POSSIBILITIES OF PETROGEOTHERMAL ENERGY RESOURCES UTILIZATION IN CENTRAL PART OF POLAND

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Abstract. The current utilization of geothermal energy in Poland consists in development of geothermal waters for needs of heating systems and balneotherapeutic and recreational centres. In Poland, possibility of using the energy accumulated not in waters but in rocks deep-lying below the earth surface represents a new problem. The paper presents results of estimating the petrogeothermal energy resources accumulated in sedimentary rocks of central Poland. This region was distinguished as the most prospective in Poland for the possibility of locating systems that utilize petrogeothermal energy accumulated in sedimentary rocks, with regard to criteria of temperature and depth of occurrence of reservoir rocks.The carried out assessment of petrogeothermal energy resources accumulated in sedimentary rocks has shown a significant potential for using the heat from sedimentary rocks and has enabled indication of the best prospective locations for Enhanced Geothermal Systems. The most abundant resources occur in three locations of central Poland: Kutno area (the Lower Triassic reservoir), Pleszów (the Lower Carboniferous reservoir) and Konin area (the Upper Rotliegend reservoir). In these areas the potential for builiding system based on petrogeothermal energy was identified.
Keywords: *geothermal energy, enhanced geothermal system, petrogeothermal resources, Poland, sedimentary rocks.*

Introduction

Currently in Poland hydrogeothermal energy is utilized, for which warm groundwater produced from boreholes represents the energy carrier. On the other hand, petrogeothermal energy that constitutes heat resources of rocks, has not yet been utilized. At present geothermal applications involve space heating, balneotherapy, bathing and recreation, however, research on the possibilities of using geothermal energy for other purposes (including producing electricity) are carried out (Wójcicki et al. (eds.), 2013; Bujakowski and Tomaszewska (eds.), 2014).

The development of geothermal energy is driven by a number of interacting factors and the relationship between market and policy can be critical. For instance, electricity can be produced from geothermal resources through many different processes, and with varying efficiency. Where high-temperature hydrothermal resources are available, in many cases geothermal electricity is competitive with newly built conventional power plants. Binary systems can also achieve reasonable and competitive costs in several cases, but costs vary considerably depending on the size of the plant, the temperature level of the resource and the geographic location. EGS (Enhanced Geothermal System) cost cannot yet be assessed accurately because of the limited experience derived from pilot plants, but it seems to become competitive in a near future. Therefore, it seems important to have knowledge of existing geothermal resources. Effective used of geothermal energy is based on information about amount of resources (both hydro and petrogeothermal). In addition geothermal is associated with the geological risk. The geological risk exists especially at sites with only partially known subsurface

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conditions: the geothermal resource could be below expectations the fluid could be insufficient. Over the last 100 years, the production of geothermal energy has been concentrated in areas where rich hydrothermal resources are available. However, the development of advanced technologies has enabled the production of geothermal energy at low temperature in all European countries (EGEC, 2013).

Low-temperature systems (< 150°C) are more common and cover much larger areas in comparison to high-temperature ones. Also in Poland geothermal systems are characterized by low-temperature parameters. Poland has natural sedimentary-structural basins of diversified reservoir temperatures, from 20 to 80-90°C, in some cases even over 100°C. Geothermal energy resources in Poland are accumulated in underground reservoirs in various stratigraphic units and at various depths in the areas of the Polish Lowlands, the Carpathians and in some locations in the Sudety Mts and Carpathian Foredeep.

Geothermal resources in Poland are relatively well recognized as a result of a number of works and geothermal projects carried out by AGH University of Science and Technology in collaboration with other leading scientific centers. 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; Górecki (ed.) et al., 1995; Górecki (ed.) et al., 2006a; Górecki (ed.) et al., 2006b) as well as geothermal atlases of the Carpathians (Górecki (ed.) et al., 2011; Górecki (ed.) et al., 2013a) and Carpathian Foreedeep (Górecki (ed.) et al. 2012) which represent unique works. Assessment of hydrogeothermal resources in different part of Poland has been the subject of numerous publications (e. g. Górecki (ed.) et al., 2013b; Sowiżdżał, 2010; Sowiżdżał and Górecki, 2013; Hajto and Górecki, 2010; Hajto et al., 2007; Hajto, 2011; Tomaszewska et al., 2010; Sowiżdżał, 2015) and allowed the identification of prospective areas and directions of geothermal energy development.

Petrogeothermal resources are the subject of global research on the technology of heat recovery for power generation in binary systems, often in combination with heat production. In case of sedimentary cover, reservoir rocks contain a small amount of groundwaters, so the utilization system is called EGS. EGS was defined as engineered reservoirs that have been created to extract economical amounts of heat from low permeability and/or porosity geothermal resources. EGS include conduction-dominated, low permeability resources in sedimentary formations. In EGS, the naturally occurring hot rock does not contain enough water and generally lies at greater depth than is typical of hydrothermal systems (Tester et al., 2006). In Poland, such systems do not yet exist. Since 2010, the work connected with assessment of analysis of the possibility of using petrogeothermal energy is carried out. 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 EGS. As the result of geological surveys (Wójcicki et al. (eds.), 2013) and petrophysical analysis of lithologies involves (Sowiżdżał and Kaczmarczyk, 2013; Sowiżdżał et al., 2013a) the central part of Poland was selected as one of the perspective areas for EGS development in sedimentary rocks (see *Figure 1*). The results of the project were presented in numerous publications (e. g. Wójcicki et al. (eds.), 2013; Sowiżdżał et al., 2013a; Sowiżdżał et al., 2013b; Sowiżdżał et al., 2014; Sowiżdżał and Kaczmarczyk, 2013; Sowiżdżał and Kaczmarczyk , 2014; Górecki et al., 2013b; Bujakowski et al., 2015).

An Enhanced Geothermal System is an underground reservoir that has been created or improved artificially. The concept of Enhanced Geothermal Systems is going greatly

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increase geothermal potential as it allows for the production of geothermal electricity nearly anywhere in Europe with medium and low temperature. This concept involves:

- Using the natural fracture systems in the basement rocks
- Enlarging its permeability through massive stimulation
- Installing a multi-well system
- Through pumping and lifting, forcing the water to migrate through the fracture system of enhanced permeability ("reservoir") and use the heat for power production.

A major effort to introduce EGS could create a substantial base-load electric power production, as geothermal energy is available independent from the time of day or year, of climate, weather, etc. A steady increase in geothermal power production could be expected in all EU countries (EGEC, 2013).

Geothermal energy from EGS represents a large, indigenous resource that can provide base-load electric power and heat at a level that can have a major impact on the many region of the world, while incurring minimal environmental impacts. With a reasonable investment in R&D, EGS could provide large amount of cost-competitive generating capacity in the next years. Further, EGS provides a secure source of power for the long term that would help protect against economic instabilities resulting from fuel price fluctuations or supply disruptions (Tester et al., 2006). The Polish economy is heavily dependent on fossil fuel prices. Diversification of energy sources as well as and increased use of more environmentally friendly sources, is vital in many region of Poland. Geothermal energy utilization is particularly justified in areas characterized by unique values of nature, 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.

Location of analysed area

In order to determine the most prospective area for EGS within sedimentary cover of Poland, based on international experiences (Brown et al., 2012; Tester et al., 2006; Tenzer, 2001; Sausse et al., 2007; Antkowiak et al., 2010), requirements for EGS in sedimentary rocks have been specified. 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). The maximum depth of reservoir was assess based on case studies (Baria et al., 2005; Tester et al., 2006). EGS will reach an optimum depth after which drilling deeper wells will not be more economical. However, studies by Tester and Herzog (1991) have shown that the optimal depth for minimum costs is on a fairly flat cost-versus-depth surface for most geothermal gradients. The insensitivity of project cost to depth, in the neighborhood of the optimal point, permits a range of economically acceptable depths. Lithology and mechanical properties of reservoir rocks are also important because of hydrofracturing. In case of sedimentary rocks the compact sandstones or limestones should be appropriate (de Graaf, et al, 2010; Tester et al., 2006).

