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Geophysical Surveys for Geothermal Investigation in Central Poland

Wiesław Bujakowski , Antoni Barbacki, Barbara Czerwińska, Leszek Pająk, Marcin Pussak, Michał Stefaniuk, Zygmunt Trześniowski

31-261 Kraków, Wybicki St. 7, Poland

buwi@min-pan.krakow.pl

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ABSTRACT

Geothermal research activities in central Poland have focused on the elaboration of exploration methodology and its application to medium and low enthalpy geothermal systems occurring in Cretaceous, Jurassic and Triassic sedimentary formations. Research works included two geophysical methods – seismic and magnetotelluric surveys carried out close to Łowicz city to create a detailed geostructural model that included its anisotropic fracture system. This was performed to highlight formations with high fracture permeability and presumable flow paths for geothermal media as high productivity zones.

1. INTRODUCTION

The aim of research activities at the Skierniewice test site was the elaboration of exploration methodology and its application to medium and low enthalpy geothermal systems occurring in Cretaceous, Jurassic and Triassic sedimentary formations. Research works included two geophysical methods – seismic and magnetotelluric surveys. These surveys were carried out close to the Kompina-2 well to create a detailed geostructural model that included the anisotropic fracture system of the area. This was performed to indicate formations with high fracture permeability and presumable flow paths for geothermal media as high productivity zones. The Kompina-2 well was selected due to the highest free outflow of brine with temperature exceeding 100°C from Early Triassic formations and its location close to an operating geothermal heat plant. The operators of this plant are very interested in exploiting this geothermal energy for electricity production. Presented work was performed within the frame of UE-6th-Framework Program entitled "*Integrated Geophysical Exploration Technologies for deep fractured geothermal systems*" (acronym I-GET).

2. SITE CHARACTERISATION

The Skierniewice site covers an area of about 100 km² and is located NE of the town of Łowicz in the Lodz Voivodeship of central Poland. Geologically, the area belongs to the Mesozoic basin within the precincts of the Grudziadz-Warsaw sub-basin (Pożaryski 1969), and it is considered to be a synclinorium located at the boundary between two big tectonic units: the Precambrian platform - Baltica and the Paleozoic platform - Caledonides & Variscian Belts. A cross sectional diagram of the Polish Lowlands is shown in Figure 1.

Formations that host Triassic, Jurassic and Cretaceous aquifers (Figure 2), are mainly of sedimentary origin, and sedimentation cycles had a major influence on water mineralization, temperature range, and other reservoir parameters (Hajto, 2007). High productivity aquifers (with outflow exceeding 100m³/h) are generally located in Lower Cretaceous, Jurassic, and Upper Triassic formations, whereas less productive but high-temperature aquifers are hosted in Lower and Middle Triassic formations (Górecki et al. 1995).

The most interesting results with respect to geothermal heat and power purposes were found for Triassic formations in the Kompina-2 well (Pussak, Bujakowski 2007). The free outflow of brine with TDS of 337 g/dm³ and a temperature of 107 °C was obtained at depths of 4110-4115 m. Water inflow with lower mineralization and temperature was also observed at lower depths. Well test results for Kompina-2 are shown in Figure 3, including a plot of temperature with depth.

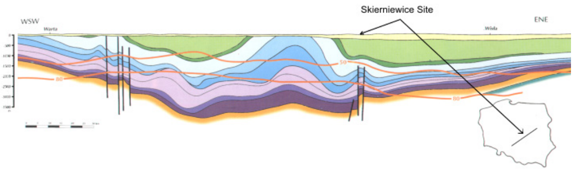

Figure 1: Geological cross-section through Polish Lowlands showing the structural position of main aquifers (Górecki et al. 1995).

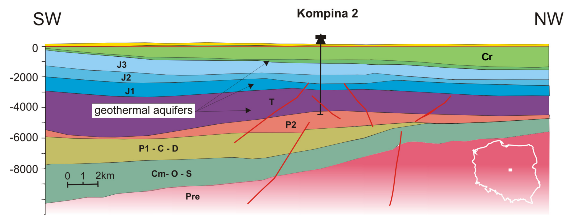

Figure 2: **Geological cross-section through Skierniewice - Łowicz - Sochaczew area (Dembowska, Marek, 1985)**.

