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Mapping Geothermal Reservoir Using Broadband 2-D MT Survey in Theistareykir, Iceland

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SUMMARY

This initial 2-D MT survey has confirmed the finding of previous TEM survey in the Theistareykir field about the existence of a high temperature reservoir under the Theistareykja area, and also outlined better the boundaries of the reservoir along each long 2-D MT survey lines. This study establishes the relationship between resistivity, temperature and lithology. 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.

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). 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 recently 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.

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. 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).

Regional geological setting

Iceland is located where the asthenosperic 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 is slowly dragged to NW but is displaced back on a fixed hot spot by ridge jumps occurring with few-million-year intervals. The plate boundary in Iceland is located inside the neovolcanic zone, a chain of active volcanoes, which traverses the middle part of Iceland.

The 2-D MT 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 acquisition and processing

A total of 78 MT survey sites were acquired mainly in four 2-D survey lines and a small area with 3-D grid in the survey area. For each MT survey site, we conducted two measurements, one is AMT and the other is MT. The 2-D MT survey result has confirmed the existence of two kinds of geothermal reservoir in the Theistareykir area, one has a resistivity value less than 10 Ωm with the depth less than 1,000 m or less than 1,500 m in some locations, the other is a deep geothermal reservoir whose resistivity characterizes as relatively high in conductive surrounding and its depth is usually large than 1,500 m. The shallow geothermal reservoir boundary and depth mapped by 2-D MT data confirmed the finding of previous TEM survey in the Theistareykir field about the existence of a high temperature reservoir under the Theistareykja area. But the MT survey results have much large depth than that the TEM survey could reach. The rough boundary of the geothermal reservoir has been mapped by 2-D MT survey. The deeper geoelectric feature of more than 10 km has been discovered first time by using 2-D MT survey in the Theistareykir area. This information will help us to better understand the source rock distribution and migration of the geothermal in the area.

Data interpretation

The MT data processing and interpretation results indicate that there are two types of resistivity anomalies associated with geothermal reservoir in Theistareykir area. A conductor is seen beneath the lower geothermal layer, its low resistivity layer is considered as the heat source of the overlying geothermal layer (Figure 1). More importantly, it is the striking geothermal resource that might in supercritical state which most researchers consider that its energy is much great than that in normal geothermal field if it could be exploited smoothly.

Geological circumstances in Theistareykir differ from other parts of the volcanic zone in the world. The hot water flows up through basaltic lava, hyaloclastites and intrusives which are 0.5 km ~ 1 km thick according to previous TEM measurements. Thus, comparison with other geothermal fields can be misleading. However, 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 is thought to originate from changes in mineralization at deeper levels, from clay minerals which have loose ions and hence low resistivity, to the more resistive high-temperature alteration minerals, like epidote and chlorite. The change generally happens at temperatures around 250°C. This may not necessarily be representative for the present temperature conditions in the geothermal system, but it has at least reached such temperatures during its lifetime. Shallow exploration drilling has confirmed the existence of mineral alteration related to high temperatures at shallow levels, supporting this theory (Georgsson, et al, 2000).

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. Figure 2 shows the comparison result of the lithology of geologic cross-section in SW Iceland with the observed 2-D MT resistivity in the survey area up to 2,700 m depth. 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.

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 > 500 °C.

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 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.

Conclusions

This initial 2-D MT survey has confirmed the finding of previous TEM survey in the Theistareykir field about the existence of a high temperature reservoir under the Theistareykja area, and also outlined better the boundaries of the reservoir along each long 2-D MT survey lines. This study establishes the relationship between resistivity, temperature and lithology. 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.

