



Recognition of Lower Cretaceous geothermal potential of Central Poland with the application of geophysical methods

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Abstract

In Poland, geothermal energy and waters are utilized in several geothermal plants as well as in balneological and recreation centers. The research projects run in last years aimed to recognize the geothermal potential in various regions of Poland. These projects were especially focused on selection of sites prospective for development of geothermal resources. For this purpose, various integrated exploration methods were applied to reduce the geological risk, which affects any design of geothermal installation. Among the convenient exploration tools are geophysical methods widely applied to the recognition of geological structure of the Earth and to petroleum exploration. Taking into account the Malanów area located in the Mogilno-Łódź Trough (central part of the Polish Lowlands), the authors present the opportunities provided by the usage of archival geophysical data for characterization of geothermal aquifer. The results demonstrate that geophysical methods can effectively support the selection of areas favorable for future geothermal investments. Simultaneously, such methods can be useful in determination of hydrogeothermal parameters of particular aquifer. In the study area, local depressions of the top surface of geothermal aquifer are known, which can be identified with the seismic data. Moreover, seismic inversion can be applied to porosity estimations of Lower Cretaceous aquifer. The most favorable reservoir properties occur in the NE part of the study area where the top surface of Lower Cretaceous formation is located at < 1500 m depth and in its marginal parts where this surface drops down to even 1900 m depth. Seismic data also indicate that the Lower Cretaceous aquifer remains tectonically undisturbed.

Keywords Geothermal water · Geothermal parameters · Geophysical methods · Poland · Lower Cretaceous

Introduction

The development of geothermal energy resources in Poland has started in early 1990s when the first geothermal plant has been launched in the Podhale region (southern Poland). Since that time, geothermal installations have

been successively activated in various regions including 6 district heating plants, 10 health resorts, and 13 recreation centers (Kępińska 2016). Moreover, geothermal energy can be utilized for many other purposes, e.g., timber seasoning, underoil heating of football pitches or fish farming. In many regions of Poland, consecutive research projects were recently run dealing with the effective utilization of geothermal energy and geothermal waters resources (e.g., Górecki et al. 2015; Miecznik et al. 2015; Sowizdżał et al. 2013; Sowizdżał 2015, 2016). Despite many successful results of R&D studies leading to the publication of guidebooks for investors, the progress in development of geothermal energy resources in Poland is very slow. In 2014, geothermal energy shared only 0.25% of overall domestic renewable energy generation (dominated by biofuels—76%) (Berent-Kowalska 2015). In comparison to the previous years, no significant increment of installed power capacity was noticed and most of the new projects focus on utilization of geothermal waters for recreation, not for power generation.

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The characteristic feature of geothermal energy utilization (and all other renewable energy sources) is high capital cost compared to relatively low running costs. In the case of geothermal energy, the capital costs are generated mostly by drilling operations. Taking into account also the high geological risk of first well drilling, it is not surprising that utilization of domestic geothermal resources is very low, despite many economic, environmental, and social advantages. Recent experiences indicate that potential investors are afraid of geological risk generated by drilling of the first geothermal well, despite the fact that geothermal projects are very attractive for many cities. The essential of geological risk is the possibility that true hydrogeothermal conditions found after well completion will differ from those anticipated in the project. The most important factors controlling the economic effectiveness of geothermal installation are: reservoir temperature and discharge, the latter dependent on petrophysical parameters of reservoir rocks and on thickness of geothermal water horizon. Another important factor is the content of total dissolved solids (TDS), which increases with the depth to groundwater horizons. The increasing TDS rises the viscosity of groundwaters, which lowers the discharge and increases the temperature drop during exploitation of geothermal reservoir. In deeply buried, central parts of geothermal basin, where high reservoir temperature is an advantage, the groundwaters show high TDS values. Moreover, the reservoir rocks represented by deep-water basinal facies are subjected to diagenetic transformations resulting in deterioration of reservoir properties, which, in turn, reduces the discharge and hampers the injection of the spent water back to geothermal reservoir. From the point of view of geothermal water utilization, the most favorable are waters, which have: (1) the highest reservoir and wellhead temperatures, (2) the maximum discharge under artesian conditions, and (3) the lowest TDS (Górecki et al. 2006; Sowizdżał 2010).

