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Shallow subsurface temperature at the selected locations in Poland

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ABSTRACT

Assessment of resources and environmental conditions for the implementation of low-temperature (low-enthalpy) geothermal energy as a source of carbon-free energy is one of the tasks carried out by the Polish Geological Institute - National Research Institute (the Polish Geological Survey). These activities are being implemented to assess the temperature regimes in the context of the local geology, tectonics, hydrogeology and anthropogenic influence, providing reference data for the development of the low-temperature geothermal potential maps and supporting decarbonization of the energy sector.

In 2021 five boreholes were drilled at diverse locations across the country to take into account different natural conditions. Each borehole has a heat exchanger with a single U-pipe installed. In 2021, the test temperature measurements and TRT tests were conducted, while in 2022-2023 regular measurements were carried out at quarterly intervals for the individual year seasons. Results for the most shallow part of the subsurface, up to about 2-5 meters deep, indicate a strong relationship between its temperature and the climatic and weather conditions. Further on, this subsurface temperature zone is referred as to a zone of daily and seasonal temperature changes. Below subsurface temperature variability gradually decreases with depth and is less dependent on external factors. At the depth of usually 15-25 meters, depending on location, temperature stabilizes and is close to the value of average ambient air temperature at the given location. This subsurface temperature zone, called the zone of neutral or transient temperatures, can persist down to about 50-60 meters of depth or even more. Deeper down the subsurface temperature starts to increase according to the value of the geothermal gradient. Subsurface temperature values derived from research presented in this paper depend also to some extent on various geo- and anthropogenic factors, such as thermal properties of the rocks, e.g. thermal conductivity, presence of aquifers, climatic anomalies and presence of subsurface infrastructure.

1. INTRODUCTION

The Polish Geological Institute - National Research Institute under the terms of the Polish Geological Survey implements a continuous task entitled "Assessment of energy potential and environmental conditions to support the sustainable development of low-temperature geothermal energy". This includes temperature logging and measurements as well as tests of thermal properties of shallow subsurface within the geological observation boreholes made especially for this purpose.

In general, borehole temperature logging is performed to study spatial and temporal changes according to Davis et al. (2010) as well as temperature distribution in the subsurface at local and regional scales. Subsurface temperature data is crucial for providing reference data for the development of the low-temperature geothermal potential maps completed by the PGI-NRI under the terms of the international projects, such as TransGeoTherm, Geothermal4PL and GeoPLASMA-CE as well as the national project i.e. "Map of Poland's low-temperature geothermal potential in 1:50 000 scale. Stage I - continuous task", shortly called MPGN. Results of subsurface temperature measurements are also useful for observing climatic changes, according to e.g. Bodri and Čermák (1997) and Chisholm and Chapman (1992), monitoring the performance of borehole heat exchangers and other low-temperature geothermal installations according to e.g. Aranzabal et al. (2019), Michalski and Klitzsch (2019), Beier et al. (2012) and Beier et al. (2013), characterizing aquifer dynamics and estimating thermal properties of subsurface according to e.g. Moscoso Lembcke (2016) as well as for some other reasons.

This paper presents the results of research carried out between 2021 and 2023. The main goal of the studies was to identify the temperature regime of the subsurface in the context of the local geology and hydrogeology and in some cases also anthropogenic influence. The research results provide data for the development of the maps of low-temperature geothermal potential for the selected areas in Poland. The overall goal of the task of the Polish Geological Survey described in this paper is to support the development and use of low-temperature geothermal energy as a renewable energy source in the context of decarbonizing the national economy.

2. MATERIALS AND METHODS

2.1 Location and construction of the observation boreholes

In spring 2021 five boreholes were drilled at diverse locations in Poland, i.e. in Bielsko-Biała, Budzów, Halinów, Wojcieszyce and Wrocław. Their position as well as the location of the low-temperature potential maps sheets is shown in Figure 1. This selection ensures the conducting of observations under diverse natural conditions. Each observation borehole has a borehole heat exchanger (BHE) installed, i.e. a single U-tube filled with an aqueous solution of propylene glycol, the so-called brine. The boreholes are not used to obtain thermal energy from the subsurface, while their design allows for carrying out temperature point measurements, temperature logging and thermal response tests (TRT). Each single U-tube is made of two sections of PE pipe with an inner diameter of 40 (mm), connected at the bottom with a welded sleeve thus constituting a closed hydraulic system. The endings of the PE pipes are led to an inspection well and closed with the ball valves, while one of them has a manometer mounted. The inner diameter of all five boreholes is 140 (mm), and the total depth is 99.0 meters. The space between the BHE and the wall of each borehole along its entire length is grouted with cement showing a high thermal conductivity coefficient, the so-called thermocement. Grouting aims at isolating the aquifers, preventing the mixing of different types of water, inrush of fluids into and along the borehole as well as the migration of any substances from the ground surface. The main purpose of grouting with the thermocement, however, is to ensure the best possible thermal contact between the solution in the U-tube and the subsurface (rocks and groundwater). Figure 2 illustrates the inner construction of the observation boreholes.

