

Resistivity structure of Sumikawa geothermal field, northeastern Japan, obtained from magnetotelluric data

Toshihiro Uchida

Geological Survey of Japan
1-1-3 Higashi, Tsukuba, Ibaraki 305, Japan

ABSTRACT:

Resistivity models were obtained with two-dimensional inversion of magnetotelluric data at the Sumikawa geothermal field, northeastern Japan, to extract resistivity features of the field. The inversion method employed is an iterative least-squares scheme with smoothness constraint. The optimum smoothness was selected based on a statistical criterion ABIC. This inversion scheme works very stably by objectively adjusting the trade-off between the contributions of the misfit minimization and the roughness minimization. Final resistivity models were interpreted in comparison with drilling data such as temperature, porosity, clay-mineral contents, and resistivity logs. Two major features recognized from the models of three survey lines are as follows. First, resistivity of the cap layer is very low, as low as $1\text{--}3\ \Omega\cdot\text{m}$. This is due to low-temperature clay minerals such as montmorillonite. Second, resistivity of the reservoir layer is rather high, an order of $100\ \Omega\cdot\text{m}$, in spite of its high temperature, approximately 300 degrees Celsius. Chlorite, the dominant clay-mineral in this zone, does not decrease the formation resistivity so much.

Keywords: magnetotelluric method, two-dimensional inversion, reservoir structure, clay mineral, Sumikawa geothermal field.

1. INTRODUCTION

Resistivity structure is one of the important information which we often rely on in geothermal exploration. Currently, magnetotelluric (MT) method is the only tool to obtain a subsurface resistivity model down to a depth of about five kilometers, which is usually required for proper reservoir evaluation. However, the MT technology, both in the data acquisition and interpretation, is still a developing subject. It was not so long time ago when first versatile two-dimensional (2-D) inversion codes became available to public (deGroot-Hedlin and Constable, 1990; Smith and Booker, 1991). Since then, realistic 2-D earth models began to be produced from actual field data. Some other inversion algorithms which reduce the computation time or provide more stable results have been published (Oldenburg and Ellis, 1991; Uchida, 1993). Owing to these improvements of numerical techniques, it has become easier to obtain reliable resistivity models for geothermal exploration as well as other MT applications.

When we interpret a resistivity model obtained in a geothermal field, we are used to expect that geothermal reservoir has low resistivity due to its saline fluid and high temperature. However, recent experience has revealed that reservoir layers are not so conductive, but there is a more conductive layer above the reservoir horizon (e.g., Uchida, 1990; Pellerin *et al.*, 1992). Although the temperature of this conductive layer is low, it has plenty of clay minerals in it. Effect of the clay minerals on resistivity decrease is dominant in this zone. It is important to accumulate more case studies and rock-property experiments to ensure this feature for future exploration.

New Energy and Industrial Technology Development Organization (NEDO) and Geological Survey of Japan (GSJ) carried out MT surveys in the Sumikawa geothermal field, northeastern Japan, in 1993. The purposes of the surveys were to test a newly developed data acquisition system of NEDO and to

obtain detailed resistivity structure beneath the field. The aim of this paper is to examine how the 2-D inversion code developed by GSJ (Uchida, 1993; Uchida and Ogawa, 1993) works on the data obtained in a geothermal field whose geology is very complicated.

2. DATA

The Sumikawa geothermal field is located in northeastern Honshu, Japan's main island. Figure 1 is a topography map of the area showing the magnetotelluric sites. The Sumikawa field is on the northeast foot of a Quaternary volcano, Mt. Yakeyama. There are a number of hot springs associating with the volcanoes. NEDO has conducted several drillings for geothermal exploration in the area. SN-7D, the deepest of them, successfully hit a large volume of geothermal reservoir in 1988. Subsequent production test revealed that the well can produce as much as 160 t/h steam and 310 t/h hot water. A new power plant is now being constructed by a private company based on several other production wells as well as SN-7D.

The MT survey discussed in this paper was carried out in 1993. Three survey lines were arranged to cross the heart of the field near SN-7D. The lengths of the lines are approximately 6 km. Two west-east lines, SG-C and SG-I, were surveyed by NEDO (NEDO, 1994). Both MT and CSAMT data were obtained; the MT acquisition system is NEDO's original one, and the CSAMT system is a modified version of Zonge GDP-32. The numbers of the MT sites are 24 for the line SG-C, and 25 for SG-I. For the CSAMT data, electric fields were measured continuously along the lines with 50m-long dipoles; the numbers of the sites are more than 120 on both lines. The north-south line, SG-2, was measured by GSJ using a Phoenix V-5 system. An in-loop transient EM (TEM) measurement was also conducted at each site to apply static correction on MT apparent resistivities. The number of the sites is 10, which is sparser than the other lines. Data quality is generally good except the sites in the construction area whose signals are contaminated with noises generated from the construction activities.

