CONTEMPORARY AND FOSSIL METAMORPHIC ICE IN MEDENA KOTLINA (SLOVAK TATRAS), MAPPED BY GROUND-PENETRATING RADAR

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Bogdan Gądek, Andrzej Kotyrba: Contemporary and fossil metamorphic ice in Medena kotlina (Slovak Tatras), mapped by ground-penetrating radar. Geomorphologia Slovaca et Bohemica, 7, 2007, 1, 4 Figs., 1 Tab., 40 Refs.

This paper shows results of detailed ground-penetrating radar surveys at 500 MHz of glacieret in the Medena kotlina – the largest in the Tatras patch of metamorphic ice. The recorded radar image showed the substratum and the internal structure of the glacieret together with its hydrothermal features. It revealed also the occurrence of fossil metamorphic ice that is a glacial trace of former climate and simultaneously it is a form of contemporary permafrost. The penetration range of the performed survey reached 25 m.

Key words: glacierets, fossil ice, alpine permafrost, cryospheric indicators, GPR surveys, the Tatra Mountains

1 INTRODUCTION

Metamorphic ice (glacier ice) originates as a result of snow (sedimentary ice) transformation and diagenesis under the influence of temperature, pressure, and partly with the share of melting and meteoric waters (SHUMSKIY 1955). In Tatra Mountains it builds multi-annual firn-ice patches (WDOWIAK 1961, JAWOROWSKI 1966, WIŚLIŃSKI 1985) called glacierets (UNESCO 1970), which are considered to be sensitive indices of climate change (WATANABE 1988, JANIA 1997, GRUNEWALD et al. 2006). The largest Tatras' glacieret is situated in Medena kotlina (**Fig. 1**) – about 200 m below the climatic snow line (HESS 1996). It exists thanks to avalanche accumulation of snow. In literature it was mentioned as early as in the 18th century, but Zejszner pointed out its glacial features in 1839 (after LITWIN and KOŁODZIEJ 2000). It was occasionally investigated since the 1920s (GADOMSKI 1925, KSANDR 1954, VITÁSEK 1956, LITWIN 1997), and since 1992 the glacieret is included in terrophotogrametric monitoring (JANIA 1997, GĄDEK et al. 2005). Changes of the glacieret surface result from contemporary balance of its mass. At the end of the ablation season the glacieret usually covers cca 2-3 ha. Multi-annual mass balance is reflected in the size and number of annual layers of firn and ice, and, simultaneously in the volume of the whole form. Preparation of the first documentation of internal structure of Medený glacieret was the main aim of ground-penetrating radar (GPR) surveys carried out in October 2002. This method is excellent for mapping the internal structure of ice bodies because ice has low energy dissipation (ARCONE et al. 2000). The obtained results revealed the existence of fossil ice (GĄDEK, KOTYRBA 2003). They were the inspiration for complex geophysical, geomorphologic and topoclimatic investigations of the Medená kotlina (RĄCZKOWSKA 2004 and 2005; GĄDEK and ŻOGAŁA 2005, GĄDEK et al. 2005, GĄDEK and KĘDZIA 2006, GĄDEK et al. 2006). They give 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 GPR data and their interpretation have not been earlier published as a whole.

2 STUDY AREA

Medena kotlina is located in the eastern fringe of the High Tatras in the upper part of the Kežmarská Biela voda valley (**Fig. 1**). It represents a poorly develo-

