Thermal waters of the Polish part of the Carpathians

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Occurrences of thermal waters, their TDS and chemistry are briefly characterised. When considering usage, the most important are thermal waters occurring in the Podhale Basin due to their high temperature (to 82°C at the surface), yield (to 270 m^3/s — outflow) and low TDS (to 3 g/dm^3). Thermal waters in the Podhale Basin are protected by a complex of low permeable or almost impermeable, flysch rocks.

Key words: *Polish Carpathians, Tatra Mountains, Poland, Podhale, thermal waters, water wells, characterization*

Introduction

The Carpathians have always attracted research interest as a potential groundwater reservoir, however, the literature dealing with thermal waters of this region since the 1960s was very scarce. A dynamic development of investigations on thermal waters in the Carpathians was initiated just in the 1960s (Sokołowski, 1973; Poprawa, 1978; Karnkowski & Jastrząb, 1994; Marszczek & Płochniewski, 1989; Chowaniec & Poprawa, 1985, 1995; Ostrowicka-Chrząstowska & Płonka, 1986; Chowaniec et al., 1997b).

Polish Geological Institute has been participating in the investigations on thermal waters for over thirty years.

Thermal waters are specific groundwaters whose temperature at a spring outlet or at well head outflow is at least 20°C. In Poland thermal waters are known to occur in three major regions of the country: the Polish Lowland, the Sudeten, and the Carpathians.

Thermal waters which might be of economic or balneologic importance have been identified in Podhale region, in Poręba Wielka, in the vicinity of Wiśniowa near Strzyżów, in Jaworze and Ustroń spas (Fig. 1).

General geological characteristics

The Carpathians show an extremely diversified geological structure as to both their litho-facial development and tectonics. With respect to the geological diversity and historical development, the Carpathians are divided into the Outer and Inner (Central) Carpathians, the latter including the Tatras, Podhale Basin, and Pieniny Klippen Belt (Fig. 1). In the Tatras two facial-tectonic series are distinguished: the southern, High-Tatric Series being widely spread and the northern, Sub-Tatric Series extending as a narrow belt along the northern margin of the Tatras. The High-Tatric Series is built of Paleozoic, igneous and metamorphic rocks as well as of Mesozoic sedimentary rocks. The Sub-Tatric Series consists of nappes thrust over the folding High-Tatric Series from the south. This process took place from the Upper Cretaceous to the Middle Eocene. The Sub-Tatric Series is built of sedimentary rocks of the Triassic–Jurassic–Cretaceous age.

The Podhale Basin, located between the Tatras and the Pieniny Klippen Belt, is filled up with Paleogene sandstone-shale deposits of the thickness reaching up to 3,000 m. These deposits rest on the Mesozoic Tatric Units. The bottom, transgressive part of the Paleogene is formed by calcareous rocks developed as conglomerates, nummulite limestones and mudstones.

The Pieniny Klippen Belt, separated from the Podhale Basin (as from the Outer Carpathians) by a dislocation zone is built of calcareous and sandstone-shale Jurassic–Cretaceous–Tertiary rocks. A number of separate tectonic-structural units are distinguished which can be traced along the whole klippen belt.

The Outer Carpathians are built of some tectonic units of the lower order, strongly folded, faulted into blocks and segments and thrust over each other (Fig. 1). These are: the Magura Nappe, Fore-Magura Unit, Dukla–Grybów Unit occurring in tectonic windows of the Magura Nappe, Dukla scales and folds, Silesian Nappe, Sub-Silesian Nappe and

