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Exploring for geothermal reservoirs using broadband 2-D MT and gravity survey in Hungary

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SUMMARY

Geothermal energy is playing a larger role as an alternative energy source for both electricity generation and for space heating. Magnetotelluric (MT) and gravity surveys were conducted throughout Hungary in basins which were felt to be prospective for geothermal exploration. Integrated interpretations of the MT and gravity data have identified potential geothermal reservoirs and new drilling opportunities. The success of these surveys has resulted in additional 2-D MT and gravity data acquisition and the onset of a drilling program to evaluate the identified geothermal potential in Hungary.

Keywords: Magnetotellurics, gravity, geothermal reservoir, inversion, Hungary

INTRODUCTION

Higher temperatures and salinity of the pore water, as well as the concomitant increased rock alteration associated with geothermal areas, often contribute to a decrease in the bulk resistivity in a rock mass. The zones of low resistivity that are associated with geothermal reservoirs can be detected by electromagnetic techniques such as the MT (magnetotelluric) method.

MT/AMT (Audio frequency MT) measurements were used to acquire natural time varying electrical and magnetic fields at frequencies of 10,000 Hz ~ 0.001 Hz. The EM field propagates into the Earth as coupled electrical and magnetic fields and these fields are commonly represented in the frequency domain as a four element impedance tensor. The characteristics of the MT resistivity curves are analyzed to extract structural information (associated with resistivity contrast) that is used to determine high-permeability zones and up flow zones of hydrothermal systems.

To complement the MT data, gravity surveys were acquired along the same MT survey lines with denser spacing to assist in detecting fault systems below the surface. Fault system information can be used to analyze and to understand groundwater channels and water flow directions. At the same time, gravity data may be used to interpret the subsurface and to aid in locating prospective heat sources. Integrated interpretation of the MT and gravity data reduces the intrinsic ambiguity of either dataset and produces a more robust interpretation.

METHODOLOGY

The MT (magnetotelluric) method utilizes natural variations in the Earth's magnetic and electrical field as a source. Natural MT signals come from a variety of natural currents, including thunderstorms and solar winds. The total frequency range of MT data can be from 40 kHz to less than 0.0001 Hz. Data is acquired in a passive mode using a combination of electric sensors and induction coil magnetometers and can detect changes in resistivity to great depths. The electric sensors are used to determine the electric field which is derived from measurements of the voltage difference between electrode pairs E_x and E_y. The induction coils are used to measure the magnetic fields H_x, H_y and H_z in 3 orthogonal directions. The ratio of the recorded electric and magnetic fields $[E_x/H_y]$ gives an estimate of the apparent resistivity of the Earth at any given depth. The audio frequency magnetotellurics (AMT) method is a subset of the MT sounding technique for audio frequencies from 1 Hz to 20 kHz and higher. It achieves moderate exploration depths to about 2,000 m with higher vertical resolution, whereas the exploration depth with MT can exceed 10 km.

Gravity based geophysical methods are usually applied in order to provide additional support for the definition of geological structures at a regional scale. Gravitational surveys offer significant benefits to the interpretation of MT data with low survey cost. It is well known that the density models obtained through application of gravity methods are intrinsically non-unique and that the resolution of these models is generally low. However, this gravity information can be successfully utilized in conjunction with conventional MT data interpretation by performing joint/integrated inversion procedures. The resultant models will be automatically and reciprocally consistent because they represent the simultaneous solution of a joint minimization process honoring observed MT and gravity data at the same time and same location.

REGIONAL GEOLOGIC SETTING

Hungary is located in Central Europe and is geographically positioned in the middle of the Pannonian Basin. The basin is comprised of higher thermal conductivity Precambrian -Paleozoic-Mesozoic basement rocks and is filled with lower thermal conductivity Cenozoic sediments. According to thermo-tectonic models the initial crustal thinning or rifting of the Pannonian basin occurred in the Middle Miocene and the subsequent thermal subsidence or post-rift phase extended up to the present (Royden, et al., 1983a and b, Royden, 1988). The Pannonian sediments are multilayered and comprised of sand, shale, and silt beds. While the lower Pannonian sediments (e.g. clay, silt, marl) are impermeable, the upper Pannonian and Quaternary formations contain vast sand and sandstone beds formed by the upper Pannonian which are porous and permeable (Bobok, et al., 1998). Significant strike slip movements along the basement rocks have caused high secondary porosity and along some tectonic lines, high pressure geothermal conditions were generated (Árpási, et al., 2000, Tóth and Almási, 2001). The objective for the study is to utilize electrical resistivity and gravity data to locate significant geothermal reservoir potential areas between 1 km and 4 km of depth in order to support the development of geothermal power plants and for space heating needs.