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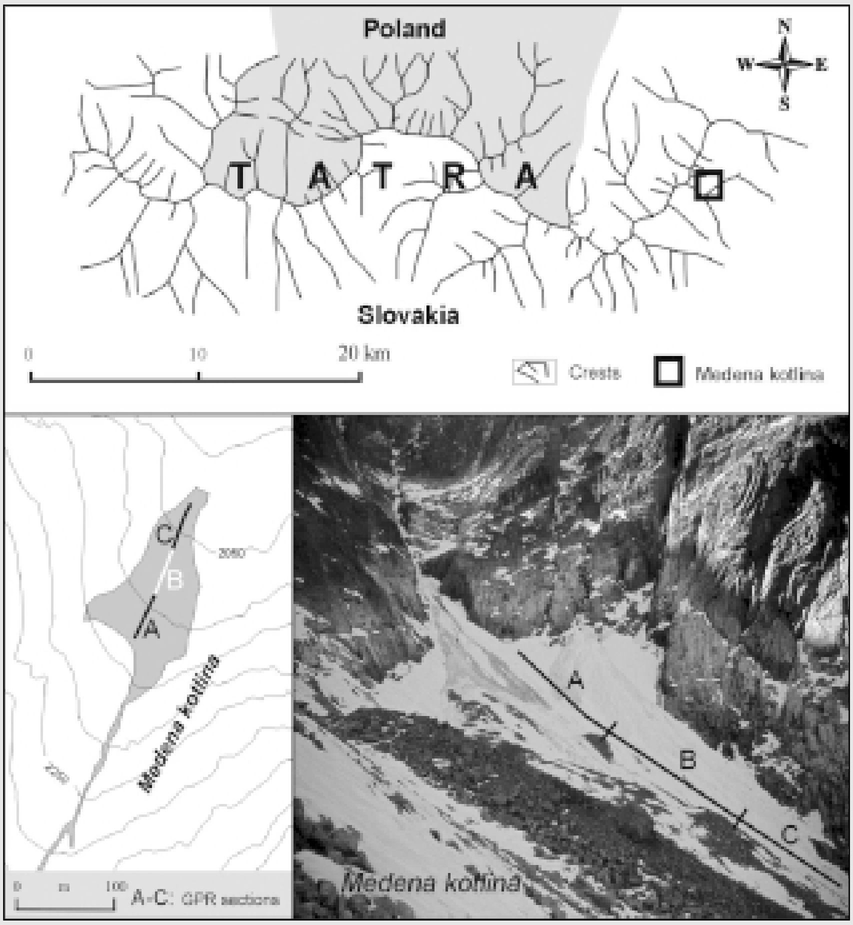


Fig. 1 Location of Medeny Glacieret and ground-penetrating radar survey lines

ped hanging glacial cirque sloping the north. From the east, south and west rocky walls of the surrounding summits, which are over 2 500 m a.s.l, shade it. The Medeny glacieret, alimented by snow avalanches, covers the western part of the cirque. 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, KOTYRBA 2003). The eastern part of the Medena kotlina bottom is covered by gravitational and alluvial cones as well as nival niches (LUKNIŠ 1973; RĄCZKOWSKA 2004). Alluvial cones are cut across by channels of debris flows and the largest of them have rocky bottoms. In the whole area forms of active structural soils occur and effects of intensive frost activity are visible (RĄCZKOWSKA 2005). The cirque is located in the temperate cold climatic zone of the Tatra Mountains, where MAAT = 0 ÷ –2 °C (HESS 1996) and permafrost occurs (DOBIŃSKI 1997 and 2004, KĘDZIA 2004, GĄDEK and KĘDZIA 2006).

3 METHODS

The measurements were performed by reflexive method with use of data acquisition system SIR2 (manufactured by *Geophysical Survey Systems Inc.).* The mono static transducer (transmitter-receiver in one unit) with central frequency of 500 MHz was applied. Time windows of data collection were selected for 200 and 300 ns. The transducer was moved manually down of the glacieret surface. Depending on the speed of the transducer motion a real coverage of surveyed section by radar signal traces (amplitude - time series of radar reflections coming back to receiving antennae in transducer) ranged from 70 to 100 for 1 m. The measurements were performed along a profile line situated in central part of the glacieret divided for three even sections (A, B and C) with total length 150 m and average inclination 39°. The elevation of the beginning point of the profile line was at the height of 2120 m a. s. l., and the end at the height of 2 025 m a. s. l. (**Fig. 1**). The RADAN 4 software was used for data interpretation.

The values of the relative dielectric constant (ε_r) and the velocities of radar pulses propagation (υ) in explored glacieret were connected with the ice moisture content. They were calculated basing on opening angle of the recorded hyperbolic diffractions with the application of the following formula (MOORE et al. 1999):

$$\varepsilon_r = \left(\frac{c}{\upsilon}\right)^2 \qquad [1]$$

where: c – velocity of electromagnetic waves in vacuum (300 m μs^{-1}).

$$\upsilon = \sqrt{\frac{z^2(T_1^2+T_2^2)+2x\sqrt{T_1 T_2(x^2+z^2)-(T_1^4+T_2^4)z^2}}{(T_1^2-T_2^2)}} \qquad [2]$$

where: T_1, T_2 – the one-way travel times to the reflector for two points on the surface with separation x, z – depth of the reflector.

$$z = \frac{x}{\sqrt{(T_2^2/T_0^2)-1}} \qquad [3]$$

where: T_0 – the shortest travel time to the reflector (measured on top of the reflector).

$$\overline{\upsilon} = \frac{x}{\sqrt{T_2^2-T_0^2}} \qquad [4]$$

where: $\overline{\upsilon}$ - the average velocity of the electromagnetic wave between glacieret surface and the point reflector.