Figure 4 presents the result of the calculations of the temperature of the brine at the wellhead depending on the flowrate and extraction time.

Different uses of the geothermal heat from the Kompina-2 well are possible depending on the flowrate, including the production of electricity with a binary system and a low temperature energy source (with temperatures up to 60°C) for compression heat pumps. In the case of the direct use of the geothermal water for heating (excluding heat pumps), it was assumed that the heat plant will operate with heating installation designed for 90/70°C (i.e. inlet/outlet temperature at the lowest outdoor temperature calculated), as is the standard in Poland. The expected outflow temperature for a 50 m^3/h flowrate is high enough to enable the use of the geothermal water for standard heating installations, excluding heat pumps. Electricity production using binary power stations requires the flowrate to be higher than 50 m^3/h.

3. 2D REPROCESSING OF 2D ARCHIVE SEISMICS LINES

Seismic surveys have been performed on a regional scale since the 1960s. Initially, they were performed with the use of analogue devices, but they were replaced in the 1970s by 12 folding multi channel digital seismic facilities, which made it possible to trace very strong reflection from the boundaries of Early Cretaceous and Jurassic formations and

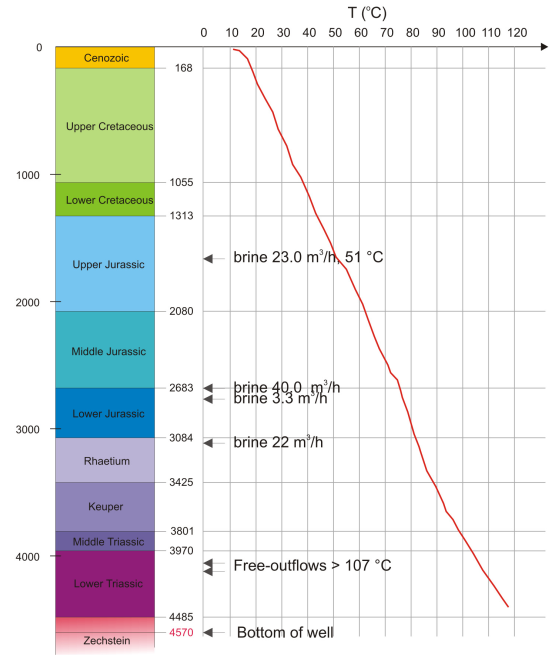

Figure 3: Temperature recorded at the Kompina-2 well and the well test data

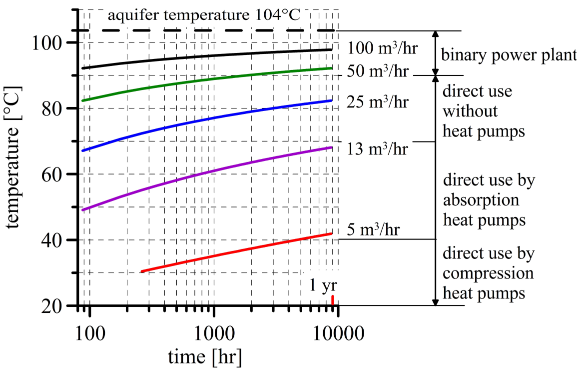

Figure 4: Wellhead temperature of the brine for the Kompina-2 well as a functions of time for different flowrates.

weaker reflection from the Triassic (mainly from dislocation zones and salt pillows in the Zechstein formations). Six 2D archive seismic lines with a total length of 208.40 km and VSP from 9 wells in the vicinity of the Kompina-2 well have been selected for reprocessing and reinterpretation.

