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# Characterization of petrophysical parameters of the Lower Triassic deposits in a prospective location for Enhanced Geothermal System (central Poland)

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In the years 2010–2013, analysis of rocks that build the sedimentary covers in Poland was carried out from the point of view of utilization of energy accumulated in Hot Dry Rock – used in Enhanced Geothermal Systems (EGS). As a result of a number of analytical studies, the area situated in the central part of Poland was selected as one of prospective areas for location of EGS in sedimentary rocks. This area encompasses a major part of the Mogilno–Łódź Trough, a part of the Kujawy Swell and a small fragment of the Fore-Sudetic Monocline. The most favourable conditions for development of EGS occur in the Lower Triassic deposits in the Krośniewice–Kutno vicinity, where they are buried to depths greater than 5000 m b.s.l., their thicknesses exceeds 1500 m, porosity is about 3% and permeability is about 0.02–0.1 mD. In the study area, thermal characterization of the formation was carried out for location of the EGS in sedimentary rocks. The temperature at the top of the Lower Triassic reservoir is modelled in the range of 165–175°C. Characterization of petrophysical parameters was the basis for further modelling of EGS utilization in this area.

Key words: Enhanced Geothermal System (EGS), Polish Lowlands, Lower Triassic, petrophysical parameters.

## INTRODUCTION

The concept of utilization of heat from Hot Dry Rock assumes drilling boreholes in areas characterized by high temperature anomalies and intense heat transfer (Tester et al., 2006). In 1970, it was proposed as a method for exploiting the heat contained in those vast regions that contain no fluids in place. The HDR (Hot Dry Rock) system recovers the Earth's heat via closed-loop circulation of fluid from the surface through a man-made confined reservoir (Brown et al., 2012). Hot Dry Rock for a long time has been a synonym for heat extracted from deep hot crystalline rock (Tenzer, 2001). In most of the HDR projects in the world, granites constitute reservoir rocks for closed geothermal systems (Tenzer, 2001; Sliaupa et al., 2005; Tester et al., 2006; Sausse et al., 2007; Brown et al., 2012). Solutions that utilize energy of hot sedimentary rocks are rare, though such projects do exist. For example, the Limestone Coast Geothermal Project (Australia) is designed to demonstrate that geothermal resources within Australia's hot sedimentary basins can be used to generate large amounts of competitively priced zero-emission base-load power (Graaf et al., 2010). In case of sedimentary cover, reservoir rocks contain a small amount of groundwater, so the utilization system is called EGS (Enhanced Geothermal System). 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 includes conduction-dominated, low-permeability resources in sedimentary formations (Tester et al., 2006). In EGS, the naturally occurring hot rock does not contain enough water and generally lies at a greater depth than is typical of hydrothermal systems. Fracturing of this rock and the introduction of geofluid (assuming water initially, but later other fluid may be used, such as $CO_2$) is necessary to enable the extraction of useful heat energy. Again, the fluid is passed through a power plant on the surface and subsequently reinjected (Antkowiak et al., 2010). Local and regional geologic and tectonic phenomena play a major role in determining the location and quality of geothermal resources. The first requirement 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. Thermal energy is extracted from the reservoir by a coupled transport process (convective heat transfer in porous and/or fractured regions of rock and conduction through the rock itself). The heat extraction process must be designed with the constraints imposed by prevailing in situ hydrological, lithological and geological conditions (Tester et al., 2006). Integrated geothermal exploration strategy covers all aspects from geosystem analysis, reservoir characterization and reservoir geomechanics. Such an integrated approach might be essential for an economic and sustainable exploitation not only of EGS but of all geothermal systems (Moeck et al., 2010).

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The research project, carried out in the years 2010–2013 by leading scientific centres [the Consortium composed of: the Polish Geological Institute – National Research Institute, the AGH University of Science and Technology (AGH-UST), the Mineral and Energy Economy Institute of the Polish Academy of Sciences, and the PBG Geophysical Exploration Co. Ltd.], is the first enterprise of this type in Poland, which tends to recognize the potential of Hot Dry Rock for heat and electricity production. The main objective of the project was to assess the possibility of using geological successions for building EGS in the territory of Poland through cartographic imaging of selected successions, prospective for this type of systems in Poland. The goal of the research conducted by the AGH-UST team was to indicate the best location for EGS in sedimentary rocks (Górecki et al., 2013).

## GEOLOGICAL SETTING

The area selected for detailed structural-parametric and thermal modelling in terms of preliminary assessment of potential for EGS development possibility is located in central Poland. Geological settings and evolution of that area are very complex. Its evolution starting from the Paleozoic to Cenozoic resulted in its potential suitability for geothermal utilization. The area covers the marginal part of the West and Central European Paleozoic Platform (WCEPP), including an array of smaller areas known as the Trans-European Suture Zone (TESZ; Królikowski, 2006; Nawrocki and Poprawa, 2006; Fig. 1A), and to a lesser extent the East European Craton (EEC). The area also covers their tectonic border, the NW–SE trending Teisseyre-Tornquist Zone (TTZ; Pożaryski and Brochwicz-Lewiński, 1978; Dadlez et al., 1995; Dadlez, 1997a, b; Grabowska et al., 1998; Grabowska and Bojdys, 2001; Kutek, 2001; Grad et al., 2002a) which is among the most important deep lithospheric boundaries in Europe (Grad et al., 2002b; Dadlez et al., 2005; Grad and Guterch, 2006a, b; Krzywiec, 2006a). TTZ is replaced towards the NW by its prolongation – the Sorgenfrei-Tornquist Zone (Krzywiec, 2006a; Jarosiński et al., 2009). The area of TTZ and partly TESZ roughly corresponds to the location of the axial part of the Polish Basin, known as the Mid-Polish Trough (MPT), which in turn was part of the Permian–Mesozoic system of epicontinental basins of Western and Central Europe (Ziegler, 1990a; Krzywiec, 2006a, b; Jarosiński et al., 2009), overlapping much of the Southern Permian Basin (SPB) area (Pharaoh et al., 2010). The Polish Basin was the eastern part of the SPB (Kiersnowski et al., 1995; Wees et al., 2000; Gast et al., 2010; Pharaoh et al., 2010). Its development resulted from long-term thermal subsidence, which started in the Permian and lasted until the Late Cretaceous. It comprised three major pulses of extension-related accelerated tectonic subsidence during Late Permian to Early Triassic times, in the Oxfordian to Kimmeridgian, and in the Early Cenomanian (Dadlez et al., 1995; Stephenson et al., 2003; Krzywiec, 2006a). Throughout Permian and Mesozoic times, the regional subsidence patterns of the Polish Basin followed the evolution of MPT. Locally, they were altered by salt movements that started during the Early Triassic within the central (Kuiavian) part of the trough, in the vicinity of the Kłodawa salt structure (Krzywiec, 2004, 2006a, b). Zechstein salts were engaged in a complex system of salt structures developed in the central and northwestern segments of the MPT (Pożaryski, 1977a, b; Krzywiec, 2004, 2006a, b). As a result

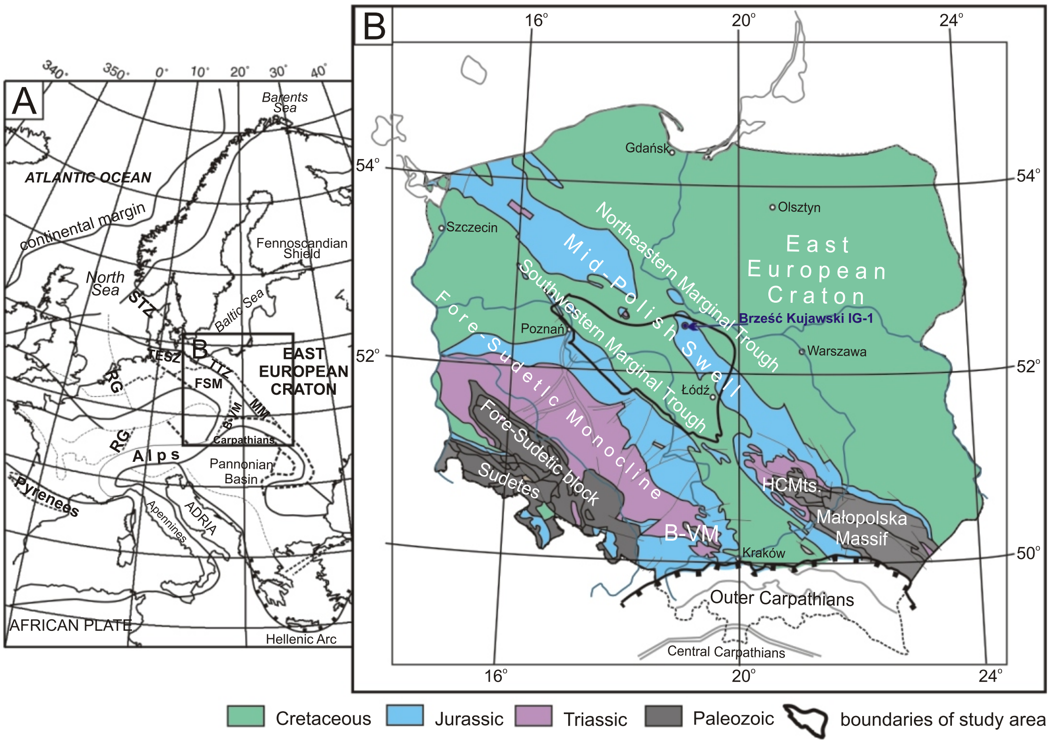

**Fig. 1A – study area on the background of the tectonic map of Central Europe, B – tectonic setting of Poland without the Cenozoic cover (after Jarosiński et al., 2009)**

