GOSPODARKA SUROWCAMI MINERALNYMI – MINERAL RESOURCES MANAGEMENT

2025 Volume 41 Issue 1 Pages 5–27

DOI: 10.24425/gsm.2025.153172

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# Geothermal potential of South-Western Poland

## Introduction

In general awareness, the southwestern region of Poland has been considered non-perspective in terms of the occurrence of geothermal waters to date. Previous studies on geothermal conditions in Poland (Sokołowski et al. 1995; Górecki ed. 2006a, 2006b) have generally left this area unexplored. Only local occurrences of geothermal waters, mainly due to their balneotherapeutic properties, have been the subject of prospecting, identification, and research (Ciężkowski 1980; Dowgiałło 2002; Dowgiałło and Fistek 2003; et al.).

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It was not until Bruszewska (2000) that an attempt was made to present the geothermal conditions of Lower Silesia. Szewczyk and Gientka (2009) then presented the variability of heat flux density for the entire area of Poland, whereas Majorowicz (2021) compiled the results of previous studies and, thus, revised and updated the state of the knowledge of the problem in question.

Studies in recently drilled deep boreholes, together with archival results, allow an assessment of geothermal conditions and their variability in SW Poland. Geographically, this study covers the Sudetes, the Sudetic Foreland, and the Silesian Lowland south of the river Odra. Geologically, in turn, the study area includes the Lower Silesia Block, the western part of the Opole Basin (OB), and the southern part of the Fore-Sudetic Monocline (FSM). These tectonic units are composed chiefly of crystalline rocks and compact sedimentary rocks, a staircase descending toward the northeast and forming distinctive steps. The highest of these is the uplifted mountainous massif of the Sudetes; the intermediate position is held by the Fore-Sudetic Block (FSB), while the Fore-Sudetic Monocline represents the lowest step. The subsequent steps are covered by a layer of Cenozoic sediments, generally thickening towards the northeast. The central tectonic units differ in their lithological composition and geological structure, hydrogeological conditions, and, consequently, geothermal conditions. Dowgiałło (2002) described the area in question as the "Sudetic geothermal region".

Geothermal energy, as understood in this paper, refers to the internal energy of the Earth accumulated in rocks and groundwater, with geothermal waters being the natural energy carrier in the Sudetes region. The paper presents, for the first time, the thermal characteristics of the study area, considering its division into smaller tectonic units and using data from recent deep boreholes reaching depths of up to 2,500 m b.g.l.

## 1. Characteristics of the study area

### 1.1. Geological background

The Alpine tectonic activity resulted in the formation of two large blocks in the northeastern part of the Bohemian Massif, the Sudetic Block (SB) and the Fore-Sudetic Block (FSB), collectively referred to as the Lower Silesia Block. These units are separated by the Sudetic Marginal Fault (SMF), throwing down the Fore-Sudetic Block, north of which the Fore-Sudetic Monocline (FSM) is located. The boundary between the two latter units is defined by faults of the Middle Odra Horst (Żelaźniewicz and Aleksandrowski 2008).

The Sudetic Block is composed of several smaller fault-bounded units of varying rank and extent, giving its tectonic structure a mosaic-like character (Figure 1A).

In this paper, only tectonic units are considered, where deep boreholes (> 500 m depth) have been drilled, and the data from which were used for study and analysis.

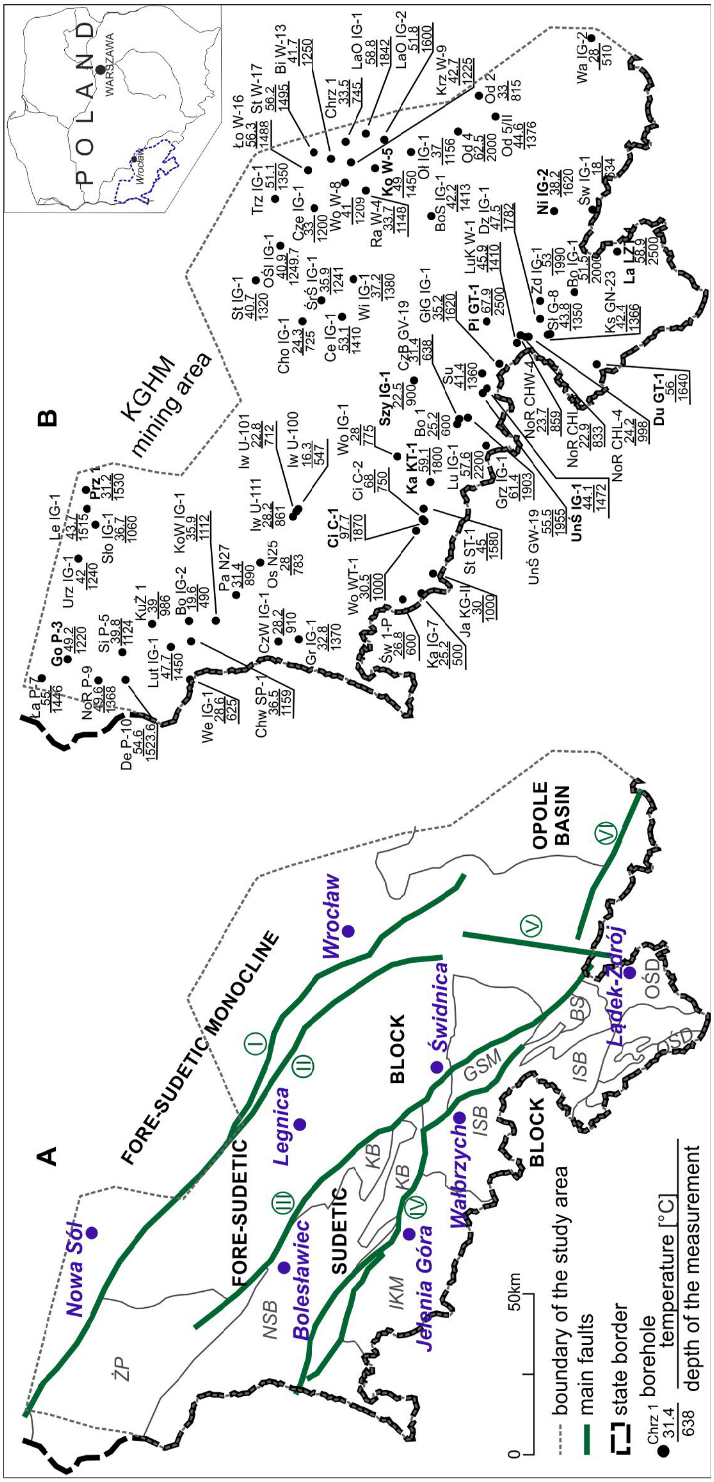
In the discussed area, the exposed rocks were either deformed during the Variscan orogeny or represent the late Paleozoic to Mesozoic sedimentary cover. The latter constitutes the upper structural level, composed of sedimentary rocks representing either late Variscan intra-montane basin fill such as the Carboniferous of the Intra-Sudetic Basin or the post-Variscan (Permian through Cretaceous) sedimentary succession fragmentarily preserved in syncline depressions of the Intra-Sudetic Basin (ISB) and the North-Sudetic Basin (NSB). The western part of the Sudetic Block is composed mainly of gneisses and mica schists, into which the Karkonosze granite intruded during the Carboniferous, forming the Izera-Karkonosze Massif (IKM). The northern boundary of this massif is the Intra--Sudetic Fault (ISF), which separates it from the North-Sudetic Basin (NSB) and from the Kaczawa Belt (KB), which continues into the Fore-Sudetic Block. The North-Sudetic Basin (or Synclinorium) is filled with late Paleozoic clastic and marine deposits (copper-bearing shales, carbonates, sulfates) covered by Mesozoic formations. The Kaczawa Belt consists of low-grade metamorphic rocks ranging in age from the Lower Cambrian to the Lower Carboniferous.

