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Recognizing Geothermal Horizons Inside Crystalline Rocks Using Geophysical Methods, Example of Lądek Zdrój Reservoir, Sudetes Area, Poland

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ABSTRACT

Hydrogeothermal reservoirs usually occur inside crystalline massifs in Sudetes area, the most frequently as fractured zones accompanying faults. Such conditions demand specific selection of geophysical methods and survey methodologies. Representative for the region is Lądek Zdrój area known since several hundred years as a place of occurrence and use of hot springs. The reservoir occurs there in specific geological conditions characteristic for Sudetes area. It is of fracture type and occurs in artesian conditions. Development of the Health Resort caused the need of better recognizing of hydrogeothermal reservoir and its geological vicinity. Geophysical surveys were made in the area for this aim. The magnetic, gravity and surface geothermic methods as well as VLF profiling, resistivity profiling and soundings and continuous magnetotelluric profiling were applied. As results of the survey tectonic zones were interpreted and temperature anomalies were discovered and, in limited range, space recognizing of fractured aquifer horizons was made.

1. INTRODUCTION

There could be distinguished in Polish conditions three areas of radically different geological characteristics that demand separate methodology of geophysical surveys. These are: Polish Lowlands, Flysch Carpathians and Region of Sudetes. The Sudetes region, including Sudetes and a Fore-Sudetic Block is characterized with diversified and often highly complex geological structure. A high degree of geological structure complexity is translated into difficulties in exploratory works or, more generally, in geological and geophysical deep prospecting studies (Bujakowski at al. 2010). In particular, magmatic and metamorphic Sudetes orogeny 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, such as gravity and magnetic methods and particularly electromagnetic methods, with the most comprehensive variant being the magnetotelluric method (Stefaniuk et al, 2011, Stefaniuk 2018). The area of Sudetes is highly interesting for the mineral prospection including geothermal energy and mineral water resources. Geophysical methods are commonly used in geothermal water reservoirs prospection as well as in recognition of its resources and conditions of occurrence. They are applied mainly as methods of entrance phase of prospection, however, they are more and more frequently used in recognizing of structure and retention conditions of hydrogeothermal reservoirs and deposit parameters.

Hydrogeothermal reservoirs usually occur inside crystalline massifs in Sudetes area, the most frequently as fractured zones accompanying faults. Such conditions demand specific selection of geophysical methods and survey methodologies. 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 was 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 and Lądek Zdrój area (Figure 1). 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. 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 (Stefaniuk et al 2017, Stefaniuk 2018). 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.

Representative for the region is Lądek Zdrój area known for several hundred years as a place of occurrence and use of hot springs. The reservoir occurs there in specific geological conditions characteristic for Sudetes area. It is of fracture type and occurs in artesian conditions. Development of the Health Resort caused the need of better recognizing of hydrogeothermal reservoir and its geological vicinity. Geophysical surveys for recognition of general geological conditions of the reservoir and its vicinity were made in the area. The magnetic, gravity and surface geothermic methods as well as VLF profiling, resistivity profiling and soundings and continuous magnetotelluric profiling were applied. The review of earlier geophysical surveys and reinterpretation of magnetotelluric and gravity data are the subject of the paper. The reinterpretation works included review of data acquisition, verification of procedures and results of data processing and interpretation as well as extended interpretation of magnetotelluric sounding curves with use of 2D inversion. As results of the survey tectonic zones were interpreted and temperature anomalies were discovered and, in limited range, space recognizing of fractured aquifer horizons was made.

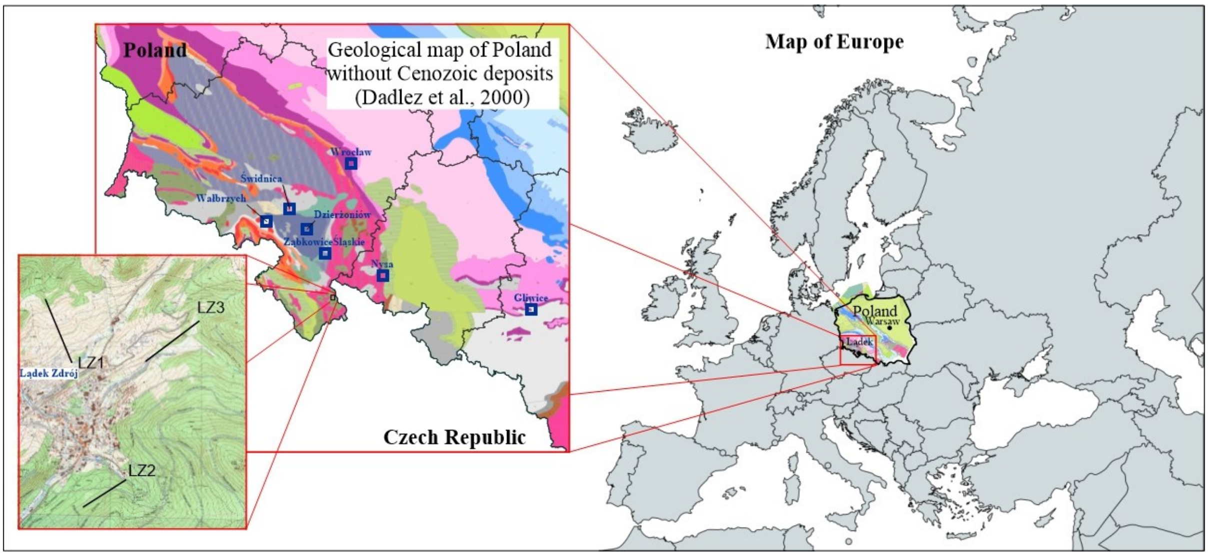

Figure 1: Location of geoelectric surveys made in Sudetes area at the background of Geological map of Poland (Stefaniuk et al 2011, modified, Geological map: acc. Dadlez et al 2000).