B-VM – Bruno-Vistulicum Massif, FSM – Fore-Sudetic Monocline, HCMts. – Holy Cross Mountains, MM – Małopolska Massif, RG – Rhine Graben, STZ – Sorgenfrei-Tornquist Zone, TESZ – Trans-European Suture Zone, TTZ – Teisseyre-Tornquist Zone of long-lasting subsidence, the Permian–Mesozoic thick sedimentary cover was deposited in the MPT, resulting in a column of over 8 km thick sediments, comprising Zechstein, Triassic, Jurassic and Cretaceous successions (e.g., Marek and Pajchlowa, 1997; Becker, 2005a; Krzywiec 2006a, b; Bachmann et al., 2010; Gast et al., 2010; Peryt et al., 2010; Leszczyński, 2012). The final stage of the Mid-Polish Trough evolution was the Late Turonian–Paleocene inversion which also affected the Sorgenfrei-Tornquist Zone, the Bohemian Massif and the North German Basin (Ziegler, 1990a, b; Krzywiec, 2006a; Jarosiński et al., 2009; Pharaoh et al., 2010). Inversion of the MPT was a broad uplift typical for basins having thick salts. The total uplift during basin inversion could reach 2500 to 3000 m, as seen in the Mid-Polish Antictlinorium (MPA; Dadlez, 1980). In the Polish Lowlands, the Cenozoic sequence is thin typically about 250 m. The remnant topographic relief of the MPA was reduced by erosion during the Eocene and was completely overstepped by mid-Oligocene times (Ziegler, 1990a), with no evidence for Pyrenean or Savian inversion (Jarosiński et al., 2009; Pharaoh et al., 2010). Inversion and subsequent erosion created the sub-Cenozoic tectonic pattern of the Polish Lowlands. Staring from the south, the investigated area covers the northern rims of the Fore-Sudetic Monocline, and the Mogilno–Łódź segment of the Southwestern Marginal Trough (Fig. 1B). The most EGS prospecting part of the area covers the Kuiavian segment of the Mid-Polish Anticlinorium (Swell) (Narkiewicz and Dadlez, 2008; Karnkowski, 2008; Żelaźniewicz et al., 2011). The Lower Triassic section starts with the Lower Buntsandstein Subgroup (LBS) which is of continental to marginal marine origin (Warrington, 1974; Ziegler, 1990a; Röhling, 1991; Geluk, 1999; Becker, 2005a; Bachmann et al., 2010). The Lower Buntsandstein Subgroup in Poland is represented by the Baltic Formation (Fig. 2). In the Kuiavian segment, it is underlain by the ca. 30 m thick Rewal Formation (Szyperko-Tellerand and Moryc, 1988; Becker, 2005a; Feldman-Olszewska, 2008). Its thickness is approximately 400 m in depocentres of the Mid-Polish Trough (Szyperko-Teller and Moryc, 1988; Szyperko-Teller, 1997; Iwanow and Kiersnowski, 1998; Bachmann et al., 2010). These are alluvial and fluvial deposits derived from the surrounding Variscan and older Bohemian massifs and the Fennoscandian Shield, accumulated in marginal areas and passing distally into finer-grained mud-flat and marginal marine sediments (Pieńkowski, 1991; Szyperko-Teller, 1997; Iwanow and Kiersnowski, 1998). The main clastic input into the Polish Basin was from the southern and southeastern margins of the current SPB area (Marek and Pajchlowa, 1997; Bachmann et al., 2010). An important structural reorganization took place at the end of Lower Buntsandstein sedimentation. Tensional and transtensional stresses created NNE–SSW trending highs and lows that dissected the sedimentary basin of the Lower Buntsandstein Group into local areas of subsidence related to grabens, and much wider areas of uplift and erosion (Bachmann et al., 2010). The Middle Buntsandstein Subgroup (MBS) successions in the Mid-Polish Trough have a thickness exceeding 1000 m. The MBS in the Mid-Polish Through is represented by the Pomerania and Połczyn formations composed of alternating thin-bedded sandstones, siltstones and claystones of marginal marine to playa-flat and lacustrine origin (Szyperko-Teller, 1997; Iwanow and Kiersnowski, 1998; Becker, 2005a, b). In the research area, some authors (Szyperko-Teller, 2008) distinguish the informal Clayey Formation instead of the Połczyn Formation (Fig. 2). In Poland, the topmost Lower Triassic deposits are represented by rocks equivalent to the Röt Formation. In the research area, this is sabkha of the Barwice Formation (Feldman-Olszewska, 2008). The Röt Formation is marked by an regional increase in marine influence. Open-marine conditions existed at that time in the foreland of the Holy Cross High, but generally in

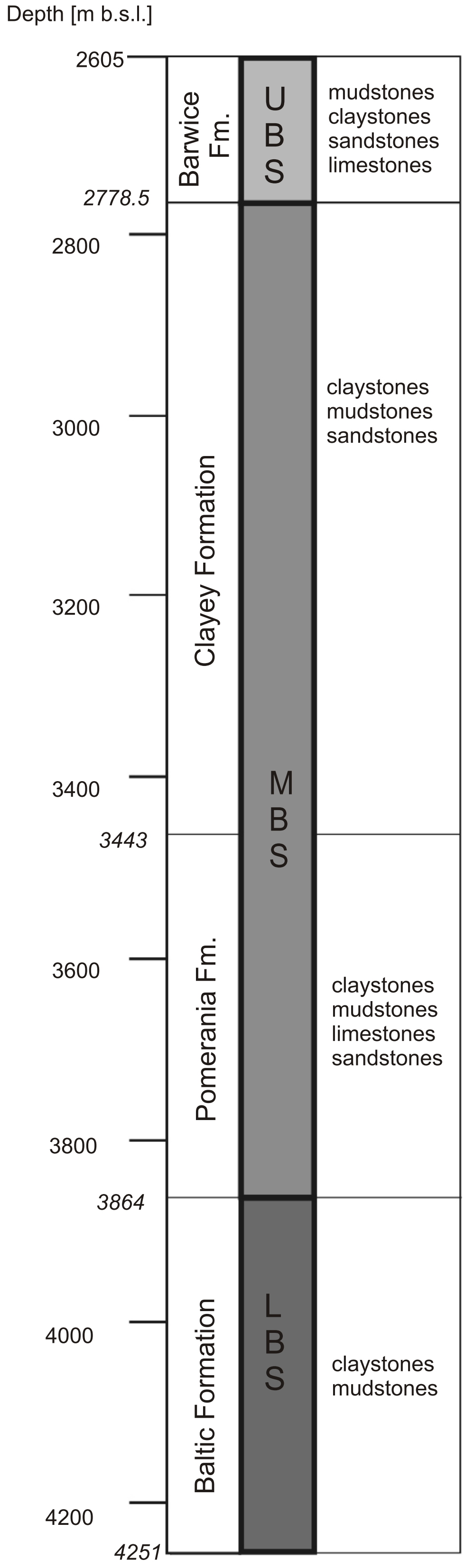

**Fig. 2. Stratigraphy of the Lower Triassic in the Brześć Kujawski IG 1 borehole (after Szyperko-Teller and Szulc, 2008)**

UBS – Upper Buntsandstein Subgroup, MBS – Middle Buntsandstein Subgroup, LBS – Lower Buntsandstein Subgroup the Polish Basin, the facies pattern of the lower Röt Formation is typical of a semi-closed evaporitic basin (Becker, 2005a, b). Following evaporite deposition, a large brackish-water lagoon developed, with deposits of predominantly red fine-grained clastics (Szulc, 2000). A widespread transgression began during the latest deposition of the Röt resulted in the shallow sea carbonate sedimentation (Szyperko-Teller, 1997; Szulc, 2000; Bachmann et al., 2010) which prevailed during Middle Triassic times.

## MATERIALS AND METHODS

Geothermal energy consists of the thermal energy stored in the Earth's crust, which is distributed between the constituent host rock and the natural fluid that is contained in its fractures and pores at temperatures above ambient levels. The source and transport mechanisms of geothermal heat are unique to this energy source. Local and regional geological 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 (Tester et al., 2006). EGS concepts would recover thermal energy contained in subsurface rocks by creating or accessing a system of open, connected fractures through which water can circulate down injection boreholes, heated by contact with the rocks, and return to the surface in production boreholes to form a closed loop (Tester et al., 2006). Therefore, the reservoir geometry should be appropriate (requirements of minimum thickness).

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

Lithology and mechanical properties of reservoir rocks are also important because of hydrofracturing. In case of sedimentary rocks, compact sandstones or limestones should be appropriate.

The first step of the preliminary analysis was based on the existing geological and geothermal data, e.g., those collected in geothermal atlases (Górecki, 2006a, b) supplemented with new data. Complementary analyses of raw data and maps of surface heat flow density, subsurface temperatures, and maps of gravimetric and magnetic anomalies allowed determining several prospective locations. The most promising conditions (temperatures >150°C at a depth of 5 km) occur in central Poland in the Southwestern Marginal Trough and in small part of Mid-Polish Swell regions (Fig. 1). Preliminary analyses revealed prospects for building EGS in the Lower Triassic reservoir, which seems to be a complex meeting the EGS requirements. However, the Permian and Carboniferous sandstones also have been identified as a potential reservoir for EGS in this area (according to temperature requirement). The advantage of the Lower Triassic reservoir was the considerable thickness of sedimentary rocks combined with the favourable reservoir parameters for EGS (low porosity and permeability). In order to select the best possible sites and rock complexes for locations of EGS within a pre-indicated area, thermal, structural and parametric modelling was performed.

## STRUCTURAL AND PARAMETRIC 3D MODELLING

Methodology of basin-scale structural and parametric modelling of the sedimentary cover used by the AGH-UST team has been developed over past 20 years. The first regional digital models were borehole-based structural maps in a form of digital 2D grids with horizontal resolution of 5000 × 5000 m. They were later replaced by structural and isopach grids displaying resolution of up to 1000 m and relevant maps and corresponding grids of petrophysical and thermal parameters (porosity, permeability, density, distribution of subsurface temperature; Górecki, 2006a, b; Doornenbal et al., 2010). These, in fact 2.5D solutions, were gradually replaced by fully 3D Petrel-based geomodels developed according to the modern structural and parametric (static) modelling trends (e.g., Dubrule,1998, 2003; Zakrevsky, 2011). That methodology was applied to complete research in the fields of petroleum geology (Papiernik et al., 2009, 2010, 2012), Carbon Capture and Storage – CCS (Wójcicki, 2012), and geothermal systems assessment (e.g., Górecki, 2011, 2012). Structural surfaces were used in the study as input data for modelling of a 3D geometrical framework. They are a combination of regional and semi-regional 2D grids. Structural 2D grids with horizontal resolution of 1000 × 1000 m (Górecki, 2006a, b; Doornenbal et al., 2010) were used as conditioning regional trends for detailed digital surfaces displaying 250 × 250 resolution, which were locally updated with new boreholes (e.g., Pabianice 1 and Kaszewy 1), detailed structural maps created for CCS aims (Wójcicki, 2012) and the new seismic interpretations completed for the research purposes. The resultant basic structural framework of the EGS model covers an area of ca. 36,000 km$^2$. The area selected for the possible EGS location covers ca. 19,000 km$^2$ (Fig. 3, black line). It is composed of thirteen structural horizons starting from the base of the Carboniferous up to the top of the Cretaceous, and it contains twelve stratigraphic zones (stratigraphic complexes in the Petrel system nomenclature), equivalent to stratigraphic epochs (Fig. 3).

The structural framework is relatively simplified as it is completed without a fault model. The presence of faults is clearly reflected in the geometry of Petrel horizons, however, faults were not modelled as a Petrel Fault Model due to a very large area of the 3D model and generally weak seismic control of vertical and horizontal extents of individual faults. The distinguished zones (stratigraphic complexes) were divided into proportional layers and their vertical resolution was accepted according to the expected suitability of each complex for the EGS purposes, dividing 4 to 20 proportional layers with the minimum thickness of 5 m.

Next steps of the modelling process were lithological and parametric modelling. The lithology model is based on geophysical logs and includes eight lithology types – sandstones, claystones, mudstones, marls, carbonates, evaporites, gravels and others (e.g., volcanic rock). It was estimated with the use of Sequential Gaussian Simulation algorithm. Parametric models are based on geophysical logs of porosity – PHI (data from 54 boreholes), shale volume – Vsh (35 boreholes) and bulk density – RHOB (24 boreholes). The model of permeability – PERM – was based on core data from 90 boreholes. For the sake of simplicity, the parametric models were calculated with the use of Kriging Interpolation. Location of boreholes used in parametric modelling is shown in Figure 4.

The results of structural and parametric modelling were converted into maps of average parameters and effective thicknesses, superimposed on maps of temperatures related to the tops of the mapped zones.

