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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. Our recent magnetotelluric (MT) and gravity surveys in Iceland and Hungary have both characterized known geothermal reservoirs and identified new drilling opportunities. The success of these surveys has resulted in additional 2D and 3D MT and gravity data acquisition and the onset of a drilling program to evaluate the identified geothermal potential.

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.

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

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.

Study areas – Iceland and Hungary

Iceland is one of the best-studied large-volume volcanic anomalies in the world. It features the largest sub-aerial exposure of any portion of the global spreading plate boundary and is considered to be a ridge-centered hotspot (Foulger, Natland, and Anderson, 2005). Heat sources for hydrothermal systems include magma chambers, young dikes, and frictional heating due to faulting. Fault zones buried below the surface control fluid circulation and are hard to delineate using surface geological mapping tools (Malin, Onacha, and Shalev, 2004). In order to map the geothermal reservoir in depth ranges from surface to greater than 5,000 meters or more in the Theistareykir area, North-East Iceland, we have recently conducted a wide frequency range 2-D MT survey. The goal of the study is to utilize electrical resistivity data to characterize a known geothermal reservoir in order to justify the development of a large capacity geothermal power plant in north Iceland.

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. 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 between 1 km and 4 km of depth in order to support the development of geothermal power plants and for spacing heating needs.

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 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 $[(E_x/H_y\ (\omega)]$ 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 honouring observed MT and gravity data at the same time and same location.

Data interpretation

We relate the resistivity variations to temperature: an increase in temperature will increase fluid mobility causing more electrons to flow and thus reduce resistivity. The presence of a geothermal reservoir often is associated with a localized increase in porosity and this may be detected by gravity measurements as a decrease in density.

Iceland: The shallow geothermal reservoir boundary mapped by 2-D MT data confirmed the finding of a previous TEM survey in the Theistareykir field, however, as the MT survey has far greater depth of investigation than TEM, a deeper geoelectric feature of more than 10 km has been discovered for the first time in the Theistareykir area. The MT/AMT data suggests the presence of a four layered resistivity model down to a depth of 7,000 m (figure 1). The layers are: *a surface layer* (resistive except in some geothermal spots), *a conductive second layer*, *a deep resistive third layer* and *a deeper conductive fourth layer*. Around 12,000 m (or more) depth, a resistive basement is identified. Based on the MT interpretation, the heat source in the survey area is intrusive at a depth of 4,000 m to 9,000 m (layer 4). The hot water flows up through basaltic lava, hyaloclastites and intrusives which are 0.5 km ~ 1 km thick as corroborated by the prior TEM measurements.

Hungary: 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. Gravity methods are useful in detecting fault systems below the surface and in turn may help identify zones of fracturing and faulting. 2D survey lines were acquired where the MT/AMT site spacing was 1,000 m and the gravity station spacing was 250 m. Each survey line identified potential targets of lowered resistivity (high temperature) which was supported by and correlated to gravity supported tectonic interpretation (low density - fracturing and faulting zones). An integrated interpretation example is shown in figure 2.

Conclusions

2-D MT/AMT surveys have been conducted in Iceland and Hungary. To complement the MT data, gravity surveys were also acquired. In Iceland, MT data confirmed the findings of a previous TEM survey in the Theistareykir field, outlined the boundaries of the geothermal reservoir and for the first time identified and mapped a deeper conductive layer. In Hungary, a combination of MT/AMT and gravity 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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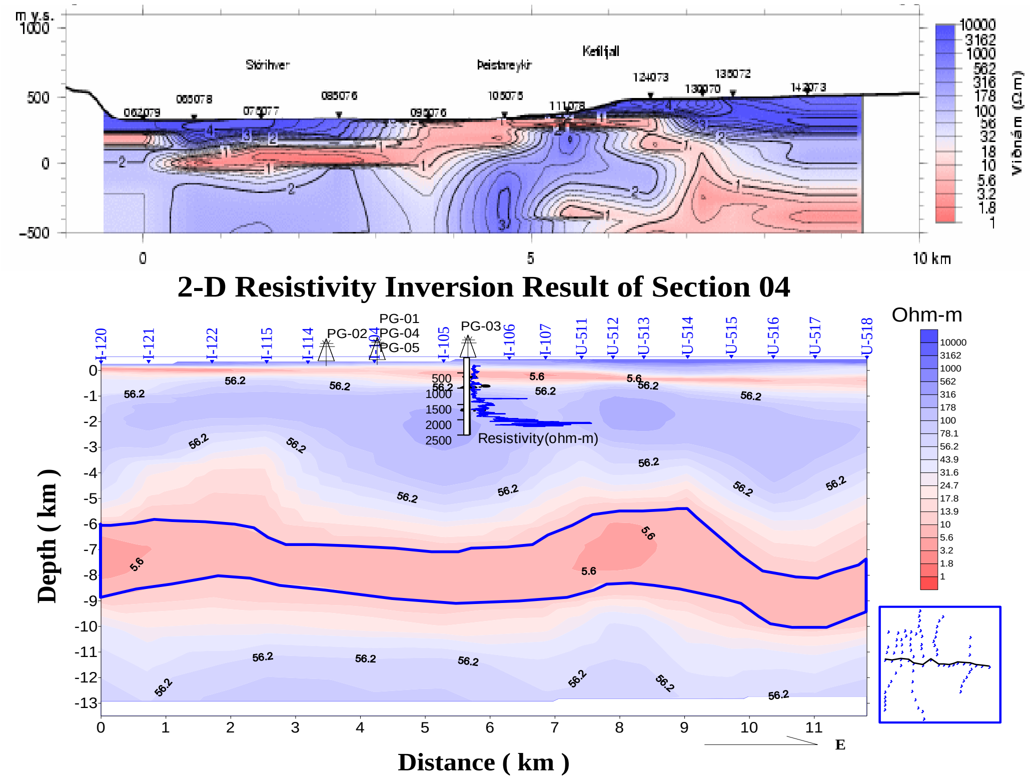

