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Three-Dimensional Interpretation of AMT Data in Ogiri Geothermal Field, Japan

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ABSTRACT

An audiofrequency magnetotelluric (AMT) survey was conducted for detailed investigation of the reservoir at the Ogiri geothermal field, southwestern Japan. The AMT stations were arranged with an interval of about 150 m on a grid-like array whose size was approximately 1.5 km x 1.5 km. This survey was targeting an expansion of the currently producing geothermal reservoir to the east. There had been conducted several stages of MT surveys in the same area before. This report presents three-dimensional (3D) inversion of the AMT data, together with comparison with 3D models of the MT data. The resultant 3D AMT models are consistent with the MT models reported in the past. The boundary between the low-resistivity cap layer and the high-resistivity reservoir zone is more complicated in the AMT model than the MT models. This suggests that high-resolution imaging is possible for delineating the top surface of geothermal reservoir by the AMT method.

1. INTRODUCTION

The magnetotelluric (MT) method is one of the major geophysical tools in geothermal exploration. The resistivity structure of a geothermal reservoir is often characterized by a combination of a low-resistivity clay-rich cap layer above and a relatively high-resistivity reservoir zone below (e.g., Arnason and Flovenz, 1992; Uchida, 1995; Anderson et al., 2000; Ussher et al., 2000). This resistivity structure is usually applicable when clay minerals are dominant hydrothermal alteration in a geothermal field.

The penetration depth of the AMT method is smaller than that of MT. However, it may be a good tool for geothermal exploration because of its faster and easier data acquisition in the field survey than MT. The purpose of this study is to examine how the AMT data can provide sufficient resistivity information for geothermal exploration.

2. AMT SURVEY

The Ogiri geothermal area is located in the southern part of Kyushu Island, southwestern Japan. A 30-MWe geothermal power plant has been operated by Nittetsu Kagoshima Geothermal Co., Ltd. (NKG) since 1996 (Figure 1). The neighboring Shiramizugoe field to the southeast is thought to be a promising area for future expansion of steam production. The survey area is situated on a highland whose elevation is from 700 m to 900 m. The area is underlain by Quaternary volcanic rocks with a thickness of 2–3 km. Below this layer is a Mesozoic metamorphic formation that forms the basement rocks of this region.

