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Research Article

Seismic Methods in Geothermal Water Resource Exploration: Case Study from Łódź Trough, Central Part of Poland

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The geothermal waters constitute a specific type of water resources, very important from the point of view of their thermal energy potential. This potential, when utilized, supplies an ecological and renewable energy, which, after effective development, brings many environmental, social, and industrial benefits. The key element of any geothermal investment is the proper location of geothermal installation, which would guarantee the relevant hydrogeothermal parameters of the water intake. Hence, many studies and analyses are carried out in order to characterize the reservoir parameters, including the integrated geophysical methods. For decades, the geophysical surveys have been the trusty recognition methods of geological structure and petrophysical parameters of rock formations. Thus, they are widely applied by petroleum industry in exploration of conventional and unconventional (shale gas/oil, tight gas) hydrocarbon deposits. Advances in geophysical methods extended their applicability to many other scientific and industrial branches as, e.g., the seismic survey used in studies of geothermal aquifers. The following paper presents the opportunities provided by seismic methods applied to studies of geothermal resources in the central Poland where the geothermal waters are reservoired in both the Lower Cretaceous and the Lower Jurassic sedimentary successions. The presented results are obtained from a network of seismic profiles. An important advantage of the seismic survey is that they may support the selection of an optimal location of geothermal investment and determination of the geometry of geothermal aquifer. Furthermore, the application of geophysical methods can significantly contribute to the reduction of estimation error of groundwater reservoir temperature.

1. Introduction

Studies on conditions within the geothermal aquifers have been carried out in Poland since the 1980s, when the regional studies have been initiated at the Institute of Fossil Fuels of the Faculty of Geology, Geophysics and Environment Protection, AGH University of Science and Technology, in Kraków. The Research and Development (R&D) project was focused on utilization of geothermal waters from the Lower Jurassic reservoir in the Polish Lowlands and Mesozoic and Paleogene-Neogene reservoirs in the Carpathians. Together with the basic studies, dealing mostly with the estimation of geothermal resources, the development projects were run. This resulted in the construction of first geothermal installation in Poland, in the Podhale region, in 1994 [1, 2]. Recently, 6 district heating plants, 10 health resorts, and 13 recreation centers operate in Poland [3]. They are mostly located in the area of the Polish Lowlands, which appears to be the largest domestic geothermal province (Figure 1).

The geothermal conditions in Poland are relatively well-recognized at regional scale. The comprehensive information about domestic geothermal resources is provided by the series of geothermal atlases, which include the Polish Lowlands, the Carpathians, and the Carpathian Foredeep [5–9]. These areas are favorable not only for utilization of hydrogeothermal resources, first of all for heat generation, but also for balneotherapy, recreation, and other purposes. Generally, the geothermal waters in Poland are suitable for binary, electricity, and heat generation systems [10], which indicates

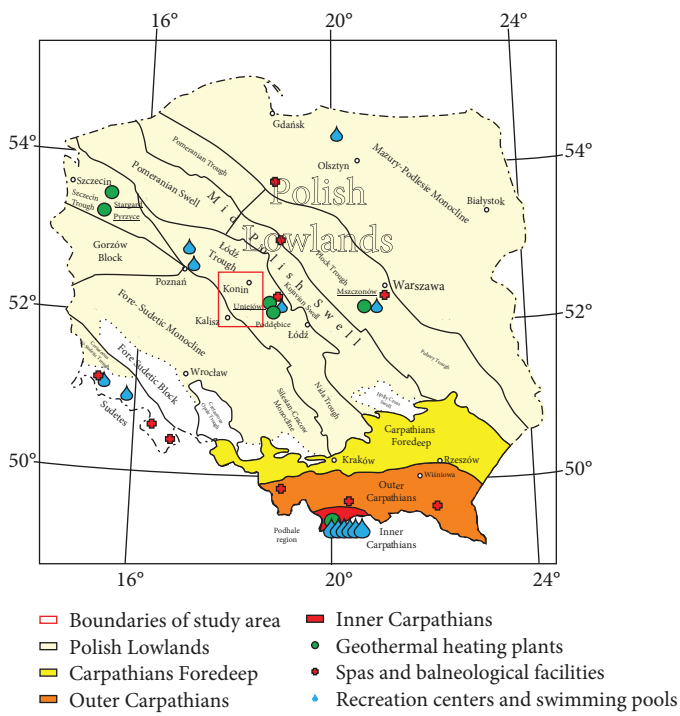

Figure 1: Geological regional division of Poland without Cenozoic cover with location of geothermal installations (after [4], modified).

the utilization of low-temperature geothermal resources for electric power generation. This technology is recently unused in Poland. In the last years, the research projects have been run, concerning the utilization of hot, dry rock (HDR) energy potential using the enhanced geothermal systems (EGS) [11].

The obvious profits resulting from operation of the existing geothermal installations together with promising results of many R&D projects do not stimulate the progress in geothermal energy utilization, which is still rather low in Poland. This is the joint effect of high capital costs and competitiveness of other resources of renewable energy. The high costs are incurred mostly by drilling of new wells or reconstruction and adaptation of the existing wells. Moreover, the important negative factor is the high geological risk incurred by the potential investor. Taking into account the previous experience, it is obvious that many interesting geothermal projects have not been implemented due to geological risk related to the first well drilling and other hydrogeothermal conditions than expected in the project [12].

From the investor's point of view, the crucial parameters controlling the economic effectiveness of geothermal investments are as follows: the temperature and the discharge dependent on petrophysical properties of reservoir rocks. Also, the content of total dissolved solids (TDS), which increases with the depth of groundwater horizons and directly affecting the drilling costs is important. The higher TDS increases the viscosity of reservoir fluids, which deteriorates the productivity of the system and, indirectly, triggers some other negative phenomena such as, e.g., clogging of the wellbore walls. Unfortunately, the deep-seated geothermal reservoirs of most favorable high temperatures show also the high TDS values, which make the efficiency lower [5, 13].

