Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Application of geophysical methods for the recognition of geothermal reservoirs parameters in Poland

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Keywords: geophysical methods, geothermal parameters, seismics, magnetotellurics.

ABSTRACT

Geothermal energy in Poland is connected with low - temperature resources accumulated in four geothermal provinces: Polish Lowlands, Carpathians, Carpathians Foredeep and Sudetes Region. Each of these provinces is characterized by different geological conditions and various geothermal water parameters, the determination of which can be supported by geophysical methods widely applied to recognition of the geological structure of the Earth and to petroleum exploration. Seismic and magnetotelluric methods are most frequently used under Polish conditions predominant by low - temperature geothermal resources associated with sedimentary complexes and partly with crystalline rocks. The paper presents the examples of hydrogeothermal investigation supported by geophysical investigation in sedimentary complexes of Polish Lowlands and crystalline rocks of Sudetes area. The results of the research shows that geophysical methods can effectively support the selection of areas optimal for future geothermal investments. Simultaneously, such methods can be important for determination of hydrogeothermal parameters of particular aquifer.

1. INTRODUCTION

Poland is characterized by low-temperature geothermal resources which are typically used in direct-use applications, such as district heating, greenhouses, balneotheraphy etc. Geothermal resources are strictly geologically determined. Poland is situated at the interface between three main European geostructural units: the Precambrian East European Platform, the Paleozoic units of Central and Western Europe (Caledonian and Variscan) and the Carpathian range (part of the Alpine system). Each of these structures is characterized by distinct geothermal conditions. Sedimentary rocks cover almost whole territory of Poland, main exception is the area located in south-west of Poland (Sudetes Mts.) where mostly crystalline (igneous and metamorphic) rocks occur.

Geophysical methods are widely applied in geothermal issues. Low temperature geothermal associated mainly with sedimentary complexes and partly with crystalline rocks is predominant under Polish geological conditions. In this situation most frequently seismic and magnetotelluric methods are used. In the study of the structure and lithology of regular sedimentary complexes the most effective is the seismic reflection method. The results demonstrate that geophysical methods such as seismic structural interpretation and seismic inversion can effectively support the selection of areas optimal for future geothermal investments. Simultaneously, such methods can be important for determination of hydrogeothermal parameters of particular aquifer. Seismic inversion can be applied to porosity estimations. The application of non – seismic methods in recognition of sedimentary basins is rather supplementary. The magnetotelluric continuous profiling method was used for studying of near salt dome geological structure in the area of Polish Lowlands (Czerwiński and Stefaniuk 2003, Stefaniuk and Czerwiński 2005, Stefaniuk et al. 2008). The spatial study with use of magnetotelluric soundings as well as magnetotelluric continuous profiling were applied to support seismic survey in recognition of hydrogeothermal condition in Kompina area (Bujakowski et al. 2010). Within the crystalline rocks non–seismic methods are usually used, mainly different variants of magnetotelluric method. This method is based on analysis of resistivity differentiation of geological medium with use of broad frequency range of natural or artificial electromagnetic field. Geothermal reservoirs inside crystalline rocks are usually connected with fractured tectonic zones filtrated by hot and mineralized water. Such zones appear as low resistivity at the background of predominant, high resistivity igneous or metamorphosed rocks. Most of the fragmentary hydrogeothermal investigations carried out so far in the Polish part of the Sudetes were limited to zones of occurrence of thermal waters utilized for therapeutic purposes, or to a few areas in which prospection has been carried out for such waters (Dowgiałło 2002, Ciężkowski, 2011).

In this work application of geophysical methods for the recognition of geothermal reservoirs is presented. The examples of hydrogeothermal investigation in sedimentary complexes of Polish Lowlands and crystalline rocks of Sudetes area are used. Seismic structural interpretation and seismic inversion were applied for determination of hydrogeothermal parameters of Lower Cretaceous and Lower Jurassic aquifers located in the Mogilno-Łódź Trough, central part of the Polish Lowlands (Fig. 1).