DATA ACQUISITION AND PROCESSING

Multiple 2-D survey lines were acquired where the MT/AMT site spacing was 1,000 m and the gravity station spacing was 250 m. Two MT measurements were conducted at each site, one for AMT and the other for MT. A 24 bit recording unit was utilized with “porous pot” electrical sensors and two types of induction coils: a high-frequency coil for AMT measurements (12,500 Hz down to 0.35 Hz) and a low-frequency coil for MT measurements (400 Hz down to 0.00025 Hz. So as to acquire high quality data, remote reference site was measured for data processing. Low frequency MT measurements were made overnight with more than 12 hours of recording elapse. Gravity measurements were collected along the same MT survey line with denser spacing (Figure 1).

Figure 1. MT and gravity survey equipment: MT recording unit (upper left), AMT/MT coils (lower left), gravimeter (upper right), and electrical sensor (lower right).

DATA INTEPRETATION

It is believed that the optimal temperature for electricity generation is between 120 °C and 170 °C, corresponding to a target depth of between 2,000 m and 3,000 m. It is expected that the rock matrix permeability is low and as a result, it is essential to look for tectonic features that could provide greater permeability through such mechanisms as fracturing and faulting. With fractures present, it is very likely that hot water will rise up through the fissures and may be detected by the AMT/MT method. The AMT/MT method will supply additional structure control. Gravity methods are useful in detecting fault systems below the surface and in turn may help identify zones of fracturing and faulting.

Survey lines identified potential targets from 2-D resistivity-depth profile inverted from MT data under the constraints deduced from known geological model and gravity inversion results; and which in turn correlated to gravity derived tectonic interpretations (low density - fracturing and faulting zones). Figures 2 to 4 display geological prediction profile along the survey line, cooperative constrained MT and gravity inversion results and resistivity logging data used in the interpretation of the survey line in one of survey areas. A well-based structural cross section along survey line can be seen in figure 2.

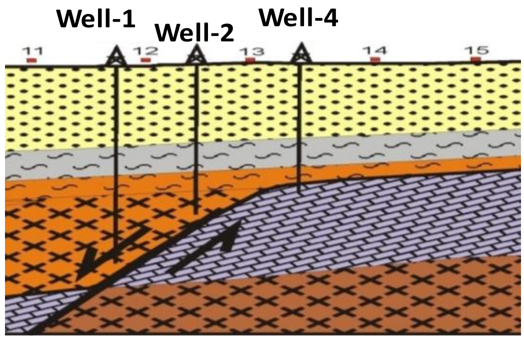

Figure 2. Well and seismic based structural cross section along survey line in one of survey areas.

The section in figure 2 has a S-N direction. There are 3 former wells along the survey line. The Neogene basin is deepening in south direction (left side). The Miocene layers, consisting of mostly volcanic rocks and sediments, are very thin in north (right side) but very thick in south direction. The basement consist of thick Triassic limestone, and Paleosoic formations beneath it. In the middle of the section a large single normal fault is located.

The 2-D inversion of MT data collected along the survey line yields a structural interpretation that strongly resembles the geological cross section (Figure 3). The survey line intersects the well-1 and the resistivity log for this well is shown in figure 4. The onset of higher resistivity at 2,000 meters (from 10 Ωm to 50 Ωm) in the well-1 corresponds to the increase in resistivity shown in the inversion results of the survey line (Figure 4).

Figure 5 shows a comprehensive geothermal interpretation from cooperative constrained MT and gravity data inversion. The identified zone represents a structurally advantageous position for geothermal energy that corresponds to lower resistivity and density values.

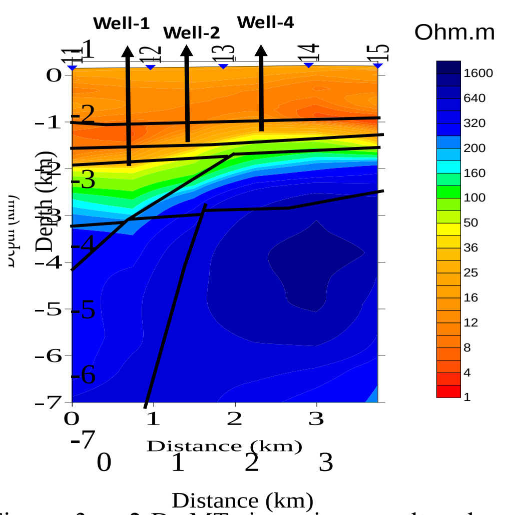

Figure 3: 2-D MT inversion results along survey line. The pre-survey structural interpretation is superimposed on the resistivity values. Note the location of well-1.

