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GEOELECTRICAL INVESTIGATION OF THE KAKKONDA GEOTHERMAL FIELD, NORTHERN JAPAN

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ABSTRACT

The Geological Survey of Japan (GSJ) and the New Energy and Industrial Technology Development Organization (NEDO) have carried out magnetotelluric (MT) surveys with a dense station coverage in the Kakkonda geothermal field, northern Japan. The Kakkonda geothermal plant is utilizing steam and hot water produced from reservoirs at depth of 1000 - 3000 meters. A very young granitic rock was found at a depth of approximately 3 km. MT measurements have been done on several survey lines covering the geothermal field in order to delineate the resistivity structure of the reservoir and the granite. Due to the complicated resistivity structure, dominant strike direction of the impedance rotates from higher frequency to lower. Shallow parts of two-dimensional models have good agreement with reservoir structure and resistivity logging data, showing very conductive zone of the clay-rich cap layer of the reservoir. Main body of the young granite was interpreted as a low-resistivity zone. However, due to the three-dimensionality, some of the 2-D models seem to be poor in delineating resistivity structure in deeper portions.

1. INTRODUCTION

Subsurface resistivity distribution is one of the key information factors for exploration of geothermal reservoirs. Highly active geothermal areas usually have low resistivity values as compared with surrounding non-geothermal zones, because the circulation of high-temperature geothermal fluid and production of alteration clay minerals generally decrease the formation resistivity.

Electromagnetic methods, such as natural source magnetotellurics (MT) and controlled-source audiofrequency magnetotellurics (CSAMT), are now widely applied in geothermal fields (e.g., Romo et al., 1997). The introduction of robust two-dimensional inversion programs (e.g., deGroot-Hedlin and Constable, 1990; Uchida, 1993) in the past decade has proven the usefulness of MT data for understanding reservoir structures, by providing detailed and reliable resistivity images.

However, geologic structure of geothermal fields is often very complicated because of irregular volcanic formations and non-uniform hydrothermal circulation and alteration. This study is aiming at a 3-D interpretation of MT data in a geothermal field. In this paper, however, models obtained by 2-D inversion of a dense MT dataset are discussed.

2. DATA

NEDO and GSJ conducted a 3-D magnetotelluric survey in 1998 at the Kakkonda geothermal field, located in northeastern part of Honshu Island, Japan. The survey consisted of 89 stations which are mostly arranged along four survey lines: Line B, C, D and E (Fig. 1). There were some other MT surveys carried out by NEDO and GSJ in 1994 and 1996: Line 1, 2 and 3. In this paper, models of four lines in 1998 and Line 1 and 3 in 1994 (Line-1) are shown.

The geothermal field is located in a small valley of WNW-ESE direction, which is surrounded by several peaks of Quaternary volcanoes in both northern and southern sides. This area is underlain by Quaternary volcanic rocks. However, there is thick Tertiary sedimentary and volcanic formations beneath the young volcanics. The power plant, whose installed capacity is 80 MWe, is located in the middle of the valley. The size of the production and re-injection zone is approximately 3 km along the valley and 2 km across the valley. The plant utilizes hot-water-dominated geothermal fluid produced from the reservoir at depth of 1000 – 3000 m. Deeper portion of the reservoir is associated with the fracture systems which were created by intrusion of Quaternary granite (Doi et al., 1998). The granite is very young, less than 0.3 Ma, and estimated to be the heat source of the reservoir system. NEDO drilled a deep research well, WD-1, at the northwestern edge of the production zone to seek a deep high-temperature reservoir.

The direction of the four survey lines (Line-B, C, D and E) is approximately 70 degrees from north. MT stations were placed every 200 meters along the lines. Since there is an active power station, it is not possible to put a site near power lines and steam lines which mostly run along the valley. Line-1 has a direction of 110 degrees from north. It has 14 tensor MT sites and 48 scalar MT sites.

Fig. 2 shows induction vectors at 8 Hz and 0.3 Hz at the stations of the 1994-1996 surveys. Tipper amplitude is relatively small at 8 Hz and the induction vectors generally point toward the mountain side. The impedance strike at this frequency is greatly affected by the topography. Tipper becomes bigger at 0.3 Hz: as large as 0.3 to 0.5. The vectors generally point toward east or ESE direction. This indicates that a large low-resistivity body is situated in the south-eastern part of the surveyed area.