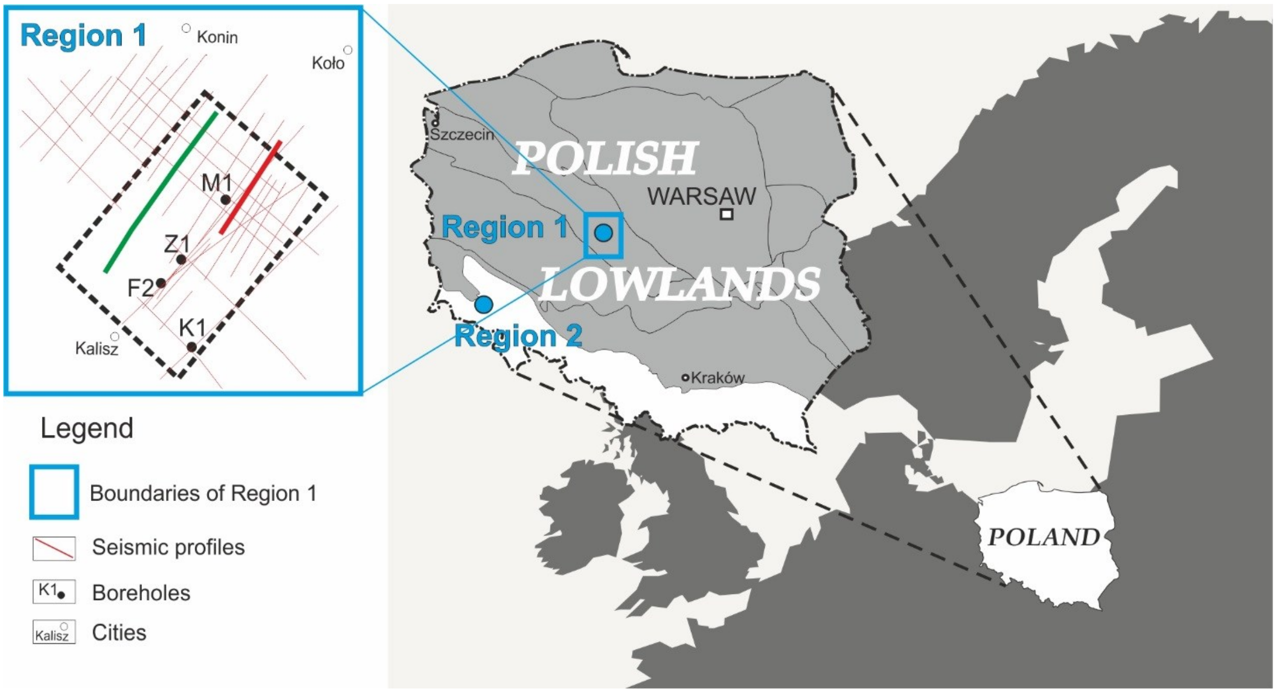

Figure 1: Location of geophysical survey for geothermal resources in Poland. Blue spots: 1 - example of seismic survey in Mogilno – Łódź trough; 2 - example of magnetotelluric survey in Cieplice - Zdrój area. Green seismic profile is presented in fig. 2, red seismic profile is presented in fig. 3.

2. MOGILNO-ŁÓDŹ TROUGH

The area of Mogilno-Łódź Trough, located in the central part of the Polish Lowland, is one of the most attractive areas in Poland in terms of geothermal resources. The so-far research works confirm the existing geothermal potential and possibilities of further effective management of geothermal waters in this region (see e.g. Górecki and Hajto (Eds.) et al. 2006a,b, Wójcicki, Sowiżdżał, Bujakowski (Eds.) et al. 2013; Bujakowski and Tomaszewska (Ed.) et al. 2014; Górecki et al. 2015, Sowiżdżał et al. 2017; Kępińska et al. 2017, Sowiżdżał 2018). In recent years, on the basis of regional exploration of hydrogeothermal properties in the area of Mogilno-Łódź Trough, several new places were pointed, which are characterized by favorable reservoir parameters for geothermal waters. All of them confirm excellent geothermal parameters of both Lower Cretaceous and Lower Jurassic intakes. The area of Mogilno-Łódź Trough was also the subject of the geothermal parameters evaluation from the results of seismic survey (Maćkowski et al. 2019, Sowiżdżał et al. 2019).