The well-verified recognition method of geological setting in any area is the seismic survey successfully applied to petroleum exploration. An important problem is the implementation of seismic methodology to geothermal basins and reservoirs. Localization of seismic profiles made for recognition of hydrocarbon deposits is generally not optimal for geothermal purposes. Moreover, in the case of older seismic profiles, the acquisition parameters were selected for better illustration of the oil traps located deeper than the shallow deposits of geothermal reservoirs. This will affect the choice of the most suitable locations for geothermal plant. The limiting barrier is the high cost of seismic survey. Before 2001, seismic has not been used in geothermal projects except for a single case in 1987, when the Polish oil industry signed a contract with the Institute of Fossil Fuels of the AGH University of Science and Technology in Kraków, which enabled the extension of 2D seismic survey run in the Skoczów–Wadowice–Sucha area for six seismic

sections localized in the Podhale Depression. This data set was then used in positioning of the wells: Biały Dunajec PAN-1, Poronin PAN-1, and Nowy Targ PIG-1. In the years 2001/2002, the 3D seismic survey was run for the Geotermia Podhalańska Company (Czerwińska 2014).

An alternative for specialized seismic geothermal projects is the use of archival seismic data obtained for hydrocarbon exploration (Czerwińska 2014) and then subjected to data re-processing. Such procedures have been applied in last years, in many research projects focused on recognition of geothermal potential in various regions of Poland (see, e.g., Bujakowski et al. 2010, 2014; Sowizdżał and Kaczmarczyk 2016; Górecki et al. 2013). Current world literature supports the demand for integrated geophysical studies as a part of geothermal exploration projects (Kana et al. 2015; Li-jun Su et al. 2017; Cumming 2016).

The opportunities offered by modern seismic data interpretation systems enable the researchers to extract the new, much more detailed information from the archival data, particularly concerning the geological setting of study area, the reservoir geometry and the imaging of its inhomogeneity, the characteristics of faults, or the determination of reservoir parameters. Hence, this method can be successfully used for the purposes of geothermics.

The archival seismic data recorded in the mid 1970s were used for recognition of hydrogeothermal parameters of the Lower Cretaceous aquifer in the Malanów area (Central Poland, Mogilno–Łódź Trough).

Geological setting

The study area is located in the Łódź Trough, close to its southern border with the Fore-sudetic Monocline (Fig. 1). The Łódź Trough is commonly described together with the



Fig. 1 Location of the study area (red square) in Central Poland

Mogilno Trough as a joint structure—the Mogilno–Łódź Trough characterized by the extreme thickness of Cretaceous sediments in Poland (up to about 3000 m) resting directly upon Jurassic and Triassic strata (Stupnicka 1997).

The Łódź Trough is an asymmetric structure of relatively complex geological setting influenced by salt diapirs. It is also recognized as the area of most depressed fresh groundwater table in Poland caused by intensive exploitation of Upper and Lower Cretaceous aquifers, which lowered the groundwater table and disturbed the hydrodynamic regime (Paczyński 1995; Wiktorowicz 2011).

In the Malanów area, Cretaceous sediments pinch out from the northeast to the southwest, as documented by data from deep wells (Fig. 2). Hence, Cretaceous strata are absent in the well 4. In the remaining deep wells, in the top part of the sequence, lithology comprises mostly siliceous rocks (well 3, top surface at 71 m b.s.l.), limestones, marly limestones, and glauconitic marls (well 2, top surface at 52 m b.s.l., well 1, top surface at 65 m b.s.l.). In the bottom parts of the sequence, marls and random-grained sandstones (well 2) with limestones and sands (well 1) are common. Thickness of Cretaceous succession in the Malanów area varies from 3795 m in the well 3 to over 1200 m in the well 1.

The Jurassic succession in the central part of the Łódź Trough varies in thickness from 250 to over 3000 m and comprises relatively uniform lithology—mostly marly limestones or sandy limestones with marls and common interbeds of gypsum and anhydrite (Wiktorowicz 2011). In the Malanów area, Jurassic formation includes in its top part

calcareous claystones, gray marls, gray limestones, and marly limestones (well 2, top surface at 825 m b.s.l., well 1, top surface at 1346 m b.s.l.) as well as fine-grained sandstones (well 3, top surface at 4505 m b.s.l.). In the bottom part, Jurassic strata are alternating fine-grained sandstones and gray claystones interbedded with mudstones (well 2 and well 1). Thickness of Jurassic succession varies from 997 m in the well 1 to 1524 m in the well 4.

The Triassic sequence of the Łódź Trough comprises mudstone–claystone complexes with sands, dolomitic marls, and marls of total thickness reaching up to 1500 m. In the Malanów area, thickness of Triassic strata is higher than trough the central part and varies from 1135.5 m in the well 4 to 1852.5 m in the well 2. The Triassic strata are mostly claystones, dolomites, sandstones, limestones, conglomerates, marls, and anhydrites.

The overburden includes chiefly Paleogene, Neogene, and Quaternary sediments (Wiktorowicz 2011), which are clays and sands (well 2) or clays (well 1) of total thickness ranging from 37 m in the well 4 to 71 m in the well 3 (Fig. 3).