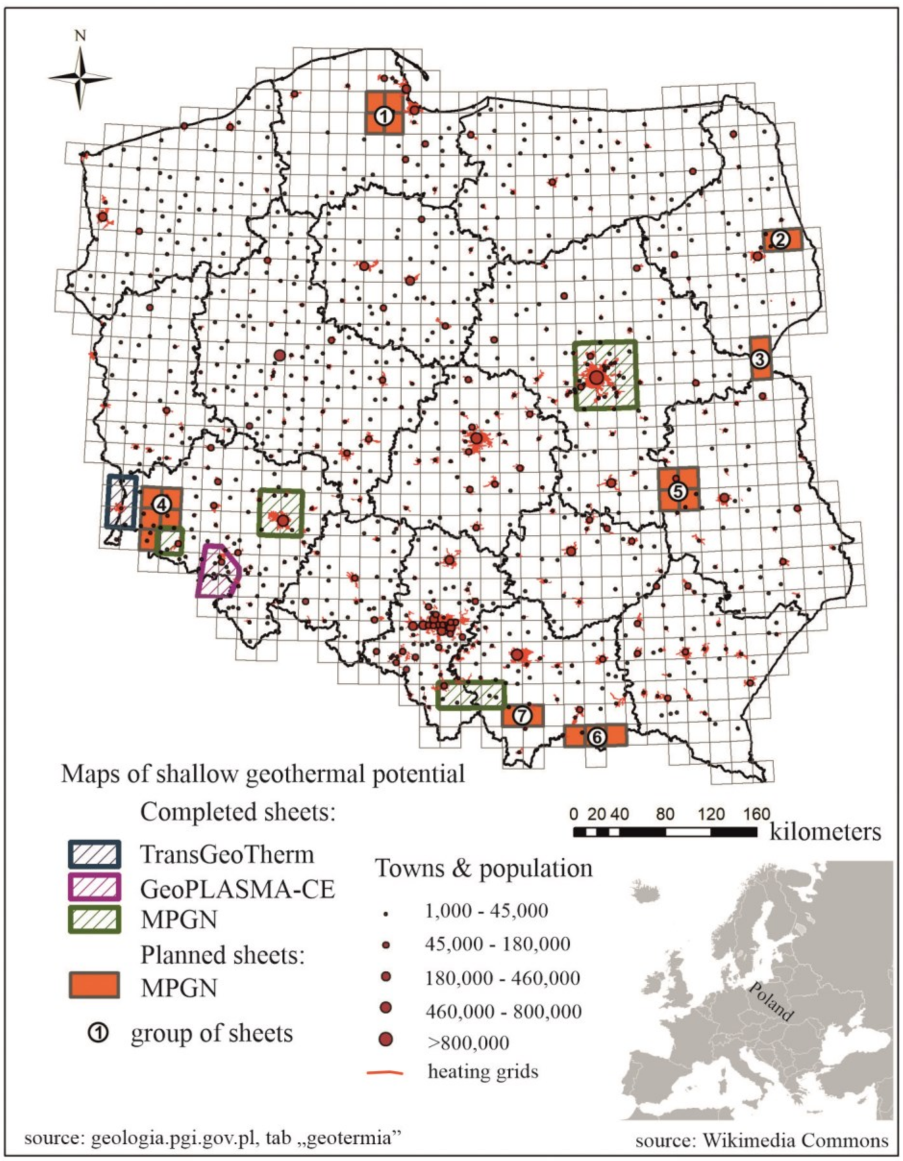

Figure 1: Location of the observation boreholes and sheets of the low-temperature potential maps on the contour map of Poland.

