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VARIABILITY OF GRADIENTS OF THERMAL WATERS IN THE AREA OF LESSER POLAND VOIVODESHIP

The objective of the project was to investigate the variability of gradients of thermal waters in the area of Lesser Poland voivodeship. Gradients, i.e. the increase of temperature in relation to 100 m in depth, in the area of Lesser Poland voivodeship change substantially, depending on the age and lithology of water-bearing layers. This occurs where the presence of thermal waters has been confirmed, i.e. the waters having a temperature above 20 °C. The formations containing thermal waters in the study area are: carbonates of the Devonian, Triassic, Jurassic and Cretaceous as well as clastic Carboniferous and Miocene. They have been found at a depth from 200 to 3200 m in over 150 borings. Performed gradient calculations indicate their substantial variability from 0.6 to 6.0 °C·100 m^{-1}, depending not only on the stratigraphy and lithology of water-bearing layers, but also on the depth of waters having a similar age.

1. INTRODUCTION

Groundwater existing in the deeper zones of the Earth's crust is often characterized by elevated temperatures. If these temperatures exceed 20 °C, they are considered the so-called thermal waters [5]. The water temperature depends on the depth of the water-bearing layer, thermal properties of rock composing the aquifer, and on the geothermal level of the given area. The geothermal level is the increase of depth inside the Earth expressed in meters accompanied by a unitary rise in rock temperature by 1 °C [3]. The geothermal gradient, a reverse of geothermal level, is the rise of temperature (in °C) of the Earth with progressive depth, which usually occurs for every 100 m. The gradient of thermal waters varies greatly, depending on the location in the voivodeship and also the Earth depth. This variability is based on drilling results [3] in the area of Lesser Poland voivodeship. The goal of the study was to analyze the geothermal gradient with regard to the age and lithology as well as the depth of water-bearing layers.

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2. OBJECTIVES AND METHODS

The aim of the study was to determine the size and the variability of gradients of geothermal underground waters occurring in Paleozoic layers (Carboniferous and Devonian), Mesozoic layers (Triassic, Jurassic and Cretaceous) and Cenozoic (Miocene) in the area of Lesser Poland voivodeship.

The data used for analysis comes from a complex investigation of boreholes drilled through thermal water bearing formations [3]. The data includes borehole depth with groundwater temperature, water pressure (head), the general mineralization of water as well as the flow rate value, i.e. the efficiency of the water-bearing layer. The research encompassed a total of 150 borholes in the following formations: Carboniferous (6), Devonian (13), Triassic (14), Middle Jurassic (25), Upper Jurassic (30), Cenomanian (29), Senonian (16) and Miocene (17). The boreholes were drilled in stratigraphically different morphological and tectonic units of Lesser Poland voivodeship.

In the area of Lesser Poland voivodeship, the reservoirs of thermal waters are found at various depths. Most often they are related to Miocene formations, Tertiary formations of the outer Carpathians, Upper Cretaceous (Cenomanian and Senonian), Middle Jurassic (Dogger) and Upper Jurassic (Malm), Triasssic of Cracovian monocline and Podhale basin, as well as Carboniferous and Devonian.

The reservoirs in the Lower Carboniferous units in the area of Chrzanów, Oświęcim and Kraków districts are found in limestones, marls, sandstones, mudstones, and siltstones at depths of 340–3190 m. Water temperatures here range from 26 to 74 °C with the artesian flow rate being from 1.1 to 9.0 $m^3 \cdot h^{-1}$ and water mineralization from 0.5 to over 12 $g \cdot dm^{-3}$.

The reservoirs in Middle and Upper Devonian in the area of Olkusz, Kraków, Miechowice, Proszowice, Wieliczka and Bochnia districts are found in marls, limestones, dolomites and siltstones at depths of 1000–3051 m. Here the groundwater reaches temperature of 28–90 °C at inflow or artesian flow rates of 115 $m^3 \cdot h^{-1}$ and water mineralization from 12 to 210 $g \cdot dm^{-3}$.