Lower Cretaceous geothermal aquifer

The most perspective hydrogeothermal aquifers in Central Poland are located in Lower Cretaceous and Lower Jurassic sandstones (Górecki et al. 2015). Also the Lower Triassic aquifer is an interesting target for hot dry (or almost dry) rock energy extraction technologies (Sowizdżał et al. 2013).

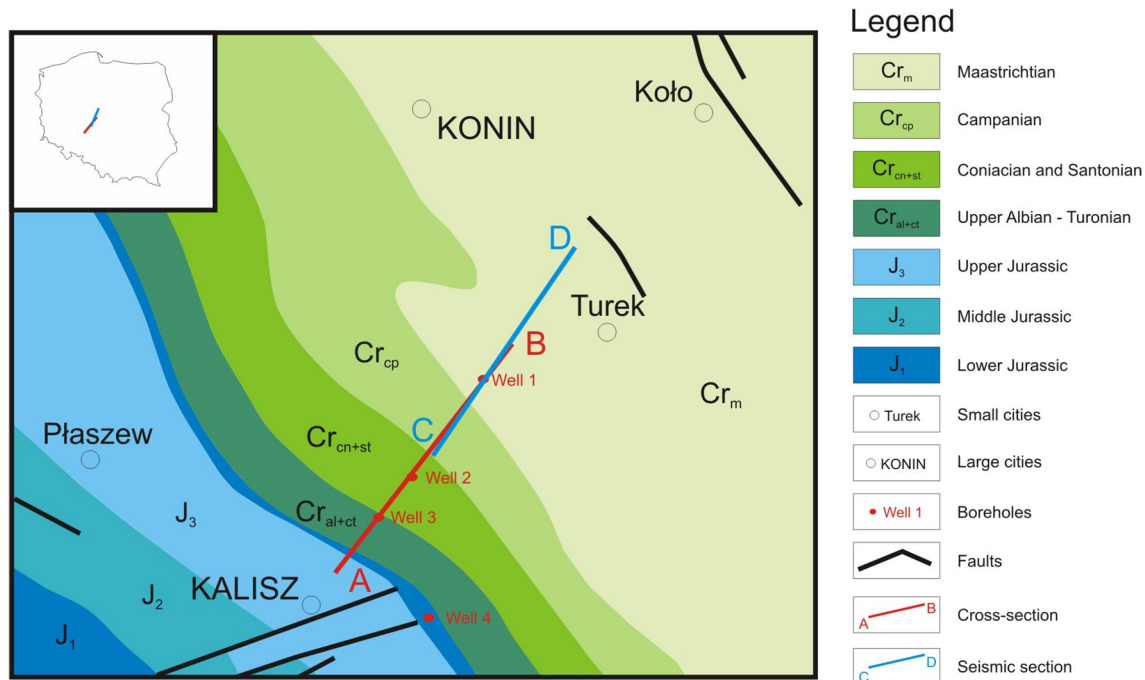


Fig. 2 Geological map of study area without Cainozoic deposits (based on Dadlez et al. 2000)



Fig. 3 Stratigraphy and thickness of mesozoic, tertiary, and quaternary strata along the A–B cross section in Fig. 2

In the study area, Lower Cretaceous aquifer is particularly interesting as the geothermal energy source, as confirmed by currently operating geothermal heating plants in Uniejów and Poddębice. Due to deep burial of Lower Cretaceous strata, the Mogilno–Łódź Trough is regarded as most prospective geothermal area in Poland.

The top surface of Lower Cretaceous succession in the study area is located at depths from 400 to 1200 m b.s.l. Temperatures of groundwaters may locally exceed 80 °C and thickness of the whole succession varies usually from 100 to 200 m. The percentage of permeable rocks changes from 30 to 90% and even more along the paleo-outcrops of Lower Cretaceous sediments in the southeastern limb of the trough (Górecki et al. 2006).

The Lower Cretaceous groundwater horizon is quite well recognized in the Uniejów area where reservoir temperature of 68 °C was measured in wells drilled in the 1970s, which proved the presence of geothermal waters in this stratigraphic unit. The following drillings completed in the 1990s documented discharges at the level of 90 m³/h, reservoir temperatures about 70 °C, and low TDS (5 g/dm³). The water belongs to Cl–Na type with F and B. The reservoir rocks are sandstones located at depths from 1900 to 2000 m. In 2005, exploitation of the geothermal water was approved with a submersible borehole pump of flow rate 120 m³/h. The installed geothermal capacity is about 2.75 MWt, the capacity of biomass-fired peak boiler is 1.8 MWt, and that of fuel–oil-fired emergency boiler is 2.4 MWt (Sapińska-Śliwa 2011).

