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CHARACTERIZATION OF GEOTHERMAL RESERVOIRS PARAMETERS IN POLISH PART OF CARPATHIAN FOREDEEP

Anna SOWIŻDŻAŁ
AGH University of Science and Technology, Faculty of Geology, Geophysics and Environmental Protection, Department of Fossil Fuel, Al. Adama Mickiewicza 30, 30- 059 Krakow, Poland, E-mail: ansow@agh.edu.pl

Abstract: Geothermal energy in Poland is accumulated in four geothermal provinces characterized by different geological conditions and varied geothermal water parameters. One of them is Fore-Carpathian geothermal province, which has not been before a subject of comprehensive geothermal research. Characterization of geothermal reservoir parameters as well as estimate of geothermal waters parameters accumulated in these rocks in the Polish part of Carpathian Foredeep were carried out in order to indicate the best locations for different types of geothermal energy utilization. The analyses show that the geothermal potential for recreation and/or balneotherapy is much higher than that related to applications for heating purposes. The best parameters are revealed by waters accumulated in the Devonian and Carboniferous carbonate sequences of the western part, the Middle Jurassic sandstones in the eastern part, the Upper Jurassic carbonate rocks and the Cenomanian sandstones in the central part of Carpathian Foredeep. The problem of geothermal water utilization in research area is related to low discharges of wells. Only the Cenomanian aquifer is characterize by high discharges (up to 200 m^3/h) over the whole area of its occurrence. Potential discharge of wells in other reservoirs does not exceed 60 m^3/h. Mineralization of groundwaters vary in wide range from 25 to 150 g/dm^3. Temperatures in the top of perspective aquifers are mostly below 90°C. Highest temperatures (on the order of 150°C) were observed in the Upper Silesia region (western part of the area). In this region the Carboniferous, locally Devonian deposits seem to be prospective for petrogeothermal energy development.

Key words: Poland; Carpathian Foredeep; geothermal reservoirs; low-temperature systems; hot dry rock;

1. INTRODUCTION

Geothermal energy in Poland is one of renewable energy sources which can be important for numerous regions. This internal energy of the Earth can be used for different purposes and is particularly justified in areas characterized by unique values of nature and tourist amenities, and in towns exposed to the influence of gas and particulate pollutants as a result of burning of traditional energy carriers in local boiler plants and domestic furnaces. Geothermal energy resources in Poland are accumulated in underground water reservoirs in various stratigraphic units and at various depths in areas of the Polish Lowlands, the Carpathians and in some locations in the Sudety Mts and Carpathian Foredeep.

The activities on geothermal heating deployment were initiated in Poland in the 1980s. The experimental stage of the first geothermal plant was opened in the Podhale region in 1992. Since that time six district heating plants have been launched. In recent years a growing interest has been observed in the recreation and balneotherapy sector expressed by seven new centres (and two which received the health resort status) opened in 2006-2012. Other minor uses comprised semi-technical wood drying and greenhousing, as well as heating up a football playground. In case of the geothermal heat pumps sector, some faster growth has been observed during last years (Kępińska, 2013).

Currently in Poland hydrogeothermal energy (connected with geothermal water) is utilized. Although petrogeothermal energy that constitutes heat resources of rocks has not yet been utilized, the research work tending to assess the possibility of utilization of this type of energy is carried out (Sowiżdżał et al., 2013b; Wójcicki et al., 2013). Poland has low-temperature geothermal resources connected mostly with Mesozoic sedimentary formations. At present geothermal applications involve space heating, balneotherapy, bathing and recreation, nevertheless, research on the possibilities of using geothermal energy for other purposes are carried out (Bujakowski & Tomaszewska, 2014). In Poland, geothermal waters have been used in bathing and medicine for many years. Natural thermal springs were known from time immemorial in the Polish part of the Sudetes at Cieplice and Lądek (Dowgiałło, 2002).

