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Characterizing a geothermal reservoir using broadband 2-D MT survey in Theistareykir, Iceland

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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) surveys in Iceland have both characterized known geothermal reservoirs and identified new drilling opportunities. 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. The success of these surveys has resulted in additional 2D and 3D data acquisition and will be incorporated into the drilling program to evaluate the identified geothermal potential.

Keywords: Magnetotellurics, electrical structure, geothermal reservoir, Iceland

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 (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.

REGIONAL GEOLOGIC SETTING

Iceland is located where the asthenospheric flow under the NE Atlantic plate boundary interacts and mixes with a deep-seated mantle plume. The buoyancy of the Iceland plume leads to dynamic uplift of the Iceland plateau, and high volcanic productivity over the plume produces a thick crust. The Greenland-Faroe Islands represent the Iceland plume track through the history of the NE Atlantic. The current plume stem has been imaged seismically down to about 400 km depth, throughout the transition zone and more tentatively down to the core-mantle boundary. Iceland geology is characterized by the interplay of the spreading of the mid-oceanic plate boundary and a hot spot, which has a centre located under the NW part of the Vatnajökull glacier. The plate boundary in Iceland is located inside the neovolcanic zone, a chain of active volcanoes, which traverses the middle part of Iceland.

The MT/AMT survey area lies within the Neovolcanic Zone (NZ) along the Mid-Atlantic Ridge (MAR) extending from the Reykjanes to the Kolbeinsey Ridge in the north. The Neovolcanic Zone is composed of three main branches, the Northern Volcanic Zone (NVZ), the Eastern Volcanic Zone (EVZ) and the Western Volcanic Zone (WVZ). The NZ is composed of central volcanoes and fissures swarms. The geology of the survey area is dominated by basaltic lava, hyaloclastites and intrusives.

DATA ACQUSITION AND PROCESSING

A total of 78 survey sites were acquired mainly in four 2-D survey lines and a small area with 3-D grid in the NW corner of the survey area (see Fig.1). For each survey site, we conducted two measurements, 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).

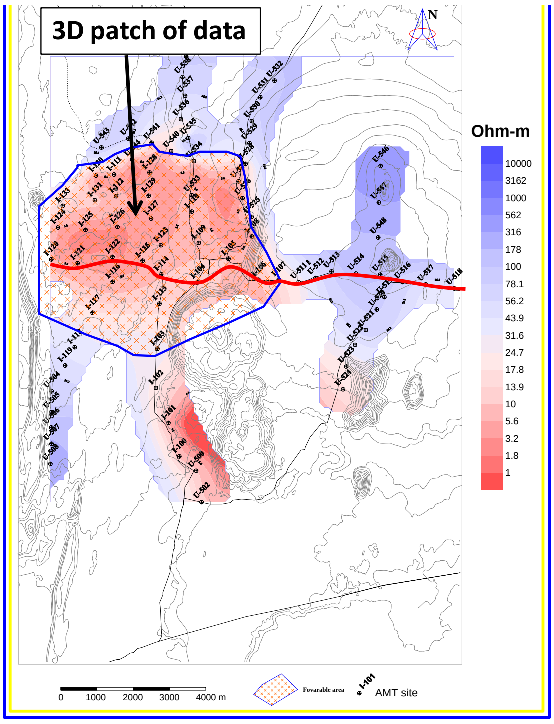

Figure 1. Map of survey area with site locations. Section 04 is highlighted in red. Inversion results from a depth of 500 m are overlain and describe the aerial extent of the upper conductive zone.

DATA INTEPRETATION

Geological circumstances in Theistareykir differ from other zones of volcanism seen around the world. Hot water flows up through basaltic lava, hyaloclastites and intrusives which are 0.5 km ~ 1 km thick according to previous TEM measurements. The low resistivity, 1 Ωm ~ 5 Ωm, measured within the Krafla fissure swarm and the high-resistivity core are difficult to explain except by high-temperature geothermal activity. The high-resistivity core is thought to originate from changes in mineralization where clay minerals with loose ions and hence low resistivity are altered to the more resistive high-temperature minerals, like epidote and chlorite. The change generally takes place at temperatures around 250°C. This may not represent current temperature conditions in the geothermal system, but it has likely reached such temperatures during its lifetime. Exploration drilling has confirmed the existence of mineral alteration related to high temperatures at shallow levels, supporting this theory (Georgsson, et al, 2000). A schematic of the geothermal study area and the fluid flow is shown in Fig. 2.