3. TWO-DIMENSIONAL MODELS

The direction of the survey lines in 1998 is not always consistent with the regional resistivity strike. It was because the accessible area is limited due to heavy forests and environmental regulation of the national park. Based on the induction vectors and general trend of impedance strikes, we chose the rotation direction of the impedance as east-west for the lines in 1998 and Line-3. For Line–1, the impedance was rotated to the line direction, 110 degrees from north. Distortion decomposition (Groom and Bailey, 1989), such as the Groom-Bailey Decomposition, was not applied this time, and only single mode impedance (TM mode) was used for the 2-D inversion. The frequency range of the data is approximately from 0.1 Hz to 100 Hz. The inversion method applied is the linearized least-squares inversion with smoothness regularization (Uchida, 1993).

Four models of the lines of the 1998 survey, B, C, D and E, are shown in Fig. 3. These lines cross the valley. Major features of the resistivity structure are as follows.

1) There is a shallow low-resistivity zone, less than 10 Ωm, below the surface in the eastern part of the four lines. It has a thickness of less than 1 km.
2) A thick resistive layer, as high as several hundred ohm-meters, is widely distributed at the elevation from 0 km to -2 km. It is more resistive in the western part of the lines.
3) Below the elevation of –2 or –3 km, there is a very low-resistivity anomaly in the middle of the lines. It is the deepest at the valley, and become shallower as we go eastward.

A 2-D model of Line-1 is shown in Fig. 4. Line-1 is approximately parallel to the valley and is located in the eastern side. General features of the resistivity structure are similar to those of the four models described above. There is a shallow low-resistivity zone in the center of the line, from sites 22 to 55. This low-resistivity layer continues and becomes thicker toward the southeastern end of the line. The reason why the induction vectors at 0.3 Hz point southeastward is this thick low-resistivity zone. There are four resistive anomalies in the middle of the line at elevation of 0 km to –1 km. Data quality near the power plant is not always good, however, these anomalies are always produced by the inversions even if we change the parameters for inversion, such as noise assumption. Therefore, the existence of these anomalies seems true. In the deeper portion, there is a very low-resistivity body in the middle of the line. It corresponds to the deep conductive anomaly interpreted in the four lines above.

A 2-D model of Line-3 is shown in Figure 5. The resistivity structure is again similar to the other models described above. There is a shallow conductive layer near the surface, a thick resistive layer at elevation of 0 km to –2 km, then below is a low-resistivity zone.

4. INTERPRETATION AND DISCUSSIONS

Figure 6 is a simplified geology section of the Kakkonda geothermal reservoir along the valley (Doi et al., 1998). Temperature around and in the Quaternary granite is very high, and a record high temperature, 500 degrees Celsius, was observed at the bottom of WD-1 (e.g., Muraoka et al., 1998). From the temperature data and distribution of clay and metamorphic minerals, three zones are interpreted for the reservoir system: 1) surficial cap layer to a depth of several hundred meters, 2) hydrothermal convection zone approximately from 1 km to 3 km depth, and 3) thermal conduction zone in the granite body.

Figure 7 compares the resistivity logging data in WD-1 and models of Line-1 and Line-B. Since those sites are located on a rapid change of resistivity in the models, the comparison with the logging data is not easy. However, the shallow low-resistivity layer and mid-depth high-resistivity zones are well determined by the MT models. The logging data gave high-resistivity in the granite, while MT models indicate low resistivity. Resolution of the MT models for deeper portions is not high, therefore, it is dangerous to say that the granite has low-resistivity. However, it was found from the chemical analysis of the water sampled from the bottom of WD-1 that the granite contains dense brine in its pore. Therefore, it is reasonable to interpret that the inner portion of the granite has low resistivity.

When we interpret the resistivity model of Line-1 (Fig. 4), the shallow low resistivity zone corresponds to the cap layer of the reservoir. This low resistivity is caused by high content of clay minerals, such as montmorillonite. The very low-resistivity anomaly below –2 km level indicates the inner body of the granite. In between those two conductive layers, there is a thick and relatively resistive zone which corresponds to the hydrothermal convection zone of the geothermal reservoir. However, the resistivity distribution in the reservoir zone is complicated and reliability of the model is not sufficient. Low-quality data easily change the final model. Also, 2-D inversion itself has a limitation when applied to a 3-D environment in geothermal fields.

