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# PROSPECTIVE ZONE OF THERMAL WATER OCCURRENCE IN THE AREA OF THE ORLICA-ŚNIEŻNIK DOME

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**Abstract:** The paper describes a prospective area of thermal water occurrence linked to the strike of a deep tectonic fracture within the Orlica-Śnieżnik dome. The indicated area contains $CO_2$-rich waters, carbonated waters and thermal waters with mean temperatures oscillating from 10.3°C to 35.0°C. The TDS content in these waters oscillates from 0.8 to 11.5 g/L. The mean intake discharge varies from 1.67 $m^3$/h to 36.3 $m^3$/h. The conducted research demonstrated a correlation between discharge variation, water temperature and the $HCO_3^-$ ion content in Duszniki-Zdrój intakes. Based on an analysis of the physico-chemical properties of the discussed waters, an attempt was made to estimate deposit temperatures by using chemical geothermometers. The obtained results were corrected by including the results of water saturation variability analysis in relation to rock medium. The probable temperatures of the analysed waters in particular deposits fall within the range of 71°C to 140°C.

***Keywords*:** *thermal water, tectonic deep fracture, Orlica-Śnieżnik dome, Sudety Mts*

## 1. INTRODUCTION

The least studied conditions of thermal water occurrence in Poland are these in the Sudetes, including the area of the Orlica-Śnieżnik dome. This is due to the varied (mosaic-like) geological structure, as well as a small number of regional-scale field hydrogeological surveys. Locally, only thermal medicinal water deposits in Cieplice-Jelenia Góra and Lądek-Zdrój have been studied more thoroughly. In Poland thermal waters

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are types of water deposits which are classified as minerals according to geological and mining laws (GML, 2011).

The occurrence of thermal waters in the Sudetic province is related to the strike of regional faults, often consistent with the strike of photolineaments (Doktór et al. 1987), which might also indicate the strike of deep tectonic fractures. A synthetic overview of the network of deep fractures in the Sudetes and the adjacent part of the Bohemian massif was proposed by M. Michniewicz (1981) and later supplemented with corrections of the strike of the Karkonosze fracture (Przylibski ed. 2007).

## 2. GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

The central Sudetes comprise the Orlica-Śnieżnik dome intersected by the upper Nysa Kłodzka trough. To the west of the Nysa trough, metamorphic rocks build the Orlica-Bystrzyca metamorphic complex. It is generally dominated by two Proterozoic rock complexes: mica schists with transitions to paragneisses, and structurally diverse gneisses and granite-gneisses (Fig. 1).

The Lądek-Śnieżnik metamorphic complex, delimiting the upper Nysa trough in the north-east, is a tectonic unit built of two rock formations: the Stronie series and the Gierałtów-Śnieżnik series. The former one is made up chiefly of mica schists, quartzites and crystalline limestones. The latter consists of two varieties of gneiss: Śnieżnik gneisses and Gieraltow gneisses.

The upper Nysa Kłodzka trough is a unit filled with Upper Cretaceous (Cenomanian, Turonian and Coniacian) sediments. These are chiefly mutually interbedding sediments of the sand facies, marls, mudstones and claystones (Radwański, 1975). In a regional view, the upper Nysa Kłodzka trough is sometimes described as an integral part of the Intra-Sudetic Basin (Oberc 1972).

Neogene and Paleogene sediments in the discussed area take the form of varved clays occurring west of Kłodzko (Kiełczawa 2001a) and in the vicinity of Ścinawka and Lądek (Oberc and Dyjor 1968).

Pleistocene and Holocene deposits take the form of a discontinuous sediment cover of glacial, fluvioglacial, fluvial, slope and aeolian origin.

Two fracture systems have been identified in the Sudetic province: one with a NW–SE strike and the other – with a NNE–SSW (Fig. 1) strike. These are:

1) The Buszyn fracture zone (BF), whose small fragment crosses the southern part of the upper Nysa Kłodzka trough;
2) The Karkonosze fracture zone (KRF), partially crossing the southern boundary of the Sudetic province. The latter runs across the Turoszów depression, then crosses Janské Lazně and Batňovice to re-enter the Polish territory in the Kudowa depression, progresses via Duszniki-Zdrój and Gorzanow, then assumes a more latitudinal strike and as a presumed zone crosses Lądek-Zdrój and runs

as far as Prudnik. Thermal water and carbon dioxide occurrences observed along this fracture zone are the evidence of its depth and regional scale (Bażyński et al. 1981; Fistek 1977; Kiełczawa 2001a).

In the hydrogeological division of Poland, the discussed area is a part of the Sudetic province and the Wałbrzych-Kłodzko subregion (Paczyński and Płochniewski 1996).

The conditions of thermal and $CO_2$-rich water occurrence, described by a number of authors including Fistek (1977; 1989), Ciężkowski (1990), Dowgiałło (2001), Dowgiałło and Fistek (2007), and Liber (2001), confirm the fact that these are tectonic zones which are the principal paths bringing these waters and the accompanying carbon dioxide from large depths to the surface.