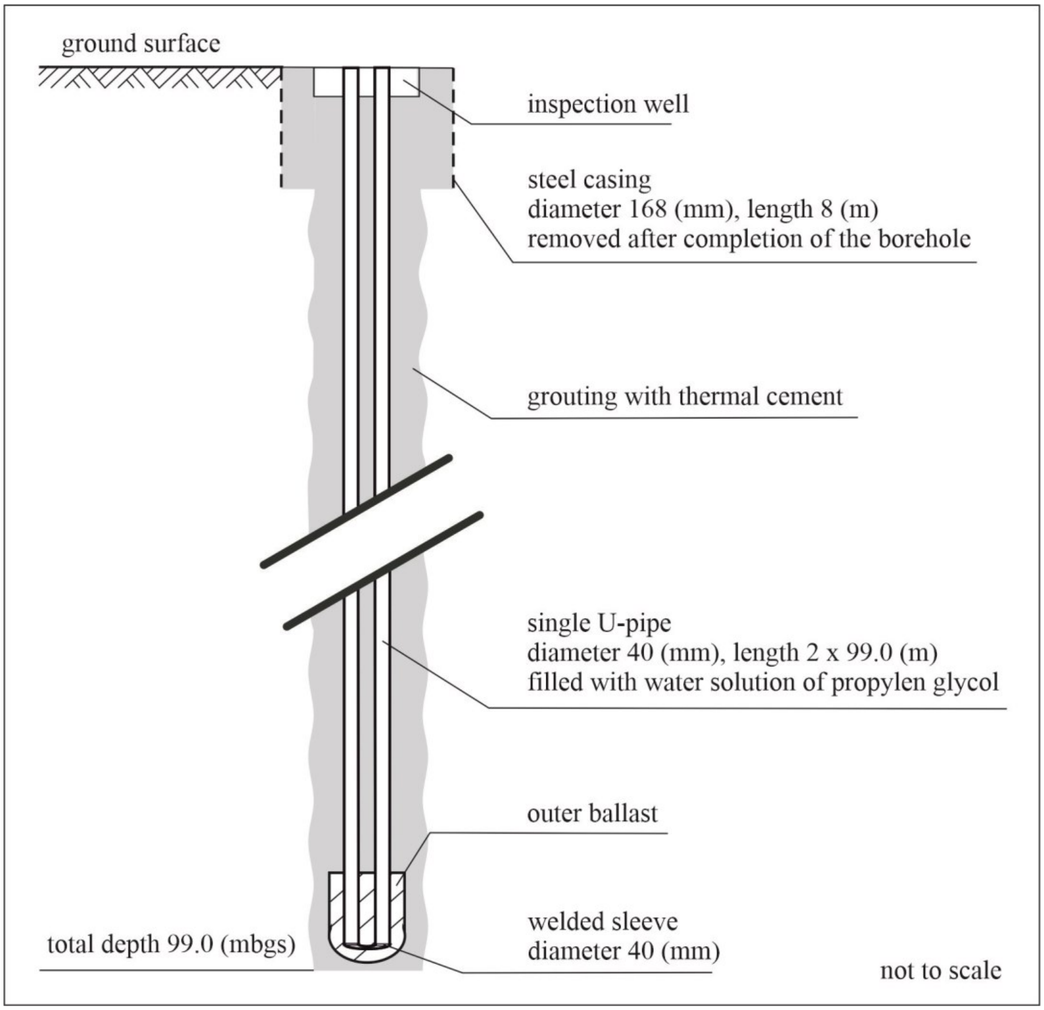

Figure 2: Schematic inner construction of the observation boreholes.

2.2 Geology and hydrogeology

The studied observation boreholes are described below in order of their altitude measured in (masl) – from the highest to the lowest value. General characteristics of the observation boreholes are given in Table 1.

The observation TP-1 Wojcieszyce is located in southwestern Poland, in the Lower Silesian Voivodship, approximately 100 kilometers southwest of Wrocław. The borehole is placed in the green area of the village at an altitude of 426.75 (masl). Geologically it is situated in the western part of the Sudetic Block dominated by the Izera-Karkonosze Massif constituting according to Kozłowski et al. (2016) a crystalline basement. The borehole profile contains diverse types of granitoides and gneisses. The hard rocks are normally covered with a thin layer of regolith. The fissured and weathered zones within the crystalline massive form three thin aquifers, two bottom ones of them are confined, however, their hydrogeological properties are rather limited.

The observation borehole TP-1 Bielsko-Biała is located in southern Poland, in the Silesian Voivodship, approximately 50 kilometers south of Katowice. The borehole is placed in the built-up area at the altitude of 349.14 (masl). Geologically it is situated within the southern part of the Upper Silesia Block called Bielsko-Biała Dome. This is formed by the Neoprotherozoic crystalline rocks and Ediacarian metaclasstic rocks covered with the younger sedimentary series of the Outer Carpathians as proved by Golonka et al. (2009). The top of the borehole profile comprises about 10 meters thick Quaternary rocks including regolith, sands and gravels. Underneath lies a thick series of Cretaceous dark shales and marly shales with interbedded layers of sandstones. The Cretaceous formation is underlain by the Jurassic sandstones, shales and limestones the top of which lies well below the bottom of the borehole. The confined aquifer is formed by the fissured-porous Cretaceous rocks with its top at 24.0 (mbgs).