The central part of the Sudetic Block is dominated by the Intra-Sudetic Basin (Synclinorium), where clastic material was deposited from the late Early Carboniferous to the Late Cretaceous (with a hiatus during the Jurassic). During the Carboniferous and Permian, intense volcanic activity took place in this area.

The eastern rim of the Intra-Sudetic Basin is formed by the Góry Sowie Massif (GSM), composed of various types of gneisses (mostly early Paleozoic) with inclusions of amphibolites and granulites. The massif is divided by the Sudetic Marginal Fault (SMF) into the Sudetic and Fore-Sudetic parts (Figure 1A).

Paleozoic sedimentary deposits (Upper Ordovician to Lower Carboniferous in age) fill the next tectonic unit, located south of the Góry Sowie Massif, known as the Bardo Structure (BS). South of the Intra Sudetic Basin and the Góry Sowie Massif, the Orlica-Śnieżnik Dome (OŚD) is located. In the east, it extends up to the Staré Město Belt, separated by the Nyznerov Overthrust from the Moravian-Silesian structure (Żelaźniewicz and Aleksandrowski 2008; Żelaźniewicz et al. 2011). It is composed mainly of the so-called Śnieżnik and Gierałtów gneisses, occurring in various types (biotitic, migmatitic, augen, layered, and streaky gneisses). The Gierałtów gneisses are folded together with the so-called Stronie Series (mica schists, paragneisses, crystalline limestones, amphibolites, and amphibolitic schists), additionally cut by Neogene basalts (Gierwielaniec 1970; Don et al. 2004).

Generally, the same types of rocks occur within the Fore-Sudetic Block as in the Sudetic Block: metamorphic and magmatic rocks of Neoproterozoic-Paleozoic age, locally along with Mesozoic sedimentary rocks. These are covered by Cenozoic deposits of varying thickness, locally exceeding 500 m in tectonic grabens. In the western part of the Fore--Sudetic Block, the Permian-Mesozoic succession defines the so-called Żary Pericline – a very gentle, shallowly WNW-dipping anticline, affecting Permian, Triassic, and Upper Cretaceous sedimentary rocks. At a depth of approximately 1400 m, Permian volcanic rocks (andesites) were drilled (Chmielewski and Oszczepalski 2021).


A
B
FORE-SUDETIC MONOCLINE
FORE-SUDETIC BLOCK
SUDETIC BLOCK
OPOLE BASIN
KGHM mining area
POLAND
WARSZAWA
Wrocław
Nowa Sól
Legnica
Bolesławiec
Jelenia Góra
Wałbrzych
Świdnica
Lądek-Zdrój
ŻP
NSB
IKM
KB
GSM
ISB
BS
OŚD
I
II
III
IV
V
VI
0
50km
boundary of the study area
main faults
state border
Chrz 1
31.4
638
borehole
temperature [°C]
depth of the measurement

To the north of the Fore-Sudetic Block lies the Fore-Sudetic Monocline, a homoclinic unit characterized by shallow-angle northeast-dipping Permian-Triassic sedimentary succession. Generally, clastic marine formations predominate there, with a significant presence of chemo-genic formations (salt cyclothems).

The eastern part of the study area includes the western part of the Late Cretaceous Opole Basin (OB), formed on top of the eastern margin of the Fore-Sudetic Block, and the northern part of the Moravo-Silesian Structure (MSS). It is composed of Upper Cretaceous carbonate and sandy-clayey formations with a thickness of over 350 m. They were formed during a marine transgression that lasted from the Cenomanian to the Upper Coniacian, leaving carbonate and sandy-clayey formations.

Fig. 1. Documentation map against the background of the geological structure of the study area (based on Żelaźniewicz and Aleksandrowski 2008)
explanatory notes to map A: ŻP – Żary Pericline, NSB – North-Sudetic Basin, IKM – Izera-Karkonosze Massif, KB– Kaczawa Belt, ISB – Intra-Sudetic Basin, GSM – Góry Sowie Massif, BS – Bardo Structure, OŚD – Orlica-Śnieżnik Dome; I – North Odra Fault, II – South Odra Fault, III – Sudetic Marginal Fault, IV – Intra-Sudetic Fault, V – Nyznerov Thrust, VI – Kędzierzyn-Paczków Fault
explanatory notes to map B (in bold – boreholes quoted in the text): Bi W-13 – Bielawa W-13, Bo IG-1 – Bo-guszyn IG-1, BoS IG-1 – Borek Strzeliński IG-1, Bo IG-2 – Borowe IG-2, Bo 1 – Borówno 1, Ce IG-1 – Cesarzowice IG-1, Cho IG-1 – Chomiąża IG-1, Ci C-1 – Cieplice C-1, Ci C-2 – Cieplice C-2, Chrz 1 – Chrząstawa 1, Chw SP-1 – Chwalimierz SP-1, CzB GV-19 – Czarny Bór GV-19, Cze IG-1 – Czerńczyce IG-1, CzW IG-1 – Czerwona Woda IG-1, De P-10 – Dębinka P-10, Du GT-1 – Duszniki GT-1, Dz IG-1 – Dzikowiec IG-1, GłG IG-1 – Głuszyca Górna IG-1, Go P-3 – Górzyn P-3, Gr IG-1 – Gronów IG-1, Grz IG-1 – Grzędy IG-1, Iw U-100 – Iwiny U-100, Iw U-101 – Iwiny U-101, Iw U-111 – Iwiny U-111, Ja KG-II – Jakuszyce KG-II, Ka IG-7 – Karkonosze IG-7, Ka KT-1 – Karpniki KT-1, KoW IG-1 – Kościelna Wieś IG-1, Ko W-9 – Kotowice W-5, Krz W-9 – Krzyków W-9, Ks GN-23 – Księżno GN-23, KuŻ 1 – Kunice Żarskie 1, LaO IG-1 – Laskowice Oławskie IG-1, LaO IG-2 – Laskowice Oławskie IG-2, La LZT-1 – Lądek LZT-1, Le IG-1 – Lelechów IG-1, Lu IG-1 – Lubaw-ka IG-1, LuK W-1 – Ludwikowice Kłodzkie W-1, Lut IG-1 – Lutol IG-1, Ła P-7 – Łazy P-7, Ło W-16 – Łosice W-16, Ni IG-2 – Niedźwiedź IG-2, NoR P-9 – Nowa Rola P-9, NoR CHW-4 – Nowa Ruda CHW-4, NoR CHL-3 – Nowa Ruda CHL-3, NoR CHL-4 – Nowa Ruda CHL-4, OŚl IG-1 – Oborniki Śląskie IG-1, Od 4 – Odra 4, Od 2 – Odra 2, Od 5/II – Odra 5/II, Oł IG-1 – Oława IG-1, Os N25 – Osieczów N25, Pa N27 – Parowa N27, Pi GT-1 – Pieszyce GT-1, Prz 1 – Przyborów 1, Ra W-4 – Radwanice W-4, Si P-5 – Sieciejów P-5, Sło IG-1 – Słocina IG-1, Sł G-8 – Słupiec G-8, St ST-1 – Staniszów ST-1, St W-17 – Stępin W-17, St IG-1 – Stęszów IG-1, Su – Suliszów, Szy IG-1 – Szymanów IG-1, Św IG-1 – Świdna IG-1, Sw 1-P – Świeradów 1-P, ŚrŚ IG-1 – Środa Śląska IG-1, Trz IG-1 – Trzebnica IG-1, UnŚ GW-19 – Unisław Śląski GW-19, UnŚ IG-1 – Unisław Śląski IG-1, Urz IG-1 – Urzuty IG-1, Wa IG-2 – Wawrzyńcowice IG-2, We IG-1 – Węgliniec IG-1, Wi IG-1 – Wilków IG-1, Wo IG-1 – Wojcieszów IG-1, Wo WT- 1 – Wojcieszyce WT-1, Wo W-8 – Wojnów W-8, Zd IG-1 – Żdanów IG-1

Rys. 1. Mapa dokumentacyjna na tle budowy geologicznej obszaru badań

### 1.2. Outline of hydrogeological conditions

The study area, according to the regional hydrogeological division, occurs within the Sudety Region (Sudetic Block), the Fore-Sudetic Subregion (Fore-Sudetic Block), and the Lower Silesia Region (Fore-Sudetic Monocline, Opole Basin; Paczyński and Sadurski eds. 2007).