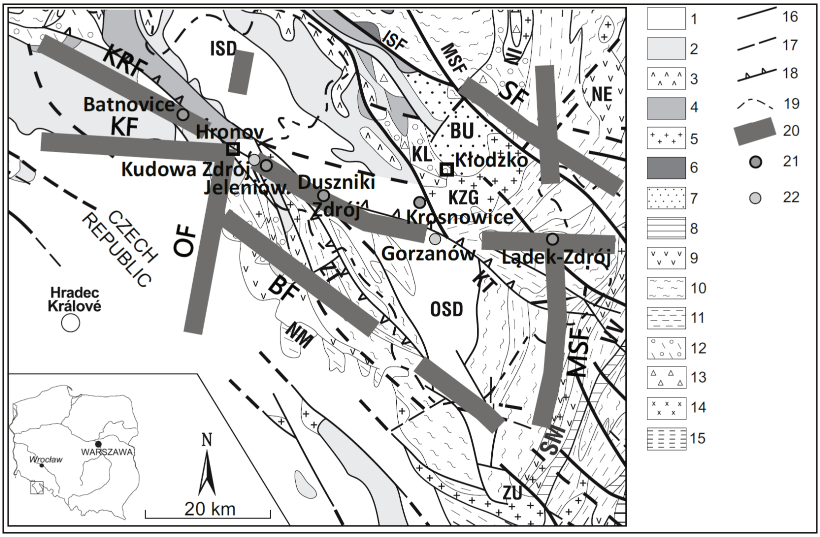


Fig. 1. Simplified geological map of the Sudetes and Fore-Sudetic Block with indication of the main geological units (based on Cymerman 2016; Przylibski et al. 2007). Explanations: 1 – Guadalupian-Mesozoic deposits, 2 – Cisuralian sedimentary rocks, 3 – Cisuralian volcanic rocks, 4 – Pennsylvanian sedimentary rocks, 5 – Variscan granitoids, 6 – Mississippian sedimentary rocks, 7 – Upper Devonian-Mississippian deposits, 8 – Devonian metasediments, 9 – metabasic rocks, mainly greenstones, 10 – orthogneisses and migmatites, 11 – mica schists and paragneisses, 12 – phyllite and slates, 13 – ophiolitic rocks, 14 – Cadomian granitoids, 15 – Neoproterozoic sedimentary rocks, 16 – main Alpine faults, 17 – presumed Alpine thrusts, 18 – main Alpine thrusts, 19 – state boundaries, 20 – deep fracures, 21 – thermal waters, 22 – potentially thermal waters; Domes: OSD – Orlica-Śnieżnik; granitoid massive: KZG – Kłodzko-Złoty Stok; sedymentary basins: BU – Bardo, ISD – Intrasudetic; other units: KL – Kłodzko complex, NE – Niedźwiedź amphibolites, NI – Niemcza shear zone, NM – Nové Město Belt, SM – Staré Město Unit, VV – Velké Vrbno Unit, ZU – Zábřeh Unit; fracture zones: KRF – Karkonosze, KF – Klatov, OF – Orlica, BF – Buszyn, MSF – Moravia-Silesia, SF – Sudety; faults: ISF – Intrasudetic Fault, KT – Krosnowic Thrust, MSF – Marginal Sudetic Fault, ZT – Zieleniec Thrust

The zones that are particularly predisposed for thermal water outflow could be regional tectonic fracture zones enabling deep circulation of these waters and heat migration from a rock medium with a higher temperature.

## 3. THERMAL AND POTENTIALLY THERMAL WATER DEPOSITS

The Orlica-Śnieżnik dome comprises a distinctive tectonic zone with a NW–SE strike, being the eastern part of the Karkonosze fracture (KRF). The strike of this part of the fracture is consistent with the strike of the Hronov-Gorzanow fault accompanied by the Krosnowice overthrust (Cymerman, 2016). This fault is one of the most important dislocations cutting through Cretaceous deposits within the upper Nysa trough (Kiełczawa 2005). The tectonic zones of the studied area are consistent with the strike of satellite photolineaments (Doktór et al. 1990).

The Karkonosze fracture extends into the Czech territory, where, in the area of Hronov, it branches into a northern part running towards the Karkonosze (NW–SE) and a southern one – the Kozákov-Hronov (klatovski – KF) fracture (W–E) (Michniewicz 1981; Fistek 1977; Jetel and Rybarova 1979; Przylibski et al. 2007).

Within the discussed fracture, medicinal waters are found in Batňovice, Kudowa-Zdrój and Jeleniów, Duszniki-Zdrój and Gorzanów (thermal waters in Batňovice, Jeleniów and Duszniki), and waters with increased temperatures – in Krosnowice.

The dominant type of water in the discussed zone are carbonated waters and $CO_2$-rich waters with a varied complex of principal cations, with the prevalence of calcium--sodium $CO_2$-rich waters (the deposits in Gorzanów and partially – Duszniki-Zdrój and Jeleniów). Sodium-calcium $CO_2$-rich waters prevail in Kudowa-Zdrój. In Duszniki and Jeleniów there are also calcium-magnesium $CO_2$-rich waters. Carbonated waters from Batňovice represent a different sodium-sulphate-chloride type (Table 1).

In **Batňovice**, Ba-1 well captures thermal waters from Proterozoic crystalline bedrock c. 1 km west of the Hronov-Gorzanów fault. The borehole is 1324 metres deep. Immediately after its execution (in 1966), at the depth of 1142 m waters of Na-Cl-$SO_4$ type, with a temperature of 45°C, c. 22.3 g/L of dry residue and c. 1 g/L of dissolved $CO_2$ were obtained. The temperature at the bottom of the well was 58°C. Currently, Na-$SO_4$-Cl waters with a temperature of 24.4°C (Table 1) and ca. 11.5 g/L of dry residue with increased concentrations of iron ions (18.8 mg/L) are extracted from the depth of 1250–1280 m (Krásný et al., 2012).

Medicinal waters in **Kudowa-Zdrój** and Jeleniow are related to Upper-Cretaceous sedimentary rocks of Kudowa depression. These are waters of infiltration origin, saturated with $CO_2$ in dislocation zones (Fistek et al. 1987). The $CO_2$-rich waters from Kudowa-Zdrój are related to similar waters in Bohemia, where the Kudowa depression turns into the Hronov trough where outflows of mineral waters and $CO_2$-rich waters have been discovered. In Kudowa-Zdrój, medicinal waters are captured in seven boreholes and two springs. These waters are currently extracted from a shallow (4 metre--deep) well Górne and two boreholes: Moniuszko (No. 2) and K-200, with the depths of 23.4 m and 192 m., respectively. The Gorne and K-200 intakes are flowing wells, and water is pumped from well No. 2. The extracted medicinal waters are $CO_2$-rich Na-Ca-$HCO_3$, Fe, F waters with TDS levels from 1.3 to 3.3 g/L (Table 1) and mean $CO_2$ content oscillating in the range of 2.1–2.3 g/L.