The first step of the preliminary analysis was based on the existing geological and geothermal data, e.g., those collected in geothermal atlases (Górecki et al., 2006a; Górecki et al., 2006b) supplemented with new data. Complementary analyses of raw data and maps of surface heat flow density, subsurface temperatures, maps of gravimetric and magnetic anomalies allowed to determine several prospective locations.

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The most promising conditions (temperatures > 150°C in the depth of 5 km) occur in 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 (see *Figure 1*). The area covers approximately 19 200 km^2 (Sowiżdżał et al., 2013b).

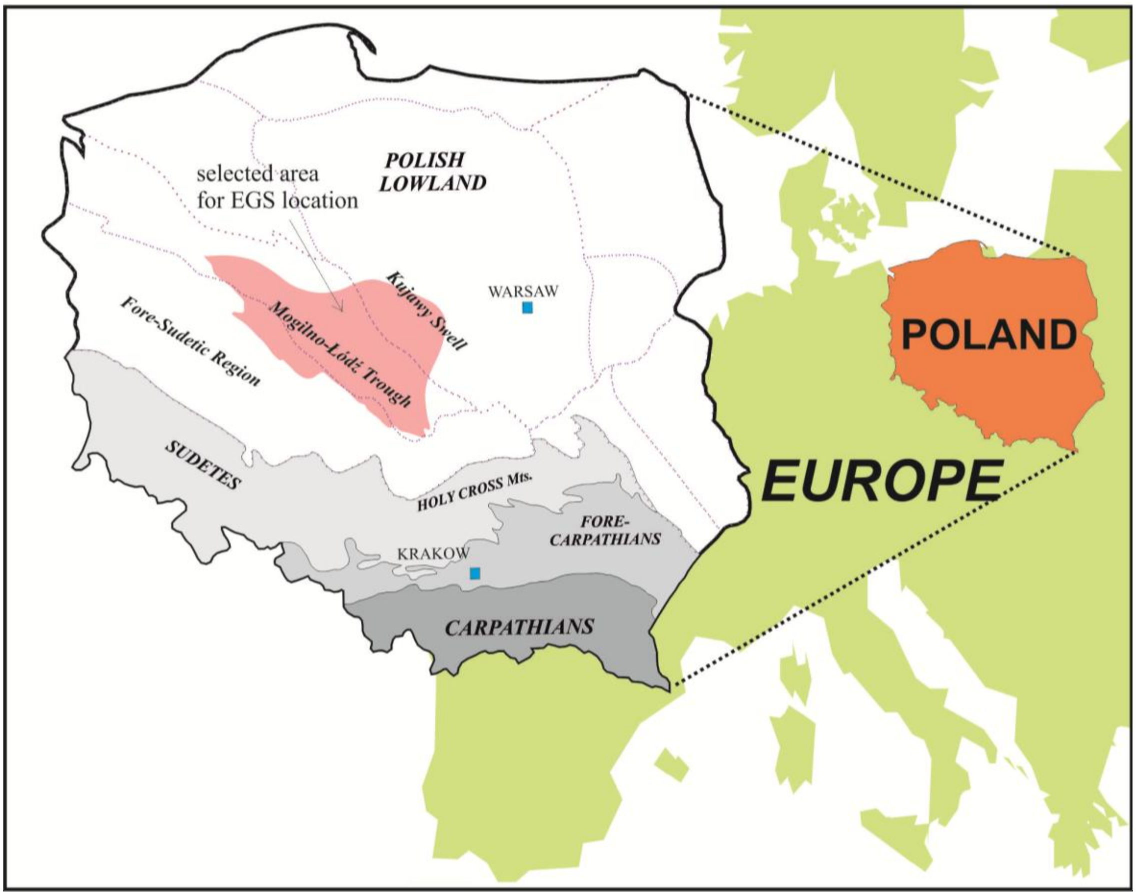

Figure 1. *Location of prospective areas for unconventional geothermal systems in sedimentary rocks.*

Geological background

In the area, preliminary analyses of petrophysical properties, including thermal ones, allowed to indicate the Triassic (mainly the Lower Triassic but locally also the Middle Triassic), the Lower Permian and the Lower Carboniferous formations as potential reservoir rocks for EGS systems. Stratigraphic information has been compiled on the basis of boreholes data as well as cited references. For interpretation of the distribution of subsurface temperatures, synthetic thermograms were employed, which were recorded in conditions of the stable thermal equilibrium (in the form of continuous measurements) (Sowiżdżał et al., 2013).

The Lower Carboniferous strata

The Lower Carboniferous strata are developed as follows: in the area of the postorogenic molasses (to the east and northeast of Poznań, and in the Konin, Sieradz, Łódź and Piotrków Trybunalski areas) – as the flysch lithofacies, so called exoflysch

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(debrites, turbidites); in the area of the Kujawy Swell – as sandstones, siltstones and claystones (pseudoflysch), and as sandstones and siltstone-claystone deposits (Karnkowski, 1999; Pożaryski and Karnkowski, 1992; Narkiewicz and Dadlez, 2008). Both the limited extent of occurrence and thickness of the Carboniferous formations (only locally exceeding the boundary thickness of 300 m) were decisive factors for claiming that better prospects of building the enhanced geothermal systems (EGS) will be related to the Lower Carboniferous strata. In the selected area, thickness of the Lower Carboniferous rocks varies from approximately 200 m to over 2500 m. Among the analysed reservoirs, the top of the Lower Carboniferous reservoir rests deepest, locally deeper that 6 km below sea level (b.s.l.). Assuming the depth of 6 km b.s.l. to be a criterion of the EGS profitability, the estimation of geothermal resources was performed only for areas where the reservoir rests shallower. Mean porosity of the Lower Carboniferous rocks ranges between 1.5 and 2.5%. In a major part of the chosen area, permeability is close to zero (about 0.1 mD), mean bulk density varies from 2.72 to 2.76 kg/m^3 and clay content ranges from approximately 56 to over 60%. It can be observed that temperature increases to the east where the top rests deeper than the established 6000 m b.s.l., therefore that zone was ruled out from further analyses. In the zone of shallower occurrence of the Lower Carboniferous strata, temperatures at the top range from 110 to 200°C (Wójcicki et al. (eds.), 2013). Analysis of petrophysical parameters, as well as analysis of the depth of occurrence of the Carboniferous strata with the predetermined thickness, have shown that the zone, where hot sedimentary rocks for EGS should be searched for, is located in the western part of the study area.

The Lower Permian (called Rotliegend)

The Lower Permian is represented by terrigenous deposits, originated from a desert, which were sedimented in the dry and hot climate. They typically form thick complexes of varigrained rocks which are diagonally bedded or lumpy. In the Polish Lowlands, the Lower Permian formations rest, with a distinct sedimentary gap, on basement rocks characterized by the Variscan and Caledonian consolidation. Among the Rotliegend formations, the Autunian effusive rocks (in the western part of Poland) play an important role. The Saxonian deposits are widely distributed and developed as facies of red clastic rocks (Pokorski, 1976). In the Saxonian profile, a number of sedimentary cycles can be distinguished, succession of which is sandstone – siltstone – claystone. The top of the Rotliegend strata is deepest in the eastern part of the analysed area (deeper than 7000 m b.s.l.). In the remaining parts, it is somewhat shallower (3500-6500 m b.s.l.). The accepted profitability criterion is the reason of elimination of the eastern part of the chosen area. The prospective Upper Rotliegend strata are thickest in the northern part of the area, where they exceed 750 m in thickness. Almost in the entire chosen area, the Upper Rotliegend thickness exceeds 300 m; only in marginal parts of the area it locally falls to smaller than 250 m. The Upper Rotliegend rocks are characterized by high (as for EGS) values of effective porosity (locally over 10%) and permeability (up to higher than 15 mD), which cause that they most frequently represent reservoirs of hydrogeothermal energy. Only locally in the central and eastern parts of the study area, porosity falls to less than 2%, which allows to infer that reservoirs of petrogeothermal energy may occur there. The decrease of porosity and permeability results from the depth of occurrence of the reservoir in these parts (deeper than 6000 m b.s.l.). Only in the Konin area, the top of the Rotliegend is shallower (approximately 5500 m b.s.l.). Also the clay content exceeds 50% there and density of rocks amounts to

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about 2.5 kg/m^3 (Wójcicki et al. (eds.), 2013). In consideration of prospects for locating the EGS systems within the Lower Permian reservoirs, a significant part of the originally chosen area has to be excluded due to the depth of occurrence of its top, its thickness, and reservoir parameters. The only prospective zone is situated in the vicinity of Konin where temperatures at the reservoir top reach 190°C.