Triassic reservoirs, part of the Cracovian monocline, are located in Zakopane, Myślenice, Sucha Beskidzka, Wieliczka, Bochnia, Brzesko, Olkusz, Miechowice and Dąbrowa Tarnowska districts. They are found in siltstones, mudstones with inclusions of conglomerates, and sandstones at depths of 500–2910 m. Water temperature here is in the range of 20–80 °C at artesian flow rates not exceeding 10 $m^3 \cdot h^{-1}$ and with variable water mineralization (1.36–235.00 $g \cdot dm^{-3}$).

Triassic reservoirs are also present in the area of Podhale basin, and Nowy Targ and Tatra Mts. districts. Water temperature varies here from 20 to 86 °C with the flow rate being 3.9–270.0 $m^3 \cdot h^{-1}$ and water mineralization of 0.3–3.1 $g \cdot dm^{-3}$.

The reservoirs in Middle Jurassic (Dogger) are located mainly in the northern part of Lesser Poland voivodeship, specifically in Olkusz, Miechowice, Proszowice, Kraków, Wieliczka and Myślenice districts. The groundwater here is found under

artesian and sub-artesian conditions at depths from 175 to 2392 m. The flow rate in boreholes varies in the range from 0.3 to 13.0 $m^3 \cdot h^{-1}$, temperature from 23 to 65 °C, and water mineralization from 0.4 to 80 $g \cdot dm^{-3}$.

The reservoirs of Upper Jurassic (Malm) are comprised mainly of karsted, chapped or weathered limestones of Oxford and Kimmerid, and in the eastern part of the area – of dolomites. These formations lie at depth from 310 to 2937 m. Water temperature of Upper-Jurassic reservoirs varies from 20 to 75 °C at flow rates of 0.15–120 $m^3 \cdot h^{-1}$ and water mineralization from 0.5 to 120 $g \cdot dm^{-3}$.

Upper Jurassic (Cenomanian) formations are found mainly in Miechowice, Kraków, Wieliczka, Bochnia, Brzesko and Dąbrowa Tarnowska districts. These reservoirs are found in limestone, conglomerates and sandstones at depth from 132 to 2582 m. Groundwater in these reservoirs reaches temperature from 20 to 76 °C at flow rate of 0.5–120 $m^3 \cdot h^{-1}$ and water mineralization from 0.3 to 115.6 $g \cdot dm^{-3}$.

In the northern and north-eastern parts of Lesser Poland voivodeship, specifically in Wieliczka, Bochnia, Brzesko, Tarnów and Dąbrowa Tarnowska districts, there is a reservoir in Upper Jurassic (Senone). It is found in marls occurring at depth from 200 to 2135 m. Groundwater in this reservoir is characterized by temperature ranging from 20 to 68 °C at flow rate of 7.3–21.4 $m^3 \cdot h^{-1}$ with artesian flows and water mineralization from 2.6 to 93.0 $g \cdot dm^{-3}$.

Outer Carpathian reservoirs are most often found in flysch sandstone-slate Tertiary layers. They are often in hydraulic contact with older Cretaceous layers. Water temperature here varies from 22 to 42 °C at an artesian flow rate of 4.5–29.6 $m^3 \cdot h^{-1}$ and water mineralization of 11.0–26.4 $g \cdot dm^{-3}$.

Miocene reservoirs in the area of Lesser Poland voivodeship are found in Bochnia, Brzesko, Tarnów and Dąbrowa Tarnowska districts. They are in sandstone complexes at depth from 150 to 1775 m. Underground water in these reservoirs is characterized by temperature ranging from 20 to 58 °C at inflow rate of 0.25–60 $m^3 \cdot h^{-1}$ with artesian flow and water mineralization from 0.5 to 122 $g \cdot dm^{-3}$.