In **Jeleniów**, situated c. 3 km south-east of Kudowa-Zdrój, $CO_2$-rich Ca-Na-$HCO_3$, Rn waters with 1.4 g/L of TDS and 2.1 g/L of $CO_2$ are extracted. Currently, $CO_2$-rich waters are extracted from borehole J-150a, which in 2018 replaced the previously used well J-150 (Table 2). In Jeleniów there is also an unused P-5 well with the depth of 133 m drilled in 1982. The captured $CO_2$-rich Ca-Na-$HCO_3$ water (at the depth of 127–133 m) is characterised by TDS content of c. 2.3 g/L and outflow temperature of 20.2°C. Moreover, the water contains 1.9 g/L of dissolved $CO_2$ (Fistek et al. 1987; Dowgiałło 2001; Ciężkowski et al. 2011; 2016; Kiełczawa et al. 2018b).

Table 1. Characteristics of thermal and potentially thermal medicinal water deposits

| Water deposit | Type of rock (age) | Depth of intake /intakes | Admissible volume or discharge* | Water temperature | Type of water |
|---|---|---|---|---|---|
| | | m | $m^3/h$ | °C | |
| Batňovice | chlorite and mica schists, granitoids (Proterozoic) | 1324.0 | 1.19* | 24.4 | carbonated water Na--$SO_4$-Cl, Fe, F |
| Kudowa--Zdrój | sandstones and marls (Upper Cretaceous) | 4.0–192.0 | 2.5–6.0 | 13.9–14.5 | carbonated water Na-Ca-$HCO_3$, Fe, F |
| Jeleniów | mudstones and marls (Upper Cretaceous) | 63.7–133.0 | 5.8–11.4 | 12.2–20.2 | carbonated and $CO_2$-rich waters Ca-Na (-Mg)-$HCO_3$, Rn, (Fe) |
| Duszniki--Zdrój | mica schists, gneisses (Proterozoic) | 78.0–1695.0 | 15.8–39.0 | 15.8–35.0 | $CO_2$-rich waters Ca-Mg--$HCO_3$, Fe, $CO_2$, Ca-Na--$HCO_3$, Ca-Na-(Mg)--$HCO_3$, Fe, Rn |
| Gorzanów | sandstones and marls (Upper Cretaceous) | 25.0–275.5 | 2.81–36.30* | 10.3–15.6 | carbonated and $CO_2$-rich waters Ca-$HCO_3$, Ca-Na-$HCO_3$, Fe |
| Krosnowice | sandstones (Upper Cretaceous) | 525.0 | 4.0 | 22.0 | carbonated waters Na(-Ca)-$HCO_3$, F, $CO_2$ |

The medicinal waters of **Duszniki-Zdrój** are $CO_2$-rich waters representing the Ca-Mg-$HCO_3$, Ca-Na-$HCO_3$, Ca-Na-(Mg)-$HCO_3$, Fe, Rn type with TDS content of 0.8–3.5 g/L (Table 1) and carbon dioxide content of 1.6 g/L. These are fissure waters of infiltration origin, whose outflow is related to a dislocation zone (Dowgiałło and Fistek 2007; Paczyński and Płochniewski 1996). Apart from $CO_2$-saturated waters, natural exhalations of this gas are observed. Currently, waters from three boreholes: Pieniawa Chopina, Jan Kazimierz and No. 39 (with depths of 78 m, 162 m and 180 m, respectively) are exploited. They are extracted from flowing wells (Table 2). In 2000–2001, a 1695-metre borehole GT-1 was drilled. It captured two horizons of thermal waters. One of them yielded waters with an outflow temperature of 29°C and chemical type Ca-Na-Mg-$HCO_3$, containing c. 3.2 g/L of TDS and c. 2.2 g/L of $CO_2$, with increased $Fe^{2+}$ ion and metasilicic acid content. The waters of the lower horizon, with an outflow temperature of 34.7°C, are characterized by TDS levels of 3.3–3.5 g/L and the Ca-Mg-$HCO_3$ type, with increased ferrous ion concentrations (Table 2). The temperature at the bottom of the borehole was 55.8°C (Dowgiałło and Fistek 2003; 2007). The thermal waters from borehole GT-1 are not used.

Table 2. Characteristics of intake discharge and temperature changes in thermal waters and potentially thermal medicinal waters

| Water intake | Observation period | Number of measurements | Discharge $m^3/h$ | | | Water temperature °C | | |
|---|---|---|---|---|---|---|---|---|
| | | | Min. | Average | Max. | Min. | Average | Max. |
| Kudowa-Zdrój | | | | | | | | |
| Górne | 2002–2020 | 874 | 1.50 | 3.43 | 6.18 | 8.6 | 12.0 | 13.9 |
| Moniuszko | 1993–2020 | 1316 | – | –* | – | 10.6 | 12.5 | 14.7 |
| K-200 | 1993–2020 | 1322 | 0.06 | 1.67 | 3.90 | 9.3 | 12.8 | 14.5 |
| Jeleniów | | | | | | | | |
| J-150 | 1993–2020 | 1065 | 0.0 | 5.75 | 55.0 | 11.0 | 12.2 | 14.5 |
| J-150a | 2018–2020 | 153 | – | –* | – | 12.0 | 12.3 | 13.0 |
| Duszniki-Zdrój | | | | | | | | |
| Pieniawa Chopina | 1976–2020 | 2192 | 2.90 | 18.01 | 28.00 | 17.1 | 18.2 | 21.6 |
| Jan Kazimierz | 1975–2020 | 2068 | 2.90 | 4.18 | 6.40 | 15.8 | 17.0 | 18.0 |
| 39 | 1996–2020 | 1272 | 5.60 | 11.33 | 13.20 | 17.1 | 18.1 | 19.5 |
| Gorzanów | | | | | | | | |
| No. 1 Kaczka | 1998–2000 | 47 | 11.25 | 16.15 | 18.00 | 8.9 | 10.3 | 11.5 |
| No. 5 bottom level | 1970–1973 | 167 | 29.82 | 36.30 | 42.30 | 9.3 | 14.1 | 15.8 |
| | 1974–1981 | 451 | 26.70 | 31.80 | 31.80 | 12.5 | 14.0 | 15.0 |
| No. 5 top level | 1970–1973 | 166 | 18.00 | 22.62 | 32.70 | 9.0 | 12.6 | 14.5 |
| | 1998–2000 | 47 | – | –* | – | 10.0 | 11.4 | 13.1 |
| No. 5 combined levels | 1974–1976 | 23 | 12.30 | 14.07 | 16.86 | 12.5 | 13.2 | 13.5 |
| No. 6 | 1998–2000 | 45 | 2.52 | 2.81 | 3.38 | 12.5 | 14.1 | 15.4 |