5. CONCLUSIONS

A 3-D magnetotelluric survey was performed in the Kakkonda geothermal field for the purpose of delineating resistivity structure of deep reservoirs. 2-D inversion of the MT data on several survey lines gave a good indication to understand the reservoir structure: low-resistivity cap layer near the surface, relatively resistive reservoir zone, and low-resistivity granitic intrusion. However, 2-D models differ when we choose a different rotation direction of the impedance. Further development of 3-D technology is necessary for precise and reliable interpretation of deep structures.

ACKNOWLEDGMENTS

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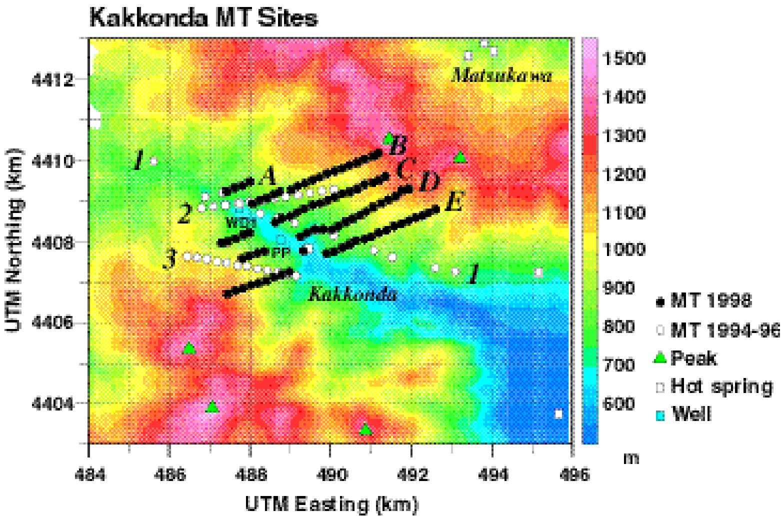

Figure 1. Magnetotelluric survey stations (open and solid circles) at the Kakkonda geothermal field, northern Honshu, Japan, shown on a topography map. Triangles are peaks, open squares are hot springs, and solid squares are drillholes. PP indicates Kakkonda power plant, and WD1 is a research well drilled by NEDO.

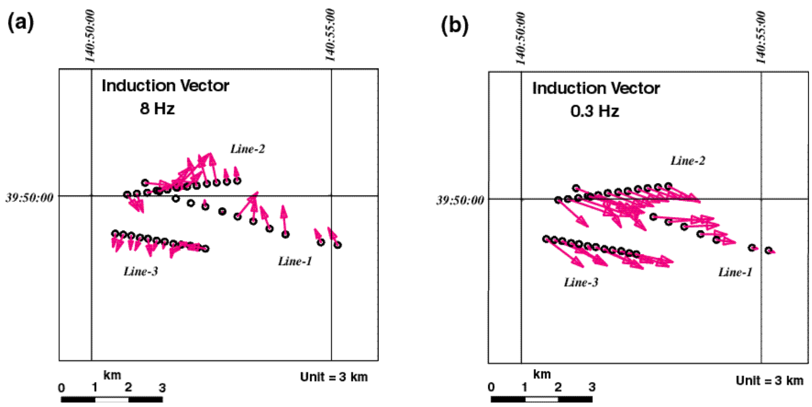

Figure 2. Induction vectors at (a) 8 Hz and (b) 0.3 Hz at the MT sites of the 1994 and 1996 surveys. Unit amplitude corresponds to a length of 3 km.