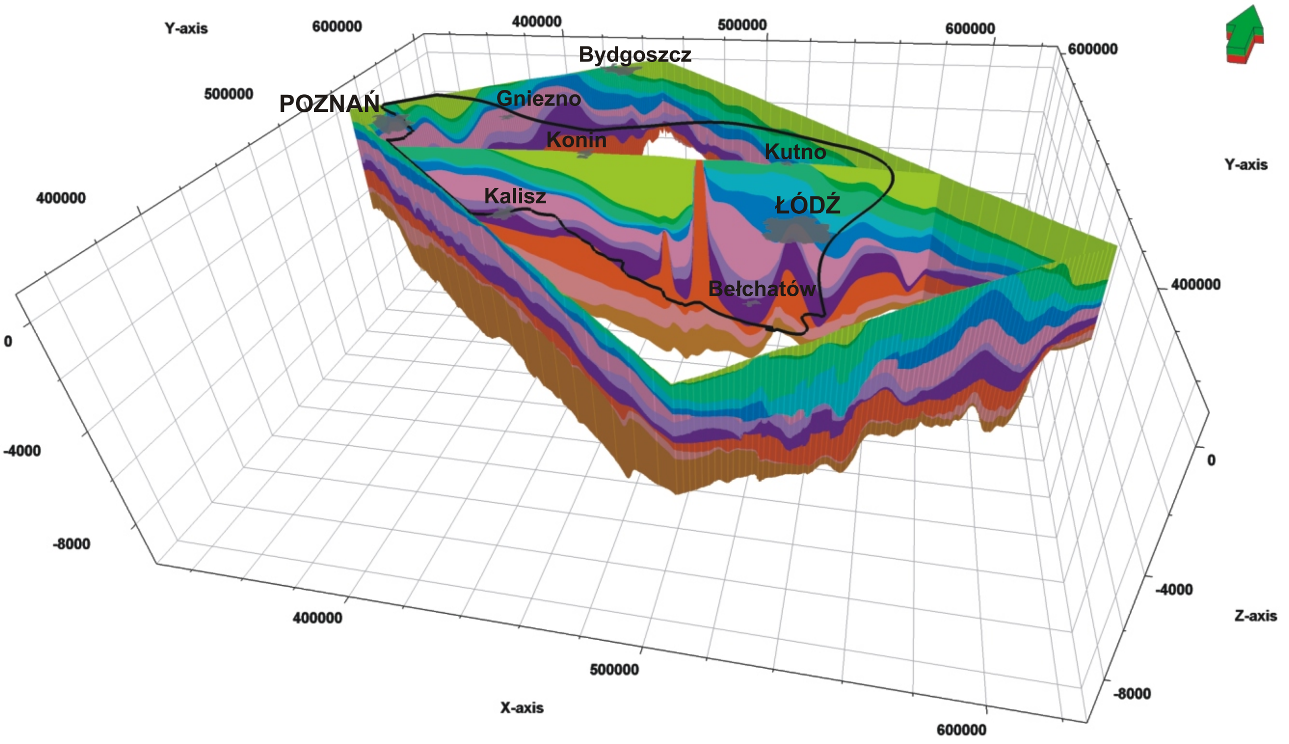

**Fig. 3. 3D geometrical framework in the selected area for EGS location**

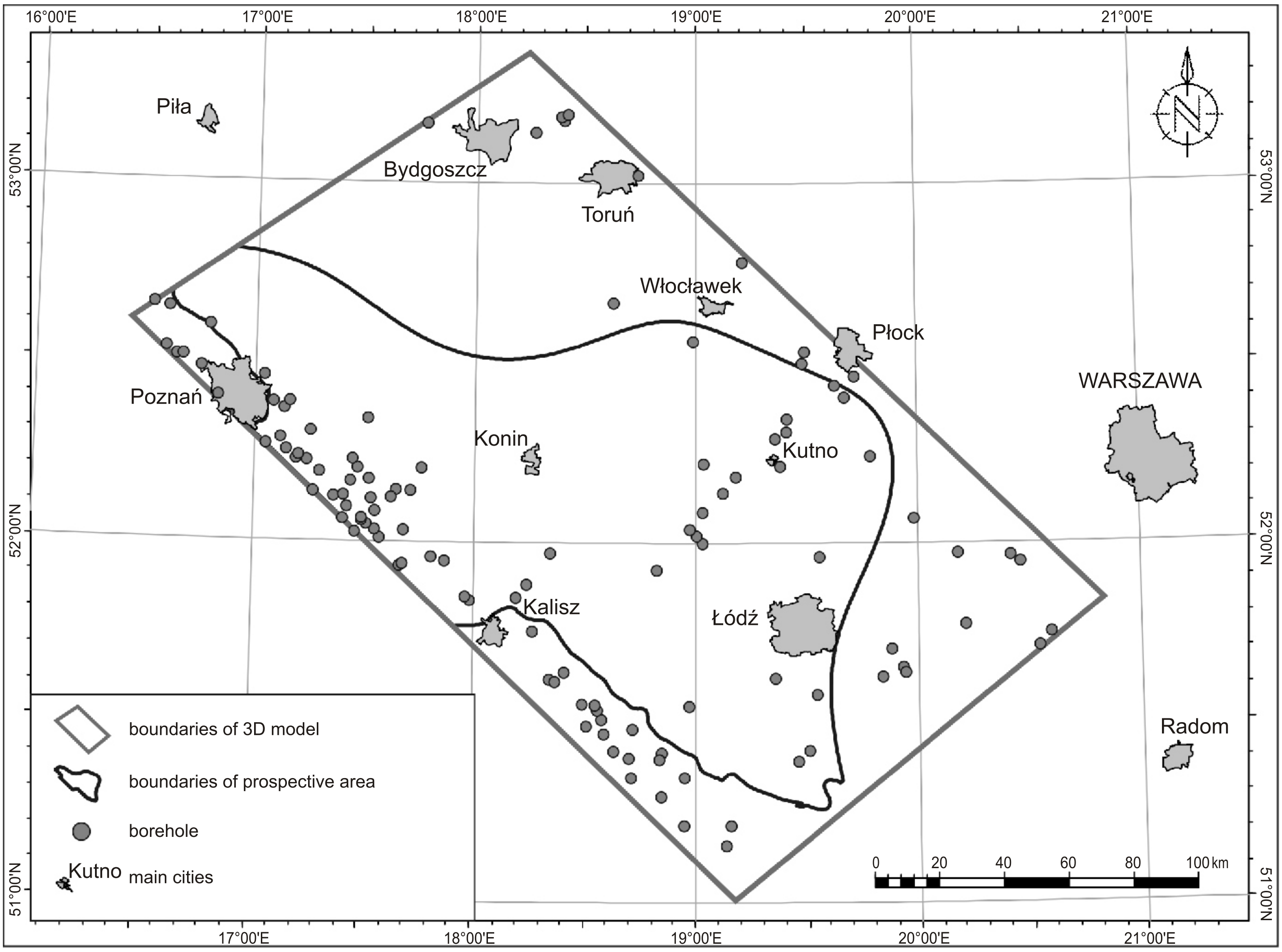

**Fig. 4. Location of boreholes used in parametric modelling**

## SUBSURFACE THERMAL FIELD ANALYSIS

Parameters which decisively control the subsurface temperatures are: density of Earth's heat flow and diversity of thermal properties of rocks, particularly their thermal conductivity (Szewczyk, 2002). The heat flow determines the rate of energy transfer in time unit from higher- to lower-temperature sites, whereas the temperature is a quantitative measure of thermal energy accumulated in a rock formation at the observation site.

Temperature measurements made in deep boreholes are the main source of information about internal thermal regime. These data are collected from:

1. Measurements under quasi-stationary state, carried out during recognition of geothermal conditions.
2. Temperature measurements under unstabilized thermal conditions.
3. Measurements of bottom-hole temperature (BHT).

For recognition of true temperatures of rocks, the most important are measurements carried out under conditions possibly closest to the geothermal balance. Within the area of geothermal investigation, nine temperature measurements were made in the following deep boreholes under conditions closest to those regarded as stabilized (so-called "measurements for the purpose of geothermal gradient"): Czeszewo IG 1, Krośniewice IG 1, Kutno 1, Objezierze IG 1, Piotrków Trybunalski IG 1, Poddębice PIG-2, Września IG 1, Zakrzyn IG 1 and Zgierz IG 1. The measurements represented a direct source of information on the subsurface thermal regime.

It is well known that the subsurface temperature measurements, even when done with proper care, are affected by a number of errors. Disturbance of the natural thermal regime of rocks caused by drilling operations, mostly by the long-lasting circulation of drilling mud, significantly changes the temperatures recorded along the borehole. Disturbances are relatively largest in the top parts of the temperature logs and smallest in the deepest parts of borehole that remains under disturbing conditions for a short time. Completion of drilling initiates the long-lasting process of stabilization, when the thermal regime returns to the natural state. However, the possible vertical convection of drilling mud in the borehole forced by temperature gradients between various parts of the borehole may cause that the disturbances are practically irreversible. An important indicator of stability of thermal measurements is the rough consistency between temperatures recorded in the subsurface zone of the borehole site and those measured in the adjacent areas.

For interpretation of the distribution of subsurface temperatures, synthetic thermograms were employed, which were recorded in conditions of the stable thermal equilibrium (as continuous measurements). The compiled thermograms included also the so-called climatic correction related to temperature disturbances in the upper part of the geological profile due to temperature changes at the earth surface, occurring in glacial cycles (ice ages) during the Late Holocene (e.g., Beck, 1992; Šafanda and Kubik, 1992; Beltrami et al., 2001; Šafanda and Rajver, 2001; Majorowicz et al., 2002; Szewczyk, 2002; Szewczyk et al., 2007; Szewczyk and Gientka, 2009).

The coverage of the study area is relatively regular. Most boreholes with the temperature measurements are located to the north of Łódź (Kutno 1, Zgierz IG 1, Poddębice PIG-2 and Krośniewice IG 1 boreholes). A key question for evaluation of the quality and usefulness of the collected synthetic thermograms was to ascertain whether the subsurface temperature measurements were made really in the stabilized thermal conditions (after a suitably long standstill time). Conformability of temperature measurements recorded in the near-surface zone is a valid indication of the stability of thermal measurements (their solidity). Serious discrepancies between these temperatures indicate measurements made in conditions departing from stabilized (Plewa, 1966, 1994). In order to assess the quality of the input data, analysis of the temperature distribution with depth in particular boreholes was made. The scale of temperature disturbances in the near-surface zone and in the reservoir intervals was evaluated. Making use of the linear regression model, interval gradients and mean gradients for the whole boreholes were estimated.

Analysis of the regression curves indicates some departures from the estimated values of temperature in the near-surface zone from values of temperatures $T_o$ recorded in the thermally neutral zone, extent of which in Poland is estimated at about 18–20 m below ground level (Plewa, 1966, 1994). Matching of the regression model to the measurement curves, determined by the coefficient $R^2$, varies in a narrow range from $R^2 = 98.3\%$ for the Krośniewice IG 1 borehole to $R^2 = 99.8\%$ for the Objezierze IG 1 borehole, which indicates a very good match of the measurements to the linear model of variability in the subsurface temperatures. A linear regression model was also adopted for drawing the map of geothermal gradient, which was used as an auxiliary parameter to determine the change of temperature at different depths – on maps. The mean geothermal gradient is a parameter that allows estimating the formation temperature at a particular depth, without knowledge of heat flow values and thermal properties of rocks in a geological profile in a given location. The analysis of geothermal gradient distribution in the study area was based on interpretation of fourteen thermal curves recorded in quasi-stationary conditions (Szewczyk and Gientka, 2009), of which nine boreholes were located within the compass of the prospective area. On the basis of the compiled data, a map of variations in the mean gradients was constructed for the whole study area. The map is presented in Figure 5.