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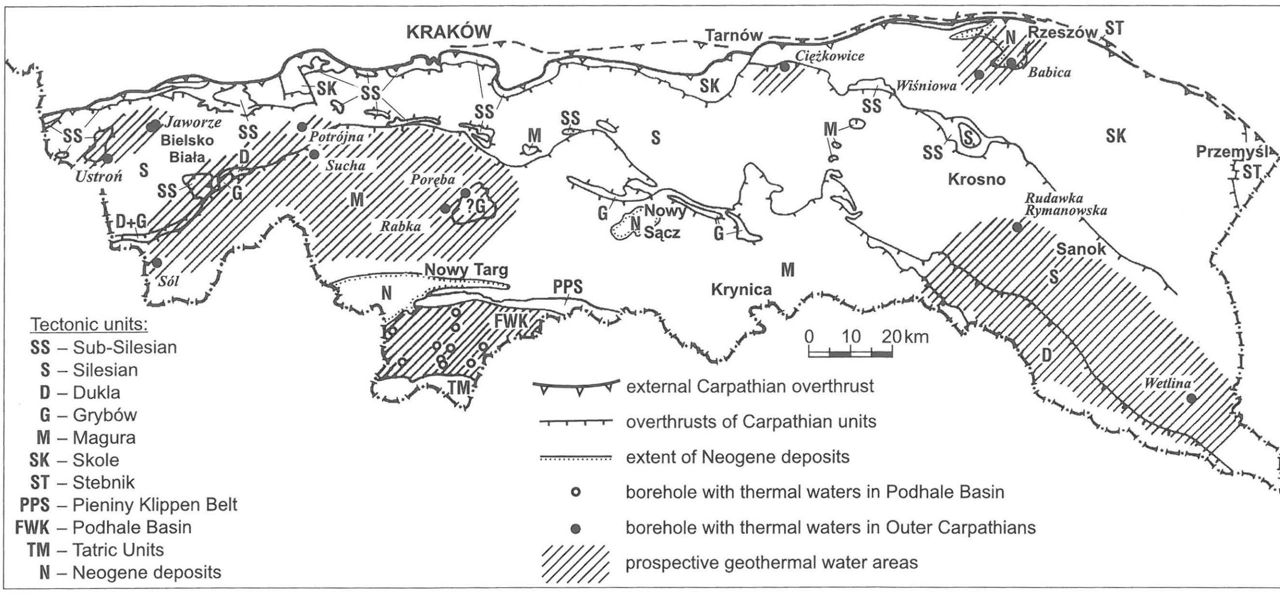

Fig. 1. Tectonic map of the Polish Carpathians and location of geothermal water boreholes

Skole Nappe. Particular units are developed as flysch, sandstone-shale deposits of the Upper Jurassic to the Lower Miocene.

Thermal waters of the Podhale Basin

The Podhale Basin is built of Paleogene deposits underlain by calcareous Mesozoic rocks. A litho-stratigraphic profile of these deposits has been recognized best by boreholes Zakopane IG-1 (Sokołowski, 1973) and Bańska IG-1 (Sokołowski, 1985).

In subsequent years the boreholes which were located as shown in Fig. 2 provided a very advantageous information. Results of the investigations show that the sub-Paleogene substratum is an extension of geological-structural elements of the Tatric massif to which the Sub-Tatric and High-Tatric nappes belong. Moreover, in profiles of some deep drillings out-of-sequence deposits (Sokołowski, 1973; Chowaniec, 1989) as well as the facial elements similar to certain rock types of the Pieniny series were stated. After a retreat of the Upper Cretaceous sea, a subsequent transgression took place in the Middle Eocene that resulted in formation of conglomerates, limestones and dolomites in the initial phase. These deposits form a base member of the Podhale Paleogene. Then typical flysch deposits were formed. Sediments of the calcareous Eocene are know from numerous natural exposures at the outlets of the valleys of the Tatric massif and from the drillings made in the area of the Podhale Basin. Directly on the transgressive deposits of the calcareous Eocene rest the younger stratigraphic beds of the Paleogene — the Podhale flysch. The largest thickness of the latter, ca 3,000 m, was stated in the borehole Chochołów PIG-1. The Szaflary Beds exclusively occurring in the northern part of the basin are generally assigned to the oldest flysch members or units (Chowaniec et al., 1997b, Kępińska, 1997). To the younger members belong: the shale flysch of the Zakopane Beds, regular and sandy flysch of the Chochołów Beds while their age-equivalents in the eastern part of the Podhale — to the beds from Brzegi. The youngest are the Ostrysz Beds forming the culmination of Ostrysz Mt. in the western Podhale. In the Neogene, the Tatric mega-anticline has been formed that caused leaning of the Paleogene deposits from their initial position. Then, an asymmetrical basin, delimited by the Pieniny Klippen Belt in the north and the Tatras in the south, was formed. An uplift of the Tatric massif brought about formation of fissures and cracks, local folds and dislocations (sometimes of a regional extent) which have their sources in the Mesozoic rocks. The most important are faults of Jurgów–Trybsz, Biały and Czarny Dunajec, and Krowiarki (Fig. 2).