The Lower Triassic

The Lower Triassic is represented by the Lower, Middle and Upper Buntsandstein rocks which in a major part of the Polish Lowlands are developed as lithofacies with predominance of claystone-siltstone deposits. In the Lower Buntsandstein of the southern part of the Polish Lowlands basin, sandy fluvial and (less frequently) eolian deposits occur. In the remaining area of Poland, the Lower Buntsandstein is developed as a monotonous complex of claystone-siltstone rocks with interbeds of oolitic limestones (except the eastern part of the Mogilno-Łódź Trough) and sandstones (Szyperko-Śliwczyńska, 1977; Szyperko-Śliwczyńska, 1979; Szyperko-Teller, 1982). The Middle Buntsandstein in the southern part of the basin is represented by sandstones and siltstones (Szyperko-Teller, 1997). In the Fore-Sudetic Monocline area, sandstones are dominant and toward the Mid-Polish Swell they pass into clayey sediments. The Upper Buntsandstein is analysed together with the Muschelkalk ($T2+Tp_3$) in consideration of its predominant development as carbonates, whereas sandstones of the Lower and Middle Buntsandstein (Tp_1+Tp_2) are treated as prospective formations of the Lower Triassic. In the distinguished study area, the top of the Lower Triassic strata rests at depths from deeper than 2000 m b.s.l. in the southwestern margin of the area down to approximately 6000 m b.s.l. in the eastern part. Within the extent of occurrence of the prospective Lower Triassic strata, the top rests at depths between 4000 and 6000 m b.s.l. (thus it meets the depth criterion everywhere). Practically in the entire distinguished area, total thickness of the Lower Triassic formations exceeds 300 m, acquiring the greatest values (over 2000 m) in its eastern part (the determined extent of the prospective Lower Triassic). Within the determined prospective extent, rocks are characterized by porosity ranging from nearly zero to 4%, low permeability (close to zero), bulk density between 2.6 and 2.7 kg/m^3 and clay content on the order of 50-60%. At the top of the analysed horizon, temperature is equal to 120 and 170°C, with the highest temperatures observed in the eastern part of the chosen area (east of Kutno), in places of the deepest top of the Lower Triassic (Sowiżdżał et al., 2013b).

The Middle Triassic

The Middle Triassic is represented by the Muschelkalk which can be divided into the Lower, Middle and Upper Muschelkalk. The Lower Muschelkalk of the Mogilno-Łódź Trough is developed as grey and beige limestones, often bedded and laminated with claystones and marls. In the northern part of the Kujawy Swell, marly and dolomitic limestones are dominant. The Middle Muschelkalk, represented by interbedding dolomitic claystones, dolomitic marls and anhydrites, reveals relatively homogeneous development over vast areas. As a rule, the Upper Muschelkalk is composed of limestones in the lower part of the profile and claystones with small limestone intercalations in the upper part. This lithologic type is characteristic of the Upper Muschelkalk in the Mogilno-Łódź Trough (Gajewska, 1997). In the area under discussion, the Middle Triassic is represented by the Muschelkalk that is divided into

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the Lower, Middle and Upper Muschelkalk (Senkowiczowa and Szyperko-Śliwczyńska, 1972). In the Mogilno-Łódź Trough, the Lower Muschelkalk is formed of grey and beige limestones, often bedded and laminated with claystones and marls. In the northern part of the Kujawy Swell, marly and dolomitic limestones are dominant. The Middle Muschelkalk, represented by intercalating dolomitic claystones, dolomitic marls, dolomites and anhydrites, shows relatively homogeneous development in large areas. The Upper Muschelkalk, as a rule, is composed of limestones in the lower part of its section, and of claystones with thin limestone interlayers in the upper part. Such lithology is characteristic of the Muschelkalk in the Mogilno-Łódź Trough (Gajewska, 1997). In consideration of the development as carbonates, the Upper Buntsandstein is analysed together with the Muschelkalk. Within the extent of the prospective formations, the top of the Muschelkalk rests at depths from 3500 to 4500 m b.s.l. These formations are characterized by relatively small thickness that is unfavourable for EGS, although areas appear with thickness exceeding the established 300 m. Rocks occurring within the determined extent are characterized by high values of effective porosity (over 2% everywhere), low permeability, bulk density on the order of 2.5-2.7 kg/m^3, and relatively low clay content, from 25 to 40% (Wójcicki et al. (eds.), 2013) .

Materials

In order to assess the geothermal energy resources, the authors used abundant materials gathered and analysed by a broad group of specialists during their research work. A key element was to determine thermal and petrophysical parameters of rocks that form the selected petrogeothermal reservoirs and were subjects of the resource assessment. A principal source of information on the subsurface thermal regime was represented by results of direct temperature measurements in deep wells. For interpretation of the subsurface temperature distribution, thermograms were used, for which analysis of measurement errors had been performed earlier, including corrections of subsurface temperature measurements, resulting from various reasons, technical and environmental in nature, e.g. effects of drilling mud. For evaluation of the quality and usefulness of gathered thermograms, it was cardinally important to determine whether the subsurface temperature measurements were really made in thermal stability conditions (after an appropriately long standstill). An essential indicator of the thermal measurement stability (honesty of the measurements) is consistency of results of temperature measurement in the near-surface zone with average values of the soil temperature in the near-surface zone (Wójcicki et al. (eds.), 2013). Sandstones and possibly dolomites and limestones should be potential reservoir rocks for locating the unconventional geothermal systems in sedimentary rocks. Among the analysed types of sedimentary rocks, sandstones are characterized by the best thermal parameters (specific heat, thermal conductivity). A significant feature of rocks that form petrogeothermal reservoirs is represented by their low porosity and permeability and high values of thermal parameters. The results of the examination of thermal properties, carried out on sedimentary rock samples collected from formations selected as potentially prospective for EGS, indicate considerable differentiation of both the thermal conductivity and specific heat of the analysed rock samples. Among sedimentary rocks, principally sandstones and limestones with reservoir parameters favourable for this type of systems are considered to be petrogeothermal reservoirs. As well the average thermal conductivity as the specific heat measured for carbonate

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rocks are characterized by lower average values in comparison with those measured for terrigenous rock samples, which does not mean that the latter cannot be considered to be prospective reservoirs of petrogeothermal energy. On the other hand, the relationship between thermal parameters of the rock and its porosity is unequivocally noticeable: the tighter is the rock, the better thermal parameters can be recorded (Sowiżdżał and Kaczmarczyk, 2014). Reservoir geometry is an essential element for the geothermal resource assessment. The reservoir layers should be at least 300 m thick to enable the reservoir fracturing. In potential areas with hot dry rocks (HDR), tectonic disturbance zones should not occur; if such zones do occur, throws of faults should be small and the faults should be local in nature. To assess the resources, results of structural modelling performed within the framework of the research work were applied (Wójcicki et al. (eds.), 2013; Sowiżdżał et al., 2013b). The distinguished reservoir horizons were characterized in detail from the point of view of their reservoir parameters. Analysis of petrophysical parameters, including thermal ones, performed on collected rock samples, allowed for determination of properties of hot dry sedimentary rocks (sandstones, limestones and dolomites), which are essential for modelling of their heat capacity. Results of petrophysical measurements and parametric modelling were used as the input material for assessment of petrogeothermal resources (Wójcicki et al. (eds.), 2013; Sowiżdżał et al., 2013b; Sowiżdżał et al., 2014).

