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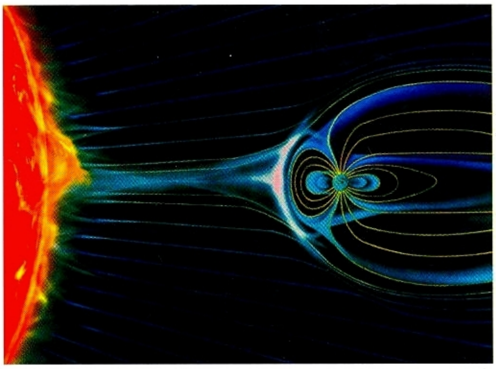

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EM Methods in the Study of Energy and Resources Exploration

Mapping Geothermal Reservoir Using Wide Frequency Range2-D MT Survey in Theistareykir, Iceland

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Introduction

Iceland is one of the best-studied large-volume volcanic area in the world. It features the largest subaerial exposure of any portion of the global spreading plate boundary and is the example of a ridge-centered hotspot. However, how to discover the detail subsurface information of a certain area still proves difficulty. 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 magnetotelluric method is a frequency domain electromagnetic tool that utilizes natural variations in the Earth's magnetic field as a source. Variations in the Earth's natural magnetic field supply frequencies ranging from nearly DC (0.0001 Hz) to more ten kilo Hertz. The wide frequency range MT gives us the ability to study the electric substructure of the Earth from near surface to great depth. The large frequency range also means that the method can handle conductive overburden and has large penetration depth. The MT method measures simultaneously the electric and magnetic fields in two perpendicular directions. This provides useful information about electrical anisotropy (mostly structural) in an area. It is also considerably more cost efficient than for example deep reflection seismic surveys.

The high frequency portion is called Audio frequency MagnetoTellurics (AMT) method. It covers the audible frequency band of 1 Hz to 20 kHz so as to achieve moderate exploration depths to about 2,000 m depending on the terrene conductivity. Like the MT technique, AMT surveys are good at detecting conductive layers and also at measuring thickness of a conductive layer unless they are very thick. The higher temperatures and salinity of the pore water along with increased rock alteration seen in geothermal areas often contribute to a decrease in the bulk resistivity in a rock mass. The AMT method within its exploration depth limit can be useful tool for geothermal investigation. AMT surveys made in about 40 known geothermal areas in the western United States (Sharma, 1997) generally show low resistivity which in many cases appear to correlate with hydrothermal convection systems of high temperature and large stored heat capacity.

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.

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 (figure 1).

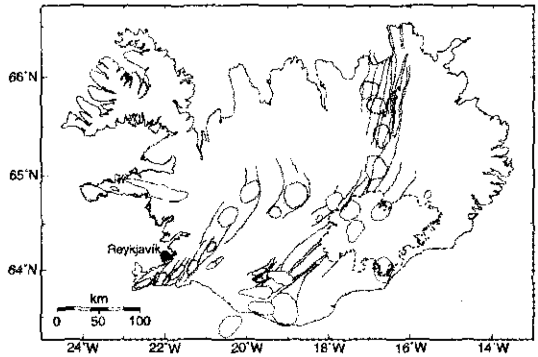

Figure 1: The map of Iceland. The central volcanoes of the Neovolcanic Zone are circled and their fissure swarms shaded gray. The Vatnajökull glacier is outlined with dashed line. All the figures are drawn using the Generic Mapping Tools program. (Soosalu, H., 2004)

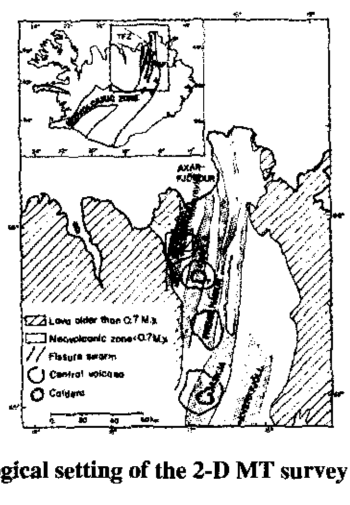

Figure 2:The map of regional geological setting of the 2-D MT survey area (Malin, et al.E2004).

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 (figure 2).