The observation borehole TP-1 Budzów is located in southern Poland, in the Lesser Poland Voivodship, approximately 35 kilometers southwest of Cracow. The borehole is placed in the green area of the village at an altitude of 334.58 (masl). Geologically it is situated within the sedimentary series of the Magura Nappe which is the largest unit of the Outer Carpathians in Poland. This geological unit consists mainly of the Paleogene and the Upper Cretaceous rocks comprising the interbedded layers of shales and sandstones called the Carpathian Flysch as proved by Golonka et al. (2009). At the top of the borehole profile lies the 9 meters thick layer of the Quaternary sands and tills. Beneath the Paleogene flysch series is present consisting of the interbedded layers of pale gray sandstones with calcite, sandstones with glauconite and dark gray shales. The confined aquifer is formed within the fissured-porous sandstones and shales present at a depth of about 15.0 (mbgs).

The observation borehole TP-1 Wrocław is located in southwestern Poland, in the Lower Silesian Voivodship, in the southern part of the city. The borehole is placed in the green area in the outskirts of the city center at an altitude of 125.21 (masl). Geologically it is situated within the relatively narrow zone of the Middle Odra Horst covered with younger deposits. The upper part of the deposits, according to Badura et al. (2004), are formed by the Cainozoic sediments. The borehole profile covers the various Quaternary sediments about 44 meters thick consisting of interbedded layers of fine and coarse sands, gravels, loams and tills of fluvioglacial origin. A layer of coarse sands and gravels forms the unconfined aquifer. The underlying Neogene sediments comprise mostly of clays and tills as well as to a lesser extent of sands and gravels forming the confined aquifer.

The observation borehole TP-1 Halinów is located in central Poland, in the Masovian Voivodship, approximately 25 kilometers east of Warsaw agglomeration. The borehole is placed in a wasteland lying in the industrial area at the altitude of 117.94 (masl). Geologically it is situated within the Quaternary and Neogene sediments deposited on the much older rocks on the East European Platform. The Quaternary sediments consist of tills, sands and gravels of fluvioglacial origin. Their thickness in the borehole reaches 24.0 meters. Those are underlain by the Paleogene deposits with prevailing clay layers with some thin insertions of graves and loams. The confined porous aquifer is formed by the 10 meters thick gravels the top of which lies 14.0 (mbgs).

Table 1: General characteristics of the observation boreholes.

Parameter Observation borehole	Altitude (masl)	Depth (mbgs)	Rock types*: age, lithostratigraphy, depth range (mbgs)	Aquifers*: depth range (mbgs), hydraulic type, matrix type, depth to groundwater table (mbgs), thickness excluding interbedding aquicludes (meters)	Land use type
TP-1 Wojcieszyce	426.75	99.0	Q, regolith, tills, 0.0-8.0 Pt + C dark augen and banding gneisses with intrusions of granitoides, 8.0->99.0	35.0-36.0, u, f, NN, 1.0 55.0-56.0, c, f, NN, 1.0 60.0-61.0, c, f, NN, 1.0	rural, green area
TP-1 Bielsko-Biała	349.14	99.0	Q, sands, gravels and regolith, 0.0-12.0 Cr, interbedded layers of sandstones, dark shales and marly shales, 12.0->99.0	24.0-NN, c, f-p, NN, NN	urban, built-up area
TP-1 Budzów	334.58	99.0	Q, sands and gravels, 0.0-9.0 P, interbedded layers of fine- and coarse sandstones and dark gray shales, 9.0->99.0	15.0-NN, c, f-p, 1.77, NN	rural, green area
TP-1 Wrocław	125.21	99.0	Q, interbedded layers of tills, gravels and medium and coarse sands, 0.0-44.0 Ng, clays, loams, sands and gravels, 44.4->99.0	6.0-16.0, c, p, NN, 8.0 76.0-78.0, c, p, NN, 2.0 86.0-NN, c, p, NN, NN	urban, green area
TP-1 Halinów	117.94	99.0	Q, tills, medium sands and coarse sands with gravels, 0.0-24.0 Ng, clays, clays with insertions of loams, 24.0->99.0	14.0-24, c, p, 3.5, 10.0	industrial, wasteland

*order of description is from the top to the bottom of the borehole

Stratigraphy: Q – Quaternary, Ng – Neogene, Pg – Paleogene, Cr – Cretaceous, J – Jurassic, C – Carboniferous, Pt – Proterozoic