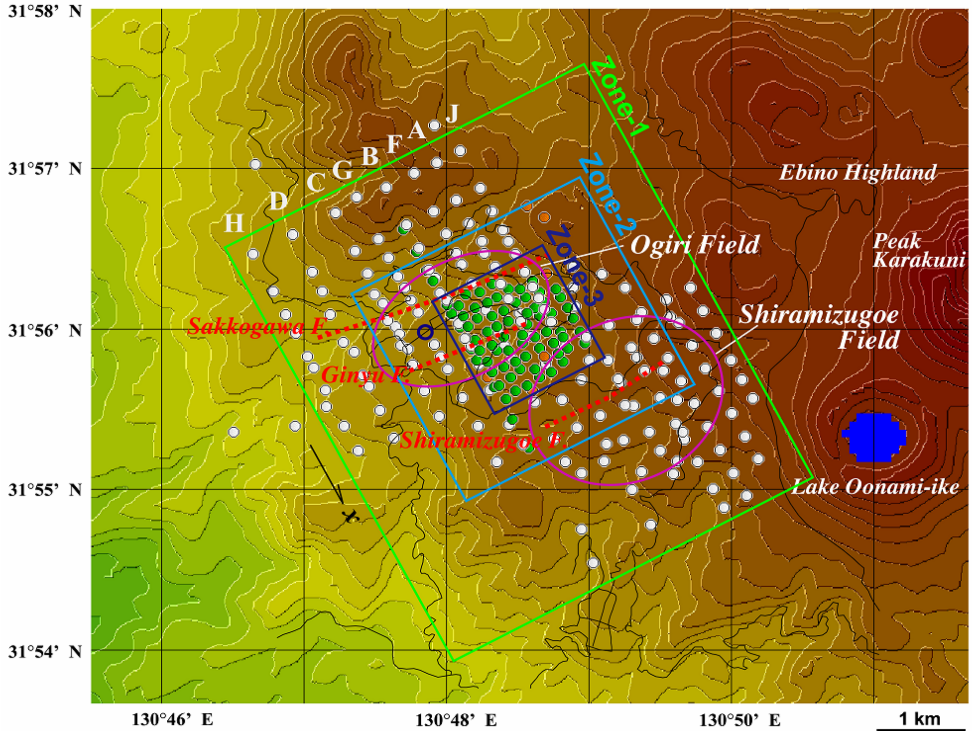

Figure 1: AMT (green dots) and MT (white and orange dots) stations in the Ogiri geothermal field. The background is topography contour. Red dashed lines are estimated faults; large pink ovals indicate areas of geothermal reservoirs; the black open circle indicates location of the power plant; three large rectangles are zones for 3D interpretation.

Three faults trending in a NE-SW direction were identified in the survey area. From north to south they are the Sakkogawa, Ginyu, and Shiramizugoe faults. The major production zone of the Ogiri geothermal reservoir is associated with the Ginyu Fault (Goko, 2000). This geothermal reservoir is situated at a depth of 500 - 1500 m. The geothermal reservoir in this area is distributed in the Quaternary volcanic layers that mostly consist of tuff and lava erupted from Kirishima Volcano to the east of the area. The New Energy and Industrial Technology Development Organization (NEDO), NKG and Geological Survey of Japan (GSJ) conducted magnetotelluric (MT) surveys from 1996 to 2000 over the Ogiri and Shiramizugoe geothermal fields, at several stages in their research and exploration. The total number of MT stations exceeded 180. A part of 2D and 3D interpretation results of these MT data was reported in Uchida (2005).

AMT data were obtained in the center of the area in 2004 by NKG. An average interval of AMT sites was 150 m. The number of AMT sites was 66. The AMT survey covered an area of approximately 1.5 km x 1.5 km. This survey was targeting an eastern expansion of the currently producing Ogiri geothermal reservoir along the Ginyu Fault. In addition, fourteen AMT soundings were conducted on one survey line in the studied area by AIST in 2002 (Takakura, 2003).

Time-series data acquisition of the AMT band was conducted for 7 or 9 hours during night at each site using Phoenix MTU-5A systems. The frequency band of the AMT system is from 0.3 Hz to 10,000 Hz. According to previous studies, AMT data acquisition during night provided better quality for high frequency data above 1 kHz than the measurement during daytime in this area (Takakura, 2003). A remote reference site was set up at approximately 40 km to the south of the survey area.

Two examples of AMT apparent resistivity data are shown in Figure 2. Site-914 is located on an alteration zone along Ginyu Fault. Therefore, apparent resistivity is small (below 10 ohm-m) at almost all frequency ranges. Site-955 is located in the center of the AMT survey area, showing a typical apparent resistivity curve; larger than 100 ohm-m at frequencies higher than 100 Hz and reaches about 10 ohm-m below 10 Hz. Data quality was generally fine at frequencies above a few hertz for all sites.

3. 3D INVERSION

3D inversions were performed for several subsets of the AMT and MT data (Table 1). Case-1 utilized all MT sites in Zone-1 shown in Figure 1. Case-3 utilized AMT sites in Zone-3. For intermediate Zone-2, Case-2b utilized both AMT and MT data, while Case-2a utilized only MT sites for comparison.

The impedance was rotated to the direction of the NW-SE survey lines. Directions of x- and y-axes were 150 and 60 degrees clockwise from north, respectively. Off-diagonal components of the impedance (apparent resistivity and phase) were used as the observed data. The inversion scheme was based on the 3D finite-difference forward modeling and the linearized least-squares inversion (Sasaki, 1999, 2004; Uchida and Sasaki, 2003). Topography was not included in the modeling. Static shifts were solved simultaneously in the inversion.