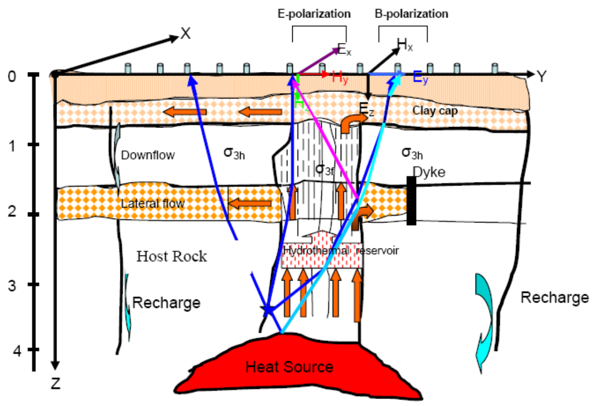

Figure 2. Schematic describing the geothermal reservoir at the study area (after Malin, Onacha, and Shalev, 2004)

The constituent of rock and its pore fluids in high temperature geothermal fields includes a temperature contribution to the resistivity. Thus 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 resistivity contrasts cause polarization & splitting in the measured MT data. (Malin, Onacha, and Shalev, 2004).

The shallow geothermal reservoir boundary mapped by 2-D inversions of the MT/AMT data confirmed the findings of a previous TEM survey in the Theistareykir field, however, as the MT survey has far greater depth of investigation than the TEM survey, 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 10,000 m (Fig.3). 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.

The hydrothermal reservoir consists of two parts. The upper reservoir, to a depth of 1,000 m, is water saturated with a mean temperature ~205 °C. The main aquifers in the lower geothermal part are associated with fissures and intrusives. This lower geothermal reservoir part is boiling with temperatures ranging from 300 °C to 350 °C or more. The bottom of the upper geothermal reservoir is seated about 900 m ~1,200 m in depth, and its coverage size is ~32 km2. The lateral extent of this upper unit is shown in Fig.1. The buried depth of the bottom of the lower geothermal reservoir ranges from 2,600 m to 5,000 m. In the highest potential hydrothermal zone, the bottom seated depth is about 3,200 m ~ 3,400 m and covers ~46 km2. Additionally, a deep conductive geothermal reservoir which has coverage of more than 54 km2 has been found by MT inversions with results in depth ranging from 4,000 m to 7,000 m or more. The temperature is expected to be > 500 °C. Well ties along section 04 demonstrate a strong correlation between borehole resistivity and the MT data, confirming the inversion results of the data (see Fig. 4).

Based on the linkage between temperature and (clay) mineral alteration and the linkage between resistivity and mineral alteration, MT interpretation results indicate the relationship between resistivity and temperature. These results are calibrated by using local data from drilled wells and reference data from other areas. The temperature base on MT interpretation result is featured as: low resistivity relates the upper hydrothermal in shallow subsurface up to 1,000 m in depth, high resistivity associated with the lower (deep) hydrothermal reservoirs ranges from 1,000 m ~ 4,000 m in depth, and the deep low resistivity layer implies the heat source with high temperature in depth range larger than 4,000 m to 9,000 m. 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 survey measurements.

Interpretation of the 3D MT survey was performed with a 3D inversion approach. The site spacing was optimized for the target's depths and spatial spacing requirements. 3D results supported the 2D interpretation, but provided for a more reliable and detailed 3D representation of the subsurface. The inversion results were interpreted as a 3D cube, as shown in Fig. 5.

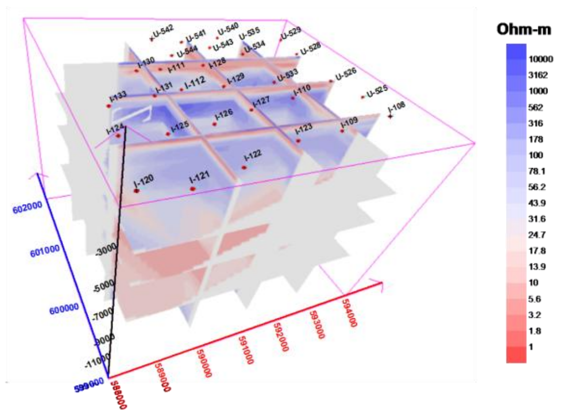

Figure 5. Slices from the 3D inversion of the MT/AMT data

CONCLUSIONS

This MT/AMT survey has corroborated the findings of a previous TEM survey in the Theistareykir field and confirmed the existence of a high temperature reservoir under the Theistareykja area. It has also better outlined the boundaries of the reservoir along each of the 2-D MT survey lines. Additionally, a small 3D survey has demonstrated the value of collecting denser MT measurements suitable for 3D inversion techniques. This study establishes the relationship between resistivity, temperature and lithology and the benefits that can be realized from MT/AMT data for the mapping of geothermal reservoirs. The success of this survey has resulted in additional 2D and 3D data acquisition and the expanded use of MT/AMT to identify geothermal potential.

