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# Characterizing a Geothermal Reservoir Using Broadband 2-D MT Survey in Theistareykir, Iceland

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## ABSTRACT

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 transient electromagnetic (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 2-D and 3-D data acquisition and will be incorporated into a drilling program to evaluate the identified geothermal potential.

## 1. INTRODUCTION

Iceland is one of the best-studied large-volume volcanic anomalies in the world. It features the largest subaerial exposure of any portion of the global spreading plate boundary and is considered to be a ridge-centered hotspot (Foulger, Natland, and Anderson, 2005). Relict or active hydrothermal systems are areas of complex fluid circulation, tectonic activity, and volcanic activity. Heat sources for hydrothermal systems include magma chambers, young dikes, and frictional heating due to faulting. Ancient hydrothermal flow is recorded in hydrothermally metamorphosed rock masses and veins. Faulting zones buried below the surface control fluid circulation. Because of this location, they are hard to delineate using surface geological mapping tools (Malin, Onacha, and Shalev, 2004).

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 low resistivity geophysical anomalies observed over most geothermal systems have been very useful exploration targets. As better and deeper imaging of the resistivity structure of geothermal systems has become possible with the use of methods such as magnetotelluric (MT) surveying, it has been shown that the lowest resistivity is usually in a zone above the reservoir and that the resistivity of the actual reservoir can be much higher (Ussher, et al., 2000). MT surveys have been used in several geothermal fields in steep terrain and their interpretations have reliably located the geothermal reservoirs (Errol Anderson et al., 2000)

In order to map the geothermal reservoir in depth ranges from surface to 5,000 meters or more in the Theistareykir area, North-East Iceland, we have carried out a wide frequency range 2-D MT survey. The goal is to use 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.

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

## 2. METHODOLOGY

The magnetotelluric method is a frequency domain electromagnetic tool that utilizes natural variations in the Earth's magnetic and electrical field as a source. Variations in the earth's natural magnetic field supply frequencies ranging from nearly DC to several kilohertz, thus giving one the ability to study the electric substructure of the earth to great depths. The large frequency range also means that the method is not hampered by the presence of conductive overburden or sampling frequencies that do not allow for deep penetration. 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.

Cagnaird (1953) and Tikhonov (1950) developed the theory underlying the magnetotelluric method independent of each other in the 1950's. They both observed that the electric and magnetic fields associated with telluric currents that flow in the Earth as a result of variations in the Earth's natural electromagnetic field, should relate to each other in a certain way depending on the electrical characteristics of the Earth. The ratio of the horizontal electric field to the orthogonal horizontal magnetic field gives the electromagnetic impedance. A major advantage of the MT method is that it simultaneously measures the electric and magnetic fields in two perpendicular directions. 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. 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.

In magnetotelluric (MT) method, the tensor resistivity properties of the rocks are determined from the orthogonal components' natural time measurements varying electrical and magnetic fields. The electrical fields are measured by two sets of orthogonal non-polarizing electrodes while the magnetic field is measured by two sets of orthogonal induction coils. 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.

In this project we have used MT/AMT measurements acquired 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 E- and H- fields. The 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 that is used to determine high-permeability zones and up flow zones of the hydrothermal systems (Malin, Onacha, and Shalev, 2004).

## 3. REGIONAL GEOLOGIC SETTING

Iceland is located such that 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. During the last 60 Ma, Greenland, Eurasia, and the NE Atlantic plate boundary have migrated northwestwards at a rate of 1 ~ 3 cm/year relative to the surface expression of the Iceland plume.

Currently, the plume channel reaches the lithosphere under the Vatnajökull glacier, about 200 km southeast of the plate boundary defined by the Reykjanes and Kolbeinsey Ridges. During the last 20 Ma the Icelandic rift zones have migrated stepwise eastward, keeping their positions near the surface expression of the plume and leading to a complicated and changing pattern of rift zones and transform fault zones.

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's 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 (NZ), a chain of active volcanoes, which traverses the middle part of Iceland (Trønnes, 2002, Georgsson, et al., 2000, Foulger, et al, 2003).