Several aquifers with the characteristics of general-use groundwater are known from the tectonic units described above. The youngest aquifer includes alluvial formations of river valleys and fossil valleys (Malinowski ed. 1991). By far the most abundant are aquifers in the complex of Mesozoic formations (mainly Cretaceous and Triassic), representing dual-porosity (porous and fractured) groundwater reservoirs in the Fore-Sudetic Monocline, North-Sudetic Basin and Intra-Sudetic Basin, as well as the Opole Basin. In turn, in the crystalline Variscan basement rocks, groundwater is present mainly either in their weathering coat or within the tectonic fracture zones, which collectively represent the Proterozoic-Paleozoic aquifer.

The Sudetes' blocky structure, containing numerous tectonic discontinuities, such as faults and fracture zones (some of which show lineament characteristics), creates conduits favourable for deep water migration. This makes it possible for poorly mineralized geothermal water to occur within the basement rock of the Lower Silesia Block. This is illustrated by the documented occurrences of geothermal waters, such as those in Jelenia Góra-Cieplice and Karpniki (Sudetic Block) as well as Lądek-Zdrój and Duszniki-Zdrój (Orlica-Śnieżnik Dome).

They are of key importance both in terms of the possibility of exploiting the thermal energy they transport and in terms of offering an opportunity to determine the thermal potential of the study region.

## 2. Materials and methods

The results of measurements made in boreholes deeper than 500 m allow for the assessment of temperatures in the basement of the Lower Silesia Block area to a maximum depth of 2,500 m. The deepest of the analyzed boreholes does not exceed this depth, and, in general, as the depth increases, the amount of usable data decreases. In total, data from 80 boreholes drilled between the 1950$^{s}$ and the present time were verified (Figure 1B). In Fore-Sudetic Monocline, Opole Basin, Fore-Sudetic Block, and Sudetic Block 18, 5, 15, and 42 boreholes were drilled, respectively. These boreholes were drilled primarily in the 1960$^{s}$ and 1970$^{s}$, mainly as exploratory or mineral deposit-verifying boreholes. The most detailed assessment of the bedrock thermal conditions has only been conducted in hydrogeological boreholes in the last 20 years.

The temperatures at depths of 500, 1,000, 1,500, and 2,000 m were determined based on 73, 58, 35, 9, and 2 measurements, respectively. An analogous amount of data was available for measurements at specific depth levels (see Table 2). The most profound measured temperature was established in the Pieszyce GT-1 borehole at a depth of –2,150 m above sea level (a.s.l.). The boreholes from which the temperature profiles were taken are located at various elevations, from 65 m a.s.l. (Przyborów 1 borehole) To 698 m a.s.l. (Unisław Śląski GW-19 borehole).

This study is based exclusively on data coming from deep boreholes where continuous thermal profiling was conducted under conditions of steady and/or quasi-steady thermal equilibrium (after varying shutdown periods). Profiling results from 80 boreholes have been selected from the data available in the Central Geological Database. The exceptions to these are 3 deep boreholes where temperature measurements were performed during exploitation from artesian flow (Jelenia Góra-Cieplice C-1, Duszniki GT-1, Karpniki KT-1). In those cases, only the results of measurements from greater depths were used, assuming that exploitation/artesian flow caused only minimal disturbance to the primary thermal conditions.

The interpolation of the temperature data was performed using the kriging method. One of the most popular geostatistical methods, the Inverse Distance Weighted (IDW) concept, was chosen to perform the interpolation. Several interpolation methods were analyzed, including IDW, Ordinary Kriging (OK), and Radial Basis Functions (RBF). The application of all methods has shown similar interpolation error values, so the method that visually best represented the stratigraphy (smoothed, without kinks or serrations) was selected. The IDW method emphasizes local-scale variability and assumes that the spatial data differences depend on the distance between points. The weights in this linear combination are proportional to the inverse of the distance between the interpolated and control points (Philip and Watson 1982; Burrough and McDonnell 1998). In the literature, IDW has been applied to investigate air temperature distributions (Chuanyan et al. 2005; Ninyerola et al. 2007), as well as heat flow maps (Galgaro et al. 2015; Espinoza-Ojeda et al. 2023). The equation of the IDW can be expressed as (Bartier and Keller 1996):

$$z_{x,y} = \frac{\sum_{i=1}^{n} z_i w_i}{\sum_{i=1}^{n} w_i} \tag{1}$$

↳ $z_{x,y}$ – the interpolated point value,
$z_i$ – the control point value for the "ith" sample point,
$w_i$ – weigh that determines the significance of control points $z_i$,
$n$ – the number of control points located about the estimated point.

The effectiveness of the interpolation method can be assessed by calculating the interpolation errors, such as the root mean square error (RMSE). The formula for RMSE is:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(z_i - z_{x,y})^2} \quad (2)$$

↳ $n$ – the total number of observations.

The error values are presented in Table 1.

Table 1. *RMSE* (Root Mean Square Error) values for IDW (Inverse Distance Weighted) interpolation for selected drill holes

Tabela 1. *RMSE* (średni błąd kwadratowy) dla interpolacji IDW (metoda średniej ważonej odległością) dla wybranych otworów

| No. | Parameter | Number of points | *RMSE* |
|---|---|---|---|
| 1 | Heat flow | 68 | 15.8°C |
| 2 | Temperature at a depth of 500 m | 73 | 5.5°C |
| 3 | Temperature at a depth of 1,000 m | 58 | 5.7°C |
| 4 | Temperature at a depth of 1,500 m | 35 | 9.8°C |
| 5 | Depth where the temperature is 20°C | 66 | 127 m |

A map of the spatial variability of the heat flux density was also prepared, with different measurement sections used due to varying shutdown periods and borehole depths. The shallowest sections of the boreholes were excluded from the analysis, as it would be necessary to account for both climatic corrections (Pleistocene glaciations) and the influence of cold water of the shallow circulation system, which lowers the temperature of the rock medium/hydrothermal system. To date, these factors have been taken into consideration at only two locations in the Sudetes: in the Lądek-Zdrój and Niedźwiedź IG-2 boreholes (Puziewicz et al. 2012; Kiełczawa et al. 2024). Therefore, for boreholes with depths equal to or greater than 2,000 m, the geothermal gradient was determined for the lower sections, from a depth of 1,500 m to the bottom of the borehole. In the case of shallower boreholes, i.e., up to 1,000, 1,500, and 2,000 m, the sections from 500, 1,000, and 1,500 m to the bottom of the borehole were considered, respectively.

The data on the thermal conductivity of rocks were taken from geological/hydrogeological documentation and literature sources (Plewa 1994; Plewa et al. 1995; Plewa ed. 1996; Downorowicz 2018). Conductivity values were determined using the weighted average method, where the weights were the thicknesses of individual lithological units in the respective borehole sections.

Due to the geothermal classification of groundwater in Poland, as specified in the Geological and Mining Law (GML 2011), which classifies water with a temperature of no less than 20°C at the wellhead, the analyses also determined the probable depths at which such waters may occur.