The area of Mogilno-Łódź Trough, in its geological evolution, initially constituted a part of Mid-Polish Trough. Mogilno-Łódź Trough is filled with Upper Cretaceous sediments resting on older rocks emerging on the sub-Cenozoic surface in south-western wing of the Middle-Poland Ridge and on Fore-Sudetic Monocline and on elevations Stupnicka, 1997, Mizerski 2011). The Permo-Mesozoic cover made up by the sediments filling Mogilno-Łódź Trough lies on older sediments: Rotliegend, Upper Carboniferous, Lower Carboniferous, Devonian, Silurian, Ordovician and Cambrian deposited on crystalline and volcanic rocks of Pre-Cambrian substrate. Variscan orogeny units (Varistcan externides) are poorly recognized on this area, due to a very large thickness of the Permo-Mesozoic cover (Karnkowski 1980, Narkiewicz and Dadlez 2008, Mizerski 2011). The archival seismic data recorded in the mid 1970-ties were used for recognition of geometry of the Lower Cretaceous and Lower Jurassic reservoirs, which are the most perspective hydrogeothermal aquifers in Central Poland.

The quality of seismic imaging is very good in the shallow part of the newest seismic sections in the interval of Cretaceous and Jurassic measures occurring (Fig. 2). The contacts of seismic reflections in the form of wedging could be seen that are connected among others with vanishing of Lower Cretaceous geothermal aquifer in the marginal part of study area. In the deeper part of the trough seismic reflecting boundary connected with the top this aquifer (Fig. 2) is clearly visible as a result of significant differentiation of acoustic impedances between carbonate sediments of Upper Cretaceous and porous sandstones of Lower Cretaceous. The good quality of seismic data in this interval allows to perform seismic inversion and evaluate variability of reservoir sandstones porosity.

