# 3D MAGNETOTELLURIC SURVEY AT THE YANAIZU-NISHIYAMA GEOTHERMAL FIELD, NORTHERN JAPAN

Toshihiro Uchida[1], Shinichi Takakura[1], Takumi Ueda[1], Masaho Adachi[2], Hitoshi Ozeki[2], Kunikazu Kamada[3], Tatsuya Sato[4]

[1] Geological Survey of Japan, AIST, 1-1-1 Higashi, No. 7, Tsukuba, 305-8567, Japan
[2] Okuaizu Geothermal, 1-11-1 Ohsaki, Shinagawa-ku, Tokyo, 141-8584, Japan
[3] Tohoku Electric Power, 1-1-1 Honcho, Aoba-ku, Sendai, 980-8550, Japan
[4] Geothermal Energy Research and Development, 1-22-4 Shinkawa, Chuo-ku, Tokyo, 104-0033, Japan
e-mail: uchida-toshihiro@aist.go.jp

**ABSTRACT**

We conducted three-dimensional (3D) magnetotelluric (MT) survey at the Yanaizu-Nishiyama geothermal field, Fukushima Prefecture, northern Japan, where a 65 MWe geothermal power plant has been in operation since 1995. The purpose of the survey was to obtain a detailed electrical resistivity image around the geothermal reservoir over the field, where a sophisticated electromagnetic survey was not conducted since the exploration stage of the geothermal field in 1980s. The 3D MT measurement was carried out at 30 locations in 2010. In addition to these, we utilized existing MT data obtained for a 2D MT survey by the Geological Survey of Japan in 2000 and 2001. Sixteen stations from this existing MT dataset were used for the 3D interpretation. The resistivity model obtained by a 3D inversion indicates clear upper and lower boundaries of the clay cap layer over the geothermal reservoir. Distribution of feed zones recognized in production boreholes is confined below the lower boundary of the low-resistivity clay cap. The shape of the low-resistivity layer also shows a good correlation with the distribution of underground temperature.

**Keywords**: magnetotelluric survey, 3D inversion, geothermal reservoir, Yanaizu-Nishiyama

## 1. INTRODUCTION

The Yanaizu-Nishiyama geothermal power plant started its operation in 1995 with an installed capacity of 65 MWe. The steam production is run by Okuaizu Geothermal, Co., Ltd. (OAG), while the power generation and distribution are operated by Tohoku Electric Power Co., Inc. The running capacity dropped several years after the inauguration and has been at a level of 50 MWe in the past few years. According to OAG, the reservoir evaluation conducted before the installation seemed to be a bit optimistic as compared with the real capacity of the reservoir. Under such circumstances, in order to investigate detailed reservoir structure of the field and to seek for valid information for selecting locations for make-up drillings, a 3D MT measurement survey was conducted in 2010 under a joint research project among Tohoku Electric Power, OAG and AIST. The only intensive electromagnetic survey applied over the geothermal field before the exploitation was long-offset time-domain electromagnetics (LOTEM) with 1D interpretation (Nitta et al., 1987). In addition, electrical logging was not performed in most of production and injection wells drilled in the exploitation stage. Therefore, electrical resistivity structure has not been deeply studied in the area. The aim of the current MT survey is to provide a reliable 3D resistivity model for understanding the reservoir structure better.

## 2. MT DATA

The main survey area, for which we planned to construct a 3D model, is approximately 3.5 km x 3.5 km in size (Fig. 1). The local geological strike is approximately in an NW-SE direction, if we follow the direction of main faults in the field. These faults are estimated to act as conduits for hydrothermal circulation and form a reservoir system (Nitta et al., 1987). The number of MT stations we made measurement in 2010 is 30. Fortunately, AIST conducted another MT measurement in the area in 2000 and 2001 under a geothermal technology research project. We re-processed all of the time series data in this work. Then, we arranged new MT stations to make a grid-like array, by utilizing these existing MT stations. An average station interval is approximately 500 m, although we moved most of the stations in the mountain area to avoid steep terrain change or so. The field instruments used are Phoenix MTU series. The remote reference site is located approximately 200 km away in northern Honshu Island.