## 3. Results

The results of the conducted analyses are consistent with the general pattern of increasing groundwater temperatures with the depth of the aquifer horizons. Nevertheless, zones in the boreholes with slightly lower groundwater temperatures often occur, indicating the inflow of colder waters from shallow circulation systems.

The temperatures at the analyzed depths and elevations are summarized in tables (Table 2a, 2b).

Table 2a. Summary of temperatures at the analyzed depths

Tabela 2a. Statystyki wartości temperatur na analizowanych głębokościach

| Depth (m) | Number of measurements | Temperature (°C) | | | |
|---|---|---|---|---|---|
| | | min. | max. | arithmetic mean | standard deviation |
| 500 | 73 | 13.1 | 45.3 | 22.8 | 5.8 |
| 1,000 | 58 | 24.1 | 52.2 | 33.9 | 5.9 |
| 1,500 | 35 | 31.1 | 78.4 | 46.9 | 8.4 |
| 2,000 | 9 | 50.0 | 96.1 | 59.8 | 14.5 |
| 2,500 | 2 | 58.9 | 67.9 | 63.4 | 6.4 |

Table 2b. Summary of temperatures at the analyzed ordinates

Tabela 2b. Statystyki wartości temperatur na analizowanych rzędnych

| Ordinate (m a.s.l.) | Number of measurements | Temperature (°C) | | | |
|---|---|---|---|---|---|
| | | min. | max. | arithmetic mean | standard deviation |
| 0 | 68 | 8.4 | 32.7 | 16.5 | 5.0 |
| –500 | 63 | 19.1 | 43.5 | 28.3 | 4.9 |
| –1,000 | 51 | 27.1 | 70.0 | 40.4 | 6.9 |
| –1,500 | 18 | 48.6 | 90.4 | 56.6 | 9.7 |
| –2,000 | 2 | 58.8 | 64.2 | 61.5 | 3.8 |

It was observed that the average temperature values increase from 22.8°C at a depth of 500 m to 63.4°C at a depth of 2,500 m. In turn, the average temperatures at individual elevations increased from 16.5°C at 0 m above sea level to 61.5°C at 2,000 m above sea level. So far, the highest temperature in the discussed area, 97.7°C, was recorded at a depth of 1,870 m in the Jelenia Góra-Cieplice C-1 borehole (Figure 2). It should be noted, however, that this borehole is located on a geothermal anomaly that influences the thermal conditions at this location (Fistek and Dowgiałło 2003).

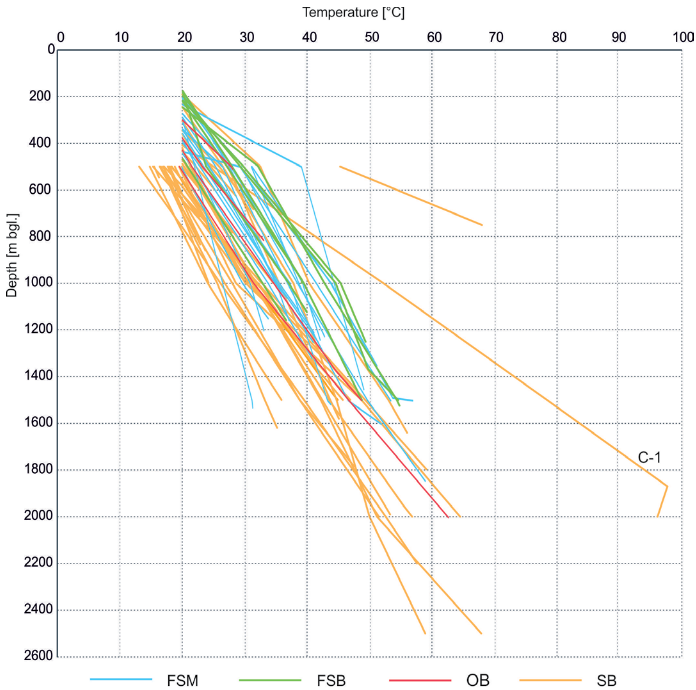



Fig. 2. Results of thermal logs in the analysed boreholes
FSM – Fore-Sudetic Monocline, FSB – Fore-Sudetic Block, OB – Opole Basin; SB – Sudetic Block

Rys. 2. Wyniki profilowań temperatur w analizowanych otworach
FSM – monoklina przedsudecka, FSB – blok przedsudecki, OB – niecka opolska, SB – blok sudecki

Temperatures of 20.0°C are observed over the depth range between approximately 180 m b.g.l. to 785 m b.g.l., with an average depth of 446.9 m b.g.l. (Table 3), the graphical presentation of which is shown in Figure 3.

The Żary Pericline and the region of Lądek-Zdrój and Duszniki-Zdrój (southeastern part of the study area – Figure 3) are areas where the mentioned temperature values were identified, on average, in the shallowest parts of the rock massifs, i.e., at approximately 210 m and 217 m b.g.l., respectively.

Table 3. Summary of the depth at which a temperature of 20°C can be reached

Tabela 3. Głębokości, na których można osiągnąć temperaturę 20°C

| Geological Unit | | Number of measurements | Depth (m) | | | |
|---|---|---|---|---|---|---|
| | | | min. | max. | arithmetic mean | standard deviation |
| Forsudetic monocline (FSM) | | 15 | 205 | 510 | 336 | 89 |
| Opole Basin (OB) | | 4 | 185 | 520 | 363 | 128 |
| Fore-Sudetic Block (FSB) | without Żary Pericline | 7 | 280 | 785 | 532 | 177 |
| | Żary Pericline (ŻP) | 6 | 180 | 250 | 210 | 27 |
| | all data | 13 | 180 | 785 | 383 | 209 |
| Sudetic Block (SB) | North-Sudetic Basin (NSB) | 9 | 305 | 780 | 536 | 132 |
| | Intra-Sudetic Basin (ISB) | 15 | 345 | 760 | 602 | 107 |
| | Bardo Structure (BS) | 2 | 420 | 680 | 550 | 184 |
| | Izera-Karkonosze Massif (IKM) | 3 | 360 | 520 | 429 | 82 |
| | Orlica-Śnieżnik Dome (OŚD) | 2 | 190 | 245 | 217 | 39 |
| | Góry Sowie Massif (GSM) | 1 | 430 | 430 | – | – |
| | Kaczawa Belt (KB) | 1 | 549 | 549 | – | – |
| | all data | 33 | 190 | 780 | 542 | 148 |

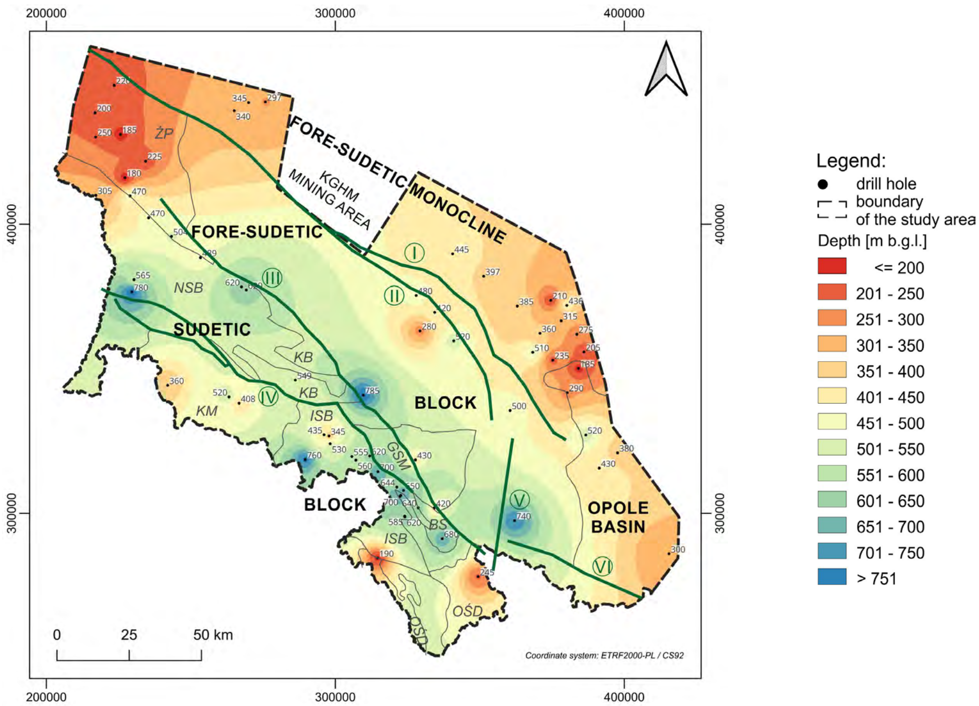



Fig. 3. Depths at which 20°C was measured; explanation of tectonic units as in Figure 1