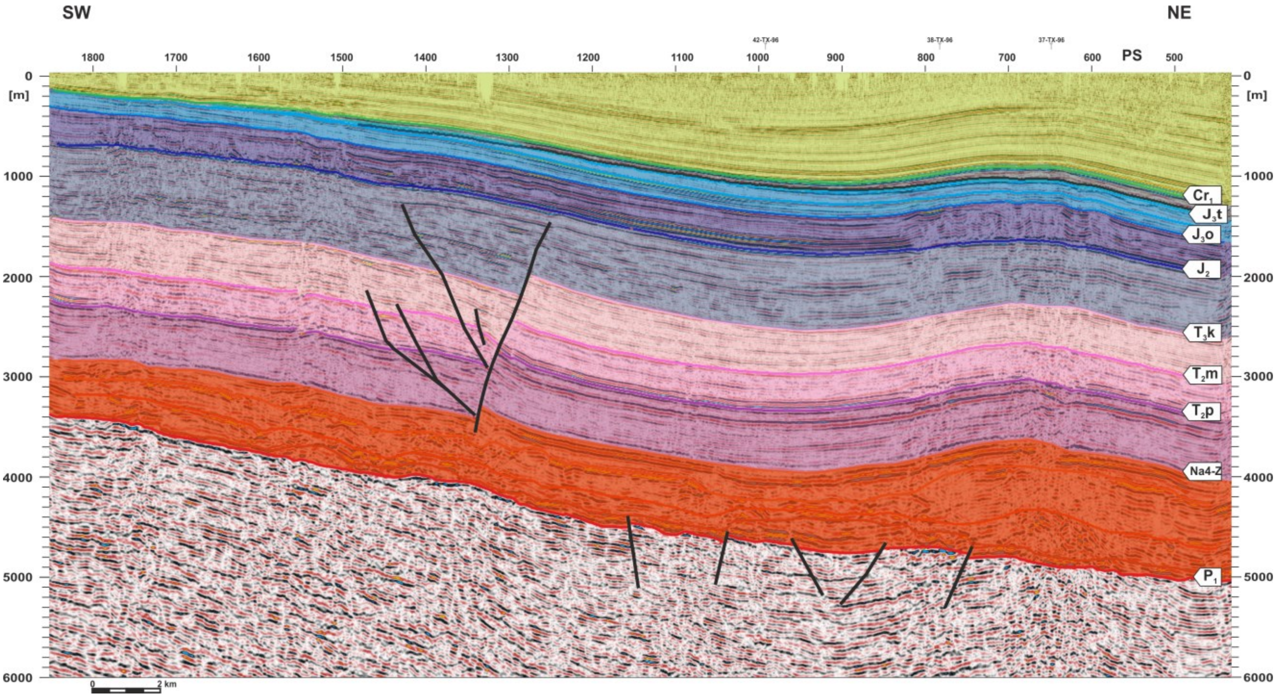

Figure 2: Results of structural interpretation of seismic depth section (green line in Fig. 1). Explanations of seismic horizons: Cr_1: top surface of the Lower Cretaceous, J_3t: top of the Tithonian (Upper Jurassic), J_3o: top of the Oxfordian, J_2: top of the Middle Jurassic, T_3k:top of the Keuper, T_2m: top of the Muschelkalk, T_2p: top of the Middle Bunter Sandstone, Na4-Z: top of the Zechstein, P_1:top of the Lower Permian.

The seismic signatures typical for carbonate reefs are clearly legible in the Upper Jurassic sediments (Fig. 2). The reefs are created on the local anticlinal elevations connected with salt pillows occurring deeper in the Zechstein measures. Evident vanishing of reflections inside reef forms is observed, only chaotically dispersed parts of reflections of small amplitudes is visible. The seismic reflections in Oxfordian sediments are continuous outside reef forms. Reef forms occurrence causes lateral differentiation of seismic wave velocity that influence destructively on seismic imaging of deeper part of seismic section (Fig. 2). The characteristic narrow zones of noise level increase and breaks in reflections continuity are observed on seismic sections below the reefs bottoms. This seismic artefacts suggest occurrence of tectonic dislocations in Triassic and Zechstein measures. The seismic boundary between carbonate measures of Upper Jurassic and clastic sediments of Middle Jurassic is clear in the area of Mogilno – Łódź Trough and appear as reflection of high negative amplitude. However, there is little indication in seismic image of deeper seismic reflection connected with the roof of Lower Jurassic geothermal aquifer, that is caused by relatively low contrast of acoustic impedance between clastic sediments of Middle and Lower Jurassic.
Strong seismic reflections of regional spread in the all area of Mogilno – Łódź Trough occur inside Triassic sediments and appear on important lithological boundaries. Stratigraphically this reflections are connected with roofs of Keuper, Mushelkalk and Middle Bundsandstein. In the seismic image of Zechstein the zone of clear increasing of thickness of evaporitic sediments creating form of salt pillow is observed between reflections Na4-Z and P_1, in the NE part of area (Fig. 2). The process of forming of this salt structure generated the local elevations of younger sediments among others, mentioned above geothermal aquifers of Lower Cretaceous and Lower Jurassic.

Another example of the use of seismic methods in geothermal exploration is reservoir porosity evaluation from seismic inversion. 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 (AI) in a broad spectrum of frequencies (Simm and Bacon 2014). For better stabilization, additional ties were applied in order 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 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:

$$PHI=-0.00352462*AI+49.28 \quad R = -0.91$$

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. 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 (Fig. 3).