MT data were first rotated to the average directions of the lines. Then, TM-mode apparent resistivity and phase, which is from a electric field along the line and a magnetic field perpendicular to it, were calculated, assuming that the survey lines were perpendicular to the geologic strike. Since the lines have two different directions and the real geology is very complex, this assumption is not valid for all of the lines. However, if we know a general trend of geology before a survey, we can set a survey line perpendicular to it and run a TM-mode inversion safely. According to induction vectors calculated from the observed MT data, general strike direction in the area is approximately NNE-SSW. This is consistent with the regional geologic trend. Therefore, 2-D inversion of the TM mode data is adequate for the west-east lines. On the other hand, for the line SG-2, TM-mode inversion would be in trouble because the line direction of the southern half is not appropriate for the TM-mode 2-D inversion. The induction vectors point eastward at those sites, while the amplitudes are small. As an alternative, determinant resistivity and phase were tested for 2-D inversion.

Original MT data cover more than five decades of frequency: from 0.001 Hz to 300 Hz. However, due to a limitation of

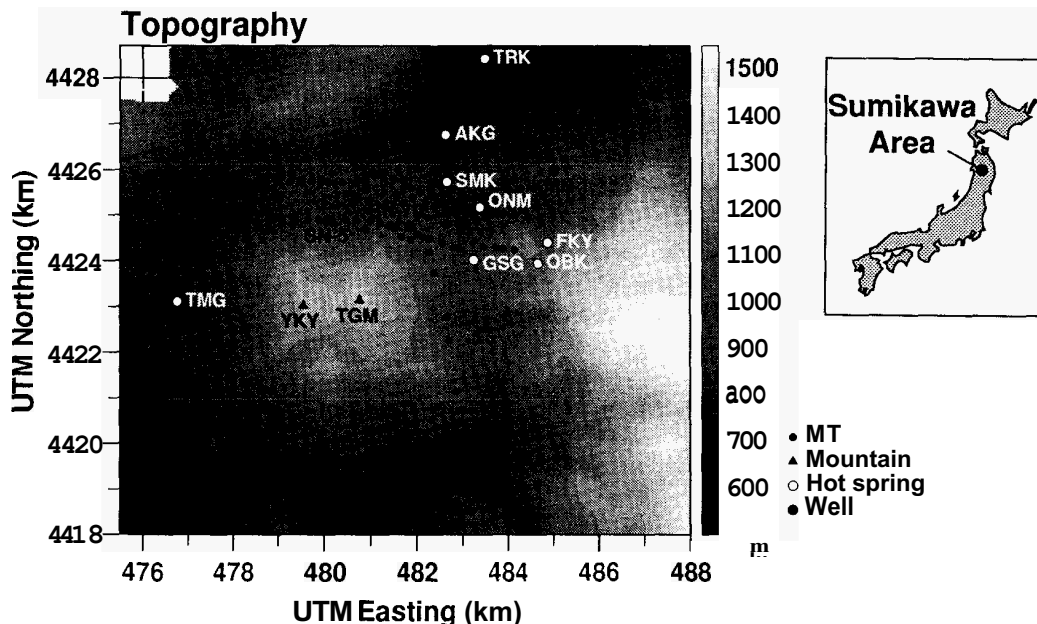


Figure 1. Magnetotelluric sites (small solid circles) on a topography map at the Sumikawa area. Triangles are mountains, open circles are hot springs, large solid circles are survey drillings. Abbreviations for hot springs and mountains are as follows; TRK: Toroko, AKG: Akagawa, SMK: Sumikawa, ONM: Ohnuma, GSG: Goshogake, FKY: Fukukeyu, OBK: Obuka, TMG: Tamagawa, YKY: Yakeyama, and TGM: Tsugamori.