Also water content in ice (*W*) was determined using the formula (MACHERET et al. 1993):

$$W = \frac{3(\varepsilon_r - \varepsilon_i)}{\varepsilon_w} \qquad [5]$$

where: ε_r – the permittivity of the ice above the hyperbola, ε_i – the permittivity of solid dry ice (3,19), ε_w – the permittivity of water (86).

The radar travel times were converted to depths using a permittivity value of 3,19 corresponding to a radar-wave velocity of 168 m μs (ARCONE et al. 2000). Close or the same values were recorded only in the dry part of the glacieret but errors of estimated depth did not exceed 7 %.

4 RESULTS AND INTERPRETATION

Recorded on the radar images reflections from the line and point objects (**Fig. 2**) made it possible to determine both the ice thickness and internal structure of the glacieret (with water content). Moreover an attempt was made to evaluate its volume and to explain reasons of its qualitative differentiation. The depth range of the performed survey was 25 m.

THICKNESS AND VOLUME OF ICE

The strongest reflection horizon was generated at the boundary of solid granite-diorite rocks and ice. It was recorded almost along the whole length of the measurement profile, however in the lower part of the glacieret, the contrast of values of dielectric constants of both physical bodies was much smaller than in the upper part of the glacieret. Moreover, in the upper section (A) the time of wave transition along the distance surface - bedrock – surface of the glacieret was included in a time window 200 ns (**Fig. 2a**), and along two other sections (B and C) in a time window 300 ns (**Fig. 2b**). The thickness of the depicted ice increased along the measurement line from about 8 m above the ice cham-

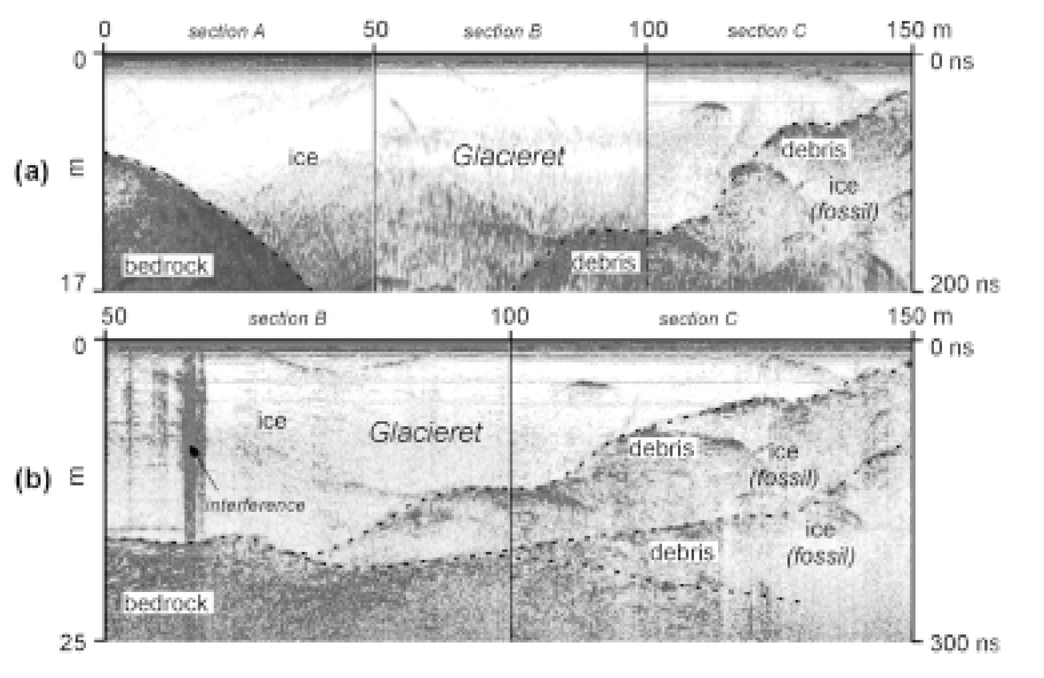


Fig. 2 GPR sections of Medený Glacieret in time window of 200 ns (a) and 300 ns (b); raw data. *Dashed lines: main reflection horizons*