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 1,200 ms 2T, i.e., 1,600 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.

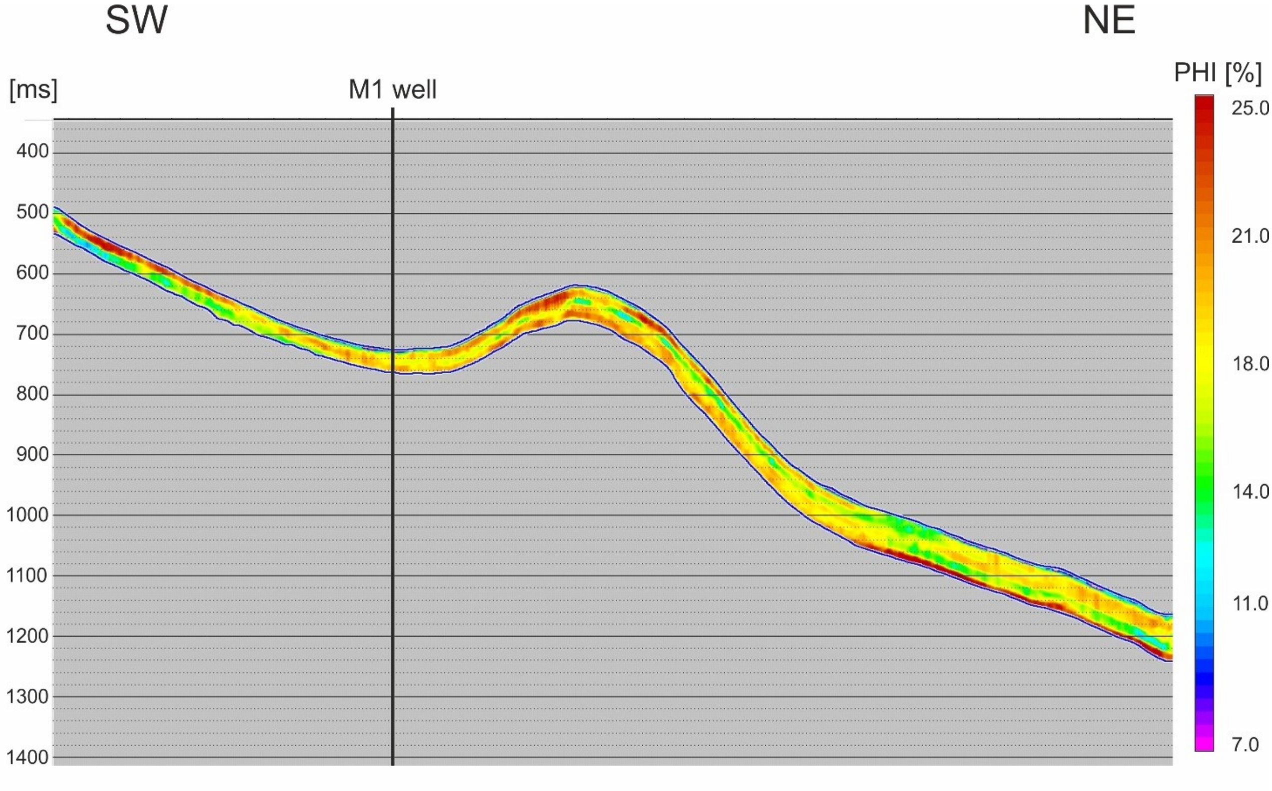

Figure 3: Porosity of Lower Cretaceous geothermal aquifer based on seismic inversion (red line in Fig. 1).