For many years, the seismic survey has been widely applied to recognition of geological structure of the bedrocks and to exploration of conventional and unconventional hydrocarbon accumulations (shale gas/oil and tight gas). In the case of geothermal energy utilization, the possible application of geophysical methods not only in the exploration of geothermal reservoirs but also directly for the purposes of geothermics is important [12, 14, 15]. The seismic methods can be successfully used in verification of potential geothermal reservoirs, providing the credible seismic image of exploration targets. However, the costs of comprehensive seismic survey are high, which strongly limits their applicability.

The seismic survey is still rather rarely applied in Polish Geothermal research. Before 2001, only one such project was completed when the Skoczów-Wadowice-Sucha 2D seismic survey was extended for additional profiles, thanks to the agreement between the petroleum industry and the Institute of Fossil Fuels, AGH University of Science and Technology, signed in 1987. The results of these studies were then used in positioning of the Biały Dunajec PAN-1, Poronin PAN-1, and Nowy Targ PIG-1 wells located in Carpathians, southernmost Poland. Later on, in the years 2001–2002, one of the Polish geophysical companies completed the seismic survey for the Geotermia Podhalańska Co.—the operator of a geothermal heat plant in the Podhale region [16]. Some seismic and magnetotelluric surveys were run for geothermal purposes in the Polish Lowlands (central Poland, [17]) and in the Sudetes [18].

In order to reduce the costs of field seismic survey, the reprocessing of archival seismic data is commonly applied. Such datasets originating from hydrocarbon exploration projects [16] were widely used in various R&D studies recently run in Poland (see, e.g., [5–9]).

Considering the progress in available interpretation software, the more detailed reprocessing of archival data is possible even if quality of source data is low. The reinterpretation not only provides the new information about geological setting of the project area but also enables the researchers to obtain more accurate geometry of the reservoir and more detailed image of its heterogeneity (location of faults, unconformities, etc.). Particularly valuable for potential investors is the opportunity of evaluation of geothermal parameters from the results of seismic survey, which reduces high geological risk of the investment [19].

1.1. Low-Temperature Geothermal Resources in Poland. In Poland, the geothermal resources are accumulated in four main hydrogeothermal provinces: the Polish Lowlands, the Carpathians, the Carpathian Foredeep, and the Sudetes. Unfortunately, these are mostly the low-temperature resources of wellhead temperatures below 100°C.

The Polish Lowlands is the largest hydrogeothermal province in Poland. The geothermal resources are hosted in the Mesozoic sedimentary formations, among which the most prospective are the Lower Jurassic and Lower Cretaceous aquifers. Local accumulations are known also from the Middle/Upper Jurassic and the Triassic sedimentary successions, but these formations show much lower geothermal potential. This distribution of geothermal resources is confirmed by parameters of currently operating geothermal heating plants, which utilize the waters from the Lower Jurassic (Pyrzyce, Stargard) and the Lower Cretaceous (Uniejów, Mszczonów, and Poddębice) aquifers [1].

The Podhale region is a "geothermal gemstone" in Poland. Here, the oldest and the largest geothermal heating installation has been in operation since the 1990s. Geothermal water is produced from three wells of permissible discharge of 960 m^3/h at a temperature of 80–86°C. The reservoir rocks are the Middle Triassic limestones and dolomites [3].

In the remaining part of the Carpathians, complicated geological settings result in low discharge of production wells and in recharge problems of geothermal reservoirs, which increase the geological risk of location of geothermal installations. However, the premises to consider the geothermal investments exist in some areas (e.g., Wiśniowa).

The geological setting of the Carpathian Foredeep is less complicated. Here, the geothermal waters are reservoired in both the Devonian and the Carboniferous carbonate sequences (in the western part) and in the Middle Jurassic sandstones (in the eastern part), as well as in the Upper Jurassic carbonates and the Upper Cretaceous (Cenomanian) sandstones (in the central part of the foredeep) [8, 20]. The highest potential discharges (over 200 m^3/h) were determined just in the Cenomanian aquifer. This is a unique value because in the most part of the foredeep and in most of its geothermal aquifers, the estimated discharges are from several to a dozen of m^3/h (never exceeding 60 m^3/h), which brings development problems of geothermal resources utilized for heating purposes [12].

The studies were carried out in the central part of the Polish Lowlands. The research area has been located in the Łódź Trough, between Kalisz and Konin towns (Figure 1). Apart from the aforementioned Podhale region, the central part of the Polish Lowlands is the most prospective area for large-scale utilization of geothermal waters in Poland. Recently, the geothermal installations operate in nearby Uniejów and Poddębice, where geothermal heating plants were constructed.

In Poddębice, the construction of geothermal district heating plant was commissioned in 2012. Geothermal aquifer is hosted by the Lower Cretaceous sandstones at the depth 1.95–2.06 km b.g.l. The geothermal district heating (geoDH) of 10 MWth geothermal capacity is based on 68°C water (maximum ca. 250 m^3/h, TDS 0.4 g/L). Since 2014, the plant supplies some public buildings, school, hospital (and its rehabilitation part), and several multifamily houses. Some part of water stream is sent to a swimming pool [3, 21].