* No possibility of performing discharge measurements.

In **Gorzanów**, there are currently 12 intakes of carbonated and $CO_2$-rich waters representing the chemical type Na(-Ca)-$HCO_3$. The deepest of them are intakes No. 5 and No. 6 (with respective depths of 270 m and 165.5 m). Three water-bearing zones of artesian character with considerable discharges were accessed. Eventually, waters of the upper horizon, found in Upper-Cretaceous marls and sandstones, were captured for exploitation. The waters from the discussed deposit are characterised by TDS levels in the range of 0.4–1.7 g/L and the maximum $CO_2$ content of c. 1.3 g/L. The highest water temperature at the outflow was 15.8°C (Table 2) (Kiełczawa 2001a; 2001b; Kiełczawa et al. 2018a).

In the 1990s, a 525 m-deep borehole was executed in **Krosnowice**. The borehole accessed two water-bearing horizons, and the one within Turonian sandstones was captured (at the depth of 420 m). It yielded carbonated waters (with $CO_2$ content of c. 0.3 g/L) of Na(-Ca)-$HCO_3$ type, characterized by an increased fluoride ion content (1.6 mg/L) and outflow temperature of 22°C. Their TDS content is 1.6 g/L (Dowgiałło and Fistek 2007). The static water table is stabilized at c. 10 m above the ground level (Table 1). The temperature at the bottom of the borehole was 27.8°C. The borehole is not operated currently (Kiełczawa et al. 2018b).

### 3.1. VARIATIONS IN MAIN DEPOSIT PARAMETERS

In order to determine the character and the range of changes in selected deposit parameters of the discussed water deposits, the results of monitoring carried out by the health resort geological services were used.

The discharges of flowing wells Gorne and K-200 in Kudowa-Zdrój, capturing medicinal waters, has varied from 1.5 to 6.18 $m^3$/h, and from 0.6 to 3.9 $m^3$/h, respectively, within the last 20 years. The evident considerable changeability of this parameter is linked to difficult technical conditions of discharge measurements in these intakes.

Also, the discharge of J-150 well in Jeleniów varies from lack of artesian flow to 55 $m^3$/h. Periodical disappearance of artesian flow is related to strong interaction with a new borehole, J-150a, from which water is pumped. This is the reason why reserves of 11.4 $m^3$/h were approved jointly for the double-well intake (Table 1).

The mean temperature of water flowing out of Kudowa and Jeleniow intakes is higher than the mean annual air temperature and ranges from 11.8 to 12.8°C. The maximum water temperature of 14,7°C was recorded in Moniuszko well (Table 2). Owing to variable discharge measurement conditions in Kudowa-Zdroj and Jeleniow intakes, it is impossible to precisely link the outflow dynamics with water temperature and/or measured qualitative parameters such as $HCO_3^-$ ion and $CO_2$ content. In 2020, the total mean discharge of operated intakes Gorne, Moniuszko, K-200, and J-150 was 9.85 $m^3$/h. The total water abstraction for medicinal purposes and bottling (industrial reserves) amounted to 1.9 m3/h, which is a small fraction of the determined safe yield (medicinal water resources from the balance area that may be extracted).

The occurrence of gasified medicinal waters with increased temperatures in the area of Kudowa-Zdrój, including an outflow of thermal $CO_2$-rich waters in Jeleniow, as well as a possibility of obtaining considerable exploitable reserves and safe yield point to the possible occurrence of larger quantities of thermal waters in this area.

The discharges of operated medicinal water intakes in Duszniki-Zdrój in the last few decades have been very changeable (Table 2). The discharges of wells Pieniawa Chopina, Jan Kazimierz and 39 have oscillated from 2.9 to 29 $m^3$/h, from 2.9 to 6.4 $m^3$/h and from 5.6 to 13.2 $m^3$/h, respectively. Discharge fluctuations are characteristic of intakes yielding considerable amounts of carbon dioxide, whose artesian flow is of pulsating nature. Additionally, carbon dioxide is obtained by being abstracted from the operated wells.

In 2020, the total mean discharge of the three operated intakes in Duszniki was 28.56 $m^3$/h, only 0.36 $m^3$/h of which was used for medicinal purposes. The average temperature of waters from the operated intakes varies from 17.0 to 18.2°C. The maximum water temperature at the outflow from Pieniawa Chopina well is 21.6°C. This is the highest temperature of $CO_2$-rich waters extracted in this area. In 2011, during deposit surveys, artesian flow from Pieniawa Chopina intake was reduced by 25%, 50% and 75%. At that time, apart from measuring discharge, changes in water temperature and $HCO_3^-$ ion and $CO_2$ content were measured. The surveys demonstrated that reduced discharge coincided with an almost simultaneous rise in water temperature and $HCO_3^-$ ion concentration (Fig. 2), while no significant changes in $CO_2$ content in water were observed.