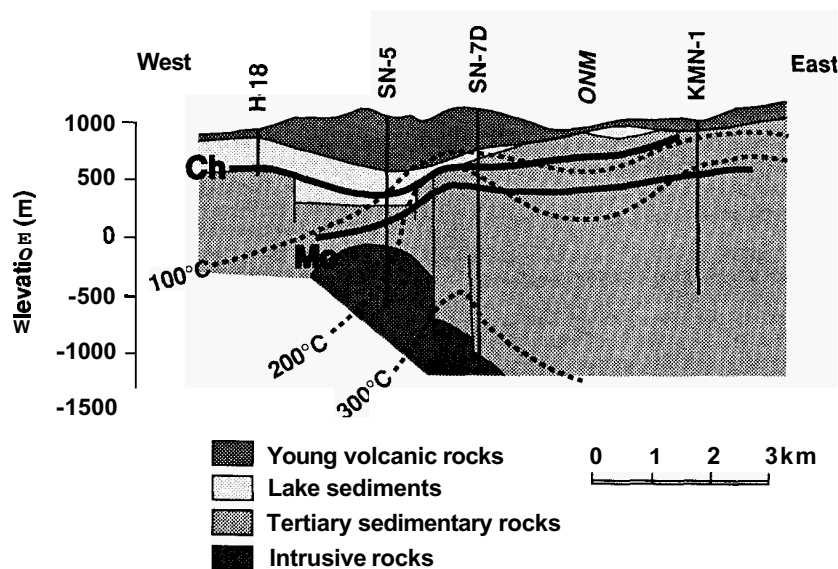


Figure 2. A west-east geologic model estimated from drilling (NEDO, 1988). 'Mo' stands for the lower limit of the occurrence of montmorillonite, and 'Ch' indicates the upper limit of chlorite occurrence. Vertical exaggeration is approximately 2.

computer capability, only 14 frequencies from 0.012 Hz to 128 Hz were used for the inversion. For a joint inversion of MT and CSAMT, seven frequencies of CSAMT data were added to MT dataset. Those frequencies are from 16 Hz to 1024 Hz.

3. GEOLOGY OVERVIEW

A geologic section (Figure 2) was estimated using borehole data along the western half of SG-I and the eastern half of SG-C (NEDO, 1988). The dominant formation in the surveyed area is Tertiary sedimentary and volcanic rocks called Green Tuff which was closely associated with shallow sea-bottom volcanic

activities in Tertiary time. It is covered by Quaternary lake sediments which filled a caldera-like small basin beneath Mt. Yakeyama. Then, young volcanic lava and pyroclastic rocks covered throughout the surveyed area. Tertiary intrusive rocks were found in some drillholes in the Green Tuff layer. As for the NEDO's boreholes, major fractures were encountered in SN-7D at some levels deeper than 1500 m in Green Tuff and the intrusive rocks. Those in the intrusive rocks seem to be more dominant as geothermal reservoirs. Temperature distribution indicates that SN-7D is the closest to the heat source, and that the high-temperature zone becomes shallower in eastern half of the section.

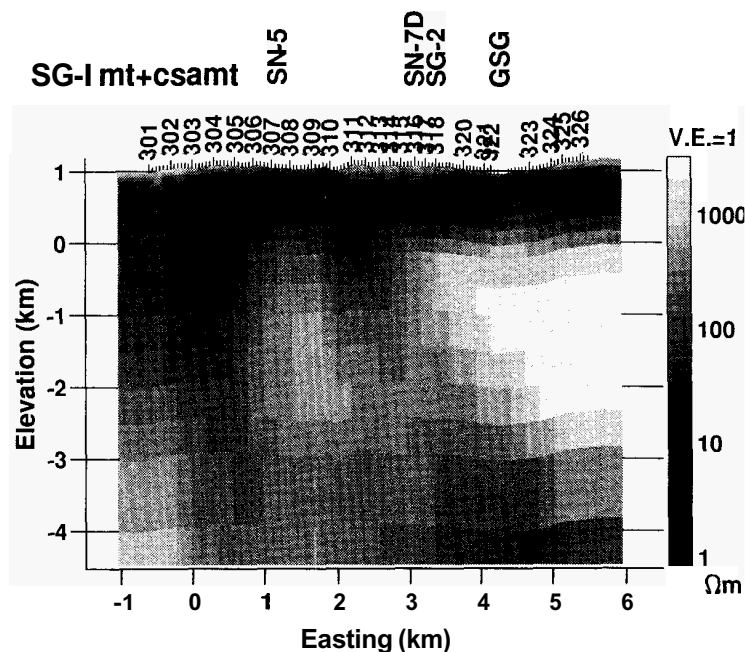


Figure 3. Two-dimensional model of the line SG-I obtained from the inversion of TM-mode MT data joint with CSAMT data. Vertical exaggeration is 1.