Data acquisition and processing

Three sets of Phoenix MTU-5A systems were used for the AMT/MT data acquisition. We obtained high-resolution electrical conductivity images of the subsurface geological structure at depths between 10 m and more than 10,000 m. The recorded orthogonal components of the electromagnetic field were processed to get the tensor impedance measurements, which can be used for interpreting complex 2-D geological structure. Two pairs of non-polarized electrodes were used for measuring electric field components. Two pairs of high sensitivity induction coil magnetometers were used to measure the magnetic field, one pair which has frequency ranges from more than 10 kHz to 0.01 Hz is used for AMT data acquisition, and the other pair of low frequency induction coil magnetometers used for MT data acquisition has a frequency range from 400 Hz to 0.00025 Hz. The time-domain EM measurements of the electric and magnetic fields acquired in the field were converted into the frequency-domain EM measurements by Fourier transform. The magnetotelluric signal amplitude and phase were calculated by a transfer function. The acquired data needed to be processed by using the system parameters and calibrated data, thus the processed data can be guaranteed to be accurate and without contamination from the acquisition system.

The MTU-5A system program defines time windows and central frequencies without the influence of the sampling interval or data acquisition start time. The horizontal electric field (Ex, Ey) and the horizontal magnetic field (Hx, Hy) were transformed into a 4-component (2×2) tensor magnetotelluric impedance Z through the use of the ROBUST program. Ground resistivity can simply be calculated from the ratio of the amplitudes of the components of the magnetic and electrics fields generated by the currents in the ground (telluric currents). Apparent resistivity ρ in Ωm is roughly $(0.2/f)*(E/H)^2$, where ρ is the apparent resistivity, E is the amplitude of the component of the electric field, and H is the amplitude of the orthogonal components of the magnetic field. Most of sounding sites have high-quality data because the working area is relatively quiet with low environmental EM noise. The result of high frequency data is very important because it provides reliable surface resistivity and high resolution resistivity in shallow depth, which act as important role in the 2-D MT data inversion.

Data analysis

Correlating the resistivity of rocks in Iceland with other geophysical parameters shows that together with temperature and salinity of the fluid, it is the surface conduction along fracture walls (interconnected pores) that dominates the electrical conduction of water-saturated rocks. Hence, variations in the electrical resistivity of rocks are mainly due to different fracture porosity, temperature and alteration minerals lining fractures.

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).

Base on the above discussion and the drilling results in Theistareykir, we consider that there are two geothermal systems in the survey area; one system is from surface to less than 1.5 km in depth. In this system, the resistivity is mainly affected by the hot water and mud flows up through basaltic lava, hyaloclastites and intrusives. The resistivity characterizes relatively low, the temperature is usually less than 250°C. The other system is the deep geothermal reservoir system. In this system, the resistivity is higher than the surrounding rock because of the mineralization caused by hot environment. These give us a way to relate the wide frequency range 2-D MT result to geothermal reservoir.

The 2-D MT survey line layout is shown in figure 3. Figures 4, 5, 6, and 7 are the 2-D MT inversion results of Line 01 to Line 04. The Line 01 to Line 03 is from South to North, and the Line 04 is from West to East. The resistivity, which ranges from 1 Ωm to 15 Ωm, of the shallow geothermal reservoirs is relatively low than the bed rocks, and the depth of the shallow geothermal reservoir is from surface (in MT survey sites I-104, I-105) to about 1,400 m. The resistivity feature of the deep buried geothermal reservoir is more than 200 Ωm and less than 500 Ωm, about twice as or three times higher than its overlying and underlying rocks. To date, we have outlined the deep geothermal reservoir which has a thickness less than 2,500 m. We have find two relatively high resistivity sections and the thickness is larger than 4,000 m (figures 6 and 7), whether they are also geothermal reservoir need further research and more field work to ascertain.

A small area 3-D MT survey on the North-West corner of the survey area also provides detailed 3-dimenaional subsurface resistivity structure. The resistivity contour map (figure 8) and 3-D display (figure 9) of the 3-D MT inversion result on the North-West corner of the survey shows a low resistivity body (less than 1,000 m) below the surface, and followed by a relative high resistivity anomaly (up to 3,000 m) around the new shallow well location I-112 area. This is in consistence with other geothermal reservoirs mapped by the 2-D MT survey in the survey area.