Rys. 3. Głębokości, na których pomierzono temperaturę 20°C; objaśnienia jednostek jak na rys. 1

Most likely, due to the anomalous thermal conditions of the Jelenia Góra-Cieplice area, the 20°C temperature can also be observed relatively close to the ground surface at this location. The deepest occurrences of such temperatures were observed in the Intra-Sudetic Basin and Bardo Structure areas (Table 3, Figure 4). Even more significant differences can be observed when analyzing the elevations at which the temperature of 20.0°C was measured. They range from –568 m a.s.l. to 336 m a.s.l. (Figure 5).

On average, this temperature was recorded at the elevation of –181.5 m a.s.l., the lowest within the North-Sudetic Basin and Fore-Sudetic Block (excluding the Żary Pericline). At the same time, the highest was found in the Lądek-Zdrój area of the Orlica-Śnieżnic Dome. Despite the varied amount of data in the spatial distribution, it can generally be observed that at a depth of 500 m b.g.l., temperatures clearly increase towards the NW and NE, ranging from approximately 13°C (Szymanów IG-1) to as high as 39°C (Kotowice W-9) (Figure 6a).

The resulting image indicates areas of locally elevated temperature values in the Jelenia Góra-Cieplice, Duszniki-Zdrój, and Lądek-Zdrój areas, thus confirming thermal anomalies in these locations. In general, the low-temperature fields extend roughly along the major fault zones, such as the ISF (Intra-Sudetic Fault) and SMF (Sudetic Marginal Fault).

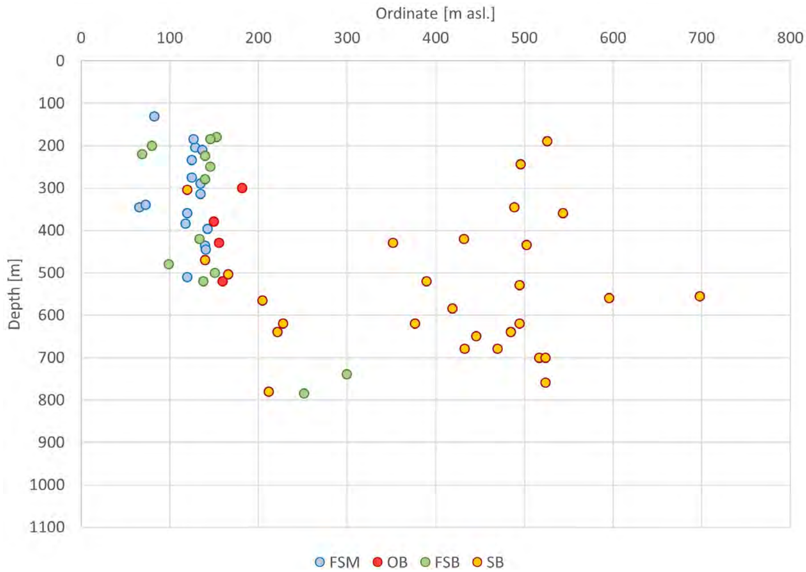



Fig. 4. Depths at which temperatures of 20°C were measured versus the height of the boreholes above sea level
FSM – Fore-Sudetic Monocline, FSB – Fore-Sudetic Block, OB – Opole Basin; SB – Sudetic Block

Rys. 4. Głębokości, na których pomierzono temperaturę 20°C
w zależności od położenia otworów nad poziomem morza

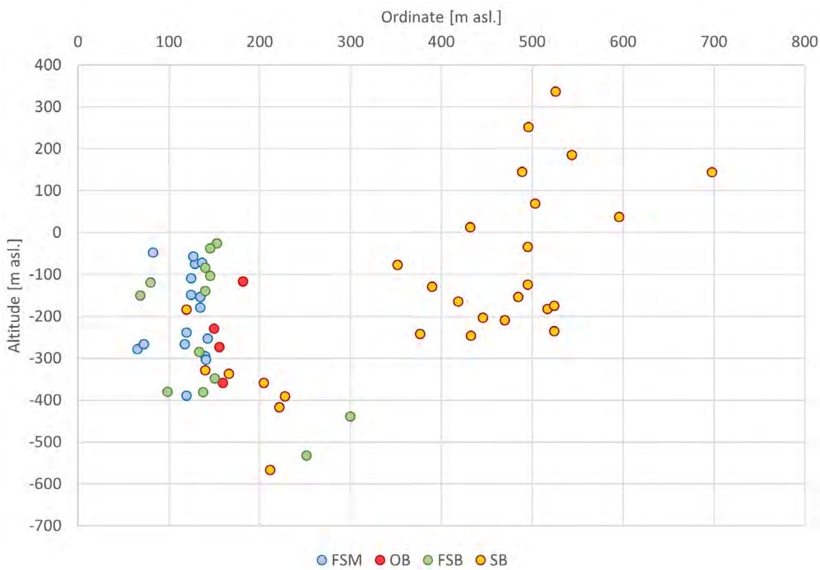



Fig. 5. Temperature ordinates of 20°C versus the altitude of the boreholes above sea level
FSM – Fore-Sudetic Monocline, FSB – Fore-Sudetic Block, OB – Opole Basin; SB – Sudetic Block

Rys. 5. Rzędne, na których pomierzono temperaturę 20°C
w zależności od położenia otworów nad poziomem morza

