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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 TROUGH AND SEDIMENTS INFILL OF THE BIAŁA WODA VALLEY (THE HIGH TATRA MOUNTAINS) USING GEOPHYSICAL AND GEOMORPHOLOGICAL METHODS

Abstract. The purpose of the paper is an attempt to explain complex structure of the bottom of the Biała Woda (Biela voda) Valley in the High Tatra Mountains using geophysical and geomorphological methods. The geophysical profiling refraction and reflection was performed along longitudinal and transverse profiles in the Slovak and Polish territories to trace bedrock under Quaternary deposits in relation to rock occurring on the slopes. It has been stated that in the portion of the glacial valley down of the outlet of the Rybi Potok Valley, two overdeepened depressions of the depth of an order of 50 m occur. Down of the outlet of the tributary Roztoka Valley the trough is 50–100 m and 140–150 m deep. The deepening of the glacial trough were conditioned by the growing glacier mass, while the lithological differentiation in general did not resulted in an increased glacial ploughing of the bedrock. The reflection profile documents both moraine and glaciofluvial deposits as well as clayey limnic sediments.

Key words: refraction and reflection seismics, Quaternary deposits, deglaciation landforms, High Tatra Mountains, Biała Woda faults

INTRODUCTION

Application of geophysical methods to geomorphologic studies in mountains is particularly valuable in protected areas because geophysical techniques, in a non-invasive manner (without drilling boreholes), allow recognizing properties of subsurface, determining topography and depths of Quaternary deposits as well as defining configuration of rocky subsurface in glacial valleys. Under favourable conditions, the geophysical methods allow assessment of depths of lithologically differing structures of the subsurface. In recent years geophysical methods are used more and more extensively in geomorphologic and geologic studies carried out in the Tatras and in other mountains. It turned out that a common field of interest of geomorphologists and geophysicists can be recognition of thickness and properties of Quaternary deposits. The geophysical methods were used here successfully and allow solving interesting problems in domains of geomorphology, geology and glaciology (Gruppo Nazionale... 1986). The most commonly used field methods are as follows: ground-penetrating radar (GPR), 2-D DC resistivity profiling and seismic refraction (2D sounding, tomography) (Sass 2007; Schrott and Sass 2008), and recently High Resolution (HR) reflection seismics and Multichannel Analysis Surface Waves method (MASW).

Geology of the Tatras used to be concluded based on natural rock outcrop, while knowledge on type, thickness, and physical properties of Quaternary deposits filling bottoms of glacial valleys is mainly based on a few seismic and electrical resistivity sounding. The seismic and electrical resistivity surveys performed in the last 30 years aimed at recognition of configuration of sub-Quaternary bedrock, thickness of Quaternary deposits and their sequence as well as lithological composition (Baumgart-Kotarba et al. 1996, 2003; Kotarba 1998; Majovsky and Hanzel 1991). The first work in the Tatras following this framework is elaboration of thickness and lithology of deposits filling the glacial overdeepenings in the broad plain of Mała Łąka (Wielka Polana glade). It has been found that the distribution of electrical resistivity values resembles a model of a lake being filled up by a delta. After filling a post-glacial lake basin, proglacial river sediments were deposited. Probably, peat is also present (Kotarba et al. 1977).

As in other regions modelled under cold climate conditions (Scott et al. 1979) the geophysical techniques (seismics, BTS and geo-electrical sounding) were applied for permafrost examination in the Tatras. They were also used for seeking and locating permafrost zones in highly-located fragments of Tatra valleys (Dobiński 1998; Dec and Dobiński 1998; Mościcki and Kędzia 2001; Kędzia et al. 1998).

B. Gądek and A. Kotyrba (2007) used georadar approach to examine the only site with glacial ice in the Tatras — in the Medená Kotlina, which is a hanging cirque of Zelene Pleso Lake in a source region of the Kežmarska Biela Voda Valley. The obtained field results confirm the presence of buried glacier ice at altitude of ca. 2,000 m.

Experience of mutual collaboration of geomorphologists of the Institute of Geography and Spatial Organisation, Polish Academy of Sciences and geophysicists of the Department of Geology, Geophysics and Environmental Protection, University of Mining and Metallurgy, obtained during 30 year long studies, resulted in papers published in 1995–1997. Papers on bedrock morphology below Quaternary deposits in the valleys of the Biała Woda, Rybi Potok streams as well as of the Sucha Woda Valley have been published. Determination of sediment thickness in lake basins of Morskie Oko and Zielony Staw Gąsienicowy was another important task. Spatial differentiation of the thickness of limnic sediments deposited after the retreat of glaciers at the turn of the Last Glaciation has been determined. Reflection seismic surveying of unconsolidated relatively thin bottom deposits (up to 7.5 m thick) was performed from ice cover in winter season. Vertical stack of receivers hung in water and the magnetic-hydrodynamic source (of sparker type) positioned at water depths which varied with each recording were used during the seismic sounding. Sedimentological interpretation of seismic reflection soundings (Ślusarczyk et al. 1996) is based on logs of the cores taken with Livingstone sampler, modified in the Institute of Physical Geography, Stockholm University (Baumgart-Kotarba et al. 1996; Kotarba 1996). Lake deposits were sampled under collaboration with the team of Swedish geomorphologists of the Institute of Physical Geography of Uppsala University under supervision of C. Jonasson (Baumgart-Kotarba et al. 1990; Jonasson 1991).

AIM AND ENVIRONMENTAL SETTING

The purpose of the paper is an attempt to explain complex structure of the bottom of the Biała Woda Valley in the High Tatras, especially in the fragment between the outlets of Rybi Potok and the Waksmundzki streams as well as in the outlet section of the Białka River where it leaves the Tatras (Fig. 1). The valley originates in the granodiorites of the crystalline core, where the system of glacial cirques and hanging valleys formed in the Pleistocene cold phases and, then, a tremendous glacial trough, dissecting sedimentary series of the Tatric nappes, came into being. The Würm glacier of the Biała Woda Valley was ca. 14 km long and can be classified as an alpine glacier (Photo 1). In general, the Białka valley follows the fault zone which separates the granite elevation of Koszysta from the depression of Široká Javorinská (Szeroka Jaworzyńska). The western slopes of the Biała Woda valley are built of Tatric granite (granodiorite) similarly to drainage basins of large valleys joining the Białka valley from the west (Rybi Potok, Pięć Stawów Polskich–Roztoka and Waksmundzka valleys). The eastern slopes of the Białka valley from the junction with the Rybi Potok valley are built of two High-tatric sedimentary rock successions (Tatricum) — folds of Szeroka Jaworzyńska and of Horvatov Vrch (Horwacki Wierch). The crystalline core of Szeroka Jaworzyńska is underlain by quartzites (quartzite II). The para-autochthonous series Scythian siliceous conglomerates, quartzites and Lower Triassic shales outcrop on Široke Sedlo 2,047 m a.s.l. south of Široka culmination 2,210 m a.s.l. In this paper the first Scythian quartzites are named quartzite I. Then, Middle and Upper Triassic limestones, dolomites and shales; Jurassic limestones; Lower Cretaceous limestones and marls occur on the western Široka-Holica slopes. Farther northward Werfenian conglomerates (quartzite III) occur.The quartzite III is lying on granitoids of the Horvacky Vrch fold, and descents to the Biała Woda Valley close to north part of the Biała Polana glade. The lower Subtatric (Križna) nappe building the culminations of Zadna Kopa and Holica thrust over the quartzite III. The lower Subtatric nappe comprises very resistant dolomites and dolomitized limestones of Ramsau type. According to J. Lefeld (Lefeld and Humnicki 1997) the Subtatric Križna nappe consists the Holica scale, the Tisovka (Czerwona Skała scale) and the Palenica scale which is the highest Subtatric unit in this part of the Tatras. Quaternary glacial, glaciofluvial and fluvial sediments fill the valley

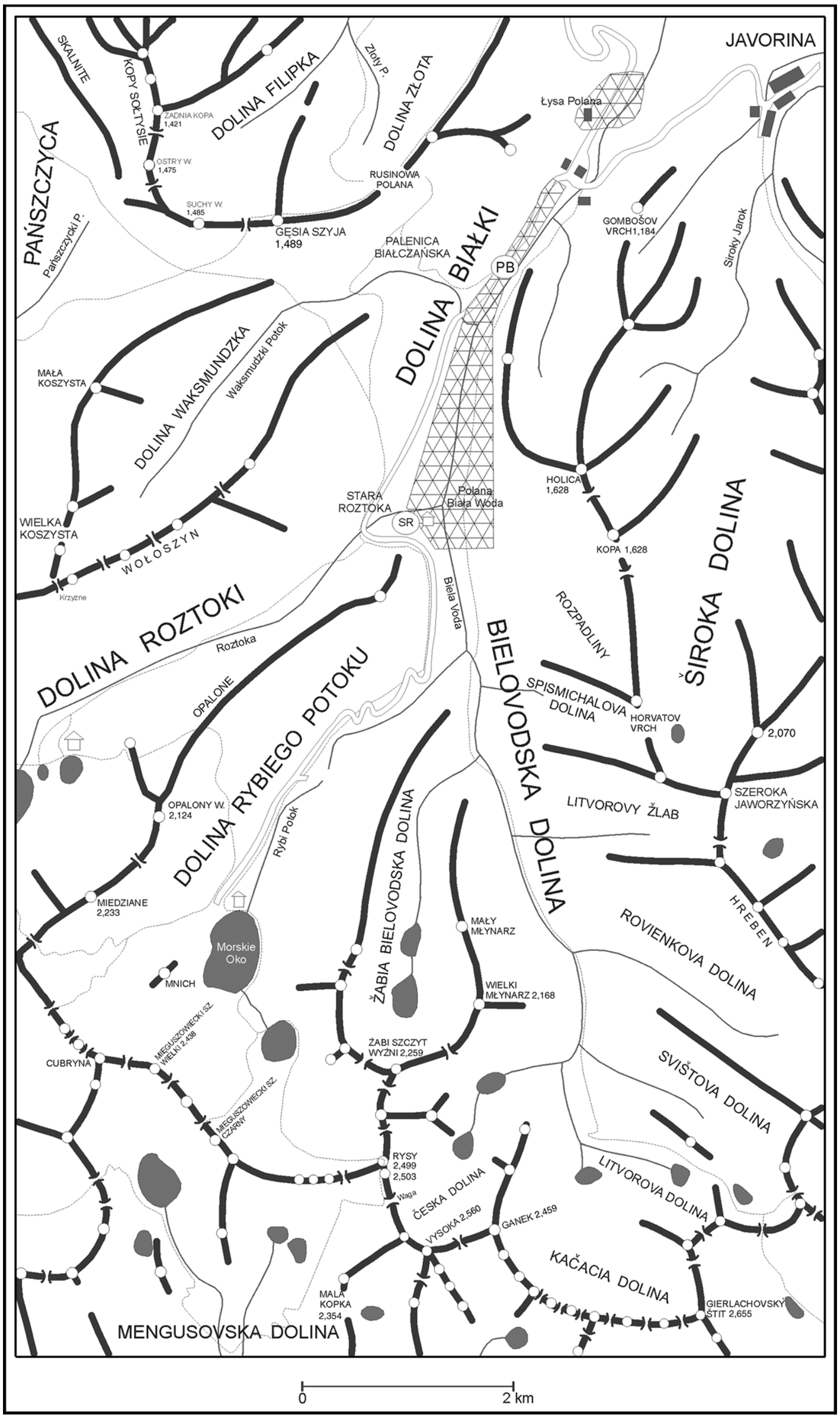

Fig. 1. Location of the study sites in the High Tatra Mountains

Photo 1. View of Białka valley bottom to the south–main mountain watershed. Alpine landscape of the High Tatra Mountains built of granodiorite in the background (Photo J. Lacika)

floor which is 500 m wide at average. The moraine deposits occur also on slope flattenings and form debris slope covers.

The geophysical profiling was performed along longitudinal profiles in the Slovak and Polish territories (S-5–S-1and R-1–R-9, respectively) (Fig. 2). The cross-profiling was meant to trace rocks under the Quaternary deposits in relation to rocks occurring on the slopes. The particular purpose of the paper is to determine the thickness of Quaternary deposits at the valley bottom, and occurrence of glacial overdeepenings which are characteristic of the glacial valleys as well as to assess how lithological differentiation of the bedrock controlled occurrence of glacial overdeepenings. The paper also aims at locating the Biała Woda fault which is schematically marked on the geologic map of the Tatras at a scale of 1:50,000 (N e m č o k , ed. 1996).

