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APPLICATION OF GROUND PENETRATING RADAR TO IDENTIFICATION OF THICKNESS AND STRUCTURE OF SEDIMENTS IN POSTGLACIAL LAKES, ILLUSTRATED WITH AN EXAMPLE OF THE MAŁY STAW LAKE (THE KARKONOSZE MOUNTAINS)

Abstract. This paper has been aimed at demonstrating the applicability of the ground penetrating radar to acquiring basic information on lake sediments and geomorphological conditions of their deposition in the basin of Mały Staw lake. The lake area is one of the most comprehensively studied part of the Polish part of the Karkonosze Mountains. The application of radar soundings enabled a fast and environmentally friendly verification as well as updating the results of previous research on the thickness and structure of the sediments of this glacial lake. Mały Staw lake is formed at the postglacial depression in the granite bedrock. The bottom of the lake is composed of limnic deposits of the maximum thickness reaching up to 15 m. The postglacial formations occurring below them probably contain a buried moraine of the youngest recessional phase. Solid rock is located about 25 meters beneath the current bottom of the lake.

Key words: GPR surveys, lacustrine deposits, Karkonosze Mts., Mały Staw lake

INTRODUCTION

The thickness and characteristics of the sediments deposited in the basins of postglacial lakes constitute an important record of the changing climate and environmental conditions. Therefore, their recognition is one of the key objectives of the paleographic studies (e.g. Cohen 2003; Fritz 2008; Kapusta et al. 2010). Studying sediments with the employment of direct methods (e.g. coring) are expensive, difficult to implement in the high mountain conditions, and often excessively intruding into the environment, which does not comply with legal forms of protection. This paper presents the attainability of obtaining basic information about lake sediments and geomorphological conditionings of their deposition with the application of ground penetrating radar (GPR) surveys. The research concerns Mały Staw lake in the Karkonosze Mountains since its geomorphological and geological conditions have been intensely studied.

This enabled mutual comparison and validation of the results of both direct observations and geophysical surveys.

The research on the morphology of the bottom, the thickness, structure and age of the sediments deposited in Mały Staw lake started in the mid-twentieth century. The earliest bathymetric measurements were carried out by T. Komar (1949), while the first drillings into the moraine surrounding the lake were performed by H. Piasecki (1958) (Fig. 1). In March 1982, coring the limnic sediments was started on the initiative of Professor J. Kondracki. The sample of the total length of 8.82 m was retrieved and subjected to specific palynological and microfaunistical analysis. Additionally, two radiocarbon dates were obtained from the core (Wicik 1984, 1986). The subsequent dating of organic sediments collected in the vicinity of the lake was performed by H. Chmal and A. Traczyk (1998). The dated material came from intermoraine depressions. At the same time, the age of the moraine was determined through thermoluminescence dating (Chmal, Traczyk 1999). In 2007, GPR surveys were carried out in the zone between the youngest and oldest moraines in the cirque of Mały Staw. The weathering degree of the moraine blocks was examined with the Schmidt hammer, and rock samples were collected for dating with the cosmogenic isotope ^{10}Be method (Engel et al. 2011). Three cores (each c. 8 m long) were retrieved from the sediments filling the basin of the former glacial lake in the intermoraine zone. The physical as well as chemical properties of the extracted material were examined, while radiocarbon and thermoluminescence dates were simultaneously obtained (Engel et al. 2008; Engel et al. 2014). The results, not always consistent, show that Mały Staw lake formed at the end of the last glaciation, i.e. at the turn of the Pleistocene and the Holocene. The basin was formed in the moraine deposits accumulated probably in the overdeepen-