Aquifer hydraulic type: u – unconfined, c – confined

Aquifer matrix type: p – porous, f – fissured, f-p – fissured-porous

NN – unknown value or parameter

2.3 Temperature measurements

In 2022, after maintaining a shut-in time of about four to six weeks, a series of test measurements and the TRT tests were performed for all observation boreholes. Since 2023 on temperature logging has been performed for each borehole regularly in spring, summer, autumn and winter. Initially, the thermometers with PT100 sensor equipped with a tape measure were used. At first, the point temperature measurements within the U-pipe were taken with a diverse resolution for different depth intervals, i.e. 0.5-1.0 meters for the upper 20 meters of the temperature profile, and 2.0-5.0 meters below that. The drawback of this method was limitation of research method to point measurements only. Thereafter a portable set of two recorders by Solinst Canada Ltd., i.e. Levelogger 5 and Barologger 5 3001 model were implemented. Each of them is equipped with temperature and pressure sensors, however, the earlier is used for downhole measurements, while the latter for measurements of the ambient conditions at the ground surface. The sensors of both recorders are calibrated by the producer and do not require calibration before each measurement series. The software Levelogger 4.6.3 enables barometric compensation of measurement records of both recorders as described in User Guide Levelogger Series Solinst Canada Ltd. (2023). The recorders Levelogger 5 and Barologger 5 enable flexible modification of sampling frequency thanks to which the temperature logging methodology was gradually optimized. The Levelogger 5 recorder was lowered down into the U-pipe on the Kevlar rope with an average speed of approximately 4 (m/min), while the temperature sampling frequency was usually set to 4 (sec). In that way, the depth-dependent temperature measurements yield nearly continuous results allowing for their detailed analysis.

2.4 Estimation of the average subsurface temperature of a borehole heat exchanger.

One of the decisive factors for the rate of heat exchange and the overall performance of BHE is the temperature of the subsurface in the vicinity of the BHE. The temperature of the subsurface can be taken as the undisturbed average temperature of the borehole wall calculated using a weighted average of the temperatures of the individual thermal zones. In the shallow parts of the subsurface, up to about 100 (mbgs), the temperature is normally influenced by the following factors:

- the annual average temperature at the ground surface, i.e. daily and seasonal temperatures,
- transient temperature zones (seasonal zone, long term variations of the mean annual surface temperature and shallow groundwater flow affected by seasonal temperature variations),
- the geothermal gradient dependent zone influenced by the following heat transport processes:
  - thermal conduction related to the terrestrial heat flux,
  - thermal advection in the presence of groundwater flow,
  - thermal convection in the presence of thick and highly permeable groundwater bodies.

The methodology for estimating the average subsurface temperature along a BHE comprises the subsequent primary procedural stages:

- evaluation and validation of temperature measurements,
- aggregation of the mean annual surface temperature,
- examination of temperature gradients at the individual borehole positions in accordance with the principal thermal zones,
- formulation of temperature gradient models for the distinct thermal zones of the uppermost subsurface,
- computation of the average temperature based on both default and explicitly defined configurations.

The mean annual ground surface temperature, denoted as T_0, serves as an initial point in this approach. For simplicity, it can be assumed that this is an average annual air temperature in the area of a given observation borehole. This computation of the resultant subsurface temperature as developed by Görtz et al. (2019) involves the summation of gradients pertinent to distinct depth zones:

- The thermal gradient spanning from the mean annual surface temperature to the constant temperature T_1 at the base of the seasonal zone at depth z_1. If shallow groundwater aquifers are present within the uppermost 20 meters of the subsurface, T_1 can be estimated by the annual mean groundwater temperature at the aquifer's bottom (z_1):

$$gradT_{0,1} = \frac{T_1 - T_0}{z_1} \tag{1}$$

  where: $gradT_{0,1}$, T_0, T_1, z_1 are seasonal zone gradient, mean annual surface temperature, constant temperature at the bottom of the daily and seasonal subsurface temperature zone, depth to the bottom of the daily and seasonal subsurface temperature zone, respectively.

- The thermal gradient from T_1 to the temperature T_2 at the base of the transient temperature zone at depth z_2:

$$gradT_{1,2} = \frac{T_2 - T_1}{z_2 - z_1} \tag{2}$$

  where: the T_1, z_1 variables mean the same as in equation (1) and $gradT_{1,2}$, T_2, z_2 are transient zone gradient, temperature at the bottom of the transient subsurface temperature zone and depth to the base of the transient subsurface temperature zone, respectively.

- The geothermal gradient applicable to depths beyond z_2, indicae a steady-state temperature regime. This geothermal gradient characterizes either the conductive steady-state temperature conditions or may be influenced by deep circulating groundwater zones leading to steady-state conditions.

$$gradT = \frac{q}{TC} \tag{3}$$

where: *gradT, q, TC* are geothermal gradient, terrestrial heat flux and subsurface thermal conductivity, respectively.

Given that the entire length of a BHE, denoted as "*l*," encompasses all thermal zones within subsurface model, the weighted average subsurface temperature is computed as follows:

$$T_{mean}(l) = T_0 + gradT_{0,1} \cdot \frac{z_1^2}{l} + gradT_{1,2} \cdot \frac{(z_2-z_1)^2}{l} + gradT \cdot \frac{(l-z_2)^2}{l} \tag{4}$$

where: T_{mean}, T_0, $gradT_{0,1}$, z_1, l, $gradT_{1,2}$, z_2 are average subsurface temperature, mean annual surface temperature, seasonal zone gradient, depth at the base of the seasonal zone, BHE length, transient zone gradient, depth to the base of the transient zone, respectively.