For decades the AGH University of Science and Technology has conducted scientific research and has issued a lot of publications related to the occurrence of geothermal waters in sedimentary basins of Poland. At the Department of Fossil Fuels, geological conditions of the occurrence of geothermal waters are analyzed, together with the energy resources and technology required for development of the geothermal resources within geological units of the Polish Lowlands, Carpathians and Carpathian Foredeep. Recapitulation of the studies of the occurrence and utilization of geothermal waters and energy has been reflected in geothermal atlases of the Polish Lowlands (Górecki (ed..) et al., 1990; 1995; 2006a; 2006b) as well as geothermal atlases of the Carpathians (Górecki (ed.) et al., 2011; 2013) which represent unique works. In 2012 Geothermal Atlas of the Carpathian Foredeep (Gorecki (ed.) et al., 2012) was published. The Atlas constitutes a comprehensive and exhausting source of information on the occurrence and production potential of geothermal waters in the Polish part of the Carpathian Foredeep. The Atlases are intended for all persons who are interested in the geothermal energy utilization (e.g. students, governments etc.). Representatives of the state administration and activists of local governments will find in the Atlases essential information on geothermal waters and possibility of their utilization. The Atlases comprise important information for investors involved in recognition and production of warm brines for practical uses.

Since 2010, the work connected with analysis of the possibility of using reservoirs in sedimentary rocks for building the closed geothermal systems is carried out. The research was initialized by the project carried out in the years 2010-2013 by a consortium which includes leading scientific institutions in Poland. The results of the project were presented in numerous publications (e. g. Wójcicki et al., 2013; Sowiżdżał et al., 2013a, b; Sowiżdżał & Kaczmarczyk, 2014; Górecki et al., 2013). As one of the consortium members, a research team from the AGH University of Science and Technology conducted the work connected with analysis of the possibility of using reservoirs in sedimentary rocks for building the closed geothermal systems. The Silesian Region belonging to the Carpathian Foredeep was indicated as one of the most prospective locations for utilization of the heat from hot sedimentary rocks in Poland. However, finally it was decided that the most promising conditions for the Enhanced Geothermal Systems (EGS) occur in the central part of Poland in an area covering the Mogilno-Łódź Trough region and a small part of the Kujawy Swell and Fore-Sudetic regions (Wójcicki et al., 2013; Sowiżdżał et al., 2013a, b). The western part of the Silesian region is characterized by very favourable conditions for such systems and also seems to be prospective.

2. RESEARCH AREA

2.1. Polish geothermal provinces

Due to the specific geological structure and therefore different hydrogeothermal conditions, Poland can be divided into four major geothermal provinces. The largest in area (approximately 87% of the country) and the most perspective is a province of the Polish Lowlands (Fig. 1).

Particularly favourable conditions for the utilization of geothermal energy are in the region of the Polish Trough, where geothermal energy is currently used in several locations (for heating, bathing and balneotheraphy), and several other projects are in progress at various stages of advancement. The fundamental research and implementation work conducted in AGH University of Science and Technology (Górecki (ed.) et al., 1990; 1995; 2006a, b; Sowiżdżał 2010; 2012; Hajto & Górecki, 2005; 2010) shows that in many areas of the Polish Lowlands utilization of geothermal waters with relatively high temperatures (even in excess of 100°C) and high capacities is real and economically justified. In some locations (the Gorzów Wielkopolski and Łódź areas), characterized by high temperatures and appropriate reservoir properties of rocks, there are suitable conditions for development of petrogeothermal energy in the future (Wójcicki et al., 2013; Sowiżdżał et al., 2013b). In this case, in contrast to hydrogeothermal reservoirs, appropriate reservoir properties mean very low permeability and porosity.

The next prospective region for hydrogeothermal energy development in Poland is the Podhale area, located in the Carpathian Geothermal Province. In the Polish part of the Carpathians, the best reservoir and exploitation properties for geothermal water utilization occur just in Podhale, and are represented by: favourable reservoir parameters and lithologies, usually high yields and regional extent of the aquifer (in both the

Figure 1. Research area on a background of geothermal provinces in Poland.