A DC train system is operated near the survey area. The nearest train station is about 20 km southeast from the area. Therefore, noisy waveforms caused by frequent load changes of the DC railway were observed at all stations (Fig. 2). Also, the geothermal power plant, located in the center of the survey area, was in operation throughout the survey period. Although we ran data acquisition at least for three days at each site (maximum of six days), average quality of the processed data was not very good. Examples of typical good and bad data are shown in Fig. 3. Station 601 is close to a local village, but the data quality is one of the best among all stations. Station 610, located between the turbine building and one of the well pads, shows the worst quality. Even so, high frequency data above about 0.3 Hz is generally clean for all stations.

Figure 4 shows distribution of induction vectors for six frequencies. Directions of induction vectors at 100 Hz seem to be very random and amplitude is generally small, while vectors at 1 Hz and 0.1 Hz show bigger amplitude and a northward trend at the center of the survey area. At 0.01 Hz, vectors become small, which indicates small resistivity change in lateral directions in a corresponding deeper layer. Induction vectors at 1 Hz and 0.01 Hz make a selection of optimal direction for 2D interpretation difficult. This frequency range is important for delineating the resistivity structure at depth of 1 and 2 km. Actually, a trial of 2D inversion for NE-SW profile and NW-SE profile indicated inconsistent resistivity structure with each other. So, we only refer to 3D inversion result in this report.

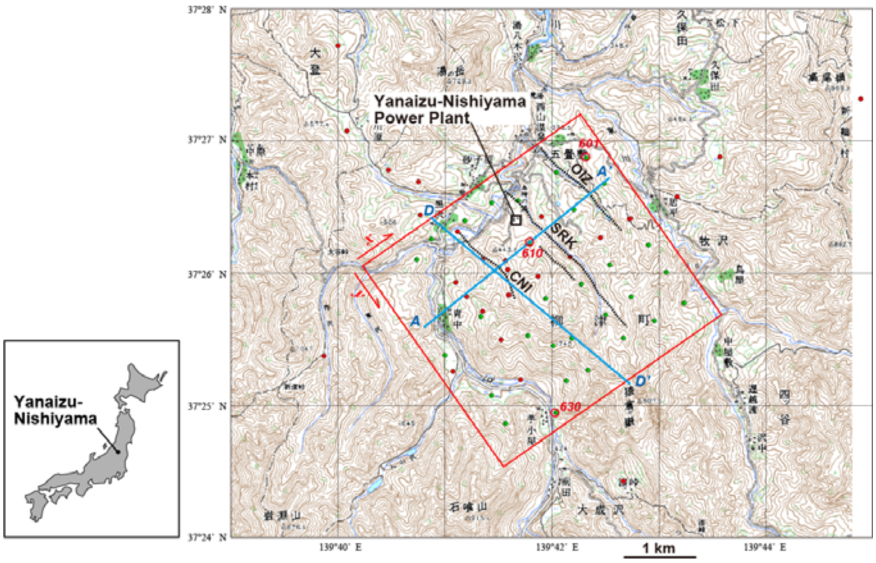


Fig. 1. MT survey stations at the Yanaizu-Nishiyama geothermal field. Green and red dots are MT stations in 2010 and 2000/2001, respectively. Dashed lines are estimated faults; CNI: Chinoikezawa Fault, SRK: Sarukurazawa Fault, OIZ: Oizawa Fault. The red rectangle is a zone for 3D interpretation. Cyan lines are profiles for comparison between resistivity model and drilling data.