In 2012, another geothermal heating plant was put into operation in Poddębice, also based on the resources of Lower Cretaceous aquifer. The current capacity of that heating system is around 4–5 MWt supported by peak-load boiler capacity of around 2 MWt. Wellhead temperature is 71 °C, TDS is only 0.4 g/dm³, and the average discharge is 116 m³/h (Kepińska 2013). The Lower Cretaceous geothermal horizon comprises porous, fine-, locally also medium-grained sandstones. Examples of successful development of Lower Cretaceous geothermal aquifer justify further exploration in this area.

Identification of the boundaries of Lower Cretaceous aquifer using the seismic section

The stratigraphic identification of seismic reflections related to the boundaries of Lower Cretaceous geothermal aquifer was based on matching of synthetic seismograms to real reflections seen in seismic section at the well site. Synthetic seismograms are calculated by convolving the reflectivities determined from digitized sonic and density logs with the source wavelets (Bacon et al. 2003). The model of seismic trace was created using the source wavelet extracted from seismic section at the well site. High correlation was obtained of synthetic and real reflections (Fig. 4). Due to high quality of well log data and favorable localization of the Well 1 in the deeper part of the Mogilno–Łódź Trough where both the Lower and the Upper Cretaceous successions

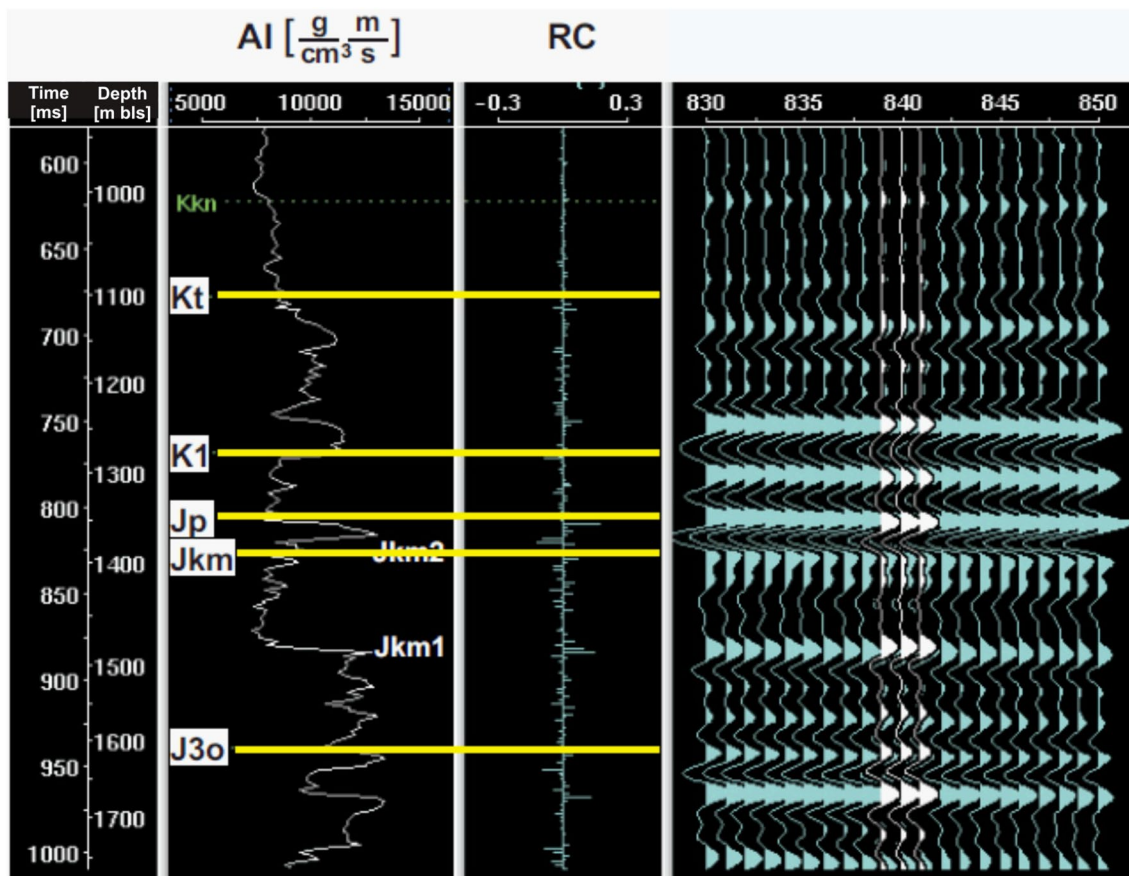


Fig. 4 Correlation of synthetic seismogram (white traces) with real seismic reflections (blue traces): *AI* acoustic impedance; *RC* reflection coefficient

are fully developed, the synthetic seismogram calculated for this well is credible and perfectly characterizes reflections recorded in the shallower part of seismic section.