3. RESULTS AND DISCUSSION

Thermal waters in the area of Lesser Poland voivodeship are related to such tectonic and morphological units as Polish Carpathian Foredeep (Miocene), Nida basin (Cretaceous), Kraków–Wieluń Monocline (Jurassic and Triassic), Upper Silesian Foredeep (Carboniferous and Devonian), outer Carpathians (Tertiary) and Podhale basin – inner Carpathians (Triassic).

The calculations were performed using the data assembled in tables [3] with the age of water-bearing layers taken into account. The analysis indicates that the largest average geothermic gradient, i.e. 3.49 $°C \cdot 100\ m^{-1}$, is related to Triassic layers of the

inner Carpathians, while the smallest gradient, 1.78 °C·100 m^{-1}, is related to Tertiary layers of the outer Carpathians. Gradients for the other water-bearing layers are between those values: for Devonian formations, 2.49 °C·100 m^{-1}; Carboniferous, 2.73 °C·100 m^{-1}; Triassic of Miechowski basin and Polish Carpathian Foredeep, 2.40 °C·100 m^{-1}; Jurassic (Malm), 2.54 °C·100 m^{-1}; Jurassic (Dogger), 2.53 °C·100 m^{-1}, Cretaceous (Senonian), 2.53 °C·100 m^{-1}; Cretaceous (Cenomanian), 2.46 °C·100 m^{-1}; and Miocene, 2.98 °C·100 m^{-1}. These values are averages of data from the entire area under study (figure 1).

Geothermal gradient variability depends not only on the type of tectonical or lithostratigraphical unit being researched, but also on the depth of the thermal water-bearing layers. An evaluation of the thermal gradient as regards to depth (figure 2) allows the following conclusions to be drawn:

- In Devonian rocks at depth from 910 to 2828 m, the geothermal gradient varies from 1.57 °C·100 m^{-1} to 5.33 °C·100 m^{-1}. Down to the depth of 1472 m linear gradients grow to the maximum value, and then to the final depth, their alternate growth and decrease are observed.
- In Carboniferous formations at depths from 340 to 2729 m, the gradient varies between 0.59 and 3.98 °C·100 m^{-1}. To the depth of 2049 m gradients grow gradually to a maximum value and then they substantially decrease to a minimum value.
- In Triassic formations of the inner Carpathians, the gradient changes with depth in the range of 1.29–5,47 °C·100 m^{-1}. To the depth of 1768 m it increases rapidly to the maximum value, and then it decreases.
- In Triassic formations of Miechowice basin and Polish Carpathian Foredeep, at a depth of 500–2885 m the gradients vary from 0.68 °C·100 m^{-1} at a depth of 1400–1548 m to 4.62 °C·100 m^{-1} at a depth of 1073–1203 m. To the depth of 1203 m the gradient increases progressively to the maximum value, then it increases and decreases alternately.
- In Jurassic (Malm) formations, at depth ranging from 201–2437 m the gradients vary from 1.12 to 6.0 °C·100 m^{-1}. The maximum gradient occurs at a depth of 648–748 m with the minimum one near the surface of the area. The geothermal gradient of 6 °C·100 m^{-1} has also the highest value of all the gradients of various age recorded in the whole area of Lesser Poland voivodeship. In the deepest zones of these formations, the gradients range from 3.48 to 3.57 °C·100 m^{-1}.
- In water-bearing layers of Jurassic (Dogger), at depths of 175–2260 m the gradients vary in the range of 1.0–5.05 °C·100 m^{-1}. The minimum gradient in profile, 1.0 °C·100 m^{-1}, is at a depth of 457–758 m and the maximum one just below it, namely in the middle section of the profile at a depth of 1360–1578 m. Below these levels, the gradients are smaller, 2.38–3.14 °C·100 m^{-1}.
- In Cretaceous (Senonian) at the depth of 203–2129 m the geothermal gradients vary from 1.21 to 5.91 °C·100 m^{-1}. They linearly decrease from the surface to a depth

of 910 m. Then they increase to reach the maximum value in the lower part of the profile at a depth of 2129 m.