2. REVIEW OF GEOPHYSICAL SURVEYS CARRIED OUT IN THE AREA OF LĄDEK ZDRÓJ.

The first systematic magnetic ΔT tests of a semi-detailed and partly detailed character were made at the end of the sixties of the last century (Jagodzińska et al., 1969). They were supplemented and reprocessed in 2005-2007 as part of a semi-detailed magnetic study of the Sudetes area (Kosobudzka, Wrzeszcz 2007, Figure 2). The results of magnetic tests were used to recognize the tectonics of the area. They confirmed the occurrence and course of previously known faults and suggested the existence of dislocations previously unknown.

The first regular gravity surveys carried out in the Sudetes region of a regional or semi-detailed character were made in 1966 (Okulus 1968). They were supplemented in 1971 and 1973 (Cieśla, Margul 1972, Okulus et al., 1974). A small concentration of measurement work does not allow the use of these data for detailed deposit analyzes. In the general sense, the convergence of the distribution of gravity field anomalies with maps of outcrops of geological units, differing in lithological development, and thus in rock densities, is noticeable (Figure 3). More clearly, the above dependence is visible on the map of residual anomalies related to the level 0 - 1 km p.p.t. (Figure 4).

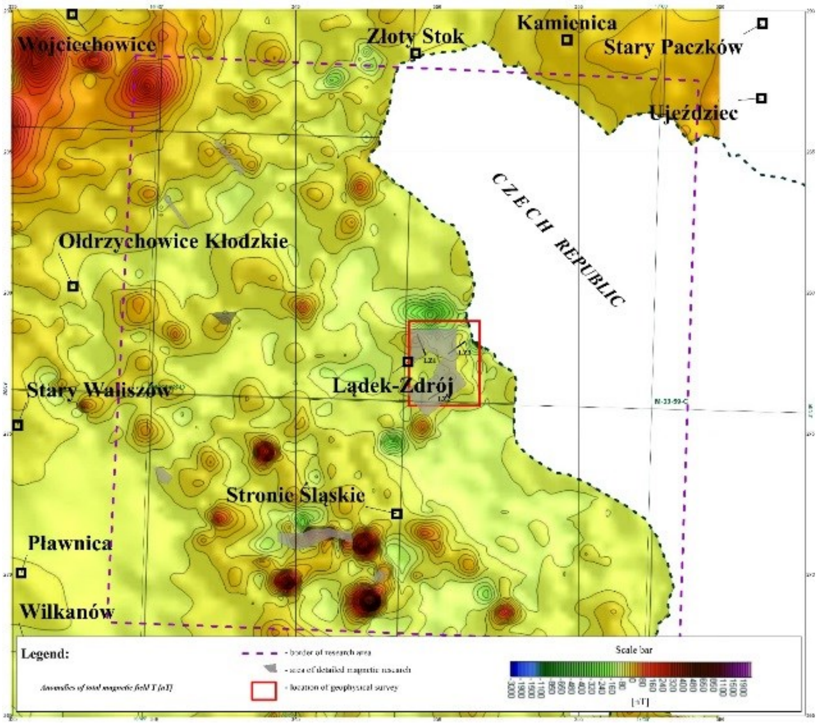

Figure 2: Map of anomalies of the total magnetic field T, Lądek Zdrój area, (based on data according: Kosobudzka, Wrzeszcz 2007)

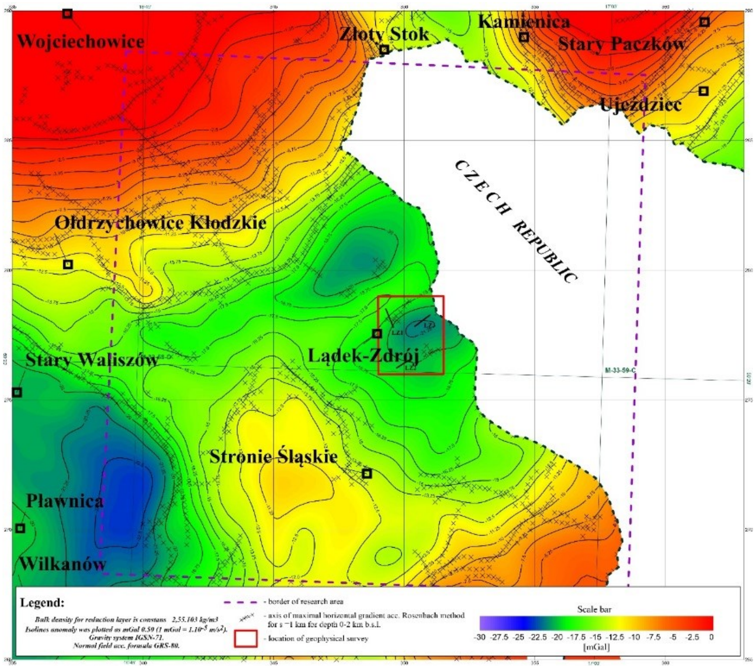

Figure 3: The map of anomalies of gravity force field in Bouguer' reduction, Lądek Zdrój area (based on data contained by survey reports).

