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Exploring for geothermal reservoirs using broadband 2-D MT and gravity 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 this data have identified new drilling opportunities. The success of these surveys has resulted in additional 2D MT and gravity data acquisition and the onset of a drilling program to evaluate the identified geothermal potential.

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 method.

MT/AMT 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 MT survey lines 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. Integrating the MT and gravity data reduces the intrinsic ambiguity of either dataset and produces a more robust interpretation.

Methodology

The 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 Ex and Ey. The induction coils are used to measure the magnetic fields Hx, Hy and Hz in 3 orthogonal directions. The ratio of the recorded electric and magnetic fields [Ex/Hy] 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 and are only about 10% of the MT 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 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 geological 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). Figures 1 and 2 describe the regional telluric conductance and Bouger anomalies. The objective for the study is to utilize electrical resistivity and gravity data to locate significant geothermal reservoir potential between 1 km and 4 km of depth in order to support the development of geothermal power plants and for space heating needs.

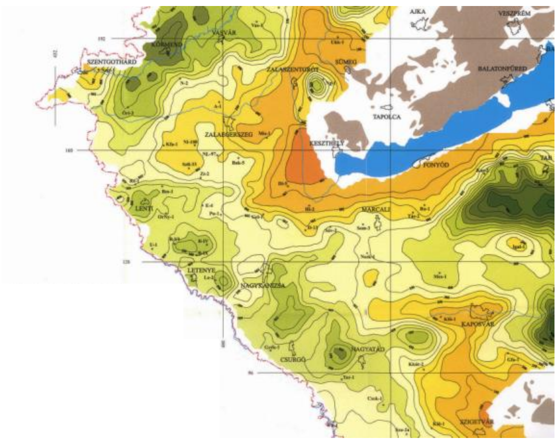

Figure 1: Telluric conductance map used to investigate sedimentary sequence (thickness & structure of underlying high resistivity basement) of mainly Cenozoic age & low resistivity in Carpathian Basin (László, MEMESI, 2000).

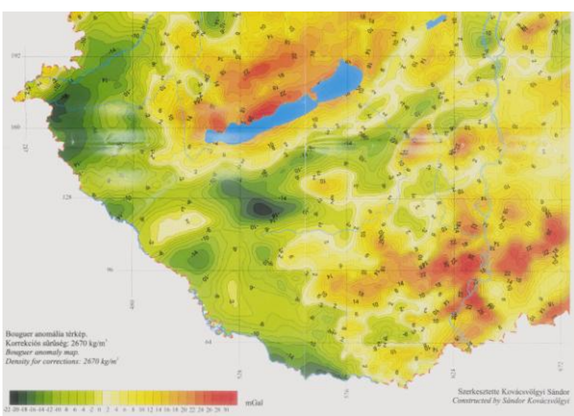

Figure 2: Bouger anomaly map (László, MEMESI, 2000).

Data acquisition and processing

Multiple 2D 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, 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). Gravity measurements were collected with a Lacoste & Romberg Gravimeter model G.

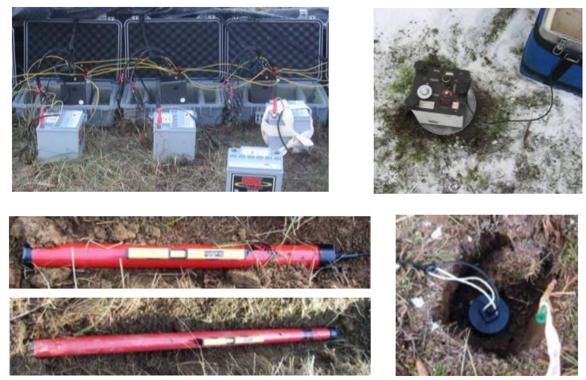

Figure 3: MT and gravity survey equipment: MT recording unit (upper left), MT/AMT coils (lower left), electrical sensor (lower right), and gravimeter (upper right).

Data interpretation

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 MT/AMT method. The MT/AMT 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 inversion which in turn were supported by and correlated to gravity derived tectonic interpretations (low density - fracturing and faulting zones). A well-based structural cross section along survey line 2 can be seen in figure 4. The 2-D inversion of MT data collected along line 2 yields a structural interpretation that strongly resembles the cross section (figure 5). Line 2 intersects the well-1 and the resistivity log for this well is shown in figure 6. 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 line 2 (figure 5).

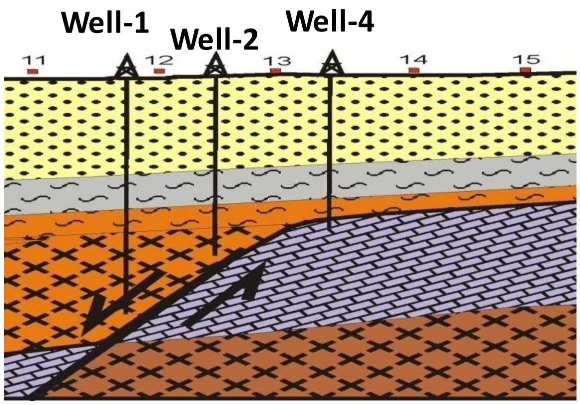

Figure 4: Well and seismic based structural cross section along survey line 2.