Case-3, for example, the number of AMT sites was 73. The number of frequencies used for the inversion was 13 (from 1.17 Hz to 5200 Hz). A surface cell had a size of 50 m (x) x 50 m (y) x 25 m (z) for the 3D modeling, and the finite difference mesh consisted of 63 (x) x 63 (y) x 38 (z) cells. This mesh created the maximum numerical error of about 2% in apparent resistivity for a 100 ohm-m homogeneous earth. The number of blocks, whose resistivity values were unknown for the inversion, was 14 (x) x 13 (y) x 16 (z); 2912 blocks in total. The number of observed data used for the inversion was 3660. The noise floor of the observed data was assumed as 1%. The cell sizes on the surface for Zone-1 and Zone-2 were 150 m and 100 m, respectively, to deal with wider modeling areas.

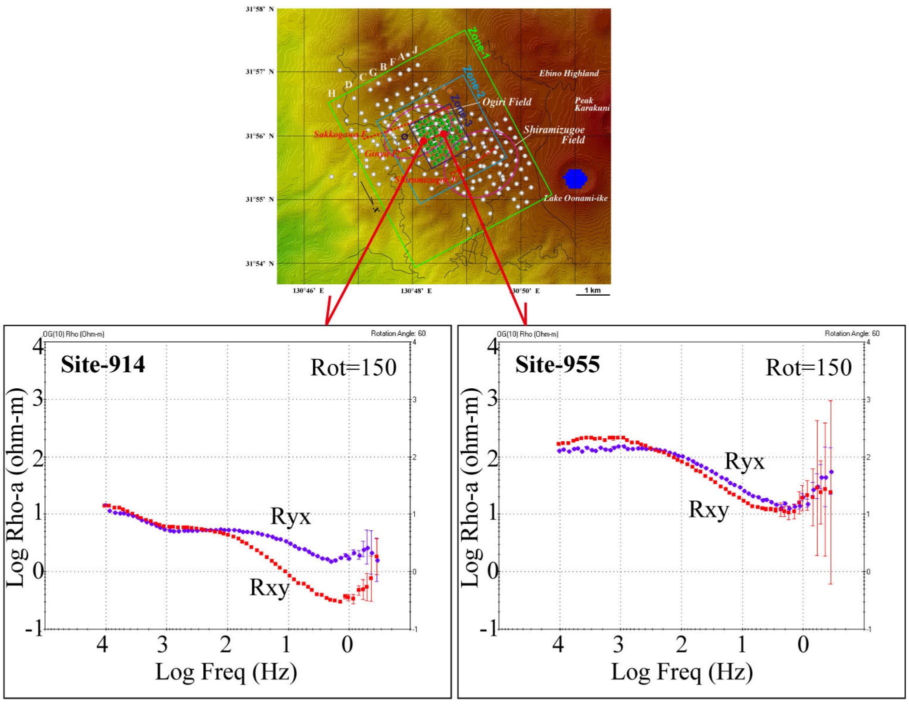

Figure 2: AMT apparent resistivity at Sites 914 and 955. Site 914 is located on an alteration zone along the Ginyu Fault.

Table 1: Settings for 3D inversions of MT and AMT data for four different inversions.

Case	Zone	MT sites	AMT sites	# Freq	Frequency (Hz)
Case-1	1	164	0	11	0.0703 - 72
Case-2a	2	85	0	12	0.187 - 384
Case-2b		85	78	13	0.140 - 640
Case-3	3	0	73	13	1.17 - 5200

Figure 3 shows depth slice resistivity sections of the AMT 3D model (Case-3). The iteration number was 16 and the final normalized RMS misfit was 10.3 with an assumption of 1% noise floor. The RMS value of assumed static shifts was 0.687 in the natural logarithmic domain.