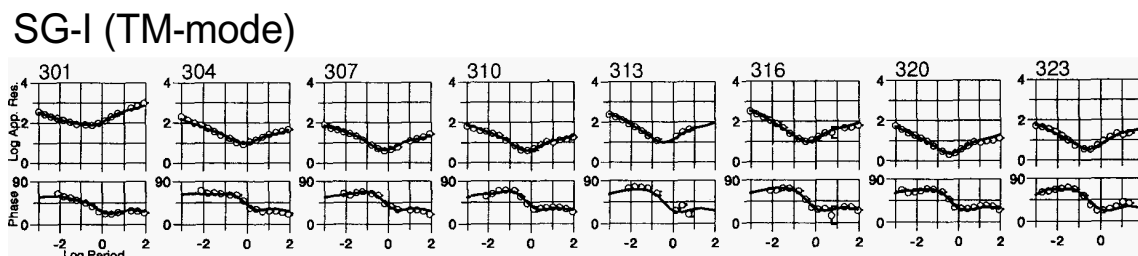


Figure 4. TM-mode apparent resistivities and phases at several MT sites on the line SG-I; observed (open circles) and calculated ones from the model in Figure 3 (solid lines). Observation error of one standard deviation is also shown.

4. TWO-DIMENSIONAL MODELS

The 2-D inversion method applied in this work is described in Uchida (1993). That is an iterative least-squares inversion with smoothness constraint. It utilizes the finite-element method for a forward calculation of MT responses; a Jacobean matrix consisting of a full set of partial derivatives of the responses with respect to model parameters are also computed. This matrix is solved together with a smoothing matrix to obtain modification steps of the parameters. The optimum smoothness is chosen based on a statistical criterion ABIC (Akaike's Bayesian Information Criterion). The initial model is a $100 \Omega \cdot \text{m}$ homogeneous earth for these datasets; the iteration continues several times to reach convergence.

Final resistivity section for the lines SG-I is shown in Figure 3. The data used for the inversion are TM-mode MT data and CSAMT data. Examples of observed and calculated apparent resistivities and phases are shown in Figure 4. Final resistivity section for the line SG-2 with the determinant MT impedances after static correction is shown in Figure 5. Figure 6 compares the observed and calculated determinant apparent resistivities and phases. The fit is very good visually for both models except noisy data at the sites near the well SN-7D.

The resistivity model of the line SG-I is similar to that of SG-C (not shown). It has shallow thin resistive layer of approximately

$100 \Omega \cdot \text{m}$. This corresponds to young volcanic rocks. It is underlain by a conductive layer of $1\text{--}10 \Omega \cdot \text{m}$. This is interpreted as the Quaternary lake sediments and upper sub-layers of Green Tuff. Resistivity of the conductive layer is very low at eastern sites where hot spring manifestation is active. Below the conductive layer, resistive basement of more than $100 \Omega \cdot \text{m}$ is present. Its depth is approximately the sea level; shallower at eastern half of the section, and deeper in the western part. All of this resistive zone corresponds to Green Tuff and the intrusive rocks. There is another conductive layer beneath the resistive basement at the eastern half of the section, although it is not shown because it exceeds the plotting range.

The 2-D model of the line SG-2 has a similar pattern to that of SG-I down to the depth of 2 km. It has a resistive surface layer, conductive second layer, and a resistive third layer. However, Below the third layer, there is another conductive anomaly in the southern half of the section. There is no boreholes drilled, however, it might be due to an extremely high temperature zone. The deep resistive body recognized in the eastern end of the SG-I model seems to extend northward in the SG-2 section.

Although two models of SG-I and SG-2 basically agree with each other, they are not exactly same at the intersection of the lines, because the data modes used for the inversion are different; TM for SG-I and determinant for SG-2.

