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Geology of the Pieniny Klippen Belt and the Tatra Mts, Carpathians
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Part XX

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Geological conditions of groundwater occurrence in the Pieniny Klippen Belt (West Carpathians, Poland)[2]

(Figs 1–6; Tabs 1–7)

Abstract. The paper presents selected results of hydrogeological research carried out in the Pieniny National Park and adjacent areas during the period of 1995–2004. The objectives of the studies were to explore the geological environment and conditions of groundwater occurrence, its circulation and drainage system, as well as the physico-chemical properties of groundwaters. An important part of the research were rock fissuring measurements in natural outcrops which made it possible to determine the fissures spatial orientation, the fissuring parameters, and the fissure permeability coefficient. Investigations of rock matrix hydrogeological parameters in selected lithostratigraphic complexes of the Pieniny Klippen Belt were also carried out. Groundwater occurrence conditions in alluvial and weathering cover deposits are characterized as welll.

Key words: Pieniny Klippen Belt, hydrogeological studies, rock matrix parameters, permeability coefficients.

INTRODUCTION

The Pieniny Klippen Belt has a special position not only in the geology but also in the hydrogeology of the Polish Carpathians. Deposits composing the Pieniny Klippen Belt are so strongly folded, imbricated and locally shattered into lenses and metre-sized blocks that Birkenmajer (1958) and Świdziński (1962) called them "tectonic megabreccia". A mosaic geological structure, manifested by a wide range of rock types varying over small areas, obviously controls the variability and complexity of hydrogeological conditions within the Pieniny Klippen Belt.

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In hydrogeological terms, the Pieniny Klippen Belt has a two-fold character. Down to a depth of tens of metres, fissure, fissure-karst and pore waters of the Tatra Mts and Podhale, including the Pieniny Klippen Belt, belong to a joint near-surface aquifer strongly responding to climatic factors and vulnerable to direct infiltration of surface contaminants. In this case, the whole upper part of the Dunajec drainage basin is a coherent hydrogeological system and its boundaries are delimited by surface watersheds (Małecka, 1981).

The deep groundwater circulation system explored by a number of deep exploratory wells shows different features. Meteoric waters, infiltrating across the Tatra Mts massif percolate, consistently with the dip of aquifers down to beneath the Podhale Flysch, into a typical artesian basin. Moving northwards, they meet a tight barrier of the Pieniny Klippen Belt rocks which force the change of flow direction to the latitudinal one (Małecka, 1992).

Negative hydrogeological results of the Maruszyna IG-1 borehole supported earlier views that the northern flank of the Podhale Trough is a barrier to deep groundwaters (Macioszczyk, 1964; Małecka, 1981). According to Birkenmajer (1986), this borehole pierced a number of strongly folded and brecciated "rock units and their Upper Cretaceous mantle". The strata vertical position suggests that a similar structural style may be observed down to a depth of at least 5 km.

The paper presents selected results of hydrogeological research carried out on the near-surface aquifer in the Pieniny National Park and adjacent areas (Fig. 1). The investigations were conducted in the years 1995–2004. The main objectives were to explore the geological setting and conditions of groundwater occurrence, the water circulation and drainage systems as well as physico-chemical properties and quality of ground and surface waters (Małecka & Humnicki, 2001, 2002; Humnicki, 2003, 2005, 2007). The Pieniny Klippen Belt presents a valuable test area allowing the recognition of natural hydrogeological conditions within an area undisturbed by direct human economic activity.

It is obvious that only selected nature-friendly research methods could be used to explore hydrogeological conditions in this valuable, unique and protected area.

REVIEW OF PREVIOUS HYDROGEOLOGICAL STUDIES IN THE PIENINY KLIPPEN BELT

With the abundance of papers on the history of the evolution of the Pieniny Klippen Belt geological-structural unit, hydrogeological reports focusing on the Pieniny Mts. themselves and their immediate neighbourhood are scarce. Both early notices from the mid-19-th century on hydrogeological problems in this region and later reports (e.g. Szajnocha, 1891) mostly discussed a much greater area of the Inner Carpathians, including the Tatra Mts. and Podhale which were the areas of most interest. Researchers focused mostly on the occurrence of water springs, their origin and especially on hydrochemical characteristics of water. In the Pieniny region, the greatest attention was paid to mineral water springs at Krościenko upon

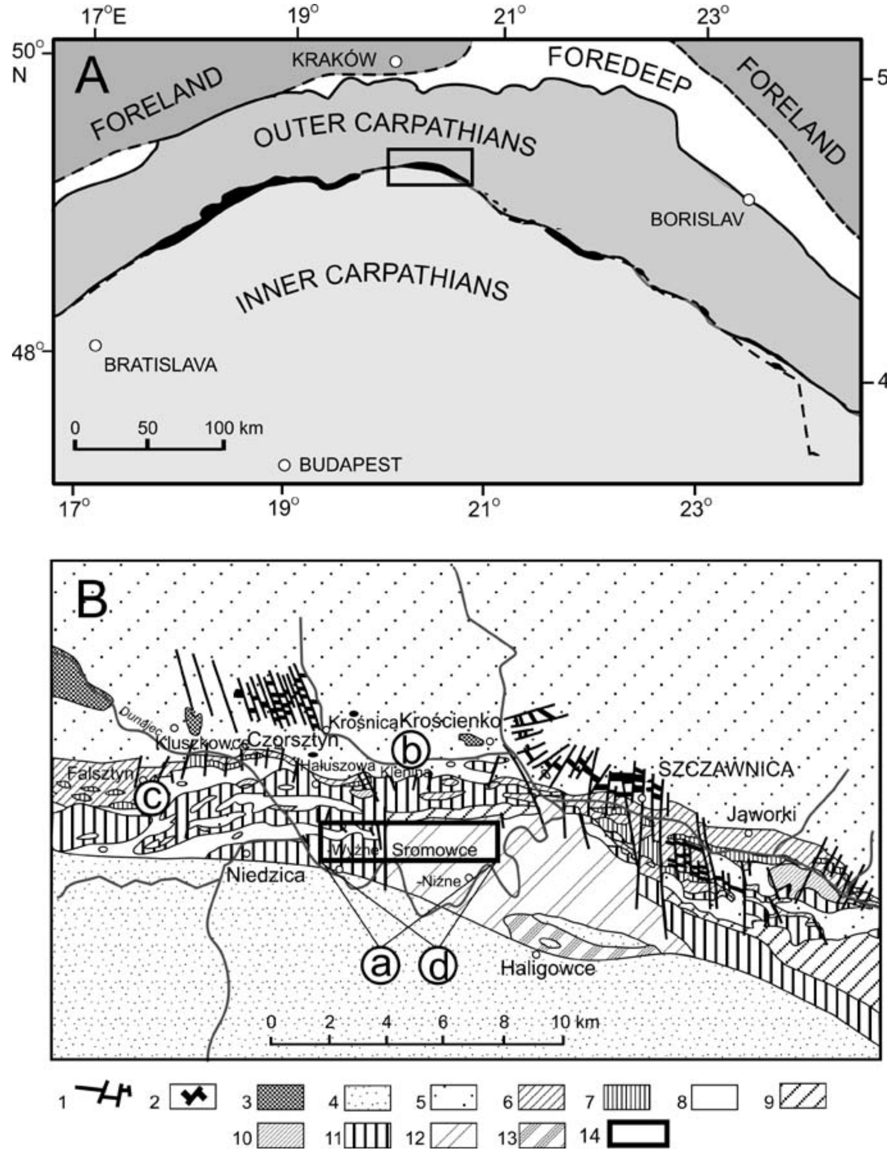

Fig. 1. **A.** Position of the Pieniny Klippen Belt (in black) in the West Carpathians (after Birkenmajer & Gedl, 2007); **B.** Geological sketch of the Pieniny Klippen Belt (after Birkenmajer & Gedl, 2007, modified), with position of the studied section in the Pieniny Klippen Belt. a – fissure measurements; b–d – determinations of hydrogeological parameters of the rock matrix: b – Klenina (No 2, 3 after Table 4); c – near Falsztyn (No 13 and 21–24 after Table 4); d – Głęboki, Limbargowy, Straszny, Macelowy and Szopczański stream catchments (No 1, 4–12 and 15–20 after Table 4). *1* – Miocene faults; *2* – Miocene andesite intrusions; *3* – Miocene fresh-water aquifers; *4* – Podhale Palaeogene (autochthonous); *5* – Magura Palaeogene (Magura Nappe and autochthonous Palaeogene in the Pieniny Klippen Belt); *6* – Jarmura Formation (Maastrichtian): Grajcarek Unit and Pieniny Klippen Belt; *7* – Jurassic–Campanian of the Grajcarek Unit; *8–13* – Klippen successions (*8* – Czorsztyn; *9* – Czertezik; *10* – Niedzica; *11* – Branisko; *12* – Pieniny; *13* – Haligove); *14* – studied area

Dunajec, Szczawnica and Červený Kláštor (Korczyński, 1909; Marchlewski, 1914a, b; Gołąb, 1948, 1952; Birkenmajer, 1956, 1963; Hynie, 1963; Barczyk, 1986; Poprawski *et al.*, 1995; Rajchel *et al.*, 2003; Ciężkowski & Rajchel, 2005).

Studies of isotopic composition of water and its constituents highly contributed to the recognition of the origin of mineral waters in the Pieniny Mts. foreland. Discussions on the origin of the Krościenko and Szczawnica mineral waters are still taking place, and the difficult problems of evolution and specific composition of the mineral waters have not been decisevely explained so far (Dowgiałło, 1980; Zuber & Grabczak, 1985; Oszczypko & Zuber, 2002).

Geological and hydrogeological studies of the area included also the problems of water springs located at the contact zone of the Pieniny Klippen Belt with Podhale Flysch Basin (Watycha, 1959; Macioszczyk 1959, 1964) and the Magura unit (Bober & Oszczypko, 1963a, b; Oszczypko, 1963; Kostrakiewicz, 2002).

In all regional hydrogeological reports and maps concerning the Carpathians (Kolago, 1970; Chowaniec *et al.*, 1977–1979, 1981; Małecka & Murzynowski, 1978; Małecka, 1981, 1982; Malinowski, ed., 1991), the Pieniny Mts were treated as an undivided whole. In the "Hydrogeological map of Podhale and adjacent areas", scale 1:100,000 (Małecka, 1982), the Pieniny Klippen Belt was characterized as an area of highly variable lithology and complex tectonic structure where numerous folds and slices, cut by a dense fault network, produce complicated systems of fissure water circulation. That author paid attention to the prevalence of run-off over infiltration, to small storage capacity of the rock volume manifested by low specific discharge of wells and springs, as well as to hydraulic connection of pore waters from the Dunajec alluvial deposits and fissure waters in the bedrock.

A detailed hydrographic analysis of the Pieniny National Park area was provided by Kostrakiewicz (1965). In his study much attention was devoted to the Pieniny springs, their types, discharge rates and water mineralization. His interest in crenology of the Pieniny area resulted in publication of further papers (Kostrakiewicz, 1982, 1991a, b, 1992, 1993, 1995, 1996).

A new research field was developed in the Pieniny region during the construction of the Czorsztyn dam on the Dunajec River. A number of hydrogeological reports associated with this project were aimed at the recognition of hydrogeological and geological-engineering conditions and at the assessment of the surface water reservoir influence on groundwater. Worth noting are the comprehensive reports by Niedzielski (1965), Łukaszek and Niedzielski (1973, 1976), Dziewański (ed., 1998) with references given therein, and by Małecka (1996) and Małecka *et al.* (1996).

Mapping works on the Szczawnica-Krościenko sheet of the Hydrogeological Map of Poland, on the scale 1:50,000 (Chowaniec & Witek, 1997a, b) resulted in exploration of the Quaternary aquifer in the eastern area. It is composed of gravel and sand deposits filling the Dunajec River valley along the section from the river dam at Sromowce Wyżne to Sromowce Niżne (units No 2a Q II and No 3a Q II). Another Quaternary aquifer was characterized in the area covering the Dunajec River valley from Szczawnica-Piaski in the south to Krościenko-Łąkcica in the north (unit No 1 *a*Q/*Tr* II). According to the requirements of the map construction procedures, groundwater quality and vulnerability categories were determined for these units. No hydrogeological characteristics were given for areas composed mostly of the Podhale Flysch shales and those belonging to the Pieniny Klippen Belt "due to great diversity of the geological structure and commonly low water-bearing capacity" (Chowaniec & Witek, 1997b). These areas were considered waterless because they have not met even the very low criteria adopted for the Carpathians: thickness of the aquifer at least 2–3 m, transmissivity of 25 m^2/24h and well's potential discharge of 2–5 m^3/h (Paczyński, ed., 1999).