Thermal waters in Podhale attracted the interest from the previous mid-century, when Zejszner (1844) discovered the spring of temperature of 20.4°C in Jaszczurówka. This is the only natural discharge of thermal waters in the area of the entire Carpathians.

The first hydrogeological drilling (to the depth of 150.3 m) was located in Jaszczurówka, in a direct neighbourhood of the hot spring and aim at obtaining waters of the temperature exceeding that of the spring. Indeed, at the borehole depth of 20.0 m the temperature of water reached 22.7°C. However, the further drilling led to a decrease in water temperature due to inflow of cool surface waters by a system of fissures. Thermal waters of temperature of 36°C were obtained for the first time in borehole Zakopane IG-1 (Sokołowski, 1973), and then temperatures were 20°C in borehole Siwa Woda IG-1 (Chowaniec & Poprawa, 1985) and 26°C in borehole Zakopane-2 (Małecka, 1981).

New interesting results referring to the occurrence of thermal waters in the Podhale Basin and on their exploitation possibilities were obtained from the investigations performed in five boreholes selected by the Carpathian Branch of the Polish Geological Institute and Podhale Geotermia S.A. at the turn of 1996 (Chowaniec et al., 1997a). The basic hydrogeological parameters obtained during the investigations have been summarized in Tab. 1.

The investigations performed during the pumping tests, determination of the age, temperature and ionic composition of the waters combined with the existing results allowed to determine a number of rules governing the groundwaters of the artesian Podhale Basin. Despite the differences in depths of intakes and in distances from recharge areas, the coefficients of hydraulic conductivity are of similar order of