3. KARKONOSZE GRANITIC MASSIF AREA

The Sudetic region, including Sudetes and a Fore-Sudetic Block is characterized with diversified and often highly complex geological structure. At the same time, it is a very interesting area from the mineral point of view. Certainly, geothermal energy and mineral water resources are crucial from the economic and ecological point of view. A high degree of geological structure complexity is translated into difficulties in exploratory works or, more generally, in geological and geophysical deep prospecting studies. In particular, magma and metamorphic Sudetic orogen and crystalline substrate of its pre-frontier are a difficult area for the seismic method, being the main tool in structural studies of sedimentary complexes. In this situation, in exploratory works and in structural studies a new field opens to use other geophysical methods, and particularly electromagnetic methods, with the most comprehensive variant being the magnetotelluric method (MT -1… 1996, Stefaniuk et al. 2011).

The area of the Sudetes comprising south-western part of Poland is considered to be prospective for geothermal water connected with zones of deep tectonic breaks and granitic massifs (Fig. 4). Thermal water and mineral water reservoirs in the Polish Sudetes Mts. are connected with near fault fractured carriers in high resistivity igneous and metamorphic rocks. Thus, they manifest themselves as low-resistivity zones (Wojdyła et al. 2008, Stefaniuk et al. 2011). Magnetotelluric continuous profiling were used for location and recognition of fault zones filtrated by thermal and mineral waters in Sudetes area. The example of application of this method to the survey made in well-known area of thermal waters occurring inside the Granitic Karkonosze Complex close to the Cieplice-Zdrój town in Jelenia Góra Depression area (Fig. 4).

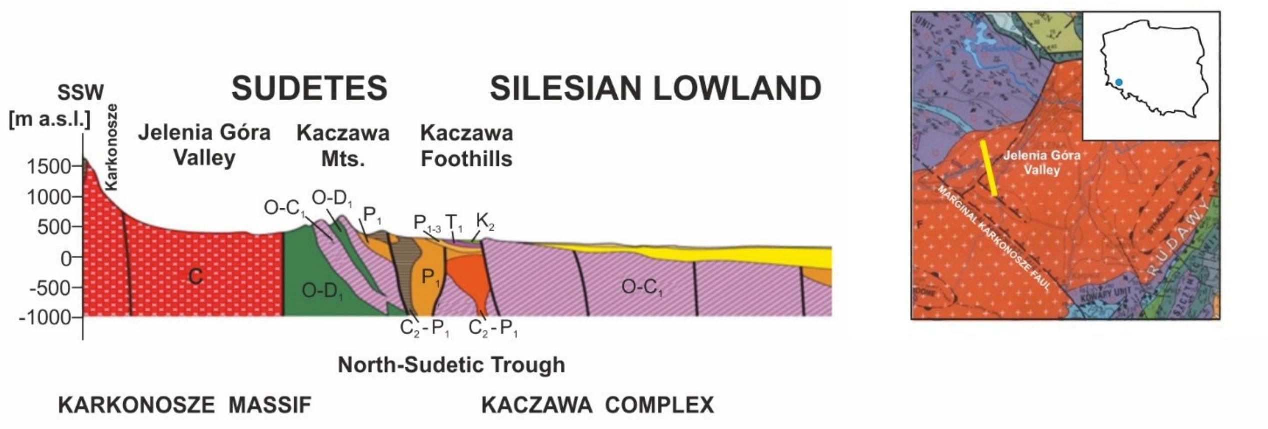

Figure 4: Location of magnetotelluric survey in Cieplice - Zdrój area of Sudetes Region (The cross-section: Marks et al. 2006) and map of location of MT/AMT continuous profile at the background part of tectonic map of the Sudetes (after Cymenman 2004, Stefaniuk 2018).

The presented profile is located inside outcrops of granitic massif and cuts the zone of crossing faults (Fig. 4). The ascension filtration of thermal waters in this area is connected with fractured fault zone. The structure of the zone marks of evident resistivity differentiation along the cross-sections computed with all of used algorithms of 1D inversion i.e. EMAP (Torres-Verdin and Bostick 1992, Bostick 1977) and Occam (Constable et al. 1987) as well as with 2D inversion with use of non-linear conjugate gradients (Rodi and Mackie 2001, Fig. 5 - 6). The presence of water in fractures inside fault zone causes remarkable decreasing of resistivity of geological medium. This effect is amplified by high water mineralization (salinity) and its higher temperature. As the result the resistivity is lowered up to range of 100 [Ωm] in tectonic zone, whereas normal resistivity of crystalline rocks used to reach several thousand [Ωm]. The roof of high – resistivity ingenuous rocks is covered by complex of relatively low – resistivity comparable with resistivity of tectonic zone. The thickness of this complex locally reaches 300 – 400 [m].