The valley between the mouths of Rybi Potok and Waksmundzki Potok streams follows meridional direction, then, downstream changes its orientation to NE and keeps it down of Łysa Skałka. The valley fragment down of the Waksmundzki stream outlet, called "Palenica Białczańska section" in this paper, is incised in ridges built of the rocks of the lower Subtatric (Križna) nappe. In the Polish territory the contact zone between the Subtatric Carpathian Keuper and the Podhale flysch runs almost parallel to the small valley, close to a serpentine road ascending from the valley floor at Łysa Polana to Wierch Poroniec (Fig. 3). Another important purpose is to determine glacial erosion associated with the sys-

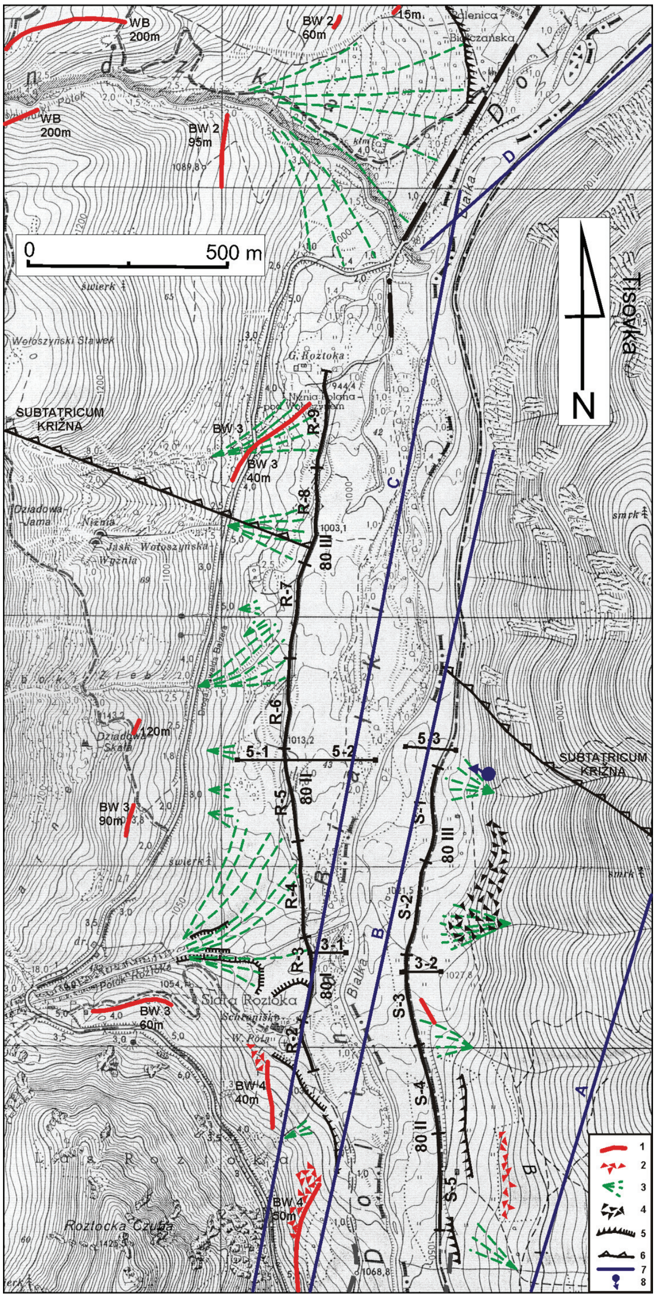

Fig. 2. Fragment of topographic sheet of Białka valley (Bielovodska dolina) and location of geophysical profiling in the territory of Poland and Slovakia. Topographic underlay at a scale of 1:10,000 „Polish Tatra Mountains", Służba Topograficzna WP, 1992. Refraction profiles — solid lines, reflection profile — broken line. 1 — moraine ridge, 2 — moraine boulder cover, 3 — glaciofluvial and fluvial cones, 4 — slope boulder cover, 5 — erosion escarpments, 6 — limit of Subtatricum, 7 — presumed fault system A–D, 8 — sulphate spring

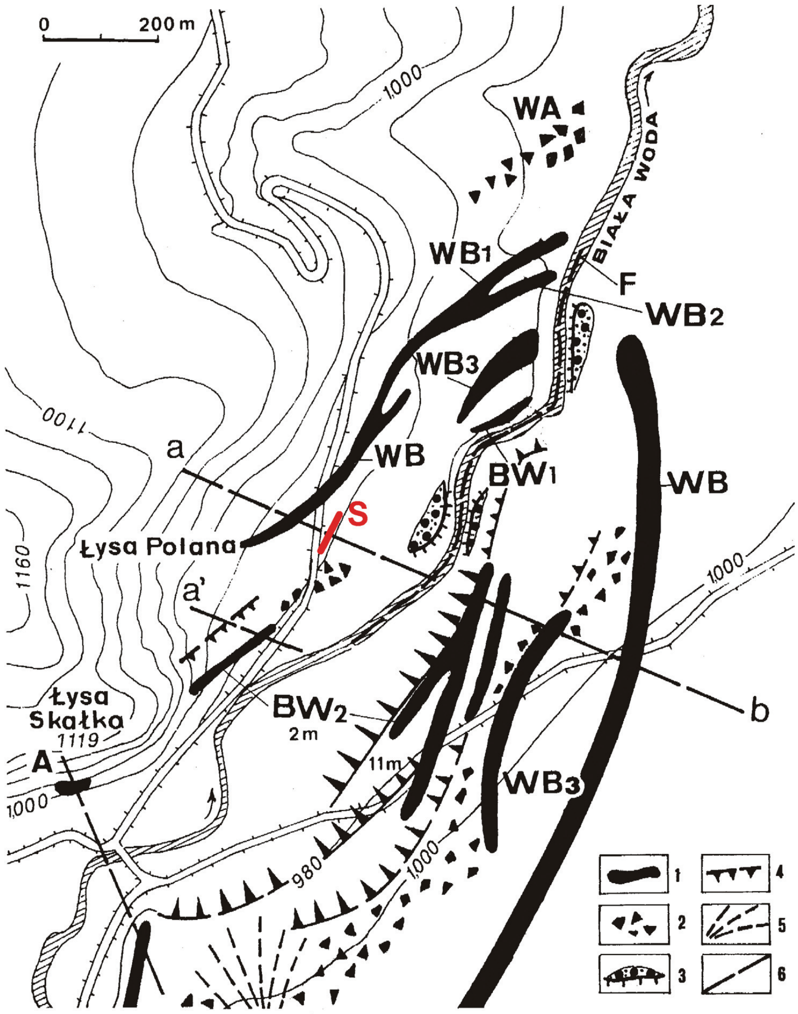

Fig. 3. The extent of Würm moraines and location of cross-profiles: a–b and a' across moraine ridges. 1 — moraine ridge, 2 — bouldery covers, 3 — transitional cone, 4 — edge of kame terrace, 5 — alluvial cone, 6 — course of profiles (according to Baumgart-Kotarba and Kotarba 1997). Red line S shows location of refraction profile Łysa Polana (Fig. 7)

tem of the Biała Woda glacier fed by tributary glaciers from the Rybi Potok, Roztoka and Waksmundzka valleys. The analysis is also meant to assess whether glacial overdeepenings are associated with confluence sites of tributary glaciers and the main body of the Biała Woda glacier or whether they are controlled by a lower resistance of bedrock.

PHYSICAL FUNDAMENTALS OF GEOPHYSICAL EXAMINATIONS

Analysing bedrock and Quaternary deposits, their geometry and geological setting, one can state that these structures are not uniform and homogenous, but are characterized by a significant vertical and horizontal variability. Because of that values of physical parameters describing such media are also highly differentiated and divert from the values which describe homogenous media. In the field geomorphologists determine elements of glacial relief, reconstruct the extent and thickness of glaciers in recessional phases from the fragments of preserved lateral and frontal-lateral moraines. They conclude terminal depressions and find relation between frontal moraines and moraine ridges preserved at the foreland, and attempt to reconstruct not only the recessional stages but re-advances as well.

Geophysical techniques are particularly useful for examining objects with simple geometry where strata are almost horizontal and thicknesses are rather small (below 1 m). Large inclination of the underlying strata, negative vertical velocity gradient, attenuation of energy of geophysical fields in media containing rocky boulders and blocks make the measurements as well as their interpretation difficult.

In the initial stage of geophysical data interpretation, a relatively simple model of the medium is assumed. In such a model horizontal flat-parallel arranged homogenous strata are considered. Theoretical modelling allows assessing how well the assumed model reflects the geological structure of the studied medium. In most cases it is possible to find relatively quickly discrepancies between the model and the examined medium. Under conditions of the complicated geology of mountain massif, which is the case of the Tatras, just at the initial stage one can state that only some geomorphologic hypotheses can be substantiated by geophysical investigations. The geophysical methods are based on measurements of anomalies of certain geophysical parameters, for example density, wave velocity, apparent resistivity or magnetic susceptibility etc.

Morskie Oko Lake performed hitherto, allow presuming that the medium is unconsolidated, comprising singular boulders and rocky crumbs of various sizes which are products of weathering and mass movements on the slopes. If we assume for those sediments such values of physical parameters as for gravel and sand, then these parameters are inadequate due to presence of boulders. Yet, a larger number of measurements provide an opportunity to choose and accept the most optimal physical parameters describing the examined sediments (Baumgart-Kotarba et al. 1996).

During seismic sounding of the deposits filling the bottom of the Rybi Potok valley, a high variability in velocity was observed in the overburden and along the bedrock. It is related to varied numbers of boulders in moraine and glaciofluvial deposits as well as to numbers of cracks and fracturing of the bedrock. Moreover, it has been also noticed that the local bedding occurring in the glacial deposits at the valley bottom results in a change in a wave field image. Certain waves disappear while other come into sight. Such situation can arise when the deposits originating from various phases of glaciation are present.

In the Biała Woda Valley, where the largest Tatra glacier occurred in Würm, cognition of the conditions described above allowed for an attempt to assess a depth of the bedrock in the section from the mountain hostel in Stara Roztoka to Łysa Polana (Fig. 1). When constructing the model the initial assumption was that the variability in the glacial drift deposits corresponded with a fairly wide range of seismic velocities (1,000–2,300 $m \cdot s^{-1}$) and was conditioned by a number of boulders stuck in glacial matrix. In the bedrock the large range of velocities was expected as well, yet their causes were believed to be different. The glacier scoured its glacial trough in variety of rocks which dip steeply or almost vertically in this section and are characterized by wide ranges of velocities (5,000–6,000 $m \cdot s^{-1}$ conglomerate quartzites with siliceous cement, 3,300–4,500 $m \cdot s^{-1}$ granodiorites, 2,800–5,000 $m \cdot s^{-1}$ limestones). Starting from Stara Roztoka due to small depth of the bedrock under the Quaternary deposits and large angle of dips of particular rock layers, the reflection seismics had to be excluded. Under such circumstances the refractive method was used with penetration range increased when the bedrock deepened. As the free location of sounding profiles was impossible and because of limitation imposed on their number, the first assessment of the model stimulated new methodological questions resulting from a low energy of the signal, large dip angle of the bedrock etc. In the refraction surveying, spread, i.e. the distance between the seismic source and the first receiver, was systematically adjusted to the depth of refracted layer boundary and varied from 30–300 m, while the length of profiles along the valley axis was generally 230 m, and on the cross-profiles — 115 m.

