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Summary

2-D AMT/MT and gravity surveys were completed in 12 su survey areas in Hungary during 2008. The main objective of this project was to locate potential geothermal targets for alternative energy development in Hungary. We selected here the Szentlőrinc (Szl) survey area because the geothermal drilling project just completed.

The main geothermal reservoir systems found in Hungary are the Mesozoic carbonate–karstic basement rocks and the Pliocene-Upper Pannonian porous sedimentary formations (Árpási, Lorberer, and Pap, 2000). The interpretation of 2-D AMT/MT and gravity focuses on locating potential geothermal areas of the geothermal reservoir system within Mesozoic fractured carbonate–karstic basement rock for drilling locations.

We estimated that the faults within the north-south strike in the Szl survey area were developed in the deep basement. In addition, dense fractures have also been widely developed in the top basement (limestone) of the two survey areas. Thermal energy, which was transported up along the fault systems from the deep Earth, seems to be the heat source of geothermal formation. A set of thick tertiary deposits, are located above the formation. Fractured karst limestone and dolomite deeply buried in the Mesozoic system contain the targeted geothermal reservoirs. Based on the cooperative constrained inversion of magnetotelluric (MT) and gravity data, we surmise that the geothermal aquifer is characterized by a relatively low apparent resistivity and low density, while the higher porosity and permeability formations are unique for faults and fractured zones.

The distribution characteristics of the fault zones with relatively low resistivity and with boundaries outlined by cooperative constrained inversion of MT and gravity data indicate that the prospective zones for potential geothermal reservoirs in the Szl survey area indicate that the mid-northern part of AMT/MT line 1 and the middle part of AMT/MT line 2 are potential areas for geothermal power plants or space heating.

Introduction

Hydrothermal exploration has traditionally used resistivity methods. Calibration of this method against drilling results has been done in several geothermal field tests in the past, and the results have indicated that resistivity measurements can be used as a subsurface thermometer (Malin, Onacha, and Shalev, 2004). The correlation between resistivity and temperature is associated with the local degree of hydrothermal alteration. Most high-temperature hydrothermal systems are indicated by a low resistivity layer over the geothermal reservoir which is caused by clay mineral alteration. The use of resistivity methods provides information about rock properties, temperature, and the degree of hydrothermal alteration. This information can be used to determine the geometry of hydrothermal reservoirs, the depths of the hydrothermal reservoirs, location of fracture zones, and the permeability distribution (Malin, Onacha, and Shalev, 2004). Resistivity variations are typically related to salinity, water saturation, porosity, and cation exchange capacity in hydrated clays. Understanding the nature of low resistivity zones is fundamental for accurate targeting of high temperature up flow zones.

We acquired AMT/MT 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 (Malin, Onacha, and Shalev, 2004).

To complement the MT data, gravity surveys were acquired along the same lines to assist in detecting fault systems below the surface. Fault system information can be used to analyze and 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.

Gravity surveying methods are useful in detecting underground fault systems. Conversely, gravity data may be used to analyze volcanic rock distribution and then help to discover the heat source. Gravity data is normally displayed on a contour map, i.e. a Bouguer anomaly map. This anomaly map can be used to identify regional deep and shallow fault systems. The study requires understanding of the deep structures, which can be studied with a gravitational survey; thus improving the interpretation of the MT measurements.

It is widely accepted that the density models obtained through the application of gravity methods are intrinsically non-unique and that the resolution of these models is generally low. However the intrinsic ambiguity of the gravity data can be reduced by a high level of overlap of the acquired data sets. After obtaining relatively dense gravity survey data, a detailed density profile can be successively utilized in conjunction with conventional MT data to perform cooperative constrained inversion procedures.