In the early 1970s, D. Małecka started developing a groundwater monitoring network covering selected wells and groundwater springs in the Tatry and Podhale regions, including the Pieniny Klippen Belt. Data obtained from the monitoring were analysed against the regional hydrogeological background of the upper part of the Dunajec drainage basin and presented in a number of publications (Małecka, 1985, 1996; Małecka & Humnicki, 1989; Małecka & Lipniacka, 1990; Kazimierski *et al.*, 1999).

Worth noting is also a report by Żurawska (2002) who discussed the problem of water-bearing capacity of the Pieniny Klippen Belt, based on groundwater monitoring results of several springs located in its western part. These data were compared with cartographic material, showing that rocks forming the Pieniny Klippen Belt cannot be considered waterless. In terms of hydrogeological parameters, they display a characteristics similar to the Podhale Flysch deposits.

In the Slovakian part of the Pieniny Mts, geological and hydrogeological investigations were carried out to a lesser extent and at smaller map scales. The Pieniny region was treated in Slovakia together with the adjacent areas of the Čergovska, Ľubovnianska and Ondavska vrchovina (Nemčok, 1981 ed., 1990; Jetel, 2000).

A hydrogeological map on the scale 1:50,000 by Jetel (2000), covering, like a geological map of this region, a much larger area, provides a general characteristics of the Pieniny Mts groundwater, indicates highest discharge of springs and presents approximate intervals of transmissivity coefficient values with close reference to the lithologic units depicted in the map by Nemčok (1981). Due to the lack of drilling exploration in this area, indirect geological methods were applied (Jetel & Kullmann, 1989; Jetel, 1989) and wide-ranging analogies to other Carpathian regions were made.

The Pieniny Mts are very poorly explored by hydrogeological drillings. The only productive drilled water well within the the Pieniny Klippen Belt is located at Szczawnica near the mouth of the Dunajec Gorge. It supplies water to a tourist information hall of the Pieniny National Park. Its depth is 30.0 m and water is extracted from limestones of the Pieniny Limestone Formation. The maximum pumping test discharge was 2.4 m^3/h at a drawdown of 15.5 m. Admissible volume of extracted groundwater is estimated at 2.2 m^3/h with a drawdown of 11.8 m (Tab. 1).

The remaining wells in the Pieniny Klippen Belt have appeared either to be negative ones with very low, if any, discharge rates, or they are located outside the area of the Pieniny Mts (at Szaflary).

Table 1

Water wells extracting fissure water in the Polish part of the Pieniny Klippen Belt and adjacent areas
(based on data from the Central Hydrogeological Database HYDRO)

No.	Map sheet 1: 50 000	Object number after Hydro database	Locality User	Geologic unit	Well			Aquifer					Permeability coefficient		Resources [m^3/h] drawdown [m]	Well discharge (at ma×imum test pumping discharge) [m^{3}'h*1m]
					Year of drilling	Depth [m]	Elevation [m a.s.l.]	Stratigraphy	Lithology	Top [m] Bottom [m]	Thickness [m]	Ground water table depth [m b.g.l.]	[m/s]	[m/24h]		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1.	Szczawnica - Krościenko	10500059	Sromowce Wyżne Ośr. Turystyczny N3	Pieniny Klippen Belt	1999	30.0	481.4	Cr	Shales and sandstones	11.2 >30.0	>18.8	4.2	1.1×10^{-6}	0.09	0.9 12.9	0.06
2.		10500060	Sromowce Niżne Ujęcie PPN -2		1999	30.0	470.0	Cr	Limestones and shales	25.0 >30.0	>5.0	4.0	1.0×10^{-5}	2.59	0.8 13.0	0.07
3.		10500061	Szczawnica Ujęcie PPN -1		1998	30.0	431.8	Cr-J	Limestones and shales	10.0 >30.0	>11.0	4.4	1.0×10^{-5}	0.86	2.2 11.8	0.15
4.	Nowy Targ	10490069	Szaflary Wytwórnia Nart 1		1988	30.0	632.5	Cr	Marly limestones	15.0 >30.0	>7.5	4.0	6.0×10^{-6}	0.52	1.5 6.0	0.13
5.		10490075	Szaflary Wytwórnia Nart 2		1988	25.0	632.6	Cr	Marly limestones	10.0 13.0	3.0	4.0	2.4×10^{-5}	2.07	1.4 4.0	0.33
6.		10490106	Szaflary Wytwórnia Jogurtu		1993	30.0	629.0	Cr-J	Shales and limestones	7.0 >30.0	>11.5	4.8	4.0×10^{-6}	0.35	2.2 7.7	0.24
7.		10490104	Szaflary St. pryw. P. Uznański		1992	33.0	675.5	J 3	Limestones	27.0 33.0	6.0	27	-	-	2.6 1.8	0.88
8.	Szczawnica - Krościenko	10500052	Osada Tur.Czorsztyn Kluszkowce K-1	Magura Unit	1995	48.0	565.0	Tr	Fine-grained sandstones	25.0 26.0	1.0	15.0	3.0×10^{-7}	0.03	0.1 9.0	0.01
9.		10500062	Kluszkowce Przystań Wodna W-1		1998	33.0	543.0	Tr	Sandstones and shales	12.0 >33.0	>12.0	7.7	6.0×10^{-7}	0.05	0.6 12.0	0.05
10.		10500015	Czorsztyn Ośrodek Kolonijny 1		1969	49.7	639.0	Cr3	Fine-grained sandstones and shales	12.5; 33.0 28.0; 44.0	7.0; 5.0	5.0; 7.0	3.3×10^{-6}	0.29	1.5 9.2	0.16
11.		10500007	Szczawnica Zdrój Zakł. Uzdrowiskowy 4		1966	25.0	458.2	Cr3	Sandstones	8.0 >25.0	>8.0	3.2	-	-	0.8 8.0	0.17
12.		10500020	Szczawnica Zdrój Szczawnica PD-4		1973	25.0	458.3	Cr	Medium-grained sandstones	3.2 >25.0	>8.0	3.2	-	-	0.42 4.6	0.17
13.		10502022	Szczawnica Zdrój Szczawnica PD-4		1973	30.0	458.3	Cr3	Sandstones	3.4 >30.0	>13.0	3.4	-	-	0.4 4.6	0.10
14.		10500057	Krośnica Szkoła Podst. KS1		1998	30.0	584.0	Cr	Fine-grained sandstones	26.0 28.0	2.0	0.4	2.0×10^{-5}	1.73	3.0 15.2	0.17
15.		10500058	Hałuszowa Bacówka C2		1999	30.0	655.5	Cr	Sandstones and shales	12.7 28.0	15.3	12.7	3.9×10^{-6}	0.34	0.6 7.6	0.08
16.		10500050	Krościenko n/D Zakł. Goldfruct SKO1		1995	3.1	492.7	Cr3	Calcareous sandstones	1.6 >3.1	>1.5	1.2	3.8×10^{-4}	32.49	2.0 0.9	7.73

There are some more wells extracting groundwater from the Magura unit flysch. A well drilled at the Czorsztyn Children Camp Centre (No 175, depth 49.7 m) extracts groundwater from Cretaceous fine-grained sandstones and shales at a depth interval of 34.4–39.5 m. The maximum pumping test discharge was 5.8 m^3/h. Admissible volume of extracted groundwater is approved at 1.5 m^3/h with a drawdown of 9.2 m.

An interesting shallow well was drilled in 1995 for the Krościenko Goldfrukt Company; it yielded up to 7.0 m^3/h (the drawdown was barely 0.9 m) fresh water from Paleogene of the Magura Nappe calcareous sandstones. That well, situated within a fault zone of the Krośnica River valley, is an example that it is possible to encounter a fractured zone of slightly better hydrogeological properties, capable of supplying greater amounts of groundwater. The well produces a very popular brand of mineral water "Kinga". In recent years, a number of wells have been drilled in this area to extract high quality water for drinking purposes ("Kinga Pienińska", "Trzy Korony", "Szczawnicki Zdrój").

RESEARCH METHODS

The most typical features of the groundwater environment in the Pieniny Klippen Belt are both a considerable lithological diversity and a particularly high degree of tectonic deformation. The rocks are so tectonically disturbed that their different types often display wide-ranging similarities in their hydrogeological properties, independently of what rock series they belong to. Therefore, a significant generalization was made while classifying the rocks from the hydrogeologicasl point of view. They have been divided into four groups: carbonate deposits (about 10% of the Pieniny Mts territory), carbonate-clay deposits (26%), flysch deposits (36%) and Quaternary deposits (28%) (Humnicki, 2007). Important elements for determination the possibility of both occurrence and circulation of ground water in the first three rock groups were fissure measurements (carried out in natural exposures) and laboratory investigations of the rock matrix hydrogeological parameters.

Fissure measurements

Fissure measurements of the rock mass in natural outcrops enabled the determination of fissures spatial orientation and of fissuring parameters, as well as fissure permeability coefficients calculation for selected lithostratigraphic complexes of the Pieniny Klippen Belt. By applying standard methods of fissure measurements in rock masses (Liszkowski & Stochlak, eds., 1976), 1121 fractures and fissures were measured in 87 outcrops on the southern slopes of the Pieniny Mts, from the Głęboki Stream drainage basin in the west to the Szopczański Stream drainage basin in the east (Fig. 1). The following parameters of fissures were measured: length, opening (aperture), roughness (on a macro scale) and surface density (spacing).

Fissure opening was determined basing on direct measurements and averaging the value separately for each fissure. In case of surface fissure density Γ and fissure roughness n_{vs}, the values were averaged within the same measuring site, most often having an area of 1 m^2. The following formulas were applied (Liszkowski & Stochlak, eds., 1976):

$$\Gamma = \Sigma\, l_i / F \qquad [1]$$

where: Γ – surface fissure density [m/m^2];
l – fissure length [m];
F – measured area [m^2].

$$n_{vs} = (\Pi^2/4) \cdot n_F = 2.464 \cdot n_F \qquad [2]$$

where: n_{vs} – fissure porosity [%];
n_F – coefficient of surface fissuring [%];
b – mean fissure opening [m].

$$n_F = (\Sigma(b_i \cdot l_i)/F) \cdot 100\% \qquad [3]$$

Determination of rock matrix hydrogeological parameters

Determinations of hydrogeological parameters of the rock matrix were done on four different rock complexes. The investigations included determination of values of both open porosity coefficient using helium method, and of the hydraulic permeability coefficient. The measurements were made at the “Petrogeo” laboratory at Wołomin. Open porosity was measured by means of the EPS HGP-200 porosimeter using the HELPOR software. Helium was applied, as a small molecule gas capable of penetration into pores and even micropores below 1 micrometre in size. A hydraulic permeability analysis was made using the EPS DGP–200 gas permeabilimeter and the GASPERM software; a nitrogen flow through a 1-inch diameter rock sample mounted in a special handle (a tightly fixed rubber collar) was applied. The collar was supported by surrounding outer pressure to prevent the gas to escape out of the rock volume. Thin sections were prepared from all of the rock samples to identify rock types.

Determination of permeability coefficient

Determination of fissure permeability coefficient in a fractured massif is a more difficult and complicated task than it is in porous deposits. There are a number of formulae developed in the literature, which use the results of field fissure measurements to calculate the permeability coefficient (Liszkowski & Stochlak, eds., 1976; Krajewski & Herbich, 1977;. Motyka & Wilk, 1984; Leśniak & Motyka, 1991; Motyka & Zuber, 1993). The mean fissure opening plays a significant role in all these formulae being raised to the second or third power. It appears that the way of averaging affects the obtained results and may change the permeability coefficient by orders of magnitude. Motyka and Zuber (1993) recommend using the weighted geometric mean of fissure lengths (b_{gw}) to the calculations. Such a method was used not only while determining permeability coefficients in Triassic limestones from the southern part of the Cracow-Częstochowa Upland (Motyka & Zuber, 1993; Motyka, 1998), but also in the Tatra Mts. (Barczyk *et al.*, 1995).

The selection of fissure openings averaging is equally important as the selection of an appropriate calculation scheme. It was decided to limit the number of formulae to two, using two different ways of averaging fissure openings in order to simplify further considerations. In addition, the calculations were made using the two formulas assuming the same constant value of fissure openings b = 0.3 mm. This value has been adopted after Lenk (1986), who carried out some experiments on the behaviour of fissures in carbonates and discovered that below a depth of 300 m the fissure opening becomes constant and keeps the value of 0.3 mm. As the result of these calculations made for different variants, six different values of fissure permeability coefficient have been obtained.