Polish and Slovakian parts) as well as recent recharge and low TDS. Podhale is a region in the Western Carpathians where geothermal waters have been recently utilized and will be utilized in the future, preferably for heat generation but also for recreation and balneotherapy (Górecki et al., 2013).

Definitely different geothermal conditions are present in the Sudetic Geothermal Region (SW Poland). Geothermal waters occur in this region only in the crystalline formations of the Sudetes. Most of the fragmentary hydrogeothermal investigations carried out so far in the Polish part of the Sudetes were limited to zones of occurrence of thermal waters utilized for therapeutic purposes, or to a few areas in which prospection has been carried out for such waters (Dowgiałło, 2002). However, the Sudetic region is characterized by favourable thermal conditions. In Cieplice, water with temperature 86.7ºC was obtained from the depth 2,002.5 m. For this reason, the Cieplice area located in the Sudetic geothermal region was a subject of a study to identify a perspective location for the HDR project in Poland (Wójcicki et al., 2013). Currently, the waters of this region are used in several towns for balneotherapy.

This paper is dedicated to the Fore-Carpathian Geothermal Province located in the southern part of Poland covering the area of the Carpathian Foredeep (Fig. 1). There are currently no facilities based on geothermal waters (geothermal plants, swimming pools, spas) in this region. The mineral water, brine and geothermal water recognized and documented in the Fore-Carpathian Geothermal Province are present in fifteen cities. They are used for medicinal purposes in six statutory spas. In the past in some other localities of the Carpathian Foredeep, health resort facilities were in operation. Their activities were based on springs of medicinal or potentially medicinal waters occurring in these localities or in close vicinity (Jasnos, 2012). In the analysed area, petroleum exploration has been carried out for many years. As a result, this area has relatively good well control. Therefore, in order to determine the geothermal potential of this province, abundant factual materials, comprising the geological information from over 4,000 wells, were gathered and analysed in terms of potential occurrence of prospective aquifers.

2.2. Geological setting of Carpathian Foredeep

The Carpathian Foredeep, genetically connected with the Flysch Carpathians, the youngest geological unit of Poland, is an asymmetric structure filled with Miocene molasse deposits developed as the sequence of shales, mudstones and sandstones, from several hundred to about 3,000 metres thick. This complex is determined as so-called Autochthonous Miocene and its sediments originated from erosion of folded Carpathian flysch deposits. The distinct southern boundary of the Carpathian Foredeep is delineated by the margin of the thrust Carpathians, although the Miocene deposits with variable thickness occur also under the Carpathian overthrust (Oszczypko, 2006; Wdowiarz, 1976; Oszczypko & Tomaś, 1985; Peryt, 2012). For this reason, the southern boundary of the area analysed in this study occurs about 15 km to the south of the border of the Carpathian overthrust. Within the Polish state borders, the Carpathian Foredeep stretches latitudinally over more than 300 km, whereas its maximum width does not exceed 100 km. The asymmetry of the Foredeep structure is marked out as well in its transversal (meridional) cross-section where maximum thicknesses of the Miocene deposits are found in the south at the front of the Carpathian overthrust and decrease northwards, as in the longitudinal cross-section where the elevation of its Precambrian-Paleozoic basement, so-called "Cracow Belt" (Ney, 1968), divides it into unequal parts: the larger Eastern Foredeep and the smaller Western Foredeep. In the eastern part, the basement of the Carpathian Foredeep is formed of erosionally truncated deposits of the West European Platform of different ages: Precambrian and Paleozoic (in the Miechów-Rzeszów area) through Mesozoic (in the Miechów Trough). In the western part, the basement is represented by Mesozoic rock complexes and (principally) Paleozoic (Carboniferous) complexes of the Upper Silesian Trough, which rest over Precambrian metamorphic rocks of the Upper Silesian Block (Moryc & Heflik, 1998; Harasimiuk et al., 2012). The depth to the platform basement of the Carpathian Foredeep ranges from several hundred metres to 3,500 m (Oszczypko, 2006).