The analysis of heat flow density distribution was carried out on the basis of 69 determinations of this parameter, of which nine are located within the prospective area for HDR systems. The heat flow determination data were compiled from Szewczyk and Hajto (2006) and Szewczyk and Gientka (2009). On the basis of the collected terrestrial heat flow data, a map of variations in this parameter was constructed for the study area (Fig. 6).

In order to illustrate the temperature variation in the vertical profile of the research area based on the temperature curve analysis, maps of isotherms for various depths, and a temperature map for the top of the Lower Triassic reservoirs were produced. Due to the varied distribution of measurement points (boreholes) in the study area, the average geothermal gradient was incorporated to assess the subsurface temperature distribution. The use of a generalized model of subsurface temperature variability in the form of maps of average geothermal gradient allowed evaluating subsurface temperatures in areas poorly documented with thermal measurements and estimating the temperatures at greater depths by extrapolating trends in subsurface temperature variability in the whole study area. The map of temperatures at the top of the Lower Triassic aquifer prospective for EGS systems is shown in Figure 7.

## RESULTS

The structural, parametric and thermal modelling allowed characterization of petrophysical parameters of the Lower Triassic deposits in the prospective location for EGS in sedimentary rocks indicated as the best sedimentary reservoir for this kind of system on the basis of preliminary determination of geometry of