The following formulae were applied:

The formulae of Kotiachow-Johns (Krajewski & Herbich, 1977) modified by Motyka and Zuber (1993):

$$k = (6.28 \cdot 10^5 \cdot b^2 \cdot n_F)/(f_1 \cdot f_2) \qquad [4]$$

The formula of Liszkowski and Stochlak (eds.,1976):

$$k = 61.5 \cdot 10^4 \cdot b^3 \cdot \Gamma \qquad [5]$$

where: k – fissure permeability coefficient [m/s]

b – mean fissure opening [m]

n_F – surface fissuring [–] – calculated according to formula [3]

F – area of the rock surface [m^2]

f_1 – coefficient involving fissure wall unevenness and tortuosity of fissures ($1.0<f_1<1.5$); $f_1 = 1.5$ means rough and tortuous fissures

f_2 – coefficient involving the tortuosity of fissures and an uniformly distributed fissure system ($1.0<f_2<1.5$) ($f_2 = 1.5$ means tortuous fissures of uniformly distributed orientations)

Γ – mean surface density of fissures [m/m^2] – calculated according to formula [1]

The ways of fissure parameters averaging:

a) b_{gw} – geometric mean of fissure openings weighted upon fissure lengths (Motyka & Zuber, 1993)

$$b_{gw} = (\Pi\, b_i \cdot b_{gw} \cdot l_i)^{1/n}/(\Sigma l_i/n) \qquad [6]$$

where: b – fissure opening [m]

l – fissure length [m]

n – number of measured fissures [–]

b) b_m – warranted average cumulative frequency, determined by the Pilgunova method (Liszkowski, & Stochlak, eds., 1976); with the number of measurements $75<n<120$, the variation interval limits are assumed to correspond to 40% (lower limit) and 60% (upper limit) of the frequency sum, with the number of measurements of $n>120$, the median value is adopted.

Formula [4] involves the coefficients f_1 and f_2 reflecting the unevenness of fissure walls. The value of f_1 was differentiated for individual geological units basing on field observations of fissure wall roughness (see Tab. 5), whereas the value of f_2 was fixed equal at $f_2 = 1.5$, assuming that tortuosity of the fissures is high eveywhere.

To obtain better characteristics of the hydrogeological conditions in the Pieniny Mts., the research was supplemented by test pumping and observations of groundwater level rise in two selected hand-dug wells located on the Dunajec R. terraces. The collected data made it possible to determine the approximate values of permeability coefficients using the Forchheimer-Rosłoński formula.

HYDROGEOLOGICAL PROPERTIES OF THE ROCK ENVIRONMENT

Spatial orientation of fissures and fractures

The collected research material makes it possible to analyse the spatial orientation of fissures and fractures within the four lithostratigraphic complexes of the Pieniny Klippen Belt (Fig. 2).

The most common orientation of the fissures and fractures is the SWW–NEE direction parallel to the strike of geologic structures. Cretaceous marls and variegated shales, included in the Jaworki Marls Formation ($K_{mł}$) (Birkenmajer, 1977), show some distinctions manifested by the dominant SW–NE and strictly W–E directions. In the remaining units, these directions are subordinate. In compact cherty limestones of the Pieniny Limestone Formation (JK_{wr}), in Jurassic nodular limestones (Czorsztyn Limestone Formation) and in crinoidal limestones (Krupianka and Smolegowa Limestone formations) (J_w) two complementary perpendicular directions (NW–SE and SW–NE) are distinctly marked. The predominance of strike values ranging from 75 to 85° in flysch sandstones and shales of the Sromowce Formation ($K_{pł}$) is due to taking account of interlayer pathways while measuring.

However, it must be pointed out that the results of fissurity measurements presented here, concern only the upper (i.e. subsurface) zone of the massif. In this zone fissures, resulting from weathering and interlayer fugues, are dominant. Presumably, that is why the dominant fissure runs have WSW–ENE direction, i.e. parallel to the extent of tectonic structures, instead of the expected NNE–SSW direction, i.e. along faults parallel to the Pieniny Klippen Belt. The parallel faults cut this geological unit quite densely, especially in the area of the Pieniny Watershed (Birkenmajer, 2007), and obviously play an important role in groundwater circulation.

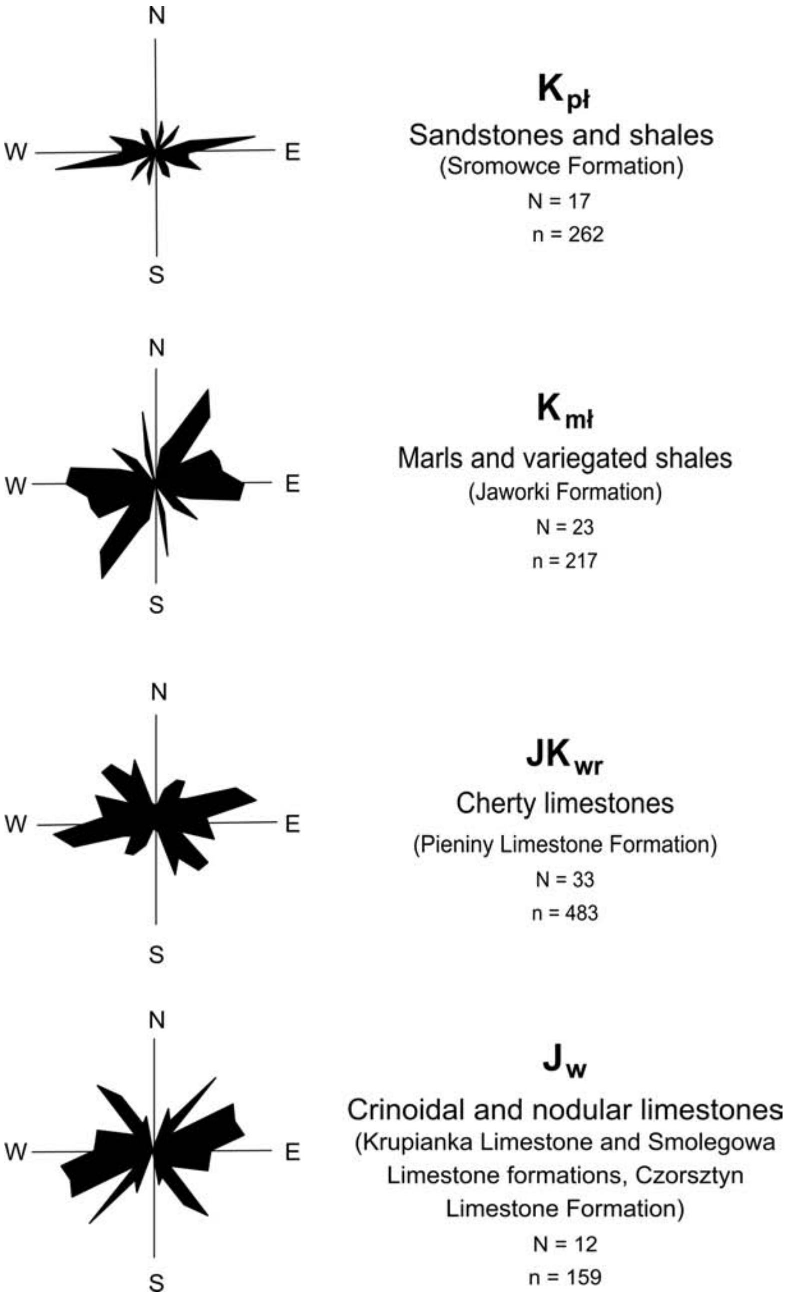

Fig. 2. Orientation of fractures and fissures within selected lithostratigraphic complexes. N – number of exposures; n – number of fissures and fractures measured

Table 2

Dips of fractures and fissures in selected lithostratigraphic complexes

Direction	Angle	Sandstones and shales (Sromowce Formation) **K_{pl}**			Variegated marls and shales (Jaworki Formation) **K_{ml}**			Cherty limestones (Pieniny Limestone Formation) **JK_{wr}**			Crinoidal and nodular limestones (Krupianka and Smolegowa Limestone formations and Czorsztyn Limestone Formation) **J_W**			Total			Σ%	
		n	%	Σ%	n	%	Σ%	n	%	Σ%	n	%	Σ%	n	%	Σ%		
South	0-5	0	0.0	56	0	0.0	53	21	4.3	51	0	0.0	39	21	1.9	51		
	5-15	0	0.0		3	1.4		10	2.1		0	0.0		13	1.2			
	15-25	6	2.3		2	0.9		15	3.1		0	0.0		23	2.1			
	25-35	2	0.8		8	3.7		21	4.3		3	1.9		34	3.0			
	35-45	15	5.7		21	9.7		36	7.5		6	3.8		78	7.0			
	45-55	33	12.6		18	8.3		34	7.0		23	14.5		108	9.6			70
	55-65	20	7.6		22	10.1		29	6.0		13	8.2		84	7.5			
	65-75	28	10.7		15	6.9		22	4.6		4	2.5		69	6.2			
	75-85	24	9.2		21	9.7		14	2.9		6	3.8		65	5.8		22	
	85-90	19	7.3		5	2.3		43	8.9		7	4.4		74	6.6			
North	85-90	2	0.8	44	2	0.9	47	9	1.9	49	0	0.0	61	13	1.2	49		
	75-85	21	8.0		28	12.9		40	8.3		8	5.0		97	8.7			
	65-75	24	9.2		14	6.5		45	9.3		4	2.5		87	7.8			
	55-65	15	5.7		20	9.2		55	11.4		24	15.1		114	10.2			
	45-55	27	10.3		6	2.8		28	5.8		10	6.3		71	6.3			
	35-45	11	4.2		18	8.3		19	3.9		8	5.0		56	5.0			
	25-35	6	2.3		6	2.8		37	7.7		13	8.2		62	5.5			
	15-25	4	1.5		7	3.2		1	0.2		9	5.7		21	1.9			
	5-15	5	1.9		0	0.0		3	0.6		16	10.1		24	2.1			
	0-5	0	0.0		1	0.5		1	0.2		5	3.1		7	0.6			
		262	100.0	100	217	100.0	100	483	100.0	100	159	100.0	100	1121	100.0	100		

Therefore, far-reaching conclusions concerning the importance for groundwater circulation at depth (below the weathering zone) of most commonly oriented fissures are not authorized.

There is a general trend of numerical predominance of fissures and fractures dipping southwards, most clearly expressed in the Sromowce Formation flysch ($K_{pł}$). The only exception are nodular and crinoidal limestones (J_w), where northward dips predominate (Tab.2).

The analysis of data presented in the table implies a conclusion that the Pieniny Mts are typical of a considerable contribution of steep and very steep fissures and fractures (>45°) locally nearly vertical (>75°), with uncommon horizontal fractures. This situation is favourable for both the amount of infiltration rates and depth into to which rainwater can percolate. At the same time it favours an intensive groundwater drainage.

Carbonates

Despite the relatively small area occupied by carbonates, they play a very important role in shaping the Pieniny Mountains landscape, its landforms and hydrogeological conditions.

Amongst the carbonates, the most significant rock types are the Upper Jurassic–Lower Cretaceous white siliceous (cherty) limestones representing the Pieniny Limestone Formation (JK_{wr}), and various Jurassic limestones including nodular limestones (Czorsztyn Limestone Formation), crinoidal limestones (Krupianka and Smolegowa Limestone formations) and organogenic limestones (J_w).

Carbonates are naturally prone to karst processes. The hydraulic network in such rocks commonly includes three overlapping systems of pores, fissures and caverns, as well as karst forms secondarily filled with clastic material.

The comparison of the relationships between permeability and water storage capacity of particular constituents of the hydraulic network provides the possibility of understanding mechanisms of groundwater circulation and enables us to identify the groundwater reservoir type (Krajewski & Motyka, 1999).

Karst landforms are relatively poorly developed in the Pieniny Mts. This is due to the complicated geological structure of the area that disfavours water seepage and groundwater circulation, controlling both the dissolution of carbonates and the permanent supply of fresh water unsaturated with solutes. Negative factors include also the occurrence of limestones in the form of slices and blocks, the presence of numerous interbeddingss of karst-resistant rocks (radiolarites and hornstones) within the limestones, and the isolation of individual blocks within low-permeability rocks such as marls, shales and claystones. All of these factors cause reduction in the extent of potential karst systems (Birkenmajer, 1958, 1979).