The subjects of special attention in this work are geoelectric studies carried out in the region of Lądek-Zdrój. The first such tests with use of resistivity soundings made along measurement profiles (SGE), complementing the semi-detailed magnetic tests, were made at the end of the 1960s to identify tectonic elements (Jagodzińska et al., 1969; Fistek et al., 1975). Another series of resistivity soundings supplemented with VLF (Very Low Frequency) electromagnetic profiling was made in 2005 after about 30 years (Farbisz 2005)

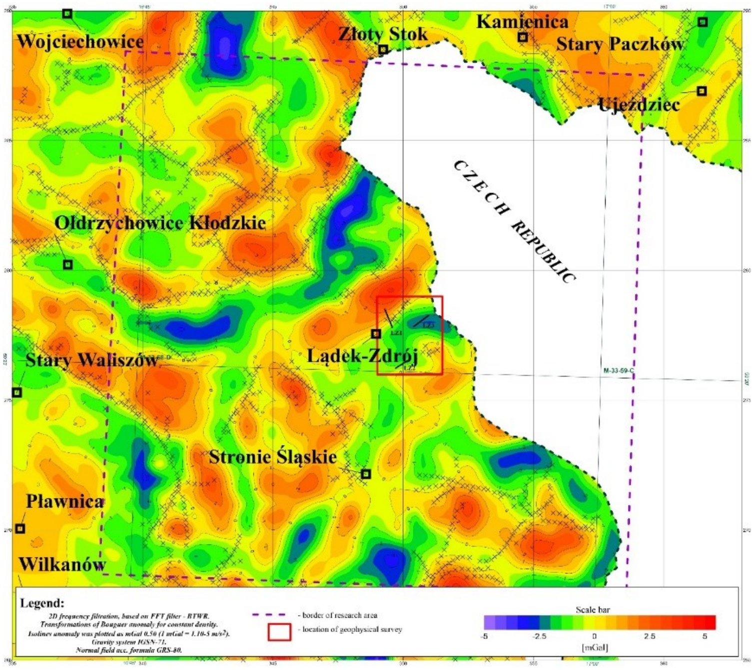

Figure 4: The map of residual gravity anomalies, Lądek Zdrój area, related to the depth range 0 – 1 km p.p.t. (Figure 5). The complementation and continuation of earlier geoelectrical works were research using the magnetotelluric continuous profiling method, made in 2008 (Farbisz, Wojdyła 2008).

VLF profiling was used to verify the course and determine the nature of tectonic zones considered as potential routes for geothermal waters. On the basis of these works, the courses were verified and the character of the main faults presented on the tectonic sketches from this region was determined (Gierwielaniec 1968). It was found that all examined faults with NW - SE directions were confirmed in the measurement results by registering anomalous values (Farbisz 2005). In addition, an anomaly which can be associated with a fault previously unknown was also measured. From the point of view of searching for thermal waters, the faults of Lądek - Gierałtów and Rasztowiec - Karpna (Lądek-Bielice, according to Cymerman 2004) were considered as the most promising.

Research with use of resistivity sounding method (VES) was used to identify perspective fault zones up to a depth of 250-300 m ppt. Conducting research using the magnetotelluric continuous profiling (CMTP, Continuous Magnetotelluric Profiling, Figure 7) method in 2008 was a complement to earlier geoelectrical works on geophysical research with a greater depth range (up to a depth of 2-3 km) (Farbisz, Wojdyła 2008). The profiling was carried out along three profiles with a total length of 1.9 km located transversely to selected parts of tectonic zones, in places with good measurement conditions.

Measuring profiles were marked in sequence: LZ1 with a length of 0.7 km - in the fault zone (faults) Rasztowiec - Karpno, LZ2 with a length of 0.5 km - in the fault zone (faults) Lądek - Gierałłów and LZ3 with a length of 0.7 km - in the fault zone (overthrust) of Lądek Zdrój (Figure 5, 6). The magnetotelluric data acquisition was made using the 2000.net system of Canadian Phoenix Geophysics Company, in a high frequency range of variation called the Audiofrequency Magnetotelluric Method (AMT, Goldstein, Strangway 1975, Stefaniuk et al., 2011, 2008). In order to eliminate the influence of electromagnetic interference, measurements were made as two-point with the so-called remote reference point on which electric and magnetic fields components were recorded (Figure 7, Gamble et al., 1979). Synchronous recording at the field and reference points provided input data for processing. The results of the research were presented in the form of pseudo 2D depth cross-sections of resistivity developed on the basis of 1D inversion according to the Occam algorithm (Constable et al., 1987). Resistivity contrasts in the geological conditions of the Lądek Zdrój region were related to the lithological diversity of the rock series, high-resistance gneisses and lower resistance metamorphic shales and to tectonic phenomena. A typical symptom of tectonic phenomena is lowering the value of electrical resistivity associated with cracking and weathering of rocks, groundwater circulation (including geothermal) and often occurrence of ore mineralization (Stefaniuk et al. 2011, 2017, Stefaniuk 2018). Sections with intense fracturing of fault zones associated with anomalous lower resistance values with a high probability of occurrence of geothermal waters, especially at bigger depths have been exposed. The results of these tests were used to determine two deep drilling locations for the purposes of geothermal water intake (Farbisz, Wojdyła 2008, and Ciężkowski et al 2016).