3. METHODS

In order to identify the geothermal potential of the Fore-Carpathian Province and indicate the most prospective areas for geothermal energy utilization, a number of analytical studies were carried out. Both the potential of hydrogeothermal energy and petrogeothermal energy were analysed. Detailed interpretation was carried out for the following eleven geothermal aquifers occurring in the Carpathian Foredeep: Miocene; Upper Cretaceous (without Cenomanian); Cenomanian; Lower Cretaceous; Upper Jurassic; Middle Jurassic; Upper Triassic; Middle Triassic; Lower Triassic; clastic Carboniferous; and carbonate Devonian and Carboniferous. In consideration of the large Miocene thickness exceeding locally 3,000 m and wide variations in the development of particular stratigraphic units in its profile, for determination of hydrogeothermal parameters in the Miocene aquifer, depth intervals were distinguished, for which the analytical work was done (500-1,000 m below sea level (bsl); 1,000-1,500 m bsl; 1,500-2,000 m bsl; 2,000-2,500 m bsl; and 2,500-3,500 m bsl).

The work tending towards the assessment of the geothermal potential comprised: characterization of the geological setting of the Carpathian Foredeep (Peryt, 2012) together with construction of a structural-parametric model (Papiernik et al., 2012); interpretation of hydrogeological parameters (Haładus et al., 2012); hydrochemical characterization of groundwaters (Sowiżdżał & Jasnos, 2012); and thermal analysis (Hajto & Szewczyk, 2012). The construction of the parametric model was based on results of quantitative interpretation of geophysical well logs (Czopek et al., 2012). The work resulted in assessment of geothermal resources in distinguished resource groups (Hajto & Kotyza, 2012). The calculation of the geothermal resources for the needs of the Atlases was made using the unified criteria of the resource classification and the calculation methodology developed at the Department of Fossil Fuels, AGH University of Science and Technology.

A key problem was delineation of prospective areas for development of geothermal waters for various purposes. Ways of the geothermal energy utilization are mostly determined by the water temperature and discharge of wells. Direct temperature measurements in deep wells are the main sources of information on the subsurface thermal regime (Szewczyk, 2010). With regard to the limited amount of available measurements in quasi-stationary conditions, analysis of the thermal field distribution was mostly based on interpretation of results of maximum temperature (bottom-hole temperature, BHT) measurements (Hajto & Szewczyk, 2012).

Discharges were calculated with the Darcy-Dupuit formula, applied for unlimited groundwater horizon exploited under stationary conditions. Theoretical discharge from a production well was calculated by superposition of three maps: permissible drawdown, hydraulic conductivity coefficient and thickness of groundwater horizons, according to the following formula (Kulma, 1995):

$$Q = 2\pi * k * m_f * \frac{S}{\ln \frac{R}{r}} \quad (1)$$

where, Q - discharge of production well [m^3/s]; k - hydraulic conductivity coefficient [m/s]; mf - thickness of groundwater horizon (limited by working length of screen) [m]; S - permissible drawdown [m]; r - radius of production filter [m]; R - radius of depression cone [m].

Radius of depression cone was calculated with the Sichardt's formula:

$$R = 3000 * S * \sqrt{k}; \quad (2)$$

where, S - drawdown [m], k - hydraulic conductivity coefficient [m/s].

In Poland, space heating represents the main sector of the geothermal water utilization. During the last years utilization of geothermal waters in balneotherapy and recreation has gained growing popularity because in such cases requirements regarding temperatures and discharges are much lower than those in heat engineering (where discharges of at least several tens of m^3/h are required). As an effect, geothermal waters usable for the former purposes occur in numerous regions of Poland.