In Uniejów, the geoDH has been operating since 2001. Geothermal aquifer is hosted by the Lower Cretaceous sandstones at the depth 1.9–2.1 km b.g.l. The maximum discharge from one production well is 33.4 L/s of 68°C water while TDS are ca. 6–8 g/L. The exploitation system includes also two injection wells. The total installed capacity of the plant is 7.4 MWth including 3.2 MWth from geothermal, 1.8 MWth from biomass boiler, and reserve 2.4 MWth from fuel oil peak boilers. Since 2008, a part of geothermal water has been used in geothermal spa and recreation center "Termy Uniejów" for pools and curative treatments (ca. 8.4 L/s of 42°C water; ca. 1 MWth, 7.7 TJ). The center is also heated by geothermal energy. Some amount of spent water (ca. 5.6 L/s, 28°C) is then used to heat up a lawn of football playground (ca. 1 MWth, 8.7 TJ) and walking paths. In 2012, Uniejów received a formal status of health resort thanks to curative geothermal water [3, 21].

In 2015 in Konin, new borehole dedicated for geothermal purposes was made. The water temperature of the Lower Jurassic aquifer confirmed very good thermal conditions of the region like high temperature at the level of 95°C. Currently, the borehole is at the initial stage; the high efficiency is expected [21]. Other towns in the region plan to utilize the geothermal resources [19].

1.2. Geological Background. The research area is located in the Łódź Trough, which is a central part of the Polish Lowlands (Figure 1). The origin of the Łódź Trough, which is an asymmetric tectonic palaeoform, is ascribed to the Laramide transpression of the Polish Basin, which triggered the inversional rearrangement of its axial part [22]. From southwest, the Łódź Trough borders with the Fore-Sudetic Monocline and from northeast with the Mid-Polish Swell (Figure 1). Tectonic character of its southwestern border is documented by a deep-rooted Poznań-Kalisz dislocation zone and related the Mesozoic tectonic graben, which was formed in the Late Triassic and at the Triassic/Jurassic turn [23]. Moreover, locally tectonic character is manifested by

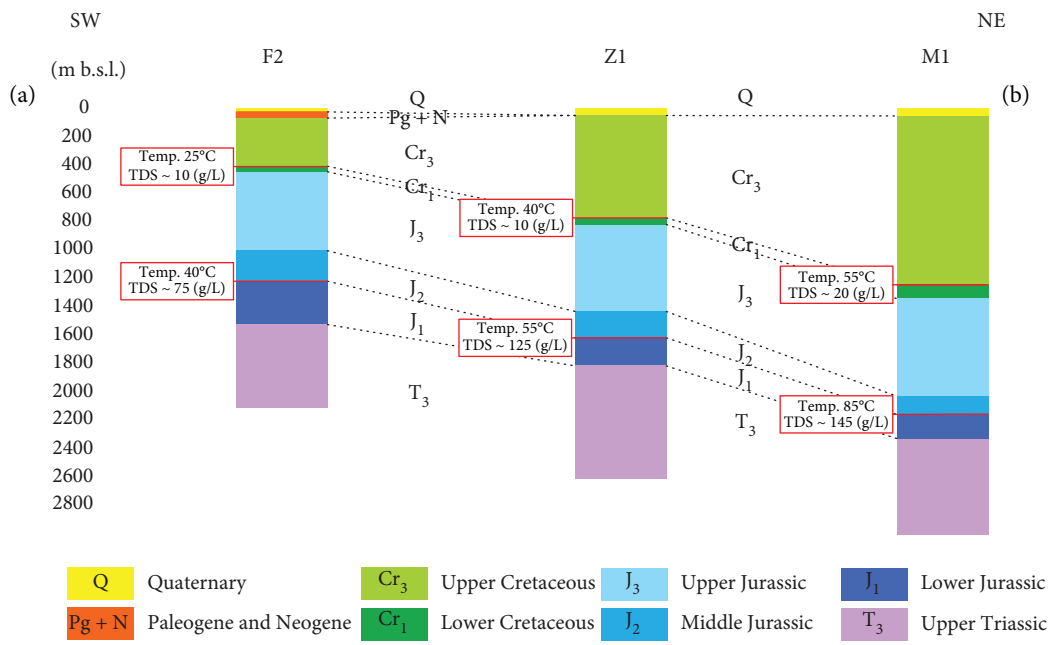

Figure 2: Geological correlation of deep boreholes in the research area (along the green dotted line in Figure 3).

the deposition of the Lower Jurassic strata as documented thickness increase measured in the F2 well (Figure 2), located in the marginal part of the graben. The sub-Cenozoic surface of the Łódź Trough comprises both the Permian and Mesozoic rocks.

The intensive subsidence in the Cretaceous of the Łódź Trough manifested by significant thickness of the Cretaceous sediments, which attained the maximum value in Poland—3000 m in the vicinity of Turek town [24]. In the research area, thickness of the Cretaceous succession varies from 379.5 m in the F2 well to over 1200 m in the M1 well (Figure 2).

In the research area, the Cretaceous sediments in the top part of the sequence, lithology comprises mostly gaizes (F2 well) followed by limestones, marly limestones, and glauconitic limestones (Z1 well). In the bottom part of the succession, marls and fine-grained sandstones (Z1 well) with limestones and sands (M1 well) are common.

The Jurassic sediments in the central part of the Łódź Trough varies in thickness from 0.25 to over 3000 m [25]. In the research area, the thickness of Jurassic succession varies from 997 m in the M1 well to 1082 m in the F2 well.

In the research area, the Jurassic deposits begin with calcareous claystones, grey marls, grey limestones, and marly limestones (Z1 well) as well as fine-grained sandstones (F2 well). In the bottom part of the sequence, the Jurassic strata is represented by sandstones and grey claystones interbedded with mudstones (Z1 and M1 wells). The Zechstein sequence comprises four cyclothems: Werra (PZ1), Stassfurt (PZ2), Leine (PZ3), and Aller (PZ4). In the northern part of the research area (vicinity of Turek town), the Zechstein rock salts form the salt structure [26, 27]. The geothermal water horizons in the research area (Lower Cretaceous and Lower Jurassic horizons) are recharged mostly by the subcrops of the Cretaceous sediments directly beneath the Quaternary strata. The southeastern part of the Łódź Trough forms a recharge zone of the Cretaceous aquifer whereas the opposite side of the trough is a discharge zone [5]. In the Łódź Trough, the recharge proceeds from both the Mid-Polish Swell and the Fore-Sudetic Monocline, as evidenced by the change of groundwater chemistry, i.e., the TDS contents increasing from the peripheries to the center of the structure [25, 28].