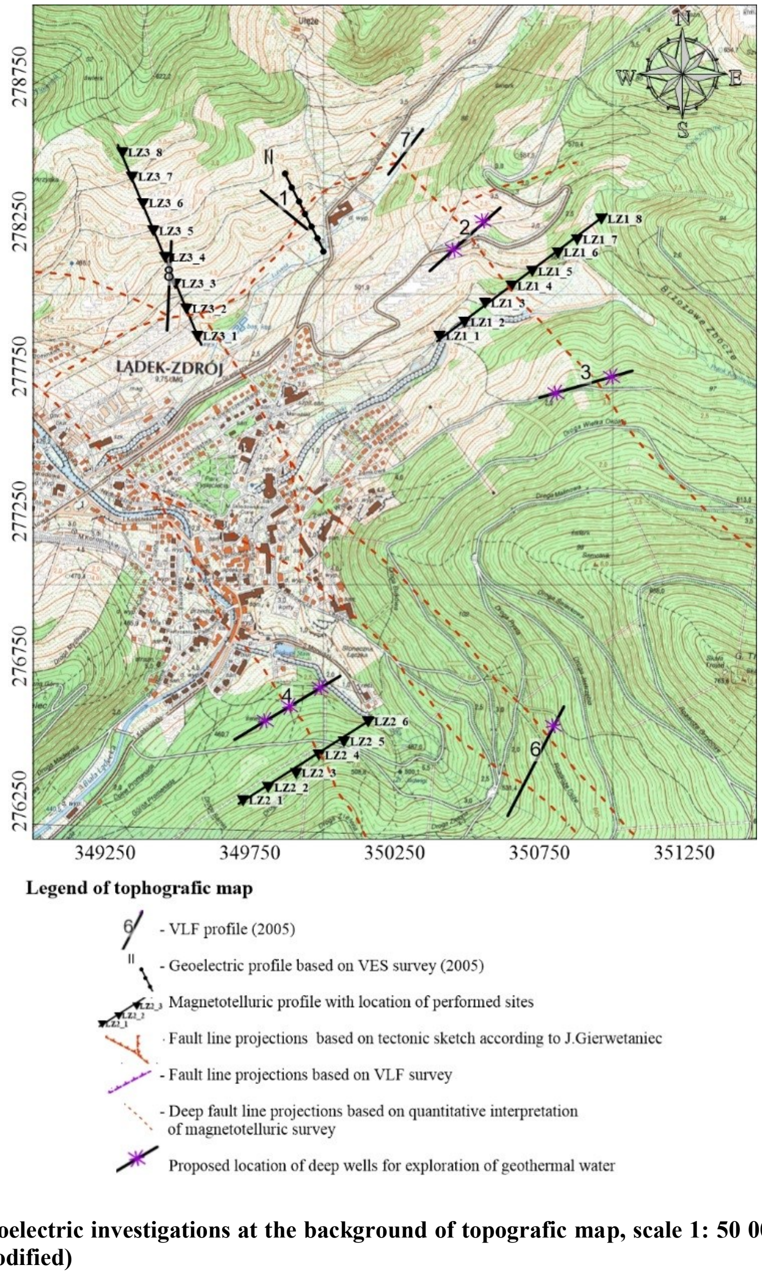

Figure 5: Location of geoelectric investigations at the background of topografic map, scale 1: 50 000 (according to Farbisz, Wojdyła 2008, modified)