Shallow sections up to 200 m depth generally show high resistivity, larger than 100 ohm-m, except the location of surface alteration zone on the Ginyu Fault (around Station 914). This high resistivity layer corresponds to less-altered volcanic rocks. Resistivity is very low at a depth range from 400 m to 1000 m. Then, below is a relative higher resistivity layer.

Figure 4 shows observed and estimated apparent resistivity and phase data for eight AMT stations along the second western-most line. Calculated apparent resistivity with static shift estimate successfully fit to the observed data at all stations. Stations 914 and 915 are located in the alteration zone along Ginyu Fault, hence their apparent resistivities are very low as compared with other stations. Note that 2D features in the apparent resistivity curves are in opposite directions for Stations 914/915 and 916; former two sites show $\rho_{a\text{-}xy} < \rho_{a\text{-}yx}$, while the latter site shows $\rho_{a\text{-}xy} > \rho_{a\text{-}yx}$ at lower frequencies. Station 916 is located on the resistive side on the shallow depth-slice sections.

Figures 5, 6 and 7 compare 3D models by the inversions of Case-1, Case-2b and Case-3 (Table 1). Locations of the x-slice sections and y-slice sections are almost same for three figures, while the sizes of plotted areas differ among them.

These resistivity models indicate very good correlation with the reservoir model of this area. The surface high-resistivity zone corresponds to fresh or less-altered volcanic formations. Low-resistivity second layer is clay-rich cap layer of the reservoir system. Upper part of the high-resistivity third layer (basement layer in the resistivity model) is interpreted as a high-temperature reservoir zone. Depth to the high-resistivity third layer is shallow for Ogiri and Shiramizugoe reservoirs (Figure 5).

These three 3D models correspond well with each other. However, depth of the high-resistivity third layer is very small beneath the Ginyu Fault (around Station 914) in the AMT 3D model (Case-3, Figure 7). For the precise delineation of the boundary between the low-resistivity second layer and high-resistivity basement, inclusion of dense AMT data can provide more detailed structure.

