Magnetotelluric Soundings in the Takigami Geothermal Area, Japan

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ABSTRACT

The Takigami geothermal area is located in the Hohi geothermal region, northeastern Kyushu Island, Japan. This paper demonstrates the application of magnetotelluric (MT) method for geothermal investigation in the Takigami area to determine the subsurface resistivity structure, which is correlated to the potential geothermal reservoir and the distribution of fault systems and geological trends. Advanced interpretation techniques of one-dimensional (1-D) and two-dimensional (2-D) inversions were used to derive a new insight of the geothermal system in the Takigami area. The resistivity section obtained by 1-D inversion of a survey line (Line-1:southwest-northeast direction) was compared with electrical resistivity logs of several wells drilled in the same direction. The result shows a good correlation. The 2-D inversion result of the same line (Line-1) was also compared with the temperature and lost circulation data obtained during the course of drilling. The result shows a good agreement. It is concluded from the MT survey that the geothermal reservoir of the Takigami area is separated by the Noine fault at different depths. The geothermal reservoir in the east of the Noine fault is shallower than the reservoir in the west. The results of MT survey are in a good agreement with a three-dimensional (3-D) geological model constructed by the use of drilling data and well logging data in the Takigami area.

1. INTRODUCTION

Central Kyushu is cut by a volcano-tectonic depression that has developed within a tensile stress field since Neogene time, resulting in volcanism since Pliocene and and Pleistocene times (Hase et al., 1985). The northeastern part of central Kyushu, known as the Hohi region, is one of the most active geothermal areas in Japan.

This geothermal region is associated with a negative Bouguer anomaly referred to the Shishimuta low-gravity zone. The Takigami geothermal area is located on the eastern margin of this low-gravity zone. The northeastern part of the geothermal area extends to a local gravitational high, while the western portion of the field has a low gravity anomaly (-35 mgal). A north-south (N-S) striking fault system was therefore thought to exist in the area, related to the large-scale volcano-tectonic depression (Kamata, 1985). Although the Takigami area lies within the promising geothermal region, there are no surface manifestations in the area. Various geophysical methods have been conducted in the Takigami area since 1979 including electrical resistivity and MT
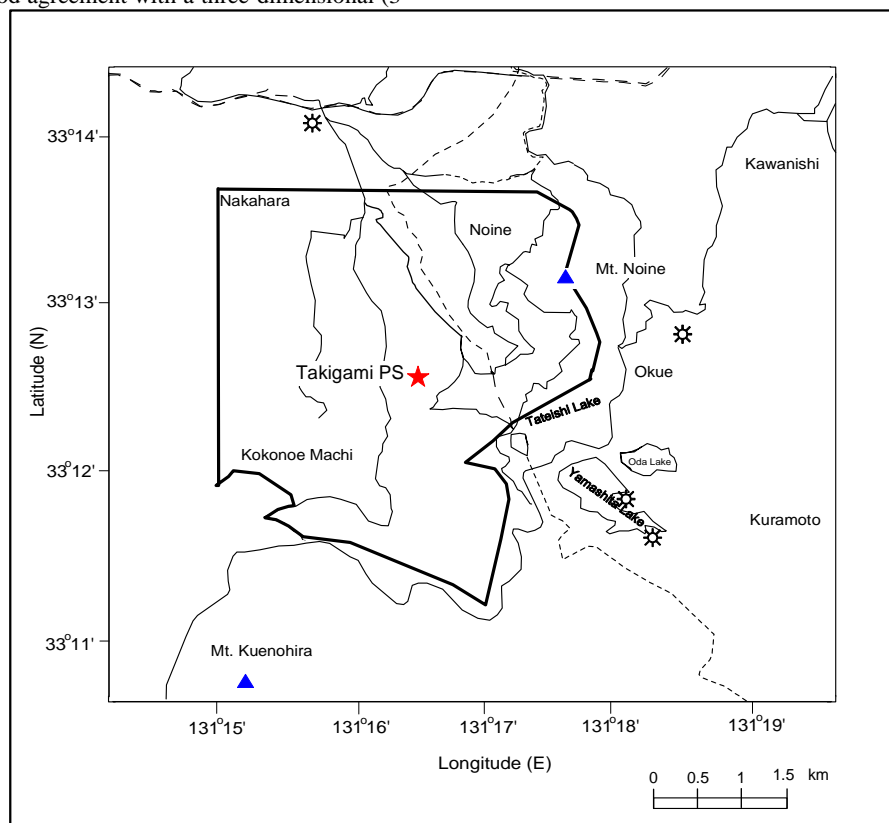