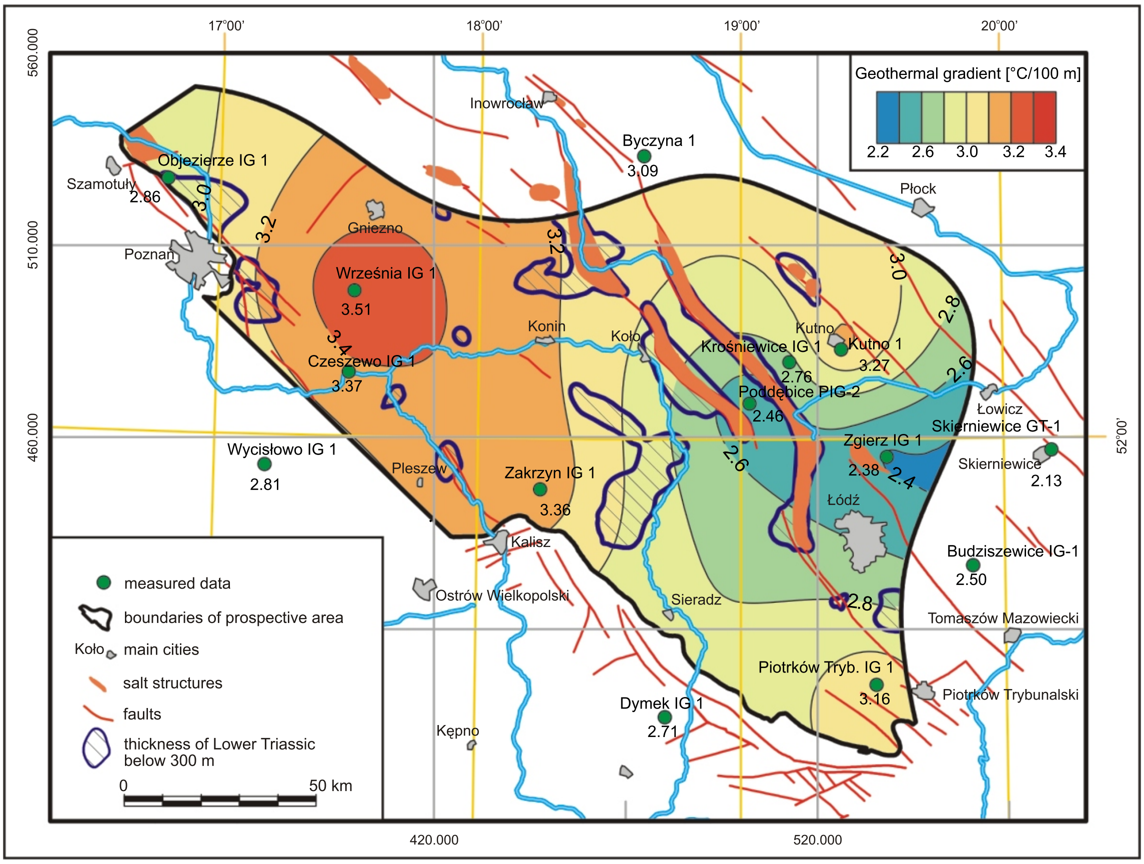

**Fig. 5. Map of average geothermal gradient in the selected area for EGS location**

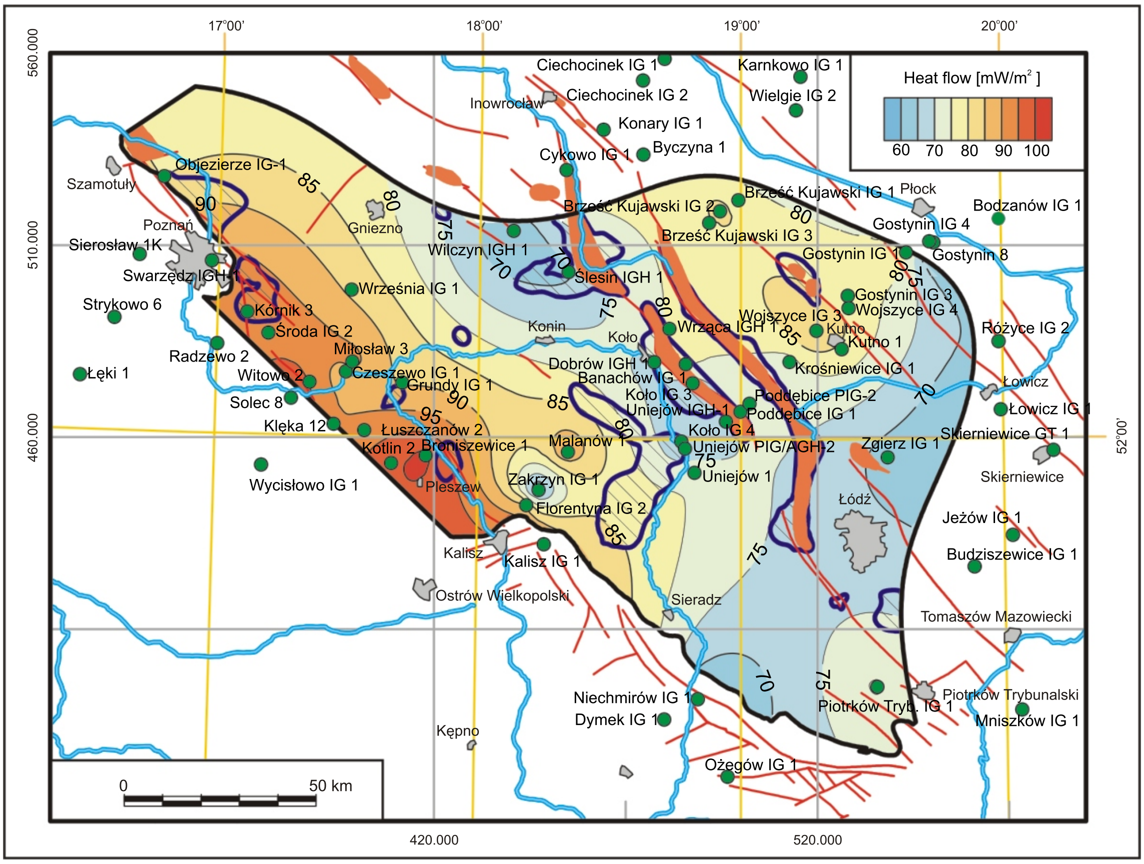

**Fig. 6. Map of terrestrial heat flow density in the selected area for EGS location**

Explanations as in Figure 5

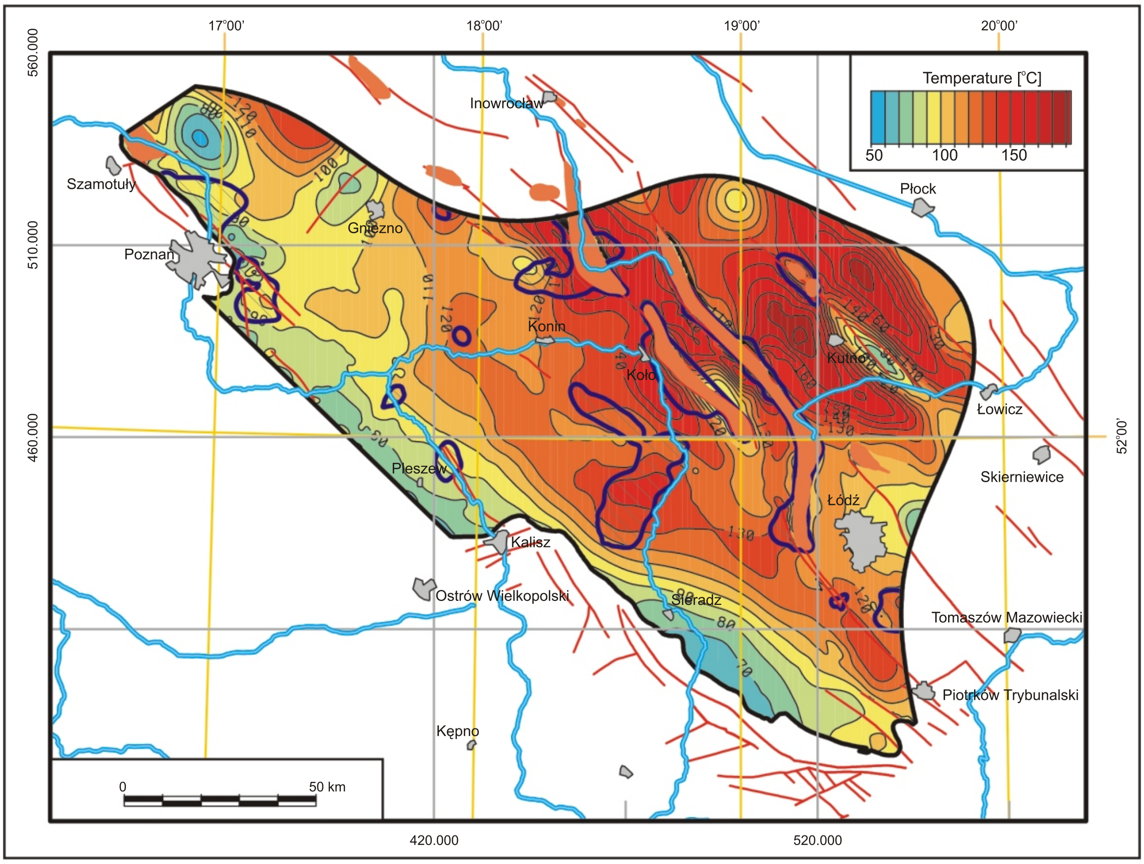

**Fig. 7. Map of temperatures at the top surface of the Lower Triassic in the selected area for EGS location**

Explanations as in Figure 5

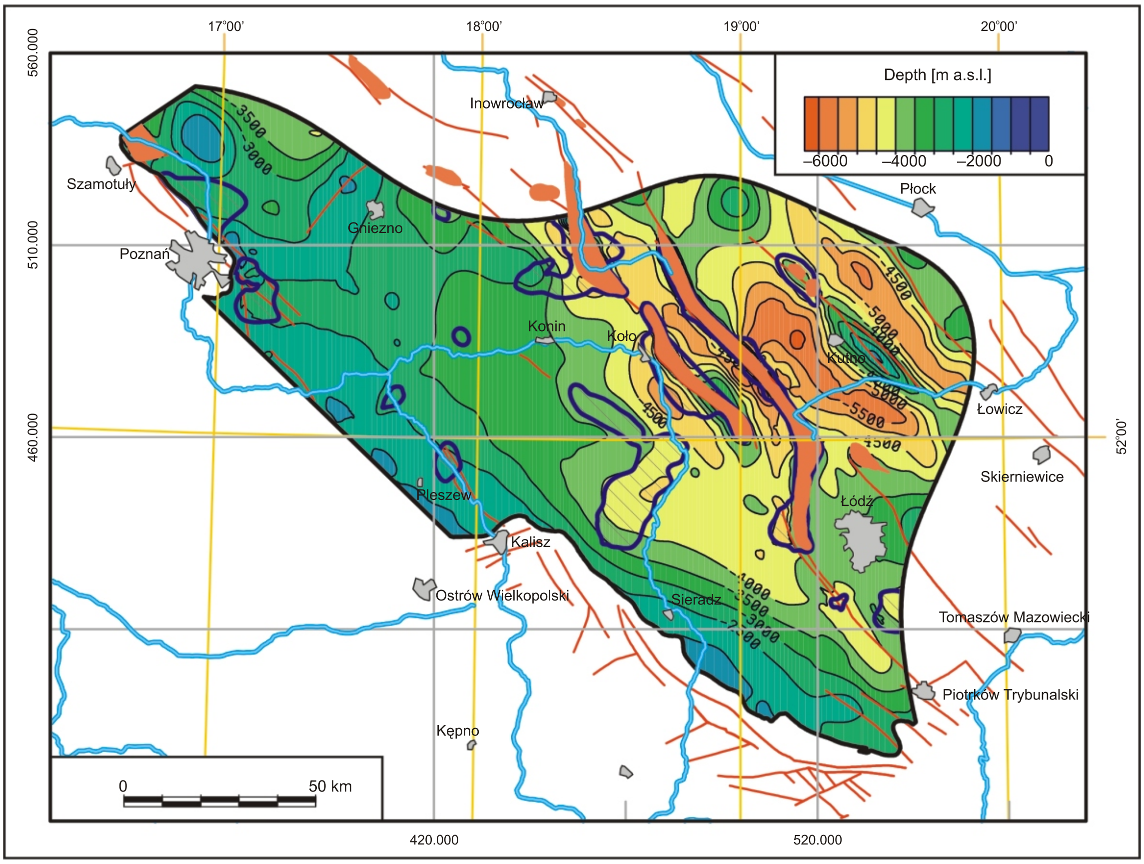

**Fig. 8. Structural map of the top of the Lower Triassic in the selected area for EGS location**

Explanations as in Figure 5

the reservoir as well as thermal parameters of the rocks. This location is shown in Figure 1.

In this area, the top of the Lower Triassic occurs at depths from 2000 m b.s.l. (at the southwestern margin of the area) to about 6000 m b.s.l. (in the eastern part; Fig. 8). The total thickness of the Lower Triassic deposits is appropriate for EGS practically in the whole area because it exceeds the required 300 m and reaches the greatest values (over 2000 m) in the eastern part of the investigated area (Fig. 9). The Lower Triassic zone of the modelled area is dominated by claystones (nearly 40%), siltstones (28.5%) and sandstones (27.5%). The greatest thickness of sandstones, which are considered as reservoir rocks for EGS, is found in the central and southeastern part of the area, where they prevail in the Lower Triassic succession. The rocks of this area are characterized by shale volume in the range of 50–65% (on average 60%; Fig. 10). The porosity of the Lower Triassic varies from 0 to 21%, with the global average for the entire model equal to 3.92% (Fig. 11). The permeability model of the Lower Triassic formations was based mainly on laboratory data. It was correlated with the porosity model based on the borehole logs; its credibility may be low. The modelled permeability for the Lower Triassic formations ranges from 0 to 32.84 mD, with an average for the entire model of 0.36 mD (Fig. 12). The modelled temperature at the top of the analysed horizon varies from about 120 to more than 170°C (Fig. 7).

Analysis of the heat flow map indicates that the heat flow in the study area varies from 60 to 110 mW/m$^2$. The general trend of variations in the heat flow indicates its increase from the east to the west and south-west. Increased heat flow values were recorded along the southwestern boundary of the Mogilno–Łódź Trough at the contact with the Fore-Sudetic area where the heat flow has its maximum values. In this area, the highest heat flow values were recorded in the boreholes of Broniszewice 1 (106.2 mW/m$^2$), Kotlin 2 (103.8 mW/m$^2$) and Witowo 2 (100.1 mW/m$^2$). Reduced heat flow values (about 70 mW/m$^2$) are characteristic of the Łódź area. Local negative heat flow anomalies (on the order of 70–75 mW/m$^2$) occur along the northeastern boundary of the Mogilno–Łódź Trough at the contact with the Kujawy Swell (Fig. 5).

## SELECTION OF PROSPECTIVE LOCATION FOR EGS

Analysis of the results of structural, parametric and thermal modelling for the pre-indicated area (central Poland) allowed specifying the prospective location for EGS in sedimentary rocks.

The main requirement for EGS is possibility to extract thermal energy from a reservoir, so thermal parameters are very important. The highest temperatures are observed in the eastern part of the modelled area (Krośniewice–Kutno region), in places of the deepest position of the Lower Triassic deposits, where the temperature at the top of the Lower Triassic is in the range of 165–175°C. Despite the considerable depth to the reservoir (5–7 km below sea level), the upper part of the reservoir fulfils the accessibility requirements (max. 6 km below sea level). Because of the necessity to create a system of connected open