In the vicinity of the well 1, high-amplitude reflections have not been identified within the Upper Cretaceous formations, neither in the synthetic nor in the real seismic sections. The first reflection with distinct positive amplitude can be tied with the top surface of Upper Albian carbonates, which directly cover the Lower Cretaceous strata and which show increased acoustic impedance (AI). The top surface of Lower Cretaceous (Cr1) sandstone reservoir having low AI correlates well with negative amplitude of interfered reflection. The positive-amplitude reflection located below is tied to a thin interbed within the Lower Cretaceous succession, which shows increased AI and, thus, lower porosity. The bottom surface of Lower Cretaceous aquifer correlates with a positive-amplitude reflection from an interbedding plane separating sandstones from underlying Portlandian carbonates of much higher AI.

Similarly, the synthetic seismogram was applied to stratigraphic identification of deeper reflections originated from reflectors in Jurassic and Triassic formations.

Geological interpretation of seismic sections

In the shallower part of seismic sections, corresponding to Cretaceous and Jurassic successions (to about 1000 ms), quality of seismic imaging is satisfactory (Fig. 5). Evident are contacts of reflections in the form of pinch-outs related to the termination of Lower Cretaceous aquifer in the southwestern part of the area. In the central part of seismic section, the aquifer forms an anticline related to a salt pillow located deeper. In the northeastern part of the study area, the aquifer dips monoclinaly with gradual increase of thickness.

The seismic imaging clearly demonstrates that the Lower Cretaceous aquifer is tectonically undisturbed in the study area (Fig. 5). The deep dislocations related to culmination of anticline terminate in the Upper Triassic (Rhaetian) or in the Lower Jurassic strata.

Beneath the Lower Cretaceous aquifer, within the Upper Jurassic strata, seismic signatures appear typical of carbonate reefs growing onto the anticlinal elevations. Precisely, within the reefs, continuous reflections turn into a chaotic pattern of reflection fragments, whereas, outside the reefs, reflections in the Oxfordian strata are continuous