The Haligovce unit in the territory of Slovakia shows slightly different characteristics. It is partly composed of Triassic karstified limestones, dolomitic limestones and dolomites (T_{wd}). These deposits are absent in the Polish part of the Pieniny Klippen Belt. There occur also Jurassic karstified limestones (J_w) and Cre-

Table 3

Fracturing parameters of lithologic units with reference to the classification of Liszkowski and Stochlak (eds, 1976)

Criterion	Class			Carbonates				Carbonate-clayey deposits		Flysch deposits	
				J_w		LK_{wr}		$K_{mł}$		$K_{pł}$	
				n	%	n	%	n	%	n	%
Fissure opening b [mm]	<0.03	cracks		57	35.8	190	39.3	81	37.3	76	29.0
	0.03-0.25	fissures	very narrow	21	13.2	55	11.4	44	20.3	31	11.8
	0.25-1		narrow	61	38.4	112	23.2	67	30.9	107	40.9
	1-2		medium wide	14	8.8	75	15.6	21	9.7	25	9.6
	2-5		wide	5	3.1	48	9.9	4	1.8	20	7.6
	5-10		very wide	1	0.8	1	0.2	0	0.0	3	1.1
	>10		extremely wide	0	0.0	2	0.4	0	0.0	0	0.0
		Σ		159	100.0	483	100.0	217	100.0	262	100.0
Surface fissure density Γ [m/m^2]	<1	very low		0	0	3	9	2	9	0	0
	1-2	low		0	0	4	12	3	13	2	12
	2-4	medium		4	33	6	18	7	30	3	18
	4-7	high		5	42	11	33	5	22	5	29
	7-10			2	17	3	9	3	13	3	18
	>10	very high		1	8	6	18	3	13	4	24
		Σ		12	100	33	100	23	100	17	100
Fissure porosity n_{vs} [%]	<0.25	practically non-fractured massif		1	8	5	15	4	17	2	12
	0.25-0.5			2	17	5	15	8	35	2	12
	0.5-1			3	25	5	15	5	22	3	18
	1-2	very poorly fractured		3	25	9	27	4	17	6	35
	2-4	poorly fractured		3	25	6	18	2	9	4	24
	4-12	medium fractured		0	0	2	6	0	0	0	0
	12-16	very strongly fractured		0	0	0	0	0	0	0	0
	>16	macrofractured		0	0	1	3	0	0	0	0
		Σ		12	100	33	100	23	100	17	100

taceous organodetrital limestones (K_w) typical of this unit. Information about karstification in carbonates of the Pieniny Mts. can also be derived from the results of rock-fissuring measurements, in particular from fissure opening distribution, surface fissure density and fissure porosity within individual lithologic units (Tab. 3).

Taking into consideration the geological-engineering classification of rock massifs (Liszkowski and Stochlak ed., 1976), it can be stated that the Pieniny Mts limestones are the only rock type, out of four lithological types considered, in which extremely wide-open fissures (>10 mm) and high fissure porosity were observed. These parameters allow to rank them among medium fissurized (4%) or even highly fissurized (>16%) ones. Also the number of moderately wide (1–2 mm) and wide (2–5 mm) fissures is greater in the limestones than in other rock types. It may be related to both weathering processes and the fissures widening due to dissolution.

However, it should be stressed that more comprehensive and detailed studies performed in the area of the Czorsztyn dam revealed not only a clear relationship between the water storage capacity in carbonates and the occurrence of fissures and fractures, but they also provide evidence that these fissures are numerous but very small (Dziewański, ed., 1998). It is proved, among others, by experiences from grouting works in the Dunajec River valley while creating a filtration screen under the dam body, that great water storage capacity zones were sealed with a relatively small amount of cement. No information about any voids or karst caverns is reported from this area.

Karstification processes in the Pieniny Mts are of a local nature and one should be very careful in determining the hydrogeological environment in carbonates of the Pieniny Klippen Belt as a karst-fractured or karstic one. In the study area, this might be only the case of some parts of the Golica-Płaśnia group in the Dunajec River Gap.

While assessing the hydrogeological properties of rocks, it is very important to take into account the porosity coefficient of the rock matrix. The open porosity coefficient determines the amount of empty spaces (pores, micropores and microfissures) in rocks, however refers only to a system of voids connected with one another within the rock volume, but eliminating isolated and disconnected pores and micropores.

As these investigations of the rock matrix in the Pieniny Mts are the first ones, and were carried out to a relatively small extent, the values presented here exhibit a limited representativeness because of both scarcity of samples from outcrops and statistically small subpopulations. Nevertheless, the results of laboratory determinations of hydrogeological parameters of the rock matrix in carbonates indicate low values of open porosity coefficients and a very low permeability (Tab. 4).

Considering the above, it is clear that the rock matrix of the Pieniny carbonates should be considered, according to the Pazdro and Kozerski's classification (1990), as impermeable or at best as semi-permeable. It is also worth noting that the results presented in Table 4 refer to the possibility of gas flow (nitrogen). For free water flow, the values will be lower, as proved by the so-called Klinkenberg correction, the value of which being, unfortunately, inconstant and depending on the rock fragment analysed.

The occurrence of groundwater in the Pieniny carbonates is associated exclusively with a system of joints that enables the groundwater storage and circulation.

Table 4

Hydrogeological properties of the matrix of selected lithostratigraphic complexes

Lithostratigraphic complex	Sample number	Sampling site	Rock type	Laboratory determinations			Estimated value of permeability coefficient [m/s] (after Pazdro & Kozerski, 1990)
				Open porosity coefficient [%]		Permeability coefficient [mdarcy]	
				n	$n_{śr}$		
Sromowce Formation $K_{pł}$ (N = 9)	1	Mały Cisowiec	fine-grained sandstone	0.21	**1.22**	0.03	10^{-9} – 10^{-10}
	2	Klenina	calcareous siltstone/marl/ gaize	2.55		<0.01	$< 10^{-10}$
	3	Klenina	fine-grained sandstone	1.58		0.07	10^{-9} – 10^{-10}
	4	Wąwóz Gorczyński	fine-grained sandstone	0.45		<0.01	$< 10^{-10}$
	5	Kotłowy Żleb	fine-grained sandstone	0.13		0.15	10^{-8} – 10^{-9}
	6	Szewców Gronik	fine-grained sandstone	1.70		0.20	10^{-8} – 10^{-9}
	7	Obłaźna Góra	fine-grained sandstone	3.51		2.60	10^{-7} – 10^{-8}
	8	Obłaźna Góra	fine-grained sandstone	0.80		<0.01	$< 10^{-10}$
	9	Sromowce Średnie	fine-grained sandstone	0.06		<0.01	$< 10^{-10}$
Jaworki Formation $K_{mł}$ (N = 3)	10	Czerwone Skały	marl	1.77	**1.45**	–	–
	11	Czerwone Skały	marl	1.58		0.40	10^{-8} - 10^{-9}
	12	Macelowy Potok	marl/gaize	1.00		<0.01	$< 10^{-10}$
Pieniny Limestone Formation JK_{wr} (N = 8)	13	near Falsztyn	calcareous wacke	2.03	**0.66**	0.18	10^{-8} – 10^{-9}
	14	Góra Palenica	calcareous wacke	0.17		<0.01	$< 10^{-10}$
	15	Wierch Skałki	silicified micritic limestone	0.96		–	–
	16	Macelowy Potok (upper part)	micritic limestone	0.08		<0.01	$< 10^{-10}$
	17	Wąwóz Gorczyński	calcareous wacke	1.11		<0.01	$< 10^{-10}$
	18	Magierowa Skałka	calcareous wacke	0.57		0.88	10^{-8} – 10^{-9}
	19	Wąwóz Szopczański	calcareous wacke	0.03		<0.01	$< 10^{-10}$
	20	Wąwóz Szopczański	silicified limestone/hornstone	0.31		–	–
Krupianka and Smolegowa formations Jw (N = 4)	21	near Falsztyn	micritic grain limestone	0.56	**1.19**	<0.01	$< 10^{-10}$
	22	near Falsztyn	micritic grain limestone	1.61		<0.01	$< 10^{-10}$
	23	near Falsztyn	micritic grain limestone	0.96		<0.01	$< 10^{-10}$
	24	near Falsztyn	micritic grain limestone	1.64		6.22	10^{-7} – 10^{-8}

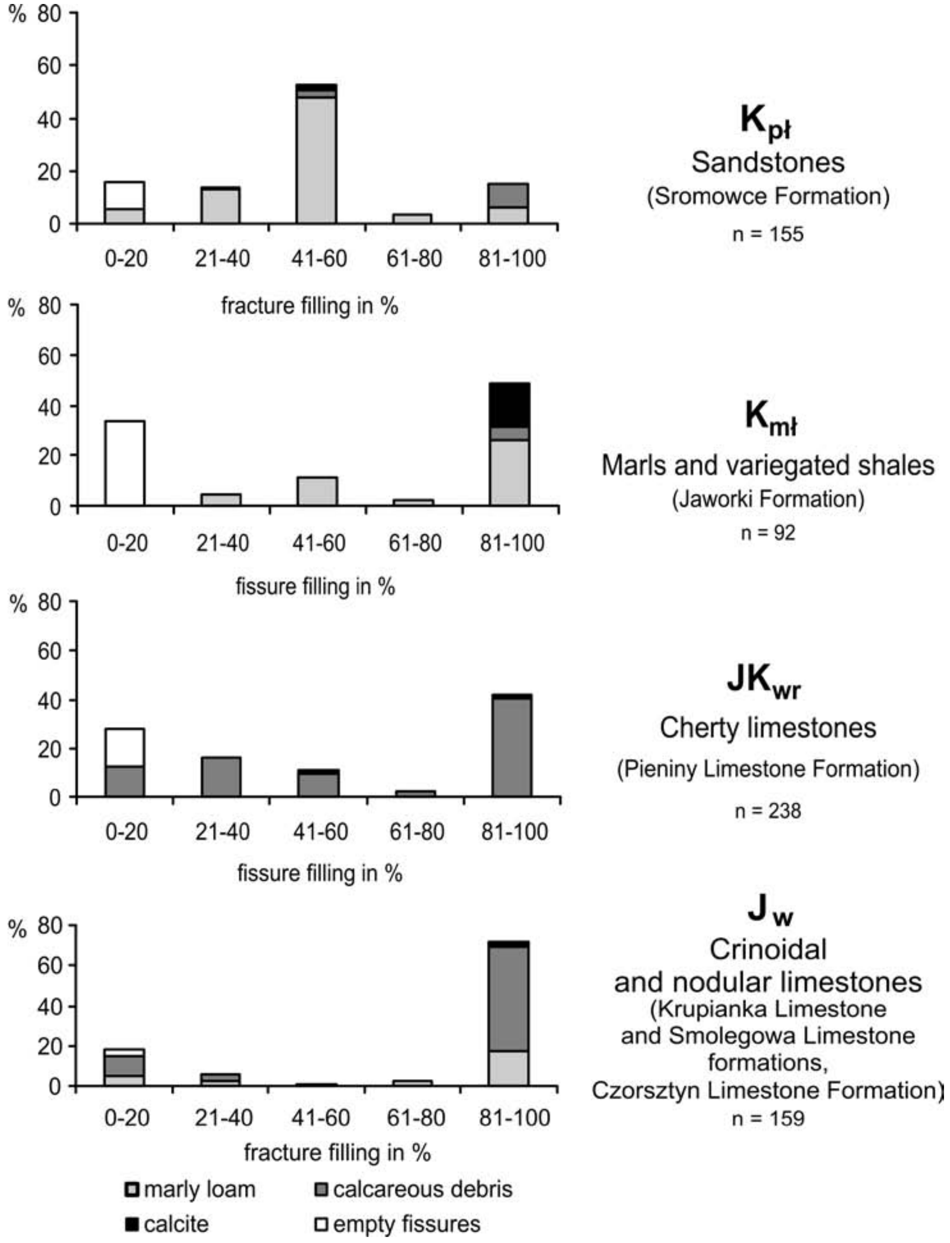

Fig. 3. Degree and type of filling of overcapillary fissures; n – number of overcapillary fissures measured

The crucial role in the groundwater circulation and water storage capacity of the rock massif is played by the opening size of fissures and the state of their filling.

Fissures in carbonates are most frequently filled with fairly well permeable calcareous debris and, to a lesser extent, with poorly permeable weathering material

Table 5

Characteristics of fissure wall uneveness

Fracture and fissure features	Lithostratigraphic complex			
	$K_{pł}$	$K_{mł}$	JK_{wr}	J_w
Rough [%]	65	91	95	82
Smooth [%]	35	9	5	18
Fissure wall unevenness coefficient (f_1) - taken for calculations (Tab. 6)	1.3	1.5	1.5	1.4

represented by argillaceous loam, or, sporadically, with almost impermeable calcite. There are differences in the degree and type of fillings between the Pieniny carbonates (JK_{wr}) as well as crinoidal and nodular limestones (J_w) where the groundwater occurrence conditions are less favourable (Fig. 3).

There is a considerable variability of fissuring porosity coefficients within the Pieniny carbonates in particular outcrops. It ranges from 0.03 to 21.8% with the mode value of 1–2%. A similar values range (0.04–23.1%) was reported by Łukaszek and Niedzielski (1976), who based on data from boreholes drilled in connection with the Czorsztyn dam construction project. Basing on measurements of water storage capacity in wells, these authors also found out that the lower depth limit of the fractured zone enabling groundwater circulation lies at the maximum depth of 110 m.