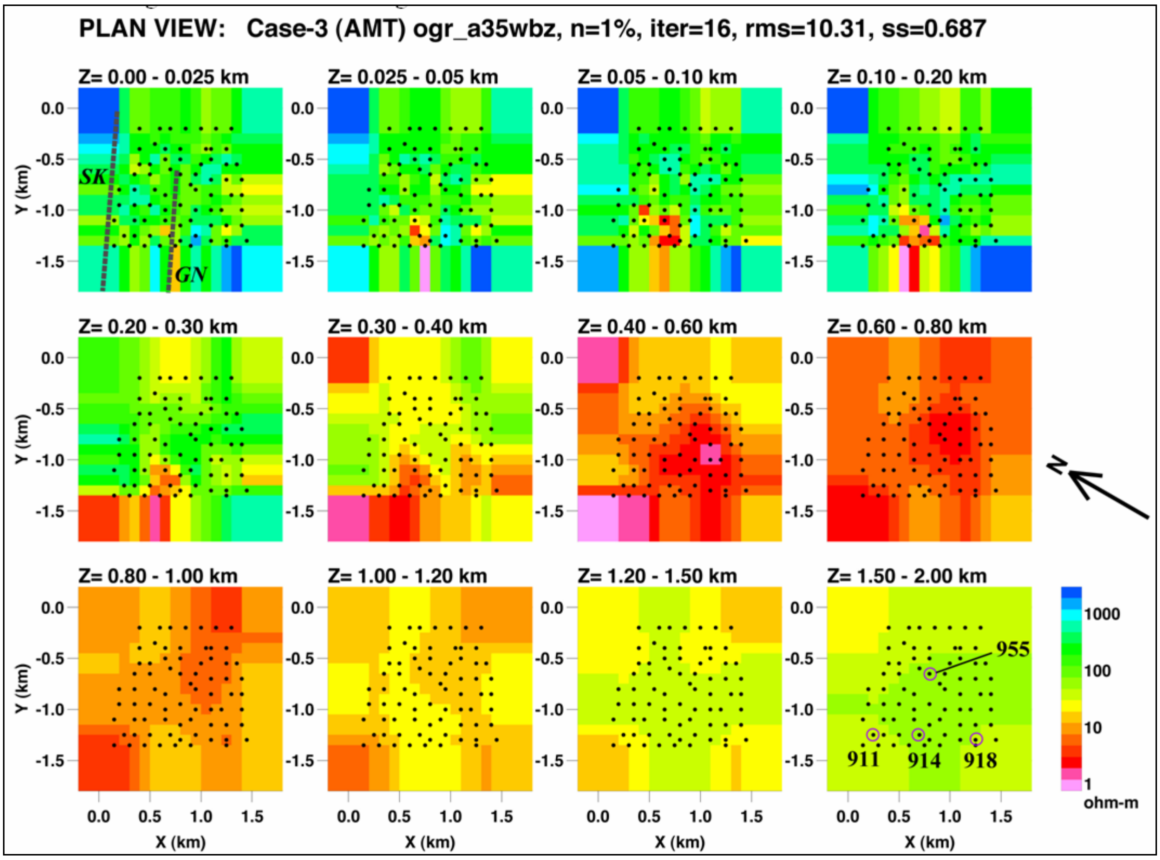

Figure 3: Depth-slice sections of the 3D AMT resistivity model (Case-3). Black dots are AMT stations. Thick gray dashed lines on the shallowest section are approximate location of faults (Sakkogawa and Ginyu).

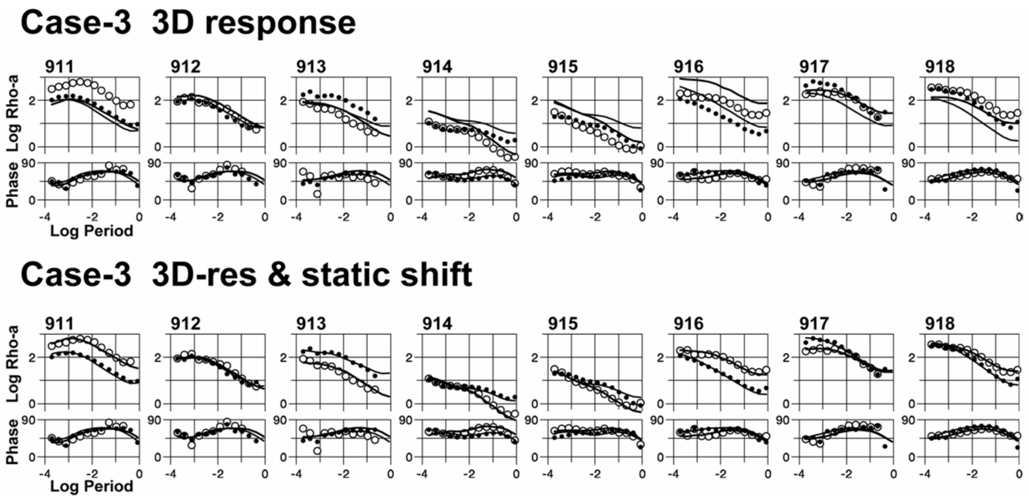

Figure 4: Comparison of observed (circle) and calculated (lines) apparent resistivity and phase data at eight AMT stations on the second western-most line. Upper panels show pure 3D responses from the 3D model in Figure 3 and lower panels include estimated static shifts. Open circles are xy-components, while solid circles are yx-components. Error bars of the data are not shown.