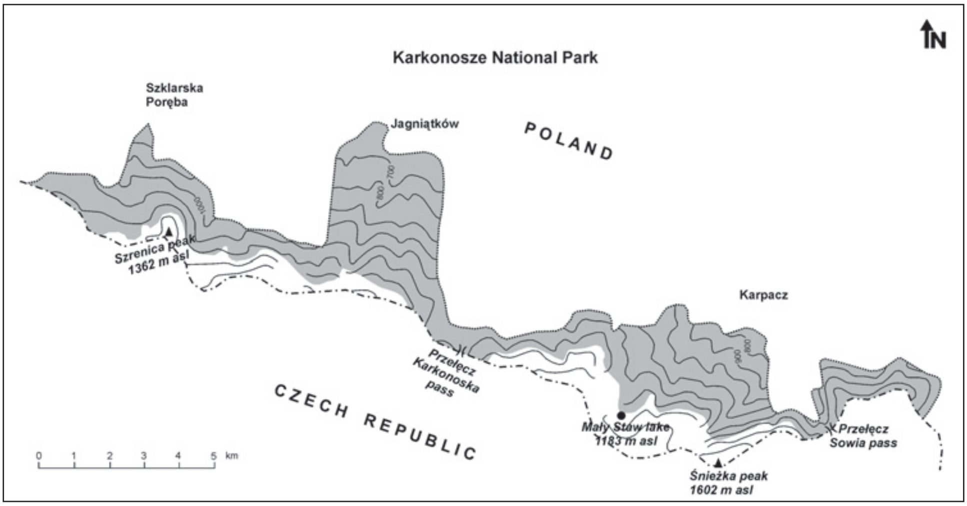

Fig. 1. The Karkonosze National Park (KNP). Location of the study area indicated by black dot. Dotted line – boundary of KNP; dashed-dotted line – state border; grey colour – forest (Parzóch 2008-revised)

ing of glacial origin within the granite bedrock. This paper presents the results of GPR surveys which were employed to verify and systematise the results of the previously conducted studies on the origin and structure of the sediments of the glacial cirque. The acquired geophysical data have also provided new details concerning the development of the environment of the Karkonosze Mountains.

SCOPE OF RESEARCH

The Mały Staw depression is the largest glacial cirque in the Polish part of the Karkonosze Mountains. Its total area is 0.59 km^2, the length – about 1430 m, and the width – 420 m. The bottom of the depression is located at the altitude of 1175 m asl and surrounded by rock walls of the relative height of 110 m (Kasprzak, Traczyk 2013). In the cirque, there are three secondary hollows. The biggest of them and the best developed is the overdeepening of Mały Staw lake (Traczyk 1989). The area of the lake covers 2.88 ha, whereas its water level is located at the 1183 m asl (Komar 1985). The catchment area of the lake partially includes the Pliocene alignment surface (Równia pod Śnieżką) situated at the altitude of approx. 1400 m asl (Migoń 2005). Mały Staw lake is located in the cold climatic zone, whereas a significant portion of its catchment belongs to the very cold zone (Hess et al. 1980). The average annual precipitation amounts to approx. 1400–1500 mm (Sobik et al. 2013).

The results of bathymetric surveys show that the overdeepening of Mały Staw lake comprises two parts (Komar 1985). The depth of the western part reaches 7.3 m, whereas of the eastern, several times larger part – 5.3 m. Both parts of the basin are separated by a wide and flat crest, located approximately 2.5 m beneath the water level. The southern and south-western sides of the lake are most intensively supplied with water, which coincidences with the development of the alluvial-talus cones there. The outflow of water is located in the northern part of the lake.

RESEARCH METHODS

The GPR method was employed to identify the thickness and structure of the lacustrine sediments. The GPR surveys is based on the emission of electromagnetic waves of a specific signal frequency into the ground and recording the waves reflected off structures having different dielectric properties. The ratio of the power of the signal transmitted to the received defines variable electrical characteristics of the examined structures (Neal 2004). A RAMAC/GPR CUII (*Mala GeoScience*) impulse radar and unshielded antennas of the 25 MHz center frequency were used in the survey. The spacing between the transmitting and receiving antenna dipoles was 4 m.

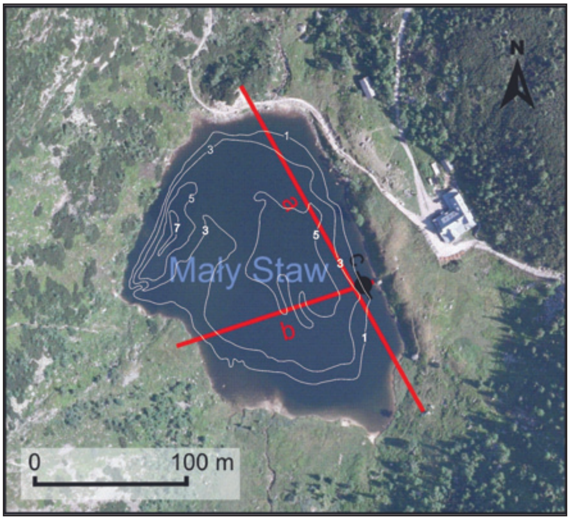

Fig. 2. Location of the GPR profiles (a and b) and the geometric centre of the CMP measurement (c) (2008 – Karkonoski Park Narodowy)