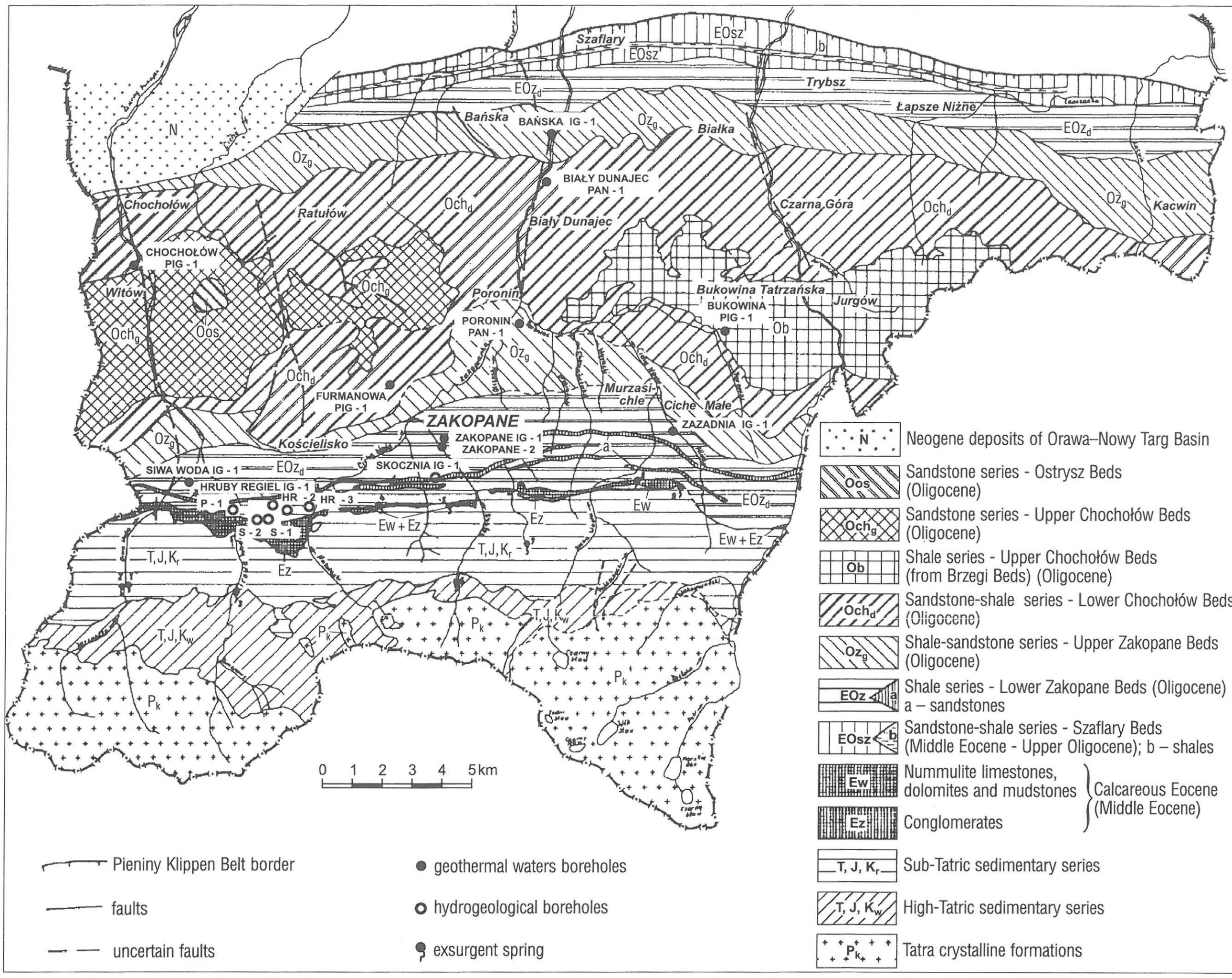

Fig. 2. Geological map of Podhale (without Quaternary deposits) after Chowaniec (1989)

Tab. 1. Results of investigations after acid treatment of the wells

Hydrogeological boreholes	Elevation above sea level	Depth [m]		Well yield Q [m^3/h]	Depression S [m]	Hydraulic conductivity k [m/s]	Permeability K_p [md]
		of the well	to the water table				
Bańska IG-1	679	5261	2565	120	185.0	$2.54x10^{-5}$	1214
Furmanowa PIG-1	1010	2324	2003	96	27.5	$9.94x10^{-6}$	470
Chochołów PIG-1	778	3572	3218	190	150.0	$6.49x10^{-6}$	307
Biały Dunajec PAN-1	685	2394	2117	270	220.0	$1.94x10^{-5}$	911
Poronin PAN-1	741	3003	1768	90	150.0	$8.88x10^{-5}$	4115

magnitude when compared with the boreholes located on Antałówka Mt. ($1 \cdot 10^{-5}$ m/s to $1 \cdot 10^{-6}$ m/s). From the comparison of the yield recorded during the drilling with that obtained during experimental studies is evident that the yields increased 4–8 times. In the case of borehole Biały Dunajec PAN-1 the difference was even much larger and the yield increased from 9 m^3/h to 270 m^3/h. Rationality behind an acid-treatment of the boreholes manifests as well in the increase in water temperature at the outflows. The differences in temperature vary from a dozen to over 30°C (Tab. 2).

Tab. 2. Comparison of water temperatures from the period of drilling and of 1996/1997

Hydrological boreholes	Temperature at the outflow [°C]			
	during drilling		after acid treatment turn of 1996/1997	difference
Furmanowa PIG-1	1990	42.0	60.5	18.5
Chochołów PIG-1	1990	70.0	82.0	12.0
Biały Dunajec PAN-1	1990	49.0	82.0	33.0
Poronin PAN-1	1990	45.0	63.0	18.0

Despite the large differentiation in geothermal gradient of the drilled borehole, one can observe a regularity which is an increase in water temperature with depth.