Case-1: MT sites (0.070 - 72 Hz)

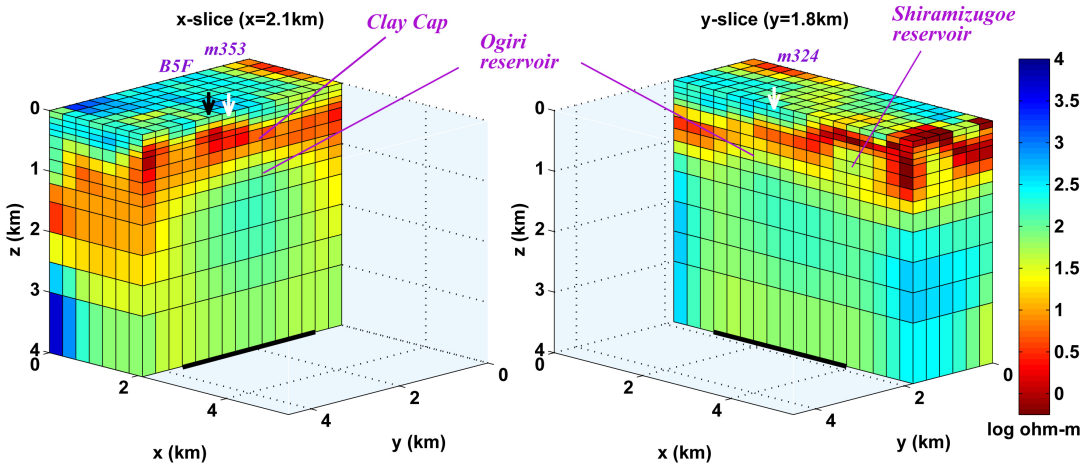

Figure 5: 3D model of the MT data (Case-1), viewed from south. The plotted area corresponds to the rectangle, Zone-1, in Figure 1. The black arrow indicates the location of Well B5F, while white arrows show location of two MT sites. The left panel is sliced at the location of Site-353, while the right panel is sliced at Site-324, for which the resistivity comparisons are shown in Figure 9. Thick black bars at the bottom of the models correspond to the zones of the models in Figure 6.

Case-2b: AMT+MT (0.140 - 640 Hz)

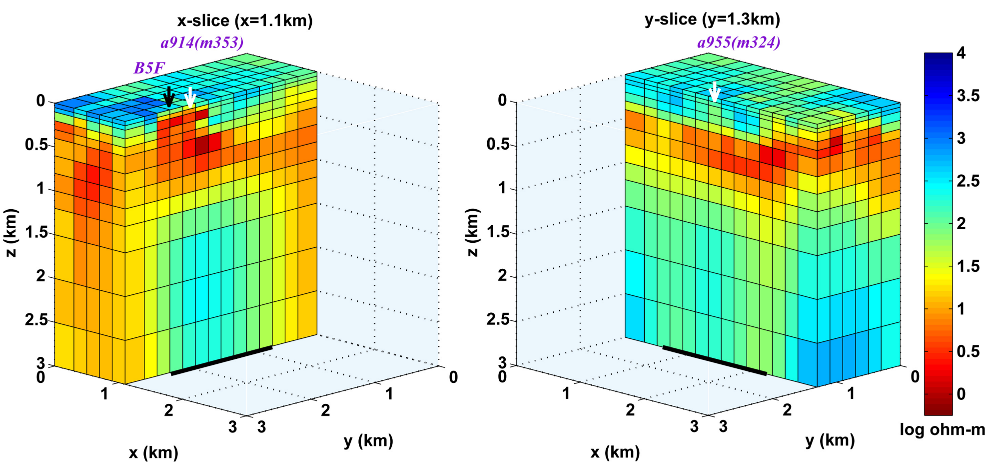

Figure 6: 3D model of the AMT and MT data (Case-2b). The plotted area corresponds to the rectangle, Zone-2, in Figure 1. Thick black bars at the bottom of the models correspond to the zones of the models in Figure 7.