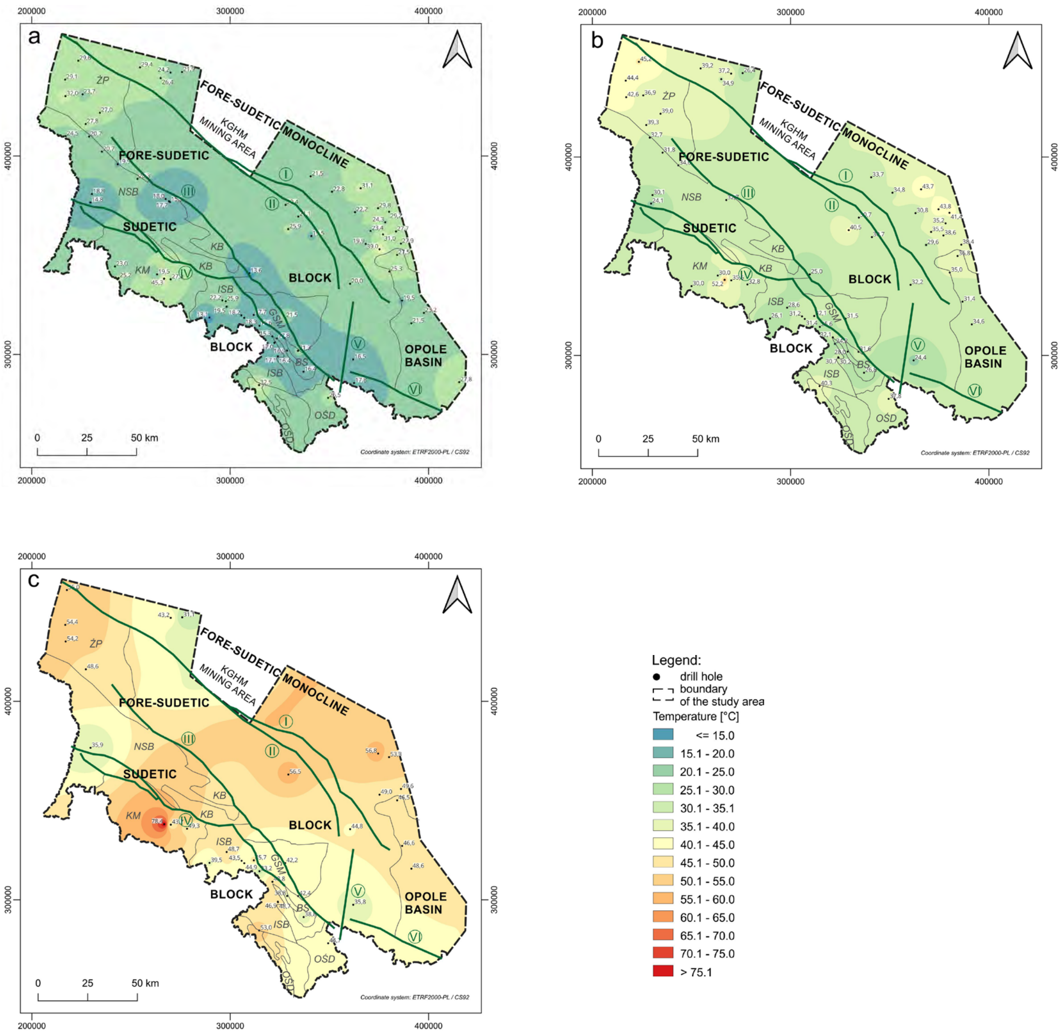



Fig. 6. Spatial temperature distribution at depths
a – 500 m b.g.l., b – 1000 m b.g.l., c – 1500 m b.g.l.; explanation of tectonic units as in Figure 1

Rys. 6. Zmienność temperatur na badanym obszarze na głębokościach
a – 500 m p.p.t, b – 1000 m p.p.t., c – 1500 m p.p.t.; objaśnienia jednostek tektonicznych jak na rys. 1

At a depth of 1,000 m b.g.l., a similar pattern was observed (Figure 6b). The temperature values range from approximately 24°C (Niedźwiedź IG-2) to a maximum of around 45°C (Górzyn P-3), with a similar trend of increasing values towards NW and NE. The area with relatively lower temperatures (25–30°C), including the distinct anomaly areas mentioned above, is significantly smaller. On the other hand, at a depth of 1,500 m b.g.l. (Figure 6c) the temperature distribution changes and anomalous areas are clearly distinguishable in the

Jelenia Góra-Cieplice (c. 78°C), Duszniki-Zdrój (53°C) and Nowa Rola (c. 54°C) areas. The extent of elevated temperatures in the NW part of the study area is confined to the Żary Pericline. The SE part of the study area is characterized by a significantly lower temperature (approximately 36°C) (Figure 6c).

The heat flux map (Figure 7) provides information on the thermal conditions shown on the previously discussed maps (Figure 6).

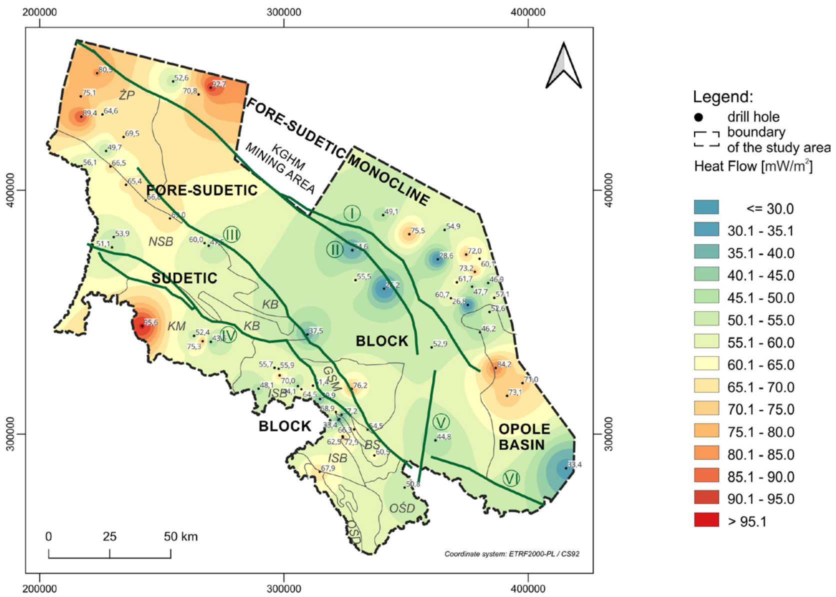



Fig. 7. Heat flux density variation; explanation of tectonic units as in Figure 1

Rys. 7. Zmienność gęstości strumienia cieplnego; objaśnienia jednostek tektonicznych jak na rys. 1

The influence of the tectonic block mosaic structure of the Sudetes and their foreland, along with their origin-lithological diversity and the variable degree of tectonic deformation, is clearly visible. The areas with the most promising thermal parameters are the Żary Pericline and the Karkonosze granitoid massif (approximately 90–95 mW/m$^2$). The Izera metamorphic complexes exhibit significantly higher heat flow values compared to the Karkonosze granitoids. This is understandable, considering the differences in the origin and lithology of these massifs. Similarly, the Orlica-Śnieżnik metamorphic complex is characterized by lower thermal parameters (heat flow around 51–68 mW/m$^2$). Similarly, reduced heat flow values (even below 30 mW/m$^2$) are observed within the Fore-Sudetic Block, with the exception of this zone being the northern part of the Opole Basin, with values ranging from 70 to 84 mW/m$^2$ (Figure 7).

Table 4. Summary of temperatures at different depths in different geological units.

Tabela 4. Zestawienie temperatur na różnych głębokościach w poszczególnych jednostkach geologicznych.

| Geological Unit | | Number of measurements | Depth (m) | Temperature (°C) | | | |
|---|---|---|---|---|---|---|---|
| | | | | min. | max. | arithmetic mean | standard deviation |
| Fore-Sudetic Monocline (FSM) | | 18 | 500 | 19.9 | 39.0 | 26.5 | 4.7 |
| | | 16 | 1,000 | 26.4 | 43.8 | 36.1 | 4.8 |
| | | 6 | 1,500 | 31.1 | 56.8 | 47.2 | 9.1 |
| Opole Basin (OB) | | 5 | 500 | 19.5 | 27.8 | 23.9 | 3.7 |
| | | 3 | 1,000 | 31.4 | 36,8 | 34.3 | 2.7 |
| | | 3 | 1,500 | 46.5 | 48.6 | 47,2 | 1.2 |
| | | 1 | 2,000 | 62.5 | 62.5 | – | – |
| Fore-Sudetic Block (FSB) | without Żary Pericline | 8 | 500 | 13.6 | 25.9 | 19.3 | 3.6 |
| | | 6 | 1,000 | 24.4 | 40.5 | 30.6 | 5.8 |
| | | 3 | 1,500 | 35.8 | 56.5 | 45.7 | 10.4 |
| | Żary Pericline (ŻP) | 6 | 500 | 23.7 | 32.0 | 28.2 | 2.8 |
| | | 6 | 1,000 | 36.9 | 45.2 | 41.3 | 3.3 |
| | | 4 | 1,500 | 48.6 | 55.0 | 53.0 | 3.0 |
| | all data | 14 | 500 | 13.6 | 32.0 | 23.1 | 5.5 |
| | | 12 | 1,000 | 24.4 | 45.2 | 35.9 | 7.2 |
| | | 7 | 1,500 | 35.8 | 56.5 | 49.9 | 7.5 |