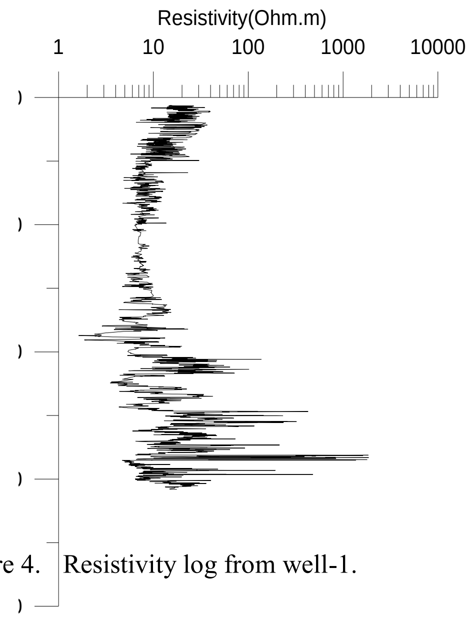

Figure 4. Resistivity log from well-1.

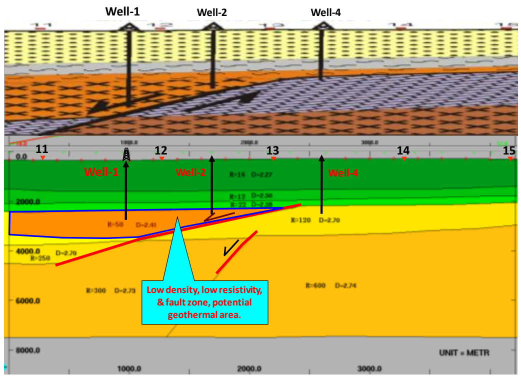

Figure 5. Cooperative constrained 2-D MT and gravity data inversion along a survey line in a survey area. The identified zone represents a structurally advantageous position for geothermal energy that corresponds to lower resistivity and density values.

Figure 6 displays a geological cross section (upper) and cooperative constrained MT and gravity data inversion results (bottom). In geological section tectonic features are located where slope changes were seen the Pre-Tertiary basement bottom depth. The section crosses two different basement rock units. Faults in the areas of stations 10/11 and 14/15 are also known from tectonic map of the area. The formations covering the basement rock are unknown where as no wells are in the area.

The 2-D MT inversion result is shown in figure 6 (bottom). The remarkable character of the inversion result is that the electrical basement becomes shallow from northwest to southeast. There are three primary resistivity layers as shown in figure 6: first, a surface layer with high resistivity of 10 ~ 20 Ωm; second, the intermediate layer with low resistivity of 4 ~ 10 Ωm; and third, an electrical basement which has a high resistivity between 16 and 400 Ωm. The remarkable character of the inversion result is that the electrical basement becomes shallow from northwest to southeast. The residual resistivity section shows that there are two relative low resistivity zones with the depth between 2 km and 4 km (Figure 7). The first one is below MT survey sites 3 to 9, and the second one is below sites 10 to 13.

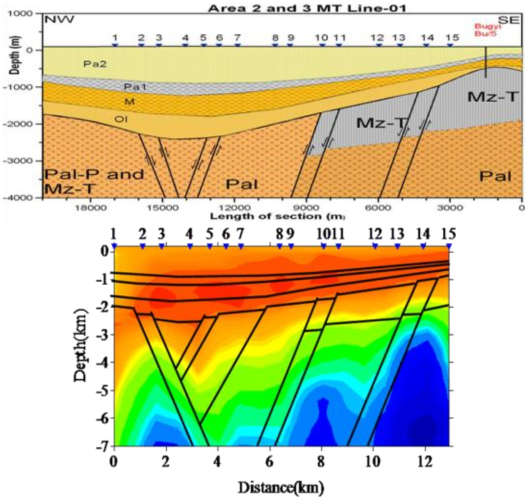

Figure 6. 2-D MT inversion results along survey line in one of survey areas. The pre-survey structural interpretation is superimposed on the resistivity values.