The 40 km ~ 50 km wide rift zones (Reykjanes, Western, Eastern and Northern Rift Zones) comprise en echelon arrays of volcanic fissure swarms, with 3 ~ 4 semi-parallel swarms across the rift zone width. The swarms are about 5 km ~ 15 km wide and up to 200 km in length. With time, they develop a volcanic center with maximum volcanic production somewhere along their length. The volcanic centers will often develop into central volcanoes with high-temperature geothermal systems, sometimes also with caldera structures produced by large ash-flow eruptions of silicic magma. Each fissure swarm, with or without a central volcano, constitutes a volcanic system. The Icelandic rift zone system consists of the Northern Volcanic Zone (NRZ), the Eastern Rift Zone (ERZ), and the Western Rift Zone (WRZ).

The thickness of the upper crustal ranges from 6 km to 10 km. The Moho surface beneath Iceland is seismically diffuse because of low densities and seismic velocities in the uppermost mantle and relatively high densities and velocities in the lower crust. Several recent models, however, agree that the crustal thickness varies from about 40 km under Vatnajökull to less than 20 km under the northern part of the NRZ and the Reykjanes Peninsula.

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

## 4. 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 Figure 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). The standard 2-D MT data acquisition procedures and QA/QC requirements were strictly followed, and the high quality MT data were acquired during the field operation.

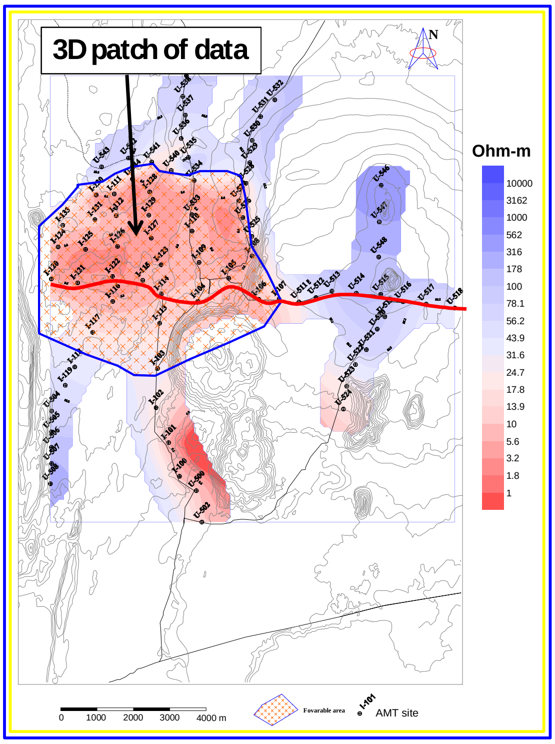


**Figure 1: Map of survey area with site locations. Section 04 is highlighted in red. Inversion results from a depth of 500 m are overlain and describe the aerial extent of the upper conductive zone**

A commercial software package was used for the data processing from the raw time series and to transfer functions, including checking the field parameter through checking the table file, checking the calibration files, calculation of the Fourier coefficient, and Robust spectral analysis.

## 5. DATA INTEPRETATION

MT data interpretation is primarily based on forward modeling and the inversion method. In order to select the optimum forward modeling and inversion method to interpret the Theistareykir 2-D and test 3-D MT data, we tested different 1-D, 2-D, and 3-D modeling and inversion programs. After extensive testing and comparison, we selected 2-D Continuous Media Inversion to invert all the 2-D MT data in the Theistareykir area. 3-D nonlinear conjugate gradients inversion was also used to invert the test 3-D MT data in the survey area.

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 Figure 2.

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 and splitting in the measured MT data. (Malin, et al., 2004).