Figure 1: Top: TEM inversion result of profile 307 (from the ISOR report provided by the client); bottom: 2-D deep MT inversion section shows the striking conductor in depth around 7 km and excellent correlation to well control

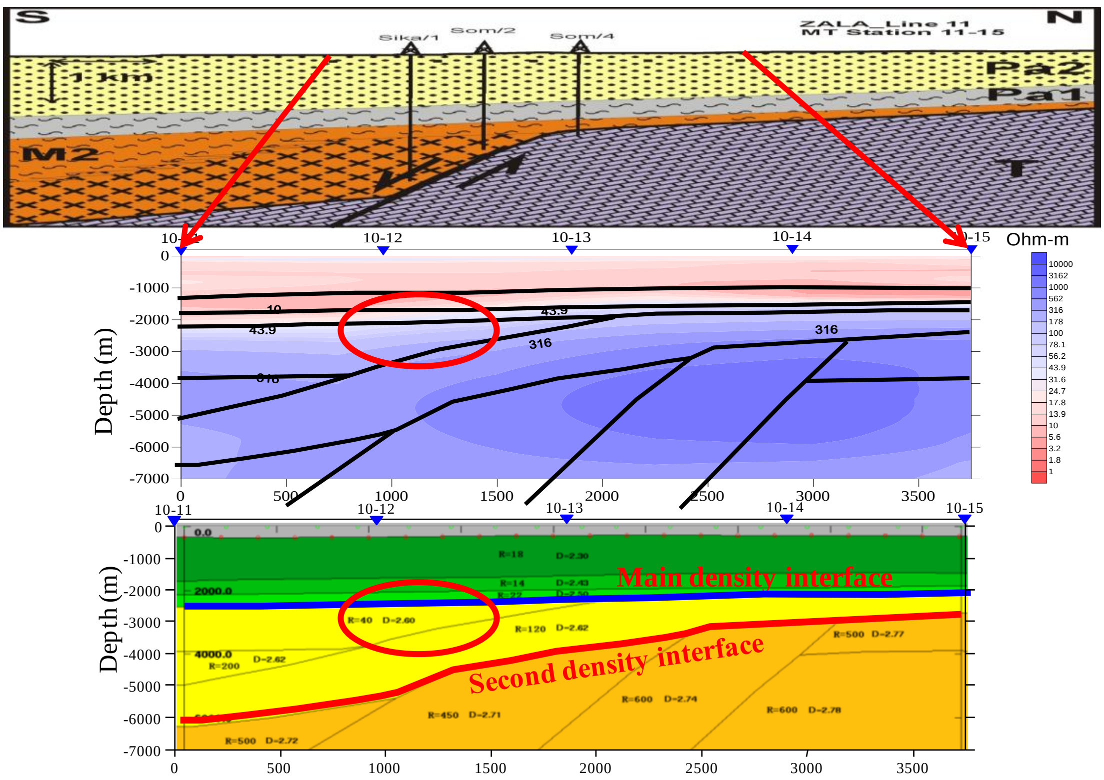

Figure 2: MT and gravity inversions strongly correlate. Resistivity anomaly (red oval) is located in structurally advantageous location for permeability.

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