Conclusions

Wide frequency range MT has higher resolution for shallow subsurface formation and deeper exploration depth than the conventional MT method. It could provide more useful and reliable information for geothermal analysis. The geothermal reservoir discovered by 2-D and 3-D MT survey has different resistivity characterization in shallow and deep formation. The shallow geothermal reservoir (up to 1,500 m) has lower resistivity and usually has a temperature less than 250°C. The deep geothermal reservoir (up to 3,000 m) has higher resistivity than its overlying and underlying rocks. Base on the prominent resistivity anomaly of the geothermal reservoir, wide frequency range MT can be effectively used for geothermal reservoir mapping in Theistareykir area and help the client to select the best sites for building geothermal power stations.

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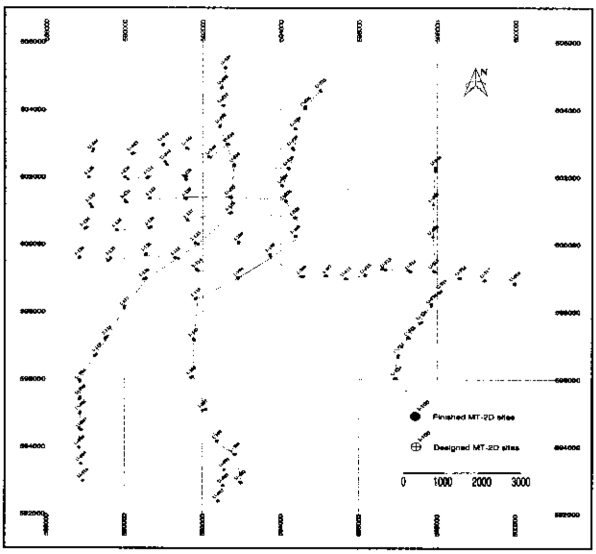

Figure3: Distribution and location of the MT survey sites in Theistareykir 2-D MT survey project.

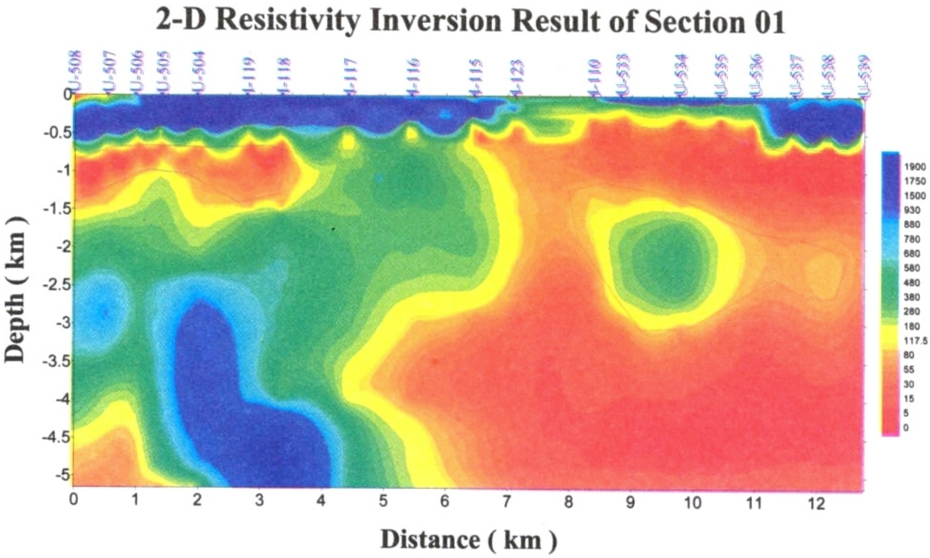

Figure 4: The 2-D MT inversion result shows the geothermal reservoirs. The shallower geothermal reservoir marked in blue polylines, and the deeper geothermal reservoir marked in red polylines.