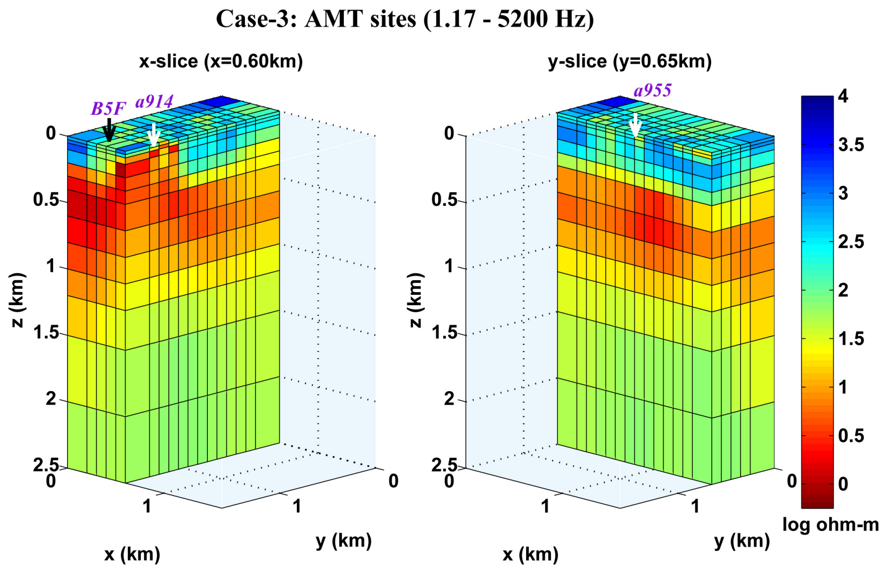

Figure 7: 3D model of the AMT data (Case-3). The plotted area corresponds to the rectangle, Zone-3, in Figure 1. The left panel is sliced at Site-914, while the right panel is sliced at Site-955.

4. GEOLOGY

Figure 8 shows a simplified geology section along a NW-SE line constructed from the drilling data (Uchida, 2005). Shapes of the lower boundary of the clay cap and the contour of 200^{o}Celsius are consistent with the boundary between the conductive second layer and the resistive third layer in the vertical resistivity sections of the 3D model (right panels of Figure 5). The Ogiri production zone is located in the high-resistivity and high-temperature anomaly in the left-hand side of the sections of the Case-1 model (x distance is approximately 1.6 km in Figure 5).

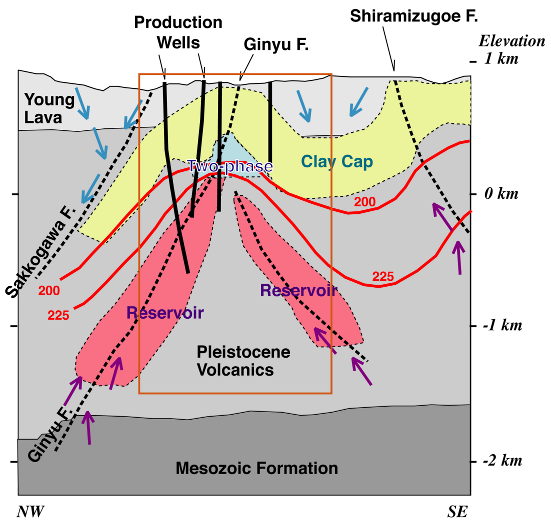

Figure 8: Simplified geology model along NW-SE cross-section. Orange rectangle corresponds to the zone of y-slice section of AMT 3D model in Figure 7 (right panel).

Location of the new production drilling, B5F, for the extension of Ogiri reservoir was not chosen at an eastern side of the existing reservoir, but was chosen at the southwestern side of Site-914. It targeted the shallow high-resistivity anomaly in AMT models (Figures 6 and 7), which is associated with Ginyu Fault. It hit a productive fracture, which is a part of Ginyu Fault, at a depth of approximately 850 m in 2005.