Methodology of assessment of petrogeothermal energy resources

In order to estimate static geothermal resources that determine the total amount of heat accumulated in free water and rock matrix, with reference to the mean annual temperature at the ground surface, the methodology developed at the Department of Fossil Fuels, AGH University of Science and Technology was employed (Górecki et al., 1995). The methodology is based on principles of geothermal resource assessment used in European Union countries (Haenel and Staroste, 1988; Hurter and Haenel, 2002) and calculating the geothermal energy resources on the basis of a volumetric calculation model (Muffler and Cataldi, 1979).

Petrogeothermal resources are mostly related to the energy accumulated in rocks, and parameters of waters occurring there in small quantities are less important. Media (usually water) introduced through wells into heated rock formations (HDR) are heat carriers in systems that utilize this type of energy. For this reason, the resource assessment refers only to energy accumulated in the rocks. The assessment of the petrogeothermal energy resources accumulated in reservoir rocks of central Poland was carried out only for areas that meet the earlier discussed criteria of the reservoir geometry.

Static resources of geothermal energy

Static resources of geothermal energy are estimated according to the formula [1], with the first part of the formula referring to resources accumulated in the rock matrix and the second part determining the amount of heat accumulated in free water with reference to the mean annual temperature at the ground surface. If we dealt with nonporous rocks, by definition represented by hot dry rocks, it would be enough to estimate the thermal potential of the rock matrix. In case of reservoir rocks, we speak of EGS systems which use rocks with low porosity and permeability as reservoirs, locally

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containing small amounts of water. Such a small amount of water contained in the rock matrix, together with water pumped into the reservoir will represent the carrier of energy transferred to the surface in EGS systems.

The static resources E_{ZS} are calculated according to the following formula:

$$E_{ZS}= A*m*[(1-p_e)]*\varrho_s*c_s]*(T_s-T_o) \qquad \text{(Eq.1)}$$

where:
- m - cumulative thickness of groundwater horizons in the reservoir [m];
- p_e - effective porosity [-];
- T_s - temperature at the top surface of groundwater reservoir [^oC];
- T_o - mean annual temperature at the Earth's surface [^oC];
- ϱ_s - mean density of rock framework [kg/m^3];
- c_s - mean specific heat of rock framework [J/ kg^oC];
- A - area of calculation block [m^2].

Static recoverable resources of geothermal energy

Static recoverable resources of geothermal energy represent a part of static resources of a given reservoir horizon, which can be exploited at the surface with regard to a given method of geothermal water exploitation. The recoverable part of geological resources is determined by so-called recovery factor of geothermal energy (Ro) for a given horizon or bed, which for exploitation through a geothermal doublet system is equal to:

$$Ro = \frac{As}{Ac} * \frac{Ts - Tz}{Ts - To} \qquad \text{(Eq.2)}$$

where:
- As - cooled area of the dublet [m^2];
- Ac - total area affected by the dublet [m^2];
- Ts - temperature at the top surface of groundwater horizon [^oC];
- Tz - temperature of water injected back to the horizon (=25 ^oC);
- To - mean annual temperature at the Earth's surface [^oC].

In EGS systems, the ratio of cooled area versus total area affected by the geothermal doublet was assumed to be constant (0.5). The parameter was taken as empirical constant value based upon experience gained from the operating geothermal installations in the Paris Basin (France) (Górecki et al., 2006).

Static recoverable resources of geothermal energy were determined according to the following formula:

$$E_{ZSW} = R_o * E_{ZS} \qquad \text{(Eq.3)}$$

- Ro - recovery index;
- E_{ZS} - static resources [J].

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The overall value of static, recoverable resources is a sum of recoverable energy accumulated in the all calculation blocks of given hyrogeothermal reservoir.

Results

As an effect of the calculations, unit and total resources of petrogeothermal energy were determined in the chosen study area for the Lower Carboniferous, Lower Permian, Lower Triassic, and Middle Triassic.

Lower Carboniferous petrogeothermal resouces

Total area of the resource calculation for the Lower Carbonifeorus reservoir amounted to 4100 km^2. Total static resources accumulated in this area are equal to **2.42 * 10^{22} J**. Unit static resources range from several to over 100 GJ/m^2. In the southwestern part of the analysed area, a zone with increased values of static resources is pronounced (locally over 70 GJ/m^2). The distribution of unit static and static recoverable resources is displayed in the map (see *Figure 2*). Total static recoverable resources amount to **6.89 * 10^{21} J.**

Lower Permian petrogeothermal resouces

Prospective formations of the Upper Rotliegend stretch over the largest area. Total area of their occurrence (with the layer thickness restricted with the minimum of 300 m), that is total area of calculation of static resources, amounted to 15,600 km^2; from this resulted the highest value of total static resources equal to **4.33 * 10^{22} J**. Unit static resources vary from several to over 40 GJ/m^2, with maximum values observed in the central part of the area (the Koło vicinity). The distribution of unit static and static recoverable resources is presented in the map (see *Figure 3*). Total static recoverable resources amount to **1.39 * 10^{22} J.**

Lower Triassic petrogeothermal resouces

Total area of calculation of static resources in the Lower Triassic reservoir amounted to approximately 3000 km^2. Total static resources accumulated in this area are equal to **6.87 * 10^{21} J**. Unit static resources vary in the range from several to over 80 GJ/m^2. The distribution of unit static and static recoverable resources is presented by the map (see *Figure 4*). Total static recoverable resources amount to **1.71 * 10^{21} J**.

Middle Triassic petrogeothermal resouces

Among the discussed reservoirs, the prospective Middle Triassic formations occupy the smallest area. It amounts to about 560 km^2 (a significant part of the area, about 340 km^2, was ruled out with regard to the criterion of minimum layer thickness equal to 300 m). The formations are characterized by the smallest thickness among the petrogeothermal reservoirs under discussion (in the considerable part of the area, the Middle Triassic thickness does not exceed 300 m). Total static resources accumulated in this area amount to **7.74 * 10^{20} J**. Unit static resources range from several to over 30 GJ/m^2. The distribution of unit static and static recoverable resources is displayed in the map (see *Figure 5*). Total static recoverable resources amount to **2.52 * 10^{29} J**.