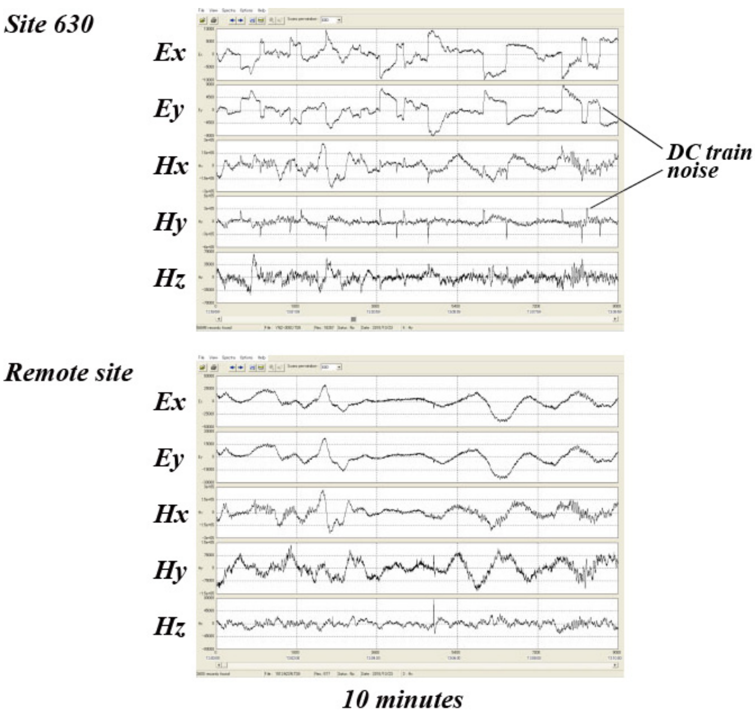


Fig. 2. Example of time series data at Station 630 and the remote reference site, showing 10-minute data starting at 9:00 pm, 23 October 2010, local time. x-direction is N32°E for Site 630, while it is north for the remote site.

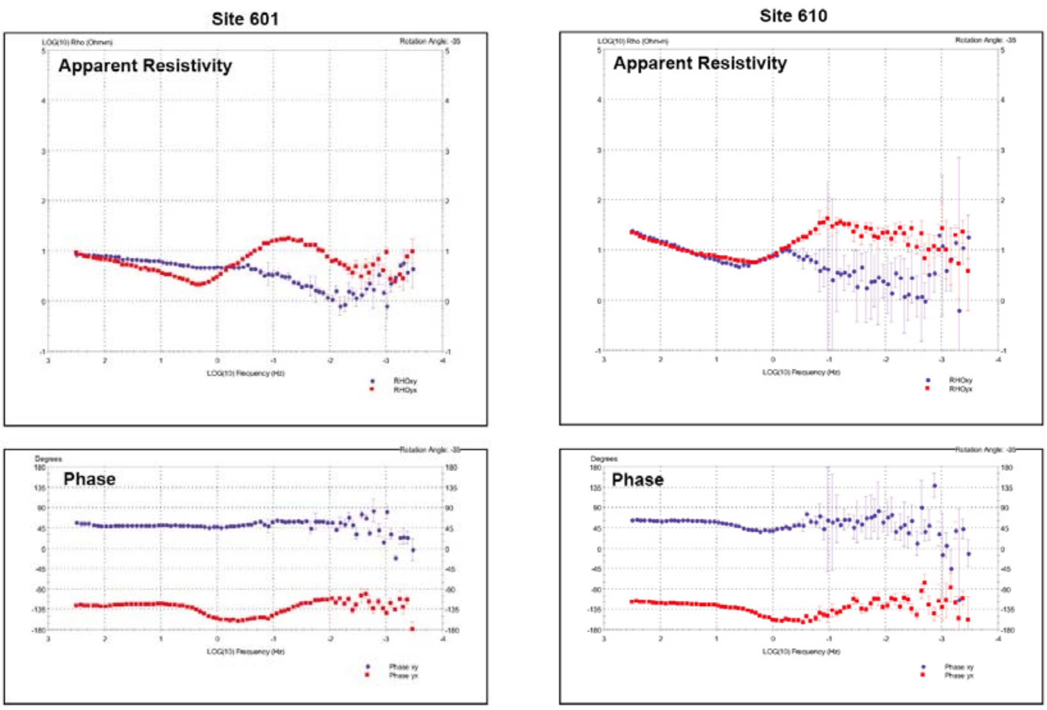


Fig. 3. Examples of apparent resistivity and phase data at (left) Station 601 and (right) Station 610. x-direction for impedance rotation is N35°W.