Fissure porosity coefficients of the Jurassic limestones (J_w) varied within a narrower range from 0.19 to 3.0%, which can also result from a smaller number of outcrops measured.

Fissuring of limestones is the most important element of the hydraulic network. It critically affects the possibility of groundwater flow. Fissure permeability coefficient is the measure of hydraulic permeability of fractured rock masses. Because free water can move only through supercapillary fissures wider than 0.25 mm, just this value was established as the limit for further calculations, neglecting narrower fissures and fractures. In the carbonates, supercapillary fissures account for about 50% of all fissures and fractures (see Tab. 3). In calculating fissuring porosity coefficients, macro-scale observations of fissure wall unevenness were also taken into consideration (Tab. 5)

Due to the complicated geological structure of the Pieniny Mts and strong tectonic deformation of the rock massif (possible changes in fissure directions within the massif), the results of surface fissuring measurements were continued to be analysed not only for individual sets of strictly defined orientations, but in an overall sense as a system of fissures providing hydraulic connections.. Fissure permeability coefficient, calculated using these assumptions, has an averaged value independent of the groundwater flow direction.

The correctness of this methodical approach is supported by research results from the Czorsztyn dam area where neither differences in permeability and distri-

Table 6

Determination of fissure permeability coefficient

Lithologic unit			Kpł	Kmł	JKwr	Jw
Number of exposures			17	23	33	12
Number of fissures			155	92	238	81
Mean fissure opening b [mm]	Arithmetic mean b_a [mm]		1.12	0.89	1.49	0.95
	Average guaranteed value(median) b_m [mm]		0.70	0.60–0.82	1.05	0.65–0.87
	Average geometric value weighted on length b_{gw} [mm]		0.63	0.63	0.87	0.63
Mean degree of surface fissuring n_F [%]			0.43	0.13	0.44	0.19
Mean fissure density Γ [m/m^2]			6.48	4.05	7.76	4.50
coefficient	– of fissure wall unevenness f_1 [-]		1.3	1.5	1.5	1.4
	– of tortuosity of fissure system f_2 [-]		1.5	1.5	1.5	1.5
	$f_1 \cdot f_2$		1.95	2.25	2.25	2.10
Fissure permeability coefficientk [m/s]	formula [4]	b_{gw}	$5.3 \cdot 10^{-4}$	$1.40 \cdot 10^{-4}$	$9.3 \cdot 10^{-4}$	$2.3 \cdot 10^{-4}$
		b_m	$6.6 \cdot 10^{-4}$	$1.3 \cdot 10^{-4}$ – $2.4 \cdot 10^{-4}$	$1.4 \cdot 10^{-3}$	$2.4 \cdot 10^{-4}$ – $4.3 \cdot 10^{-4}$
		b = 0.3 mm	$1.2 \cdot 10^{-4}$	$3.0 \cdot 10^{-5}$	$1.1 \cdot 10^{-4}$	$5.3 \cdot 10^{-5}$
	formula [5]	b_{gw}	$9.8 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$	$3.1 \cdot 10^{-3}$	$6.8 \cdot 10^{-4}$
		b_m	$1.4 \cdot 10^{-3}$	$5.4 \cdot 10^{-4}$ – $1.4 \cdot 10^{-3}$	$5.5 \cdot 10^{-3}$	$7.6 \cdot 10^{-4}$ – $1.8 \cdot 10^{-3}$
		b = 0.3 mm	$1.1 \cdot 10^{-4}$	$6.7 \cdot 10^{-5}$	$1.3 \cdot 10^{-4}$	$7.5 \cdot 10^{-5}$

Formula [4] – after Kotiachow-Johns modified by Motyka & Zuber (1993)
Formula [5] – after Liszkowski & Stochlak (eds, 1976)

bution of saturation zones between vertical, oblique and horizontal wells, nor vertical and horizontal regularity in permeability variations of bedrock have been observed (Dziewański ed., 1998).

The research results (Tab. 6) suggest that both the Pieniny limestones (JK_{wr}) and the Jurassic limestones (J_w) should be considered highly permeable rocks because of their permeability parameters. However, these limestones show slightly more advantageous hydrogeological parameters, their fissure permeability coefficients, calculated by various methods, exceeding 10^{-3} m/s as compared with 10^{-3}–10^{-4} m/s of the Jurassic limestones (J_w). Such values are typical of compact rocks with a dense supercapillary fissure and fracture network (Pazdro & Kozerski, 1990; Dowgiałło *et al.* (ed., 2002). Results of fissuring measurements in the field confirmed the high and moderate density of fissures in the carbonate rocks of the

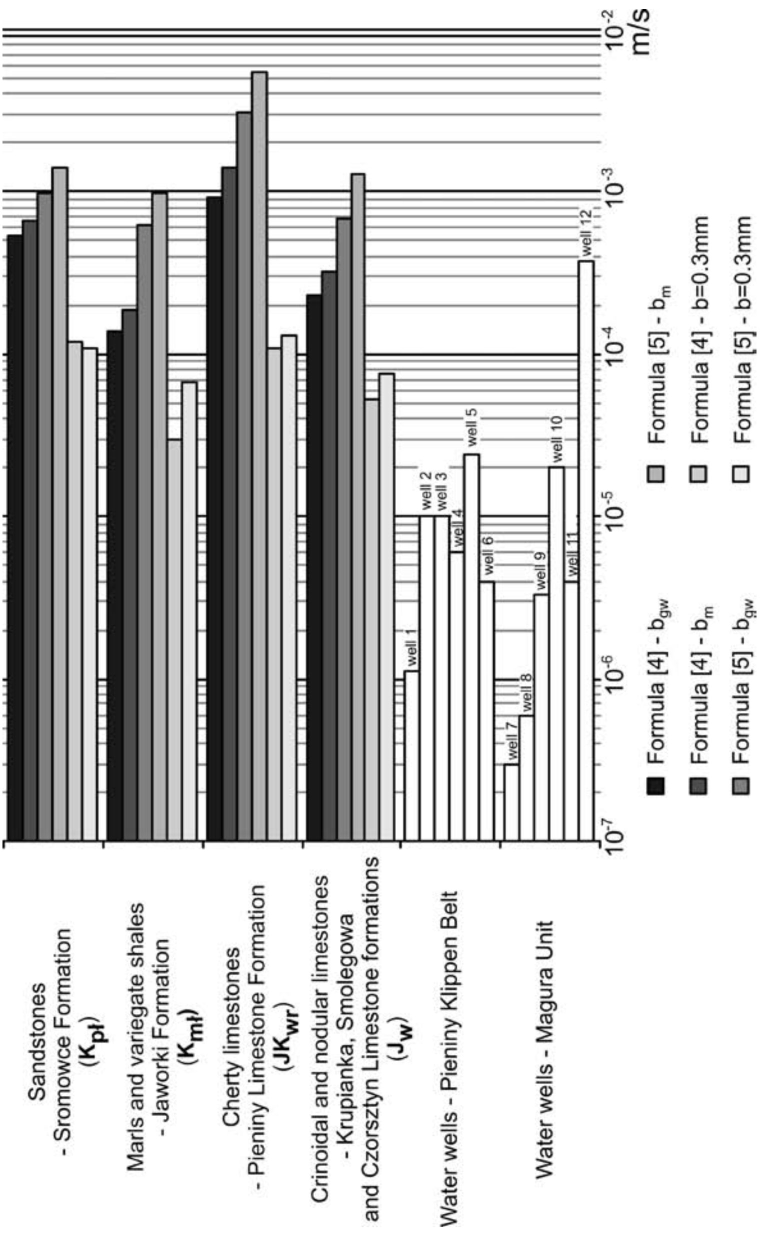

Fig. 4. A comparison of permeability coefficients calculated by various formulae (Tab. 6) with the values obtained by measurements in water wells (Tab. 1). Hand-dug wells: **1–5 Pieniny Klippen Belt:** 1 – Sromowce Wyżne; 2 – Sromowce Niżne; 3 – Szczawnica; 4 – Szaflary Ski Factory 1; 5 – Szaflary Ski Factory 2; **Podhale Depression:** 6 – Szaflary Yoghurt Plant; **7–12 Magura unit:** 7 – Czorsztyn Tourist Colony; 8 – Kluszkowce; 9 – Czorsztyn; 10 – Krośnica Primary School; 11 – Hałuszowa Bacówka; 12 – Krościenko Goldfruct

Pieniny Klippen Belt (see Tab. 3). However, the obtained permeability coefficient values are at least by two orders of magnitude greater than these those resulting from test pumping of wells extracting fracture water in the Pieniny Klippen Belt (Fig. 4).

It should be mentioned here that similar relations have been reported from the Tatra Mts. massif (Barczyk *et al.*, 1995), where, for example, the values of fissure permeability coefficient of the Eocene nummulitic limestones were also by two orders of magnitude higher than those measured in deep exploratory wells drilled in the Tatra foreland.

While analysing the values of fissure permeability coefficient, one should bear in mind that the study was performed in natural surface outcrops within the vadose zone, where not only natural relaxation of the rock mass but also mechanical and chemical weathering processes are taking place. Deep within the massif, the fissure openings are smaller due to the rock volume pressure and decreasing effect of weathering processes. This fact has a crucial significance for permeability parameters of the fractured medium within the saturation zone; however, it is practically impossible to determine it in the Pieniny region. If we assume (after Lenk 1986) that a fissure opening has a constant value of $b = 0.3$ mm, then the permeability coefficients will be smaller by at least one order of magnitude (and thus close to the values obtained during pumping tests). They are also uniform due to the dominant role of the parameter b in the formulae.

The fissure permeability coefficient formulae do not involve the degree of fissure filling. Therefore, the results of calculations become overestimated. The correction for the fissure filling should be introduced mainly for crinoidal and nodular limestones (J_w), where approximately 72% of overcapillary fissures are filled with poorly permeable weathering material represented by marly loam (see. Fig. 3). By using the formulae, those results most resemble the expected values (overestimated, but reflecting lithologic variability) which were calculated by the modified formula of Kotiachow-Johns and average geometric fissure opening weighted on their lenght.

Summing up the considerations concerning the values of fissure permeability coefficient in the Pieniny Mts, it should be stated that the presented data, although higher and overestimated in the zone of full saturation, could be used in the future to estimate groundwater vulnerability to anthropogenic contamination from the ground surface.

Assuming (after Krajewski and Motyka, 1999) that the average values of open porosity and permeability coefficients are the measures of hydrogeological features of fractured and porous media (Tab. 7), it can be suggested that the Pieniny massif, considered in terms of conceptual model of a hydraulic network in carbonate rocks (Motyka, 1998), is a fractured-porous reservoir where pores play an insignificant role in the groundwater flow. The average fissure permeability coefficient is here at least by four orders of magnitude higher than the average permeability coefficient of the rock matrix. Thus, the dominant role in groundwater flow within the carbonate rocks is played by fissures. The mean fissure porosity of the Pieniny limestones (JK_{wr}) is over three times as high as the porosity of their rock matrix. In case of the crinoidal and nodular limestones (J_w), the fissure and matrix porosity values are similar.

Table 7

Values of hydrogeological parameters of hydraulic network elements

Network element	Parameter		Lithology			
			Carbonates		Carbonate-clayey deposits	Flysch deposits
			J_w	JK_{wr}	$K_{mł}$	$K_{pł}$
Pore space	Open porosity of rock matrix [%]	Min. – max.	0.56 – 1.64	0.03 –2.03	1.00 – 1.77	0.13 – 3.51
		average	1.19	0.66	1.45	1.22
	Permeability coefficient of rock matrix [m/s]	Min.	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$	$<10^{-10}$
		Max.	$10^{-7} – 10^{-8}$	$10^{-8} – 10^{-9}$	$10^{-8} – 10^{-9}$	$10^{-8} – 10^{-9}$
Fissure space	Fissure porosity [%]	Min.– max.	0.19 – 3.02	0.04 – 23.0	0.07 – 2.66	0.11 – 3.74
		average	1.24	2.03	0.83	1.47
	Fissure permeability coefficient [m/s]	Min.– max.	$2.3 \cdot 10^{-4}$ – $1.8 \cdot 10^{-3}$	$9.3 \cdot 10^{-4}$ – $5.5 \cdot 10^{-3}$	$1.3 \cdot 10^{-4}$ – $1.4 \cdot 10^{-3}$	$5.1 \cdot 10^{-4}$ – $1.3 \cdot 10^{-3}$
		average	$6.9 \cdot 10^{-4}$	$3,6 \cdot 10^{-3}$	$5.1 \cdot 10^{-4}$	$8.5 \cdot 10^{-4}$

Carbonate-clayey deposits

An admixture of clayey material significantly lowers the values of hydogeological parameters of carbonate rocks. This is the case with the Pieniny's Jurassic mottled marls and shales ($J_{mł}$) and Cretaceous variegated marls and clays inter-bedded with sandstones of the Jaworki Marl Formation ($K_{mł}$), which occupy 1/4 of the whole study area.