In the case of reflections seismics basing on reflected waves, the methodology was less diversified, because fixed offset of 100 m was used, measurements progressed by 10 m step, and the length of spread was also 230 m. High-frequency geophones L–40a 100 Hz were used, which ensured a strong attenuation of surface waves. Grouping of geophones in order to obtain a high horizontal resolution was not used. For generating seismic waves impulsive source with acceleration EWG-III (BISON Inc. — USA) was used. This is the only environmental-friendly very mobile instrument, which is characterized by a high repeatability of signal if a field of permanent and sporadic random noise is strong. This device is also preferred as it features a user-friendly vertical summing of the records in a loose overburden. Owing to specific environment protection conditions in the Tatra National Park the location of seismic soundings according to the method requirements was impossible and thus the limitations imposed made the task even more difficult. Due to the above constrains, the seismic sources may not be located off-roads and off-tourists trails (Photo 2). Because of that the sledgehammer source was used on cross-profiles, what resulted in a reduced depth of wave penetration. In the case of registering noises difficult to eliminate it was necessary to sum singular impulses (vertical stack-

Photo 2. Impulsive source with acceleration EWG-III (BISON Inc.) used in the field for generating seismic waves (Photo A. Kotarba)

ing) until a satisfactory seismic signal was obtained. In extreme cases, if the overburden was loose and strongly absorbed seismic energy, and a spread was significant, it was necessary to sum over 20 impulses in order to obtain satisfactory quality records. Under harsh measurements, a recording system is also an important element. During the discussed studies, TERRALOC Mk3 and Mk6 digital systems manufactured by the well established and world-famous seismic instrument producer ABEM Company (Sweden) were used. Mk3 system was exploited in the first phase. The newer Mk6 system, apart from a very high recording dynamics (to 140 dB theoretically), had several options allowing for a control of recording quality during the measurements and was coupled with a computer possessing Intel 468–100 MHz processor. The records were stored on an 810 MB hard disk, which allowed data processing in the field. Results of refraction sounding were processed under SEXTETTE (ABEM) system, while results of reflection sounding and some refraction measurements were processed under Seistrix 3 (Spectratek) system and under VISTA (SIS) system in recent years.

The results of processing were presented as traveltime curves which, after accepting complex velocities, were converted to depth profiles.

The depths profiles presented in the current paper differ significantly from the profile published in 2003 in Przegląd Geograficzny (Baumgart-Kotarba et al. 2003). The former publication presented the results comprising only the shallower boundaries of the buried coarse-debris glaciofluvial cone of the Waksmundzki glacier. In 2005–2006 the supplementary reflection profiling was performed in the area of Niżnia Polana pod Wołoszynem and served to develop the seismic profile presented in the current paper.

METHODOLOGY OF THE FIELD STUDIES

The field studies in the Biała Woda Valley comprised refraction and reflection seismics along two longitudinal profiles in the Polish (R — 1,800 m long) and Slovak (S — 1,200 m long) territories (Figs 2, 4 and 5). The cross profiling was also performed on both sides of the state border, excluding active channels of the braided river. The cross-profiles on the Polish (R–1, 3–1 and 5–1, 5–2) and Slovak sides (3–2 and 5–3) make possibility to trace lithological differentiation of the western margin of Szeroka Jaworzyńska depression as well as deepening of the glacial trough (Figs. 2, 7, 8, and 9). In the section of Biała Woda (Białka) valley, down of the outlet of the Waksmundzka Valley, the valley floor is wider in the Polish territory (western side) while in the Slovak territory it forms a narrow stretch along steep rocky walls belonging to the western slope of Holica (1,628 m) — Tisovka (1,371 m) ridge. The longitudinal profile along the road starts near Waksmundzki stream, runs close to parking at the Palenica Białczańska and ends 400 m before the border bridge at Łysa Polana (Figs. 2 and 6). Down of Łysa Skałka (1,119 m) an additional, short longitudinal seismic profiling (90 m long) was performed in order to investigate thickness of Quaternary deposits in the terminal depression, closed from the north by a system of pronounced frontal moraines delineating the maximum extent of the Biała Woda glacier during Würm (Figs. 3 and 7). The moraines in questions, their course and elevation as well as their height above the gorge section of the Białka River were presented in details by M. Baumgart-Kotarba and A. Kotarba (1997). WB moraines age is 20–17 ka BP. The washed-out moraines WA which had a farther extent were related to the Early Würm glaciation (>60 ka BP). The Würm terrace has been tracked down to the Białka gorge through the Klippen Zone. There, based on archaeological examination, cold climate conditioned aggradation of the Würm deposits (Baumgart-Kotarba and Kotarba 1997) with respect to the floor of the man-used cave in ca. 60–22 ka BP (Valde-Nowak et al. 1995) has been stated.

Numerous authors studies the extents of recessional and oscillation moraines in the Biała Woda valley (Romer 1929; Partsch 1923; Halicki 1930; Klimaszewski 1962, 1988; Lukniš 1973). The extents of particular recessional stages and fragmentarily preserved lateral moraines associated with them allow defining the phases of filling up the glacial trough of the Biała Woda Valley (Fig. 2). Due to geophysical studies it was possible to reconstruct the course of

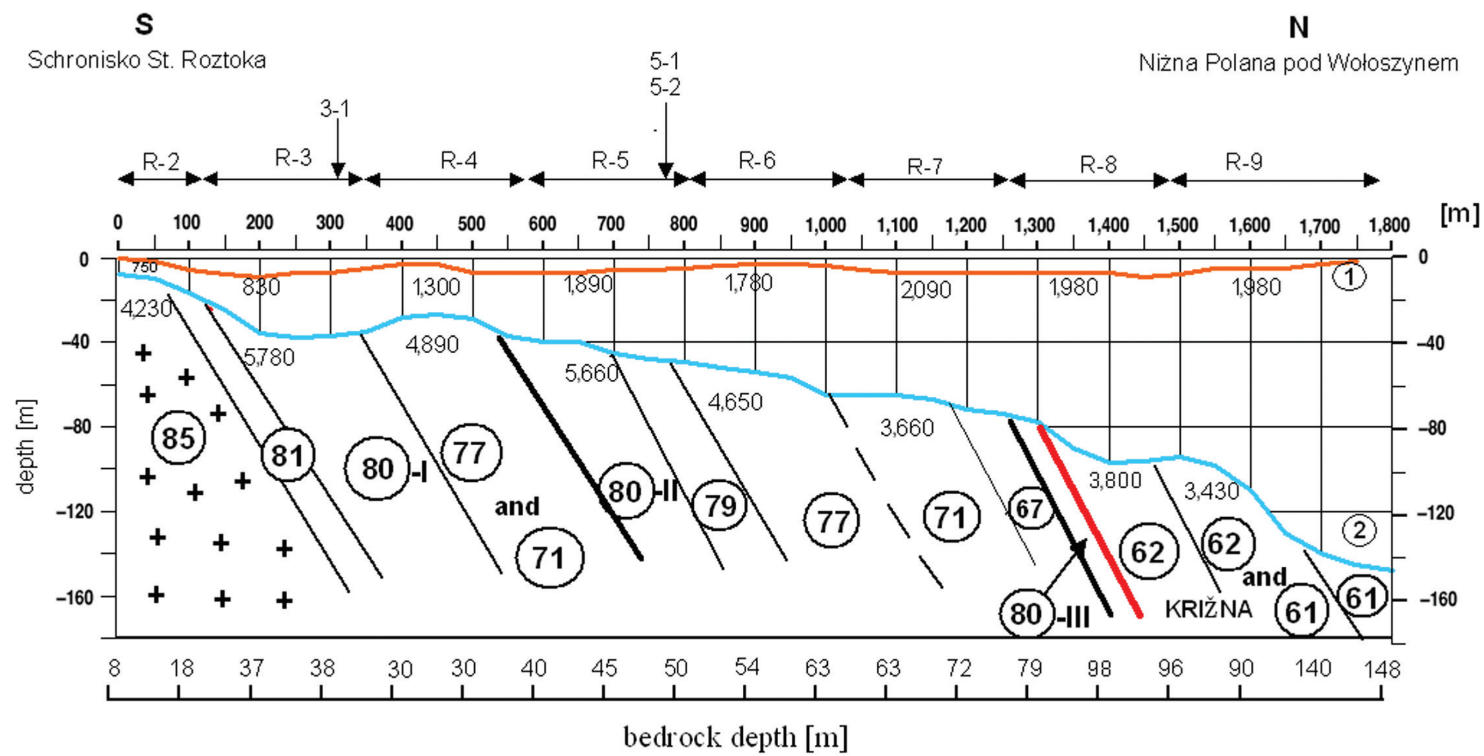

Fig. 4. Seismic refraction profile and geological interpretation along the bottom of Białka valley R-1–R-9 (Polish territory). Lithology after Geological Map of the Tatra Mountains (N e m č o k, ed. 1994), Križna nappe: 61 — variegated shales and sandy shales, quartzites, conglomerates and dolomites, 62 — massive or thick-bedded dolomites, Tatricum; 67 — shales, sandy limestones, sandstones, 71 — massive organogenic limestones, 77 — partly dolomitized limestones, wormy limestones, 79 — variegated shales, sandstones, limestones, 80–conglomerates, quartzose sandstones, quartzites, 81 — Koperšady conglomerates, 85 — granodiorites, 1 — limit of alluvial deposits, 2 — bedrock configuration. Seismic velocities in $m \cdot s^{-1}$

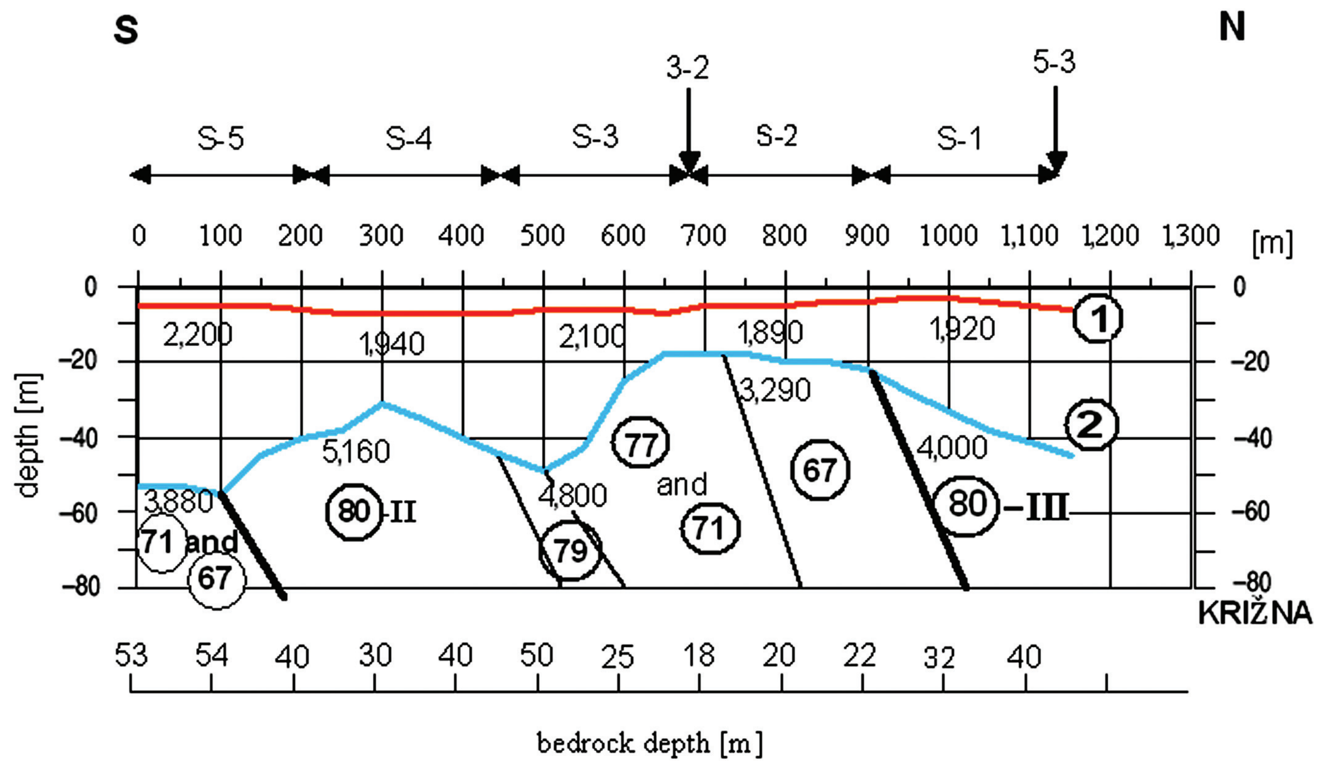

Fig. 5. Seismic refraction and geological profile along the bottom of Białka valley S-1–S-5 (Slovak territory). Lithological explanations in Figure 4