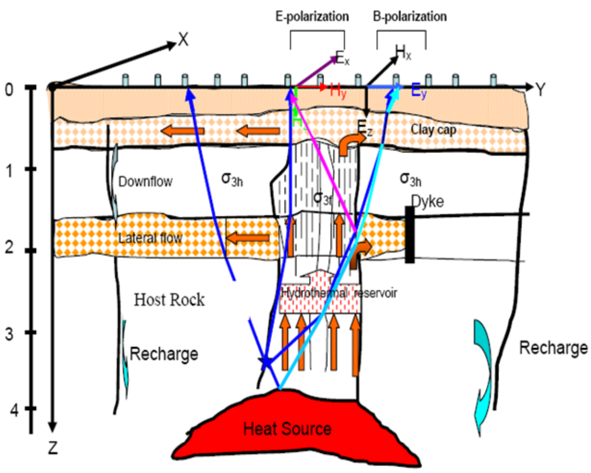


**Figure 2: Schematic describing the geothermal reservoir at the study area (after Malin, Onacha, and Shalev, 2004)**

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 (Figure 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. A resistive basement has been identified at around 12,000 m (or more) depth.

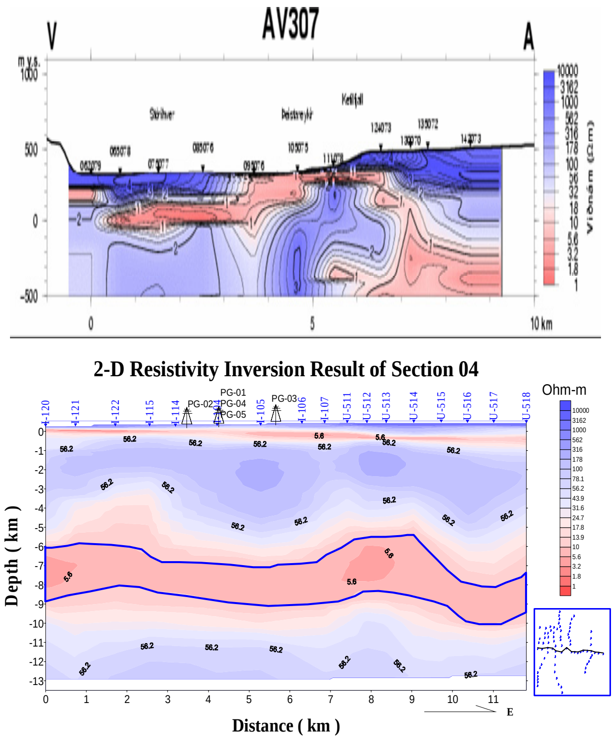


**Figure 3: Top: TEM inversion result of profile 307 (from the ISOR report provided by the client); bottom: 2-D deep MT inversion section 04 shows the striking conductor in depth around 7 km. Location and orientation of the profile is show on the right map insert**

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 km$^2$. The lateral extent of this upper unit is shown in Figure 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 km$^2$. Additionally, a deep conductive geothermal reservoir which has coverage of more than 54 km$^2$ 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 MT data, confirming the inversion results of the data.

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

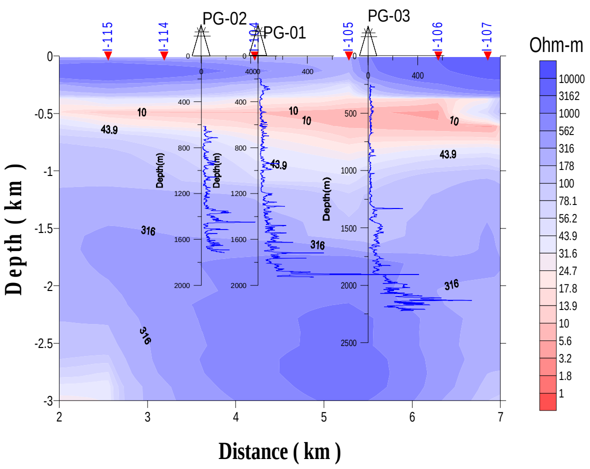


**Figure 4: Expanded view of well ties along section 04. Note the strong correlation between borehole resistivity measurements and the inversion result**