Investigations of water storage capacity carried out by Łukaszek and Niedzielski (1976) have shown, that the possibility of groundwater occurrence in marly deposits is much lower as compared to carbonate rocks. Those authors assumed the lower limit of the fractured zone within which groundwater circulation is possible, to reach the depth of around 15 m.

These observations have been fully corroborated by field research on rock fissuring. The marly deposits are characterised by the lowest fissure density (4.05 m/m^2), the lowest fissure permeability coefficients (0.06–2.7%) and the lowest percentage contribution of supercapillary fissures (about 42%), while subcapillary and capillary fissures are predominant). This, results in the lowest values of the fissuring permeability coefficient (see Tabs 3, 5, 7).

Taking also into account the fact that approximately 43% of supercapillary fissures are filled with poorly permeable marly loam or with practically impermeable calcite, the possibility of groundwater flow in these rocks is very low.

Despite of a modest scale of research, the results of laboratory measurements of rock matrix parameters in the marly deposits are interesting (see Tab. 4). The permeability is here very low (the rock is almost impermeable), whereas the open porosity coefficient measured in all the samples exceeds the value of 1%. Therefore, the mean matrix porosity of these deposits is by a factor of 1.6 higher than their fissure porosity (see Tab. 7). It means that the marly deposits are a porous-fractured reservoir while considered in terms of the hydraulic network model. Groundwater can be stored in micropores and fissures, while its percolation is possible only through fissures. A definite explanation of this problem requires further field and laboratory studies

Flysch deposits

In the flysch deposits of the Pieniny Klippen Belt, like in the whole Carpathian flysch, the alternation of deposits of potentially favourable hydrogeological parameters (sandstones, conglomerates) with poorly permeable (siltstones) or practically impermeable deposits (claystones, marls) hampers or even prevents ground water flow (Małecka & Murzynowski, 1978). In the Pieniny Mts., flysch deposits are relatively frequent and occupy approximately 36% of the total area.

Research analogous to this carried out on carbonate and carbonate-clay rocks, concerning water storage capacity was carried out in flysch deposits near the Czorsztyn dam. It revealed that the zone of increased permeability occurs down to a depth of 40–50 m in sandstone flysch, to 25–30 m in normal flysch, and to 10–15 m in shaly flysch (Łukaszek & Niedzielski, 1976).

The Sromowce Formation flysch ($K_{pł}$), the most common flysch in the Polish part of the Pieniny Klippen Belt, is referred to as a normal flysch characterized by the sandstone/claystone+siltstone ratio of nearly 1. In turn, the "Proč-Jarmuta Formation" flysch, predominant in the Slovak territory, represents a flysch type in which sandstones and conglomerates highly predominate over siltstones and claystones. The percentage of rocks of favourable hydrogeological parameters is also greater in the Palaeogene flysch of the Haligovce unit (Aksamitka sandstones and conglomerates, sandstones and shales).

Field research on rock fissuring (see Tab. 3), and laboratory studies on the flysch rock matrix (see Tab. 4), were focused primarily on sandstone beds having much more advantageous hydrogeological parameters as compared with siltstones and claystones.

Flysch sandstones are strongly fractured (prevalence of outcrops with high and very high fissures density – see Tab. 3). Supercapillary fissures considerably predominate (about 59%). The fissures are partly filled with low-permeability weathering loam. Completely filled fissures are rare (about 14%, Fig. 3). The fissure permeability coefficients are fairly high, placing thesse deposits just after the Pieniny Mts limestones in terms of permeability (see Tab. 7).

The flysch sandstones are of a low matrix porosity ranging from 0.13 to 3.51% (see Tab. 4) and, according to the classification by Pazdro and Kozerski (1990), may be numbered among low porosity, watertight rocks. Slightly wider intervals of porosity values are reported for this rock type by other authors: Małecka (1981) – from 0.1% to 7.9% (low and medium porosity watertight rocks), Watycha (1976) – 5–6% (medium porosity rocks).

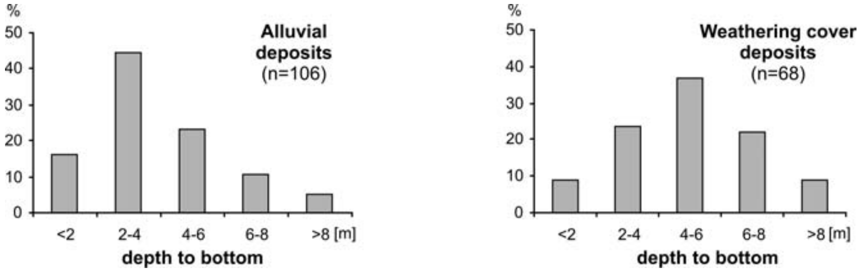

Fig. 5. Depth distribution of hand-dug wells

Like in the case of carbonate rocks, the factor deciding upon water storage capacity value of sandstones is the degree of rock fissuring. It is also manifested by much greater values of fissure permeability coefficient as compared with the porous permeability (see Tab. 7). However, it should be stressed that due to the occurrence of poorly permeable rocks with interbeddings of practically impermeable siltstones and claystones, the possibility of occurrence and circulation of groundwater in the flysch deposits as a whole is highly limited.

In conclusion to the considerations on hydrogeological properties of rocks occurring in the Pieniny Klippen Belt, it should be noted that, independently of lithology and depth of rock occurrence, the most favourable values of hydrogeological parameters are observed as local anomalies associated with fault zones and tectonic deformations. The orientation of these disturbances is independent of the stratification and lithology. These are zones of preference for groundwater circulation down to greater depths and over large distances.

GROUNDWATER IN QUATERNARY DEPOSITS

The Quaternary deposits contain pore water. The aquifers are: fluvial and alluvial fan sands and gravels as well as loams and rock debris covering older deposits.

Reservoir properties of alluvial deposits of the Dunajec River and the Krośnica River tributaries are poor. Water-richer aquifers of economic importance are represented by alluvial deposits of the Dunajec and Niedziczanka rivers, which were until recently the main sources of water supply to the population. From among 178 hand-dug wells registered during field work, 106 wells are located on the terraces of the Dunajec (63 wells) and Niedziczanka rivers (43 wells). Pumping tests done in two selected wells at Sromowce Niżne and observations of groundwater level rise made it possible to determine permeability coefficients applying the Forchheimer-Roslonski formula. The values obtained are: $3.8 \cdot 10^{-4}$ m/s and $1.0 \cdot 10^{-4}$ m/s. The thickness of the Quaternary deposits and their water storage capacity may be inferred indirectly from both the depths of the hand-dug wells (Fig. 5) and the depth to the groundwater table (Fig. 6).

Two subpopulations of wells were analysed: wells extracting water from alluvial deposits of the Dunajec and Niedziczanka rivers, and those withdrawing water

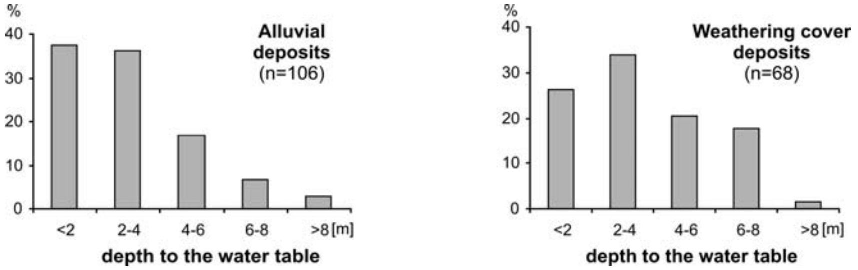

Fig. 6. Distribution of depths to the groundwater table in hand-dug wells

from Quaternary weathering covers overlying rock formations of the Pieniny Klippen Belt. It should be stressed that, for the latter case, it is difficult to delineate a definite boundary between pore waters of the weathering covers and fracture waters of the bedrock, undoubtedly participating in the wells yield. The depth to the groundwater table represents periods of summer and autumn low groundwater flows.

Over 60% of wells dug in alluvial deposits are less then 4 m deep. There are also wells deeper than 10 m (e.g. two wells at Krościenko, their depths amounting to 10.81 m and 11.17 m). The groundwater table commonly lies at depths of < 2 m b.g.l. There is a regularity observed in the Dunajec alluvial deposits: in the area between the Sromowce reservoir and Sromowce Średnie, the depth to the groundwater table does not exceed 3 m. Along the next section, downriver to Krościenko, it becomes variable tending to be placed deeper, locally even at 6–8 m (Małecka & Humnicki, 2002).

The wells dug in weathering covers are deeper, their depths commonly ranging between 4 and 6 m, but there are a number of wells reaching the maximum depth of 13.40 m (a well at Sromowce Wyżne). The groundwater table is also mostly situated at greater depths (average depth of 2–4 m b.g.l., maximum recorded depth – 7.83 m in a well at Falsztyn). This means that water storage conditions in weathering loams and rock debris are less favourable than in fluvial deposits.. These conditions are here variable depending on the bedrock type as well as on the intensity of weathering and washout processes.

Flysch and marly deposits produce weathering loams of greater thicknesses (a few metres) as compared with carbonate rocks. The thickness of weathering loams is also controlled by ground surface topography; steep pinnacle slopes are devoid of weathering cover, whereas their thicknes at the feet of the hill may reach a several metres. In terms of infiltration properties, this situation is disadvantageous. In general, the groundwater reserves in weathering cover deposits are very low and occur only on a local scale.

CONCLUSIONS

1. The most common rocks of the Pieniny Mts are flysch deposits (about 36% of the total area), Quaternary rocks (about 28%) and carbonate-clay deposits (about

26%). Carbonate rocks are the least common ones (about 10%) although they play the dominant role in the Pieniny's landscape. Due to an enormous degree of tectonic deformation, various lithological species of the Pieniny Klippen Belt show wide-ranging analogies in hydrogeological properties, irrespective of the rock series they belong to.

2. The most common fractures and fissures orientation in the subsurface (weathering) zone is SWW–NEE, parallel to the strike of tectonic structures. Typical features are: a considerable contribution of steep and very steep fractures and fissures and a small percentage of horizontal fissures. Such a rock-fissuring pattern is advantageous for higher infiltration rates and deeper penetration of rainwater into the rock massif, but simultaneously favours intense groundwater drainage.

3. The fissure permeability coefficient, values that are most similar to the expected ones i.e. ranging from $1.4 \cdot 10^{-4}$ to $9.3 \cdot 10^{-4}$ m/s (overestimated, but reflecting the lithological variability) were obtained applying the modified Kotiachow-Johns formula and the mean geometric fissure opening weighted upon their lenght. It should be stressed here that these values are typical only of some parts of the rock massif within the hypergenic zone, where weathering processes are prevailing. At greater depths of the rock they are much lower.

4. The rock matrix of the Pieniny Klippen Belt formations should be considered impermeable or, at best, semipermeable. Laboratory analyses revealed low open porosity coefficients ranging between 0.03 and 3.5% (dominant values <2%) and very low permeability commonly below 1 mdarcy, with dominant values of <0.01 mdarcy.

5. The size of fissure opening and the type of their filling play the critical role in the possibility of groundwater occurrence. In carbonate rocks, supercapillary fissures account for approximately 50% of all fissures. They are filled predominantly by calcareous debris. The lowest percentage of supercapillary fissures (about 42%) is observed in carbonate-clayey deposits. These are filled mostly with poorly permeable marly loam. The greatest percentage of supercapillary fissures (about 59%) is observed in sandstones of the Sromowce Formation flysch, where partly filled fissures are predominant. Therefore, the flysch sandstones in terms of permeability, are placed after the Pieniny Formation limestones.

6. In terms of a conceptual model of hydraulic network, the Pieniny groundwater is a fractured-porous reservoir where pores play an insignificant role in the water flow. The mean fissure porosity of the Pieniny Formation limestones (2.03%) is over three times greater than the porosity of their rock matrix (0.66%). In case of crinoidal and nodular limestones, both the fissure and matrix porosities are similar in value (1.24% and 1.19%, respectively). At the present-day state of exploration, marly deposits should be considered a porous-fractured reservoir. Groundwater can occupy micropores and fissures (1.45%), but water flow can occur only through fissures (0.83%). The flysch sandstones are characterized by higher values of fissure porosity coefficient (1.47%) as compared with the matrix porosity coefficient (1.22%). The mean fissure permeability coefficient in all the lithologic complexes is, by at least four orders of magnitude, greater than the mean permeability coeffi-

cient of the rock matrix. Obviously, fissures play the dominant role in the ground water flow.