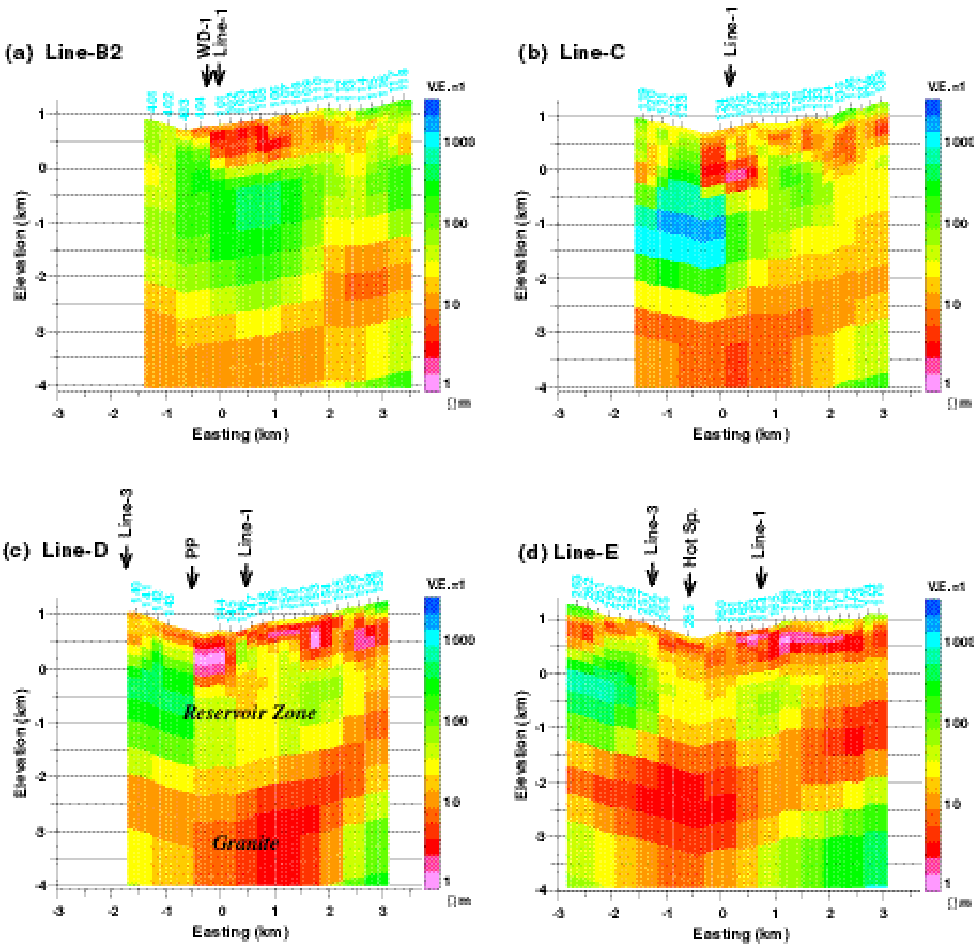

Figure 3. Resistivity models obtained by 2-D inversion of TM-mode data on four lines in 1998, (a) Line-B, (b) Line-C, (c) Line-D and (d) Line-E. Impedance used was rotated to the direction of east-west.

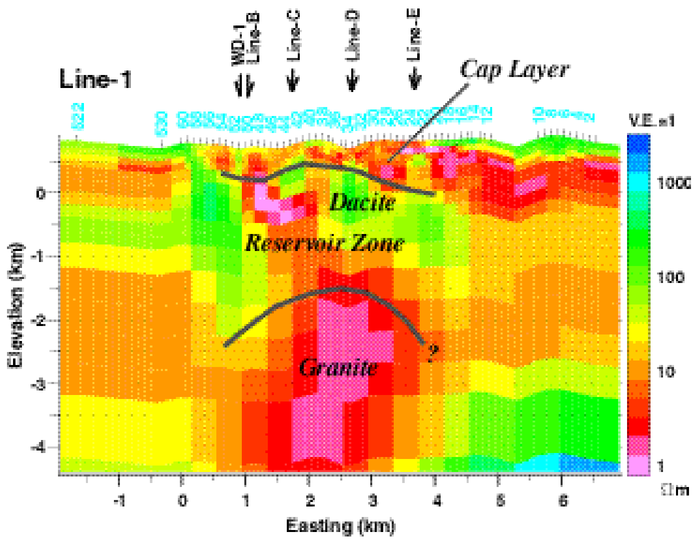

Figure 4. Resistivity models obtained by 2-D inversion of TM-mode data on Line-1. Impedance used was rotated to the direction of survey line. Preliminary geological interpretation is superimposed.