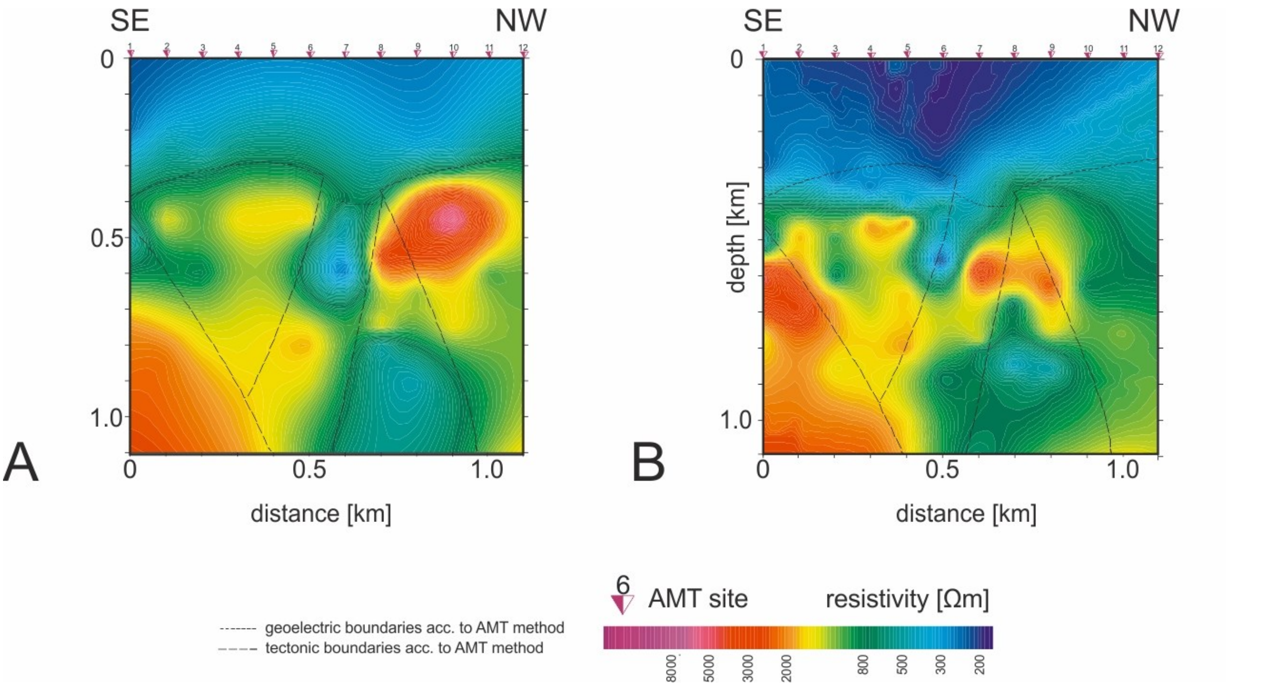

Figure 5: A - map of EMAP Inversion, B – map of Bostick 1D Inversion (after Torres-Verdin and Bostick 1992, Bostick 1977, Stefaniuk et al. 2017, Stefaniuk 2018).