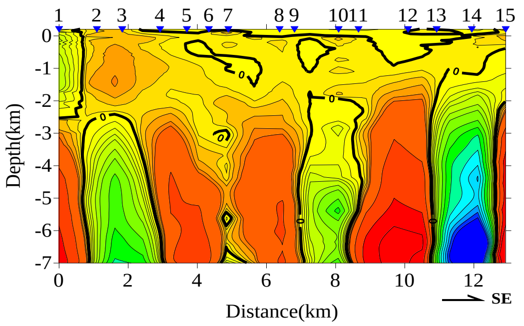

Figure 7. The residual resistivity along the MT survey line.

From the regional gravity horizontal gradient of this survey line (Figure 8, top), a deep fault might be seated between MT survey sites 11 and 12. The residual gravity horizontal gradient indicated that there might have several faults lies in the formations of top-Mesozoic (Figure 8, bottom). In addition, the residual resistivity section also reflects faults below the MT survey sites from 1 to 2, 3 to 4, 5 to 6, 9 to 10, 10 to 11, 12 to 13 and 14 to 15.

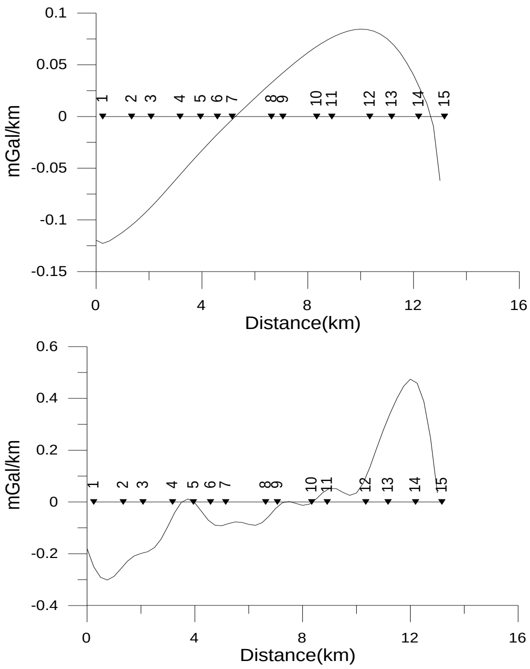

Figure 8. Regional gravity horizontal gradient (top) and the residual gravity horizontal gradient (bottom) of the survey line.

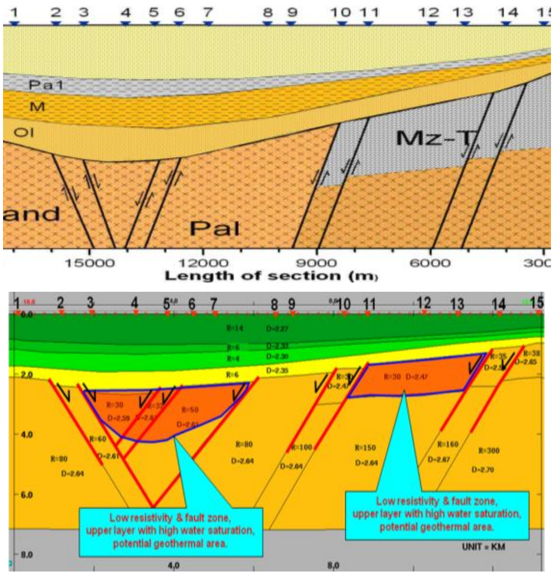

Figure 9. Integrated 2-D MT and gravity inversion along the survey line in another survey area. The identified anomaly zone represents a structurally advantageous position for geothermal energy that corresponds to lower resistivity and density values.

Figure 9 displays the comprehensive geothermal interpretation profile from the cooperative constrained MT and gravity data inversion.

Based on the integrated results of relative low resistivity zone, faults system information, geothermal gradient and cooperative constrained inversion of MT and gravity data, we consider that there has a high potential area between MT survey site 2 and 8 in depth of 2 to 4 km (Figure 8, the blue boundary area). Results of cooperative constrained inversion give the two areas resistivity of 30 ~ 50 Ωm and 30 Ωm, an integrated density of 2.59g/cm^3 ~ 2.61g/cm^3 and 2.47g/cm^3.

CONCLUSIONS

2-D MT/AMT surveys have been conducted in Hungary. To complement the MT data, gravity was acquired concurrently. The cooperative constrained MT and gravity data inversion has yielded resistivity anomalies that are supported by gravity and are interpreted to represent potential geothermal reservoirs. The success of these surveys has resulted in additional 2-D and 3-D data acquisition and the onset of a drilling program to evaluate the identified geothermal potential.

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