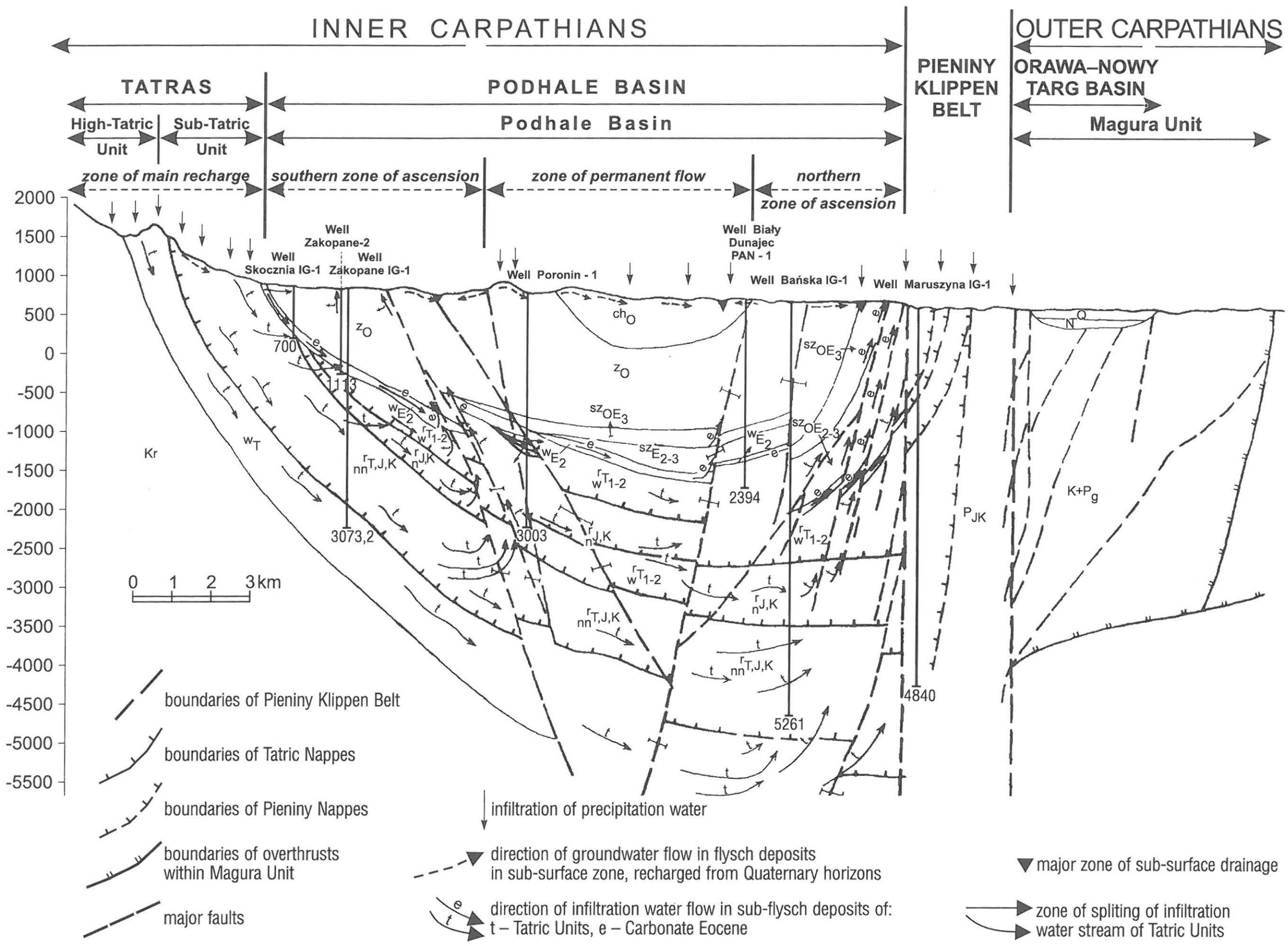

Fig. 3. Scheme of recharge and flow of groundwaters between Zakopane and Biały Dunajec (after Chowaniec, 1989). Q — Quaternary deposits of the Orawa–Nowy Targ Basin, N — Neogene depsoits of the Orawa–Nowy Targ Basin, ^{ch}O — Lower Chochołów Beds (Oligocene), ^{z}O — Lower and Upper Zakopane Beds (Oligocene), $^{sz}OE_3$ — Upper Szaflary Beds (Oligocene–Upper Eocene), $^{sz}E_{2-3}$ — Middle and Upper Szaflary Beds (Upper and Middle Eocene), $^{w}E_2$ — Calcareous Eocene (Middle Eocene), K+Pg — Magura Nappe north of the Pieniny Klippen Belt — scales and folds (Paleogene–Cretaceous), ^{P}J, K — deposits of the Pieniny Klippen Belt (Jurassic, Cretaceous), T_{1-2} — Upper Sub-Tatric Series (Lower and Middle Triassic), $^{r}{}_{n}J$, K — Lower Sub-Tatric Series (Jurassic, Cretaceous), $^{r}{}_{n}T$, J, K — Lowest Sub-Tatric Series (Triassic, Jurassic, Cretaceous), ^{W}T — High-Tatric Series (Triassic), Kr — crystalline formations

Hydrochemical characteristics of thermal waters in the Podhale Basin

The main factors modelling physical-chemical properties of thermal waters of the Podhale Basin are, first of all, circulation conditions and lithology. Waters of meteorite origin, which infiltrate in the area of the Tatric massif, according to the dips of aquifers migrate northward, and due to encountering an impermeable barrier of the deposits of the Pieniny Klippen Belt flow in a fan-like manner to the east and west, outside the state borders (Chowaniec, 1989). Such pattern causes differences in flow velocity which, according to Witczak (*vide* Chowaniec et al., 1997a), is of an order of several dozen m/year in the southern part of the basin and only a few m/year in the near-Pieninian zone. There is also differentiation in the time of contact between water and rocks that is reflected in water chemistry. In the case of Antałówka total dissolved solids do not exceed 400 mg/dm^3, while the waters in the boreholes most remote from the Tatras belong to the low mineralized ones, with TDS differing from more than 1,000 to ca 3,000 mg/dm^3. The studies carried out in 1996/1997 showed a decrease in the total dissolved solids in five of the