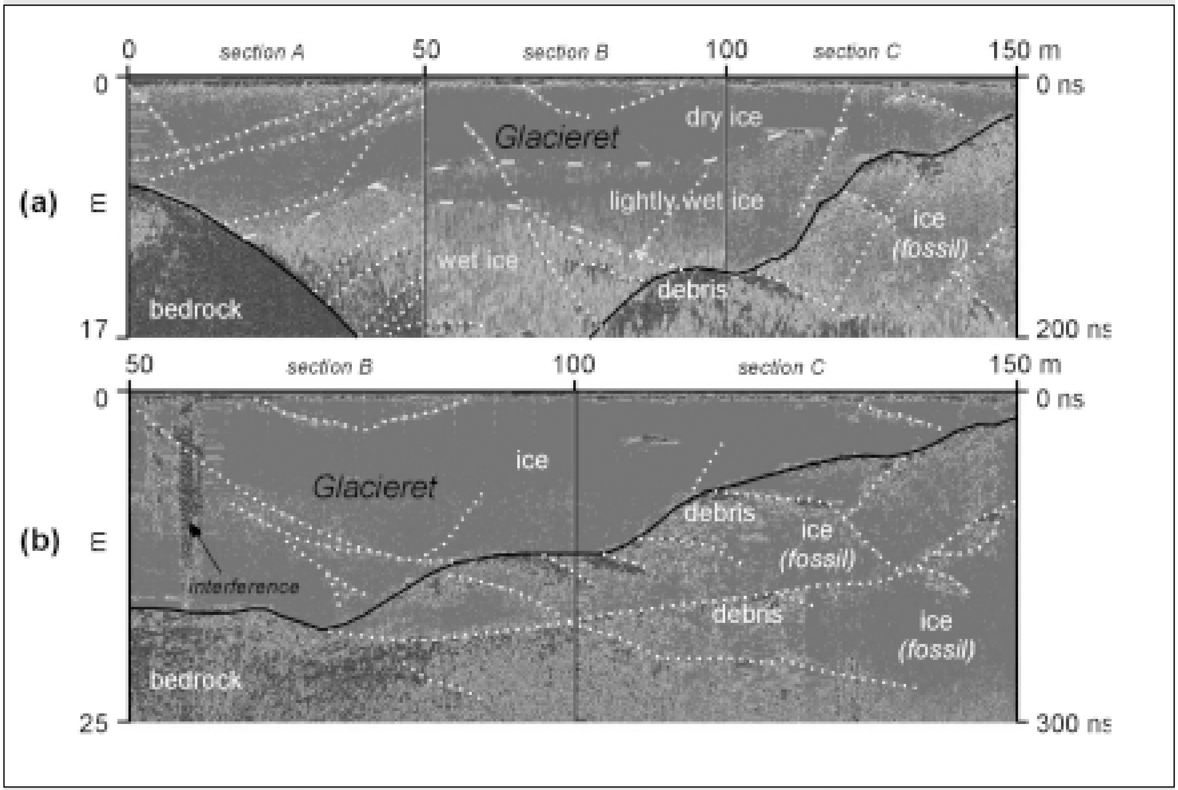


Fig. 3 Internal structure of Medený Glacieret in the light of interpretation of 500 MHz GPR sections in time window 200 ns (a) and 300 ns (b). *Black solid line: the ice- bedrock interface, white dotted lines: reflection horizons, light grey dashed and dotted lines: hydrothermal interfaces*