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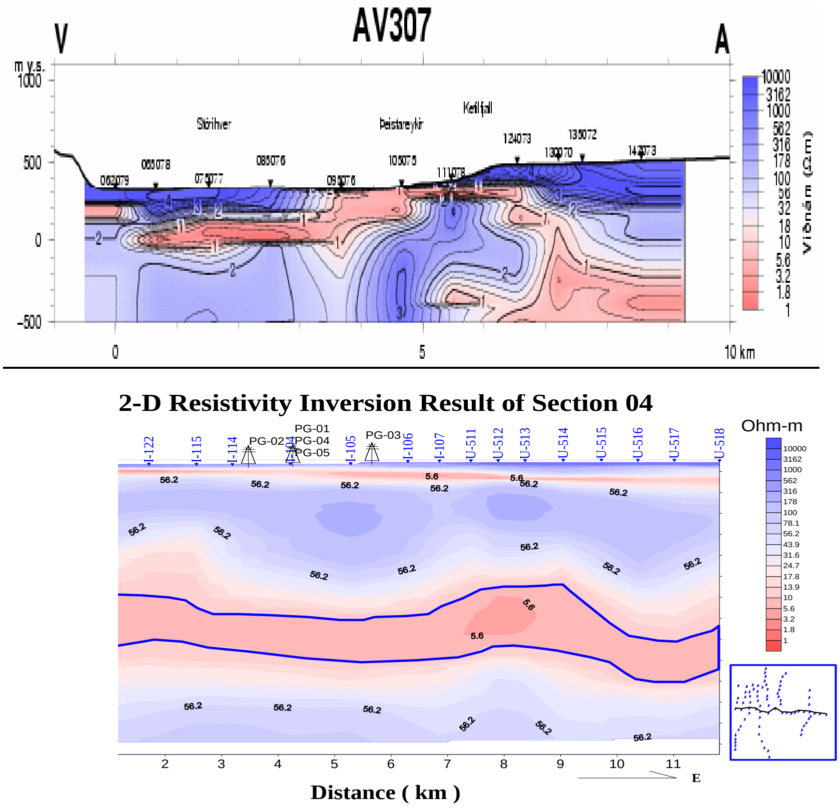

Figure 3. Top: TEM inversion result of profile 307 (from the ISOR report provided by the client); bottom: 2-D deep MT inversion section 04 shows the striking conductor in depth around 7 km. Location and orientation of the profile is show on the right map insert.

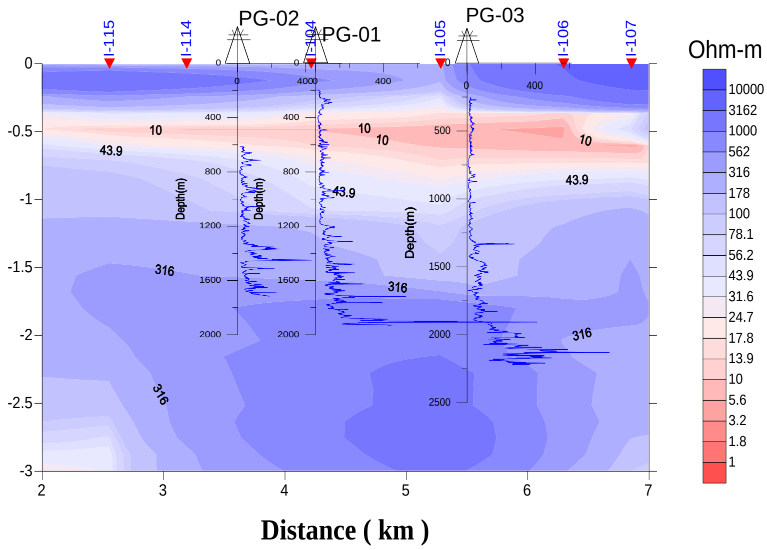

Figure 4. Expanded view of well ties along section 04. Note the strong correlation between borehole resistivity measurements and the inversion result

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