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 distinct resistivity layer model up to 7,000 m depth (Figure 1). 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 12,000 m (or more) depth, a resistive basement is identified. 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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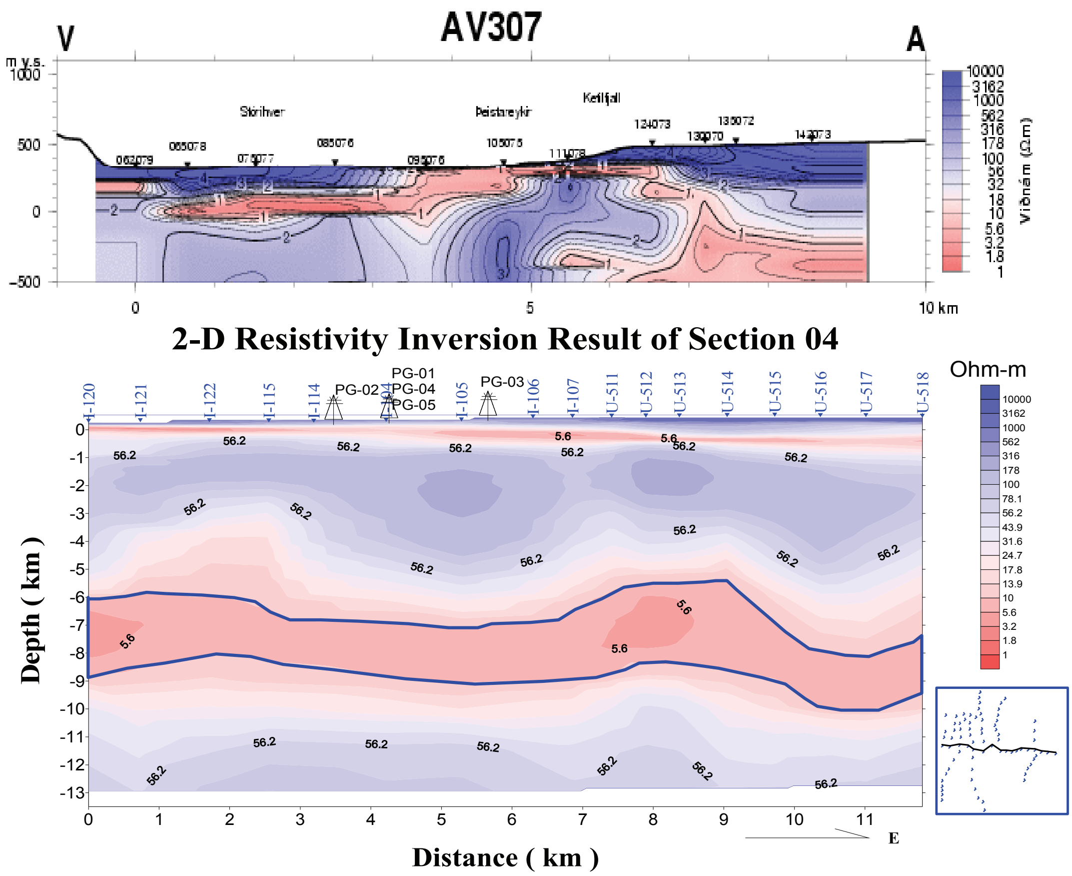

Figure 1: Top: TEM inversion result of profile 307 (from the ISOR report provided by the client); bottom: 2-D deep MT inversion section shows the striking conductor in depth around 7 km. Location and orientation of the profile is show on the right map insert.

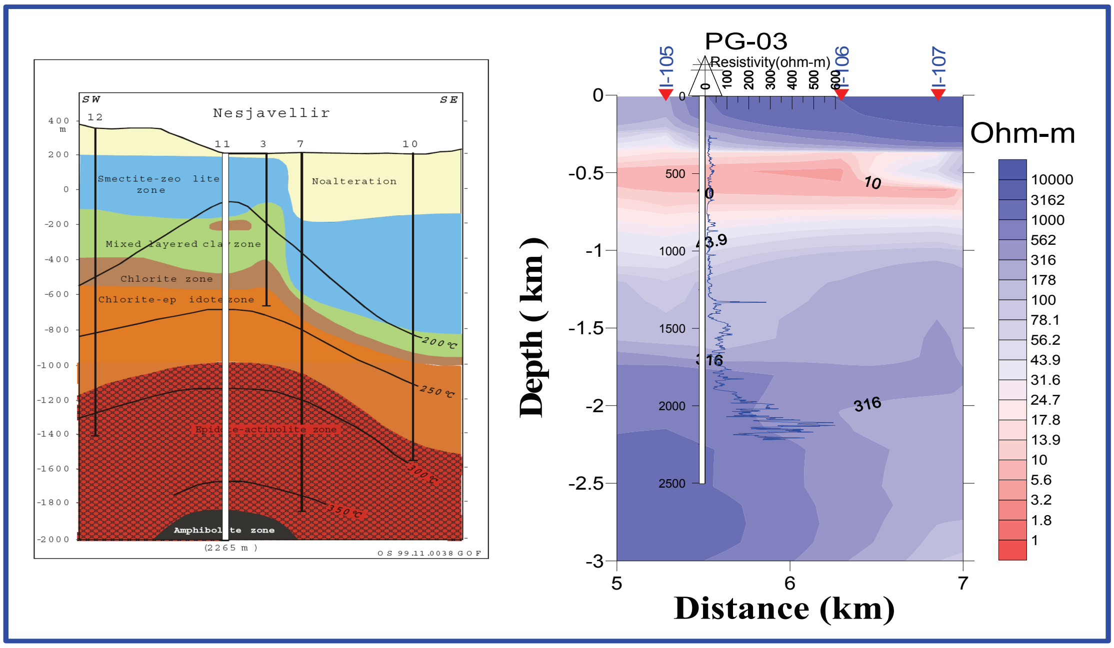

Figure 2: Comparison of the lithology of geologic cross-section across the rift zone at Nesjavellir in SW Iceland (Franzson, et al., 1986) with the observed 2-D MT resistivity in Theistareykir survey area.

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