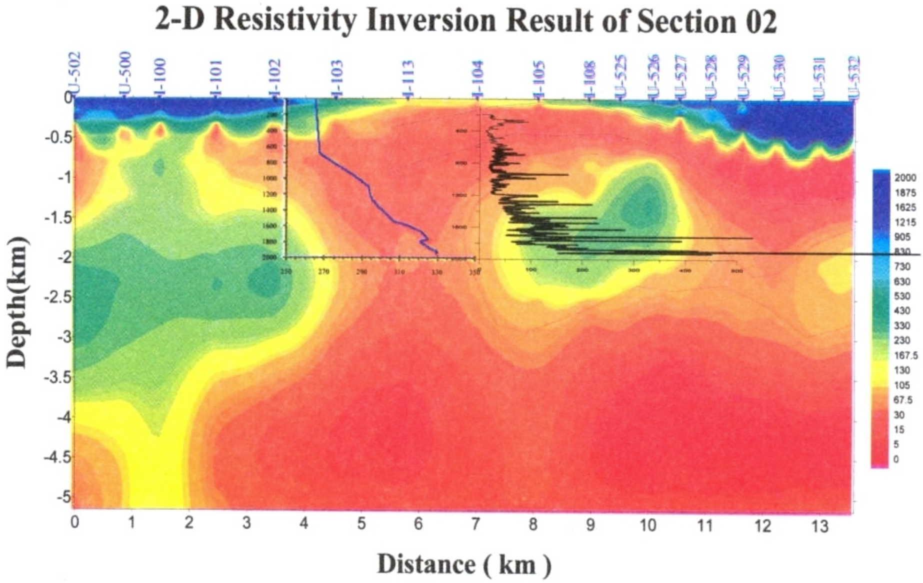

Figure 5: The 2-D MT inversion result shows the geothermal reservoirs. The shallower geothermal reservoir marked in blue polylines, and the deeper geothermal reservoir marked in red polylines. The resisivity log at well ÞG-01 (I-104) is projected in the inversion result, and the temperature log data from well ÞG-01 is plotted on the left side of the resistivity log.

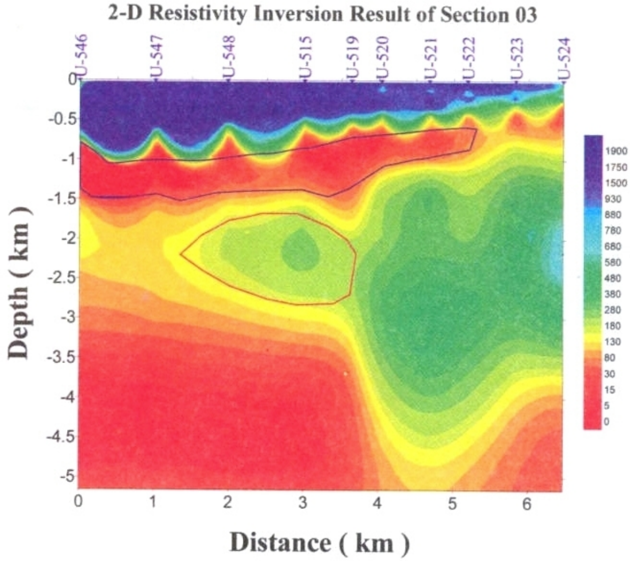

Figure 6: The 2-D MT inversion result shows the geothermal reservoirs. The shallower geothermal reservoir marked in blue polylines, and the deeper geothermal reservoir marked in red polylines.

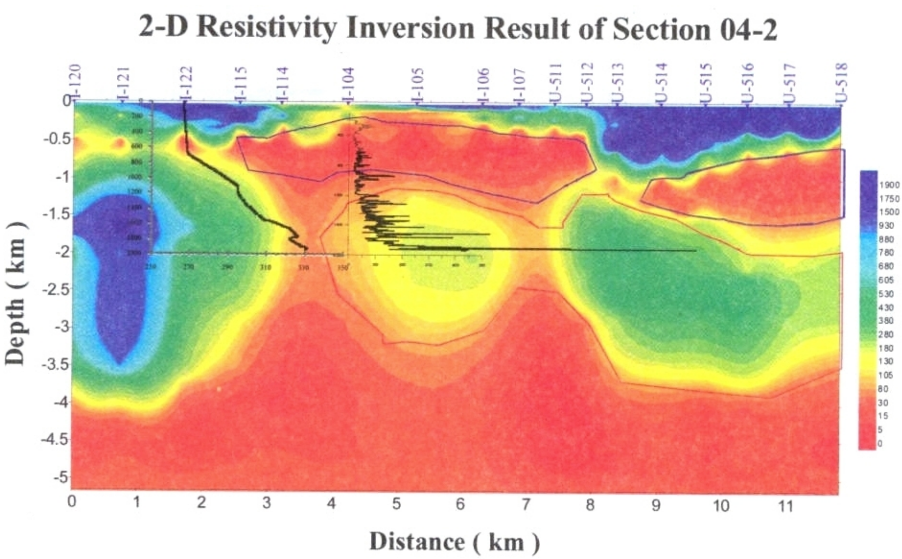

Figure 7: The 2-D MT inversion result shows the geothermal reservoirs. The shallower geothermal reservoir marked in blue polylines, and the deeper geothermal reservoir marked in red polylines. The resisivity log at well ÞG-01 (I-104) is projected in the inversion result, and the temperature log data from well ÞG-01 is plotted on the left side of the resistivity log.