7. Karstification processes occur only on a local scale in the Pieniny Mts., and one should be very careful in qualifying the hydrogeological environment in carbonate rocks of the Pieniny Klippen Belt as a karst-fractured or karstic one.

8. As regards the possibility of groundwater accumulation, the best hydrogeological conditions are observed in alluvial deposits of the Dunajec and Niedziczanka rivers. The thickness of water-bearing deposits amounts here up to 10 m , and the thickness of aquifers reaches 4 m.. The permeability coefficients determined applying the Forchheimer-Rosłoński method vary from 1 to $3.8 \cdot 10^{-4}$ m/s. Over 60% of wells dug in alluvial deposits are less than 4 m deep. The groundwater table is observed commonly at shallow depths of <2 m. b.g.l. Wells dug in the weathering cover are deeper (usually 4 to 6 m) and the groundwater table is commonly observed at greater depths (dominant depth 2–4 m).

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REFERENCES

Barczyk, G., 1986. Zmiany chemizmu wód leczniczych Szczawnicy na przykładzie źródła “Magdalena” (Changes of chemical composition of curative waters of Szczawnica on the example of “Magdalena” spring). *Przegląd Geologiczny*, 12: 707–712.

Barczyk, G., Humnicki, W. & Małecka, D., 1995. Określenie współczynników filtracji masywu tatrzańskiego na podstawie pomiarów szczelinowatości (Determination of hydraulic conductivity coefficient of the Tatra massif on the base of fissurity measurements). *Współczesne Problemy Hydrogeologii*, Kraków–Krynica, 7: 231–238.

Birkenmajer, K., 1956. Występowanie wód mineralnych na tle budowy geologicznej Szczawnicy (The mineral water occurrence in the light of geological setting of the Szczawnica area). *Przegląd Geologiczny*, 11: 409–502.

Birkenmajer,K., 1958. *Przewodnik geologiczny po pienińskim pasie skałkowym I–IV* (Pieniny Klippen Belt – Geological Guide – in Polish). Wydawnictwa Geologiczne. Warszawa.

Birkenmajer, K., 1963. Z historii odkrycia wód mineralnych Szczawnicy i Krościenka (Historical aspects of mineral waters exploration at Szczawnica and Krościenko). *Przegląd Geologiczny*, 7: 311–313.

Birkenmajer, K., 1977. Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica*, 45: 1–159.

Birkenmajer, K., 1979. *Przewodnik geologiczny po pienińskim pasie skałkowym* (Pieniny Klippen Belt of Poland, Geological Guide – in Polish). Wydawnictwa Geologiczne. Warszawa.

Birkenmajer, K., 1986. Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 88: 7–32.

Birkenmajer, K., 2007. The Czertezik Succession in the Pieniny National Park (Pieniny Klippen Belt, West Carpathians): stratigraphy, tectonics, palaeogeography. *Studia Geologica Polonica*, 127: 7–50.

Birkenmajer, K & Gedl, P., 2007. Age of some deep-water marine Jurassic strata at Mt Hulina, Małe Pieniny Range (Grajcarek Unit, Pieniny Klippen Belt, West Carpathians, Poland), as based on dinocysts. *Studia Geologica Polonica*, 127: 51–70.

Bober, L. & Oszczypko, N., 1963a. Charakterystyka hydrochemiczna kontaktu pienińskiego pasa skałkowego z jednostką magurską w okolicach Czorsztyna, Kluszkowiec i Krośnicy (Hydrochemical characteristics of transition zone between the Pieniny Klippen Belt and the Magura Unit in the vicinity of Czorsztyn, Kluszkowce and Krośnica – in Polish). *Kwartalnik Geologiczny*, 7(3): 549–550.

Bober, L. & Oszczypko, N., 1963b. Uwagi na temat chemizmu wód podziemnych występujących na kontakcie jednostki magurskiej z pienińskim pasem skałkowym (Remarks about chemical composition of groundwaters occurring in the transition zone between the Magura Unit and the Pieniny Klippen Belt). *Przegląd Geologiczny*, 7: 326–328.

Chowaniec, J. & Witek, K., 1997a. *Mapa hydrogeologiczna Polski,1 : 50 000, Ark. Szczawnica-Krościenko* (Hydrogeological Map of Poland to the scale of 1:50000, Szczawnica-Krościenko sheet). Państwowy Instytut Geologiczny & Ministerstwo Ochrony Środowiska. Zasobów Naturalnych i Leśnictwa, Warszawa.

Chowaniec, J. & Witek, K., 1997b. *Objaśnienia do mapy hydrogeologicznej Polski, 1 : 50 000, Ark. Szczawnica-Krościenko* (Explanations to Hydrogeological Map of Poland to the scale 1:50000, Szczawnica-Krościenko sheet). Państwowy Instytut Geologiczny & Ministerstwo Ochrony Środowiska. Zasobów Naturalnych i Leśnictwa, Warszawa.

Chowaniec, J., Gierat-Nawrocka, D. & Witek K., 1977–1979. *Mapa hydrogeologiczna Polski, 1 : 200 000, Ark. Nowy Sącz* (Hydrogeological Map of Poland to the scale 1:200000, Nowy Sącz sheet). Wydawnictwa Geologiczne, Warszawa.

Chowaniec, J., Gierat-Nawrocka, D. & Witek, K., 1981. *Objaśnienia do mapy hydrogeologicznej Polski,1 : 200 000, Ark Nowy Sącz* (Explanations to Hydrogeological Map of Poland to the scale 1:200000, Nowy Sącz sheet). Wydawnictwa Geologiczne, Warszawa, 1–76.

Ciężkowski, W. & Rajchel, L., 2005.Wody lecznicze górskich obszarów Polski i ich wykorzystanie (Curative waters of mountainous areas of Poland and their utilization). *Współczesne Problemy Hydrogeologii*, 12: 109–115.

Dowgiałło, J., 1980. Poligenetyczny model karpackich wód chlorkowych i niektóre jego konsekwencje (Poligenetic model of Carpathian chloride waters and its consequence). *Współczesne Problemy Hydrogeologii,* 1: 275–290.

Dowgiałło, J., Kleczkowski, A.S., Macioszczyk, T. & Różkowski, A. (eds.), 2002. *Słownik hydrogeologiczny* (Hydrogeology glossary – in Polish). Państwowy Instytut Geologiczny, Warszawa.

Dziewański, J., red., 1998. Warunki geologiczno-inżynierskie podłoża Zespołu Zbiorników Wodnych Czorsztyn-Niedzica i Sromowce Wyżne im. Gabriela Narutowicza na Dunajcu (The geological-engineering settings of bedrock of the group of water reservoirs Czorsztyn-Niedzica and Sromowce Wyżne of the Gabriel Narutowicz name, on the Dunajec River). *Studia, Rozprawy, Monografie PAN*, 60. Wydawnictwo Instytutu Gospodarowania Surowcami Mineralnymi i Energią, Kraków: 188 pp.

Gołąb, J., 1948. Nowo odkryte wody mineralne Szczawnicy (Recently discovered mineral waters of Szczawnica). *Biuletyn Państwowego Instytutu Geologicznego*, 42: 116–119.

Gołąb, J., 1952. Hydrogeologiczne stosunki Szczawnicy (Hydrogeological settings of Szczawnica area, summary). *Geologiczny Biuletyn Informacyjny (Wydawnictwo Państwowego Instytutu Geologicznego)*, 1: 13.

Humnicki, W., 2003. Odpływ podziemny w wybranych zlewniach Pienińskiego Parku Narodowego (Underground run-off of selected catchments in the Pieniny National Park). *Pieniny – Przyroda i Człowiek*, 8: 41–51.

Humnicki, W., 2005. Jakość wód podziemnych i powierzchniowych Pienińskiego Parku Narodowego i okolic (The quality of ground and surface waters of the Pieniny National Park and its vicinity – in Polish). *Zbornik z medzinárodnej vedeckej konferencie "Hydrogeochemia '05" IX. Ročnik, 21-22.6.2005*, Bratislava: 173–179.

Humnicki, W., 2007. *Hydrogeologia Pienin* (Hydrogeology of the Pieniny Mts.). Wydawnictwa Uniwersytetu Warszawskiego. Warszawa: 239 pp.

Hynie, O., 1963. *Hydrogeologie ČSSR – II. Minerálni vody* (Hydrogeology of Czecho-Slovakian

Socialist Republic. – II. Mineral water). Nakladatelstvi Československé Akademie Věd. Praha: 797 pp.

Jetel, J., 1989. Relationship between hydrogeochemical characteristics of near-surface zone of rock massif and hydrodynamic conditions. *Západné Karpaty, Séria Hydrogeológia a Inženierska Geólogia*, 8: 67–104. Bratislava.

Jetel, J, 2000. *Hydrogeologická mapa Ľubovnianskéj Vrchoviny a Pienin, 1: 50 000* (Hydrogeological Map of Lubovnianska Vrchovina and the Pieniny Mts.). Ministerstvo Životného Prostriedia Slovenskej Republiky & Štátny Geologický Ústav Dionýza Štúra. Bratislava

Jetel, J. & Kullmann E., 1989. Nepriame určenie priemernej prietočnosti z podzemného odtoku a výdatnosti prameňov (Indirect methods of mean hydraulic permeability assessment from underground run-off and springs capacity). *Regionálna Geologia Západnich Karpát,* 25: 249–257.

Kazimierski, B., Małecka, D. & Różkowski A., 1999. Cel, metody i wyniki monitoringu wód podziemnych w Polsce (Purpose, methods and results of the groundwater monitoring in Poland). *Biuletyn Państwowego Instytutu Geologicznego,* 338: 79–114.

Kolago, C., 1970. *Mapa hydrogeologiczna Polski. 1 : 1 000 000* (Hydrogeological Map of Poland to the scale 1:1000000). Wydawnictwa Geologiczne, Warszawa.

Korczyński, L., 1909. Kilka uwag o wodach szczawnickich (Some remarks about Szczawnica waters). *Pamiętnik Polskiego Towarzystwa Balneologicznego*, 2: 61–75.

Kostrakiewicz, L., 1965. Hydrografia Pienin (Hydrography of the Pieniny Mts.). *Zeszyty Naukowe Uniwersytetu Jagiellońskiego*, 117, *Prace Geograficzne*, 12: 77–111.

Kostrakiewicz, L., 1982. Hydrografia (Hydrography). *In:* Natural environment of the Pieniny Mts in the face of change). *In: Przyroda Pienin w obliczu zmian.* Zarzycki K. [red.], Państwowe Wydawnictwo Naukowe, Warszawa – Kraków: 70–93.

Kostrakiewicz, L., 1991a. Przemiany stosunków krenologicznych na terenie Pienińskiego Parku Narodowego i strefy otulinowej (Transformations of crenological conditions in the area of Pieniny National Park and its vicinity). *Parki Narodowe i Rezerwaty Przyrody*, 10 (3/4): 187–194.

Kostrakiewicz, L., 1991b. Charakterystyka fizyko-chemiczna oraz bakteriologiczna wybranych źródeł Pienińskiego Parku Narodowego i jego okolicy (Physico-chemical and bacteriological characteristics of selected springs of the Pieniny National Park and its vicinity). *Ochrona Przyrody*, 49 (1): 129–139.

Kostrakiewicz, L., 1992. Typologia źródeł pienińskiego pasa skałkowego i jednostki magurskiej (The typology of the springs in the area of the Pieniny Klippen Belt and the Magura Unit). *Wszechświat*, 93 (3): 62–64.

Kostrakiewicz, L., 1993. Wpływ posuchy atmosferycznej na stosunki hydrogeologiczne pienińskiego pasa skałkowego i jednostki magurskiej (The influence of atmospheric drought on hydrogeological settings in the Pieniny Klippen Belt and the Magura Unit). *Wszechświat*, 94 (2): 31–35.

Kostrakiewicz, L., 1995. Stężenie jonowe i tło hydrochemiczne szczelinowych wód podziemnych pienińskiego pasa skałkowego i jego przyległej części jednostki magurskiej (Total dissolved solids and hydrochemical background of fissure groundwaters in the Pieniny Klippen Belt and the Magura Unit). *Wszechświat*, 96 (4):88–94.

Kostrakiewicz, L., 1996. Regionalizacja wskaźnika krenologicznego w polskich Karpatach Wewnętrznych (Regional distribution of crenological index in Polish Inner Carpathians). *Wszechświat*, 97 (3): 61–66.

Kostrakiewicz, L., 2002. Charakterystyka fizykochemiczna wód źródła siarczkowego występującego na terenie Pienińskiego Parku Narodowego (Physico-chemical characteristic of sulfide spring water occurring in the Pieniny National Park). *Pieniny – Przyroda i Człowiek*, 7: 71–77.