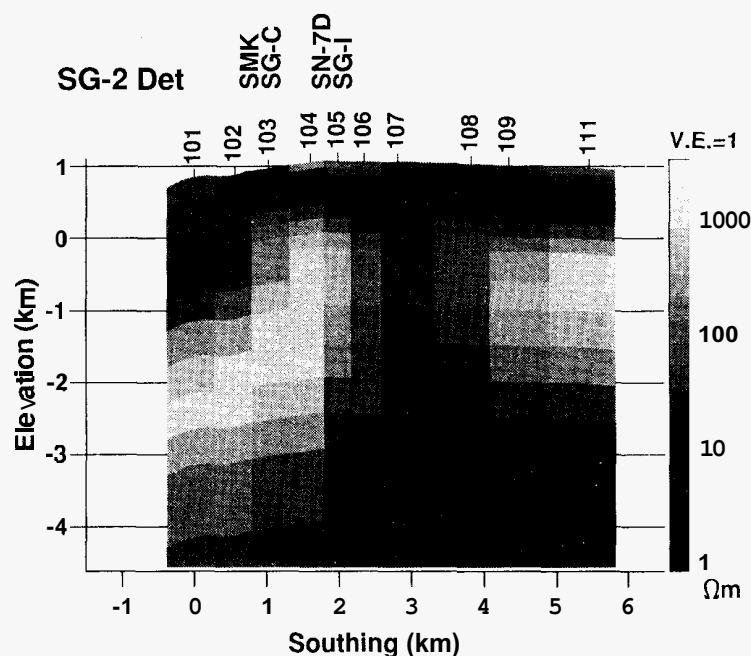


Figure 5. Two-dimensional model of the line SG-2 obtained from the inversion of determinant MT data. Vertical exaggeration is 1.

SG-2 (Determinant)

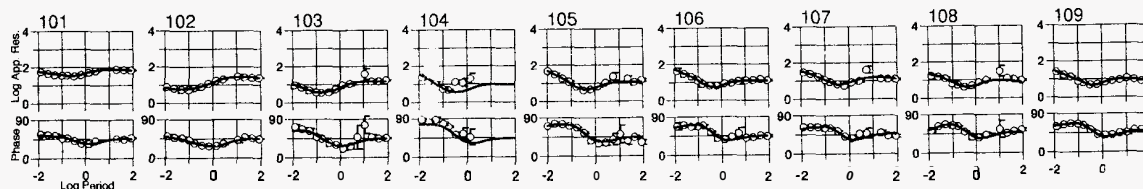


Figure 6. Determinant apparent resistivities and phases on the line SG-2; observed (open circles) and calculated ones from the model in Figure 5 (solid lines). Observation error of one standard deviation is also shown.

5. INTERPRETATION

Figure 7 compares the resistivity log in SN-7D and resistivities of the corresponding nearby blocks on the 2-D model of SG-I (Figure 3). A geologic column and temperature log are also shown. Geologic column from the surface is Yakeyama volcanic rocks (0-340m), lake sediments (340-495m), Tertiary rocks (495-2260m), and intrusive rocks (2260-2486m).

Concerning the logging data, resistivity at a depth range of 500 - 650 m is approximately $3 \Omega \cdot m$. This layer is dominated by dacite tuff. Although the logging data for the lake sediments is lacking in SN-7D, we can estimate it as $1-10 \Omega \cdot m$ from other wells. Then, as we go deep in Green Tuff, resistivity increases gradually and reaches to $100 \Omega \cdot m$ at 1000m. Below it, resistivity keeps plateau values of about $100 - 200 \Omega \cdot m$ until we go into the intrusive rocks. This depth range, from 650 to 2260m, has alternating beds of black shale, andesite-dacite pyroclastics, and altered andesite. Porosities of these sub-layers are approximately 10-15% by the neutron log. In the intrusive rocks, resistivity is approximately $1000 \Omega \cdot m$, and some low-resistivity spike anomalies due to hot-water bearing fractures are present.

The resistivity column from the 2-D model by the MT+CSAMT inversion is generally consistent with the logging profile. The volcanic rocks at the surface can be recognized as a resistive layer in the 2-D model. The only difference is that the resistivity of the

model at a depth range from 1000m to 2000m is higher than the logging value. This may be due to noises at the corresponding frequency band, or a breakdown of 2-D assumption for the real earth's structure.

The temperature increases rapidly at a depth range of 400 - 1000m; especially the gradient is very steep at 400 - 500m. This is a typical pattern of conduction-type temperature distribution. Below 1000m, the temperature is near 300 degrees Celsius, and it shows a convection-type curve. At the conduction zone, low-temperature clay mineral, such as montmorillonite is dominated. It can absorb plenty of water particles within its layered crystal structure. Then, permeability as well as electric resistivity decrease dramatically, and a clay-cap layer is created. In this field, siltstone in the lake sediments also help to form an impermeable layer.