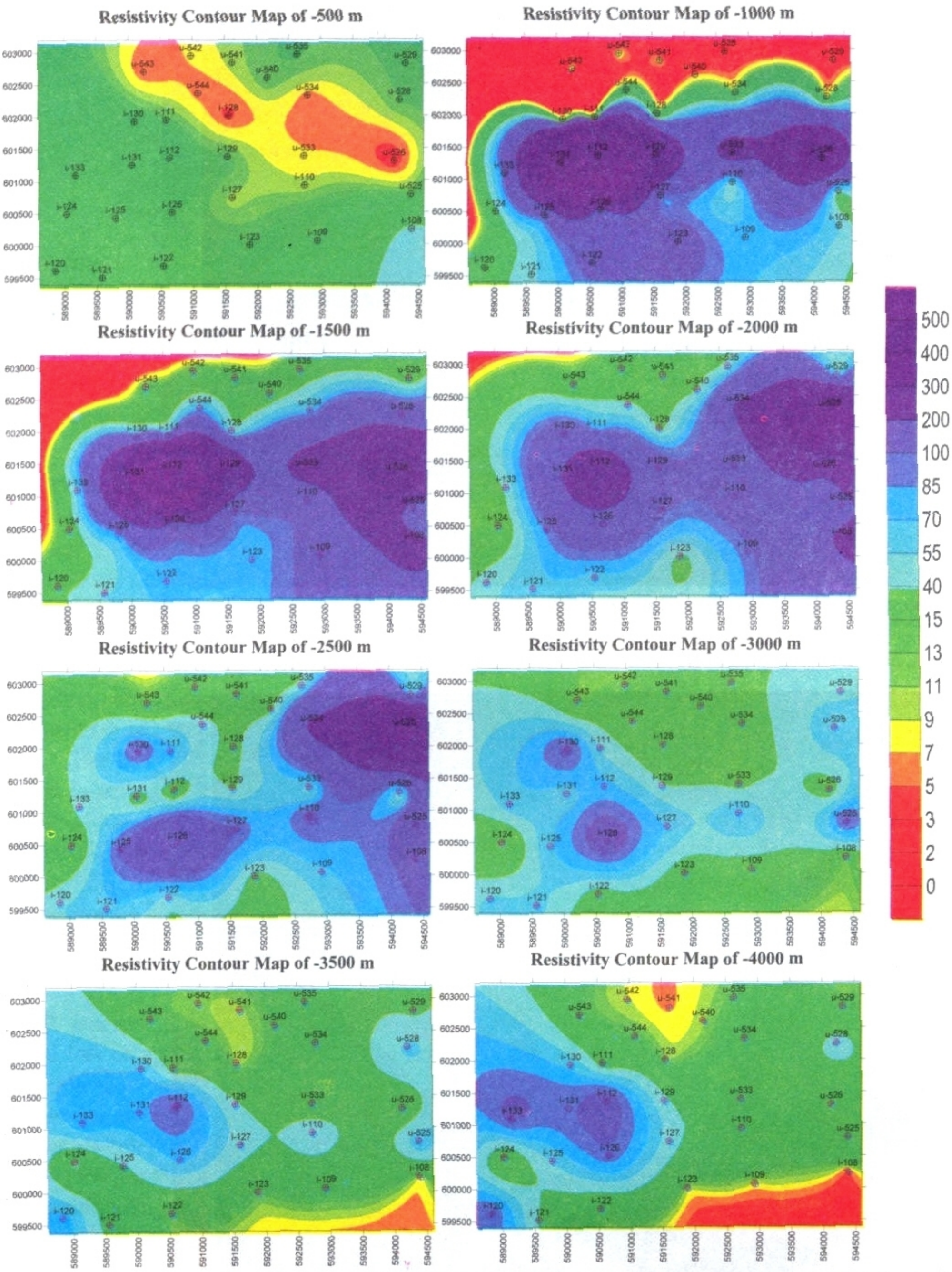

Figure 8: Resistivity contour map of the 3-D MT inversion result shows a low resistivity body (less than 1,000 m) below the surface and followed by a relative high resistivity anomaly (up to 3,000 m) around the new well location I-112 area.