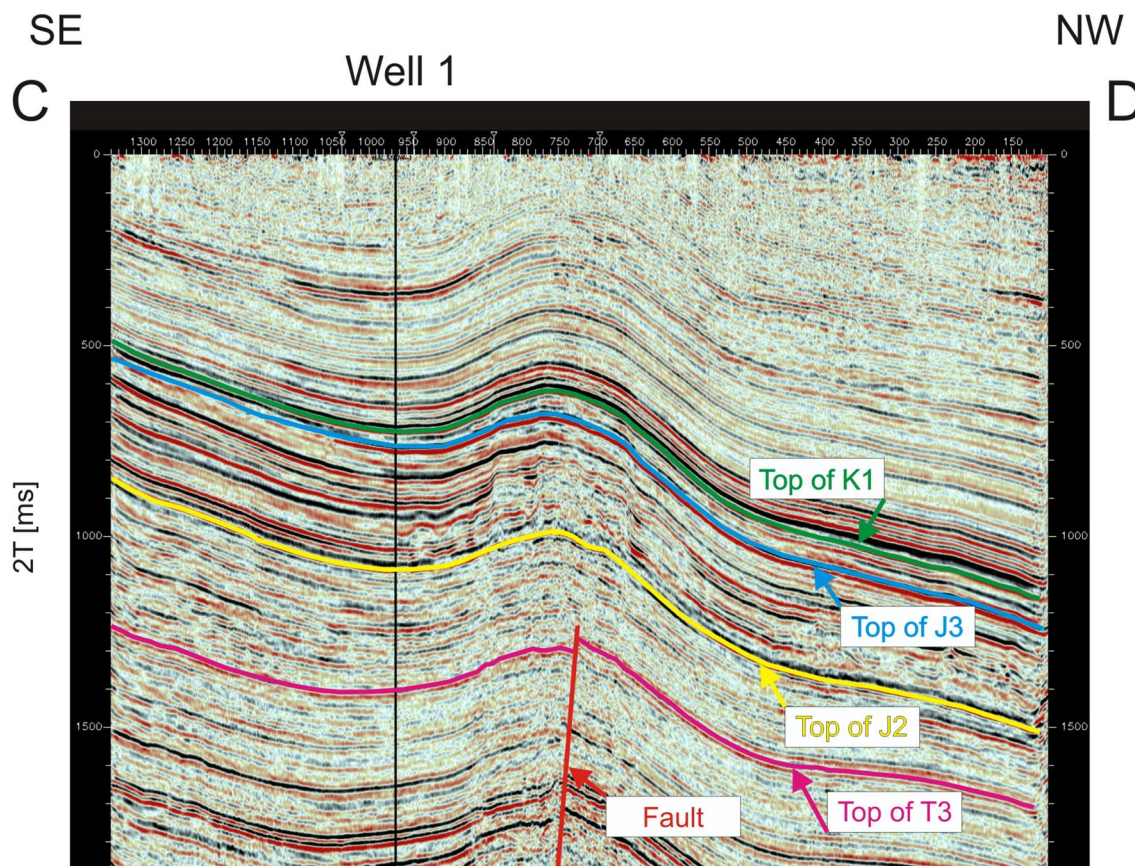


Fig. 5 Geological interpretation of seismic section along the C–D line in Fig. 2

and can be attributed to marly intercalations in carbonate formation. Variability of porosity within the Lower Cretaceous aquifer was estimated using the seismic inversion.

The seismic inversion procedure enables us to reconstruct the AI values (i.e., the product of rock density and P-wave propagation velocity) from seismic section, which can be interpreted quantitatively to determine the reservoir parameters of rock formation, first of all its porosity (Pendrel 2001). This is the best geophysical method enabling the researcher to evaluate lateral distribution of porosity in deep-seated reservoirs.

The seismic inversion in acoustic variant was calculated from seismic sections after time migration, which provided the AI distribution within the Lower Cretaceous geothermal aquifer. After inversion, data reveal better resolution due to extension of frequency bandwidth at the low-frequency end using the low-frequency trend supplied from well logs and extending bandwidth at the high-frequency end by removing the effect of the source wavelet from the input seismic traces (Bacon et al. 2003). From geological point of view, it enhances the projection of vertical variability of reservoir parameters.

The inversion procedure run without low-frequency outside trend of impedance allows for reconstruction of only relative relationships of this parameter (Ghosh 2000; Pendrel and van Riel 1997). To determine the absolute values of AI characterizing geological formation, the low-frequency component of impedance must be a priori included into the inversion procedure. It was determined using the acoustic (DT) and density (RHOB) well logs filtered with low-frequency filter of bandwidth over 10 Hz.

The seismic inversion was calculated with the sparse spike inversion algorithm (SSI), which reconstructs first a number of reflection coefficients and then distribution of acoustic impedance in a broad spectrum of frequencies (Simm and Bacon 2014). For better stabilization, additional ties were applied to reduce a priori the range of permitted variability of AI within the aquifer. Seismic inversion was calculated using the source wavelet derived from seismic section, similar to that used for calculation of synthetic seismogram.

The solution of acoustic impedance inversion was controlled by its comparison with the plot of impedance calculated from well logs and filtered to seismic frequencies.

The AI distribution obtained from seismic inversion was then scaled to show porosity basing on regression between these parameters determined from the well logs (Fig. 6):

$$\text{PHI} = -0.00352462 \times \text{AI} + 49.28 \quad R = -0.91,$$

where PHI is porosity, AI is acoustic impedance, and R is the correlation coefficient

In the southwestern part of seismic section, in the zone of gradual pinching out of Lower Cretaceous succession, two distinct layers of different impedance (and porosity) were distinguished (Fig. 7). Sandstones forming the upper layer show lower thickness but higher porosity (over 20%), whereas porosity of bottom layer is much lower (a dozen %). Such bipartition of Lower Cretaceous succession disappears in the vicinity of synclinal hinge penetrated by the well. Vertical variability of porosity is much lower with the increase down the sequence, towards the bottom of the layer. In the middle part of Lower Cretaceous succession, a thin intercalation appears of increased AI and decreased porosity. This inhomogeneity is responsible for reflection identified with both the synthetic seismogram and the real

seismic section below the top surface of Lower Cretaceous succession.

Within the anticlinal elevation, both the thickness and porosity of Lower Cretaceous sandstones increase. However, the sequence of highly porous (about 24%) sediments is interbedded by a layer of lower porosity (a dozen %). In the northeastern part of the study area, Lower Cretaceous aquifer dips monoclinally down to significant burial depth (about 1200 ms 2T, i.e., 1600 m). The results of seismic inversion demonstrate that, despite considerable burial depths, porosity of sandstones is still high, which, together with favorable thermal conditions makes the study area a promising target for future exploitation of geothermal waters.