Figure 9 compares block resistivites of the four cases of inversion at a production well B5F, and two AMT and MT sites. Unfortunately the resistivity logging was conducted only for a short depth range in B5F. When we use very high frequency data (above 1 kHz), resistivity of the surface layer is properly determined. It seems to give more reliable resistivity values in the deep layers, too. However, all the four MT models show similar resistivity profiles at the well location in this case. Even so, since the model in Figure 7 does not have good resolution in the deeper part, inversion of AMT data alone can give a reliable model only down to a depth of about 1 - 2 km.

At Sites 914 and 353 (Figure 9b), Case-1 presents rather high-resistivity for the surface layer because of the lack of high frequency data. Case-2a also shows anomalous low-resistivity layers near the surface and a depth from 300 - 600 meters. Site-914 and 353 are located in an anomalous zone near Ginyu Fault. In such a case, shallow resistivity information by AMT data is necessary. On the other hand, the resistive third layer is expressed almost similar among these models. Therefore, these models do not give significant difference for understanding the high-temperature geothermal reservoirs. This study has suggested that AMT data alone gives almost sufficient resistivity model to interpret down to the top of the geothermal reservoir.

5. CONCLUSIONS

A dense AMT measurement was conducted in 2004 at the Ogiri geothermal field within an area of 1.5 km x 1.5 km. The 3D inversion was applied to the AMT data as well as the existing MT data. The resultant 3D models are consistent with the MT models reported before. The boundary between the low-resistivity cap layer and the high-resistivity reservoir zone is more complicated. It was more precisely interpreted in the AMT models than the MT model. It is because the dense coverage of the AMT sites and higher frequency data used for the interpretation. However, the existing MT data were already dense enough for the investigation. AMT data alone is not enough to investigate the model greater than 1 - 2 km depth. Careful design is necessary when we choose MT or AMT from a point of target depth, resistivity, and station interval.

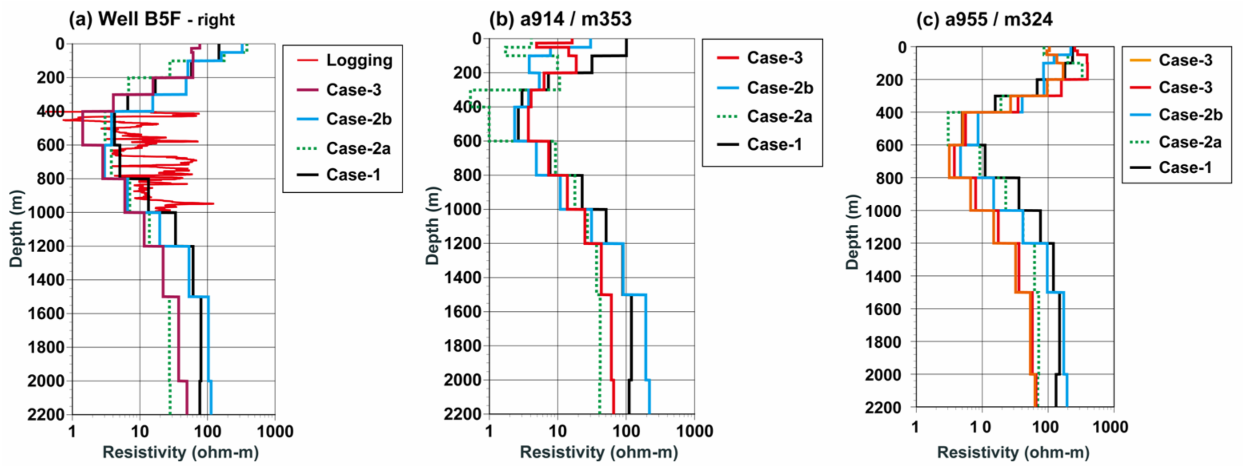

Figure 9: Comparison of resistivity values of the 3D models at (a) Well B5F, (b) AMT site 914 and MT site 353, and (c) AMT site 955 and MT site 324. A thin red line in Panel (a) is the long-normal resistivity log data. For Case-3 in Panel (c), two neighboring blocks to Site 955 are shown.

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