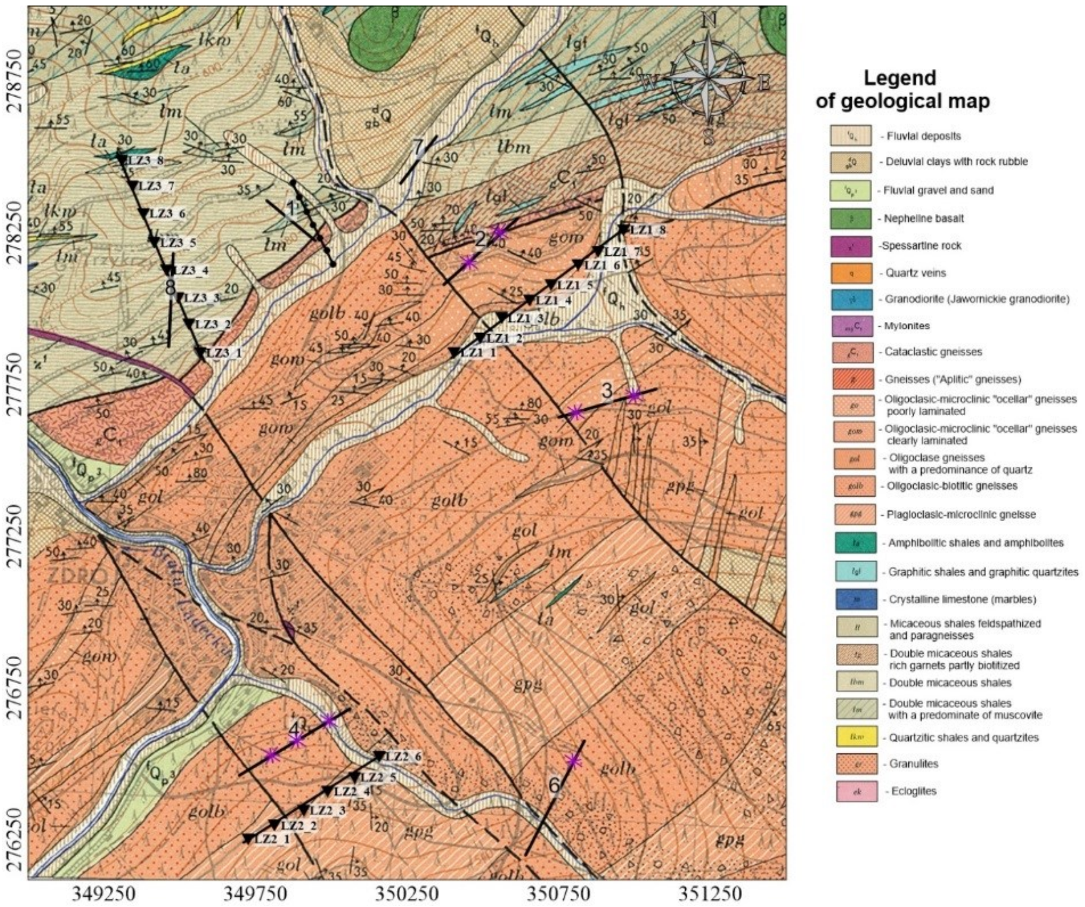

Figure 6: Location of magnetotelluric profiles in the Lądek Zdrój area at the background of Geological Map of Poland, scale 1: 25 000, Lądek Zdrój Sheet).

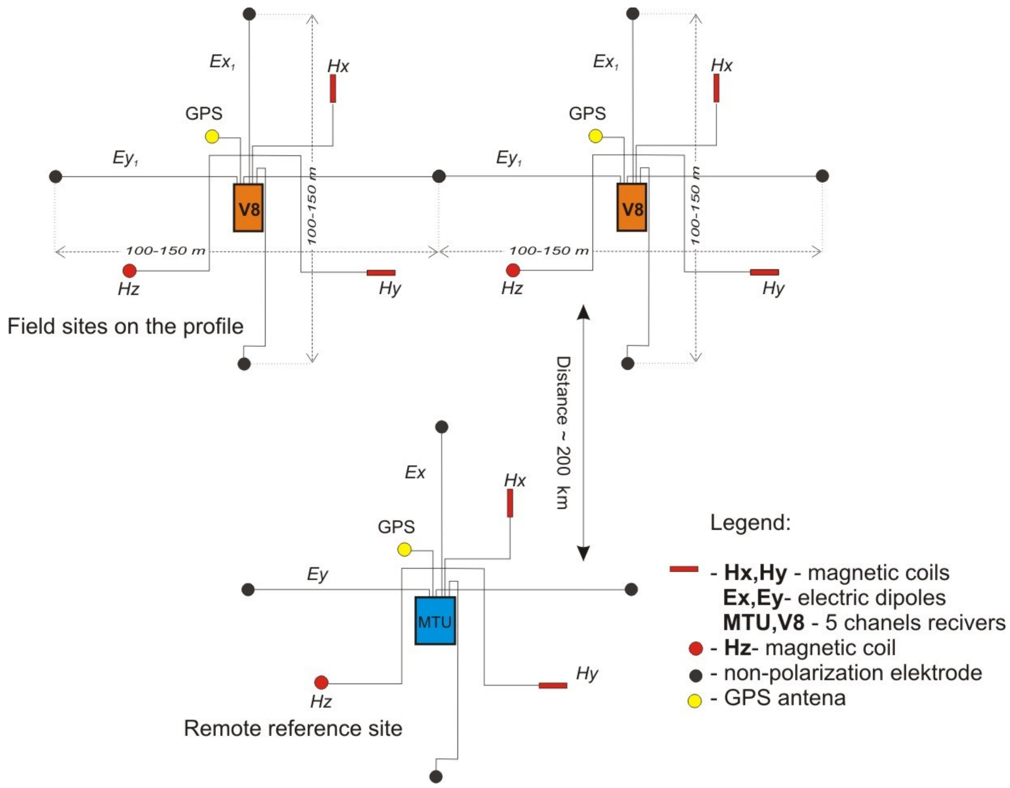

Figure 7: The outline of AMT/MT measurement array, continuous profiling version.