Conclusions

The seismic methods are widely applied to recognition of geological structure of the Earth and to exploration for conventional petroleum deposits as well as, in last years, to the localization of shale gas and tight gas deposits. However,

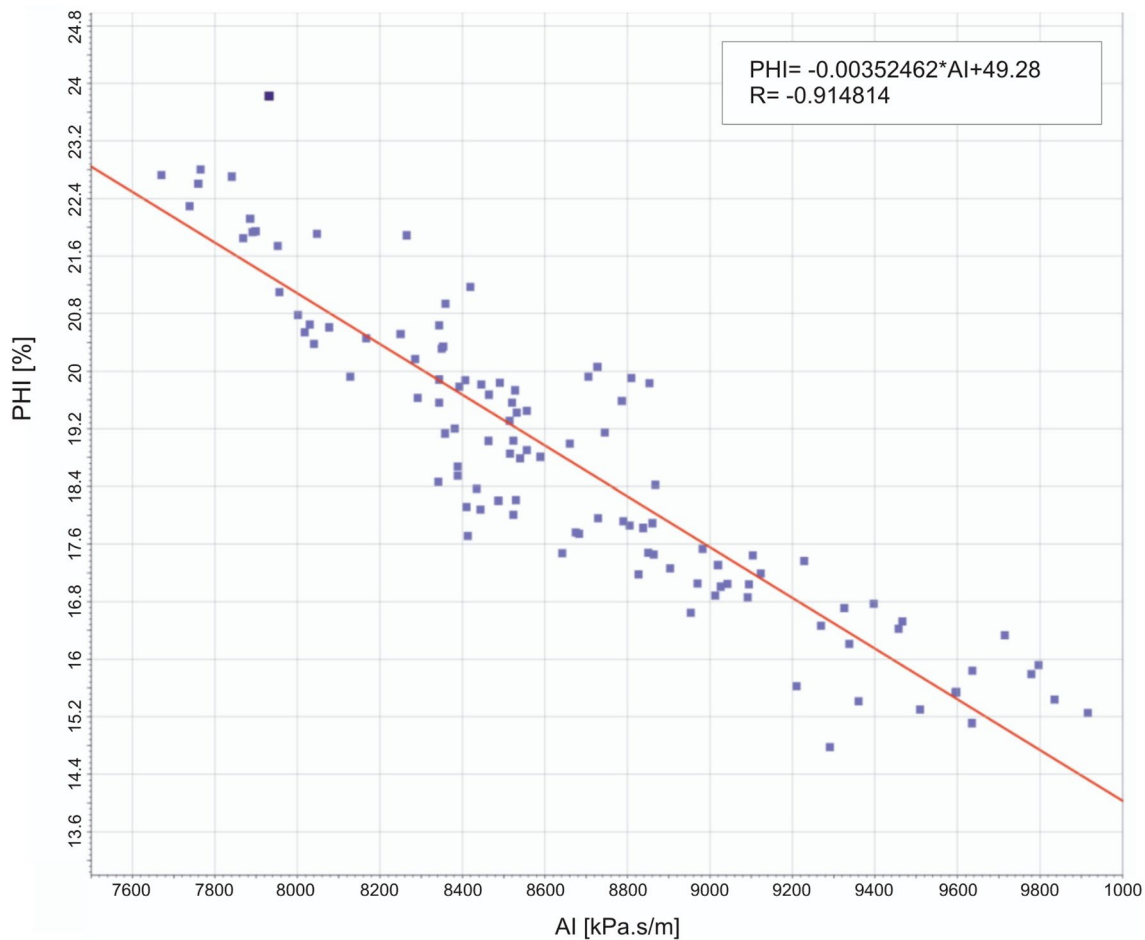


Fig. 6 PHI–AI cross plot for Lower Cretaceous sandstones, red line—regression line, R correlation coefficient