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

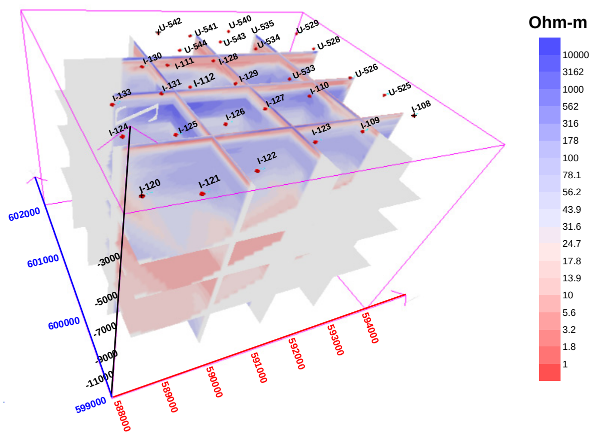


**Figure 5: Slices from the 3-D inversion of the MT/AMT data**

There are many references in the literature concerning the relationship between resistivity and temperature of the rock (Franzson et al., 1986, Fitterman et al., 1988, Oskooi et al., 2005), but to map the distribution of temperature based only on MT results is still difficult because there are too many factors that influence the electrical properties of rocks. 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 temparture will increase fluid mobility causing more electrons to flow and thus reduce resistivity. Only log data of five deep wells indicate the deep temperature of the survey area, so the temperature data from the other geothermal areas are used to establish the temperature model. Research results in Krafla area show that the average temperature of the upper hydrothermal layer, which fluid mainly consists of water, is about 205 °C up to 900 m in depth. The average temperature of lower (deeper) hydrothermal layer (also known as the "boiling layer"), which fluid mainly consists of vapor, liquid, $CO_2$ and other gas, is 300 °C to 350 °C up to 2,000 m in depth (Foulger, et al., 2005, Malin, et al., 2004). The temperature in this area is always near the critical.

Few literatures concern the temperature between 3,000 m to 7,000 m in Iceland especially in Theistareykir area. But some MT results in Iceland recognized the highly conductive material in the middle of the profile, at about 5,000 m depth (Oskooi, et al., 2005). Also, there are many MT results discovering the concealed conductors in the upper crust outside of Iceland. Most of the hydrothermal system results have been interpreted as cooling partial melt zone representing the main heat source of the geothermal system. Meanwhile, they have also been characterized as very high temperature geothermal reservoir (Oskooi, et al., 2005). The rationale which results in the low resistivity lies in several aspects include: melting, fissuring, faulting, fluids, and connate water. Some area is expected to be in supercritical state. All of these are featured as low resistivity and somewhat low seismic velocity. The similar conductor has also been found in the Theistareykir area widely bearing in depth ranges from 4,000 m to 7,000 m or more. Some portion of this conductor is interpreted as the heat source and most of the portions are of high temperature.

Based on the above discussion, the temperature in the survey area is characterized as:

- At a depth less than 1,000 m, the low resistivity area is expected to be of relative high temperature. The temperature in the conductive surface is about 100 °C. At a depth of 1,000 m, the temperature in the conductive layer is expected to be higher than 270 °C, and the temperature in the resistive layer is ranged from 200 °C to 250 °C.
- At depths of 1,000 m to ~ 4,000 m, the low resistivity area is expected to be of relative high temperature and the highest temperature. The average temperature in this depth range is expected to be 370 °C to 400 °C. Some area such as the fissure might be less than 300 °C due to recharge of the cold groundwater.
- At a depth more than 4,000 m, the low resistivity is expected to be of relative high temperature. The temperature in the striking conductive area is expected to be higher than 660 °C in depths of 7,000 m (Figure 6).