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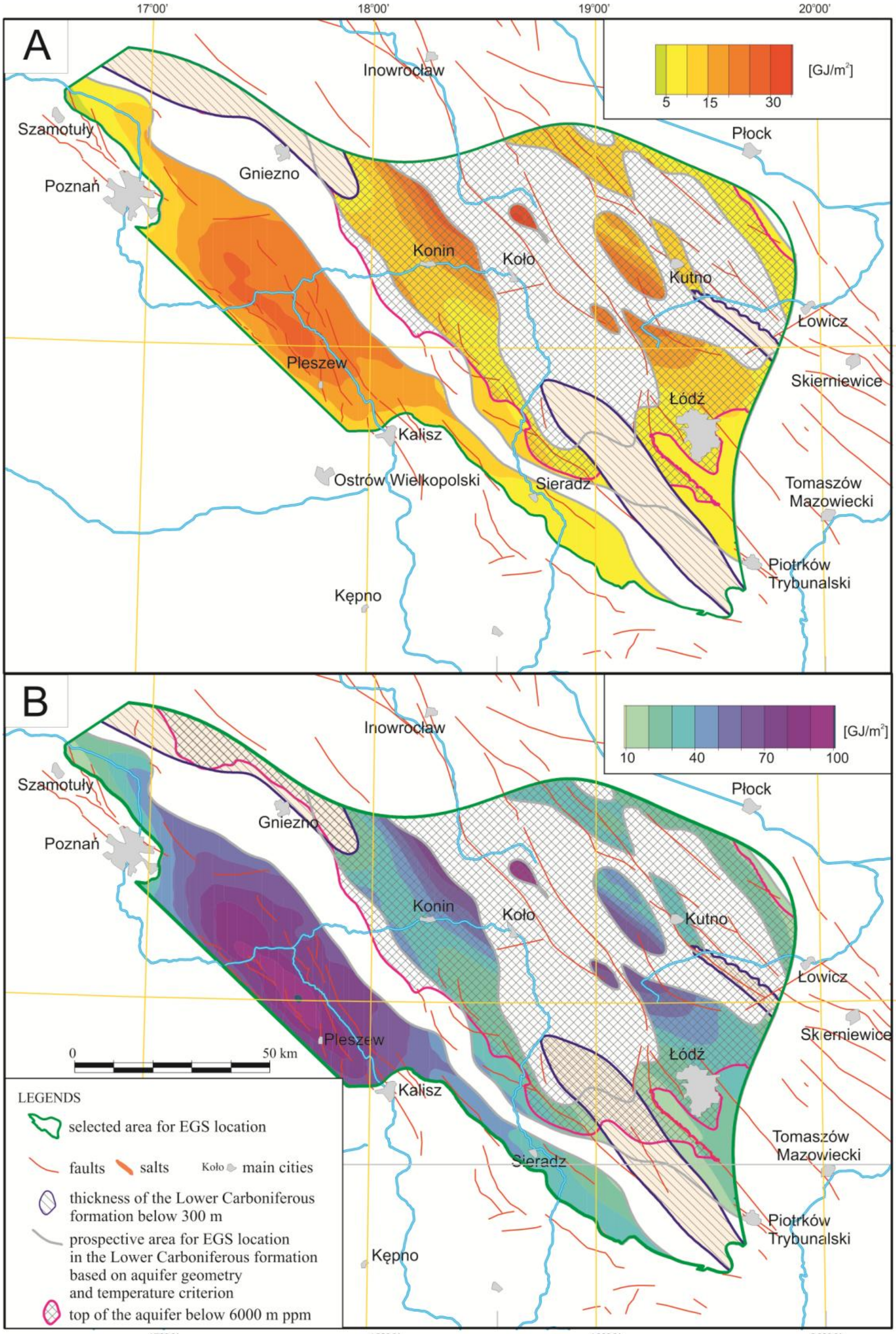

Figure 2. *Maps of unit petrogeothermal resources of the Lower Carboniferous aquifer in the selected area for EGS location: a –static recoverable resources, b- static resources.*

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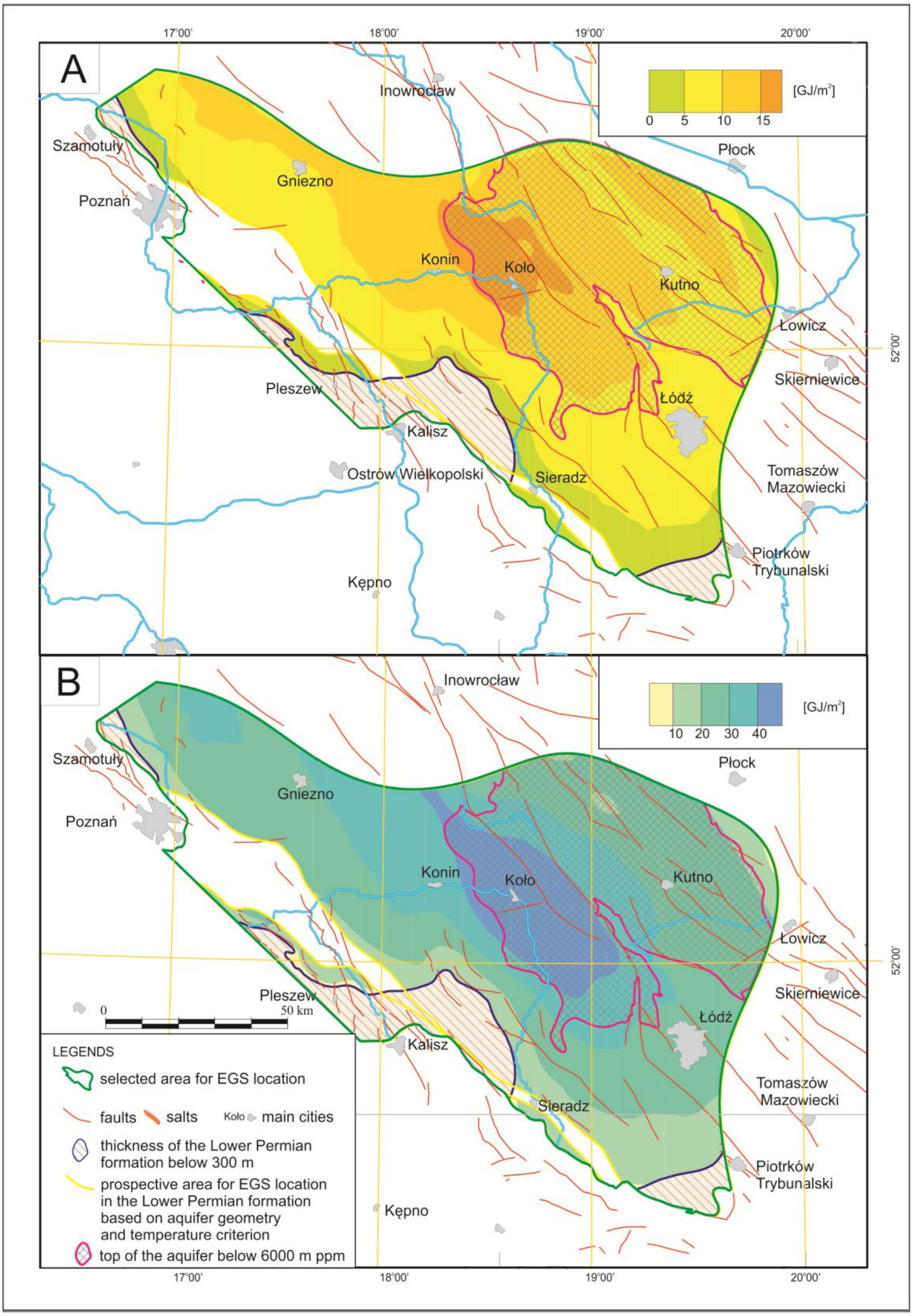

Figure 3. *Maps of unit petrogeothermal resources of the Lower Permian aquifer in the selected area for EGS location: a –static recoverable resources, b- static resources.*