With favourable water temperatures, appropriate water types and parameters of heat distribution networks, heating systems may be based exclusively on the geothermal water heat, but more frequently the systems are integrated with peak load sources of heat (traditional energy carriers or some renewables, e.g. biomass). In some systems, also heat pumps operate (using absorption or compressor heat pumps). The temperature range of applied geothermal waters is wide: from more than ten to more than 100°C (in case of currently operating heating installations in Poland it is from 40 to 86°C). The heating systems operate for space heating and sometimes also for supplying the domestic hot water (Kępińska et al., 2012).

Determination of the potential of geothermal water development for heating purposes was enabled by interpretation of reservoir, hydrogeological and thermal parameters in the geological profile of the Carpathian Foredeep. In terms of the temperature criterion, the highest temperature requirements are laid down on the geothermal water (steam) used for electricity generation. As for the major part of Poland, in the Fore-Carpathian Geothermal Province waters have too low temperatures for the electricity generation. In order to determine prospective areas for utilization of groundwaters for balneotherapy and/or recreation, maps were constructed presenting geothermal waters applicable for such purposes in particular aquifers of the Carpathian Foredeep. These maps were made applying the superposition of maps of potential discharges of wells, and water temperatures and mineralization at tops of the geothermal aquifers. The maps delimit areas in which zones of occurrence of waters with parameters required in balneotherapy or recreation should be searched. In the delimited areas, waters occur with temperatures and mineralization enabling (at appropriate well discharges) utilization for such purposes. However, it should be remembered that particular locations can be indicated only with regard to the content of water constituents with especial biochemical activity (therapeutic or potentially harmful to health). The usefulness of geothermal waters for recreational or therapeutic baths is principally determined by such parameters as the water temperatures, mineralization, chemical composition and content of specific components in amounts exceeding the lower boundary of the pharmacodynamic threshold and safe for human health at the same time (e.g. F, J). Application of the waters for the inhalation or drinking therapy requires also considering the content of constituents with especial biochemical activity (therapeutic or potentially harmful to health) (among others arsenic, barium, boron, radium) (Latour, 2012). Also the discharge of a geothermal intake should be numbered among factors controlling the geothermal water utilization for the balneotherapeutic and recreational baths. The minimum discharge of a geothermal intake of water supplying one swimming pool should range from 3 to $5m^3/h$. Other requirements for water used for bathing depend on way of utilization as follows (Paczyński & Płochniewski, 1996):

- for recreational purpose - temperature 24-30°C, mineralization $\leq$ 35 g/dm^3,
- for recreational and therapeutic purpose - temperature 28-32°C, mineralization $\leq$ 40 g/dm^3,
- for therapeutic purpose - temperature 28-42°C, mineralization $\leq$ 50 g/dm^3.