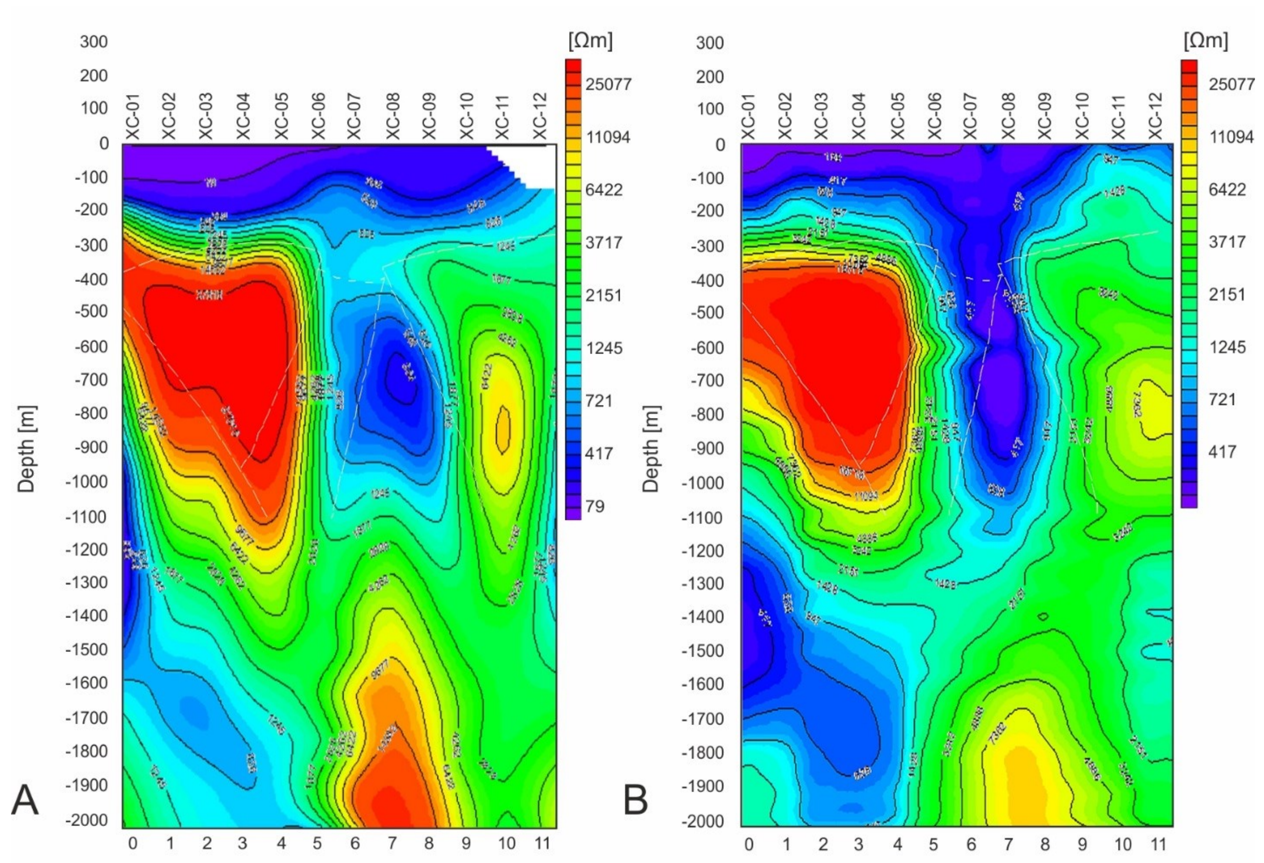

Figure 6: Results of magnetotelluric survey made in Cieplice – Zdrój area. A - map of Occam 1D Inversion, B – map of 2D NLCG Inversion (after Constable et al. 1987, Stefaniuk et al. 2017, Stefaniuk 2018).

4. CONCLUSION

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, these methods can be successfully used also in exploration and assessment of geothermal waters deposits, in order 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, clay content) with geophysical methods, including the seismics. The interpretation of seismic sections enabled us to determine the geometry of the aquifer and affects the better typing of the place for a new geothermal location.

Acknowledgements. The paper has been prepared under the AGH-UST statutory research grant No. 16.16.140.315.

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