The measurements were carried out on the surface of the lake covered with ice and snow, along and across the feature (Fig. 2). A radar pulse was generated at a regular time interval of 0.1 s. The density of traces (recording the amplitude of the radar signals returning to the receiving antenna within the time unit) was approximately 15 per meter of the profile. The time windows of the recording were between 760 and 900 ns. The radio-wave velocity of electromagnetic waves in the ground was determined with the CMP (common mid-point) method. The survey was performed on the surface of the lake (the geometric centre of the measurement marked in Fig. 2). The course of the main features on the CMP profile denoting structural boundaries in the ground was identified ten times. Basing on the obtained data, average radio-wave velocities as well as depths of the registered reflections were calculated. The standard deviations of the results were employed to estimate the measurement uncertainty.

The vertical resolution of the radar sounding with the 25 MHz antennas a function of dielectric properties of the surveyed materials. The measurements were performed within the complex of geological formations of radically different properties (water, mineral material, ice cover). The vertical resolution (¼ of electromagnetic wavelength) ranged from 0.33 m (water) to 1.68 m (ice). Its average value was 0.725 m. The detection depth reaches about 30 meters. RadExplorer v. 1.42 (DECO-Geophysical Ltd.) software was used for data processing and interpretation. The processing flow included shifting the constant component of the signal (DC-shift), adjusting the time of the pulse input to the ground (time-zero-adjustment), strengthening of the amplitude of the received signal, deconvolution and the frequency filtering. Basing on the velocity model, the vertical scale of the GPR profile expressed in time was converted into the depth. The radio-wave velocity of individual layers was obtained through the CMP measurement.

RESULTS AND INTERPRETATION

The boundaries identified on the GPR profiles show a complex of geological structures of different characteristics which form the lake cirque and its filling. The superficial layer was composed of the melting snow-ice cover. This stratum is not visible on the radar images due to its thickness smaller than the vertical resolution of the measurement. The bottom of the lake is depicted as a clear horizon registered in the deepest part at the level of 268 ns (the two-way travel time). The maximum depth of Mały Staw lake along the measurement lines was approx. 5.5 m (K o m a r 1985). Therefore, the average radio-wave velocity in this area was 4.1 cm ns^{-1}. This value is not representative of both ice and water. It is the resultant of the combination of the velocity of the radar waves travelling in both of these environments. On the basis of the CMP sounding, a clear reflection of the wave off the ground was identified at the depth of 8.56 m. The calculated radio-wave velocity equal to 5.55 cm ns^{-1} 'integrates' snow-ice cover, water and shallow lacustrine deposits. The radar waves in the sediments filling the other part of the lake cirque reached the velocity of 7.0 to 9.9 cm ns^{-1}.

Within the measurement segments from 0 to 35 meters (m) of the longitudinal profile (Fig. 3a) and from 130 to 150 meters of the cross-section profile (Fig. 3b), the registered sediments form alluvial cones. Within the lake, the sediments floor (the current bottom of the lake) exhibits a strong reflective horizon. The laminar texture of the image of the upper part of these formations may testify to well sorted-out lacustrine sediment and its tiered/layered structure. A great part of the structure of these deposits is probably composed of fine-fraction alluvial and organic material. Their thickness varied from approx. 2 m to 15 m (Fig. 3a and 3b). They cover coarse-fraction formations, which were registered on the radar-profiles in the form of a multi-reflection structure. What are 'the outcrops' of this material is the terminal moraine which closes the cirque of the lake from the north and rises to approx. 7 m above the water level (Fig. 3a; 250–270 linear meters), and the eastern lateral moraine. On the section of 160–180 meters of the longitudinal profile, this material forms a swelling of the height of approx. 5 m, which may be a fossil-bearing younger recessional moraine (Fig. 3a). The most deeply registered reflective horizon reflects the contact of the moraine deposits with the granite bedrock. The structure of the profile exhibits a clear contrast between the loose, multi-fraction sediment and the solid rock. In the part of the profile which presents the granite bedrock there are no reflections.

In the light of the acquired data, Mały Staw lake formed at the site of the glacial overdeepening of the granite bedrock. The greatest depths of this rock cirque were recorded in the central part of the lake (Fig. 3a and 3b). In the section from 120 to 150 meters of the longitudinal profile (Fig. 3a), its bottom is located approx. 25 m beneath the contemporary lake bottom. The moraine material does not only fill up but also builds up the glacial cirque by a few meters. The water reservoir formed in loose material. The largest thickness of the moraine formations deposited on the rock bar of the glacial cirque (the terminal moraine) is approx. up to 20 m. Within the lake basin, there is probably another younger terminal moraine buried in the lacustrine formations.