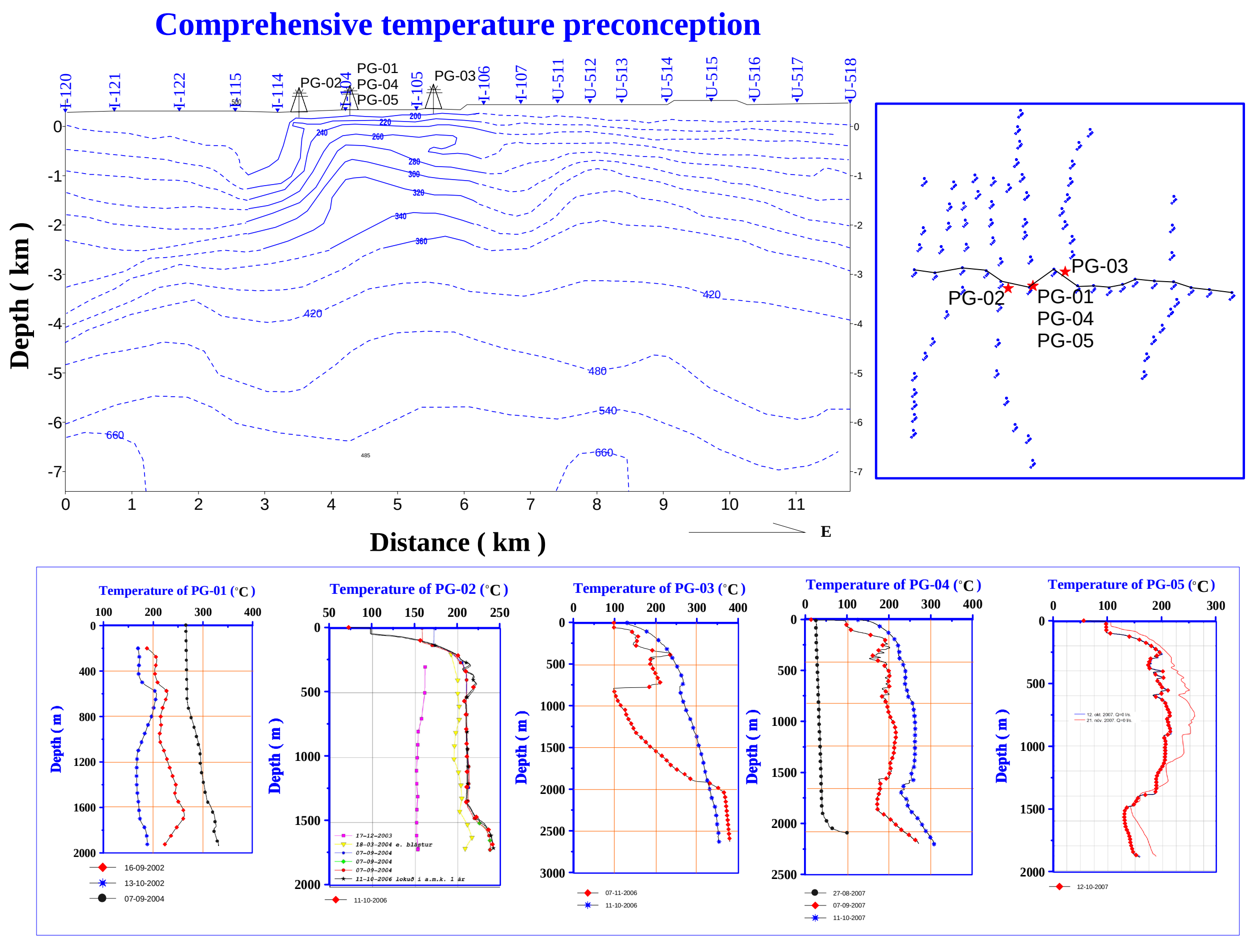


**Figure 6: The comprehensive temperature preconception (based on MT result of Section 04, referencing the data of some other areas which also belong to hot volcano geothermal or hot lava rift geothermal reservoir. Because there are no hot areas below 5 km depth that have been verified, the temperature could just be used as a reference. The solid line in the top figure is based on the result of temperature logging from Well PG-01 to PG-05, the dash line is conjectural)**

## 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 3-D survey has demonstrated the value of collecting denser MT measurements suitable for 3-D 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 2-D and 3-D data acquisition and the expanded use of MT/AMT to identify geothermal potential. The geophysical exploration activities act as a very important role to help explore and characterize a geothermal reservoir among other geoscience methods for potential geothermal power plant construction project.