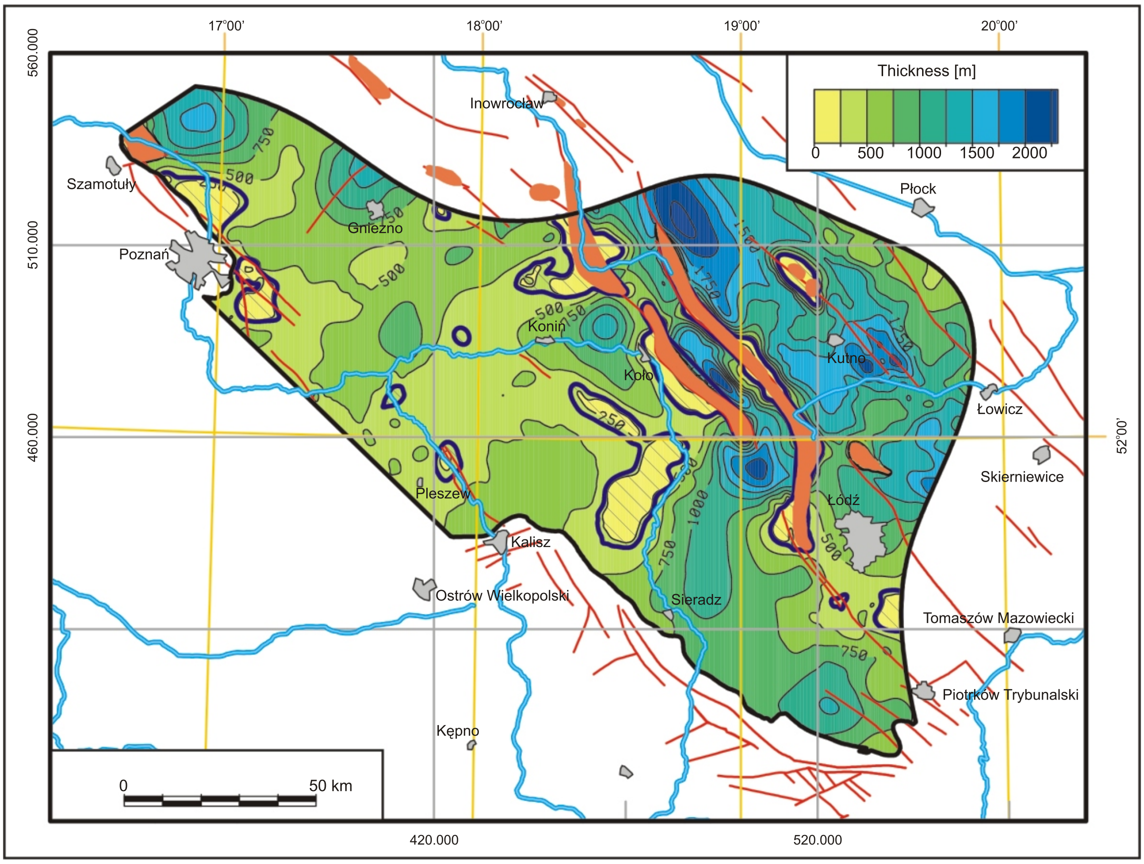

**Fig. 9. Map of total thickness of the Lower Triassic in the selected area for EGS location**

Explanations as in Figure 5

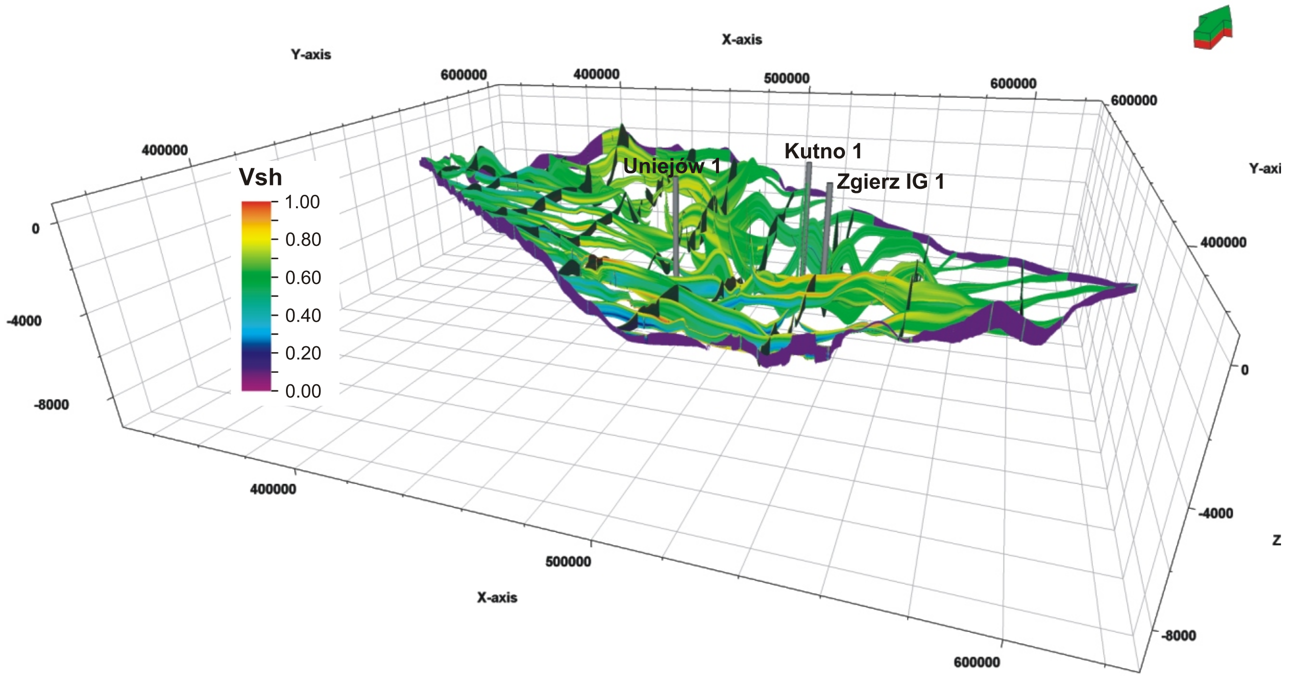

Fig. 10. Shale volume model of the Lower Triassic – fence diagram

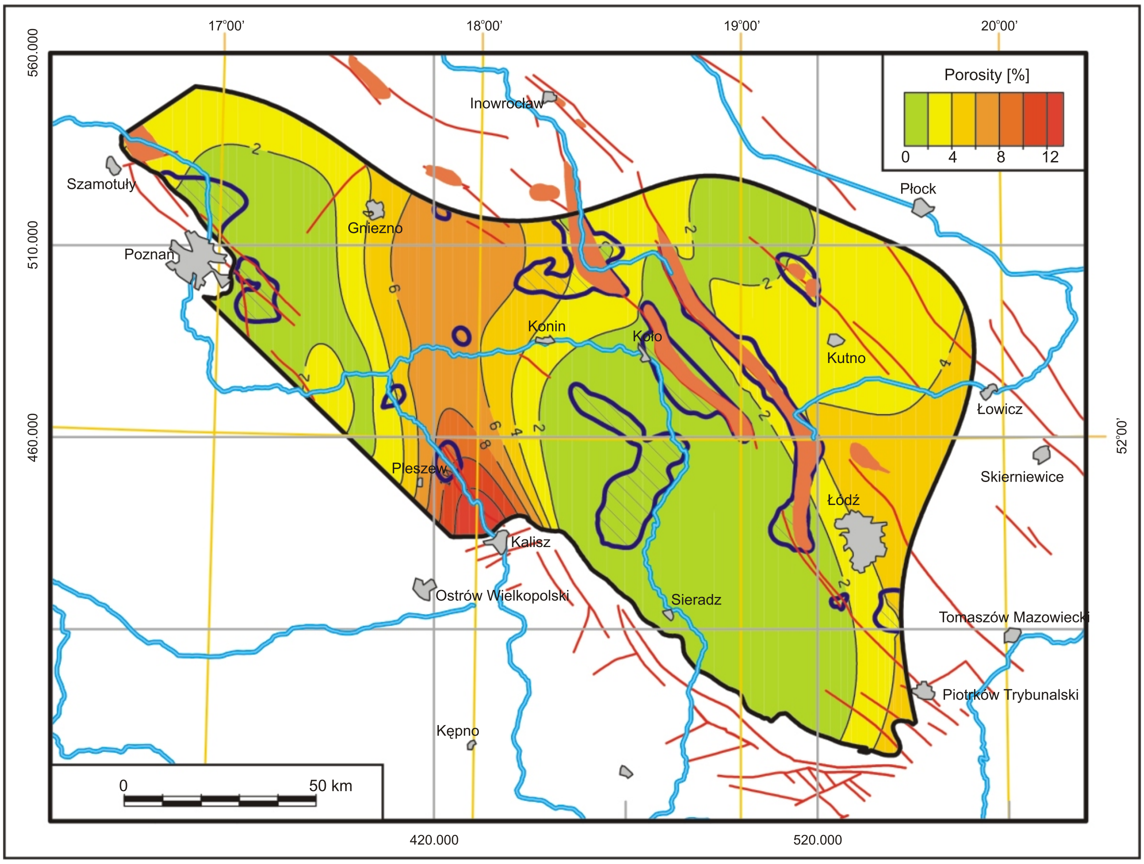

Fig. 11. Map of average porosity of the Lower Triassic in the selected area for EGS location

Explanations as in Figure 5

fractures to recover thermal energy, the unquestionable advantage is the great thickness of Lower Triassic sedimentary rocks in the Krośniewice–Kutno area, which exceeds 1500 m (Fig. 13). This considerable thickness have influence of higher temperature within the reservoir than at the top, which could attain up to 190°C. EGS includes conduction-dominated, low-permeability resources in sedimentary formations (Tester et al., 2006), so petrophysical parameters of the reservoir are also significant for EGS. In the Krośniewice–Kutno area, sandstones are taken into consideration as reservoir rocks for EGS. Based on a laboratory analysis of Lower Triassic sandstones from the Krośniewice–Kutno area (tests were performed within the framework of the HDR project at the AGH University with use of the transmitted-light optical microscope and scanning electron microscope), it is predicted that the sandstones are cemented with silica. This type of matrix should be suitable for hydrofracturing, however, there is not much experience worldwide with hydrofracturing in this type of rock for EGS. Creating the connection between the boreholes was a crucial step in developing the EGS reservoir. Rock-fluid interactions, which may have a long-term effect on reservoir operation, are also very important. Dissolution and precipitation problems in very high-temperature EGS fields are not well understood (Tester et al., 2006). Laboratory testing of mechanical properties has shown that the sandstones are strong or very strong rocks (tests were performed within the framework of the HDR project at the AGH University). In the Krośniewice–Kutno area, reservoir rocks are characterized by very low permeability (0.02–0.1 mD) and low porosity (approximately 3%). Sandstones are dominant in the lower and the middle parts of the section, attaining a thickness of several hundred metres (Fig. 13). Lithological composition of the Lower Triassic were refined in the spatial distribution of shale volume, estimated on the basis of a larger number of input data. This model indicates that the sandstones contain much clay material and represent a transitional lithological type between clayey sandstones and sandy mudstones. Even the sandstones from the Krośniewice–Kutno area contain from 40 to 65% of clay, which is a relatively high proportion.

Considering the above, the most prospective area for the EGS location in sedimentary rocks in Poland was identified in the Kuiavian segment of the Mid-Polish Anticlinorium in the Krośniewice–Kutno area. Using cross-sections through the most prospective zone, we can assess its geometry. It is elongated in the NW–SE direction, its width is approximately 8 km and the length is about 30 km (Fig. 13).

## CONCLUSIONS

The EGS technology is considered to be the technology of the future. Currently, hydrogeothermal energy is utilized in Poland, and the energy carrier is warm groundwater produced by boreholes. On the other hand, petrogeothermal energy (exploited by EGS), which constitutes heat resources of rocks, has not yet been utilized.

In most of the EGS projects worldwide, granites constitute the reservoir rocks for closed geothermal systems. Solutions of energy utilization from hot sedimentary rocks are rare, although