- Gradient variations from 0.8 to 4.75 °C·100 m^{-1} occur in water-bearing Cretaceous (Cenomanian) layers in the depth range of 133–2527 m. At the surface of the area the gradient is small, 1.04 °C·100 m^{-1}, and with depth it increases to a maximum value of 4.75 °C·100 m^{-1}. Then, at a depth of 1115 m it reaches its minimum value. At depths up to 2149 m the gradient maintains nearly the same value of 2.73–2.94 °C·100 m^{-1}, and it reaches quite a substantial value of 4.63 °C·100 m^{-1} in the bottom part.
- In Tertiary (Palaeogene) layers of the outer Carpathians, the gradients at depths of 665-1830 m increase with depth from 1.15 to 2.17 °C·100 m^{-1}.
- In Miocene water-bearing layers, at depths of 295–1763 m there are gradient variations in the range of 1.25–3.71 °C·100 m^{-1}. At unstable changes of gradient together with depth there is its increase to the maximum value in the bottom part.

4. CONCLUSIONS

In the area of Lesser Poland voivodeship, including the tectonical units of Cracovian monocline, Miechów basin, Polish Carpathian Foredeep, Upper Silesian Foredeep and outer and inner Carpathians, there are thermal waters in Carboniferous, Devonian, Triassic, Jurassic and Tertiary formations. Their temperatures vary in the range from 20 to 90 °C at artesian flows or inflow amounting to 0.5–270.0 $m^3 \cdot h^{-1}$ and water mineralization from 0.3 to 235.00 $g \cdot dm^{-3}$. The variability of geothermal gradients ranges from 1.78 °C·100 m^{-1} in Tertiary layers of the outer Carpathians to 3.49 °C·100 m^{-1} in Triassic layers of the inner Carpathians. The given gradients are similar to those reported by other authors for this area [1], [2], [4]. The gradients also vary together with their depth. The smallest value, 0.59 °C·100 m^{-1}, is found at depths of 2049–2729 m in clastic Carboniferous layers of Upper Silesian Foredeep, and the largest of 6.0 °C·100 m^{-1} at depths of 648–748 m in bicarbonate Jurassic (Malm) layers. The given maximum values differ substantially from the values obtained from boreholes Siekierczyna IG-1 and Zakopane IG-1. These boreholes in the Carpathians show maximum gradient values up to 3.85 °C·100 m^{-1} [2]. Large gradients occur in Miocene and Tertiary layers of the outer Carpathians, in Cretaceous (Senonian) in the deepest parts of the profiles investigated, in Jurassic layers of Malm and Cretaceous layers of Cenomanian in the part closer to the surface, and in the other cases either in the middle part of the profile or very near to the middle. Determining the range of gradient variations with the depth, in most cases alternation of gradient size occurs, first increasing, then decreasing and vice versa.

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ZMIENNOŚĆ GRADIENTÓW WÓD TERMALNYCH NA TERENIE WOJEWÓDZTWA MAŁOPOLSKIEGO

Badano zmienność gradientów wód termalnych występujących na terenie województwa małopolskiego. Gradienty, czyli przyrosty temperatury w odniesieniu do głębokości 100 m, na terenie województwa małopolskiego zmieniają się znacznie w zależności od wieku i litologii warstw wodonośnych, w których stwierdzono wody termalne, czyli wody o temperaturze powyżej 20 °C. Utworami zawierającymi wody termalne na terenie omawianego województwa są węglanowe skały dewońskie, triasowe, jurajskie i kredowe oraz klastyczne skały karbońskie i mioceńskie. Ich obecność została stwierdzona na głębokości od 200 do 3200 m dzięki ponad 150 odwiertom. Przeprowadzone obliczenia gradientów wskazują na ich znaczną zmienność od 0,6 do 6,0 °C·100 m^{-1} zależną nie tylko od stratygrafii i litologii warstw wodonośnych, ale także od głębokości występowania wód w tym samym wieku