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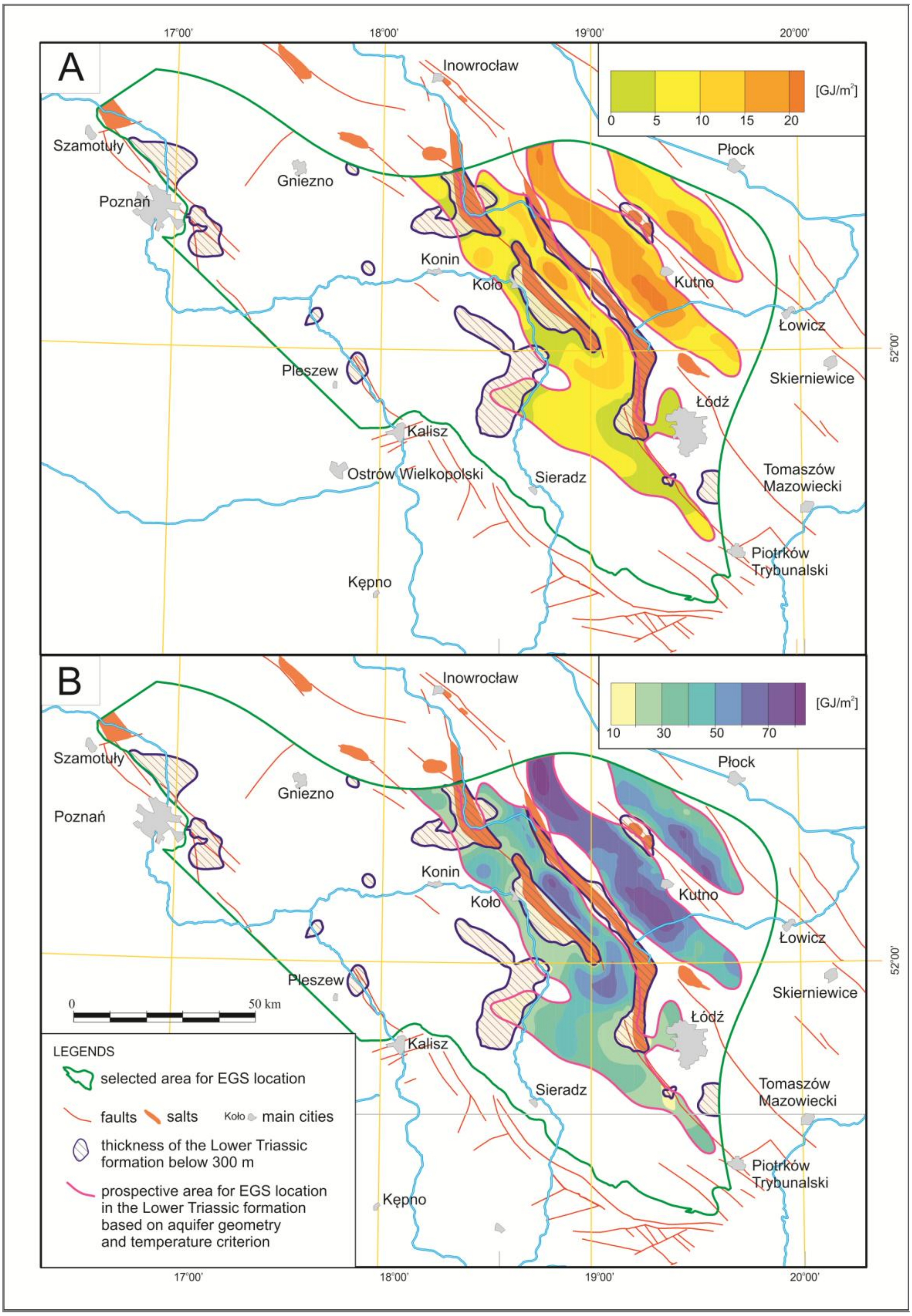

Figure 4. *Maps of unit petrogeothermal resources of the Lower Triassic aquifer in the selected area for EGS location: a –static recoverable resources, b- static resources.*

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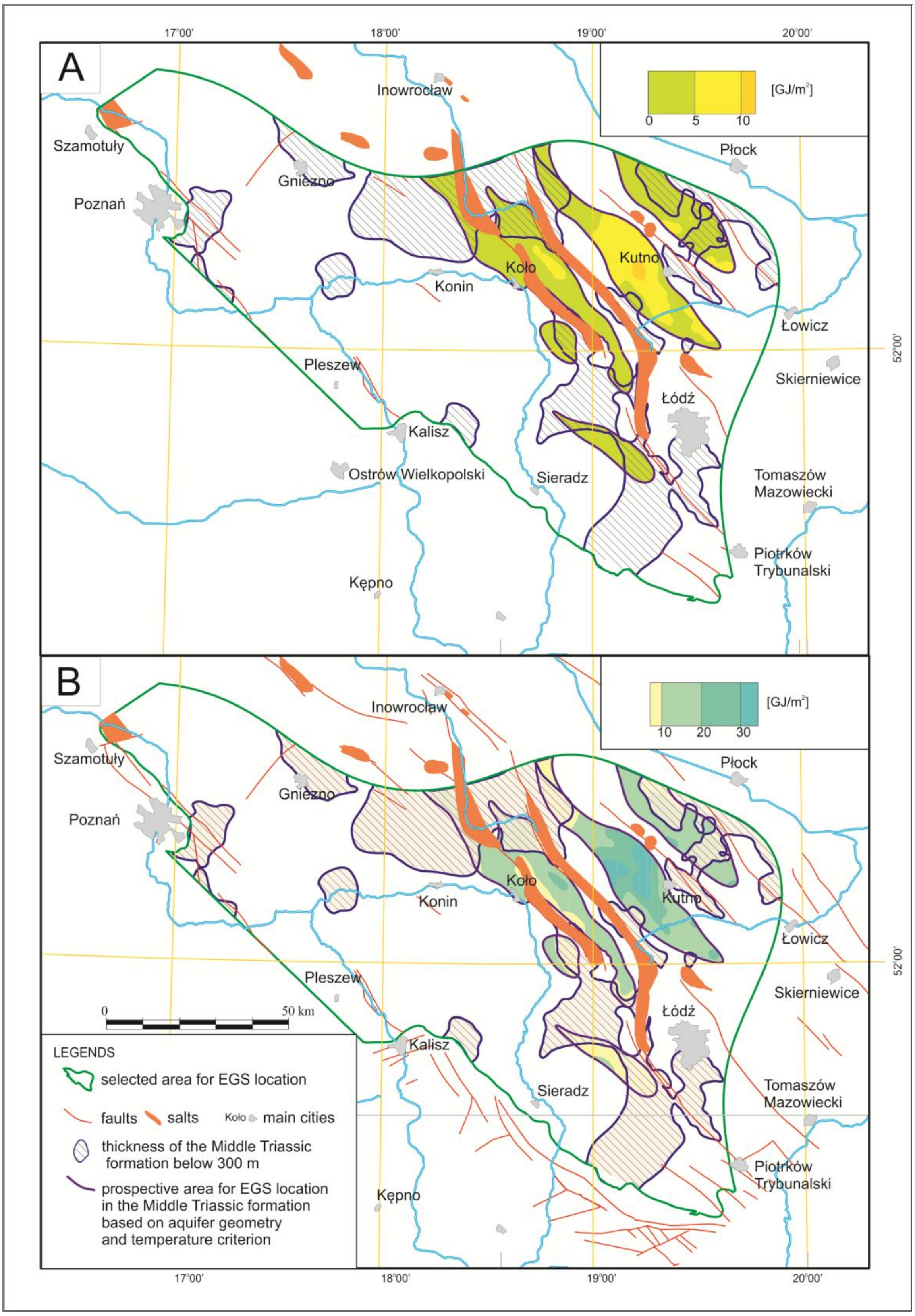

Figure 5. *Maps of unit petrogeothermal resources of the Middle Triassic aquifer in the selected area for EGS location:a –static recoverable resources, b- static resources.*

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Analysis of the results

The assessment of geothermal resources allowed for indication of the most prospective sedimentary reservoirs and locations for building the closed geothermal systems – enhanced geothermal systems (EGS) in the central part of Poland. Compilation of total static and static recoverable resources of geothermal energy in the analysed area is presented in *Table 1*. The geothermal resources were calculated with regard to the criterion of the reservoir rock thickness. In consideration of necessary fracturing in EGS systems, the minimum reservoir thickness was established at 300 m. For this reason, areas of the analysed geothermal reservoirs decreased to various degrees. The most significant decrease (almost 38%) was related to the Middle Triassic reservoir which is characterized by the smallest thickness among the analysed reservoirs. The Lower Triassic prospective area decreased by more than 13%. In case of the Lower Carboniferous and Lower Permian reservoirs, the decrease in area was insignificant (on the order of a few percent). Temperature at the top of the Middle Triassic, due to its relatively shallow occurrence is the lowest of the discussed reservoirs, which in conjunction with the smallest area of the resource calculation implicates the low values of geothermal resources (both static and static recoverable). The Lower Permian prospective formations are most widely distributed. The value of the calculated total geothermal resources is greatest there. Nevertheless, it should be kept in mind that a considerable part of this reservoir (like the Lower Carboniferous reservoir) rests deeper than 6000 m b.s.l., which has important effects on the resource estimate, at the same time imposing the techno-economic constraints on future exploitation. Total static recoverable resources represent 28.5% of total static resources in case of the Lower Carboniferous reservoir, over 34% in case of the Lower Permian reservoir, 24% in case of the Lower Triassic reservoir, and over 35% for the Middle Triassic reservoir.