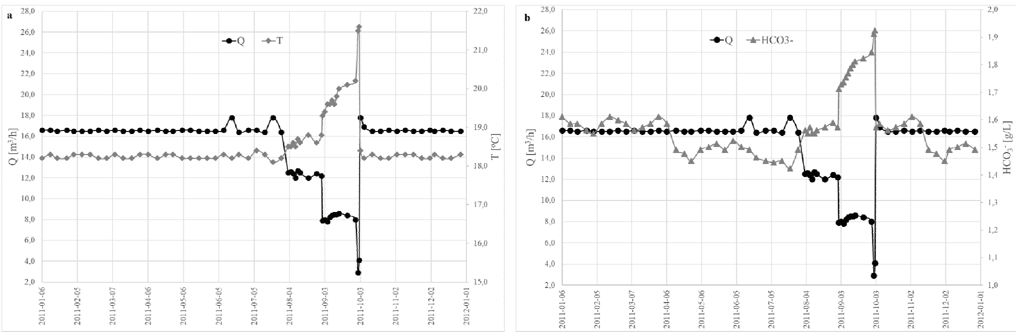


Fig. 2. Discharge changes in Pieniawa Chopina intake accompanied by changes in:
a – water temperature, b – $HCO_3^-$ ion content

To confirm the observed relationships, the authors calculated a (statistically significant) correlation coefficient of –0.94 for the relationship between discharge and water temperature, and –0.87 defining the relation between discharge and $HCO_3^-$ ion content. The observed relationships confirmed by the conducted correlation analysis demonstrate that outflow of deeper circulation waters (with a higher $HCO_3^-$ ion content) is related to an increase in water temperature, which indicates a possibility of obtaining waters with much higher temperatures than these currently observed.

The calculated mean, minimum and maximum values of intake discharge and the temperatures of $CO_2$-rich waters and carbonated waters in Gorzanow are listed in Table 2. The measurements on which the calculations of characteristic values were based had been conducted during trial extraction in the 1970s, and then repeated by the author in 1998–2000 (Kiełczawa 2001b). Because of lack of longer observations over time, it is not possible to correlate dynamic discharge variation with temperature changes. The calculated mean discharges of intakes oscillating from 2.8 to 36.3 $m^3/h$ indicate a possibility of obtaining large amounts of water. The average water temperature varies from 10.3 to 14.1°C. The maximum temperature of 15.8°C measured at the outflow from the lower horizon in well No. 5 could indicate possible thermal water occurrence in this area.

### 3.2. ESTIMATING DEPOSIT TEMPERATURES

Based on the physicochemical properties of the discussed waters, an attempt was made to estimate deposit temperatures by using chemical geothermometers.

Temperature estimations for the studied deposits were based on the results of physicochemical property analyses described in literature and archival reports, and the results of such analyses gathered by health-resort geological services. Data on intakes capturing waters from the deepest horizons at particular sites were used.

So far, a large number of equations have been proposed (e.g., by Arnórsson 1983; 2000; Fournier and Truesdell 1973; Giggenbach 1988; Tonani 1980) for calculating deposit temperatures on the basis of chemical and isotopic composition of waters and gases. The estimated deposit temperature is not always the temperature of a deep reservoir of geothermal waters as geothermometers register the temperature of the recent equilibrium with a solution (Nicholson 1993). Hence, they indicate the temperature of the parent water-logged zone (horizon), where such an equilibrium was reached (Arnórsson 2000).

For waters with less than 50 ppm silica in their chemical composition (e.g., in Duszniki $SiO_2$ concentrations are c. 97 mg/L), temperatures estimated with quartz geothermometer do not exceed 100°C (Arnórsson 2000). This is visible in deposits in Batňovice and Gorzanów, for which the $t_{Ch1}$ and $t_{Ch2}$ are close to the temperatures recorded at water outflows. Where the estimated temperatures do not exceed 180°C, Arnórsson (2000) suggests regarding the results from chalcedony geothermometers as more reliable. Thus, in the case of Duszniki, one should assume that the temperature of the system does not exceed 107°C–109°C (Table 3).

In the case of bicarbonate waters, one should be cautious with estimation results obtained with a Na-K-Ca geothermometer because of the role of $CO_2$ in forming the composition of these waters, secondary calcite precipitation and mixing with shallow system waters. Moreover, in low-temperature (<200°C) systems, thermal waters reach equilibrium either with sodium or with potassium feldspar. According to Li et al. (2019), this explains why the Na-K thermometer does not generally ensure accurate temperature estimations in low-temperature systems which we encounter in Batňovice, Jeleniów or Gorzanów (Table 3). Similarly, Nicholson (1993) argues that the Na-K thermometer is rather unsuitable in systems with temperatures below 120°C, but it provides good estimates in systems with temperatures in the range 180–350°C. Given that all the studied deposits contain waters characterized by a considerable proportion of sodium ions in their chemical composition, one should be cautious when adopting the temperatures $t_{Na\text{-}K}$ and $t_{Na\text{-}K\text{-}Ca}$ (Table 3). Special attention should be given to the results obtained for the waters from Gorzanów (137–143°C) and Duszniki-Zdrój (283–73°C), which are undoubtedly considerably overestimated.