analysed boreholes. The largest difference has been recorded in borehole Bańska IG-1, where this parameter declined from 3 g/dm^3 to ca 2.5–2.7 g/dm^3. The ionic balance of waters from boreholes Bańska IG-1 and Biały Dunajec PAN-1 shows that during the exploitation as well as during the pulse-interference pumping test that the waters unchangeably belonged to a sulphate-chloride-sodium calcareous type (Chowaniec et al., 1997a).

A decrease in the rate of the water flux from the zone of the active exchange in the southern flank of the Podhale Basin towards the axis of the basin maximum depression is evidenced by an increase in TDS, yet by a steady decrease in hydrocarbons content. Their percentage decreases in the ionic balance starting from Antałówka, via Furmanowa, Poronin to Chochołów (Fig. 3). After pumping the wells both individually and as a system the type of water in the investigated wells have not been changing. Isotope studies point to a relatively young age of the waters in a range of 100–2,000 years, which confirms a high intensity of their exchange in the Podhale Basin. According to Grabczak and Zuber (*vide* Chowaniec et al., 1997a) one may expect the youngest water occur in borehole Furmanowa PIG-1, slightly older in borehole Poronin PAN-1, much older in Chochołów, and the oldest — of the Holocene age — in borehole Bańska IG-1. As it is clear, the water age confirms not only the vertical but also horizontal hydrochemical zonality of waters of the artesian basin of the Podhale (Fig. 3).

When analysing the cross-section of the Podhale Basin (Fig. 3) the zone of ascension of sub-flysch waters and the zone of permanent flow can be distinguished. In the southern part of the Basin the zones of ascension are in the outcrops of the Zakopane Beds while in the northern part — in the Szaflary and Zakopane Beds, at the contact with the Pieniny Klippen Belt. The zone of permanent flow in the sub-flysch aquifer is in the central part of the basin that is built at the surface of the Chochołów Beds.

Thermal waters of the Outer Carpathians

In the area of the Outer Carpathians thermal waters have been stated in the flysch deposits and in the rocks of the substratum.