The TDS values for the Lower Cretaceous reservoirs range between 0 g/L and 100 g/L. In most of the Łódź Trough area, the TDS value is below 2 g/L but locally reaches over 100 g/L especially in the eastern part. For the Lower Jurassic reservoirs, the TDS value is higher and ranges between 0 and 250 g/L, locally even above 270 g/L [12]. In the research area, the TDS values for the Lower Cretaceous reservoirs range between ca. 10 g/L in the F2 and Z1 wells and ca. 20 g/L in the M1 well. For the Lower Jurassic, values are higher and increase from ca. 75 g/L in the F2 well up to ca. 145 g/L in the M1 well (Figure 2).

The water temperature in the top of the Lower Cretaceous reservoir is quite high and ranges from 40°C in the marginal part up to ca. 70°C in the northeast of Konin town. For the top of the Lower Jurassic aquifer, the water temperature is higher and reaches over 100°C in the axial part of the structure [12]. In the research area, the water temperature in the top of the Lower Cretaceous aquifer ranges between 25°C (F2 well) and 55°C (M1 well). For the top of the Lower Jurassic reservoir, temperature values range between 40°C (F2 well) and 85°C (M1 well) (Figure 2).

The porosity values for majority of the Lower Cretaceous reservoir in the Łódź Trough reach over 15%. The increase in porosity value is observed along the southern border of the trough and in the southern part reaching a maximum value at a level of 30%. Higher values are characterized by the Lower Jurassic deposits for which the porosity value achieves 20% in the predominating area of the trough. The maximum

value reaches 30% northeast of Konin town. The lowest values around 10% characterize the southern part of the trough, south of Łódź town [12, 21]. In the case of the research area, the porosity of the Lower Cretaceous reservoir ranges from ca. 22% in the F2 well to 17% in the M1 well. In the case of the Lower Jurassic, the values range from 15% in the F2 well to 14% in the M1 well.

Petrophysical parameters of the Lower Cretaceous and Lower Jurassic aquifers indicate high potential discharge of wells in the area of Łódź Trough, which ranges from a few to over 400 m^3/h for the Lower Cretaceous and from 50 to 500 m^3/h for the Lower Jurassic reservoirs. In the research area, the potential discharge of wells in the Lower Cretaceous aquifer reaches from about few to 50 m^3/h, while in the Lower Jurassic reservoir ranges from 50 to 100 m^3/h [12].

1.3. Materials and Methods. The seismic survey run in the research area comprised several projects, which have been run since the 1970s and have provided seismic sections of highly variable data quality (Figure 3). In the 1970s, several profiles have been completed, of general NW-SE and SW-NE directions. The seismic signals were recorded with 24-channel end-on spread and significant offset, which reduced the recording of waves reflected from shallow boundaries, particularly those in the Lower Cretaceous geothermal aquifer. Seismic waves were generated by explosions of dynamite charges with shot spacing 100 m and geophone spacing 50 m. The later seismic projects were run in the 1980s with the number of channels raised to 48 and with the shot spacing reduced to 50 m, which improved the maximum fold to 24.

The archival seismic records from the years 1970s and 1980s showed very high levels of noise due to low folds and poor seismic data processing methods. Many seismic sections revealed distortion of reflections; hence, the dislocation zones cannot be discerned from fictitious deformations of reflections.

The low vertical resolution of seismic records causes the lack of the proper gradation of amplitudes related to the diversity of reflection coefficients. In an extremal case, too low dominant frequency and too narrow band of elementary signal lead to the appearance of reflections which result from the interference of lateral signal oscillations, not from the contrast of acoustic impedance.

The newest seismic surveys in the research area were completed in the late 1990s, using the regular grid of profiles with the split spread and 240 recording channels. The shot spacing was 50 m, the geophone spacing was 25 m, and the fold was 60. Seismic waves were generated with the vibrators using the frequency range 8–80 Hz.

The newest seismic sections provided high imaging quality due to significant progress in data acquisition and processing methodology. Hence, the stratigraphic interpretations of the reflections became possible together with the location of boundaries of geothermal aquifers and deep faults cutting through the Zechstein and Mesozoic rocks [18, 19]. Improvement of data resolution disclosed the wedge pinch-outs caused by disappearance of the Lower Cretaceous geothermal aquifer in the southwestern part of the research area.

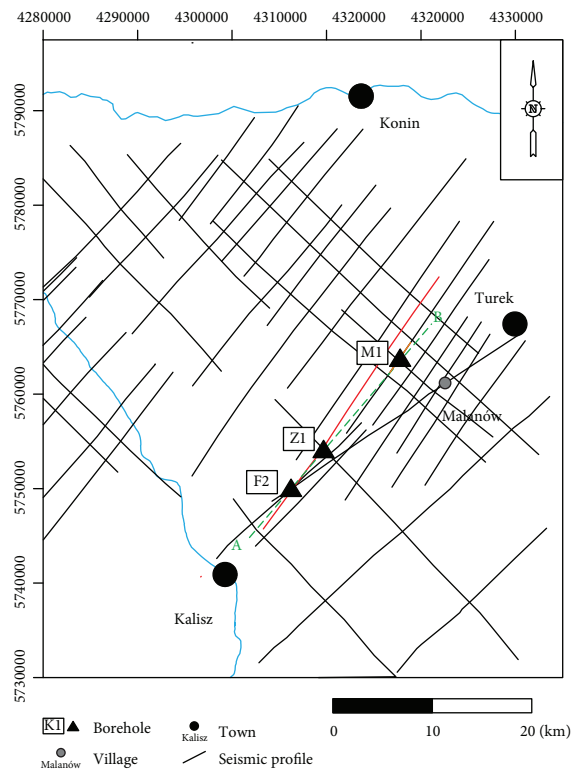

Figure 3: Map of the research area with location of deep wells and seismic profiles (correlated deep wells, along the green dotted line, are shown in Figure 2; orange part of the profile is shown in Figure 4; red line profile is shown in Figure 5).