Table 3. Overview of estimated reservoirs temperatures

| Water deposit | Estimated reservoirs temperatures (°C) | | | | | |
|---|---|---|---|---|---|---|
| | $t_Q$ | $t_{Ch1}$ | $t_{Ch2}$ | $t_{Na\text{-}K}$ | $t_{Na\text{-}K\text{-}Ca}$ | $t_{SI}$ (based on SI*) |
| Batňovice | 79 | 48 | 51 | 59 | 141 | 71 |
| Jeleniów | 91 | 61 | 63 | 41 | 97 | 82 |
| Kudowa-Zdrój | 87 | 56 | 58 | 97 | 140 | 123 |
| Duszniki-Zdrój | 135 | 109 | 107 | 373 | 283 | 141 |
| Gorzanów | 45 | 13 | 17 | 137 | 143 | 94 |

* SI – saturation index for particular minerals depending on solution temperature. $t_Q$ – temperature estimated with a quartz geothermometer (Fournier 1977): $T = [1309/(5.19 - \log SiO_{2(aq)})] - 273.15$ ($SiO_{2(aq)}$ concentration in mg/l); $t_{Ch1}$ – temperature estimated with a chalcedony geothermometer (Fournier 1977): $T = [1032/(4.9 - \log SiO_{2(aq)})] - 273.15$ ($SiO_{2(aq)}$ concentration in mg/l); $t_{Ch2}$ – temperature estimated with a chalcedony geothermometer (Arnórsson et al. 1983): $T = [1112/(4.91 - \log SiO_{2(aq)})] - 273.15$ ($SiO_{2(aq)}$ concentration in mg/l); $t_{Na\text{-}K}$ – temperature estimated with a Na-K geothermometer (Arnórsson et al. 1983): $T = \{933/[0.993 + \log(Na/K)]\} - 273.15$ (Na and K concentrations in mol/kg$H_2O$); $t_{Na\text{-}K\text{-}Ca}$ – temperature estimated with a Na-K-Ca geothermometer (Fournier and Truesdell 1973): $T = \{1647/[\log(Na/K) + ß\log(Ca^{1/2}/Na) + 2.24]\} - 273.15$ (Na, K and Ca concentrations in mol/kg$H_2O$).

In the case when thermal waters do not reach full chemical equilibrium with minerals of the water-bearing medium or when the concentrations of principal cations are not controlled by dissolution of feldspars or clay minerals, more reliable estimates of deposit temperatures are obtained by analysing variations in water saturation indices (SI) depending on changing temperatures. This method was discussed in detail by Reed and Spycher (1984), Pang and Reed (1998), and Spycher et al. (2014).

In order to determine the temperatures of the studied deposits, an application of GeoT software was used (Spycher et al. 2016a). The conducted simulations are discussed below, using an example of the thermal water in Duszniki-Zdrój (Fig. 3).

The authors assumed that the results obtained in this way will best reflect deep deposit conditions. A wide range of rock-forming minerals were chosen for the simulation, the most important being low albite, anorthite, calcite, Ca-beidellite, Mg-beidellite, chalcedony, fluorite, kaolinite, microcline, muscovite, phlogopite, quartz and talc. Due to a very low concentration of $Al^{3+}$ ions, in order to offset the influence of re-equilibration resulting from water cooling, constant supply of these ions was secured, assuming solution equilibrium with microcline or talc (Spycher et al. 2016b). Moreover, given that all the analysed waters contain dissolved $CO_2$, one should expect this gas to determine the pH of these waters, which undoubtedly contributes to changes in the solution-rock medium equilibrium. As waters are degassed along the path of their underground flow, the pH of water measured directly in the field ($pH_{field}$) is usually lower than the pH determined in laboratory conditions ($pH_{lab}$ – 6.7). The $pH_{field}$ can be estimated by analysing the solution's equilibrium with calcite at the temperature of water at the outflow. In the case of Duszniki-Zdrój waters, the determined $pH_{field}$ (5.8) indicates the degassing of waters from this intake. The corrected pH value was used in successive simulation steps. The obtained results (Fig. 3) suggest that in such temperature conditions the system is closest to chemical equilibrium with the rock medium, so it can be assumed that the area of Duszniki Zdrój contains deep circulation thermal waters with a temperature of c. 140°C (±15°C). This value is close to the temperatures obtained with the use of a classic quartz geothermometer (Table 3).

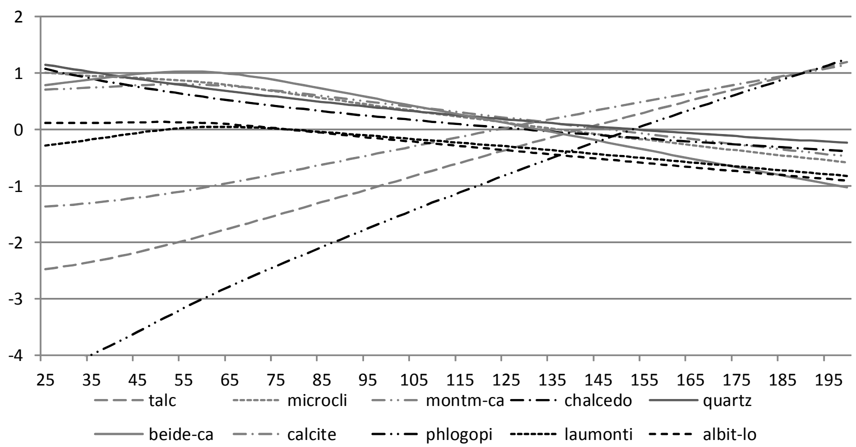


Fig. 3. Computed SI (saturation indices) as a function of temperature in Duszniki-Zdrój

Based on thus conducted simulations for Batňovice, Jeleniów and Gorzanów deposits located in Upper Cretaceous sediments, temperatures in the range 71°C–94°C were obtained. In the case of the deposit in Kudowa-Zdrój, the obtained temperature (123°C – Table 3) is, in all likelihood, the result of thermal water inflow from the crystalline bedrock of the Kudowa basin.

## 4. SUMMARY AND CONCLUSIONS

The prospective area of thermal water occurrence within the Orlica-Śnieżnik dome is, according to the authors, related to the eastern part of the deep Karkonosze fracture, whose extension in the Czech Republic is referred to as the Kozákov-Hronov fracture. The strike of this fracture co-occurs with the dislocations identified in the near--surface parts, such as the Hronov-Pstrazna-Gorzanow fault and the Krosnowice overthrust.