Table 1. *Total value of geothermal energy resources in selected area for EGS.*

Aguifer	**Total static resources [J]**	**Total static-recovery resources [J]**	**Area of calculation block [m^2]**
Lower Carboniferous	$2.42 * 10^{22}$	$6.89 * 10^{21}$	4000
Lower Permian	$4.33 * 10^{22}$	$1.48 * 10^{22}$	15600
Lower Triassic	$7.87 * 10^{21}$	$1.89 * 10^{21}$	2600
Middle Triassic	$7.74* 10^{20}$	$2.76 * 10^{20}$	560

Considering the unit geothermal resources, three most prospective locations for the unconventional geothermal systems in sedimentary rocks were indicated. They are situated:

- in the Pleszów area where the Lower Carboniferous terrigenous deposits represent reservoir rocks; unit static recoverable resources amount there to approximately 20-30 GJ/m^2 and static resources reach up to approximately 100 GJ/m^2;
- in the Konin area where the Upper Rotliegend terrigenous deposits represent reservoir rocks; unit static recoverable resources

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- are on the order of several GJ/m^2 there and static resources range from 30 to 40 GJ/m^2;
- in the Kutno area where the Lower Triassic terrigenous deposits represent reservoir rocks; unit static resources exceed 70 GJ/m^2 there and static recoverable resources are on the order of 15-20 GJ/m^2.

In spite of the fact that the poorest prospects are related to the Middle Triassic formations, the most interesting area of this reservoir was observed in the Kutno vicinity (static recoverable resources of about 10 GJ/m^2) where several metres deeper hot Buntsandstein rocks rest, with reservoir parameters favourable for EGS systems.

Ultimately, it was decided that the best prospective reservoir horizon would be the thick Buntsandstein horizon resting shallower than the other prospective reservoir horizons, which is an extraordinary asset in consideration of costs and technical possibilities of the reservoir development. Analysis of thermal and petrophysical parameters of the Lower Triassic sandstones (Sowiżdżał et al., 2013b) together with the assessment of geothermal resources have demonstrated that it is just in the Kutno vicinity where this reservoir shows the best parameters.

For the most prospective EGS location research team from Mineral and Energy Economy Research Institute of the Polish Academy of Sciences performed an electricity production model. Numerical modelling was conducted using TOUGH2 code (Bujakowski et al., 2015). The modelled net power of an EGS plant operating in the Kutno area ranged from 1.3 to 1.6 MW depending on the permeability and volume of the fractured zone used for the circulation (Bujakowski et al., 2015). In the Konin area net power of an EGS plant was estimated to range from 1.9 to 2.2 MW, while in in the Pleszów area EGS plant net power was assessed at 2.2-2.5 MW (Wójcicki et al., 2013).

Discussion

The carried out assessment of geothermal energy resources have indicated the existence of a significant potential accumulated in deep-lying rocks of the sedimentary cover. At present this potential is not used. Considering the possibility of development of the existing resources of petrogeothermal energy, a number of aspects other than geologic ones should be taken into account, among others the technical, economic and organizational aspects of an investment. In case of sedimentary rocks, numerous problematical aspects of functioning of the system should be considered, resulting mostly from the absence of the world experience in making use of sedimentary rocks as reservoir rocks for unconventional geothermal systems (although experimental installations in such rocks are under construction now) and the associating variability of crucial parameters of a modelled system (e.g. susceptibility to fracturing). There exist a number of issues which may potentially affect the efficiency of EGS functioning, e.g. heterogeneity of reservoir rocks, presence of clayey material, occurrence of mineralized water, etc.

In Poland, the geothermal energy utilization develops slowly. In spite of the existence, in a number of regions, of adequate geothermal resources, due to numerous conditions the utilization of such energy represents a fraction of a percent in the total energy balance in Poland. The hydrogeothermal energy resources used to date have been relatively well recognized and documented. The present paper has shown that the research work aimed also at recognition of the petrogeothermal energy potential has started. The world predictions indicate that the petrogeothermal energy is the energy of

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future and in the coming years development of such energy sector can be expected. Also in Poland the occurrence of the petrogeothermal energy resources possible to be utilized in future has been observed.

Considering the resources accumulated in sedimentary rocks, it should be noted that the most abundant resources occur in three locations of central Poland (the Mogilno-Łódź Trough). The best prospective is the Kutno area where the Lower Triassic terrigenous deposits represent reservoir rocks and unit static recoverable resources are on the order of 15-20 GJ/m^2. In the Pleszów area, also significant potential have been shown; there the Lower Carboniferous terrigenous formations represent reservoir rocks and unit static recoverable resources amount to about 20-30 GJ/m^2. The Konin area is the third distinguished location, with the Upper Rotliegend terrigenous deposits representing the reservoir rocks and unit static recoverable resources amounting to several GJ/m^2.

Apart from the presented study results, other research teams have conducted work aiming at assessment of petrogeothermal energy resources in volcanic and crystalline rocks. Their results have shown that prospects for development of petrogeothermal energy from volcanic and crystalline rocks are even more optimistic than from sedimentary rocks, which allows to claim that in Poland the work also on development of such resources should be started, following the example of other countries.

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REFERENCES

[1] Antkowiak, M., Snyder, N.K., Lowry, T.S. (2010): A high level geothermal system scoping model: a first step toward Enhanced Geothermal System Engineering. Proceedings, Thirty-Fifth Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 1-3, 2010: 1-8. http://www.geothermal-energy.org/pdf/IGAstandard/SGW/2010/antkowia.pdf.

[2] Baria, R., S. Michelet, S., J. Baumgartner, J., B. Dyer, B., J. Nicholls, J., T. Hettkamp, T., D. Teza, D., N. Soma, N., H. Asanuuma, H. J., Garnish, J., T. Megel, T. Kohl, T., and L. Kueperkoch, L. (2005): A 5000 m Deep Reservoir Development at the European HDR Site at Soultz. Proc. 30th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Calif., Jan. 31–Feb. 2, Paper No. SGP-TR-176.

[3] Brown, D.W., Duchane, D., Heiken, G., Hriscu, V.T. (2012): Mining the Earth's Heat: Hot Dry Rock. – Geothermal Energy, Springer, p.657.

[4] Bujakowski W., Barbacki A., Miecznik M., Pająk L., Skrzypczak R., Sowiżdżał A. (2015): Modelling geothermal and operating parameters of EGS installations in the Lower Triassic sedimentary formations of the central Poland area. – Renewable Energy 80: 441- 453.

[5] Bujakowski, W., Tomaszewska, B. (eds.) et al. (2014): Atlas of the possible use of geothermal waters for combined production of electricity and heat using binary system in Poland, Krakow. – Wydawnictwo "Jak", Kraków, 307 pp. (in Polish with English extended abstract).

[6] de Graaf, L., Palmer, R., Reid, I. (2010): The Limestone Coast Geothermal Project, South Australia: A Unique Hot Sedimentary Aquifer Development. – Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010, International Geothermal Association Publications: 3134, 1-7.