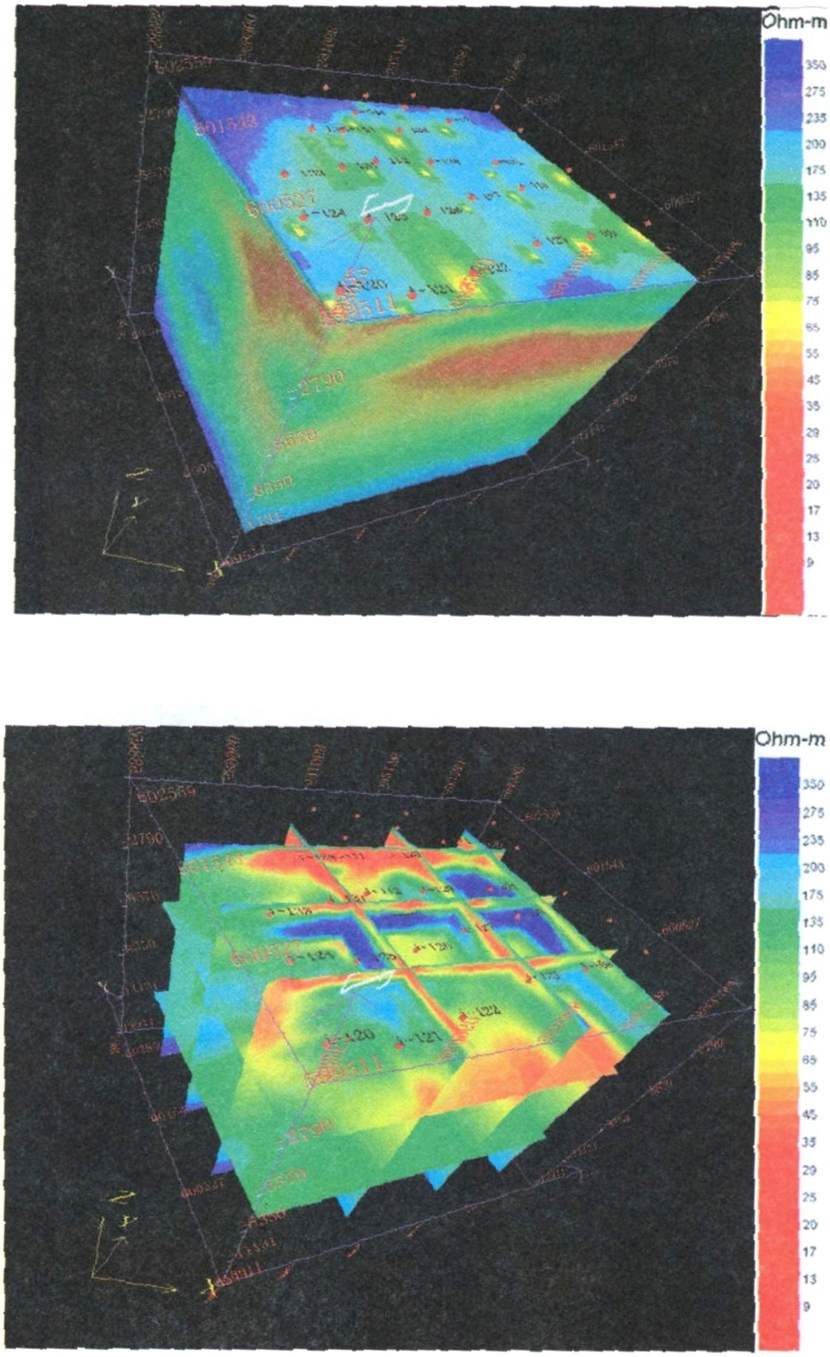

Figure 9: The 3-D MT inversion result displays show *a low resistivity* body below the surface followed *by a relative* high resistivity anomaly around the new well location I-112.

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