In the specified prospective area, thermal waters occur in Batňovice, Jeleniów, Duszniki-Zdrój and Krosnowice, and $CO_2$-rich waters and carbonated waters with increased temperatures (11.5–21.6°C) – in intakes, with large discharges, located in Kudowa-Zdrój, Jeleniów, Duszniki-Zdrój and Gorzanów. Increased water temperature, $CO_2$ presence in water, increased concentrations of metasilicic acid and high intake discharges imply a possibility of obtaining waters with much higher temperatures.

The observed inverse relationships between discharge changes and water temperature or $HCO_3^-$ ion content confirmed by the conducted correlation analysis indicate that that the outflow of deeper circulation waters in Duszniki-Zdrój is related to an increase in water temperature.

The results obtained with the use of classic chemical geothermometers provided broad ranges of probable deposit temperatures. The authors believe that the temperatures obtained for Duszniki and Gorzanów with the use of Na-K and Na-K-Ca thermometers (373°C and 283°C, and 137°C and 143°C) are significantly overestimated. It is, in all likelihood, the result of the presence of considerable amounts of dissolved $CO_2$ in the discussed waters and the precipitation of secondary carbonates (calcite). In the other deposits, this is probably the result of water enrichment in $Ca^{2+}$ ions originating from sedimentary series of the Police basin (Batňovice) or the upper Nysa trough (Gorzanów). Moreover, their parent thermal waters circulate beneath the sedimentary series of the Police basin, the Kudowa depression and the upper Nysa trough forming shallower reservoirs containing mixtures of parent liquids and modern infiltration waters.

Knowing the limited usages of particular classic thermometers and the results of temperature modelling based on SI, the authors are inclined to adopt the values obtained from modelling, i.e., those in the range of 71–141°C as the most likely deposit temperatures.

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REFERENCES

ARNÓRSSON S., 1983, *Chemical equilibria in icelandic geothermal systems - implications for chemical geothermometry investigations*, Geothermics, No. 12 (2–3), 119–128.

ARNÓRSSON S., 2000, *The quartz-and Na/K geothermometers*. I. *New thermodynamic calibration*, Proc. World Geothermal Congress, Tohoku, 28 May–10 June, 929–934.

ARNÓRSSON S., GUNNLAUGSSON E., SVAVARSSON H., 1983, *The chemistry of geothermal waters in Iceland*. III. *Chemical geothermometry in geothermal investigations*, Geochim. Cosmochim. Acta, No. 47, 547–566.

BAŻYŃSKI J., FISTEK J., GRANICZNY M., SŁAWIŃSKI A., WILCZYŃSKI M., 1981, *Interpretacja zdjęć satelitarnych w świetle badań hydrologicznych południowo-zachodniej części Ziemi Kłodzkiej*, Technika Poszukiwań Geologicznych, Vol. 20, No. 1, 14–16.

CIĘŻKOWSKI W., 1990, *Studium hydrogeochemii wód leczniczych Sudetów polskich*, Pr. Nauk. Inst. Geotech. PWr, No. 60 (19).

CIĘŻKOWSKI W., MICHNIEWICZ M., PRZYLIBSKI T.A., 2011, *Wody termalne na Dolnym Śląsku*. [In:] A. Żelaźniewicz, J. Wojewoda, W. Ciężkowski (Eds.), *Mezozoik i Kenozoik Dolnego Ślaska*, Wyd. WIND, Wrocław, 107–120.

CIĘŻKOWSKI W., KIEŁCZAWA B., LIBER-MAKOWSKA E., PRZYLIBSKI T.A., ŻAK S., 2016, *Wody lecznicze regionu sudeckiego: wybrane problemy*, Przegl. Geol., Vol. 64, No. 9, 671–682.

CYMERMAN Z., 2016, *Kopuła orlicko-śnieżnicka w świetle rozważań tektonicznych* (*The Orlica-Śnieżnik dome in the light of tectonic considerations*), Przegl. Geol., Vol. 64, No. 10, 814–830.

DOKTÓR S., GRANICZNY M., SADOWSKA M., 1987, *Analiza danych teledetekcyjnych dla prognozowania występowania wód mineralnych i zwykłych na przykładzie obszaru pomiędzy Polanicą, Dusznikami i Kudową*, Przegl. Geol., Vol. 35, No .11, 580–583.

DOKTÓR S., GRANICZNY M., KUCHARSKI R., 1990, *Opracowanie map liniowych elementów tektonicznych dla obszaru wałbrzyskiego i kłodzkiego*, PIG, Warszawa.

DOWGIAŁŁO J., 2001, *Sudecki region geotermalny – określenie, podział, perspektywy poszukiwawcze*, Współczesne Problemy Hydrogeologii, Vol. 10, 301–308.

DOWGIAŁŁO J., FISTEK J., 2003, *New findings in the Wałbrzych-Kłodzko geothermal sub-region (Sudetes, Poland)*, Geothermics, No. 32, 689–699.

DOWGIAŁŁO J., Fistek J., 2007, *Prowincja sudecka. In: Hydrogeologia regionalna Polski*. Vol. 2. *Wody mineralne, lecznicze i termalne oraz kopalniane*, Wyd. PIG, Warszawa, 57–77.

FISTEK J., DOWGIAŁŁO J., BOROWIEC A., 1987, *Kudowa-Zdrój. Nowy punkt występowania wód termalnych w Sudetach*, Przew. XLVIII Zjazdu Pol. Tow. Geol., Wyd. Geol., Warszawa, 251–254.

FISTEK J., 1977, *Szczawy Kotliny Kłodzkiej i Gór Bystrzyckich*, Biul. Geol. UW, Vol. 22, 61–111.

FISTEK J., 1989, *Rola uskoku Pstrążna–Gorzanów w kształtowaniu warunków hydrogeologicznych SW obrzeżenia synklinorium śródsudeckiego*, Prace Nauk. Inst. Geotech. PWr, No. 58 (29), 362–368.

FOURNIER R.O., 1977, *Chemical geothermometers and mixing models for geothermal systems*, Geothermics, No. 5, pp. 41–50.