The geological interpretation of all archival datasets required the reprocessing of the oldest records in order to adjust these seismic images to the newest profiles by increasing the vertical resolution of the sections and by elimination of the noise and the fictitious deformations of the reflections. Data processing was carried out using the scheme and procedures well-known from the literature (see, e.g., [29]).

The seismic image was influenced mostly by the stacking velocity analyses and the residual statics corrections. Many iterations were run in the stacking velocity analysis/residual statics corrections cycle, which provided stable static solution and stacking velocity. Significant influence of residual statics on seismic image appeared in the areas of tectonic disturbances and local velocity anomalies where remarkable improvements were obtained in comparison to archival processing. Before stack, a typical preprocessing was performed and spike deconvolution was applied in order to increase the resolution, followed by scaling of traces in a wide time gate. After stacking, the finite-difference time migration was applied together with the spectral whitening and the procedures increasing the signal-to-noise ratio, as F-X deconvolution and frequency filtration.

The reprocessing resulted in significant improvement of the oldest seismic profiles by elimination of noise, increase of vertical resolution, and correction of reflection continuity. The fictitious reflection deformations and the disruptions of reflections were rejected, which suggested the presence of dislocations in the Mesozoic and Zechstein complexes. The

seismic images were unified at the crossings of old (coming from the 1980s) and newest (recorded in the 1990s) sections. However, the problem of reflection inconsistency at the section crossings has remained unsolved, particularly in the zones where data quality was deteriorated due to the presence of the Jurassic carbonate reefs [18].

For detailed analysis of reservoir geometry, the seismic profiles located in the research area were geologically interpreted. Interpretation includes the thickness and depth diversification and identification of the occurrence and direction of dislocations.

Seismic methods also allow assessing the variability of petrophysical parameters of geothermal reservoirs, in particular the porosity value. For this purpose, the seismic inversion procedures, on which the distribution of acoustic impedance is estimated, are used [30]. For the weakly clayey sandstones and limestones, this basic seismic parameter strongly correlates with porosity, which allows for a reliable assessment of it and further optimization of the water intake. More advanced methods of seismic inversion (before stack) determine the elastic impedance and are used to estimate the clayey degree, which allow to determination of the reservoir and the variability continuity of the permeability in terms of quality [15, 31].

1.4. Geological Identification of Seismic Reflections. The stratigraphic identification of seismic reflections in time sections was based upon the stratigraphic interpretations of well-logs, the checkshot data, and the synthetic seismograms, which were correlated with the true seismic traces at the well sites (Figure 4) [32].

The most credible synthetic seismogram was prepared for the newest M1 well spud in the central part of the research area. In this well, high-quality density (RHOB) and acoustic (DT) logs were recorded, which provided the basis for calculations of distribution of seismic reflection coefficient values.

Within the Upper Cretaceous succession, the high-amplitude reflections were absent from the synthetic seismogram and from the true seismic section. The first reflection with distinct positive amplitude was identified as the top surface of the Upper Albian strata located at in the bottom part of the Upper Cretaceous succession, immediately above the Lower Cretaceous sequence. The top surface of that sequence (Cr_1) correlates well with the negative amplitude of an interfered reflection, similarly to the top surface of the Portlandian (J_3p), which is correlated with the positive amplitude. The top surface of the Oxfordian sequence is marked by weak positive amplitude due to low contrast of acoustic impedance at the Kimmeridgian/Oxfordian (J_3km/J_3o) boundary. On the contrary, the boundary of the Upper Jurassic carbonates and Middle Jurassic clastics (J_2) is seismically distinct and recorded by reflection with negative peak.

The true Lower Jurassic (J_1to) and Upper Triassic (T_3re: Rhaetian and T_3k: Keuper) reflections show very low correlation with the synthetic seismogram. This can be explained by local deterioration of data quality beneath the Oxfordian reefs. The regional, marker seismic reflections related to the top surfaces of the Middle Muschelkalk (T_2m) and the Middle Bunter Sandstone (T_2p) quite well correspond to