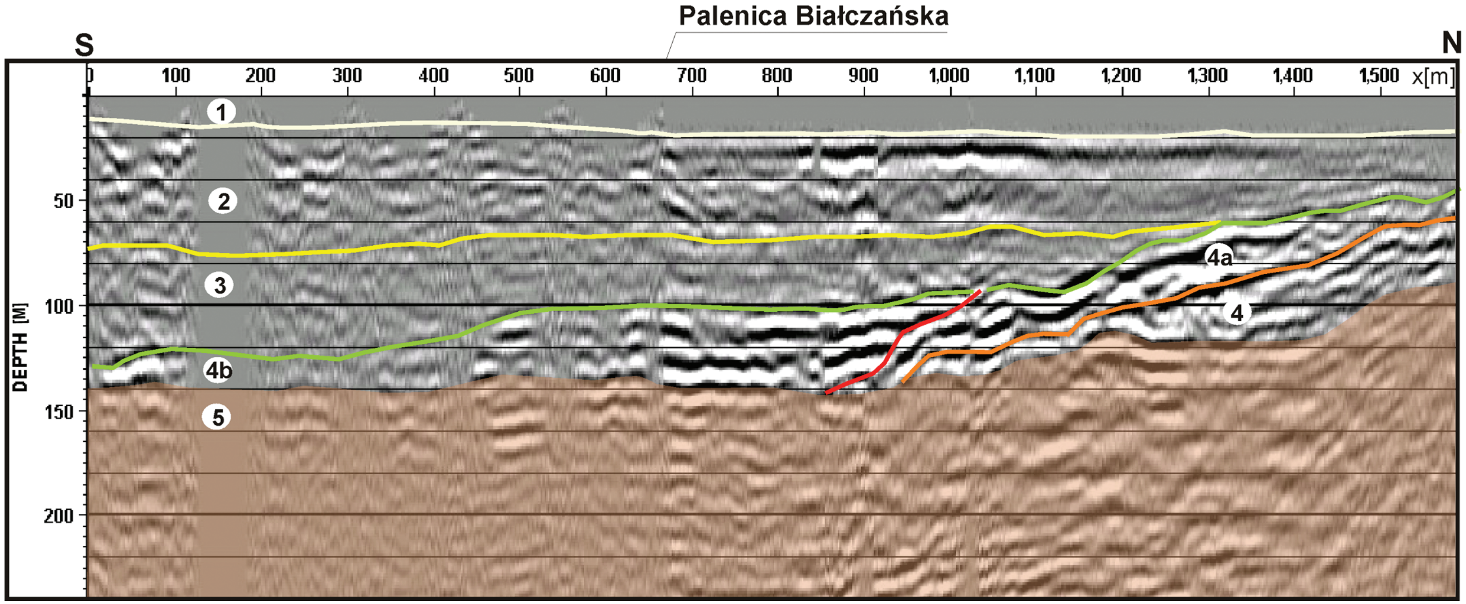

Fig. 6. Seismic reflection longitudinal profile along Białka valley starting at Niżnia Polana pod Wołoszynem (0 m) and ending 400 m upstream of Łysa Polana bridge. Seismic velocities in various substrata: 1 — alluvia: 300–500 m · s^{-1}, 2 — clay and sand deposits, high water content: 1650 m/s, 3 — limnic clay deposits: 1,800 m/s, 4, 4a, 4b — moraine: 2,000 m · s^{-1}, 5 — bedrock, sedimentary rocks: 2,800 m · s^{-1} probably less resistant Carpathian Keuper rocks

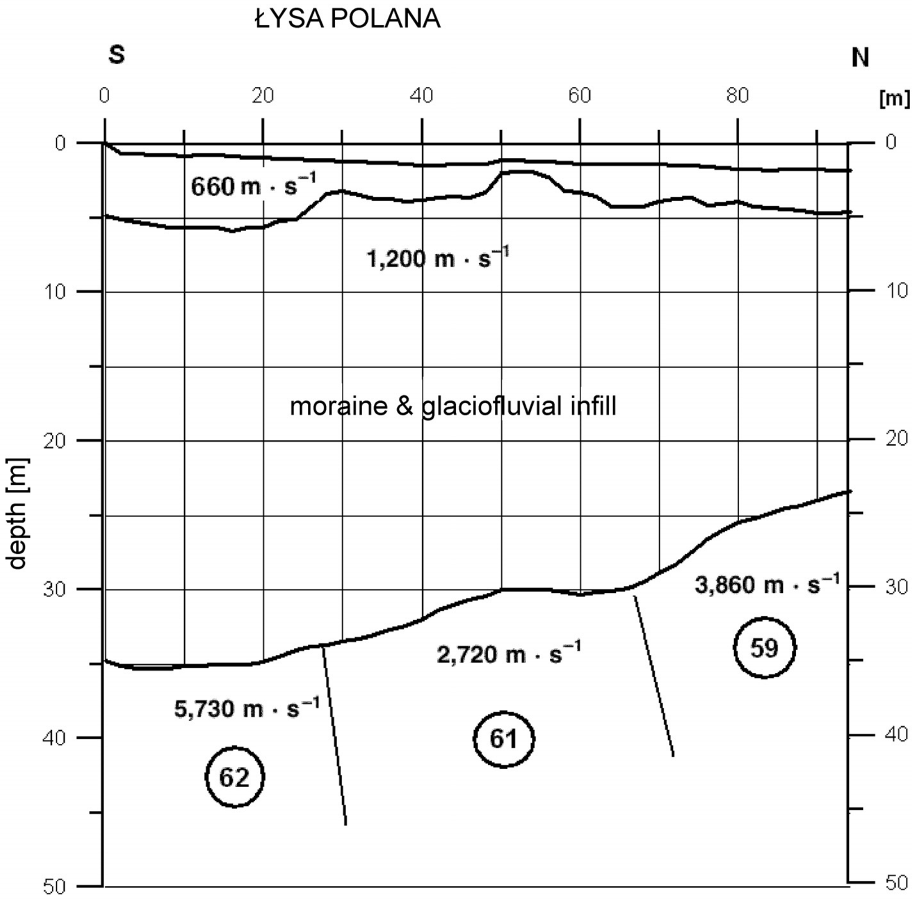

Fig. 7. Łysa Polana site. Refraction profile, 94 m long in the area of terminal moraine of Białka glacier at Łysa Polana site. 62 — very resistant Ramsau dolomites, 61 — Carpathian Keuper mainly shales, 59 — Fatra Formation, black limestones

the fossil moraine ridges. Also an important episode in the glacial trough filling was a transverse supply from large side valleys when tributary glaciers were retreating and from small valleys incised in steep slopes. The present-day active braided river system is able to transport material of a size up to 1 m in diameter during floods. The Białka River is an example of high-energy fluvial system which models a significant part of the floor of the Biała Woda Valley. The contemporary channel deposits of the Białka River do not radically differ from glaciofluvial deposits. It is why the deposits of the glaciofluvial environment cannot be distinguished from Holocene deposits of the braided river based on the velocity of seismic waves. It has been assumed that the velocities just about 2,000 m · s^{-1} can be treated as discriminative of the moraine deposits or proximal deposits of the glaciofluvial cones.

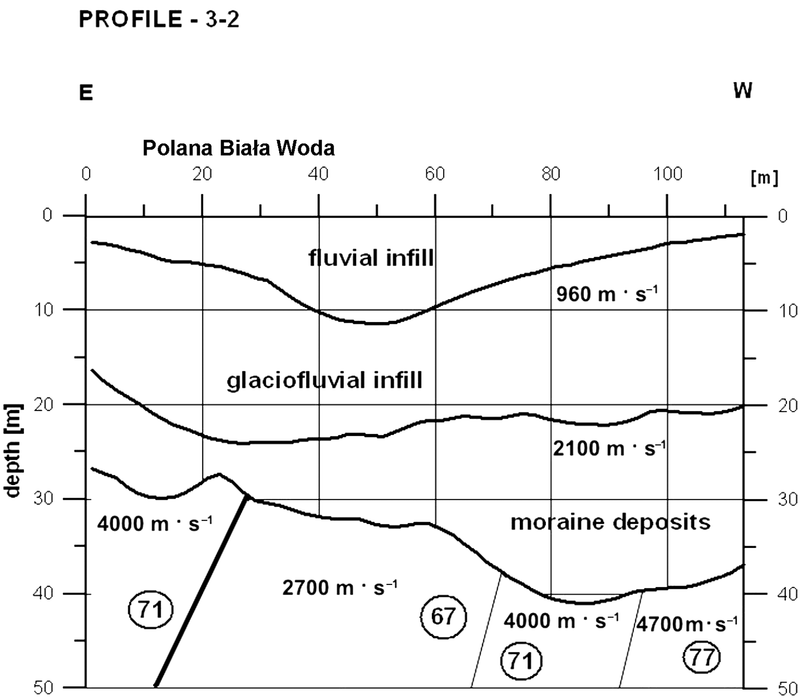

Fig. 8. Reflection cross-profile 3–2 site Polana Biała Woda (Bielovodska pol'ana). Lithological explanation in Fig. 4

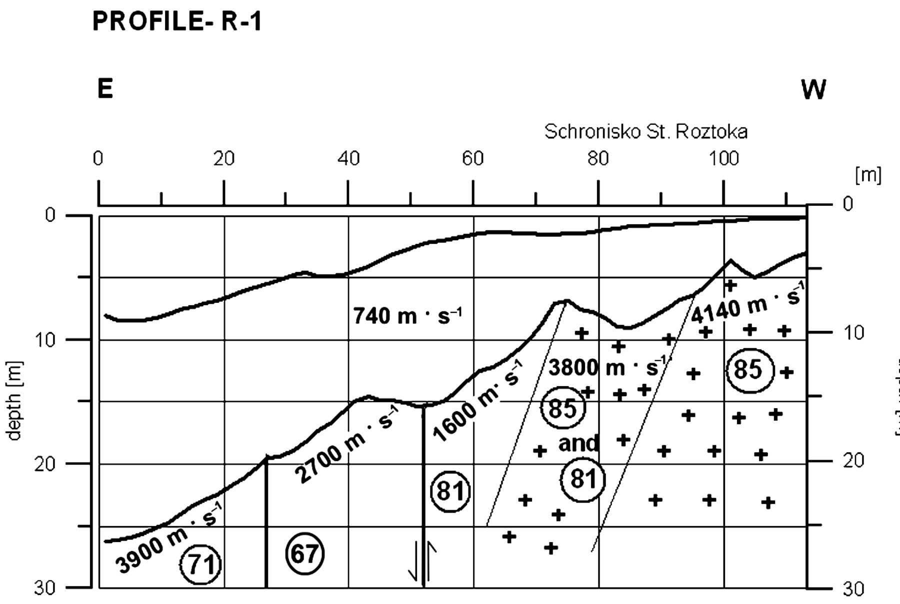

Fig. 9. Detailed refraction cross-profile R-1, 115 m long, in the Polish part of Białka valley. Lithological explanations in Fig. 4. Faults related to fault C on Fig. 2

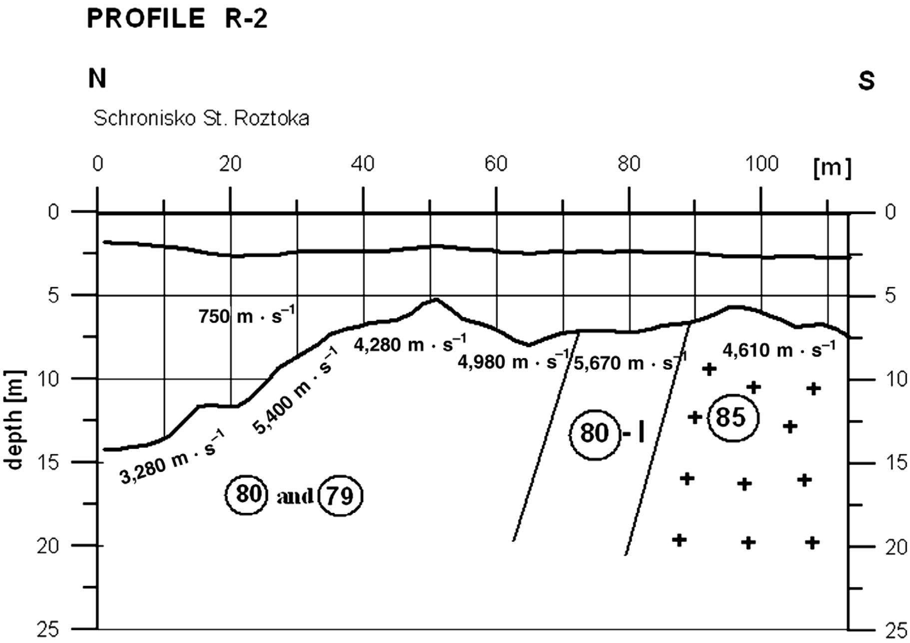

Fig. 10. Refraction cross-profile R-2. Lithological explanation in Figure 4

Electrical resistivity examinations were carried out in the Biała Woda Valley in the Slovak territory (Majovsky and Hanzel 1991). The results of these studies are important because they refer to the valley fragment down of the Polana Biała Woda glade, where seismic profiling has not been performed due to the presence of the narrow terrace below the steep and rocky slopes. In the Polish territory magnetic studies were performed by the team of geophysicists of the University of Mining and Metallurgy — AGH (Kotarba 1998) in order to locate the fault of Biała Woda.