| Geological Unit | | Number of measurements | Depth (m) | Temperature (°C) | | | |
|---|---|---|---|---|---|---|---|
| | | | | min. | max. | arithmetic mean | standard deviation |
| Sudetic Block (SB) | North-Sudetic Basin (NSB) | 10 | 500 | 14.8 | 24.5 | 19.1 | 2.8 |
| | | 6 | 1,000 | 24.1 | 34.6 | 31.0 | 3.7 |
| | | 1 | 1,500 | 35.9 | 35.9 | – | – |
| | Intra-Sudetic Basin (ISB) | 15 | 500 | 13.1 | 25.9 | 17.9 | 3.0 |
| | | 11 | 1,000 | 24.2 | 32.1 | 29.1 | 2.8 |
| | | 10 | 1,500 | 33.2 | 48.8 | 43.9 | 5.2 |
| | | 3 | 2,000 | 52.6 | 64.5 | 58.0 | 6.0 |
| | Bardo Structure (BS) | 2 | 500 | 16.4 | 21.3 | 18.9 | 3.5 |
| | | 2 | 1,000 | 26.8 | 31.6 | 29.2 | 3.4 |
| | | 2 | 1,500 | 38.8 | 42.4 | 40.6 | 2.5 |
| | | 2 | 2,000 | 51.5 | 53.3 | 52.4 | 1.3 |
| | Izera-Karkonosze Massif (IKM) | 6 | 500 | 19.5 | 45.3 | 27.6 | 9.1 |
| | | 5 | 1,000 | 30.0 | 52.2 | 36.1 | 9.3 |
| | | 3 | 1,500 | 43.7 | 78.4 | 57.1 | 18.6 |
| | | 1 | 2,000 | 96.1 | 96.1 | – | – |
| | Orlica-Śnieżnik Dome (OŚD) | 2 | 500 | 26.5 | 32.5 | 29.5 | 4.2 |
| | | 2 | 1,000 | 37.8 | 40.3 | 39.1 | 1.8 |
| | | 2 | 1,500 | 44.7 | 53.0 | 48.9 | 5.9 |
| | | 1 | 2,000 | 50.0 | 50.0 | – | – |
| | | 1 | 2,500 | 58.9 | 58.9 | – | – |
| | Góry Sowie Massif (GSM) | 1 | 500 | 21.5 | 21.5 | – | – |
| | | 1 | 1,000 | 31.5 | 31.5 | – | – |
| | | 1 | 1,500 | 42.2 | 42.2 | – | – |
| | | 1 | 2,000 | 51.2 | 51.2 | – | – |
| | | 1 | 2,500 | 67.9 | 67.9 | – | – |
| | all data | 36 | 500 | 13.1 | 45.3 | 20.5 | 5.9 |
| | | 27 | 1,000 | 24.1 | 52.2 | 31.7 | 5.5 |
| | | 19 | 1,500 | 33.2 | 78.4 | 45.6 | 9.4 |
| | | 8 | 2,000 | 50.0 | 96.1 | 59.5 | 15.5 |
| | | 2 | 2,500 | 58.9 | 67.9 | 63.4 | 6.4 |

## 4. Discussion

Using the available data, an attempt was made to compare the temperatures at different depths (Table 4) across the various tectonic units shown in Figure 2. At depths of 500 and 1,000 m, the highest average temperatures were calculated for the Fore-Sudetic Monocline, at 26.5°C and 36.1°C, respectively.

In the Opole Basin and the Fore-Sudetic Block, the average temperatures at these depths appeared to be approximately 3°C lower. In turn, over the Sudetic Block, the average temperature at depths of 500 and 1,000 m is ca. 5°C lower and amounts to 20.5°C and 31.7°C, respectively (Figure 6a, 6b). Within the Fore-Sudetic Monocline, Fore-Sudetic Block, and the Sudetic Block, at depths of 1,500 m and 2,000 m, the average temperatures reach similar values, i.e., 45.6–49.9°C (Figure 6c) and 59.5–62.5°C, respectively. So far, only two temperature measurements have been performed at a depth of 2,500 m in the discussed area, making it impossible to analyze the variability of thermal conditions for this depth.

In the Fore-Sudetic Block, at a depth up to 1.5 km, the highest temperatures were recorded in the north-western part of this unit, i.e., within the Żary Pericline (Table 4). These also represent the highest temperatures in the entire study area. If they are excluded from the general analyses of average temperature values at various depths, the resulting average temperatures become like those observed in the Sudetic Block.

Within the Sudetic Block, lower, yet mutually similar, average temperatures at various depths were recorded within the sedimentary tectonic units (North-Sudetic Basin, Intra--Sudetic Basin, and Bardo Structure). On the other hand, higher temperatures were observed within the crystalline tectonic units (Izera-Karkonosze Massif, Orlica-Śnieżnik Dome, and Góry Sowie Massif).

The relationships between temperature, lithology, and tectonics are apparent throughout the analyzed area. In the Fore-Sudetic Block, higher temperatures are observed in areas composed of Mesozoic compact sedimentary rocks (sandstones, mudstones, claystone, limestones, dolomites, etc.) occurring beneath Cenozoic sediments. On the other hand, lower temperatures, on average by 6–7°C, are observed at the same depths in areas composed of Lower Paleozoic and Proterozoic crystalline rocks. In turn, over the Sudetic Block, the conditions are different, with higher temperatures observed in areas composed of crystalline rocks (granites, gneisses, etc.). In areas where the cover of Mesozoic rocks rests on the crystalline basement, temperatures at the same depths are, on average, 6°C to 8°C lower.

Although the same temperatures are reached at greater depths in the Sudetic Block, compared to other analyzed tectonic units, it is in this unit that the highest temperatures are observed at individual elevations (Figures 2, 5, 8).

They are up to 10–20°C higher, regardless of the analyzed elevation 0, –500, –1,000 m a.s.l. Therefore, it can be assumed that this is the area with the most favorable thermal parameters in the study area, and consequently, it is characterized by the most significant thermal potential. Significantly less favorable thermal conditions occur in the central and eastern parts of the study area.