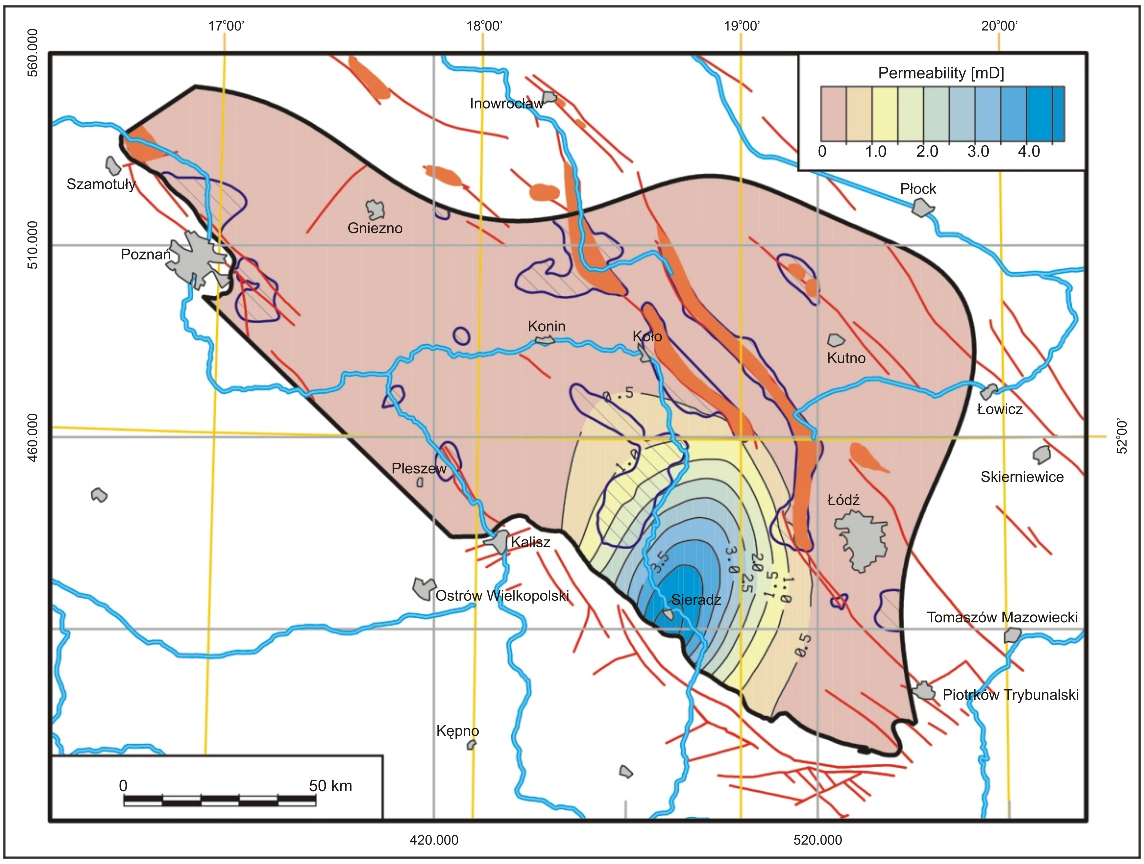

**Fig. 12. Map of average permeability of the Lower Triassic in the selected area for EGS location**

Explanations as in Figure 5

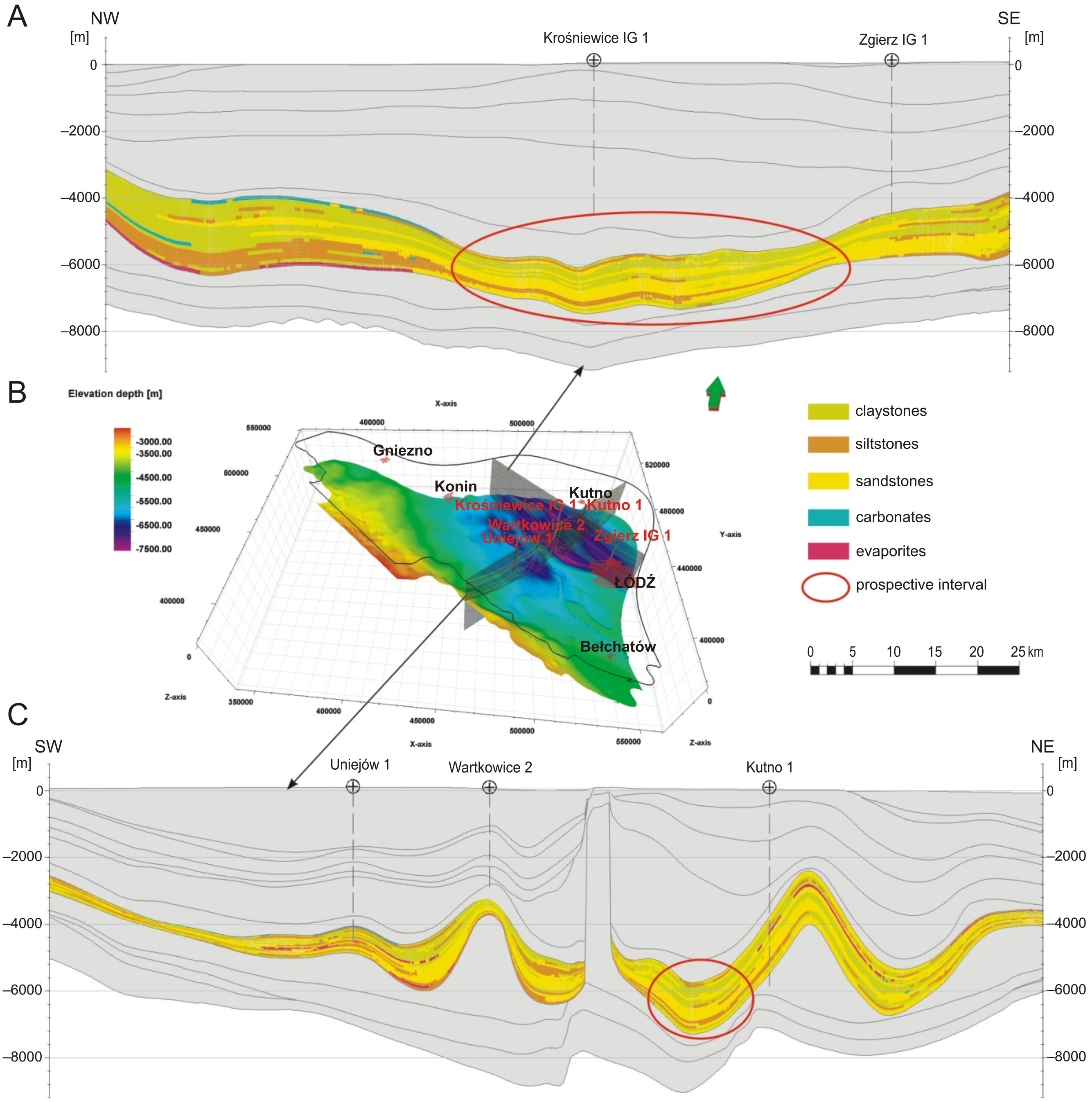

**Fig. 13. Location of the prospective depth interval of the Lower Triassic in the Krośniewice–Kutno area**

**A** – along the NW–SE cross-section, **B** – location of cross-sections shown on the background of the structural map of the top of the Rotliegend, **C** – along the SW–NE cross-section

experimental systems currently operate. The problem with sedimentary rocks can be the variability of relevant parameters of the modelled system (e.g., susceptibility to fracture rocks). There are a number of problematic issues that could potentially affect the effectiveness of EGS, such as the heterogeneity of reservoir rocks, the presence of clay material and the impact of the occurrence of mineralised waters. These problems can be solved at the stage of project implementation, but the first step to develop EGS in Poland is to recognize the geothermal potential for such systems.

Because of the distribution of subsurface temperatures and great depths to the thick sedimentary rocks, the Lower Triassic deposits of central Poland seem to be the most appropriate for EGS. Integrated thermal, parametric and structural modelling helped to identify the most prospective location for such a geothermal system in sedimentary rocks, which is the Krośniewice–Kutno area. For this particular prospective area, petrophysical parameters of the Lower Triassic are as follows:

1. The reservoir occurs at a depth from about 5000 to 6000 m b.s.l.
2. Total thickness of the Lower Triassic formation is sufficient to perform fracturing.
3. The temperature within the reservoir exceeds 165°C.
4. The porosity of reservoir rocks is approximately 3%.

5. The permeability of reservoir rocks is in the range of 0.02–0.1 mD.

Characterization of petrophysical parameters was the basis for further modelling of EGS utilization. The critical requirements for the EGS location include: thermal parameters of rocks (temperatures >150°C), thickness of the reservoir (minimum of 300 m), porosity and permeability of reservoir rocks (as the lowest) and depth to the reservoir (3–6 km). Based on these requirements, the Lower Triassic sandstones of the Krośniewice–Kutno area can be considered as potential reservoir rocks for EGS. The final assessment needs further investigation based on high-quality data as well as a significantly greater number of experiments related to the fracturing of sedimentary rocks.

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## REFERENCES

**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

**Bachmann G.H., Geluk M.C., Warrington G., Becker-Roman A., Beutler G., Hagdorn H., Hounslow M.W., Nitsch E., Röhling H.-G., Simon T., Szulc A**. (2010) Triassic. In: Petroleum Geological Atlas of the Southern Permian Basin Area (eds. J.C. Doornenbal and A.G. Stevenson): 149–173. EAGE Publications b.v., Houten.

**Beck A.E.** (1992) Inferring past climate change from subsurface temperature profiles: some problems and methods. Palaeogeography, Palaeoclimatology, Palaeoecology, **98**: 73–80.

**Becker A**. (2005a) Sequenzstratigraphie und Fazies des Unteren und Mittleren Buntsandsteins im östlichenTeil des Germanischen Beckens (Deutschland, Polen). Hallesches Jahrbuch für Geowissenschaften, Reihe B: Geologie, Paläontologie, Mineralogie, Beihefte, **21**:1–117.

**Becker A.** (2005b) Fluvial and brackish-lacustrine deposits of the Lower Triassic and their correlation in the eastern part of the Central European Basin. In: Sediment 2005. The Sediment Factory. 18–20 July in Gwatt, Lake Thun, Switzerland. Abstracts. Hannover. Deutsche Gesellschaft für Geowissenschaften: 29.

**Beltrami H., Harris R.N.,** eds. (2001) Special issue of journal Global and Planetary Change on Climate from Underground Temperatures. Global and Planetary Change, **29**: 145–360.

**Brown D.W., Duchane D.V., Heiken G., Hriscu V.T.** (2012) Mining the Earth's Heat: Hot Dry Rock Geothermal Energy. Springer.

**Dadlez R**. (1980) Tectonics of the Pomeranian Swell, NW Poland (in Polish with English summary). Kwartalnik Geologiczny, **24** (4): 741–767.

**Dadlez R.** (1997a) Epicontinental basins in Poland: Devonian to Cretaceous – relationships between the crystalline basement and sedimentary infill. Geological Quarterly, **41** (4): 419–432.

**Dadlez R.** (1997b) Tektonika kompleksu permsko-mezozoicznego. Prace Państwowego Instytutu Geologicznego, **153**: 410–415.

**Dadlez R., Narkiewicz M., Stephenson R.A., Visser M.T.M., Wees J.D. van** (1995) Tectonic evolution of the Mid-Polish Trough: modelling implications and significance for central European geology. Tectonophysics, **252**: 179–195.

**Dadlez R., Grad M., Guterch A.** (2005) Crustal structure below the Polish Basin: is it composed of proximal terranes derived from Baltica? Tectonophysics, **411**: 111–128.

**Doornenbal J.C., Abbink O.A., Duin E.J.T., Dusar M., Hoth P., Jasionowski M., Lott G.K., Mathiesen A., Papiernik B., Peryt T.M., Veldkamp J.G., Wirth H.** (2010) Introduction, stratigraphic framework and mapping. In: Petroleum Geological Atlas of the Southern Permian Basin Area (eds. J.C. Doornenbal and A.G. Stevenson): 1–9. EAGE Publications b.v., Houten.

**Dubrule O.** (1998) Geostatistics in Petroleum Geology. AAPG Continuing Education Course Note Series, **38**. AAPG, Tulsa, Oklahoma, USA.

**Dubrule O.** (2003) Geostatistics for Seismic Data Integration in Earth Models. 2003 Distinguished Instructor Short Course. Distinguished Instructor Series. No. 6 SEG/EAGE. Tulsa, Oklahoma, USA.

**Feldman-Olszewska A.,** ed. (2008) Brześć Kujawski IG 1, IG 2, IG 3. Profile głębokich otworów wiertniczych Państwowego Instytutu Geologicznego, **125**.

**Gast R.E., Dusar M., Breitkreuz C., Gaupp R., Schneider J.W., Stemmerik L., Geluk M.C., Geisler M., Kiersnowski H., Glennie K.W., Kabel S., Jones N.S.** (2010) Rotliegend. In: Petroleum Geological Atlas of the Southern Permian Basin Area (eds. J.C. Doornenbal and A.G. Stevenson): 101–121. EAGE Publications b.v., Houten.

**Geluk M.C**. (1999) Palaeogeographic and structural development of the Triassic in the Netherlands – new insights. Zentralblatt für Geologie und Paläontologie (Halle), **7–8**: 727–745.

**Górecki W.,** ed. (2006a) Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands. AGH-UST, Kraków.

**Górecki W.,** ed. (2006b) Atlas of Geothermal Resources of Paleozoic Formations in the Polish Lowlands. AGH-UST, Kraków.

**Górecki W.,** ed. (2011) Atlas of Geothermal Waters and Energy Resources in the Western Carpathians. AGH-UST, Kraków.

**Górecki W.,** ed. (2012) Geothermal Atlas of the Carpathian Foredeep. AGH-UST, Kraków.

**Górecki W., Sowiżdżał A., Hajto M., Jasnos J.** (2013) The latest results of geothermal projects in Poland. Proceedings European Geothermal Congress 2013, June 3–7, 2013, Pisa, Italy. International Geothermal Association – European Branch Publications, **HS1-34**: 1–9.

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

**Grabowska T., Bojdys G.** (2001) The border of the East-European Craton in south-eastern Poland based on gravity and magnetic data. Terra Nova, **13**: 92–98.

**Grabowska T., Bojdys G., Dolnicki J.** (1998) Three-dimensional density model of the Earth's crust and the upper mantle for the area of Poland. Journal of Geodynamics, **25**: 5–24.

**Grad M., Guterch A.** (2006a) Seismic models of the crustal structure of the Trans-European Suture Zone (TESZ) in NW and central Poland. Prace Państwowego Instytutu Geologicznego, **188**: 41–52.

**Grad M., Guterch A**. (2006b) Lithospheric structure of the TESZ in Poland based on modern seismic experiments. Geological Quarterly, **50** (1): 23–32.

**Grad M., Guterch A., Mazur S**. (2002a) Seismic refraction evidence for continental structure in the central part of Trans-European Suture Zone in Poland. Geological Society Special Publications, **201**: 295–309.

**Grad M., Keller G.R., Thybo H., Guterch A., POLONAISE WORKING GROUP** (2002b) Lower lithospheric structure beneath the Trans-European Suture Zone from POLONAISE'97 seismic profiles. Tectonophysics, **360**: 153–168.