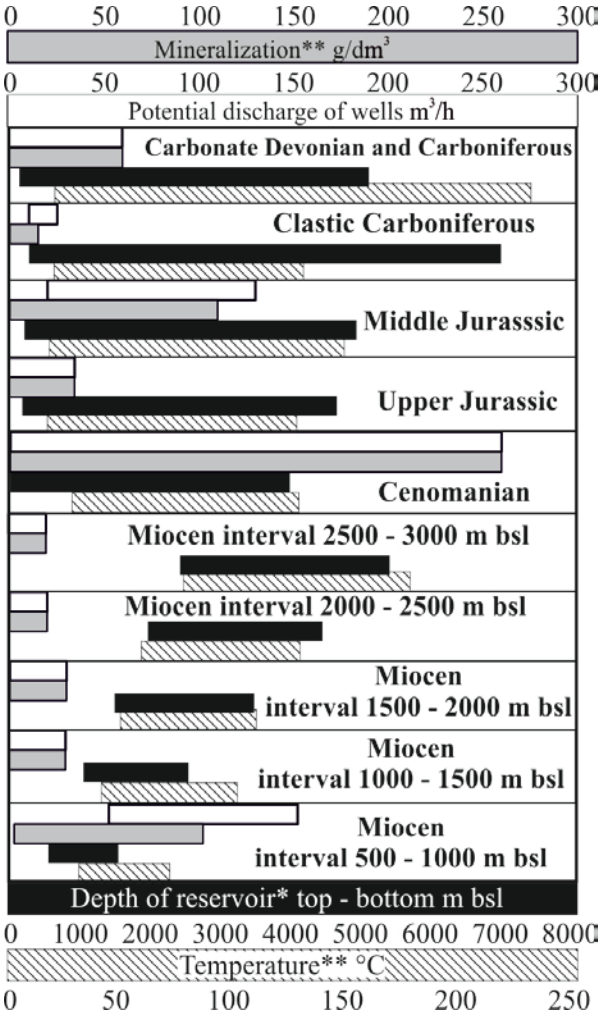
Different requirements were related to selection of reservoir rocks for Enhanced Geothermal Systems (EGS). In contrast to reservoir rocks which accumulate geothermal waters, the reservoir rocks which accumulate the petrogeothermal energy are dry (or almost dry), thus are characterized by low permeability and porosity. The concept of utilization of heat from hot dry rocks assumes drilling wells in areas characterized by high temperature anomalies and intense heat transfer (Tester et al., 2006). Local and regional geologic and tectonic phenomena play a major role in determining the location (depth and position) and quality (fluid chemistry and temperature) of a particular resource. The first requirement for EGS is accessibility. This is usually achieved by drilling to depths of interest, frequently using conventional methods similar to those used to extract oil and gas from underground reservoirs. The second requirement is sufficient reservoir productivity characterized by the temperature distribution within the reservoir. EGS concepts would recover thermal energy contained in subsurface rocks by creating or accessing a system of open, connected fractures through which water can be circulated down injection wells, heated by contact with the rocks, and returned to the surface in production wells to form a closed loop (Tester et al., 2006).

Requirements for EGS in sedimentary rocks have been specified based on international experiences (Brown et al., 2012; Tester et al., 2006; Tenzer, 2001; Sausse et al., 2007; Antkowiak et al., 2010). Critical requirements for the EGS location comprise: thermal parameters of the rocks (temperatures >150°C), thickness of the reservoir (minimum 300 m), porosity and permeability of the reservoir rocks (as the lowest) and the depth of the reservoir (3-6 km) (Sowiżdżał et al., 2013b).

4. RESULTS

In the Carpathian Foredeep, low discharges of wells in almost all the analysed aquifers present the fundamental problem. The Cenomanian aquifer is an exception, as high discharges can be expected over the whole area of its occurrence. Zones with increased potential discharges of wells are sporadically encountered in the Middle and Upper Jurassic aquifers and in the Miocene aquifer. Therefore, the best prospects for geothermal water utilization can be expected in the above-mentioned aquifers. Waters accumulated in the Carboniferous clastic deposits and in the Carboniferous and Devonian carbonate rocks can locally have favourable characteristics. Hydrogeothermal parameters of the Triassic and Cretaceous aquifers (with the exception of the Cenomanian aquifer) do not indicate any possibility of effective development of the geothermal resources (low discharges and temperatures). Parameters of the prospective aquifers and geothermal waters accumulated in them are presented in figure 2.

Analysis of reservoir, hydrogeological and thermal parameters in the geological profile of the Carpathian Foredeep allowed for determination of prospective areas in terms of geothermal water development for various purposes. The analyses performed for the Carpathian Foredeep show that the potential for the geothermal water utilization for recreation and/or balneotherapy is greater than that for heating purposes. It results as well from the lower energy demand of geothermal water intakes as from the favourable physicochemical parameters of the waters, confirmed by numerous wells over vast areas of the region under consideration.



**in case of the Miocene aquifer, a depth interval analysed*

*** in case of the Miocene aquifer value given for the central part of a depth interval; in other aquifers, the value given for the top (min-max)*

Figure 2. Hydrogeothermal parameters of geothermal reservoirs in the Carpathian Foredeep.