3. RESULTS

The depth-dependent temperature patterns measured for the studied observation boreholes are to a major extent similar in case of both 2022 and 2023. The statistical parameters of the temperature measurement results for the individual boreholes for 2022 and 2023 are presented in Table 2, while Figure 2 shows the patterns of the depth-dependent temperature logging for 2023.

The temperature values measured in all observation boreholes in 2022 ranged between 5.70-15.90 (°C), while for 2023 between 6.00 and 18.66 (°C). For each temperature profile, the different depth zones associated with different subsurface temperature variability depending on different factors can be identified. The extreme minimum and maximum temperature values were measured for winter and summer, respectively, up to the depth of approximately 2-5 (mbgs). This near-surface zone is the most dependent on external factors connected for example with weather and climate, therefore it is called the daily and seasonal changes subsurface temperature zone. The maximum difference for the temperature values between winter and summer seasons reaching up to 12.40 (°C) was recorded for the observation borehole TP-1 Halinów in 2023, while the lowest one of 7.99 (°C) was measured for the borehole TP-1 Wojcieszyce in 2022. In general, the difference between maximum and minimum temperatures for all studied boreholes was higher in 2023 than in 2022.

Underneath, the temperature is decreasing and shows gradually lesser temperature differences between the extreme values. At the depth of about 15-25 (mbgs), depending on the borehole, the temperature values reach the so-called zone of transitional or neutral temperatures where the temperature of the subsurface is close to the average value of annual atmospheric air temperature for a given location, however, it shows some small variability, i.e. it may slightly increase or decrease. The thickness of that zone is very different and varies very much between the individual observation boreholes. Below, the subsurface temperature normally increases according to the local geothermal gradient value, however, this effect is not well visible for all studied boreholes.

Table 2: Statistical characteristics of temperature measurements results (°C) in the observation boreholes for 2022 and 2023.

Observation borehole, year	Min	Max	T_{max} - T_{min}	Average	Median	Standard deviation
TP-1 Wojcieszyce, 2022	7.40	15.39	7.99	10.07	10.00	0.21
TP-1 Wojcieszyce, 2023	7.80	17.85	10.05	10.09	9.94	0.56
TP-1 Bielsko-Biała, 2022	7.20	15.68	8.48	11.27	10.93	0.33
TP-1 Bielsko-Biała, 2023	8.01	18.66	10.65	11.53	10.92	1.10
TP-1 Budzów, 2022	5.70	14.88	9.18	10.20	10.07	0.34
TP-1 Budzów, 2023	6.13	17.10	10.97	10.08	9.94	0.51
TP-1 Wrocław, 2022	7.20	15.92	8.72	10.73	10.65	0.29
TP-1 Wrocław, 2023	6.84	15.81	8.97	10.76	10.61	0.29
TP-1 Halinów, 2022	6.00	15.90	9.9	9.73	9.35	0.69
TP-1 Halinów, 2023	6.00	18.40	12.40	9.52	9.28	0.41

For the observation borehole TP-1 Wojcieszyce, in both 2022 and 2023, the daily and seasonal temperatures zone reached down to about 20 (mbgs), while the zone of neutral temperatures continued down to about 60 (mbgs). Below a slight growth of temperature can be observed. For the observation borehole TP-1 Bielsko-Biała the daily and seasonal temperatures zone in 2022 reached down to about 13 (mbgs), while in 2023 it was deeper and reached down to about 30 (mbgs). This is rather a large difference which might result not only from the natural conditions, i.e. different subsurface temperatures in 2022 and 2023 but also to a significant extent from the manner of performance of temperature profiling in the borehole. This effect might also be visible to a smaller extent in other studied boreholes. Underneath the zone of neutral temperatures was observed.

For the observation borehole TP-1 Budzów, the daily and seasonal temperatures zone reached down to about 15 (mbgs) in 2022 and 25 (mbgs) in 2023. Underneath the zone of neutral temperatures was observed below which growth of subsurface temperature started at the depth of about 50 (mbgs). For the observation borehole TP-1 Wrocław, the daily and seasonal temperatures zone reached down to about 12 (mbgs) in 2022 and 25 (mbgs) in 2023. Underneath the zone of neutral temperatures was observed below which temperature of the subsurface started to grow at the depth of about 55 (mbgs). For the observation borehole TP-1 Halinów, the daily and seasonal temperatures zone reached down to about 25-30 (mbgs) in 2022 and 15 (mbgs) in 2023. Underneath the zone of neutral temperatures was observed, however, no distinctive temperature growth can be observed for this observation borehole. Characteristics of seasonal temperature profiles for the studied observation boreholes for 2022 and 2023 are presented in Table 3.