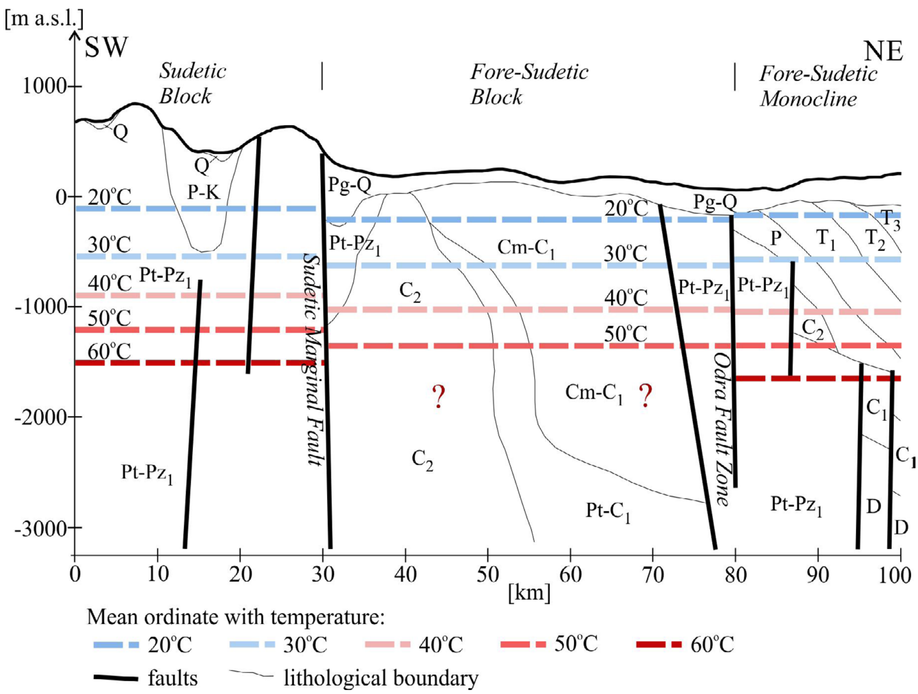



Fig. 8. Diagram of the temperature distribution in the study area
(geological structure according to https://geologia.pgi.gov.pl/mapy)
Age of rocks: Q – Quaternary, Pg – Paleogene, K – Cretaceous, $T_3$ – Upper Triassic, $T_2$ – Middle Triassic, $T_1$ – Lower Triassic, P – Permian, $C_2$ – Pennsylvanian, $C_1$ – Mississipian, D – Devonian, Cm – Cambrian, $Pz_1$ – Lower Paleozoic, Pt – Proterozoic.

Rys. 8. Schemat rozkładu temperatur na obszarze badań

## Conclusions

Although the distribution of boreholes in the discussed area is uneven, data from 80 boreholes were included in the study. Most of these boreholes are in the Fore-Sudetic Monocline area, in the northwest part of the Fore-Sudetic Block (Żary Pericline), and in three areas within the Sudetic Block (the western part of the North-Sudetic Basin, the Jelenia Góra Basin, and the former Lower Silesian Coal Basin). The remaining domains of the study area can only be characterized based on measurements taken in single boreholes.

Several factors influence the temperature variability observed at greater depths. The most important among them include the lithological variability, morphological position, tectonic involvement of the area, and its location relative to young volcanic areas. The current number of measurement points does not allow for a detailed analysis of the relationships between the factors mentioned above. The temperature distribution fields at particular depths correspond to the strike and extent of major tectonic zones such as the Intra-Sudetic Fault and the Sudetic Marginal Fault.

The temperature variations in the general picture are consistent with the extent of particular tectonic units of the Sudetic Block.

Although the results of the heat flux density analysis reflect changes in the thermal conditions across different depth sections and without accounting for the paleoclimatic correction (except for the Niedźwiedź IG-2 and LZT-1 boreholes), the resulting image provides an overview of the thermal field in the studied area, where the spatial distribution of the surface heat flux is consistent with the results of Majorowicz and of Karwasiecka and Bruszewska (after Majorowicz 2021).

The most favorable thermal conditions, and thus the highest thermal potential, were found in the areas of the Karkonosze granite and its metamorphic mantle (Jelenia Góra--Cieplice, Świeradów-Jakuszyce), as well as of the gneisses of the Orlica-Śnieżnik Dome (Duszniki-Zdrój, Lądek-Zdrój), within the Sudetic Block, and in the western part of the Fore-Sudetic Block – over the Żary Pericline (Lutol, Nowa Rola).

The lowest temperatures in the Initra-Sudetic Fault and Sudetic Marginal Fault regions are probably the result of deep migration of cold waters from shallow circulation systems into the tectonic zones of these areas.

This paper is the first such detailed analysis of the thermal conditions in the discussed area, providing an update and revision of the picture presented earlier by Bruszewska (2000).

*The research was supported by Wrocław University of Science and Technology, Faculty of Geoengineering, Mining and Geology, Department of Mining (4001/0020/23). The research is funded by the Polish National Fund for Environmental Protection and Water Management (agreement 579/2021/Wn-07/FG-go-dn/D).*

*The Authors have no conflict of interest to declare.*

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## GEOTHERMAL POTENTIAL OF SOUTH-WESTERN POLAND

Keywords

heat flux, SW Poland, geothermal potential

Abstract

The interpretation of geothermal conditions in SW Poland presented here is based on temperature logs from 80 boreholes, acquired under steady-state conditions at depths exceeding 500 m. The recent and archived drillhole data is also considered. The wells penetrate several tectonic units, including the Sudetes and their foreland, the Fore-Sudetic Monocline and the Opole Basin, each representing a different lithology and structure. Our interpretations offer the spatial temperature distribution over the study area, depending on the depth and height coordinates of the measurements. Average temperature values were observed to increase from 22.8°C at a depth of 500 m, to 63.4°C at a depth of 2.5 km. The highest temperature of 97.7°C was measured at a depth of 1,870 m in the Jelenia Góra-Cieplice C-1 well. Average temperatures at various elevations increase from 16.5°C (0 m a.s.l.) to 61.5°C (–2,000 m a.s.l.). Over the Sudetic Block, higher temperatures can be achieved at the same elevations, while greater depths are required to reach these temperatures in other tectonic units. The results are crucial to planning investments aimed at sustainable management of geothermal resources. They facilitate the identification of locations for new thermal water intakes and thus new sources of renewable energy. The knowledge of thermal conditions of the area makes it possible to plan optimal use of water and geothermal energy in various sectors of the economy (heating, agriculture, recreation, balneotherapy) thus boosting economic development of the region, increasing energy efficiency and limiting negative environmental impact.

## POTENCJAŁ GEOTERMALNY POŁUDNIOWO-ZACHODNIEJ POLSKI

S ł o w a k l u c z o w e

potencjał geotermalny, strumień ciepła, SW Polska

S t r e s z c z e n i e

W artykule przedstawione zostały warunki geotermiczne południowo-zachodniej Polski. Do interpretacji wykorzystano wyniki profilowań temperatur wykonanych w 80 otworów wiertniczych (w warunkach ustalonych) o głębokościach przekraczających 500 m. W badaniach uwzględniono dane archiwalne oraz z otworów odwierconych w ostatnich latach. Otwory te zlokalizowane są w kilku jednostkach tektonicznych (Sudety i ich przedgórze, monoklina przedsudecka, niecka opolska) o zróżnicowanej budowie litologicznej. Wykonane interpretacje umożliwiły przedstawienie przestrzennego rozkładu temperatur na badanym obszarze w zależności od głębokości i rzędnych wysokościowych pomiaru. Zaobserwowano, że wartości średnie temperatur wzrastają od 22,8°C – na głębokości 500 m do 63,4°C – na głębokości 2,5 km. Najwyższa temperatura 97,7°C została zmierzona na głębokości 1970 m w otworze Cieplice C-1. Średnie temperatury na poszczególnych rzędnych wzrastają od 16,5°C (0 m n.p.m.) do 61,5°C (–2000 m n.p.m.). Na obszarze bloku sudeckiego możliwe jest uzyskanie wyższych temperatur na tych samych rzędnych, zarazem wyższe temperatury uzyskuje się na większych głębokościach w porównaniu do warunków stwierdzonych w innych analizowanych jednostkach. Uzyskane wyniki mają kluczowe znaczenie dla planowania inwestycji ukierunkowanych na zrównoważone gospodarowanie zasobami geotermalnymi omawianego obszaru. Ułatwiają wskazanie lokalizacji dla nowych ujęć wód termalnych, a zatem nowych źródeł odnawialnej energii. Znajomość warunków termicznych umożliwia zaplanowanie optymalnego wykorzystania wody i energii geotermalnej w różnych sektorach gospodarki (ciepłownictwo, rolnictwo, rekreacja, balneoterapia) co zwiększa efektywność energetyczną i ogranicza negatywne oddziaływanie na środowisko.