3. REINTERPRETATION OF MAGNETOTELLURIC STUDIES.

The reinterpretation work included a review of measurement work, verification of procedures and results of measurement data processing. The new interpretation of sounding curves has been verified and expanded. The previous one-dimensional inversion of selectively taken sounding curves in terms of the orientation of the measurement system has been extended by analyzing the dependence of the results of 1D inversion of magnetotelluric data on the orientation of the measurement system with respect to the strike of geological structures. A multivariant two-dimensional inversion modeling was also made.

The recorded time courses were subject to numerical processing. Both in the case of primary processing (in 2008) and reprocessing, robust reference procedures implemented in the SSMT2000 software from Phoenix Geophysics Ltd. were used. The result of the data processing is the estimation of the impedance tensor components that were used to calculate the sounding curves (amplitude and phase) and also determination of directional diagrams of impedance and skew parameters of the impedance tensor (Simpson, Bahr 2005, Sims et al. 1971). Figure 8 shows examples of magnetotelluric curves from different profiles and for different orientations of the measurement system. From the geoelectric point of view, the geological medium is two- and three-dimensional. This conclusion is confirmed by the layout of directional impedance diagrams visible in the lower parts of the drawings. The sounding curves and impedance polar diagrams have been the subject of reinterpretation using the interpretation procedures included in Geosystem srl's WinGLink software.

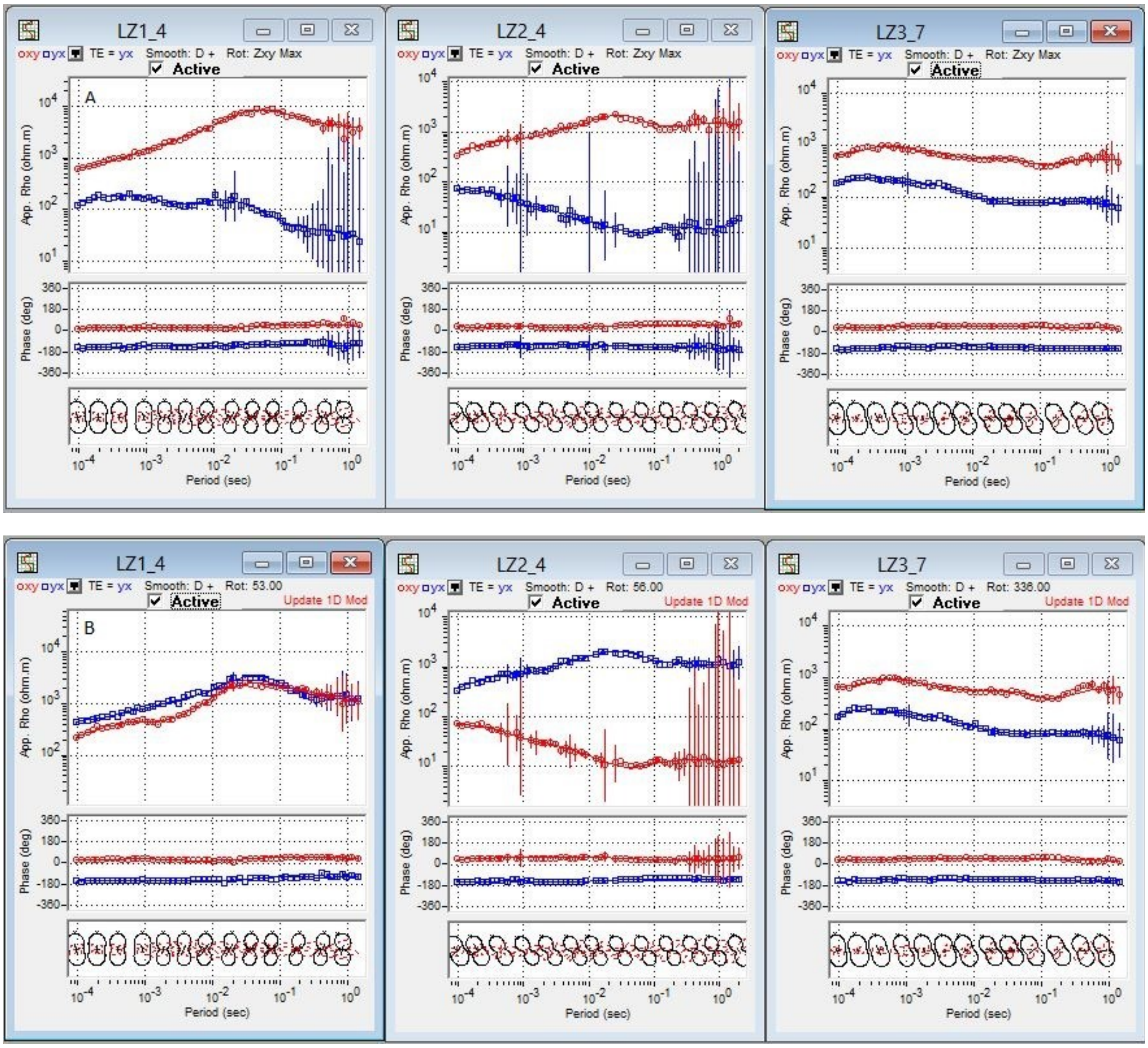

Figure 8: The examples of magnetotelluric sounding curves: A- for measurement array axes rotation to direction of Zxy Max (local strike), B- for array orientation during recording.