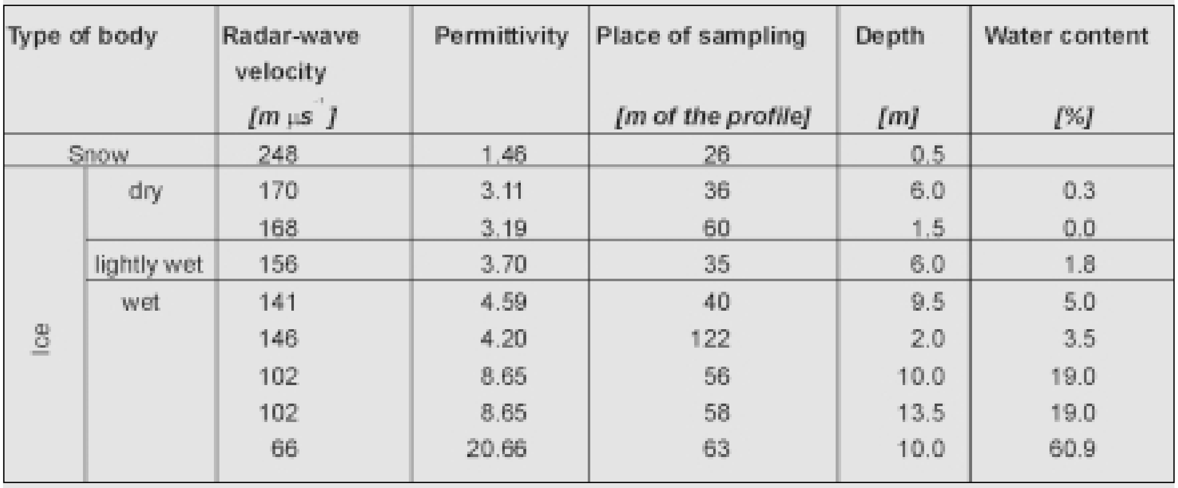
ber near marginal crevasse to about 18 m in the middle part of the glacieret and further to about 20 m near the glacieret front. In the latter section, 2 additional very clear reflection horizons were recorded. They gradually rose from the glacieret bottom towards its front, where they occupied depth of 2 m and 8 m respectively. The continuation of the upper horizon was a debris cover at the glacieret front, which terminated at that time in form of a cliff 2-2.5 m high. Two ice blocks, which are probably located below, pinch out in a debris substratum of the Medená kotlina. The maximal thickness of the active part of the glacieret (which shows mass circulation features) does not exceed 18 m. Its volume calculated from its mean depth (assuming a U-shaped transversal profile) and area during the measurement period was close to 150,000 m^3.

INTERNAL STRUCTURE AND ITS GENESIS

The GPR sections revealed also main features of internal structure of contemporary glacieret and its buried parts (**Fig. 3** and **4**). In the subsurface zone of the recorded substratum, a thin layer of fresh snow was found (**Tab. 1**). It covered ice masses locally interbedded with debris of granite-diorite material and cracked. Clear reflection horizons were generated on ice layer surfaces from summer period, on which deposition of debris material was especially large. They showed dip opposite to the direction of slope inclination of the glacieret surface, which increased with the distance increase from the marginal crevasse. This evidences rotational movement of ice (WEERTMAN 1971). The exceptions are the projections of roof of buried ice packages. Their large energy, shape and location suggest the existence of relatively thick debris covers, which used to develop in the front of the glacieret. They probably document stages of its former recessions, followed by its advance (however the glacieret did not reach its earlier dimensions). Less numerous but relatively strong (in energy magnitude) reflection horizons of opposite and large dip, probably evidence the processes of ice breaking and dislocations. Whereas numerous hyperbolic reflections were mainly generated by rock fragments and inglacial channels. Large amount of debris material was included in the packages of buried ice.

HYDROTHERMAL FEATURES

Changes of velocity of electromagnetic waves in the substratum studied, based on the spread of arms of individual hyperbolic reflections, was connected with differentiation of macroporosity of ice and water content. In the measurement period the values of both



Type of body		Radar-wave velocity $[m\ \mu s^{-1}]$	Permittivity	Place of sampling [m of the profile]	Depth [m]	Water content [%]
Snow		248	1.46	26	0.5	
Ice	dry	170	3.11	36	6.0	0.3
		168	3.19	60	1.5	0.0
	lightly wet	156	3.70	35	6.0	1.8
	wet	141	4.59	40	9.5	5.0
		146	4.20	122	2.0	3.5
		102	8.65	56	10.0	19.0
		102	8.65	58	13.5	19.0
		66	20.66	63	10.0	60.9

Tab.1 Selected examples of radar-wave velocity and water content in Medený Glacieret

these parameters increased with depth and suggested three-layer hydrothermal structure of the ice body (**Tab. 1**, **Fig. 3** and **4**).

In the cooled subsurface part the water content was almost none. This zone ranged from 0 m to 120 m of the measurement profile. Its thickness decreased towards the glacieret front. At 20 m of the profile it was closed to 7 m, and at 105 linear metres it accounted to 3 m. Deeper, the water content was close to 2 %. Towards the glacieret front, the thickness of this zone increased. The largest thickness occurred at 105 m of the measurement profile, where it accounted to 8 m. Near the bottom of the middle part of the glacieret, the water content changed from 3 % to 19 %, whereas at 63 m of the profile it accounted to as much as 60 %. This value seems to be overestimated. Probably in this case the applied in calculations hyperbola does not comply with the conditions of point reflection (MACHERET 2000).

