŚWIETLE WYNIKÓW POMIARÓW GEORADAROWYCH I MONITORINGU TEMPERATURY POWIERZCHNI GRUNTU

W pracy przedstawiono wyniki pomiarów georadarowych i monitoringu temperatury powierzchni gruntu w Miedzianej Kotlinie. Badania wykonano na największym tatrzańskim lodowczyku oraz sąsiednim gruzowym stoku, gdzie w latach 2002–2003 istniała jedyna znana w regionie karpacko-bałkańskim wychodnia pogrzebanego lodu masywnego. Celem badań było wyznaczenie zasięgu lodu w gruzowym podłożu oraz określenie jego relacji do współczesnego lodowczyka. Pozwoliło to zweryfikować interpretację wyników wcześniejszych sondowań elektrooporowych i elektromagnetycznych oraz lepiej rozpoznać podłoże lodowczyka. Nowe dane potwierdzają istnienie pogrzebanego lodu lodowcowego, zarówno w spągu współczesnego lodowczyka, jak i w gruzowym stoku Miedzianej Kotliny. Zasięg tego lodu jest jednak mniejszy niż to wynikało z poprzednich badań. W obrębie gruzowego stoku współtworzy on płat współczesnej wieloletniej zmarzliny, zawierającej głównie lód porowy. Jego istnienie jest uwarunkowane orograficznie. W świetle uzyskanych danych współczesna wieloletnia zmarzlina w piętrze alpejskim Tatr może tworzyć tylko izolowane płaty.