3.1 QUANTITATIVE ONE-DIMENSIONAL INTERPRETATION OF SOUNDINGS

The interpretation of 1D was made using the inversion algorithm Occam (Constable et al. 1987). The basic assumption of this method is to strive for the smoothest solution. As a result, the distribution of resistivity in a geological medium is generalized and devoid of clear contrasts. The unquestionable advantage of the method is its full automation. Interpreter intervention boils down to the preparation of data, the introduction of number of layers and the determination of the interval of depth interpretation. Figure 9 shows 1D geoelectric cross-sections according to the Occam algorithm. The obtained electromagnetic image along the same cross-section for the electric polarization TE and magnetic TM (curves rotated according to the directions of Zmin and Zmax) is clearly different which is related to the high degree of complexity of the geological structure.

3.2. QUANTITATIVE TWO-DIMENSIONAL INTERPRETATION

In the research area, there are no boreholes on the basis of which it would be possible to construct a starting-up model, so the cross-sections from 1D inversion were used for its construction. Two-dimensional interpretation was performed with application of the NLCG algorithm consisting in iterative matching of two-dimensional geoelectric medium to amplitude and phase measurement curves, using the minimization procedure of nonlinear conjugate gradients (Rodi & Mackie 2001). In its assumption, the NLCG method aims at a smoothed model. The solution to the inversion problem is ambiguous, i.e. there are many different models that can be adjusted to empirical data with satisfactory accuracy. In this situation, it is important to properly use the program to impose appropriate constraints on the solution obtained, and appropriate initial conditions in the form of a start-up model. The introduction of a model of near-reality limits the range of variability of its parameters in the minimization process and generally leads to good solutions.

The calculations for all sections were made simultaneously for the electric (TE) and magnetic (TM) polarizations as well as the tipper parameter. The measurement curves were used after rotation of the impedance tensor to the Zxy max direction, in the frequency range from 10400 Hz to 1 Hz (AMT band). An algorithm to remove the disturbing influence of near surface nonuniformities was also used.

2D geoelectric cross-sections show that along the profile 3 there are completely different rocks than along the 1 and 2 profiles. Sections 1 and 2 are characterized by high resistivity values within which anomalies with lowered resistivity occur (Figure 10). In section 1 there are three such anomalies: in the central part of the cross-section at the level of 100 - 200 m a.s.l. and in the final part at levels 500 - 1200 m b.s.l. and from 3 to 5 km b.s.l. The zone with reduced resistivity values also occurs in the middle part of section 2 at the level from 200 to -200 m a.s.l. From the point of view of geothermal research, the above mentioned anomalies on sections 1 and 2 seem interesting, as well as the region of profile 3, where rocks with lower resistivity dominate. However, it is not excluded that the anomalies described in profile 1 and 2 are the result of the effect of three-dimensionality of the geological medium on the 2D inversion. The explanation of these doubts would be possible after the implementation of additional magnetotelluric profiles with azimuth similar to profile 3, but definitely longer, covering both the area with reduced resistivities lying north of Lądek and the zone of high-resistance rocks occurring south of this town. An even better solution would be to create 3D magnetotelluric survey.

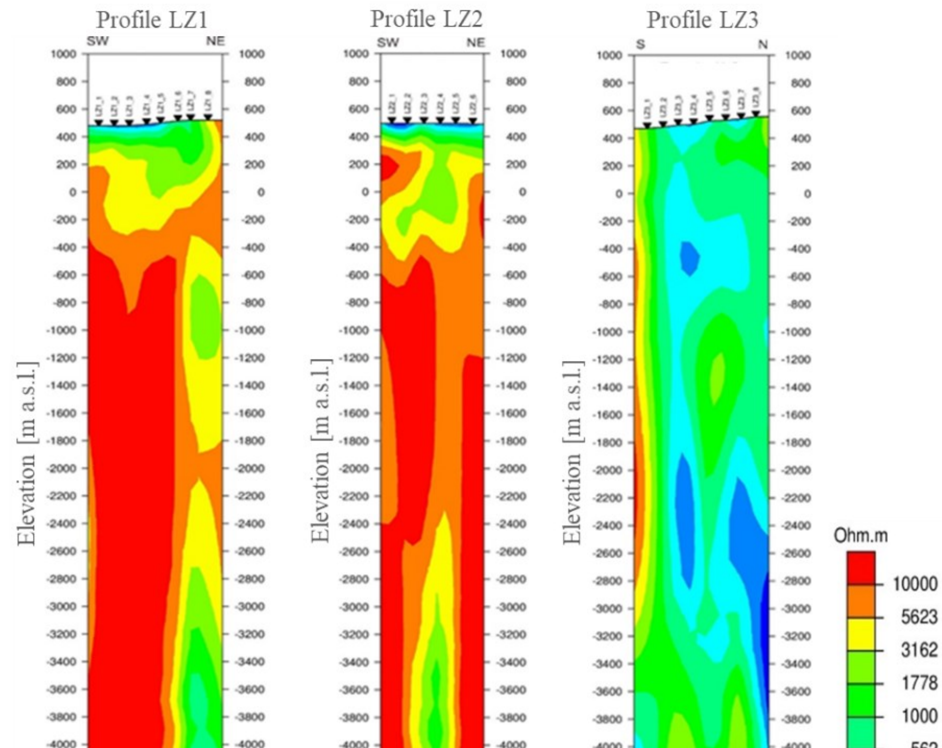

Figure 9: Resistivity cross-sections based on 1D inversion, according to Occam algorithm, magnetic polarization (TM mode)