Prospective areas for geothermal water development for balneotherapy and/or recreation are situated in the greater part of the Carpathian Foredeep. Occurrence of waters with favourable parameters for balneotherapy or recreation can be expected in the Miocene, Cenomanian, Upper Jurassic, Middle Jurassic or Lower Triassic deposits as well as in the Carboniferous clastic deposits and Carboniferous and Devonian carbonate deposits. The best parameters for heating purposes are revealed by waters accumulated in: the Devonian and Carboniferous carbonate sequences of the western part of Carpathian Foredeep; the Middle Jurassic sandstones in the eastern part of analysed area; the Upper Jurassic carbonate rocks in the area to the south of Brzesko, under the Carpathian overthrust; and the Cenomanian sandstones in the Bochnia and Brzesko areas (Fig. 3).

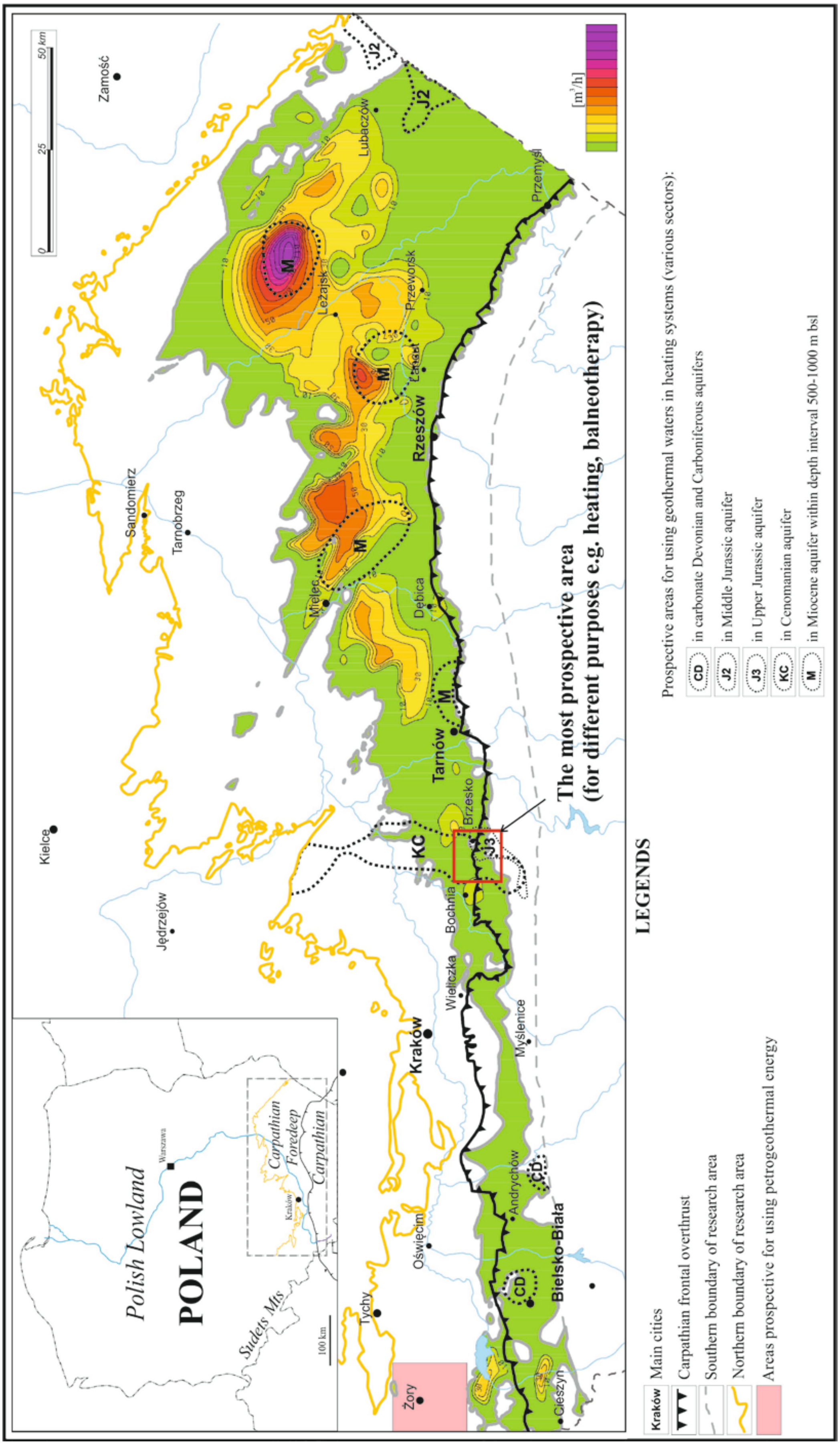


Figure 3. Prospective areas for geothermal water and energy utilization in the Carpathian Foredeep on a background of Miocene formation potential discharge of wells map (500 to 1,000 m bsl depth interval).

In the Miocene aquifer, the best geothermal potential was identified for the depth interval of 500 to 1,000 m bsl. In this interval, the Miocene succession occupies the vast areas of the central and eastern parts of the Carpathian Foredeep. The area in central part of Carpathian Foredeep (between Bochnia and Brzesko) is the most prospective for hydrogeothermal energy utilization for different purposes (Fig. 3).

The Upper Silesian region (west part of research area) is considered to be prospective also with respect to the petrogeothermal energy and the possibility of building EGS systems. However, information on deep-lying rock formations is insufficient. Most of wells documenting the reservoir rocks have been located at the boundary of the prospective area, which makes analyses more difficult. In the Upper Silesian Coal Basin, the Carboniferous (locally Devonian) deposits seem to be prospective. They are characterized by great thicknesses (even more than 3 thousand m), high temperatures (on the order of 150°C) and low porosity and permeability values which result in low water discharges. This applies also for the Mesozoic basement. The parameters are suitable for EGS systems, although location of such a system in this region would require further detailed analyses.

5. CONCLUSIONS