THICKNESS OF QUATERNARY DEPOSITS IN THE LIGHT OF SEISMIC LONGITUDINAL PROFILES AND ATTEMPT TO LOCATE LITHO-STRATIGRAPHIC COMPLEXES OF TATRICUM AND SUBTATRICUM (KRIŽNA) UNITS BELOW PRESENT-DAY VALLEY FLOOR

Longitudinal profile R running in the Polish territory points to a gradual deepening of the glacial trough from 37–38 m in the confluence zone of the Roztoka valley glacier to the depth of 148 m in zone of Niżnia Polana pod Wołoszynem (Figs. 4 and 6). The hollow at the stream outlet from the Roztoka valley is delineated by a rock bar occurring at the depth of 30 m (8 m overdeepening). Thickness of the Quaternary increases gradually starting from the depth of 45 m in quartzite II deposits (5,660 m · s^{-1}) through the depth of 54–63 m in the Middle Triassic dolomites (4,650 m · s^{-1}) to 72 m in the Jurassic limestones (3,660 m · s^{-1}). Definite step-like deepening of the glacial trough at the depths of 98 and 148 metres occurs in the deposits of the lower Subtatric (Križna) nappe (Fig. 4). These are massive dolomites (Ramsau) — with the appropriate velocities of 3,800 and 3,430 m · s^{-1}. The latter, slightly lower velocities are probably associated with an "admixture" of variegated shales and sandstones (Keuper), which occur fragmentarily in section R-9. The step separating the level of depth 63–79 m from the level of 96–90 m in the Križna nappe is probably conditioned by quartzites III steeply dipping northward. Such situation is very distinct in the case in the Slovak eastern side where deepening of glacial trough from 20 m on Lower Cretaceous shales and marls (S2) to 90–100 m depth on Keuper Shales and clays (Fig. 11) is controlled by very resistant quarzites III (Fig. 5 — S1). The outcrop with quartzite debris on the steep slopes of Holica just above the forester's lodge at Biała Woda Glade confirm this interpretation. There are seismic velocities 4,000 m · s^{-1} probably related to quartzite with some shales or sandstone admixture.

The system of 230 m long measurement sections: R-3, R-4, R-5, R-6, R-7, R-8 and R-9 only in certain cases allows finding the velocity of seismic waves which are characteristic of particular lithostratigrahic complexes. Frequently, the velocity found for 230 m long section masks the lithological differentiation of stratigraphic sequences. So, the velocity of 5,780 m · s^{-1} is characteristic of quartzite I (conglomerates, quartzite sandstones) — Lower Triassic, Scythian (Fig. 4). The velocity of 5,660 m · s^{-1} has been interpreted as an averaged velocity of quartzite II and adjoining variegated shales, sandstones and marly shales (Scythian) — Fig. 4. At the contact of granodiorite — quartzite I (para-autochthonous) "Koperšady conglomerates" have been distinguished. "Koperšady conglomerates" occur at Široke Sedlo pass (2,047 m) at the contact between leucogranites and quartzite conglomerates. Following the Geological Map of the Tatra Mts. 1:50,000 "Koperšady conglomerates — 81" occurs on granodiorites/tonalities and crops out when descending to the floor of the Biała Woda Valley, 150 m south of the Spišmichalova Valley stream outlet. On the Polish side detailed measurement on R–2 profile informs about very low seismic velocities, which are related to "Koperšady conglomerate" — 1,600 m · s^{-1} (Fig. 9).

Quaternary deposits filling the glacial trough represent the values of seismic velocities which increase from 750 through 830, 1,300, 1,890 m · s^{-1} to oscillate at ca. 2,000 m · s^{-1} in the sections of R-7, R-8 and R-9 profiles. Such distribution of the velocities indicates a larger contribution of coarse material (moraine boulders and glaciofluvial material in the zone of deepening glacial trough). In particular, the filling up of the glacial trough in the zone of the outlet of retreating tributary Waksmundzki glacier, which supplied blocky material on the surface of the steep slope of fan between the Niżnia Polana pod Wołoszynem and the Palenica Białczańska (Fig. 2).

In the Slovak territory, profile S starts ca. 450 m farther south at the elevation of 1,050 m a.s.l. while the Polish profile starts at the elevation of

1,025 m a.s.l. In section S–5 the glacial trough is overdeepened (56–54 m deep) and closed with a ca. 24 m higher rocky bar (depth 30 m) built of quartzite II (Fig. 5). The next glacial deepening (50 m deep) converts into the floor which is 18–20 m deep over a distance of 300 m. In section S–1 the deepening progresses northward. The Slovak profile ends ca 150 m north of Biela Voda glade (Polana Biała Woda). Geophysical information on the section Biela Voda glade — state border bridge at Łysa Polana originates from the electrical resistivity profile only (Majovsky and Hanzel 1991). In the section of seismic profile S-2 low seismic velocities 3,290 m · s^{-1} have been measured and they have been related to the Lower Cretaceous weakly resistant shales, marls and sandy limestones of Albian and Cenomanian. They form the youngest deposits of Hightatric units (Fig. 5) according to geological map 1:50,000 (Nemčok et al. 1994). In the section of seismic profile S-1 the velocities 4,000 m · s^{-1} were interpreted as quartzites III underlying the Holica overthrust. This quartzite III occurs on steep debris slope close to the northern part of Polana Biała Woda glade. The Slovak seismic profile seems to document overthrusted quartzite III belonging to Horvatov vrch tectonic unit (Fig. 5). The last is cut by very small tectonic scale with crystalline core belonging to Giewont fold according to Andrusov (1950, vide Birkenmajer 2000; fig. 4A) and according to J. Lefeld and W. Humnicki (1997; fig. 2). Both Horvatov unit and small crystalline unit are cut steeply by Subtatric Križna nappe — Holica unit. There are the Ramsau-type dolomites (“62” — geologic map 1:50,000).

Apart the quartzite I presented at the contact with crystallinicum, J. Lefeld and W. Humnicki (1997) have distinguished triple occurrence of the quartzites underlying the crystalline deposits of three subsequent scales. In the presented geophysical profile (Fig. 5) two quartzites (II and III) have been interpreted. They correspond to the first and the second scales distinguished by J. Lefeld and W. Humnicki (1997). In the Polish side, on the longitudinal profile (Fig. 4) triple occurrences of quartzite I–III have been identified. Quartzite I (“80”) corresponds to quartzites occurring directly on the crystalline core (“85”) in the Slovak territory near the Spišmichalova Valley outlet.

Comparison of R and S profiles indicates, that glacial overdeepenings occur both in more and less resistant rock layers in the Polish and Slovak sides. At the outlet of the Roztoka valley, the overdeepening had formed in the resistant quartzite conglomerates (quartzite I — 5,780 m · s^{-1}) while in the Slovak territory — in the less resistant Jurassic limestone and Cretaceous marls (3,880 m · s^{-1}). The second overdeepening in the Slovak territory had formed in the Lower Triassic shales and sandstones as well as in dolomitized wormy limestones (Anissian–Ladinian) — 4,800 m · s^{-1}. Deepening of the glacial trough in the zone of Subtatric (Križna) nappe is evidenced by the longitudinal profile of Palenica Białczańska (Fig. 6).

The longitudinal reflection profiling of the Białka valley from Niżnia Polana pod Wołoszynem to Łysa Polana is 1,600 m long (Fig. 6). According to this profile, the bottom of the glacial trough occurs at the depth of 140 m over the distance of

900 m, and then rises to the depth of 120 over the distance of 200 m. The final 150 metres of the profile point to a farther rise to the depth of 90 m. The bedrock over these last 150 m probably is built by crystallized dolomities and dolomitized limestones which also form the rocky slopes of Łysa Skałka near the state border crossing. Unfortunately, the measurements of velocities for these rocks were not successful, because moraine boulder deposits disperse the seismic waves and its penetration down to the bedrock is impossible. In the seismic profiling performed north of Łysa Skałka the velocity of 5,730 m · s^{-1} was measured probably in these dolomites in a small, 90 m long profile, where the bedrock occurs beneath 35 m thick Quaternary deposits in the terminal depression of maximum extent WB3 (Figs. 3 and 7). The presented situation shows that in the zone of crystallized dolomites, which dip steeply (42°) northward, a gradual reducing of the glacial trough depth between 1,200–1,600 m of Palenica Białczańska profile (Fig. 6) is conditioned by a significant rock resistance. A characteristic feature of the glacial trough of Palenica Białczańska is the presence, below the depth of 70 m, of the deposits which are interpreted as liminic clayey sediments (1,800 m · s^{-1}). Above them, at ca. 20 m below the ground surface, clayey-sandy sediments occur (1,650 m · s^{-1}) which are interpreted as the delta deposits which finished the sedimentation of limnic clays. The upper-face comprises alluvia (300–500 m · s^{-1}) which form on the top the 3–4 m high terrace. The maximum thickness of alluvia in a ca 1 km long zone (600–1,600 m in the profile) reaches 20 m. It is hard to evaluate the age of these alluvia — Late Glacial or Holocene? Assuming the beginning of Holocene was characterized by Boreal expansion of forests onto the slopes, and a supply of weathered material from the slopes was likely to diminish and therefore effective down-cutting of the Białka channel started. The alluvia in the terminal depression of Łysa Polana show the similar velocity — 660 m · s^{-1} (Fig. 7).

The moraine deposits preserved as basal moraine are marked as “4”, “4a” and “4b” (2,000 m · s^{-1}) in the profile of Palenica Białczańska. In the S profiling the velocities of 2,200 and 2,100 m · s^{-1}, in sections S-5 and S-3 respectively, point to a significant contribution of moraine deposits in the confluence zone of the glaciers from the Rybi Potok and Roztoka valleys with main glacier. The ca 40 m thick moraine deposits mantling the zone where the glacial trough depth becomes smaller (section between 900–1,600 m in the profile of Palenica Białczańska) can be interpreted as the sediments of at least two advances of the glacier (Fig. 6; deposits “4” and “4a”). Moraine deposits “4b” whose thickness increases from 20 to 40 m over the distance of 400–900 m can be interpreted as the moraines of the youngest phase of re-advance of the Biała Woda glacier. The above interpretation is based on the reflection seismogram pointing to a discontinuity plane dipping southward which marks the glacier recession and its re-advance. The lack of definite evidences of the basal moraine in the section from 100 to 400 of the profile of Palenica Białczańska can be explained by the glacial erosion of this particular section during re-advance of the glacier of phase BW2 (Bühl, 15 ka BP). According to M. Lukniš (1973) these are D-moraines (20 m high above the Białka river). Moraines marked "4a" can be related to the main phase of the maximum Würm glaciation WB, while the underlying deposits "4" can be interpreted as early Würm moraines WA or as Riss moraines. In the zone where the glacial trough depth becomes smaller, in the area of decreased glacial exaration, the conditions were suitable for preservation of the moraine deposits of various phases of glaciations which had reached to frontal moraines down of Łysa Polana. Probably the moraine deposits of 15 ka BP re-advance, which covered the moraine deposits of 20–17 ka BP phase (Fig. 6; "4a") cannot be differentiated by reflection profiling.

GLACIAL TROUGH OF BIAŁA WODA IN RELATION TO BEDROCK LITHOLOGY AND CONFLUENCE OF TRIBUTARY GLACIERS

The Biała Woda glacier was the longest glacier in the Tatras and had features of a classic valley glacier. Starting under the main Tatra crest (Gierlachovský štit 2,655 m) it was fed from the west by tributary glaciers of Kačacia, Česka, Žabia Bielovodska, Rybi Potok, Roztoka and Waksmundzka valleys. At present-day, these valleys hung over the glacial trough of Biała Woda. The geomorphologic-geophysical examination covered the area from the outlet of the Rybi Potok stream to terminal moraines, demarcating the maximum extent of the glacier at the elevation of 950 m a.s.l. (Fig. 1).