The optimal inversion method and interpretation strategy for this 2-D AMT/MT data was first selected through the comparison of different geothermal benchmark modeling and inversion tryout results using a variety of inversion methods and actual field MT data. Upon applying the optimal inversion method and interpretation strategy, the distribution of the relatively low electrical resistivity zones was estimated based on the residual resistivity profiles from standard MT inversion results. The cooperative constrained inversions of MT and gravity data for each 2-D survey line were carried out in parallel. The distribution of deep faults and the faults of top Mesozoic formation were predicted based on gravity data. Raw apparent resistivity curve types, 2-D MT inversion results, relatively low resistivity zones, cooperative constrained inversion results of MT, and gravity data have been integrated together and analyzed. The cooperative constrained inversion results of MT and gravity data and the quality distribution of the MT data, within potential geothermal areas were evaluated based on relatively low resistivity zones or fault zones.

The primary goal of this project was to use electrical resistivity data and gravity data to outline potential areas for geothermal utilization. This project involved performing a detailed geophysical exploration as part of the ongoing geothermal investigation of the Szentlőrinc survey area in order to better understand the deep geothermal field distribution and to provide critical information for the field development drilling plan.

Methodology

The MT 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 Hx, Hy and Hz in three orthogonal directions. The ratio of the recorded electric and magnetic fields [(Ex/Hy (ω)] 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 situated in Central-Europe in the Pannonian Basin. The Danube River cuts through the country separating it into two main parts: the Transdanubian Central Range with Lake Balaton in the northwest and the Great Hungarian Plain in the east and south.

Geographically, Hungary is positioned in the middle of the Pannonian Basin. The Pannonian 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 of upper Pannonian age 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, Lorberer, and Pap, 2000, Tóth and Almási, 2001). The objective of the study is to utilize electrical resistivity and gravity data to locate significant geothermal reservoir potential areas between 1 km and 4 km depth in order to support the development of geothermal power plants and for space heating needs.

In the area normal strike slip faults area found as well as indications of over-thrust Mesozoic block in seismic lines. These tectonic lines separate different basements of different permeability. Seismic data imply 5 big tectonic features in the Szl area. Four major reverse fault zones and one transfer fault zone (Figure 1).

Main basement rock in the Szl area belongs to the Tisza main units of Hungary and is divided into main rock units. South of the main reverse fautls the basement is mostly of low permeable metamorphic rocks of Paleozoic age. North of the reverse fault zone rhyolite, molasse and granite are expected also of Paleozoic age. Limestone/dolomite formations are found in wells at about 600 m depth. Below that no actual proof of this formation can be found. Seismic data imply that there might be a possibility of Mesozoic formation to be as small lenses within the fault zones.

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In the area of Szentlőrinc two MT lines were measured (Figure 1) and for both lines a geological cross section was made (Figures 2 and 3).

In general, lithology of the Szl area is as follows: Pa_1 and Pa_2 (Pannonian) commonly consist of sand, clay, sandstone, siltstone, chalky clay marl, sand. M (Miocene) layers consist of clay marl, sand, pebbles/conglomerate and volcanic tuff. Mz (Mesozoic – Triassic/Cretaceous) layers consist of limestone, dolomite and dolomite breccias. P (Permian) is expected to be of arenaceous rocks, conglomerate and some metamorphic rock (micaceous schist and serpentinite). Pal (Old Paleozoic) is of metamorphic rock (micaceous schist/gneiss).

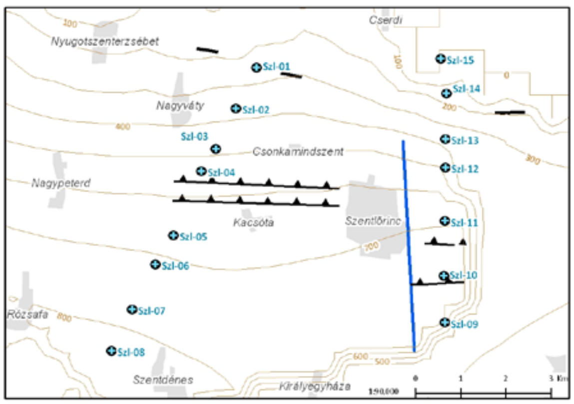

Figure 1: Szl: Location of MT sites (blue) and faults (black: reverse faults, blue: transfer fault), and expected basement depth contour lines in m b.s.l. (brown).