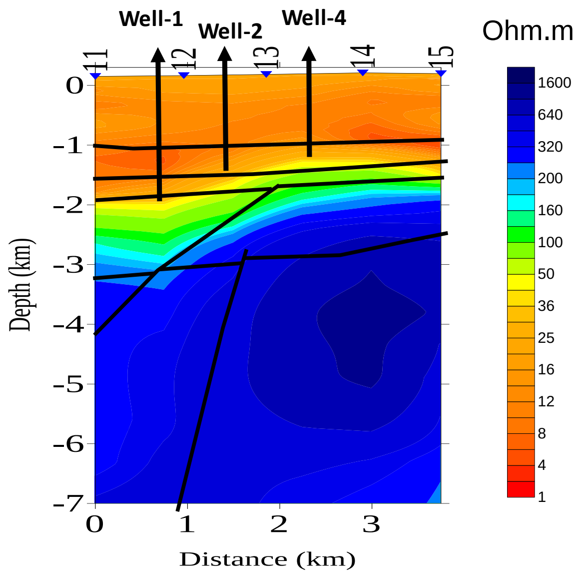

Figure 5: 2-D MT inversion results along survey line 2. The pre-survey structural interpretation is superimposed on the resistivity values. Note the location of well-1.

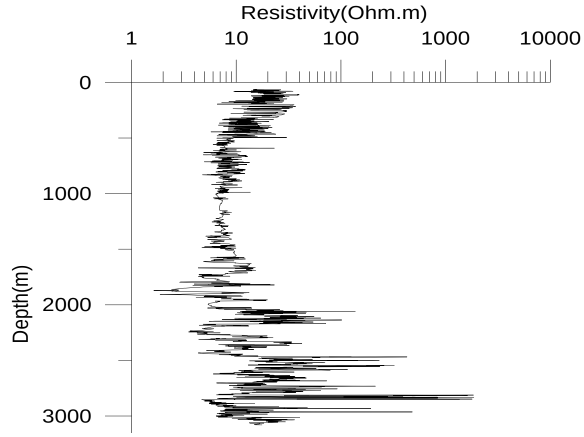

Figure 6: Reisistivity log from well-1.

Integrating gravity with MT in a process that honors both observed MT and gravity data at the same time and same location produces a more robust and unique interpretation. Resistivity and gravity data support a similar interpretation for survey line 2, as shown in figure 7. Lower resistivity and density correspond to a structurally advantageous location for a geothermal reservoir and is identified in figure 7.

Conclusions

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

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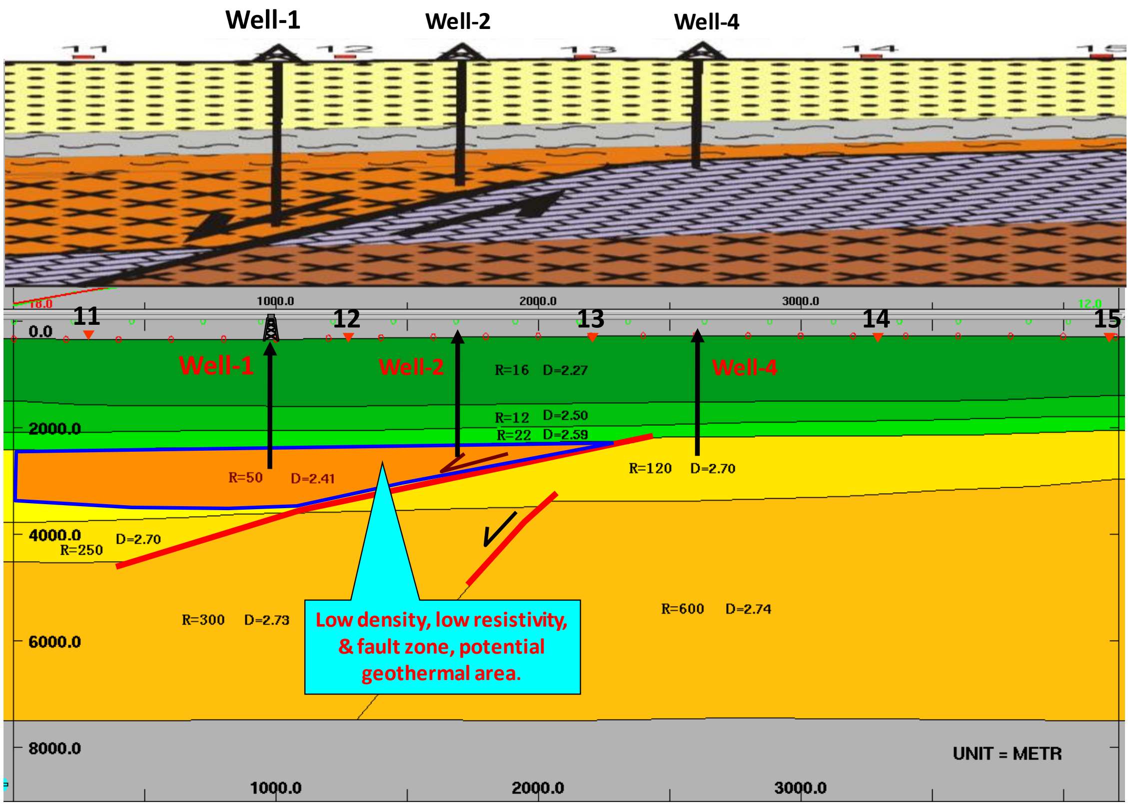

Figure 7: Integrated 2-D MT and gravity inversion along survey line 2. The identified zone represents a structurally advantageous position for geothermal energy that corresponds to lower resistivity and density values.

EDITED REFERENCES

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