In order to estimate the glacial trough width a cross-profiling has been performed. The depth of the Biała Woda trough varies. From the cross-profile 5-1, 5-2 and 5-3 the trough deepens from 50 to 90 m over the distance of 460 m, then it is 90–100 m deep over the distance of next 460 m close to Niżnia Polana pod Wołoszynem, and finally in the last 200 m long part of profile R-9 it deepends drastically to the depth of 148 m below the present-day valley floor (Fig. 11).

In the studied valley section, the glacial trough above the outlet of the Roztoka Valley is ca. 400 m wide over the distance of 900 m. In the zone of profiles 3-1 and 3-2 the trough becomes shallower on both the sides, so only the 150 m wide zone between the shoulders, which lie 20 m lower, preserves the depth of 30 m. Down of the outlet of the large glacier (7.4 km^2) from the Roztoka Valley (Klimaszewski 1988) the glacial trough becomes 800 m wide and preserves this width down to Niżnia Polana pod Wołoszynem, where, in the zone of steep rocky slopes of Tisovka in the Slovak territory, it becomes narrower (600 m). To the surprise of the paper's authors, the 140 m deep glacial trough continued in the outlet zone of the Waksmundzki glacier (glacier area of 1.9 km^2 according to M. Klimaszewski 1988). At present-day, down of the Waksmundzki stream gorge, there is a vast and relatively steep debris talus. The gorge is incised in the zone of lateral moraines deposited by the Waksmundzki glacier which, at the elevation of 1180 m a.s.l., joined the main glacier in maximum phase WB. Based on the above the thickness of the Biała Woda glacier in the zone of the Waksmundzka Valley outlet is assumed to be 200 m above the present-day Białka river

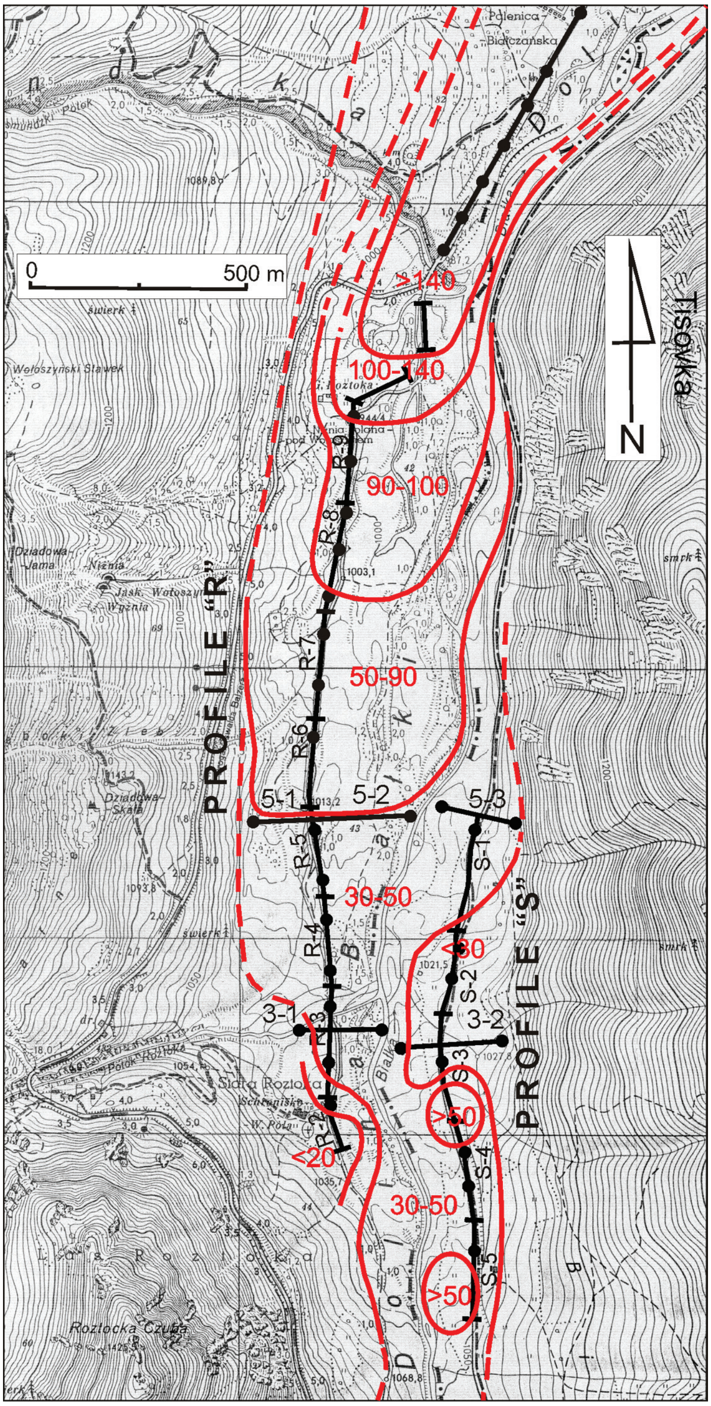

Fig. 11. Map of Quaternary sediment thickness [m] in Białka valley. Seismic profiles and shot points for measuring sediments thicknesses are shown on topographic underlay

and 340 m above the bottom of the glacial trough. At present, the gorge of Waksmundzki stream is incised 80–100 m relative to the preserved lateral moraines of the Waksmundzki glacier. During the oscillation corresponding to the alpine Bühl phase (Pomeranian stage in the Polish Lowland), lateral moraines BW2 had been preserved on slopes of the Biała Woda trough at the elevation of 1,080 m a.s.l. (85 m above the present-day Białka river). North of the gorge the discussed moraine descends from 1,045 m (60 m) to 1,030 m (50 m). Below the descending lateral moraine BW2, there is lower moraine ridge preserved at the elevation of 1,015 m (35 m) on the slopes above the parking lot at Palenica Białczańska (Fig. 2). The steep rocky slopes of the glacial trough (above 40°) cause problems in the interpretation of the seismic cross-profiles. Seismic velocities in the bedrock cannot be estimated probably because of the steep slopes with glacial drift and talus boulders active just after the glacier recession. In the literature it is called the period of “paraglacial cones” formation (Ballantyne 2002). Interpolation of the isolines values, which approximated the configuration of the glacial trough of Biała Woda in the footslope zones, was possible owing to the non-longitudinal recording obtained in profiles 5-1 and 5-2. The flat bottom at the depth of 50 m was found to occupy at least 550 m. In the distance of 1,000 m down of cross-profiles 5-1 and 5-2 the glacial trough being likely 90–100 m deep reaches the width over 400 m, which points to a significant steepness of the rocky slopes of the trough (above 40°). The larger gradients occur on the slopes of Tisovka built of dolomites of the Križna overthrust.

The glacier erosion is a function of glacier ice thickness. In the hanging cirques of the Česka, Kačacia, Litvorova and Svištova valleys the depths of lakes range from 5 to 18 m. However, the thickness of the lacustrine deposits in these lakes is unknown. The glacial trough of Biała Woda, below the above mentioned amphitheatre of the cirques at footslope of Wielki Młynarz, Polana pod Wysoką (ca. 1,300 m a.s.l.) was probably very deep. The presence of a lake in the zone of Polana pod Wysoką is evidenced by a long fragment of the flat floor of the Biała Woda glacial trough over the distance of 1,200 m at the elevation of 1,300–1,320 m a.s.l. This fragment occurs above moraine BW7 (1,280 m a.s.l.) and comprises the terminal depression of moraine BW8 stage (1,300 m a.s.l.). These moraines correspond to the alpine Daun stage — 12 ka BP (Baumgart-Kotarba and Kotarba 1997) and according to M. Lukniš (1973) are called E2 and E3.

Moraine ridges BW6 at the stream outlet from the Žabia Bielovodska valley correspond to oscillations and are related to the alpine Gschnitz phase — 13 ka BP (according to M. Lukniš (1973) — E1 stage. These well developed moraines are dissected by the Biała Woda stream at the elevation of 1,125 m a.s.l. The width of the glacier tongue, inferred from the frontal-lateral moraines BW6 was 300 m. Down of the recessional moraines of 13 ka BP, the next older, lower located moraine ridges occur which provide evidence of recession between 15 and 13 ka BP. So, above the mouth of the Rybi Potok stream a trace of recessional moraines

BW5, on Slovak side, has been preserved which evidences a local stagnation of the glacier while moraines BW4 and BW3 due to the size of the frontal-lateral ridges evidence two important stagnations of the Biała Woda glacier between 15 and 13 ka BP (Fig. 2). The glacial trough increased its width in the zone of confluence with the glacier filling the Rybi Potok Valley. The Rybi Potok glacier, of the area of 5.2 km^2 (K l i m a s z e w s k i 1988), had joined the Biała Woda glacier at the elevation of 1,270 m a.s.l. (200 m above the present-day Biela Voda channel). WA glaciation was more extensive because the lateral moraines in this confluence zone are at elevation of 1,350 m a.s.l., that is 90 m higher.

Below the Roztoka Valley outlet, the glacier of this valley merged with the main glacier at the elevation of 1,100 m a.s.l., i.e. 80 m above the Biała Woda river and 130 m above the glacial trough floor. Just after the merging of the Biała Woda glacier with the vast glacier of the Pięć Stawów Polskich–Roztoka valleys the trough reached the width of 600 m.

The detailed analysis of seismic velocities allowed for tracking the sequence of rock outcrops in the glacial floor of the Biała Woda Valley, outcrops related to sedimentary series of Tatricum and sedimentary series of Subtatric (Križna) nappe. In general, the strike of the sedimentary series is diagonal, from southern-east to northern-west, and demonstrates a steeper dipping of the western margin of the Szeroka Jaworzyńśka depression which expands northward. The widening and deepening of the glacial trough corresponds in a higher degree to an increased ice mass in the zone of confluence of the tributary glaciers rather than to lithological differentiation of subsequent rock series. The overdeepening of the glacial trough occurs also in several sites within the most resistant quartzite conglomerates and calcareous dolomites of Middle Triasic, Anisian — Ladinian (section S-3; Fig. 5). On the other hand, the weakly resistant rocks, characterised by the seismic velocities of 3,290 m · s^{-1} (section S-2) and of 3,660 m · s^{-1} in profile R-7 occur in relatively shallower fragments of the trough floor. The deepest part of the trough of the Biała Woda glacier in the area of Palenica Białczańska had formed in the weakly resistant series of the Carpathian Keuper (Geological Map of the Tatra Mts. 1:30,000). The depth 120–145 m, stated near Niżnia Polana pod Wołoszynem, occurs also in the very resistant, massive, thick-bedded dolomites of Križna nappe (Ladinian–Carnian).

In the history of the glacial trough infilling, three stages can be distinguished in cross-profile 3–2 — Polana Biała Woda glade (Fig. 8). These are filling the trough with moraine deposits (2,100 m · s^{-1}), with glaciofluvial deposits (960 m/s) and with fluvial deposits. The presented cross-profile points to a gradual deepening of the glacial trough from the depth of 27 m to 34 m and the maximum depth of the trough of ca. 40 m. This trough was cut in relatively resistant limestones and dolomites (4,000, 4,700 m · s^{-1}). It is difficult to evaluate the age of moraine deposits occurring at the depth below 20 m. The profile is located close to the terminal-lateral moraine of stage BW4. The overlying glaciofluvial deposits are at the depth of 5–12 m and can be related to the period of the Biała Woda glacier retreat towards moraines BW5 and BW6. On the 20–50 m section on profile 3–2 (Fig. 8) lateral depression probably represents an extramorainic channel filled with a local weathered cover deposits transported by wash processes.