Geological cross sections

A well-based structural cross section along survey lines 1 and 2 can be seen in Figures 2 and 3. In the area of MT line 1 (Figure 2) the basement rock is mostly of Palaeozioc age. The southern part is of metamorphic rocks and between Stations 4 and 1 there is palingene granite and granodiorite. While the northern part the basement is rhyolite and molasse of Permian age. Lenses of Mesozoic limestone layers are expected to beneath station 3 and 4. In the area of MT line 2 (Figure 3) similar basement features are expected as for line 1. Mesozoic limestone lenses are expected to be located close to the tectonic zones below stations 11 and 12.

Data acquisition and processing

Two 2D survey lines were acquired where the AMT/MT 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.

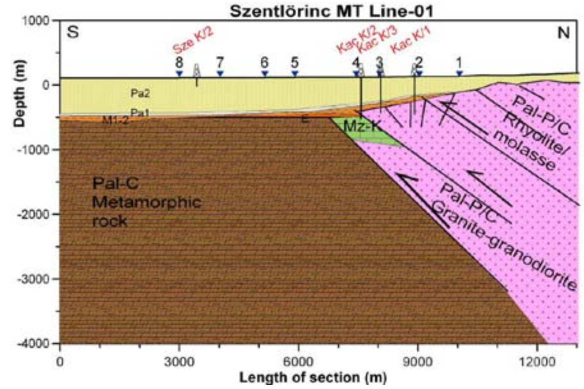

Figure 2: Schematic geological cross section for MT line 01 in Szl survey area.

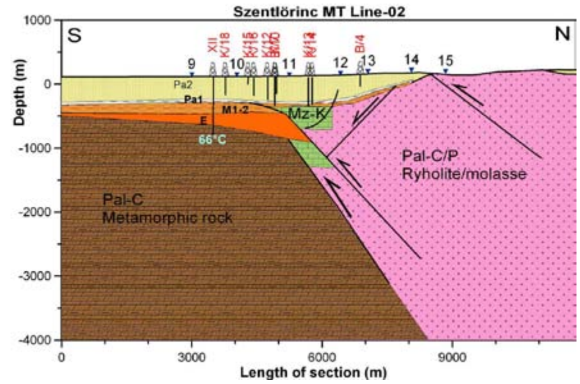

Figure 3: Schematic geological cross section for MT line 02 in Szl survey area.

Data interpretation

It is believed that the optimal temperature for electricity generation is between 120°C and 170°C, corresponding to a target depth in Hungary 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 (Tulinius, et al., 2008).

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 - fracture and fault zones). The 2-D inversion of MT data collected along lines 1 and 2 in Szl yielded a structural interpretation that strongly resembles the well derived ones (Figures 4 and 5).

The geoelectric structure identified by the 2-D MT surveys in the Szl survey area is a three-layer model up to 7,000 m in depth. The layers are: *a conductive layer at the surface, a less conductive second layer, a deep resistive layer.*

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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 lines 1 and 2. Lower resistivity and density anomalies correspond to a structurally advantageous location for a geothermal reservoir and are identified in Figure 6.

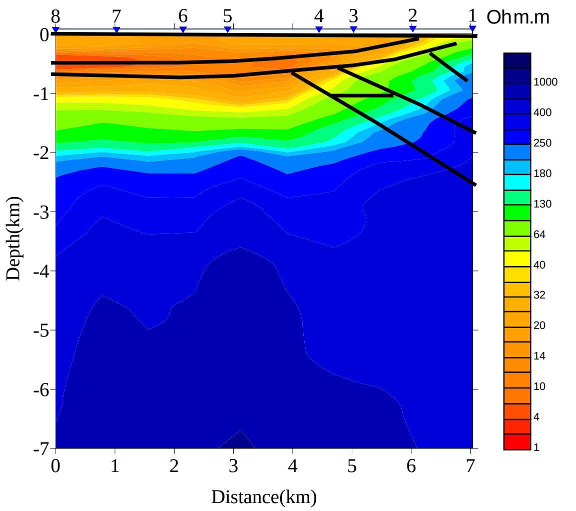

Figure 4: 2-D MT inversion results along Szl survey line 1. The pre-survey structural interpretation is superimposed on the resistivity values.