After processing and interpreting the 2-D MT data acquired in Theistareykir area we conclude:

1. Based on the prominent difference in resistivity of the geothermal reservoir, and its host rock in Theistareykir area, and larger exploration depth, magnetotelluric (MT) shows to be an effective method for the prospecting of the deep hydrothermal system.
2. The MT results agree and integrate well with the shallower TEM and VES.
3. The geoelectric structure identified by 2-D MT and testing 3-D MT data in the northwest corner of the survey area is a four-layer model up to 7,000 m depth. The layers are: *a surface layer* (resistive except in some geothermal spots), *a conductive second layer*, *a deep resistive layer* and *a deeper conductive layer*. Around a 12,000 m (or more) depth, a resistive basement is identified.
4. The hydrothermal reservoir consists of two parts. The upper reservoir part up to 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 km$^2$. 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 km$^2$. Besides, a deep conductive geothermal reservoir which has coverage of more than 54 km$^2$ 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 more than 500 °C.
5. According to the analysis of the linkage between the temperature and the mineral (clay) alteration, and the

relationship between the resistivity and the mineral alteration, the MT interpretation result indicates the relationship between the resistivity, and the temperature through the calibration by using the data from the drilled well and reference data in the other areas. The temperature base on MT interpretation result is featured as: low resistivity relates to 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 5,000 m.

6. The root of heat source in the survey area is based on the rifting model. Base on the MT interpretation, the heat source in the survey area is intrusive. The major depth of the heat source is 4,000 m to 8,000 m. The heating continues to 12,000 m or more. The highest temperature of the heat source at around 7,000 m is expected to exceed 700 °C.

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## REFERENCES

Anderson, E., Crosby, D., and Ussher, G., 2000, Bulls-eye! – Simple resistivity imaging to reliably locate the geothermal reservoir. Proceedings of World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10: 909-914.

Cagnaird, L., 1953, Basic theory of the magnetotelluric method of geophysical prospecting. Geophysics, **18**, 605-635.

Fitterman, D. V., Stanley, W. D.; and Bisdorf, R. J., 1988 , Electrical structure of Newberry Volcano, Oregon: Journal of Geophysical Research, **93**, 10119-10134.

Foulger, G. R., Natland, J. H., and Anderson, D. L., 2005, Genesis of the Iceland melt anomaly by plate tectonic processes. Geological Society of America, Special Paper, 388: 595–625.

Franzson, H., Gudmundsson, A., Fridleifsson, G. O., and Tomasson, J., 1986, Nesjavellir high-temperature field, SW Iceland-reservoir geology: Proceedings of 5th symposium WRI, Reykjavik, Iceland, 23-27.

Georgsson, L. S., Fridleifsson, G. Ó., Ólafsson, M., and Flóvenz, Ó. G., 2000, The geothermal exploration of the Öxarfjördur high-temperature area, NE-Iceland. Proceedings of World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10: 1157-1162.

Malin, P. E., Onacha, S. A., and Shalev, E., 2004. A collaborative joint geophysical imaging project at Krafla and IDDP . ICEKAP 2004, Duke University: 21-26.

Oskooi, B., Laust, B. P., and Smirnov, M., 2005, Electromagnetic induction in the Earth: The deep geothermal structure of the Mid-Atlantic Ridge deduced from MT data in SW Iceland: Physics of The Earth and Planetary Interiors, **150**, 183-195.

Tikhonov, A. N., 1950, Determination of the electrical characteristics of the deep strata of the Earth's Crust: Dok. Akad. Naut., USSR, **73**, 295-297.

Trønnes, R. G., 2003, Geology and geodynamics of Iceland: Nordic Volcanological Institute, University of Iceland, 1-2.