Major geothermal water was found at several depths in deeper parts of Green Tuff layer and the intrusive rocks. As we can notice from the logging profile, resistivities of these fractures are very low because they contain high temperature saline water. However, the host rock is rather resistive, more than $100 \Omega \cdot m$. In this zone, high-temperature clay mineral such as chlorite is dominated. Chlorite does not decrease the rock resistivity significantly. Hence, in spite of the fact that the temperature is high and we tend to expect low resistivity, the reservoir zone is relatively resistive. This clear contrast between the conductive

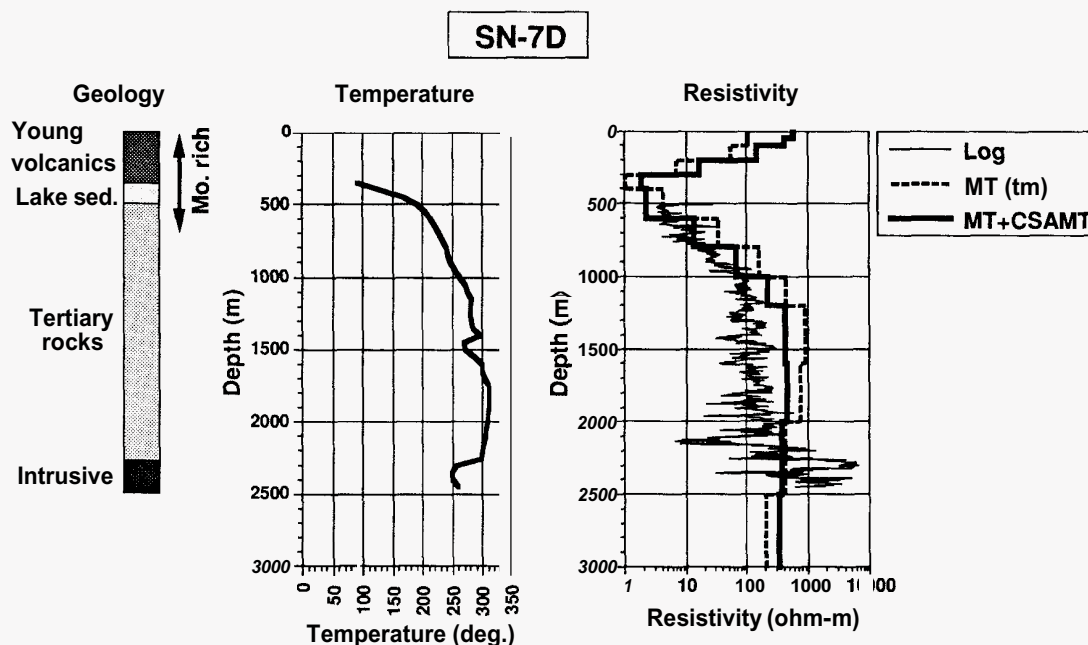


Figure 7. Comparison of the MT models with logging data of the drilling SN-7D; geology, temperature, and Latero logs. Although resistivity profiles from two 2-D models of the line SG-I are shown here, only the MT+CSAMT inversion is described in this report.

clay cap and the resistive reservoir makes it easier for MT surveys to outline the boundary.

When we compare the temperature distribution in Figure 2 and the 2-D model of SG-I (Figure 3), the contour pattern of 200 degrees Celsius and the depth profile of the resistive basement (third layer) are very consistent. When the basement is shallow, the underground temperature is high and there is a possibility of shallower reservoir. Although this is not always true, it would be one important point of the interpretation. Of course, high temperature itself is another fundamental factor which decreases the rock resistivity. For example, the deep conductive body that is found in the southern half of the line SG-2 could be related to deep high-temperature zone. Therefore, we must carefully examine these two major factors as well as other factors for our interpretation of a given resistivity model.

6. CONCLUSIONS

Employing a two-dimensional inversion to magnetotelluric data at Sumikawa geothermal field, I have successfully obtained reasonable resistivity models. The resistivity models were interpreted in comparison with existing borehole data.

The geothermal reservoir in this area is characterized by the following resistivity features which are supported by both the MT models and resistivity loggings.

- Conductive cap layer: Resistivity is very low, as low as 1-3 $\Omega \cdot m$, which is due to low-temperature clay minerals such as montmorillonite. This clay-rich layer is impermeable, hence forms a cap layer. The temperature gradient is very steep at this depth.
- Resistive reservoir layer: Resistivity is around 100 $\Omega \cdot m$. The temperature at this zone is high, around 300 degrees Celsius. Major fractures, in which large amount of geothermal water is circulated, are located in Miocene formations. Chlorite, the dominant clay minerals in this region, does not decrease the formation resistivity significantly.

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