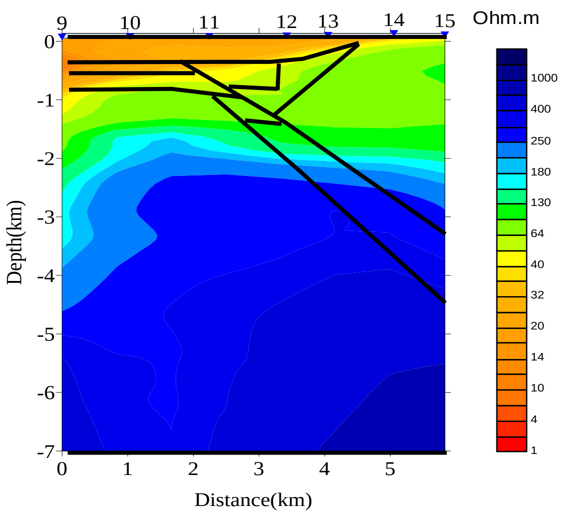

Figure 5: 2-D MT inversion results along Szl survey line 2. The pre-survey structural interpretation is superimposed on the resistivity values.

Conclusions

2-D AMT/MT and gravity data was acquired in Szentlőrinc survey area of Hungary. The AMT/MT data has yielded resistivity anomalies supported by gravity and are interpreted to represent possible geothermal reservoirs. Based on the success of these surveys and the integrated interpretation of geology, seismic, well logging, gravity and AMT/MT data, the client is currently conducting an ongoing drilling program to evaluate the identified geothermal potential in Szentlőrinc survey area (Figure 7).

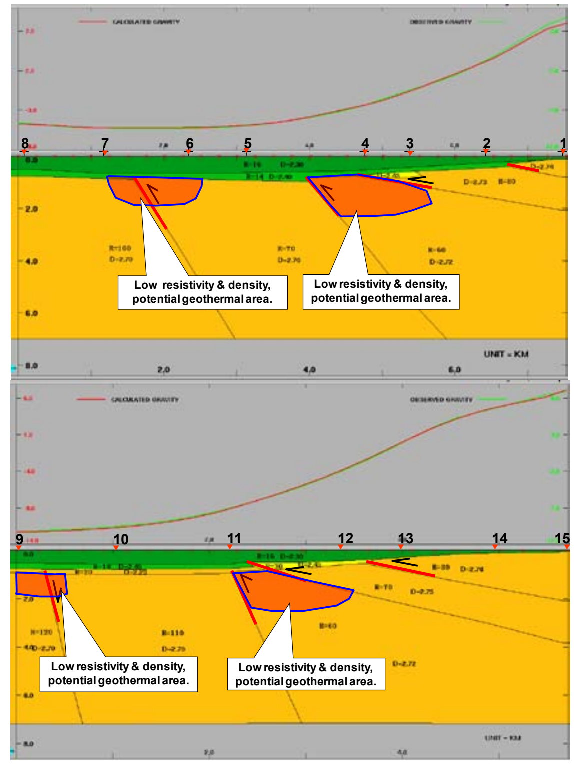

Figure 6: Integrated 2-D MT and gravity inversion along Szl survey lines 1 (above) and 2 (below). The identified zone represents a structurally advantageous position for geothermal energy that corresponds to lower resistivity and density values.

Figure 7: Ongoing drilling project for geothermal exploration in Szentlőrinc MT/gravity survey area.

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