The thermal water in the flysch deposits have been identified and documented in the following boreholes:

— Sól 5 (yield 18 m^3/h, TDS — 42.57 g/dm^3, well abandoned) in Sól near Żywiec;

— Rabka IG-2 (temperature at the outflow — 28°C) in Rabka;

— Poręba Wielka IG-1 (temperature at the outflow — 42°C) in Poręba Wielka.

Moreover, thermal waters are stated in other wells drilled by petrol industry companies and by Polish Geological Institute, yet the wells have been abandoned. These waters have also been stated in the following regions:

— Sól — well Sól 1 (temperature at the outflow — 24°C, TDS — 44.84 g/dm^3),

— Skomielna Biała — well Skomielna Biała 1 (temperature at the outflow — 38°C, TDS — 11.15 g/dm^3),

— Ciężkowice (temperature at the outflow — 32°C, TDS — 25.0 g/dm^3),

— Rudawka Rymanowska — well Rudawka Rymanowska 19 (temperature at the outflow — 40°C, TDS — 6.67 g/dm^3),

— Lubatówka — wells: Lubatówka 12 and Lubatówka 14 (outflow temperatures 23.5°C, 24.4°C, TDS — 2.4 g/dm^3, discharge 0.4 m^3/h),

— Polańczyk — well Polańczyk IG-1 (temperature at the outflow — 21°C, TDS — 2.4 g/dm^3, discharge 0.4 m^3/h),

— Babica — well Babica 1 (temperature at the outflow — 43°C, TDS — 9.4 g/dm^3, discharge 0.04 m^3/h),

— Brzegi Dolne — well Brzegi Dolne IG-1 (temperature at the outflow — 105°C in the deposits at the depth of 4,300.0 m, TDS — 121.4 g/dm^3),

— Wetlina — well Wetlina IG-2 (temperature at the outflow — 34°C, TDS — 56.0 g/dm^3, discharge 0.53 m^3/h).

Recently, thermal waters have been drilled in well Wiśniowa 1 in Wiśniowa village near Strzyżów. The characteristics of these waters are: temperature at the outflow — 84°C and TDS ca 7 g/dm^3.

In the substratum of the Carpathians, the thermal waters were stated in Ustroń (Ustroń IG-3 — 27.5°C, Ustroń 3a — 32°C), and lately in a sink hole in Jaworze (Jaworze IG-1 — 23°C, Jaworze IG-2 — 32°C), Sucha Beskidzka (Sucha IG-1 — 28°C, discharge 0.56 m^3/h) and in Potrójna (Potrójna IG-1 — 22°C). The temperatures given above were measured at the outflows. Thermal waters in the substratum of the Carpathians occur in the Devonian and Miocene deposits.

A decisive factor about temperature of groundwater is a geothermal gradient defined as a ratio of an increase in temperature to a unit of depth. It is commonly accepted that the mean geothermal gradient for the globe is 3°C per 100 m (Dowgiałło, 1972). The magnitude of the gradient varies and depends of the terrestrial heat flow. The mean geothermal gradient in the Carpathians is 2.35°C per 100 m (Plewa, 1994). In the regions where thermal waters occur in the Carpathians, the values of the geothermal gradient are higher Ostrowicka-Chrząstowska & Płonka, 1984). In the eastern part of the Polish Carpathians (Rudawka Rymanowska, Biała Woda) the gradient is higher than the average and reaches 2.33°C per 100 m which might be associated with deep tectonic deformations. The increase in the values of the gradient is also observed in westward direction: from 2.3°C per 100 m in the region of Rabka and Poręba Wielka to 3.1°C per 100 m in the region of Sól and Ustroń.

The mean geothermal gradient of the Podhale Basin and its basement is lower when compared with other Carpathian regions and differs from 1.9 to 2.1°C per 100 m (Plewa, 1994, Kępińska, 1997). The terrestrial heat flow in the case of borehole Zakopane IG-1 has been determined at 55.6 mW/m^{-2}, and borehole Bańska IG-1 — 60.2mW/m^2 (Kępińska, 1997). The thermal parameters of rocks of the Podhale flysch, Outer Carpathian flysch (sandstones and shales) as well as of the Mezosoic rocks vary in a wide range and are strongly dependent on their lithological variety (Plewa, 1994).

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