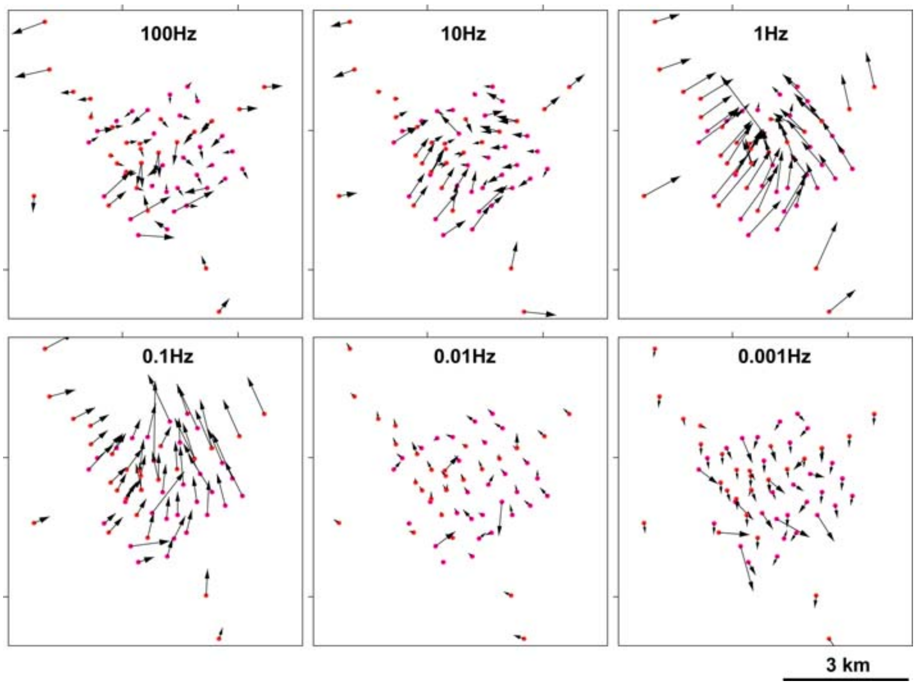


Fig. 4. Induction vectors at six frequencies. The vectors point toward a low-resistivity anomaly. A length of 3 km corresponds to unit amplitude of the tipper.

## 3. 3D INVERSION

We set a rectangular zone for the 3D interpretation, with x-axis of N55°E, and rotated the MT impedances to this direction (Fig. 1). The number of MT stations used is 51, and fifteen frequencies, 0.0134 Hz - 229 Hz, are used for the inversion. The cell size on the surface in the interpretation zone is 100m (x) x 100m (y) x 25m (z), and the number of cells is 59 (x) x 57 (y) x 40 (z) in total for the finite-difference forward modeling. Although the topography change is not small in the survey area, ranging from some 350 m to 750 m above sea level, it is not considered in the 3D inversion due to the limitation of the modeling code (Uchida and Sasaki, 2006).

Final 3D resistivity model is shown in Figs. 5, 6 and 7. Figure 5 shows depth slice sections of the 3D model. Figure 6 shows a 3D view with a horizontal slice of a 100 m depth. Figure 7 shows vertical cross-sections at x = 1.4 km and y = 1.0 km.

Low resistivity anomaly is distributed at the surface in the northern half of the survey area. It corresponds to three faults (Chinoikezawa, Sarukurazawa and Oizawa) and surrounding surface alteration zones, including Nishiyama hot spring. From a depth of 300 meters to 1 km, thick low-resistivity layer expands over the entire survey area, except for the southern end. This seems to correspond with a clay cap of the reservoir system. From a depth of about 3 km, a deep low-resistivity layer appears from southwestern side and it expands over the survey area at about 10 km depth. In Fig. 7, we can recognize that thickness of the low-resistivity cap layer varies, and it is the thinnest beneath Sarukurazawa Fault in the right hand section of Fig. 7. Along Chinoikezawa Fault, low-resistivity layer becomes thicker eastward. It indicates low-temperature layer is thickening eastward in this zone.