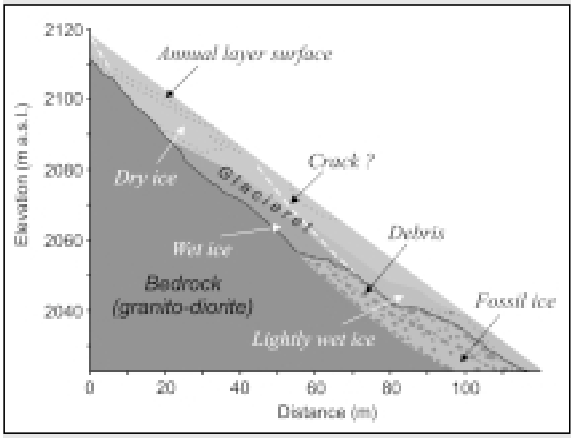


Fig. 4 Longitudinal cross section of Medený Glacieret – main internal structure features

5 DISCUSSION

Exceptional permanence of the glacieret in the Medená kotlina is conditioned by orographic factors, and it is mainly connected with concentrated and large accumulation of avalanche snow. The measured maximal thickness of metamorphic ice, despite its exceptionally small aerial dimensions during the investigation period, was larger or close to the values quoted in literature – estimated basing on observations of marginal crevasses and subglacial channels (GADOMSKI 1925, LUKNIŠ 1973).

The results of DC resistivity sounding carried out in surface moraine in Autumn 2003 (GĄDEK and ŻOGAŁA 2005) showed considerable similarity with GPR section. The applied in traditional investigations of alpine permafrost distribution high specific resistivity of ice (e.g. EVIN and FABRE 1990, VONDER MÜHLL and SCHMID 1993, DOBIŃSKI et al. 1996, MOŚCICKI and KĘDZIA 2001) occurred only for the subsurface of dry layer of the glacieret (264 kOhmm). The resistivity of its wet part (18 kOhmm) was smaller than electric resistivity of the bedrock. The water content in ice may therefore make it hinder or even impossible to detect both congelation ice (which originates as a result of water freezing) that builds typical permafrost (KNEISEL et al. 2007), and massive metamorphic ice, which has a glacial origin. Usually in both these cases the values of specific resistivity account to: from 10 kOhmm to few MOhmm and from several to over 100 MOhmm respectively (KNEISEL et al. 2007).

The recorded on the GPR sections internal structure of the glacieret is typical for small cirque glaciers (KUHN 1995). It evidences its slow movement. Mass exchange may be however complex. The results of radiocarbon dating of pine needles and twig found in the lower part of the Kuranosuke glacieret in the Northern Japanese Alps revealed the existence of ice dated to 1000 – 1700 year BP (YOSHIDA et al. 1990). The buried ice in the Medená kotlina is excluded from mass exchange and isolated from the influence of climatic fluctuations. Its seems that in high-mountain environment, even in the conditions of slope alluviation (KOTARBA et al. 1987, KOTARBA 1992 and 2004) it may be a permanent element of periglacial geoecosystem. This view is confirmed in the outcrop of massive ice in the debris foreland of the Medeny glacieret (GĄDEK and KOTYRBA 2003) as well as in morphodynamic features of it surrounding (RĄCZKOWSKA 2004 and 2005). The age of this ice will be revealed from the planned isotopic data investigations.

6 CONCLUSIONS

Metamorphic ice in the Medená kotlina occurs in two forms: active (with mass circulation) and fossil. Fossil ice represents inactive part of the modern glacieret.

Positive mass balance of the glacieret is significantly connected with an uneven distribution of snow avalanche accumulation. „Permanent" existence of the glacieret is connected with its considerable maximum thickness, which is conditioned by orography and influence, on the other hand, the permanence of the ice buried in its floor.

Metamorphic ice buried in the debris foreland of the glacieret is a glacial trace of former climate and simultaneously it is a form of contemporary permafrost – which has not been earlier determined in the Carpathian-Balcanic region. Its existence evidences also the possibility of the occurrence of typical alpine permafrost – interstitial ice in the Medena kotlina.

Patches of metamorphic ice, which occurrence is mainly conditioned by orography, represent a very permanent element of high-mountain geoecosystem. It should not be excluded, that in fossil form they occur in many other places. Their detection with application of geoelectric methods may be hindered by water content, which increases electric conductivity.

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