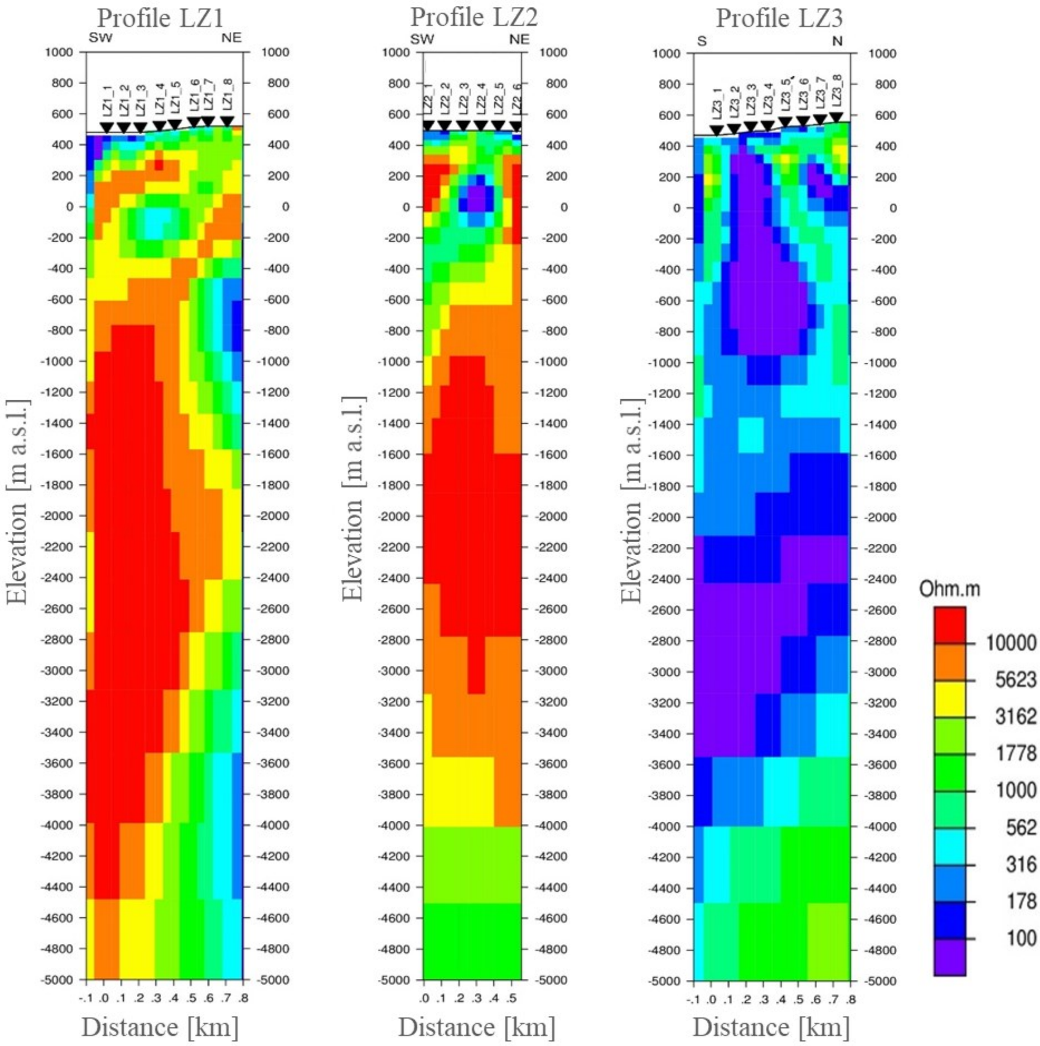

Figure 10: Resistivity cross-sections based on 2D NLCG inversion, the curves rotated to Zmax and Zmin directions

5. CONCLUSIONS

A set of geophysical works carried out in the area of Lądek Zdrój allowed for interpreting fault zones, detection of temperature anomalies and, to a very limited extent, spatial recognition of fractured aquifers. The results of the interpretation of magnetotelluric soundings indicate the presence of at least two levels (rather zones) fractured and filled with mineral (geothermal) waters. It is impossible to predetermine whether the separating layer with increased resistivity is not cut by fractures ensuring hydraulic communication between them, nor is it possible to quantify such a connection. The small range of magnetotelluric data does not allow the assessment of the spatial distribution of aquifers and the potential insulating layer. The presented analyzes indicate that the recognition of the near surface zone of the hydrogeothermal reservoir is relatively good, while the information about its depth is fragmentary and uncertain. In order to recognize the deep geological structure of the reservoir's surroundings, it will be necessary to make a magnetotelluric 3D survey or series of elongated continuous profiles intersecting the reservoir area and the outcrop of the surrounding formations. For a complete geophysical image, it will also be advisable to make a modern, surface geothermal survey and complement the magnetic and gravimetric data.

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