## 4. INTERPRETATION

Fig. 8 compares the 3D resistivity model with the borehole data, including estimated temperature and feed zones of hydrothermal fluids. Section AA', which is in an NE-SW direction, crosses the three faults. Distribution of high-temperature feed zones is located in relatively high-resistivity zones, while no feed zones are observed in the low-resistivity cap layer above. Based on the analyses of drilling data and core samples, Seki and Adachi (1997) reported that smectite-rich zone was observed in the shallow layer, while sericite and chlorite were dominant in the deep reservoir layers along a section close to AA'. Although the resolution of the 3D model is weak for deep structure, general trends in distinguishing low-temperature clay cap and high-temperature reservoir zones are very consistent with the borehole data.

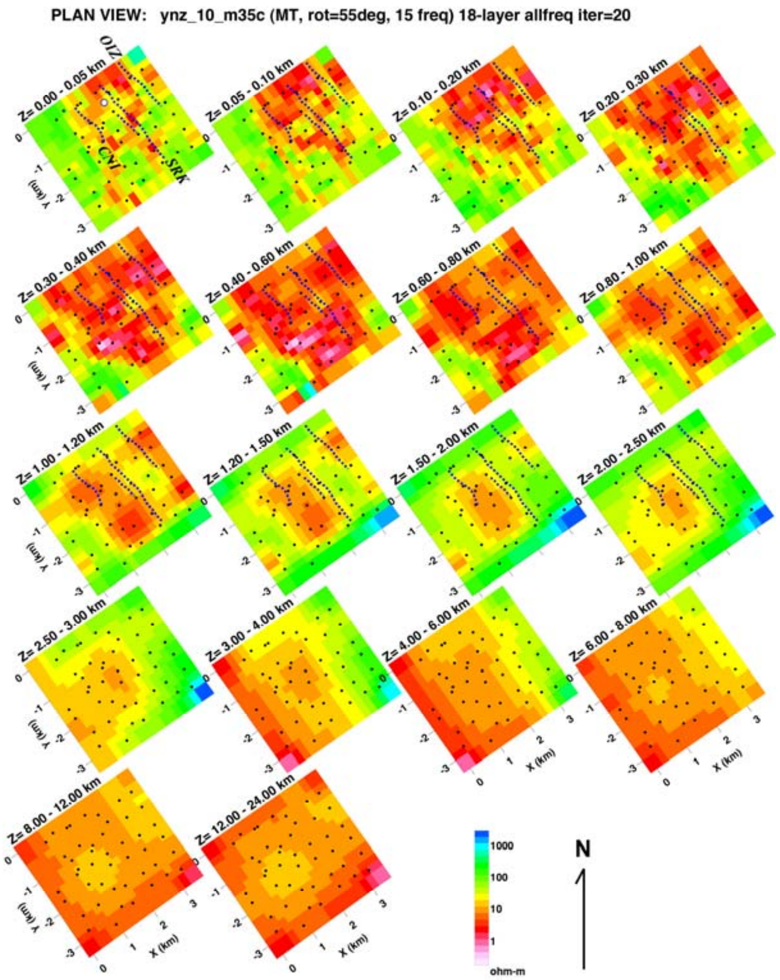


Fig. 5. Depth-slice sections of the 3D resistivity model. Dashed lines are estimated faults. The small open circle on the top-left section indicates location of the power plant building.