Krajewski. S. & Herbich P., 1977. Ocena anizotropii warunków filtracji w skałach szczelinowych na podstawie pomiarów szczelinowatości (Assessment of the anisotropy of filtration conditions in fractured rocks on the base of fissurity determination). *Biuletyn Geologiczny*, 21: 7–28. Wydawnictwa Uniwersytetu Warszawskiego, Warszawa.

Krajewski S., Motyka J., 1999. Model sieci hydraulicznej w skałach węglanowych w Polsce (The model of hydraulic network in carbonate rocks in Poland). *Biuletyn Państwowego Instytutu Geologicznego*, 388: 115–138.

Lenk, T., 1986. Metodyczne i praktyczne badania szczelinowatości skał węglanowych (Methodological and practical investigations of the fissurity of carbonate rocks). *Prace Instytutu Górnictwa Naftowego i Gazownictwa,* Kraków, 60: 82 pp.

Leśniak, T. & Motyka J., 1991. Model hydrogeologiczny złoża wapieni dolnokarbońskich w Czatkowicach koło Krzeszowic (Hydrogeological model of limestone deposits at Czatkowice, near Krzeszowice). *Gospodarka Surowcami Mineralnymi*, 7 (4): 1007–1029.

Liszkowski, J. & Stochlak J., red., 1976. *Szczelinowatość masywów skalnych* (The fissurity of rocky massifs). Wydawnictwa Geologiczne. Warszawa: 312 pp.

Łukaszek, R. & Niedzielski H., 1973. Dokumentacja geologiczno-inżynierska do projektu podstawowego zapory na rzece Dunajec w Czorsztynie-Niedzicy, uzupełniona wg zaleceń KDGI przy CUG (Geological-engineering documentation to primary project of dam on the Dunajec river in Czorsztyn-Niedzica; completed according to KDGI and CUG). PG i BW "Hydrogeo", Kraków.

Łukaszek, R. & Niedzielski H., 1976. Problemy geologiczno-inżynierskie zapory betonowej i zbiornika Czorsztyn-Niedzica (Geological-engineering problems of concrete dam and water reservoir in Czorsztyn-Niedzica). *Zeszyt Naukowy – Politechnika Krakowska, Budownictwo Wodne i Inżynieria Sanitarna,* Kraków, 2: 150 pp.

Macioszczyk, T., 1959. Niektóre problemy hydrogeologii źródeł zachodniego Podhala (Selected hydrogeological problems of the West Podhale springs). *Przegląd Geologiczny*, 8: 372–375

Macioszczyk, T., 1964. *Hydrogeologia źródeł występujących w strefie kontaktu fliszu Podhala z pienińskim pasem skałkowym* (Hydrogeology of springs occurring in the transition zone between the Podhale flysch and the Pieniny Klippen Belt). Praca doktorska (Ph.D.Thesis, unoublished). Uniwersytet Warszawski, Archiwum Instytutu Hydrogeologii i Geologii Inżynierskiej.

Malinowski, J. (ed.), 1991. *Budowa geologiczna Polski.* VII, Hydrogeologia (Geology of Poland. VII; Hydrogeology). Prace Państwowego Instytutu Geologicznego, Warszawa, 204–215.

Małecka, D., 1981. *Hydrogeologia Podhala* (Hydrogeology of the Podhale region). Prace hydrogeologiczne Instytutu Geologicznego, seria specjalna, 14, Wydawnictwa Geologiczne, Warszawa: 187 pp.

Małecka, D., 1982. *Mapa hydrogeologiczna Podhala i obszarów przyległych, 1 : 100 000* (Hydrogeological Map of Podhale and its vicinity to the scale of 1:100000). Wydawnictwa Geologiczne, Warszawa.

Małecka, D., 1985. Studia hydrogeologiczne krasu Tatr Polskich (Hydrogeological study of the karst in Polish Tatra Mts.). *Gacek*, Kraków, 2 (41): 14–30.

Małecka, D., 1992. Główne zbiorniki wód podziemnych Tatr i Podhala. *In: Materiały sesji naukowej poświęconej jubileuszowi prof. A.S. Kleczkowskiego* (The main groundwater bodies of the Podhale Basin and Tatra Mts. *In:* Proceedings of scientific session on the occasion of anniversary of prof. A.S. Kleczkowski). 61–69, Wydawnictwa AGH, Kraków.

Małecka, D., 1996. Wpływ Zbiornika Czorsztyńskiego na środowisko wodne obszarów przyległych. *In: Konferencja Komitetu Gospodarki Wodnej PAN, Jachranka 3–5 czerwca 1996 r.* (The influence of water reservoir in Czorsztyn on natural environment of adjacent areas. *In:* Proceedings of the conference of the Committee for Water Management of the Polish Academy of Sciences). Oficyna Wydawnicza. Politechniki Warszawskiej, Warszawa, 25–44.

Małecka, D. & Humnicki, W., 1989. Rola warunków hydrodynamicznych w kształtowaniu wywierzyska Goryczkowego (The role of hydrodynamic settings in formation of the Goryczkowe spring). *Przegląd Geologiczny*, 2: 72–84.

Małecka, D. & Humnicki, W., 2001. Stan rozpoznania hydrogeologicznego Pienińskiego Parku Narodowego (The state of hydrogeological recognition of the Pieniny National Park). *Współczesne problemy hydrogeologii*, Wrocław, 10(1): 45–54.

Małecka, D. & Humnicki, W., 2002. Problemy hydrogeologii i ochrony wód Pienińskiego Parku Narodowego (The problems of hydrogeology and water protection in the Pieniny National Park). *Pieniny – Przyroda i człowiek*, 7: 49–70.

Małecka, D. & Lipniacka, T., 1990. Sieć hydrogeologicznych obserwacji stacjonarnych na Podhalu –

założenia i wstępna interpretacja wyników (The network of hydrogeological monitoring points in the Podhale Basin – aims and preliminary results). *Przegląd Geologiczny*, 11: 484–491.

Małecka, D. & Murzynowski W., 1978. Rejonizacja hydrogeologiczna Karpat fliszowych (Hydrogeological zoning of the Flysch Carpathian Mts). *Wiadomości Instytutu Melioracji i Użytków Zielonych*, 56: 50 pp.

Małecka, D., Humnicki W., Małecki J. & Łabaszewski W., 1996. Charakterystyka i ocena aktualnej jakości wód w rejonie Zbiornika Czorsztyńskiego (Characteristic and evaluation of the actual quality of water in the vicinity of the Czorsztyn water reservoir). *Przegląd Geologiczny*, 11: 1103–1110.

Marchlewski, L., 1914a. Wyniki rozbiorów wód mineralnych ze zdrojów "Wandy" i "Szymona" w Szczawnicy (The results of mineral water utilization from the following springs in Szczawnica: Wanda and Szymon). *Pamiętnik Polskiego Towarzystwa Balneologicznego*, 3: 50–53.

Marchlewski, L., 1914b. Wyniki rozbiorów wód mineralnych ze zdrojów Jana, Magdaleny w Szczawnicy (The results of mineral water utilization from the following springs in Szczawnica: Jan, Magdalena). *Pamiętnik Polskiego Towarzystwa Balneologicznego*, 3: 128–133.

Motyka, J., 1998. A conceptual model of hydraulic networks in carbonate rocks, illustrated by examples from Poland. *Hydrogeology Journal*, 6: 469–482.

Motyka, J. & Wilk Z., 1984. Hydraulic structure of karst-fissured Triassic rocks in the vininity of Olkusz (southern Poland near Cracow). *Kras i Speleologia* (Wydawnictwa Uniwersytetu Śląskiego. Katowice.), 5 (14): 11–24.

Motyka, J. & Zuber A., 1993. Parametry szczelin a współczynnik filtracji skał szczelinowatych (The fissure parameters against the coefficient of hydraulic conductivity in fissured rocks). *Współczesne Problemy Hydrogeologii*, Wrocław, 6: 421–425.

Nemčok, J., 1981. *Geologická mapa Pienin, Čergova, Ľubovnianskéj a Ondavskej Vrchoviny w mierke 1: 50 000* (Geological Map of the Pieniny Mts., and the Cergov, Lubovnanska and Ondavska Hills to the scale of 1 : 50 000). Geologický Ústav Dionýza Štúra, Bratislava.

Nemčok, J., ed., 1990. *Vysvetlivky ku geologickéj mape Pienin, Čergova, Ľubovnianskéj a Ondavskej Vrchoviny w mierke 1: 50 000* (Explanations to the geological map of the Pieniny Mts. and the Cergov, Lubovnanska and Ondavska Hills to the scale of 1 : 50 000). Geologický Ústav Dionýza Štúra, Bratislava: 3 pp.

Niedzielski, H., 1965. *Aneks do projektu robót geologicznych dla fazy wstępnej projektu zbiorników: Czorsztyn-Niedzica-Sromowce Wyżne odnośnie ochrony wsi Frydman i Dębno* (Appendix to the project of geological fieldworks of the introductory phase of water reservoirs construction: Czorsztyn-Niedzica-Sromowce Wyżne, concerning the protection of Frydman and Dębno villages). PG i BW "Hydrogeo", Kraków.

Oszczypko, N., 1963. Uwagi na temat występowania źródeł siarkowodorowych w dolinie Dunajca (Remarks concerning the occurrence of hydrogen sulfide springs in the Dunajec Valley). *Przegląd Geologiczny*, 6: 276–278.

Oszczypko, N. & Zuber, A., 2002. Geological and isotopic evidence of diagenetic waters in the Polish Flysch Carpathians. *Geologica Carpathica,* 53: 257–262.

Paczyński, B. (ed), 1999. *Instrukcja opracowania i komputerowej edycji Mapy Hydrogeologicznej Polski w skali 1 : 50 000* (Manual of elaboration and digitalization of the Hydrogeological Map of Poland to the scale of 1:50000). Państwowy Instytut Geologiczny, Warszawa: 93 pp.

Pazdro, Z. & Kozerski, B., 1990. *Hydrogeologia ogólna* (General Hydrogeology). Wydawnictwa. Geologiczne, Warszawa: 624 pp.

Poprawski, L., Józefko I. & Bielec B., 1995. Wody lecznicze uzdrowiska Szczawnica: zmiany wybranych elementów reżimu hydrogeologicznego źródeł (The curative waters of Szczawnica Spa: changes of selected elements of hydrogeological regime of springs). *Współczesne Problemy Hydrogeologii*, Kraków–Krynica, 7: 395–403.

Rajchel, L., Józefko, I., Motyka, J. & Rajchel J., 2003. Zasoby i wykorzystanie wód mineralnych Szczawy, Krościenka i Szczawnicy (Resources and utilization of mineral waters of Szczawa, Krościenka and Szczawnica). *Współczesne Problemy Hydrogeologii*, Gdańsk, 11(2): 43–50.

Szajnocha, W., 1891. *ródła mineralne Galicyi. Pogląd na ich rozpołożenie, skład chemiczny i* *powstawanie* (Mineral springs of Galicya. View on their location, chemical composition and origin). Nakładem Akademii Umiejętności. Skład Główny w księgarni Spółki Wydawniczej Polskiej. Kraków: 111 pp.

Świdziński, H., 1962. *Sur la forme structurale de la Zone des Klippes Piénines des Karpates* (About the structure of the Pieniny Klippen Belt in the Carpatian Mts.). *Bulletin de l'Académie Polonaise des Sciences, Série des sciences géologiques et géographiques*, 10 (3): 133–143.

Watycha, L., 1959. Uwagi o geologii fliszu podhalańskiego we wschodniej części Podhala (Remarks about geology of the Podhale flysch in the eastern part of the Podhale Basin). *Przegląd Geologiczny*, 8 (77): 350–356.

Watycha, L., 1976. *Objaśnienia do szczegółowej mapy geologicznej Polski 1: 50 000 ark. Nowy Targ* (Description to the detailed Geological Map of Poland to the scale of 1:50000; Nowy Targ map sheet). Wydawnictwa Geologiczne. Warszawa.

Zuber, A. & Grabczak J., 1985. Pochodzenie niektórych wód mineralnych Polski południowej w świetle dotychczasowych badań izotopowych (The origin of selected mineral waters of southern Poland in the light of actual isotopic data). *Współczesne Problemy Hydrogeologii*, 3: 136–146.

Żurawska, G., 2002. *Wodonośność utworów polskiej, zachodniej części pienińskiego pasa skałkowego w świetle badań monitoringowych.* Praca doktorska (Water-bearing capacity of the Polish part of the western Pieniny Klippen Belt in the light of monitoring study, Ph. D. Thesis, unpublished). Biblioteka Wydziału Geologii, Uniwersytet Warszawski. Warszawa.