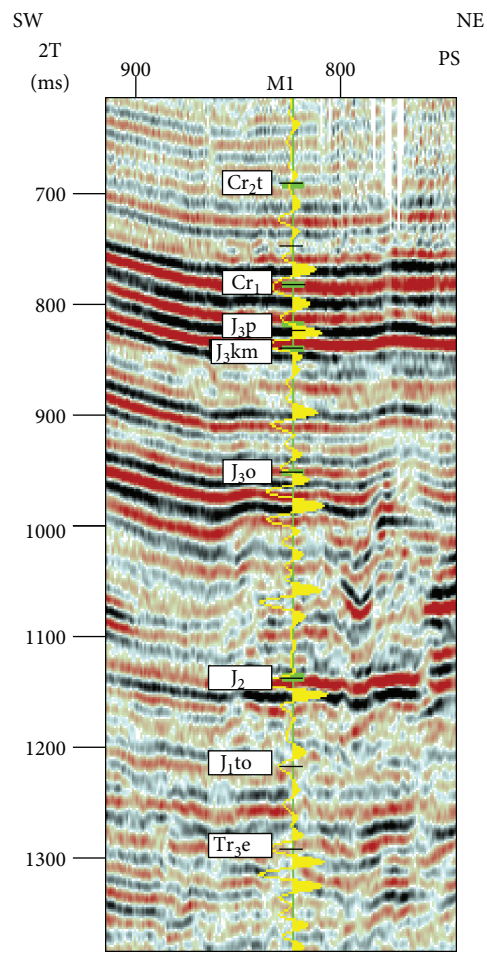

Figure 4: Correlation of synthetic seismogram (yellow trace) for M1 well with the true seismic section (red and black colour—negative and positive true seismic reflections, respectively) in the Lower Cretaceous and Lower Jurassic geothermal reservoir intervals (orange part of line in Figure 3). Explanations of seismic horizons: Cr_2t: top of the Turonian; Cr_1: top of the Lower Cretaceous; J_3p: top of the Portlandian; J_3km: top of the Kimmeridgian; J_3o: top of the Oxfordian; J_2: top of the Middle Jurassic; J_1to: top of the Lower Jurassic (Toarcian); T_3re: top of the Triassic (Rhaetian).

reflections in the synthetic seismogram. Hence, their correlation is not problematic.

The top surface of the Zechstein sequence is represented by weak reflection of negative amplitude located at the boundary of the Lower Triassic strata and the Youngest Halite (Na4) of the PZ4/Aller cyclothem. This reflection is poorly marked in the seismic record from the vicinity of the M1 well but is better visible towards the southwest, in the zone of the F2 and Z1 wells. The bottom surface of the Zechstein (top of the Upper Rotliegend: P_1) is marked by negative reflection.

1.5. Time-Depth Conversion of Seismic Data. The key problem of seismic data conversion from time to depth domain is the recognition and preparation of a model of propagation velocity of seismic waves in the geological medium. Errors in velocity estimations provide the erroneous estimations of

depth to particular layers, which, in turn, affect the planning and the execution of drilling operations for the purposes of geothermal installations.

In the case of 2D seismic datasets, common problem is the discrepancy of depths to particular reflectors at the section crossings if the models are generated separately for specific seismic sections. This problem was solved by application of 3D variant of velocity model construction for a set of seismic profiles.

The insufficient number of well-log data precluded the elaboration of credible maps of average and interval seismic wave velocities from the checkshot data for the 3D model. Moreover, the statistical dependences of the changes of interval velocities with the depth could not be determined in particular lithostratigraphic units. Hence, the solution of the problem was sought using the velocities determined from the surface seismic surveys. At the stage of seismic data processing, these are the stacking velocity or the velocities determined from various seismic data inversions. Commonly used are two methods: the coherency inversion and the tomographic inversion [33]. Although less credible than the inversion methods, the conversion of stacking velocity to interval velocities using the Dix formula is popular [34]. Unfortunately, the seismic inversion methods give ambiguous results and must be finally calibrated with the well-log data.

In order to elaborate the model of seismic wave velocity distribution in the Mesozoic complex, both the coherency and the tomographic inversions were performed for a representative grid of seismic profiles. The anomalies were eliminated at the sites of inferior seismic data quality, and the inversion solutions at the margins of the sections were rejected. At the next processing step, the velocity values were interpolated for a defined grid of seismic profiles within the 3D structural framework based upon the interpretation of the marker seismic reflections. After the 3D interpolation, the smoothing of velocity distribution was applied. The smoothing parameters were especially selected in order to minimize the averaging degree and to eliminate the generation of fictitious seismic anomalies at the profile crossings. Additional advantage of application of the averaging filter was the generation of a field characterized by smooth lateral diversity of seismic velocities, which enabled us to avoid the distortion of seismic horizons after depth conversion resulted from excessive velocity contrast, unjustified by geological conditions.

The observed fitting errors of seismic reflections after depth conversion to stratigraphic boundaries in the wells confirm the well-known opinion that the seismic velocities determined with both the tomographic and the coherency inversion methods are overestimated in relation to well-log data. Larger differences (but not exceeding 6–7%) were obtained for velocities determined with the coherency inversion than with the tomographic one. Hence, the final velocity model was based upon the results of tomographic inversion supported by calibration procedure adjusting the obtained values to the well-log data [35]. After correction, the velocity model retained the trend of changes of inversion-based velocities but was also concordant with the well-log data at the well site. Considering the domination of clastic rocks in the Mesozoic complex, the velocities gradually increase towards the northeast with the increasing burial depth of strata. In the northeastern part of the research area, velocities decrease, which is caused by elevation of the Zechstein top surface driven by uplifting of a salt pillow.

In the Zechstein complex, the tomographic inversion solutions appeared to be too much generalized due to low vertical resolution of the method, and, thus, they did not reveal the local velocity changes referred to the zones of increased thickness of high-velocity PZ1 (Werra) anhydrites. Therefore, the construction of velocity distribution was based on the two-layer model, in which the Zechstein complex was arbitrarily divided on seismic time sections into the upper layer where Zechstein rock-salt prevails intercalated by constantly thin anhydrite beds and the lower layer dominated by anhydrites. Basing on such distribution of thickness of the Zechstein layers in time domain, the interval velocity map was calculated assuming the constant velocity values derived from well-logs: for the upper, salt-dominated layer, 4.42 m/s, and for the lower, anhydrite-dominated one, 5.81 m/s.

The time-depth conversion of seismic time sections was performed by their simple multiplication by the values of average velocities. The results of structural interpretation of seismic depth section located close to the wells are presented in Figure 5. As the one result of seismic interpretation, thickness map was created. Thickness map of J_2-T_3k depth interval in the research area is shown in Figure 6.