This part of the research can be treated as a first approximation of geological structure, but it is only reliable along profiles due to long distances between seismic lines and a sparse grid. Nevertheless, the interpretation performed allowed the identification and correlation of 9 stratigraphic layers within the Lower Cretaceous, Jurassic, Triassic, and Permian formations and linked them to stratigraphic horizons in wells (e.g. the top of the Middle Buntsandstein shown in Figure 5).

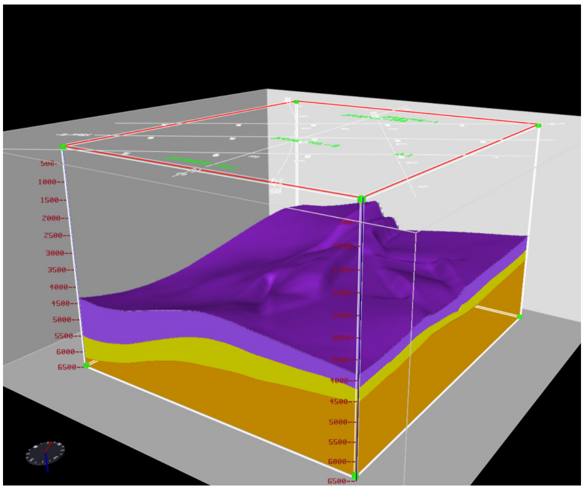

Figure 5: Spatial model of the Buntsandstein geological structure.

4. NEW SEISMICS MEASUREMENTS

Based on early experiences (Bujakowski et al., 2007), a new layout enabled the improvement of data in two ways – 1) 8 crossed 2D seismic lines in 1 km grid; and 2) 3D survey with 2.5 km² of homogeneous fold area in the center. Seismic surveys were performed along 8 lines that intersected mutually to form a grid, as shown in Figure 6.

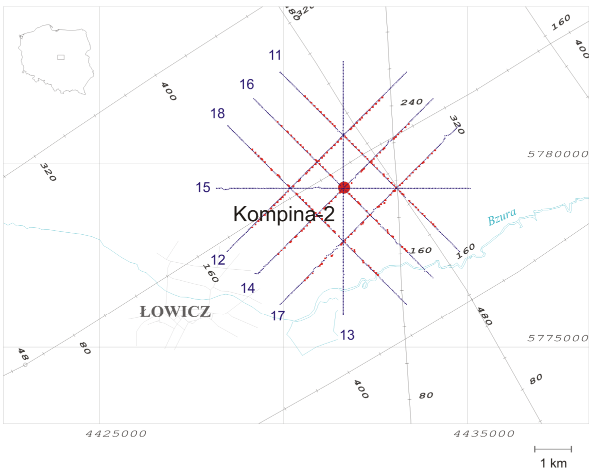

Figure 6: Location of seismic sources (red) and receivers (blue).

The processing of seismic data was performed using standard procedures similar to those used in hydrocarbon exploration with additional extensions for geothermal purposes. Processing was realized by the energy compensation of seismic signals and the achievement of real amplitude relations. Time migration tested the optimal selection of the velocity field, and the application of FK filtration (before migration) enabled the removal of the footprint effect. FXY deconvolution made it possible to attenuate interference waves after migration, which occurred on the area with reduced folding.

Finally, time sections, maps of average and interval velocity distributions for distinguished boundaries, migrated time and depth sections, structural maps and spatial models of boundaries (Figure 7), time slices, and seismic attributes (RMS amplitude, instantaneous phase, cosine instantaneous phase, and acoustic impedance) were created. The analysis performed confirms the complicated geological structure of the investigated geothermal site caused by vertical movements and salt tectonics.