Table 3: Characteristics of seasonal temperature profiles for the studied observation boreholes for 2022 and 2023.

Observation borehole, year	Approximated depth range of daily and seasonal temperatures zone (mbgs)	Type of rocks	Approximated depth range of the neutral temperatures zone (mbgs)	Type of rocks	Approximated start of temperature growth according to geothermal gradient value (mbgs)	Type of rocks
TP-1 Wojcieszyce, 2022	0 - 20	regolith & gneisses	20 - 60	gneisses with intrusions of granites	60	gneisses with intrusions of granites
TP-1 Wojcieszyce, 2023	0 - 20	regolith & gneisses	20 - 60	gneisses with intrusions of granites	60	gneisses with intrusions of granites
TP-1 Bielsko-Biała, 2022	0 - 13	sands, gravels, regolith	13 - 80	sandstones & shales	80	sandstones & shales
TP-1 Bielsko-Biała, 2023	0 - 30	sands, gravels, regolith sandstones & shales	30 - 80	sandstones & shales	80	sandstones & shales
TP-1 Budzów, 2022	0 - 15	sands, gravels, regolith	15 - 50	sandstones & shales	50	sandstones & shales
TP-1 Budzów, 2023	0 - 25	sands, gravels, regolith sandstones & shales	25 - 50	sandstones & shales	50	sandstones & shales
TP-1 Wrocław, 2022	0 - 12	tills, gravels, sands	12 - 55	tills, gravels, sands clays, loams, sands, gravels	55	clays, loams, sands, gravels
TP-1 Wrocław, 2023	0 - 25	tills, gravels, sands	25 - 55	tills, gravels, sands clays, loams, sands, gravels	55	clays, loams, sands, gravels
TP-1 Halinów, 2022	0 - 25	tills, gravels, sands	25 - NN	clays, loams, sands	NN	clays, loams, sands
TP-1 Halinów, 2023	0 - 15	tills, gravels, sands	15 - NN	clays, loams, sands	NN	clays, loams, sands