2. Discussion

Application of geophysical methods in hydrogeothermal practice can bring a number of benefits. The use of seismic methods is of particular importance for the good recognition of local structures and therefore limits the errors of geothermal water deposits assessment. The results of seismic interpretation allow specifying reservoir parameters such as, e.g., depth to the top surface of the reservoir, its thickness, and porosity. Furthermore, precise determination of reservoir geometry improves the results of estimating the temperature of water within reservoirs. An important element of such interpretation is also the ability to indicate deeply rooted faults, which are, in some cases, the migration ways for geothermal water. Moreover, seismic data may support the selection of areas optimal for future investments in geothermal installations.

In the central part of Poland, analysis of seismic depth sections enabled us to recognize the recharge zone of both the Lower Cretaceous and Lower Jurassic geothermal systems related to the tectonic graben and subcrops of the Upper Cretaceous, Lower Cretaceous, and Upper Jurassic rocks beneath the sub-Cenozoic surface in the southwestern part of the research area (Figure 5). The tectonic graben is framed by major listric faults and associated dislocations, which displace the Zechstein and the Triassic beds and cease in the Lower Jurassic strata. The seismic sections do not provide evidence for dislocations penetrating the Middle and Upper Jurassic and the Cretaceous deposits in the graben area and

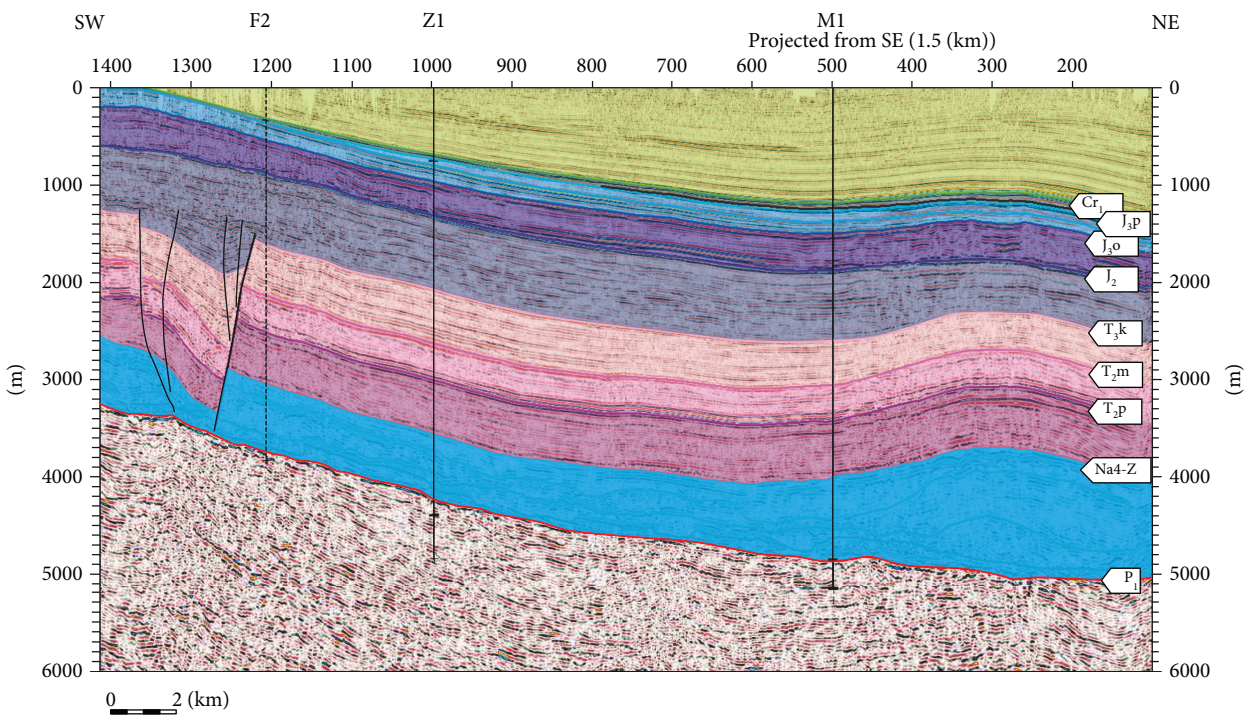

Figure 5: Results of structural interpretation of seismic depth section located close to the wells (red line in Figure 3). Explanations of seismic horizons: Cr_1: bottom surface of the Upper Cretaceous/top surface of the Lower Cretaceous; J_3p: bottom surface top of the Portlandian; J_3o: top surface of the Upper Jurassic (Oxfordian); J_2: top surface of the Middle Jurassic; T_3k: top surface of the Keuper; T_2m: top surface of the Muschelkalk; T_2p: top surface of the Middle Bunter Sandstone; Na4-Z: top surface of the Zechstein; P_1: bottom surface of the Zechstein/top surface of the Lower Permian.

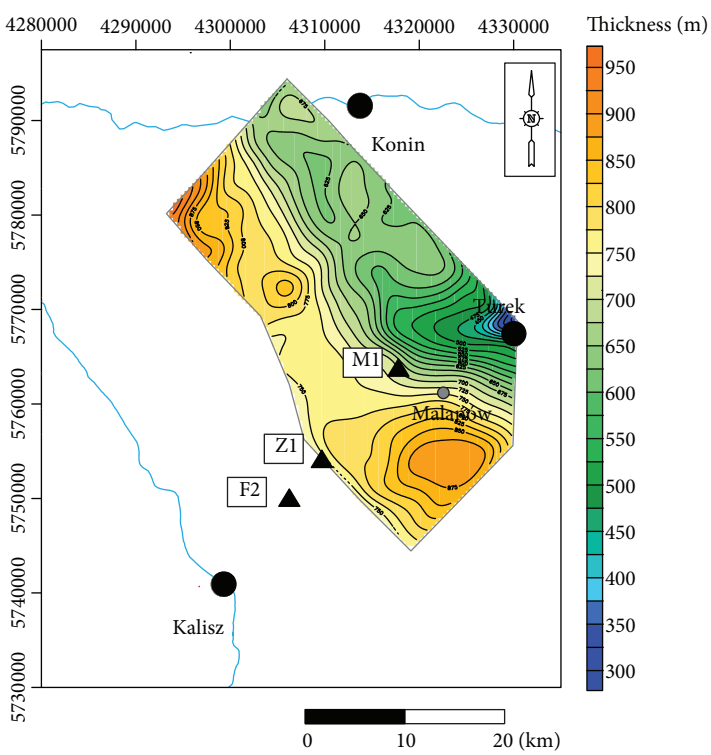

Figure 6: Thickness map of J_2-T_3k depth interval corresponding to cumulative thickness of Rhaetian, Lower Jurassic, and Middle Jurassic.