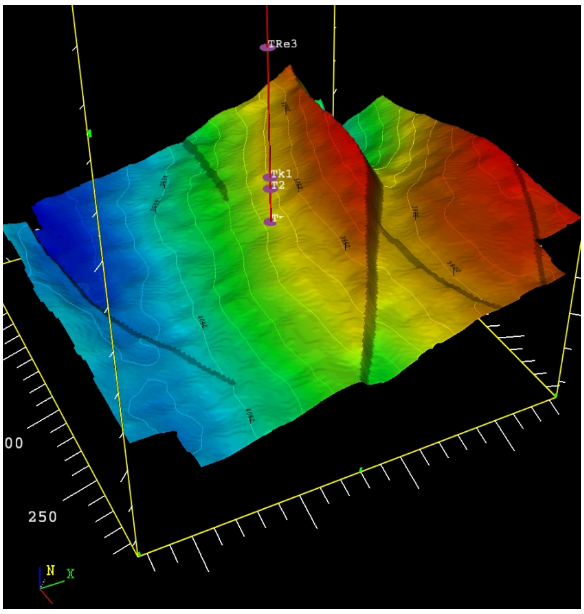

Figure 7: **Spatial view of the top seismic boundary of Buntsandstein in depth version (Kompina-2 well marked by red line, data: Geofizyka Krakow Ltd.) .**

4. MAGENTOTELLURIC SURVEY

The magnetotelluric survey was performed in two stages. During the first stage, continuous profiling was performed with the use of the MT-1 magnetotelluric system designed and produced by the Electromagnetic Instruments Inc. (EMI). The second stage included MT/AMT/CSAMT soundings performed along seismic profiles. At the second stage of the survey, data were acquired with the System 2000.net produced by Phoenix Geophysics Company Ltd. and based on the V8 receiver and TXU-30 transmitter. CSAMT measurements were made to control and supplement MT/AMT data, as the survey area appeared to be very noisy.

Standard magnetic remote referencing techniques were applied to reduce the influence of electromagnetic noise. Remote referencing sites were located at a distance of over 120 km (for the first stage) and over 300 km (for the second stage) from the survey area.

4.1 MT - data acquisition and processing

Standard remote reference processing of field data was performed with the use of the MTR15 computer program. The WinGLink system created by the Geosystem srl was applied to more advanced robust data processing. The results of data processing were amplitude and phase sounding curves, impedance polar diagrams, and skew that were input data for qualitative and quantitative geophysical interpretation.

At the second stage of the survey, data was acquired with the use of instruments produced by Phoenix Geophysics Company Ltd. MT/AMT measurements were made over a frequency range of 10,000 Hz to 0.001 Hz, and CSAMT measurements were made over a range of 10,000 Hz to 1 Hz. Five-component soundings performed with a V8 receiver were located along seismic lines spaced about 1000 m apart.

Robust processing of MT/AMT data was performed by means of two programs: SSMT 2000 and MT-Editor of Phoenix Geophysics Co. Ltd. The SSMT2000 program takes raw time series files, calibration files, and site parameter files as input. In the first step, it produces Fourier coefficients, which are then recalculated with data from reference sites using robust routines. The output is in the form of MT Plot files containing multiple cross-powers for each of the analyzed frequencies.

The MT editor program calculates and displays the resistivity and phase curves based on MT Plot files created using the SSMT2000 program. The program also displays the individual crosspowers that are used to calculate each point on the curves, so that noisy individual crosspowers are removed from calculations to increase data quality (Stefaniuk *et al*. 2008).

4.2 Geophysical and geological interpretation of MT-data

A qualitative and quantitative geophysical interpretation of magnetotelluric curves and parameters was performed. The qualitative interpretation consisted of creating and analyzing resistivity and phase pseudosections, polar diagrams, and sections and maps of the skew parameter, as shown in Figure 8. The main objective of the qualitative data analysis was the evaluation of general features of the geoelectrical medium. As a result, it can be concluded that the upper part of the medium can be approximated by a 1D model. The resistivity distribution at the deeper part of the environment is more complex and has 2D and even local 3D character. However, it should be considered that the influence of artificial electromagnetic noise may deform the pattern of MT parameter distribution.

The quantitative geophysical interpretation of sounding curves was based on 1D and 2D inversion procedures. A supplementary EMAP procedure was applied for continuous profiling analysis. 2D inversion was performed with the use of the NLCG method implemented in the WingLink program (Rodi & Mackie 2003). Results of this analysis of parametric sounding performed near the Kampina-2 well were interpreted. They were used to construct starting models and constraints for inversion procedures as well as to verify the obtained results, as shown in the plot in Figure 9. The controlled-source method supplied high-frequency data allowing for the reliable recognition of resistivity distribution in the shallow zone (Fig. 9A). As can be seen, the resistivity distribution in the shallow zone is very complicated.