The carried out analyses indicate that the geothermal potential related to utilization of geothermal waters of the Carpathian Foredeep for recreation and/or balneotherapy is much higher than that related to utilization for heating purposes. It results as well from the lower energy demand of geothermal water intakes as from favourable physicochemical parameters of these waters, confirmed by numerous wells drilled over vast areas of the Carpathian Foredeep. In some regions, it is possible to develop the groundwater also for heating purposes (space heating, agriculture, agribusiness), usually in association with other sources, including heat pumps.

Optimum geothermal water development involves cascading of geothermal energy. After the energy transfer in the heating system, the waters are directed toward successive elements of a cascade, comprising e.g. geothermal swimming-pools, warming of greenhouses, and other uses. In the study area, the cascaded system of geothermal energy distribution is recommended in order to improve the efficiency of the geothermal installation operation.

The aquifers of the Miocene, Cenomanian, Upper Jurassic and Devonian are the most prospective. However, in these aquifers, the most favourable parameters for location of geothermal intakes occur in small areas and depth intervals. With reference to some areas distinguished principally in the Miocene formations (but also in other aquifers of the Carpathian Foredeep) it should be stressed that sandstones as reservoir rocks occur often in the form of lenses or pinch-outs; their variable thickness can have an adverse effect on stable production parameters in the future perspective. Planning of future researches and investments should include appropriate studies and tests, which would help with evaluation of a hydrogeological character of these reservoirs, conditions of the groundwater recharge and flow, and renewability of resources.

The EGS technologies utilizing the energy accumulated in hot dry rocks generate growing interest in the world. However, the majority of such projects are still in the experimental phase, and at present in Poland such solutions are not applied at all. Nevertheless, long-term forecasts say that the geothermal future is related to utilization of the petrogeothermal energy. In the western part of the Fore-Carpathian Geothermal Province, in the Upper Silesian Coal Basin, conditions exist for the EGS future development. In the nearest foreseeable future utilization of hydrogeothermal resources accumulated at various depths in geothermal aquifers of the Carpathian Foredeep seems to be more practical.

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