FOURNIER R.O., TRUESDELL A.H., 1973, *An empirical Na-K-Ca geothermometer for natural waters*, Geochim. Cosmochim. Acta, No. 37 (5), 1255–1275.

GIGGENBACH W.F., 1988, *Geothermal solute equilibria. Derivation of Na-K-Mg-Ca geoindicators*, Geochim. Cosmochim. Acta, 52 (12), 2749–2765.

GML, 2011. Act of June 9, 2011, *Geological and Mining Law* (Ustawa z dnia 9 czerwca 2011 r. *Prawo geologiczne i górnicze*), Dz.U. 2011.63.981.

JETEL J., RYBAROVA L., 1979, *Minerální vody Východočeského kraje*, Ústř. Úst. Geol., Praha.

KIEŁCZAWA B., 2001a, *Wody zmineralizowane Gorzanowa*, PhD thesis, Wydział Górniczy PWr, Raport Inst. Gór. Ser. PRE No. 9, Wrocław, 1–167.

KIEŁCZAWA B., 2001b, *Wybrane zagadnienia chemizmu wód kredowego piętra wodonośnego rowu górnej Nysy Kłodzkiej*. [In:] *Współczesne Problemy Hydrogeologii* X, Vol. 1, Wrocław, 321–327.

KIEŁCZAWA B., 2005, *Związek uskoku Pstrążna–Gorzanów z zasilaniem potencjalnie leczniczych wód Gorzanowa*, [In:] *Górnictwo i geologia*, Vol. VIII, Oficyna Wydawawnicza PWr, Wrocław, 121–128.

KIEŁCZAWA B., CIĘŻKOWSKI W., DUDA M., 2018a, *Gorzanów – nowe złoże wód leczniczych w Sudetach (SW Polska)*, Acta Balneologica, Vol. 60, No. 4, 301–306.

KIEŁCZAWA B., CIĘŻKOWSKI W., LIBER-MAKOWSKA E., 2018b, *Charakterystyka termalnych wód leczniczych Dolnego Śląska*. [In:] S. Downorowicz (Ed.), *Aktualne problemy geotermiczne Polski*, Towarzystwo Konsultantów Polskich, Oddz. Lubin, Lubin, 111–119.

KRÁSNÝ J., CÍSLEROVÁ M., ČURDA S., DATEL J., DVOŘAK J., GRMELA A., HRKAL Z., KŘÍŽ H., MARSZAŁEK H., ŠANTRŮČEK J., ŠILAR J., 2012, *Podzemní vody České republiky*, Česká Geologická služa, Praha.

LI J.X., SAGOE G., LI Y., 2019, *Applicability and limitations of potassium-related classical geothermometers for crystalline basement reservoirs*, Geothermics, Vol. 84, doi.org/10.1016/j.geothermics.2019.101728

LIBER E., 2001, *Zmienność wydajności ujęć wód leczniczych eksploatowanych samoczynnie ze złóż sudeckich*, PhD thesis, Raporty Inst. Gór. Ser. PRE No. 3, Wrocław, 1–169.

MICHNIEWICZ M., 1981, *Próba interpretacji wczesnych etapów tektogenezy Sudetów w nawiązaniu do teorii diapiryzmu wgłębnego oraz koncepcji głębokich rozłamów*, Geol. Sudetica, Vol. 16, No. 2, 75–141.

NICHOLSON K., 1993, *Geothermal Fluids: Chemistry and Exploration Techniques*, Springer-Verlag.

OBERC J., DYJOR S., 1968, *Młodotrzeciorzędowe ruchy tektoniczne w Sudetach*, Prz. Geol., Vol. 11, No. 187, 493–498.

OBERC J., 1972, *Synklinorium śródsudeckie i rów górnej Nysy Kłodzkiej*. [In:] *Budowa geologiczna Polski*, Vol. IV, *Tektonika* – part 2, Wyd. Geol., Warszawa.

PACZYŃSKI B., PŁOCHNIEWSKI Z., 1996, *Wody mineralne i lecznicze Polski*, Państw. Inst. Geol., Warszawa.

PANG Z.H., REED M., 1998, *Theoretical chemical thermometry on geothermal waters: Problems and methods*, Geochim. et Cosmochim. Acta, No. 62, 1083–1091.

PRZYLIBSKI T.A., BIEL A., CIĘŻKOWSKI W., CZERSKI M., KIEŁCZAWA J., MARSZAŁEK H., MICHNIEWICZ M., STAŚKO S., TARKA R., WOJTKOWIAK A, WĄSIK M., ŻAK S., 2007, *Studium możliwości rozpoznania nowych wystąpień wód zmineralizowanych, swoistych i termalnych na obszarze bloku przedsudeckiego*, Raport Ser. SPR. I-11/S-5/2007, PWr., Wrocław, 109.

RADWAŃSKI S., 1975, *Kreda Sudetów środkowych w świetle wyników nowych otworów wiertniczych*, Biul. Inst. Geol., Vol. 24, No. 287, 5–50.

REED M.H., SPYCHER N., 1984, *Calculation of pH and mineral equilibria in hydrothermal waters with application to geothermometry and studies of boiling and dilution*, Geochim. et Cosmochim. Acta, No. 48, 1479–1492.

SPYCHER N., PEIFFER L., SONNENTHAL E.L., SALDI G., REED M.H., KENNEDY B.M., 2014, *Integrated multicomponent solute geothermometry*, Geothermics, No. 51, 113–123.

SPYCHER N., PEIFFER L., FINSTERLE S., SONNENTHAL E.L., 2016a, *GeoT. A computer program for multicomponent geothermometry and geochemical speciation. User's guide*, Lawrence Berkeley National Laboratory.

SPYCHER N., FINSTERLE S., DOBSON P.F., 2016b, *New developments in multicomponent geothermometry*. Proc. 41nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 22–24, 2016.

TONANI F.B., 1980, *Some Remarks on the Application of Geochemical Techniques in Geothermal Exploration*, Springer, Netherlands, 428–443.