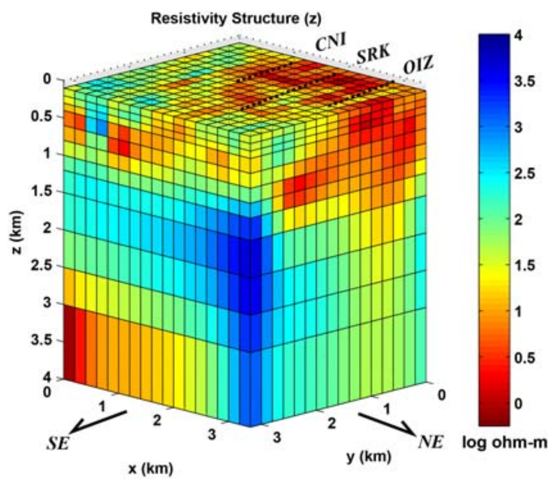


Fig. 6. 3D resistivity model, looking from east, showing a horizontal slice at 100m depth. Dashed lines are estimated faults.

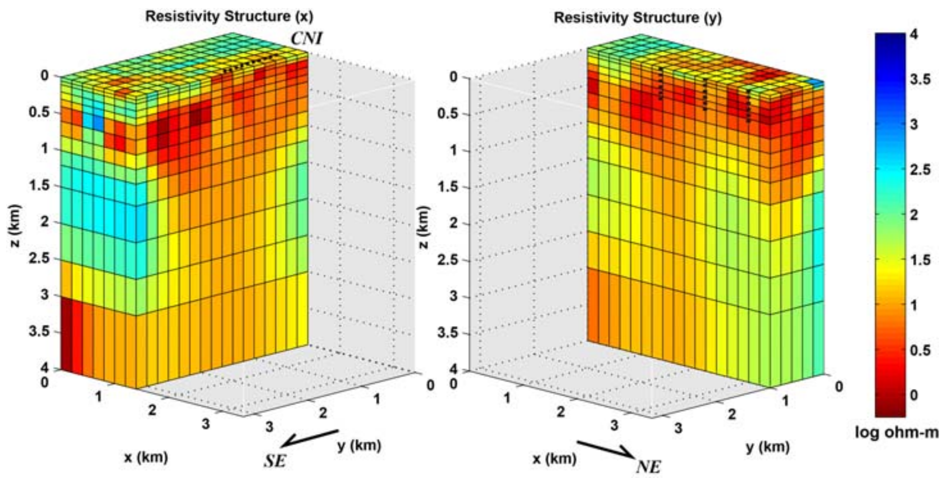


Fig. 7. 3D resistivity model, looking from east. Cross sections at (left) x=1.4 km and (right) y=1.0 km are shown. Left cross section is approximately along Chinoikezawa Fault.

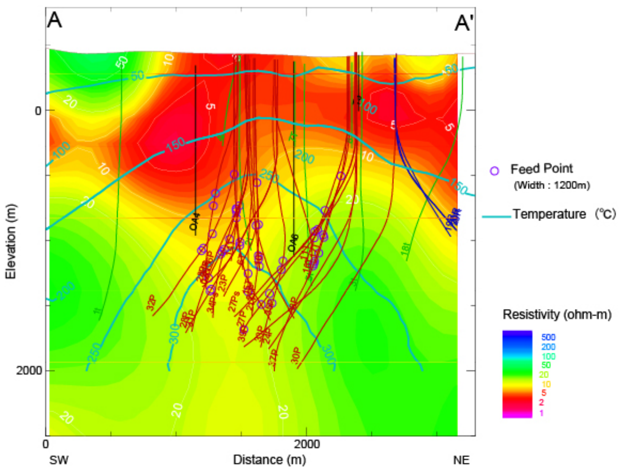


Fig. 8. Comparison of 3D resistivity model with projected borehole trajectories, underground temperature and feed points of the production wells along profile AA' shown in Fig. 1. Location of this section is almost same as the section shown on the right panel of Fig. 7.

## 5. SUMMARY

A 3D MT survey was carried out in the Yanaizu-Nishiyama geothermal field. In general, the quality of the obtained low-frequency data was not good because of noises caused by a DC train system near the survey area. The final 3D resistivity model, obtained for the first time in the field, showed clear image of low-resistivity clay cap and high-resistivity hydrothermal reservoir. These interpretations are also very consistent with borehole data compiled by Okuaizu Geothermal.

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