[7] European Geothermal Energy Council (2013) Financing Geothermal Energy, Brochure, July 2013, EGEC Policy Paper.
[8] Gajewska, I. (1997): Trias środkowy (wapień muszlowy – kajper dolny). Trias górny (kajper). Sedymentacja, paleogeografia i tektonika. – In: Marek, S. Pajchlowa, M. (eds.) Epikontynentalny perm i mezozoik w Polsce. Prace Państwowego Instytutu Geologicznego 153: 144-171.
[9] Górecki, W. (ed.) et al. (1990): Atlas of geothermal resources in the Polish Lowlands. – ZSE AGH, Krakow, 369. (in Polish).
[10] Górecki, W. (ed.) et al. (1995): Atlas of geothermal resources in the Polish Lowland. – Geosynoptics Society Geos, Krakow, 91. (in Polish).
[11] Górecki, W. (ed.) et al. (2006a): Atlas of geothermal resources of Mesozoic formations in the Polish Lowlands. – Ministry of Environment, AGH KSE, Krakow, 484 pp. (in Polish with English summary).
[12] Górecki, W. (ed.) et al. (2006b): Atlas of geothermal resources of Paleozoic formations in the Polish Lowlands.– Ministry of Environment, AGH KSE, Krakow, 240. (in Polish with English summary).
[13] Górecki, W. (ed.) et al. (2011): Atlas of geothermal waters and energy resources in the Western Carpathians. – AGH KSE, Kraków, 772. (in Polish with English summary).
[14] Górecki, W. (ed.) et al. (2012): Geothermal Atlas of the Carpathian Foredeep. – AGH KSE, Krakow, 381. (in Polish).
[15] Górecki, W. (ed.) et al. (2013a): Geothermal Atlas of the Eastern Carpathians. – AGH KSE, Krakow, 791. (in Polish with English summary).
[16] Górecki, W., Sowiżdżał, A., Hajto, M., Jasnos, J. (2013b): The latest results of geothermal projects in Poland. – European Geothermal Congress 2013, Pisa, Italy, 3-7 June 2013.
[17] Haenel, R., Staroste, E. (1988): Atlas of geothermal resources in the European Community, Austria, Switzerland and Germany. – Th. Schaefer, Hannover, Germany, 74 pp, 110 plates.
[18] Hajto, M. (2011): Potencjał geotermalny w rejonie zewnętrznych Karpat Zachodnich, Technika Poszukiwań Geologicznych. – Geotermia, Zrównoważony Rozwój, ISSN 0304-520X. — 2011 R. 50 z. 1–2 s. 37–49.
[19] Hajto, M., Górecki, W. (2010): Geological Analysis and Assessment of Geothermal Energy Resources in the Polish Lowlands. Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.
[20] Hajto, M., Górecki, W., Sowiżdżał, A. (2007): Assessment of Geothermal Energy Resources of Mesozoic and Palaeozoic Formations in the Polish Lowlands - Proceedings European Geothermal Congress 2007 Unterhaching, Germany, 30 May-1 June 2007.
[21] Hurter, S., Haenel, R. (eds.) (2002): Atlas of Geothermal Resources in Europe. – Office for Official Publications of the European Communities, Brüssel, Luxemburg, 261.
[22] Karnkowski, P.H., 1999. Origin and evolution of the Polish Rotliegend Basin. – Polish Geological Institute Special Papers 3: 1–93.
[23] Muffler, L.J.P., Cataldi, R. (1979): Methods for Regional Assessment of Geothermal Resources. – Geothermics, 7.
[24] Narkiewicz, M., Dadlez, R. (2008): Geologiczna regionalizacja Polski - zasady ogólne i schemat podziału w planie podkenozoicznym i podpermskim. – Przegląd Geologiczny 56 (5): 391.
[25] Pokorski, J. (1976): The Rotliegendes of the Polish Lowlands. – Przegląd Geologiczny 24: 318 -323.
[26] Pożaryski, W., Karnkowski, P. (1992): Tectonic map of Poland during the Variscan time, 1: 1 000 000. – Polish Geological Institute, Wyd. Geologiczne,Warsaw.
[27] Sausse, J., Dezayes, C., Genter, A. (2007): From geological interpretation and 3D modelling to the characterization of the deep seated EGS reservoir of Soultz (France).

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1402_555574

Proceedings European Geothermal Congress 2007, Unterhaching, Germany, 30 May-1 June 2007: International Geothermal Association – European Branch Publications: 1-7. https://pangea.stanford.edu/ERE/pdf/IGAstandard/EGC/2007/059.pdf
[28] Senkowiczowa, H., Szyperko - Śliwczyńska, A. (1972): Stratygrafia i paleogeografia triasu. – Biuletyn Instytutu Geologicznego 252.
[29] Sowiżdżał A., Papiernik B., Machowski G. (2014): The role of structural and parametric modelling in the process of selecting Enhanced Geothermal System location in sedimentary rocks. – Przegląd Geologiczny 62 (6): 303–307.
[30] Sowiżdżał, A. (2010): Assessment of geothermal water and energy resources of Lower Jurassic formations in the NW part of Polish Lowland (Szczecin Trough). Proceedings World Geothermal Congress 2010, Bali, Indonesia, 25-29 April 2010.
[31] Sowiżdżał, A. (2015): Characterization of geothermal reservoirs parameters in Polish part of Carpathian Foredeep. – Carpathian Journal of Earth and Environmental Sciences 10 (2): 237–246.
[32] Sowiżdżał, A., Górecki, W. (2013): Możliwości wykorzystania energii geotermalnej w rejonie zapadliska przedkarpackiego, Technika Poszukiwań Geologicznych. – Geotermia, Zrównoważony Rozwój 52 (2): 59–73.
[33] Sowiżdżał, A., Kaczmarczyk, M. (2013): Thermal parameters characteristics of sedimentary rocks forming petrogeothermal reservoirs in the central part of the Polish Lowlands Technika Poszukiwań Geologicznych. – Geotermia, Zrównoważony Rozwój 52 (2): 141–154.
[34] Sowiżdżał, A., Kaczmarczyk, M. (2016): Analysis of thermal parameters of Triassic, Permian and Carboniferous sedimentary rocks in central Poland, Geological Journal 51, 65-76.
[35] Sowiżdżał, A., Papiernik, B., Machowski, G. (2013a): 3D Static models as a tool to indicate prospective geological structures for EGS in sedimentary rocks of Central Poland In: EAGE Sustainable Earth Sciences 2013: technologies for sustainable use of the deep sub-surface: 30 September – 4 October, 2013, Pau, France: proceedings, EAGE European Association of Geoscientists & Engineers.
[36] Sowiżdżał, A., Papiernik, B., Machowski, G., Hajto, M. (2013b): Characterization of petrophysical parameters of the Lower Triassic deposits in prospective location for Enhanced Geothermal System (central Poland). – Geological Quarterly 57 (4): 729-744.
[37] Szyperko-Śliwczyńska, A. (1977): Piaskowiec pstry dolny i środkowy. In: Geological structure of the eastern part of the Mogilno-Łódź Trough (Gopło-Ponętów-Pabianice zone) (ed. S. Marek) (in Polish with English summary). – Prace Państwowego Instytutu Geologicznego 80: 128-137.
[38] Szyperko-Śliwczyńska, A. (1979): Trias dolny w północno-wschodniej Polsce. – Prace Państwowego Instytutu Geologicznego 91.
[39] Szyperko-Teller, A. (1982): Litostratygrafia pstrego piaskowca na Pomorzu Zachodnim. – Kwartalnik Geologiczny 26 (2): 341-368.
[40] Szyperko-Teller, A. (1997): Trias dolny (pstry piaskowiec). Sedymentacja, paleogeografia i paleotektonika. – In: Marek, S., Pajchlowa, M. (eds.) Epikontynentalny perm i mezozoik w Polsce, Prace Państwowego Instytutu Geologicznego 153: 121-132.
[41] Tenzer, H. (2001): Development of Hot Dry Rock Technology. – GHC Bulletin 12: 1-9.
[42] Tester, J. W., Herzog, H.J. (1991): The Economics of Heat Mining: An Analysis of Design Options and Performance Requirements of Hot Dry Rock (HDR) Geothermal Power Systems. Sixteenth Workshop on Geothermal Reservoir Engineering, January 23-25, Stanford University, Stanford, California.
[43] Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., Dipippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., Petty, S., Toksoz, M.N., Veatch, R.W. (2006): The Future of Geothermal Energy. Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. – Massachusetts Institute of Technology, http://geothermal.inel.gov.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1402_555574

[44] Tomaszewska, B., Bujakowski, W., Barbacki, A.P., Olewiński, R. (2010): Zbiornik geotermalny jury dolnej w rejonie Kleszczowa. – Przegląd Geologiczny 58 (7): 603-608.
[45] Wójcicki, A., Sowiżdżał, A., Bujakowski, W. (eds.) et al. (2013): Evaluation of potential, thermal balance and prospective geological structures for needs of unconventional geothermal systems (Hot Dry Rocks) in Poland. – Ministry of Environment, Warsaw, Krakow, 246.

http://www.aloki.hu ● ISSN 1589 1623 (Print) ● ISSN 1785 0037 (Online)
DOI: http://dx.doi.org/10.15666/aeer/1402_555574