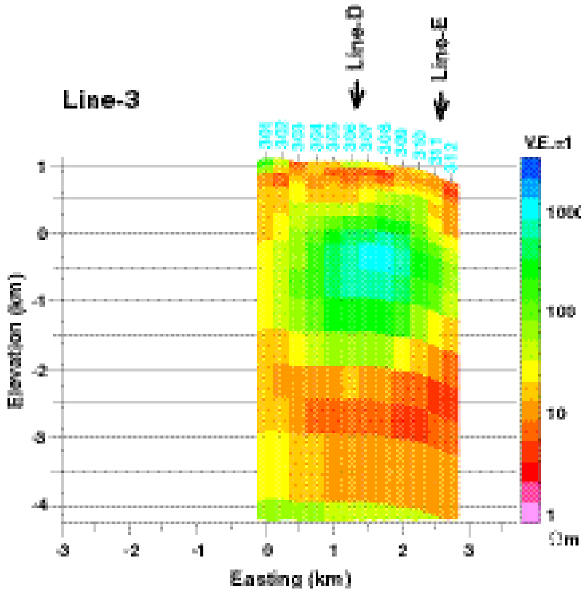

Figure 5. Resistivity models obtained by 2-D inversion of TM-mode data on Line-3. Impedance used was rotated to the direction of east-west.

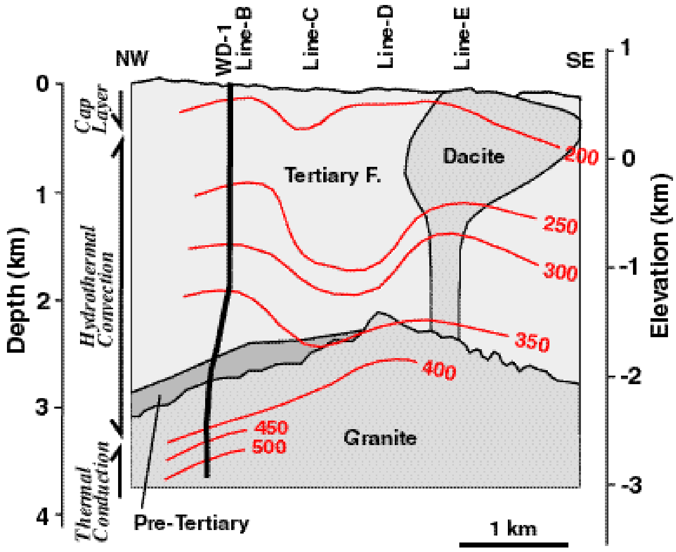

Figure 6. A simplified geology section along the valley (reproduced from Doi et al. (1998)). Contours indicate temperature distribution in degrees Celsius.

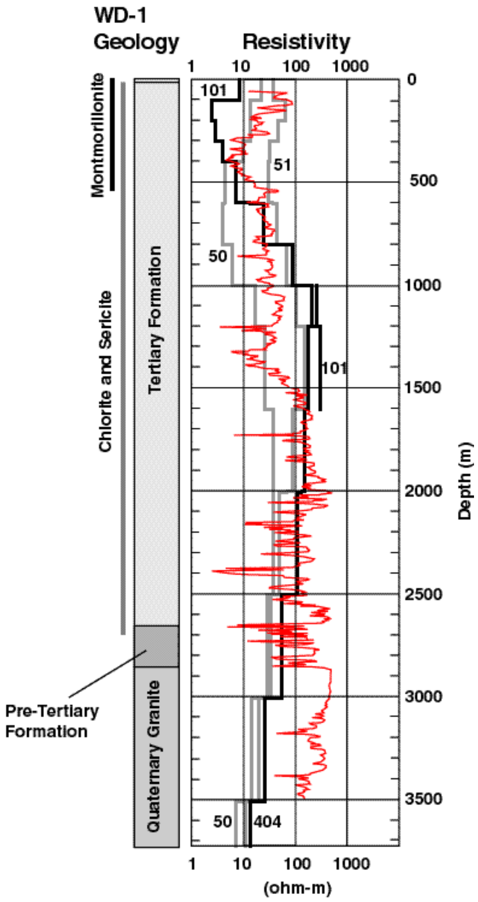

Figure 7. Comparison of the resistivity logging data (long normal array, thin solid line) in WD-1 and resistivity models of Line–B (Site 404 and 101, thick black lines) and Line-1 (Site 50 and 51, thick gray lines). Zones where clay alteration minerals distribute are also shown.