RECONSTRUCTION OF THE GLACIAL TROUGH FILLING

The filling of the Biała Woda glacial trough took place progressively as the glacier had melted. It is assumed that during the maximum glaciation WB, the older moraine deposits in distal parts of the overdeepened fragments on the sides of transverse rock bars were not subjected to glacial erosion. Such an example was shown in the zone of the trough down of Palenica Białczańska (Fig. 6). The maximum moraine WB, marked "4a" in the profile of Palenica Białczańska, is believed to be the youngest moraine preserved in the zone of this rock bar. Super-positioning the blocks of recessional stages BW1 and BW2 over moraine WB in the rock bar zone has not been recognised. In the distance of ca 2.7 km from moraines BW2 (15 ka BP) up-valley, in the Polish territory, moraine BW3 had been preserved near the southern margin of Niżnia Polana pod Wołoszynem glade (Fig. 2). The moraine ridge descends arc-wise from the elevation of 1,040 m (40 m above the present-day Białka river bottom) to 1,000 m, and probably its elongation is buried in glaciofluvial and fluvial deposits. Following the alpine scheme, this moraine ridge BW3 corresponds to Steinach stage (14 ka BP). The glaciofluvial and fluvial deposits, occurring north of moraine BW4, cover a large glaciofluvial cone deposited at the outlet of the Roztoka valley. The following recessional stage BW4 preserved both in the Polish and Slovak territories, is demarcated by frontal-lateral moraine descending from the elevation of 1,070 m (30 m above the present-day Białka river) to 1,040 m a.s.l. in the distance of 100 m from the mountain hostel in Stara Roztoka (Fig. 2). In Slovakia, the counterpart of this moraine is formed by a ridge descending from the elevation of 1,050 to 1,035 m. Probably, as in the case of moraine BW3, elongation of the moraine ridges is overlain by glaciofluvial deposits. Profile 3–2 (Fig. 8) shows that the moraine deposits occur almost 20 m below the present-day terrace surface. This provides evidence on aggradation and filling of the trough with the younger mainly glaciofluvial deposits. The glaciofluvial deposits had to form during retreat of the Biała Woda glacier towards recessional moraines BW5 (1,100 m) and frontal moraines BW6 (1,130 m). Moraines BW6 (13 ka BP) correspond with Gschnitz moraines in the Alps. This oscillation phase is evidenced by a well preserved terminal depression.

Both glaciofluvial and fluvial cones, formed at the outlets of large valleys, debris paraglacial cones and cones deposited at outlets of small valleys contributed to filling up of the trough of the Biała Woda Valley. The high of glacier body in two cross-profiles; one close to the Łysa Skałka summit and second one below the Łysa Skałka is reconstructed at 1,085 m a.s.l on profile A, and 1,025 m a.s.l on lower profile a–b (Fig. 12).

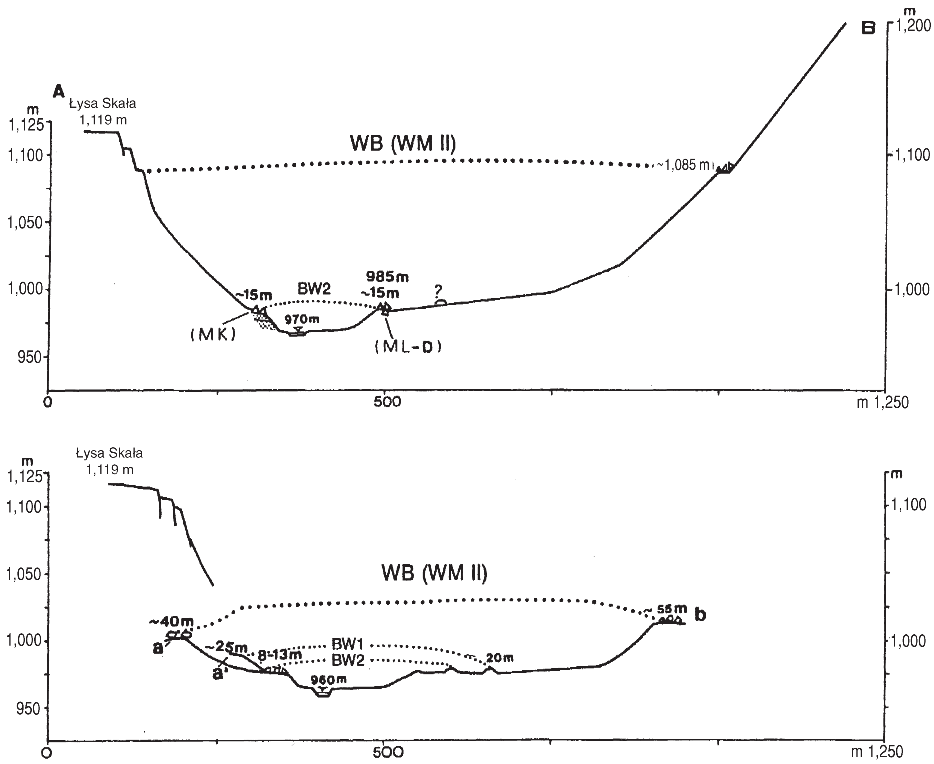

Fig. 12. Cross-profiles in the area of Łysa Skałka (A–B) and Łysa Polana (a–b), and reconstructed extents of the Biała Woda glacier during maximum WB and recessional stadium, oscillation BW2. MK–site at Łysa Skałka described by M. Klimaszewski (1961), ML–moraine ridge D, according to M. L u k n i š (1973)

At present, braided river reworks glaciofluvial and fluvial deposits during summer floods. The terraces within the flat floor of the Biała Woda Valley are 2–5 m high. The Holocene did not result in a significant incision of the Białka river because mainly sandy and fine material of a size up to 10 cm was removed by the river gorge across moraines WB. The fragment of the Białka valley floor in the area of Polana Biała Woda glade down of moraines BW4 to the outlet of the Waksmundzki stream preserved its shape that was formed by the glaciofluvial waters in 14–13 ka BP. The present-day activity of flood waters of the Białka river resembles a channel modelling during the glacier recession after the period of 13 ka BP. The age of recessional stagnation BW4 can be correlated to the stagnation of alpine glaciers in Schlern phase. The mechanism of braided river channel formation is the same as described for glaciofluvial cones down of glacial snouts as well as within the re-worked many times deposits of the Würm terrace downstream of the Tatra Mts whose washing-out provided material of diameters of 30 cm mainly (B a u m g a r t - K o t a r b a 1983). On the scale of the Holocene, from the frontal moraines of Łysa Polana to the Dunajec mouth, the braided Białka river, when washing out the Würm terrace with glaciofluvial material, transported mainly sandy and fine gravel material outside the drainage basin.

ROLE OF THE FAULT OF BIAŁA WODA IN THE TATRAS

The meaning of the Biała Woda fault, marked on the Geological Map of the Tatras at the scale of 1:50,000 (N e m č o k et al. 1994), in the light of the performed geophysical examination, manifests itself in a horizontal shift of a contact between the quartzite conglomerates (quartzite I) and ganitodiorites of the High Tatras by 1,375–1,400 m farther northward at the elevated side. The tectonic shortening is also evidenced by the distance between quartzite I and II at the elevated side — 450 m with respect to the slope of the Szeroka Jaworzyńska depression (Široka Javorinská) — 1,420 m.

The presented tectonic setting seems to show that after the Lower Cretaceous, i.e. in the main period of the overthrust of the Hightatric and Subtatric folds, the transverse structures, elevation of Koszysta and the Szeroka Jaworzyńska depression were formed. The maximum shortening of the Hightatric and Subtatric units on the Polish side is evidenced by a tectonic arrangement of the Triassic dolomities and limestones ("77") in the vicinity of the Wołoszyńskie caves. In this zone the strike measured for the Triassic limestone, with SSE–NNW azimuth and dip of 55°E (Tatricum), delineates the westernmost occurrence of the margin of the Jaworzyńska Depression, High Tatric unit. The strikes measured ca. 150 m north of there in the Carpathian Keuper rocks have NWW–SEE arrangement with the dip of 42° N (Mapa Geologiczna Tatr Polskich 1:30,000, 1979). The dip exceeding 40° northward is characteristic of the Subtatric Holica overthrust (Ramsau type of dolomities and limestones "62").

The detailed geophysical interpretation of profiles R-1 (Fig. 9) and R-2 (Fig. 10) south of Roztoka Stream outlet indicates a more complicated relation of granodiorite, "Koperšady conglomerate" and quartzite conglomerate in the contact zone between the granodiorites and Tatricum sedimentary cover along the arcute inflection of the western margin of the Jaworzyńska Depression where the direction changes from NW to NNW.

It seems that the Biała Woda fault, dislocating the quartzite I and II on the elevated side farther northward, is slightly slant with respect to the valley bottom. The Biała Woda Valley between the outlets from the Roztoka and Waksmundzka valleys is S–N oriented while the inferred fault lines are SSW–NNE oriented (Fig. 2; tectonic lines A, B, C).

An interesting fact from tectonic situation is the coincidence of occurrence of sulphate springs, which are not typical of the Tatras and have "anomalous chemical composition as for the Tatras" (Lefeld and Humnicki 1997). One of such spring occurs close to the bottom of the Biała Woda Valley at the elevation of 1,150 m and 150 m north of the stream outlet from the Spismichalova Valley, that is in the vicinity of the contact between granodiorites and quartzities I, and tectonic contact with Jurassic limestones. The second described spring occur at 1030 m, above the Biała Woda forester's lodge (Fig. 2), that is in the contact zone of quartzite III belonging to the Horvatov vrch nappe with Subtatric-Križna tectonic thrust. Mineralization of water in the discussed springs reaches 726–980 mg · dcm^{-3} and the SO_4 ion content is 505 mg · dcm^{-3}. According to W. Humnicki (1997) and J. Lefeld and W. Humnicki (1997) sulphates may originate from washing the deposits of the Lower Campilian, containing anhydrite-gypsum strata. Such strata were pierced in the deep borehole — Zakopane IG-1. The Campilian deposits occur also in the geological profiles across Szeroka Jaworzyńska which synthesizes the ideas of D. Andrusov, Z. Kotański and J. Lefeld (Lefeld and Humnicki 1997). In the geological cross-section the Campilian deposits occurs in the summit plateau fragments at Horvatsky Uplaz and below the Szeroka Jaworzyńska overthrust. Probably, two cases of sulphate springs allow for percolation of water from the summit part to the bottom of the Białka Valley using tectonic fracture zones (vertical or steep arrangement).

It is worth to emphasise, that in the electrical resistivity profile (Majovsky and Hanzel 1991) the zones in the valley floor in the Slovak side are *characterised* by distinct tectonic discontinuities ("tektonicke poruchy") or by tectonic loosening ("porušene pasmo"). In the electrical resistivity profiles one tectonically deformed zone is ca 150 m wide. This zone is located 150–300 m south of the Rozpadlina stream outlet. The 450 m farther southward, close to the Spišmichalova Valley outlet, well defined faults are also marked (Fig. 13 in Majovsky, Hanzel paper). There, the springs with high content of sulphates are manifested. Probably deep circulation of sulphate water along the Spišmichalova tectonic line take place.

Based on the electrical resistivity profile, down of the Polana Biała Woda glade, the 600 m long fragment, characterized by very shallow rocky floor, can be distinguished. This fragment terminates with a rocky sill probably corresponding to the Ramsau dolomites of the Holica overthrust. Then, 150 m farther northward, the Białka valley abruptly changes its orientation from S–N to SW–NE. In the fragment called the Palenica Białczańska section the glacial trough in the Slovak territory deepens to 100 m along 750 m section according to electric resistivity sounding. In the deepest part of the last depression tectonic fault was delineated which can be related to the overthrust of Tisovka–Czerwona Skała scale *sensu* Lefeld (Lefeld and Humnicki 1997). In the electrical resistivity profile the contact of the Mesozoic and Podhale flysch deposits is marked which occurs 600 m south of the bridge at Łysa Polana. It seems that the above interpretation is erroneous and the low electrical resistivity of 150–300 Ohm should be attributed to the weakly resistant shales (Carpathian Keuper). Along tectonic line D (Fig. 2) characteristic line of 11 vauclusian springs is located. It is possible that this linear system of springs is related to tectonic contact between Ramsau dolomites and limestones with clayey less permeable Keuper rocks along the NE oriented Biała Woda fault.

The analyse of lithostratigraphic sequences, especially quartzites I, II, and III in the light of seismic profiles and analysis of geological maps and numerous geological profiles along the Szeroka Jaworzyńska depression (from Andrusov's profiles 1950 to Birkenmajer's profiles 2000) indicate, that the Koszysta elevation was elevated by system of 3 semi parallel faults SSW–NNE direction (Fig. 2A, B, C tectonic lines). Due to such hypothesis the complicated geological structures of slopes of Zamky–Horvatov vrch dissected by Rozpadlina and next northern valleys can be easier understood. The zone of the slopes between Spišmichalova and small valleys north of Rozpadlina valley outcrops the sequence of the youngest Lower Cretaceous marls and limestones in the lowermost part of slopes, then little higher on the slopes Jurassic limestones and Middle Triassic dolomites and limestones to conglomerate quartzites underlying pegmatite granodiorites of Szeroka Jaworzyńska––Zamky summits. There are oblique slip faults, dextral probably.