NN- unknown value

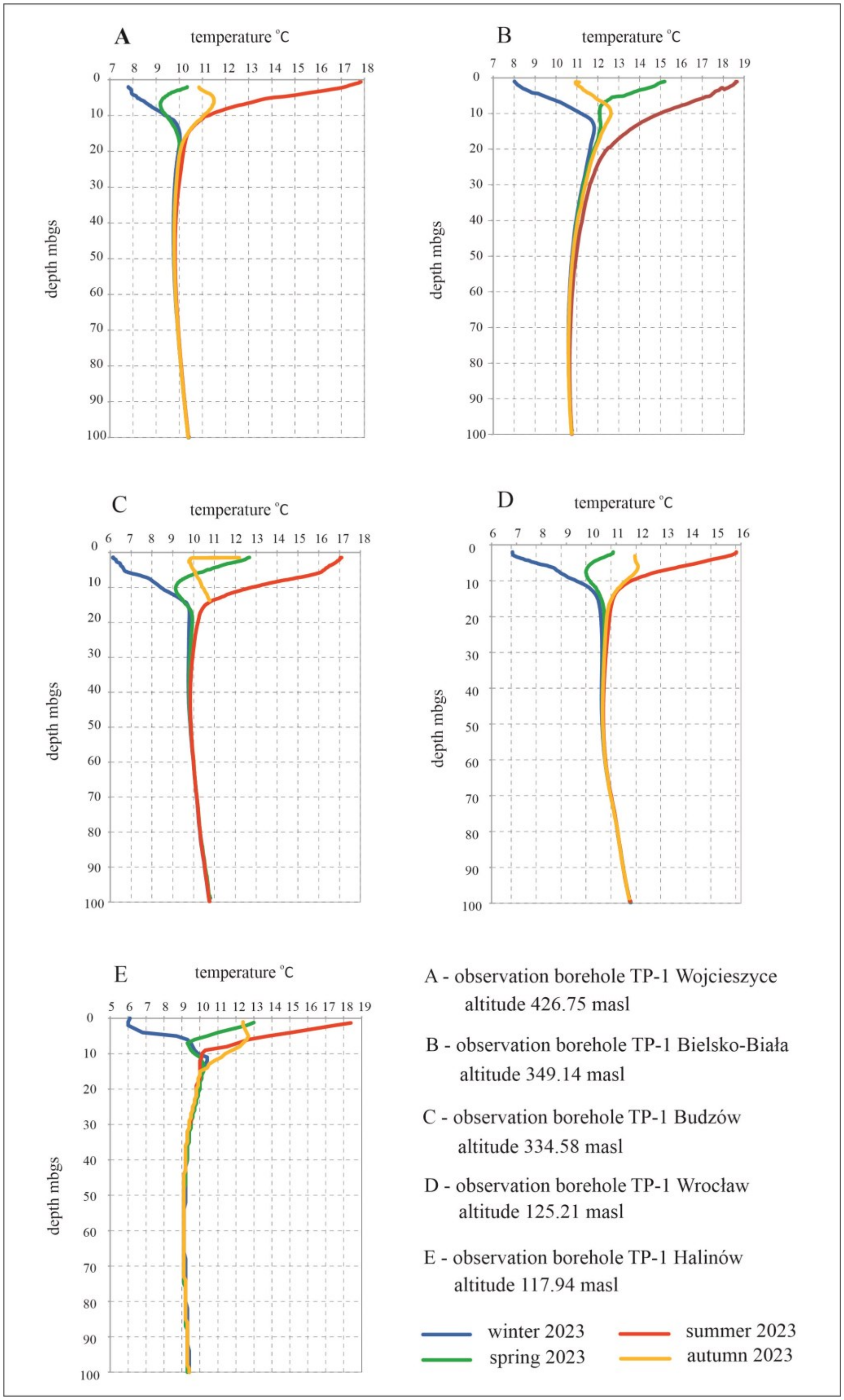

Figure 2: Depth-dependent subsurface temperature values for the observation boreholes in 2023.

The average temperature values presented in Table 2 are the arithmetic mean calculated for the entire borehole profiles. The average temperature values presented in Table 4 come from calculations according to Equation (4), which considers thermal zones determined based on changes of temperature increase trends in temperature profiles. The differences between the means for 2022 and 2023 for the observation borehole TP-1 Wrocław are as follows:

- TP-1 Wrocław, in 2022: arithmetic-weighted = -0.34,
- TP-1 Wrocław, in 2023: arithmetic-weighted = -0.14.

The weighted averages calculated according to Equation (4) are higher. The authors believe this is due to the increase in the weight of the part of the profile where the geothermal gradient has greater impact on the temperature increase.

Table 4: Average values of the subsurface temperature of the borehole TP-1 Wrocław and calculation results with use of the Equation (4).

Borehole, year	T_0 (°C)	T_1 (°C)	z_1 (m)	T_2 (°C)	z_2 (°C)	q (mW/m^2)	TC (W/m*K)	T_{mean} (°C)
TP-1 Wrocław, 2022	9.7	10.90	12	10.60	55	88	2.3	11.07
TP-1 Wrocław, 2023	9.7	10.54	25	10.49	55	88	2.3	10.90

4. DISCUSSION AND CONCLUSIONS

Results of the measurements for the daily and seasonal temperatures zone which reaches the depth of up to about 2-5 (mbgs) reveal a strong relationship between its temperature and the climatic and weather conditions, such as atmospheric air temperature, precipitation, solar radiation, etc. which was observed by many researches, e.g. Majorowicz and Šafanda (2023), Banks (2012). The subsurface temperature regime within this most shallow subsurface zone is to a great extent dependent on altitude and type of land use. Geological settings seem to play a less important role. Below, within the so-called transient or neutral temperatures zone, the subsurface temperature variability decreases. Beneath, the subsurface temperature starts to grow and depend predominantly on the value of geothermal gradient which was proved for example by Majorowicz and Grad (2020) and Majorowicz (1973). It should be emphasized that the shape of the temperature profiles inferred from the conducted research may be significantly influenced by various geo- and anthropogenic factors, such as the thermal properties of the rocks. e.g. thermal conductivity, the presence of aquifers, climatic anomalies and the presence of subsurface infrastructure. Anthropogenic factor, such as influence of urban heat island on subsurface temperature was studied by Worsa-Kozak and Arsen (2023) and Kłonowski (2021) in Wrocław and might be observed in the borehole TP-1 Wrocław. This effect could be also present in case of the borehole TP-1 Halinów. The thermal regimes within the zones of neutral temperatures and the deeper subsurface geological, tectonic and hydrogeological conditions are also important for forming thermal regime of the subsurface.

The logging of subsurface temperature in the boreholes conducted by the Polish Geological Institute - National Research Institute is pioneering research in Poland that contributes to the development of the national observation and research network. In the coming years, it is planned to drill another five new boreholes in various regions of the country, including Lower Silesia, Pomerania, Podlasie and the Lublin region.

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ACRONYMS AND SELECTED UNITS

BHE borehole heat exchanger

°C degrees Celsius

K degrees Kelvin

m meters

masl meters above sea level

mbgs meters below ground surface

PGI-NRI Polish Geological Institute – National Research Institute

PGS Polish Geological Survey

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