**Iwanow A., Kiersnowski H.** (1998) Paleografia wczesnego i środkowego piaskowca pstrego. In: Atlas paleogeograficzny epikontynentalnego permu i mezozoiku w Polsce (eds. R. Dadlez, S. Marek and J. Pokorski). Państwowy Instytut Geologiczny, Warszawa.

**Jarosiński M., Poprawa P., Ziegler P.A.** (2009) Dynamic evolution of the Polish foreland during Cenozoic times. Geological Quarterly, **53** (1): 3–26.

**Karnkowski P.H.** (2008) Tectonic subdivision of Poland: Polish Lowlands (in Polish with English summary). Przegląd Geologiczny, **56**: 895–903.

**Kiersnowski H., Paul J., Peryt T.M., Smith D.B.** (1995) Facies, paleogeography and sedimentary history of the Southern Permian Basin in Europe. In: The Permian of Northern Pangea (eds. P.A. Scholle, T.M. Peryt and D.S. Ulmer-Scholle): 119–136. Springer-Verlag, Berlin.

**Królikowski C.** (2006) Crustal-scale complexity of the contact zone between the Palaeozoic Patform and the East European Craton in the NW Poland. Geological Quarterly, **50** (1): 33 –42.

**Krzywiec P.** (2004) Triassic evolution of the Kłodawa salt structure: basement-controlled salt tectonics within the Mid-Polish Trough (central Poland). Geological Quarterly, **48** (2): 123–134.

**Krzywiec P.** (2006a) Triassic–Jurassic evolution of the Pomeranian segment of the Mid-Polish Trough – basement tectonics and sedimentary patterns. Geological Quarterly, **50** (1): 139–150.

**Krzywiec P.** (2006b) Structural inversion of the Pomeranian and Kuiavian segments of the Mid-Polish Trough – lateral variations in timing and structural style. Geological Quarterly, **50** (1): 151–168.

**Kutek J.** (2001) The Polish Permo-Mesozoic Rift Basin. Memoires du Musee Histoire Naturelle, **186**: 213–236.

**Leszczyński K.** (2012) The internal geometry and lithofacies pattern of the Upper Cretaceous–Danian sequence in the Polish Lowlands. Geological Quarterly, **56** (2): 363–386.

**Majorowicz J.A, Šafanda J., Skinder W.R**. (2002) East to west retardation in the onset of the recent warming across Canada inferred from inversions of temperature logs. Journal of Geophysical Research, **107**: B10.

**Marek S., Pajchlowa M**., eds. (1997) Permian and Mesozoic in Poland (in Polish with English summary). Prace Państwowego Instytutu Geologicznego, **153**.

**Moeck I., Brandt W., Bruhn D., Munoz G., Ritter O., Bauer K., Weber M.,Backers T., Kwiatek G., Huenges E.** (2010) From Prospecting to Drilling: New Exploration Strategies for Enhanced Geothermal Systems. Proceedings World Geothermal Congress 2010, April 25–29, 2010, Bali, Indonesia. International Geothermal Association Publications, **3147**: 1–5.

**Narkiewicz M., Dadlez R.** (2008) Geological regional subdivision of Poland: general guidelines and proposed schemes of sub-Cenozoic and sub-Permian (in Polish with English summary). Przegląd Geologiczny, **56**: 391–397.

**Nawrocki J., Poprawa P.** (2006) Development of Trans-European Suture Zone in Poland: from Ediacaran rifting to Early Proterozoic accretion. Geological Quarterly, **50** (1): 59–76.

**Papiernik B., Machowski G., Słupczyński K., Semyrka R**. (2009) Geological model of the Lubiatów-Międzychód-Grotów (LMG) oil-gas accumulation area (in Polish with English summary). Geologia, **35** (2/1): 175–182.

**Papiernik B., Górecki W., Pasternacki A.** (2010) Preliminary results of 3D modeling of petrophysical parameters for tight gas prospecting in the Polish Rotliegend Basin (in Polish with English summary). Przegląd Geologiczny, **58**: 352–364.

**Papiernik B., Kiersnowski H., Machowski G., Górecki W.** (2012) Upper Rotliegend Reservoir and Facies Models of Geomorphological and Structural Gas Traps in Silesian Basin – South-West Poland. 74th EAGE Conference & Exhibition incorporating SPE EUROPEC, June 4–7, Copenhagen, extended abstracts, P245: 1–5. http://www.earthdoc.org/publication/publicationdetails/?publication=59497

**Peryt T.M., Geluk M.C., Mathiesen A., Paul J., Smith K.** (2010) Zechstein. In: Petroleum Geological Atlas of the Southern Permian Basin Area (eds. J.C. Doornenbal, A.G. Stevenson) EAGE Publications b.v. (Houten): 123–147.

**Pharaoh T.C., Dusar M., Geluk M.C., Kockel F., Krawczyk C.M., Krzywiec P., Scheck-Wenderoth M., Thybo H., Vejbak O.V., Wees J.D. van** (2010) Tectonic evolution. In: Petroleum Geological Atlas of the Southern Permian Basin Area. (eds. J.C. Doornenbal and A.G. Stevenson): 25–57. EAGE Publications b.v., Houten.

**Pieńkowski G.** (1991) Facies criteria for delimitating the Zechstein/Buntsandstein and the Permian/Triassic boundary in Poland. Zentralblatt für Geologie und Paläontologie, **4**: 893–912.

**Plewa S.** (1966) Regionalny obraz parametrów geotermicznych obszaru Polski. Prace Geofizyczne i Geologiczne. Wyd. Geofizyka i Geologia Naftowa, Kraków.

**Plewa S.** (1994) Rozkład parametrów geotermalnych na obszarze Polski. Wyd. CPPGSMiE PAN, Kraków.

**Pożaryski W**. (1977a) Geology of Poland, IV (Tectonics). Wydawnictwa Geologiczne, Warszawa.

**Pożaryski W.** (1977b) The early Alpine Laramide Epoch in the platform development east of the Fore Sudetic and Silesian-Cracovian monoclines: Geology of Poland: 351–416. Wydawnictwa Geologiczne, Warszawa.

**Pożaryski W., Brochwicz-Lewiński W.** (1978) On the PolishTrough. Geologie en Mijnbouw, **57**: 545–557.

**Röhling H.G.** (1991) A lithostratigraphic subdivision of the Early Triassic in the Northwest German Lowlands and the German Sector of the North Sea, based on gamma-ray and sonic logs. Geologisches Jahrbuch, **A119**: 3–23.

**Šafanda J., Kubik J**. (1992) Evidence of ground surface temperature changes from two boreholes in the Bohemian Massif. Global and Planetary Change, **6**: 199–208.

**Šafanda J., Rajver D.** (2001) Signature of the last ice age in the present subsurface temperatures in the Czech Republic and Slovenia. Global and Planetary Change, **29**: 241–257.

**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). Proceedings European Geothermal Congress 2007, May 30–June 1, 2007, Unterhaching, Germany. International Geothermal Association – European Branch Publications: 1–7. https://pangea.stanford.edu/ERE/pdf/IGAstandard/EGC/2007/059.pdf

**Sliaupa S., Motuza G., Karabliova L., Motuza V., Zauludiene G.** (2005) Hot granites of southwest western Lithuania: new geothermal prospects. Technika Poszukiwań Geologicznych, Geosynoptyka i Geotermia, **3**: 26–34.

**Stephenson R.A., Narkiewicz M., Dadlez R., Wees J.D. van , Andriessen P.A.M**. (2003) Tectonic subsidence modelling of the Polish Basin in the light of new data on crustal structure and magnitude of inversion. Sedimentary Geology, **159**: 59–70.

**Szewczyk J.** (2002) Wpływ czynników paleoklimatycznych oraz hydrogeologicznych na strumień cieplny. Posiedzenia Naukowe Państwowego Instytutu Geologicznego, **58**: 31–33.

**Szewczyk J., Gientka D.** (2009) Terrestrial heat flow density in Poland – a new approach. Geological Quarterly, **53** (1): 125–140.

**Szewczyk J., Hajto M.** (2006) Strumień cieplny a temperatury wgłębne na obszarze Niżu Polskiego. In: Atlas of Geothermal Resources of Mesozoic Formations in the Polish Lowlands (ed. W. Górecki ): 143–148. AGH-UST, Kraków.

**Szewczyk J., Nowicki Z., Gientka D.** (2007) Występowanie głębokiej zmarzliny w okresie zlodowacenia Wisły na obszarze Niżu

Polskiego – implikacje paleohydrologiczne oraz geotermiczne. Współczesne Problemy Hydrogeologii, **13**: 203–211.

**Szulc J.** (2000) Middle Triassic evolution of the Northern Peri-Tethys Area as influenced by early opening of the Tethys Ocean. Annales Societatis Geologorum Poloniae, **70**: 1–48.

**Szyperko-Teller A.** (1997) Trias dolny (pstry piaskowiec). Litostratygrafia i litofacje. Sedymentacja, paleografia i paleotektonika. Prace Państwowego Instytutu Geologicznego, **153**: 121–132.

**Szyperko-Teller A.** (2008) Wyniki badań litologicznych i stratygraficznych w utworach pstrego piaskowca. Profile głębokich otworów wiertniczych Państwowego Instytutu Geologicznego, **125**: 130.

**Szyperko-Teller A., Moryc, W.** (1988) Evolution of the Buntsandstein sedimentary basin in Poland. Kwartalnik Geologiczny, **32** (1): 53–72.

**Szyperko-Teller A., Szulc J.** (2008) Szczegółowy profil litologiczno-stratygraficzny otworu wiertniczego Brześć Kujawski IG-1. Profile głębokich otworów wiertniczych Państwowego Instytutu Geologicznego, **125**: 45–59.

**Tenzer H.** (2001) Development of Hot Dry Rock Technology, GHC Bulletin, December: 1–9.

**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.

**Warrington G.** (1974) Trias. In: The Geology and Mineral Resources of Yorkshire (eds. D.H. Rayner and J.E. Hemingway), Yorkshire Geological Society: 145–160.

**Wees J.-D. van, Beekman F.** (2000) Lithosphere rheology during intraplate basin extension and inversion; inferences from automated modeling of four basins in Western Europe. Tectonophysics, **320**: 219–242.

**Wójcicki A.,** ed. (2012) Identification of formations and structures for safe geological $CO_2$ storage with the program of their monitoring (in Polish). The National Fund for Environmental Protection and Water Management, https://skladowanie.pgi.gov.pl.

**Zakrevsky K.E.** (2011) Geological 3D modeling. EAGE Publications, **3990**. DB Houten, Netherlands.

**Żelaźniewicz A., Aleksandrowski P., Buła Z., Karnkowski P.H., Konon A., Oszczypko N., Ślączka A., Żaba J., Żytko K.** (2011) Regionalizacja tektoniczna Polski. Komitet Nauk Geologicznych PAN.

**Ziegler P.A.** (1990a) Geological Atlas of Western and Central Europe (2nd edition). Shell Internationale Petroleum Maatschappij B.V.; Geological Society Publishing House, Bath.

**Ziegler P.A.** (1990b) Tectonic and palaeogeographic development of the North Sea rift system. In:Tectonic evolution of the North Sea rifts (eds. D.J. Blundell and A.D. Gibbs), Oxford Science Publications: 1–36.