The system of three faults is semi perpendicularly crossed by zones of local and regional fractured zones. It is possible to distinguish fracture zones perpendicular to the main zone of faults SSW–NNE. Another zones very well delineated by electric resistivity profiling are directed E–W. This last direction can be correlated with tectonically conditioned north margin of the Tatra Mts and southern Subtatric fault west of the Slavkovsky Mt where the southern border of the High Tatra massif change direction to SW–NE. The same NE direction represents in the Białka Valley — D-tectonic line (Fig. 2).

Three faults A, B, C seem to delineate the system of tectonic steps. The Koszysta elevation probably was elevated according to A, B, C faults or the slopes of Szeroka Jaworzyńska represent uplifted step-like elements — most uplifted on the bottom of the Biała Woda Valley. It is impossible to establish which part was earlier elevated or depressed. It is relative movement. During the Pliocene and Pleistocene both sides of the Biała Woda Valley were uplifted. The relative movement concerns Alpine orogenesis (Upper Cretaceous). These faults have also slip fault character. Similar features were documented in the area of Szeroka Jaworzyńska eastward of Biała Woda Valley by J. Michalik et al. (1997). There are also slip faults. Also geological map of D. Andrusov reinterpreted by K. Birkenmajer (2000) indicates the same system of local faults, generally NNE orientation. Such tectonic different lines presented in our paper are comparable with the results of paleostress analyses carried out by L. Štrba et al. (2008) on the Lower Triassic conglomerates and quartzites along the Litvorov Groove (Litworowy Żleb).The authors of structural research revealed existence of few fault lines, fault systems with E–W and NE–SW directions. They differentiated 5 periods of tectonic deformation as result of movements on Subtatric Rużbachy Fault System.

FINAL CONCLUSIONS

Geophysical seismic examination in the Biała Woda Valley allowed for recognizing the depth and shape of the glacial trough cut in the bedrock, i.e. in the area where no deep boreholes were drilled. It has been stated that in the portion of the glacial valley down of the outlet of the Rybi Potok Valley, two overdeepened fragments of the depth of an order of 50 m and diameters of 150 and 100 m occur. Then, down of the outlet of the Roztoka Valley, this glacial trough is 30 m deep over the distance over 200 m and reaches the width of 150 m. Down of the glacier outlet of the Pięć Stawów Polskich (Roztoka) Valley the trough is already ca. 800 m wide and 50–100 m deep. The following overdeepening of the trough down to the depth of 140–150 m (Figs. 6 and 11) can be explained by an increased volume of glacier ice after the confluence with the Waksmundzki glacier as well as by a narrowing of the trough to 550 m in the zone of the very resistant massive and thick-bedded dolomites of Ramsau type which belong to the Lower Subtatric (Križna) Nappe (Tisovka slope). The maximum height of lateral moraines WB 1,240 m a.s.l. and 240 m above the present-day river (Fig. 12), and the depth of rocky floor of 100–150 m below the present-day valley floor (Fig. 11) indicate that glacier thickness can be estimated at 330–340 m. The maximum height of lateral moraine WB below Rusinowa Polana is 1,180–1,170 m and 1,160–1,150 m a.s.l on flattening of Czerwone Brzeżki. The highest Würm lateral moraine is well preserved close to Polana pod Wołoszyne. Between steep slope of Niżna Kopka and lateral moraine ridge small Wołoszyński Stawek lake is situated. Near the valley narrowing at Łysa Skałka (1,119 m a.s.l.), lateral moraines WB descend abruptly from the elevation of 1,085 m (WB) to 1,025 m (Fig. 12; profiles A, a–b, Fig. 3). These moraines delineate the maximum extents of the glacier during 20–18 ka BP and during the oscillation of 15 ka BP. The small moraine ridge BWl indicates a short oscillation. This ridge is dissected in the Polish territory at the depth of 10–12 m and the corresponding apex of the glaciofluvial cone with blocky cover in the Slovak territory is also dissected at the depth of 12 m. They were correlated with the Chodzież phase in the Great Poland Lowland (17 ka BP).

The geophysical data indicate that down of the Roztoka Valley outlet the trough of Biała Woda glacier was formed within sedimentary rocks. The glacial overdeepening and deepening of the glacial trough were conditioned by the growing glacier mass in the confluence zone while the lithological differentiation, manifesting itself in 100–400 m long sections, in general did not resulted in an increased glacial plucking of the bedrock. Below the Waksmundzki stream outlet the bottom of glacial trough is mainly cut within Carpathian Keuper less resistant shales which represent low seismic velocity 2,700 m $\cdot$ s^{-1}. Probably the overdeepening 140–150 m is also lithologically controlled.

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STRESZCZENIE

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ŻŁÓB LODOWCOWY I JEGO WYPEŁNIENIE OSADAMI W DOLINIE BIAŁEJ WODY W TATRACH WYSOKICH — ZASTOSOWANIE METOD GEOMORFOLOGICZNYCH I GEOFIZYCZNYCH

Sejsmiczne pomiary refrakcyjne, wspomagane sondowaniami refleksyjnymi wykonano w dnie doliny Białej Wody, w odcinku od ujścia Rybiego Potoku po Łysą Polanę. Badania wykonano na profilach podłużnych po stronie polskiej (profil R) i po stronie słowackiej (profil S) i uzupełniono lokalnie profilami poprzecznymi. Profil refleksyjny wykonano wzdłuż Palenicy Białczańskiej. Celem profilowania było określenie miąższości utworów czwartorzędowych z rozdzieleniem na osady morenowe, glacifluwialne i fluwialne oraz odtworzenie konfiguracji podłoża skalnego. Określono prędkości sejsmiczne w obrębie utworów czwartorzędowych (800–2200 $m \cdot s^{-1}$) oraz w obrębie skał podłoża (2700–5780 $m \cdot s^{-1}$) i porównano z jednostkami litologiczno-stratygraficznymi, wyróżnionymi na mapach geologicznych 1:30 000 i 1:50 000. Zinterpretowano rodzaj skał pod utworami czwartorzędowymi w dnie żłobu lodowcowego. Przegłębienia występujące w podłożu skalnym, przy równoczesnym generalnym pogłębianiu żłobu z południa na północ do głębokości 148 m, były uwarunkowane rosnącą masą lodowca głównego w strefach konfluencji z lodowcami dolin Rybiego Potoku, Roztoki i Waksmundzkiej. Zróżnicowanie litologiczne, zaznaczające się na odcinkach 100–400 metrowych, generalnie nie decydowało o lokalnej erozji podłoża skalnego pod wpływem ogromnej masy lodowca.

Dzięki współpracy geomorfologów i geofizyków udało się potwierdzić istnienie wałów moren czołowo-bocznych stadiów recesyjnych BW3, BW4, zagrzebanych w utworach fluwioglacjalnych o miąższości 20 m, a także „kopalną" część stożka fluwioglacjalnego u wylotu Doliny Waksmundzkiej. Szczególną wartość ma znalezienie miąższych osadów jeziornych pomiędzy Niżnią Polaną pod Wołoszynem a północnym brzegiem parkingu na Palenicy Białczańskiej. Wydaje się, że osady te o prędkościach sejsmicznych 1800 m · s^{-1} były składane po wycofaniu się lodowca Białej Wody na moreny BW3. To jezioro było wypełniane osadami fluwioglacjalnymi Białki. Osady fluwioglacjalne i fluwialne najprawdopodobniej można wiązać z okresem recesji lodowca Białej Wody i lodowców Rybiego Potoku, Roztoki i z Doliny Waksmundzkiej w okresie allerödu i na początku holocenu, gdy po 8300 BP stopiły się ostatnie lodowce w Tatrach (venediger).

Przeprowadzone badania refrakcyjne w dnie Doliny Białej Wody po stronie słowackiej i polskiej umożliwiły interpretacje budowy geologicznej skalnego dna doliny zagrzebanego przez utwory czwartorzędowe. Oznaczany na mapach geologicznych przerywaną linią przypuszczalny przebieg uskoku Białej Wody obecnie można przybliżyć poprzez 3 uskoki o kierunku SSW–NNE (linie A, B, C na ryc. 2). Uskoki te mają charakter zrzutowo-przesuwczy (prawoskrętny). System uskoków zrzutowych jest przecięty strefami spękań prostopadłych do głównych uskoków SSW–NNE oraz uskokami W–E. Te ostatnie dowiązują do północnego i południowego tektonicznego obrzeżenia Tatr, natomiast odcinek Doliny Białej Wody poniżej ujścia Potoku Waksmundzkiego, o kierunku SW–NE (linia tektoniczna D) koreluje prawdopodobnie ze wschodnim obrzeżeniem Tatr od Sławkowskiego Szczytu po Rużbachy.

W roku 2008 zostały opublikowane materiały dwóch konferencji: Tatrzańskie Mapy Geologiczne, Zakopane 27–29 maja 2008 oraz Plejstocen Tatr i Podhala — zlodowacenia tatrzańskie, Zakopane 1–5 września 2008, zawierające objaśnienia wycieczek terenowych. Publikacja W. Rączkowskiego *Stanowisko 6: Stara Roztoka — problem glacjalnego przegłębienia Doliny Białej Wody* (2008), dotyczy części polskiego odcinka doliny od schroniska w Starej Roztoce, pokrywającego się z profilem refrakcyjnym, prezentowanym w naszej publikacji w odcinkach R-2 do R-7. Spostrzeżenia autora, o różnicy w prędkościach sejsmicznych południowej i północnej części prezentowanego profilu w formie hodografów o zróżnicowaniu litologii podłoża, jest zgodne z wynikami prezentowanymi w niniejszym opracowaniu. Większe prędkości dotyczą obszaru zbudowanego z kwarcytów, odpornych środkowotriasowych wapieni i dolomitów (R-2 do R-6), a mniejsze prędkości — wapieni jurajskich i margli dolnokredowych (R-7).

Natomiast nie można się zgodzić z sekwencją osadów lodowcowych w dolinie Białki między Rusinową Polaną a Palenicą Białczańską, proponowaną przez A. Wójcika w: *Stanowisko 8: wały moren końcowych w rejonie Łysej Polany, przekrój przez utwory glacigeniczne doliny Białki* (2008). A. Wójcik wprowadza między Rusinową Polaną z poziomem donau (1200 m n.p.m) a dnem Palenicy Białczańskiej w wysokości około 975 m n.p.m kolejno: poziom Hurkotnego (powyżej 1180 m), poziom mindelski dwudzielny (powyżej 1160 m), dwudzielny poziom risski (powyżej 1100 m, 1080 m) oraz poziom wurmski (około 1050 m). Według badań M. i A. Kotarbów (1997) poziom 1200–1170 m (Goły Wierch Hurkotne) należy do zlodowacenia riss lub WA. Lewobrzeżna morena WB lodowca Waksmundzkiego, wskazuje, że w wysokości 1180 m n.p.m (200 m) lodowiec Waksmundzki łączył się z lodowcem Białej Wody. Kolejna niższa morena obniża się z wysokości 1160 m do 1150 m. Moreny 1170 i 1160 m zlokalizowane w obrębie rozległego spłaszczenia Czerwonych Brzeżków wskazują na etapowe obniżanie się lodu wypełniającego Dolinę Białej Wody, w okresie maksymalnego stadium WB i początku recesji. Poziom głazowy, obniżający się z wysokości 1045 m (60 m) do 1030 m (50 m), reprezentuje stadium recesyjne BW2 (15 ka BP) (ryc. 2). Wiązanie poziomu Chowańcowego Wierchu 1038 m (100 m — mindel) i poziomu moren i stożka fluwioglacjalnego riss (40–50 m nad dno Białki) z profilem Rusinowa Polana–Palenica Białczańska jest błędem metodycznym, gdyż koryto Białki w strefie moren i stożka risskiego znajduje się w wysokości 920–900 m, a więc o 75–60 m niżej od koryta w strefie Palenicy Białczańskiej. Nie można traktować poziomów morenowych jak terasy rzeczne. Poniżej moren ze stadium maksymalnego WB (20–17 ka BP) występują tylko moreny boczne recesyjne a nie poziomy mindelskie i risskie.