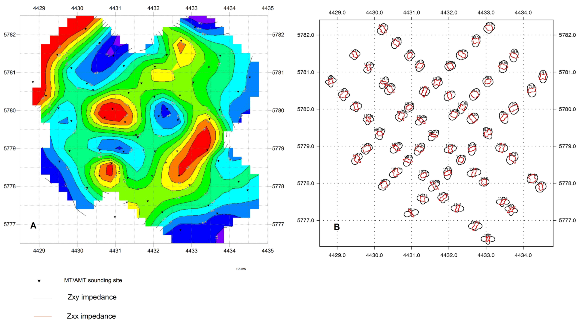

Figure 8: Map of skew (A) and polar diagrams (B) for a frequency of 0.107 Hz

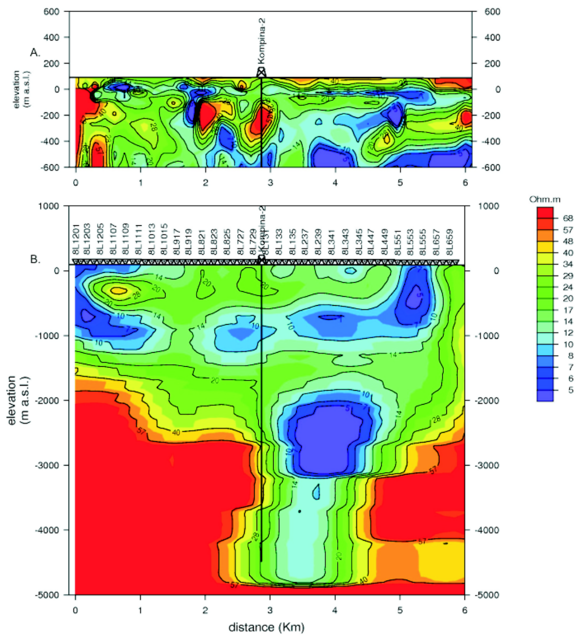

Figure 9: Results of 2D NLCG inversion performed, A – CSAMT, B – MT-1

A generalized model of resistivity distribution in the shallow zone was included in the starting model of 2D inversion of wide frequency range soundings. The results of the 2D inversion of MT/AMT data are shown in Figure 9B. A wide, low-resistivity zone is visible in the central part of the section that is probably related to the fractured area associated with a fault zone. That area is a possible candidate for the ascensive filtration of hot mineralized water from Triassic or Zechstein complexes up to Jurassic fractured and permeable hydraulic horizons.

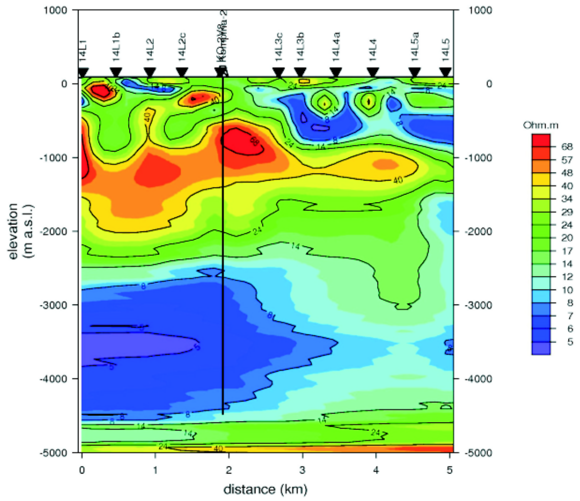

Figure 10: Results of 2D NLCG inversion (MT/AMT data)

Magnetotelluric soundings performed at the second stage of the survey were interpreted with the use of 1D and 2D inversion procedures. Resistivity cross-sections obtained with the use of the 2D NLCG inversion method were calculated for each of six lines that lined up with seismic profiles. An example of 2D NLCG inversion is presented in Figure 10. Results of the 1D and 2D MT sounding interpretation were used for 3D visualization. They are presented in Figure 11 as resistivity maps related to selected levels and structural maps of some resistivity boundaries. Based on 1D resistivity inversion, maps of resistivity variations calculated for two array orientations were constructed. Such variation represents the electrical anisotropy of the geological medium, which could reflect major structural axes and distinguish zones of intense fracturing.