DISCUSSION

On the basis of the GPR data it can be assumed that the thickness of the terminal moraine at the site of the water outflow from Mały Staw lake reaches up to 20 m (Fig. 3a). This value is consistent with the results of the coring performed at the same site by H. Piasecki (1958). This points out to the high accuracy of the selected model of the radio-wave velocity in the identified layers of the reflective profile (Fig. 3; the layers I to IV).

On the basis of the bathymetric measurements carried out by T. Komar (1949) and the results of coring in the vicinity of the lake, H. Piasecki (1958) claimed that the bottom of the lake was formed by the moraine material of the maximum thickness of 14 m. In his work, however, he made no reference to the thickness of the layer of the sediments deposited on the moraine formations. Not until the drilling carried out in 1982 had the existence of the several meters' layer of limnic sediment been confirmed. The coring was performed in the central eastern part of the lake, resulting in the collection of the core of the length

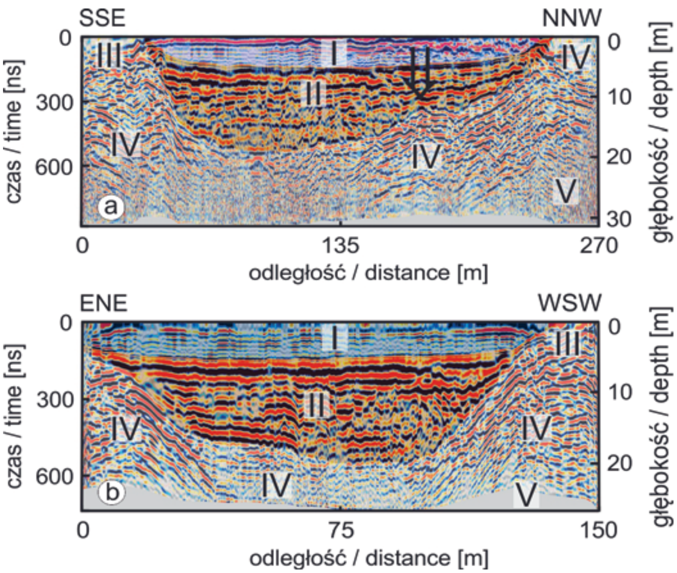

Fig. 3. GPR profiles (25 MHz) of the Mały Staw cirque: a – longitudinal profile, b – cross-section profile (see Fig. 2); I – layer of snow, ice and water II – lacustrine deposits, III – alluvial material IV – moraine formations, V – granite bedrock; the arrow indicates the fossil frontal moraine (?). Profiles do not take into account the relief of the terrain

of 8.82 m, consisting of clay, dust, sand and organic matter (W i c i k 1984, 1986). However, the information about the total thickness of the limnic sediments in the studied site was not acquired. The obtained GPR data show that it is approx. 12 m.

On the basis of the location and the results of the dating of the organic material contained in the collected limnic sediment, B. W i c i k (1984, 1986) concluded that the footwall/bottom mineral formations, being merely 25 cm thick, began to accumulate in Mały Staw lake "during a humid episode preceding the Pre-Boreal period". Given the fact that the thickness of the mineral formations is several times greater than previously assumed and may account for more than 1/4 of the thickness of all the limnic formations at the site of the coring, it may be concluded that perhaps the beginning of their sedimentation should be dated back to the end of the Allerød (?). This view is in agreement with the results of ^{10}Be dating of the terminal moraine closing the cirque of Mały Staw lake which point out that its age is 13.6 ka (E n g e l et al. 2011).

SUMMARY AND CONCLUSIONS

The employment of the GPR surveys enabled prompt verification and updating of the results of the previous studies of the sediments of Mały Staw lake. The acquired data indicate that Mały Staw is a moraine lake, which formed at the glacial overdeepening of the granite bedrock. The solid rock is located approximately 25 m below the current bottom of the lake. The maximum thickness of the limnic sediments reaches up to 15 m. They probably began to form in the Allerød. These formations may comprise the youngest buried recessional moraine from the period of the last glaciation of the Karkonosze Mountains.

The employment of GPR methods allows obtaining information about the thickness and structure of limnic deposits and about geomorphological conditionings of the development of moraine lakes. Due to the small size and low weight of the measuring apparatus, they may be recommended especially for the study on high-altitude environments. In addition, the non-invasive nature of GPR surveys allows a widespread employment of this method in protected areas of particularly high conservation values.

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