in its vicinity. However, it cannot be excluded that these dislocations propagate upward, even into the Cenozoic complex, as minor faults of throws below the seismic resolution. Unfortunately, deterioration of seismic data quality in the shallow part of the section precludes their recognition. The deeply rooted faults framing the graben, related to the extensional tectonic events, are presumably permeable and may provide migration pathways for brines ascending from deeper horizons and increasing the TDS in the overlying geothermal aquifers.

The seismic surveys allowed for recognition of the internal structure of the graben. The thickness of the Zechstein sequence is much reduced at the northeastern graben's margin and increases towards the southwest. Moreover, changes in thickness of the Lower Triassic are also evident, which may be the effect of tectonic reduction observed in many wells in Poland. They penetrate the main faults framing the Mesozoic tectonic grabens [36]. The increase of sediment thickness within the graben is observed for the Keuper and Lower Jurassic sequences. Outside the graben, in the area between the F2 and Z1 wells, the Portlandian sediments are absent and the Upper Kimmeridgian strata are covered by thin sequence of Lower Cretaceous sediments, in which thickness and depth increase gradually towards the northeast. Both the Kimmeridgian and the Oxfordian successions show more equal thicknesses but are useless for geothermal resource development due to poor reservoir properties.

In the northeastern part of the research area, the seismic sections disclosed a well-marked Zechstein salt pillow, so-called Turek pillow, and related suprasalt anticline, recorded in all interpreted seismic horizons (Figure 5) [37]. Outside the tectonic graben, the $T_{1+2}p$ and T_3p-T_2m complexes sandwiched between the Triassic marker reflectors do not show changes in thickness, which confirms the opinion that the salt diapirism did not begin before the end of Middle Muchelkalk deposition. In the culmination of the salt anticline, the thickness of T_3m-T_3k complex is reduced in relation to its northwestern limb. Hence, the initial salt movements must have commenced as early as in the Keuper, which means that they were coeval with the tectonic episode initiating the formation of the Mesozoic graben in the southwestern part of the research area.

The main stage of salt structure formation is recorded as diverse thickness of sedimentary successions sandwiched between the seismic horizons: T_3k (top of the Keuper) and J_2 (top of the Middle Jurassic) over the culmination of salt anticline and its southwestern limb (Figure 5). Taking into account the regional reduction of thickness of the Middle Jurassic succession to 150 m, the thickness diversity of the whole complex refers to the Rhaetian and Lower Jurassic sequences that determine the age of salt diapirism.

The map shows clear changes of thickness of the J_2-T_3k interval, which contours the range of the salt structure (Figure 6). Over the culmination near Turek town, the thickness of that interval is lower than 400 m, but it doubles towards the south to about 875 m. In that area, both the thickness and depth of the Lower Jurassic geothermal aquifer are the greatest, resulting in maximum water temperature. Considering similar depositional conditions in the whole syncline enveloping the salt structure, it is suggested that the facies development and the reservoir parameters of the Lower Jurassic sediments can be as favorable as those recognized in the M1 well.

3. Conclusions

The seismic surveys are applicable to the studies of geothermal aquifers as their results may reduce the geological risk thanks to more detailed recognition of the aquifer geometry and to reduction of estimation errors of reservoir temperature. The paper presents the results of the research project, which run in the research area located in the central part of the Polish Lowlands (Łódź Trough). This region is a subject of interest of the investors due to high geothermal potential.

The results of seismic surveys enabled us to

(1) Recognize the geological setting of the research area including the identification of faults and salt structures

(2) Determine the depths and the thicknesses of geothermal reservoirs

(3) Identify the recharge zone of the most prospective, Lower Cretaceous and Lower Jurassic geothermal aquifers

The detailed conclusions of the study are as follows:

(1) The recharge zone is related to the tectonic graben and to the subcrops of the Upper Cretaceous, Lower Cretaceous, and Upper Jurassic strata beneath the sub-Cenozoic surface

(2) The presence of faults framing the tectonic graben may influence the parameters of geothermal waters in shallower reservoirs, particularly their TDS, because of mixing of the waters from various horizons

(3) On the contrary to the Lower Cretaceous aquifer, the estimation of reservoir parameters and thickness of sandstones in the Lower Jurassic geothermal aquifer, using the seismic methods, is difficult and requires the specialized studies of reservoir seismics; however, the analyses presented above allow us to suggest that in the research area, the most favorable parameters of the Lower Jurassic geothermal aquifer can be expected along the axis of the syncline (east of Malanów village), whereas for the Lower Cretaceous aquifer, such good parameters can be expected in the northeastern part of the research area, over the salt structure and further in the northeast direction

Data Availability

"All data created during this research is openly available from the doctoral thesis under the title: Analysis of the Carboniferous-Lower Permian Petroleum System in the Context of Stratigraphic and Structural Traps Exploration

in Rotliegend Deposits in the Śrem-Kalisz-Konin Zone (T. Maćkowski, 2008), http://winntbg.bg.agh.edu.pl/rozprawy2/10055/full10055.pdf."

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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