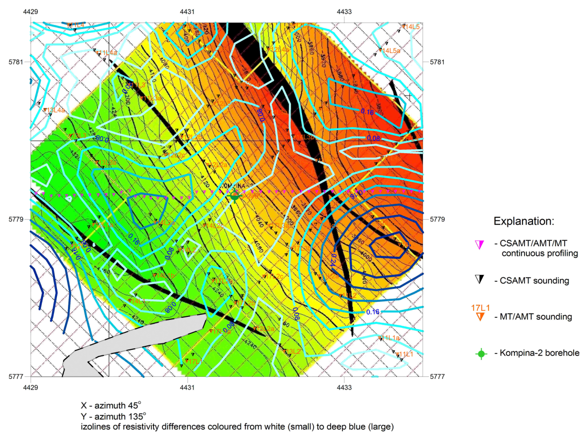

Figure 11: Map of resistivity distribution computed for XY and YX MT curves based on 1D Occam inversion of the background of structural map of Buntsandstein horizon acc. seismic data interpretation.

6. INTEGRATED INTERPRETATION OF SEISMIC AND MAGNETOTELLURIC DATA

Final geological, hydrogeological and geothermal interpretation was based on the integrated interpretation of seismic and magnetotelluric data. The integrated interpretation was supported by the analysis of borehole information, including well-logging data. The resolution of magnetotelluric methods is substantially smaller than that of seismic data, so that the structural model was interpreted based on seismic survey data. The resistivity distribution in the geological medium obtained as a result of magnetotelluric data interpretation better reflects lithological differentiation and is relatively sensitive to the presence of good porosity and fractures filtrated by hot, highly-mineralized water. Common analysis of structural maps based on the results of seismic data interpretation and maps of resistivity distribution could indicate the optimal area for geothermal borehole location.

Zones of relatively low resistivities in the central and southeastern parts of the area are probably connected to strong fracturing or high porosity formations, which could act as passageways for the filtration of geothermal water. The vertical boundaries of resistivity essentially correspond to faults interpreted from seismic data. Of great informative importance is the comparison of seismic structural maps to maps of resistivity variation computed with 1D Occam inversion for *xy* and *yx* array orientation and representing the distribution of geoelectric anisotropy in the area. Zones of maximum "anisotropy" represent probable areas of strong fracturing or/and porosity filtrated by hot mineral water. One such zone is located close to the Kompina-2 well. Another is located in the southeastern part of the study area and is probably connected to the complex fault system.

CONCLUSIONS

Much cheaper than standard 3D image realization, the methodology of the seismic survey employed in this project can be applied to other areas at a local scale, especially after some 2D surveys have been performed.

This survey can be treated as the beginning of the final stage of a reservoir scale investigation around the Kompina-2 well.

Complex analysis of the results of seismic and magnetotelluric surveys yields more detailed and reliable understanding of the lithology differentiation and the distribution of the petrophysical parameters of the geological medium (porosity, fracturing, water salinity, methods of water filtration, etc.). Compiling structural maps based on seismic data interpretation with resistivity distribution and electrical anisotropy data allows the differentiation of zones with good conditions for the location of geothermal boreholes.

The resolution and reliability of magnetotelluric continuous profiling results are substantially higher than those of a set of isolated soundings. Therefore, the application of a set of continuous profiling rather than a set of soundings in a regular but not sufficiently dense network is probably more effective for the detailed recognition of petrophysical features of a geological environment for the location of boreholes.

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