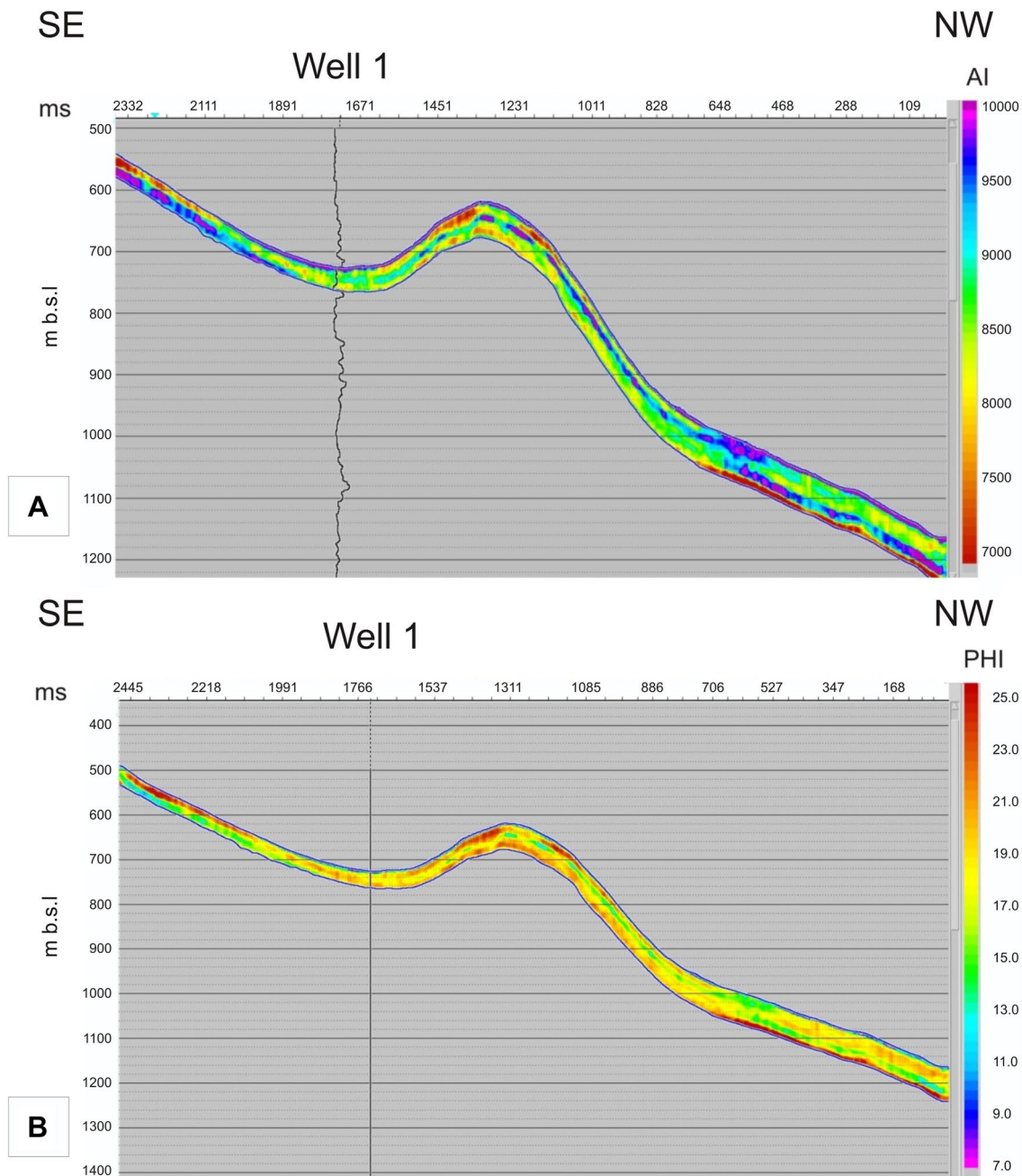


Fig. 7 Variability of acoustic impedance (**a**) and porosity (**b**) within the Lower Cretaceous geothermal aquifer

these methods can be successfully used also in exploration and assessment of geothermal waters deposits, to determine reservoir parameters, as, e.g., depth to the top surface of the reservoir, its thickness, and porosity. Moreover, seismic data may support the selection of areas optimal for future investments in geothermal installations.

In Poland, seismic surveys are rarely used as a support of geothermal projects. More common is the application of

archival seismic data to the recognition of geological structure of geothermal prospects, to determination of geometry of geothermal aquifers, to characterization of dislocations, or to imaging the heterogeneity of geothermal aquifers. Moreover, an important aspect of any geothermal project is the determination of reservoir parameters (porosity and clay content) with geophysical methods, including the seismics. To recognize the geothermal aquifer in the Malanów area,

the authors used seismic data recorded during the surveys run since the mid-1970s. The studies run in the Malanów area were focused on the recognition of reservoir parameters of Lower Cretaceous aquifer using the integrated geophysical methods, first of all seismics and geophysical logging.

The Lower Cretaceous aquifer (and the Lower Jurassic one) belongs to the most prospective reservoirs of hydrogeothermal resources in the Polish Lowlands, including the study area. It is confirmed by operating geothermal heating installations as well as by the results of research projects applying the geophysical methods. The interpretation of seismic sections enabled us to determine the geometry of the aquifer. The pinch-out zone was identified in the southwestern part of study area whereas an anticlinal structure related to the salt pillow was found in the central part of seismic section. The seismic imaging clearly indicated that the Lower Cretaceous aquifer remains tectonically undisturbed. Variability of porosity of reservoir rocks was determined using the seismic inversion. Both the porosity and the thickness of Lower Cretaceous sandstones increase within the anticlinal elevation. The trend of favorable reservoir properties (porosity over 20%) continues in the deeper parts of the aquifer and, combined with burial-induced, due to the geothermal gradients higher temperatures of the water, it provides arguments for selection of this area as the most prospective for future investments in geothermal installations. This zone is located in the northeastern part of the study area where the top surface of Lower Cretaceous succession occurs at depths from 1,500 to 1,900 m b.s.l.

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