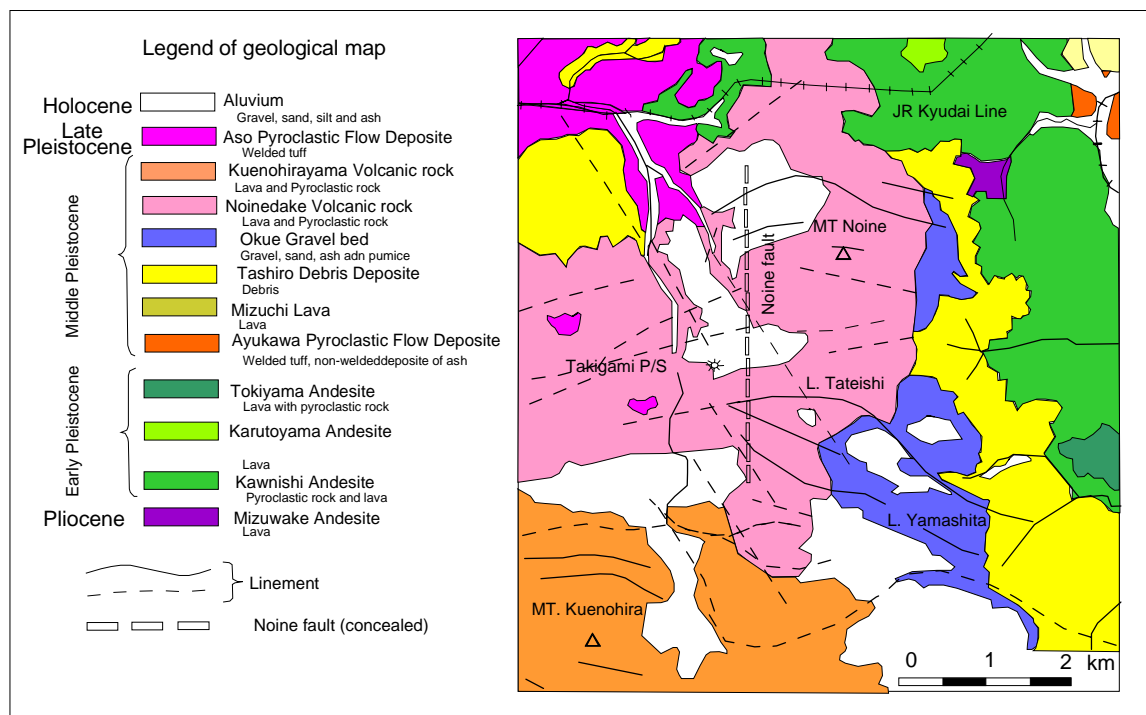**Figure 1: Location of Takigami area.**

Figure 2. Geological map of Takigami area

2. GEOLOGICAL SETTING

The studied area is mainly covered with volcanic formations of Quaternary age (Figure 2). The oldest volcanic rock is Mizuwake andesite (Pliocene) exposed in the northern part of the area. The formations in the Takigami area consist of dacitic to andestic lavas and pyroclastic of Pliocene to Pleistocene age, which are interfingered with lacustrine sediments. The Quaternary volcanic rocks are classified into four formations from bottom to top, including the Takigami formation, Ajibaru formation, Kusu formations and the Noine-dake volcanic rocks.

These Quaternary units consist of layers of andesitic or dacitic volcanic rocks. The Mizuwake Andesite (Pliocene) is Noine fault zone is not observed from the surface, but this fault divides the area into eastern and western parts stratigraphically. The vertical displacement of the faults in this zone is estimated to be more than 1000 m, based on a comparison of the depths to the Mizuwake Andesite on the western and eastern sides of the fault zone. The east-west (E-W) or northwest-southeast (NW-SE) striking fault were confirmed by a study of surface lineaments using remote sensing data. This type of faults is estimated to have smaller vertical displacement than that of the north-to-south striking faults. High permeability zones and fluid discharge zones are distributed along these fault structures. Hydrothermal alteration in the area is classified into 4 layers. From top to bottom, the first layer is not altered, the second is smectite which has a low resistivity, the third mixed layer minerals, the fourth layer is illite-chlorite layer which corresponds to Mizuwake andesite. This exists at shallow depth in the eastern, while deeper in the west.

composed mainly of altered andesite lava flows and pyroclastic rocks that have been propylitically altered. Even the deepest well in the area, TT-1 (3000 m) does not reach the Pre-Tertiary basement rocks. There are few outcrops of the deep formations at the surface because young volcanic products cover the area extensively. The geological structure of the area is characterized by two types of fault/fracture system, which have been identified mainly from studies of lineaments and correlation of subsurface stratigraphy. One system strikes almost north to south with large vertical displacement, and the other east to west or northwest to southeast. The north-to-south trending of

Table 1: Stratigraphy in the Takigami area.

| Age	Formation	Litholoy
Quaternary Pleistocene	Noine-dake volcanic rocks	pyroxene-hornblende andesite/dacite lava and pyroclastic pumice/sandy tuff
	Kusu formation	
	Ajibaru formation	hornblende andesite lava/brecciated lava
	Takigami formation	plagioclase megacrystic dacite lava/pyroclastic
Neogene Pliocene	Mizuwake andesite	tuffaceous sandstone/siltstone
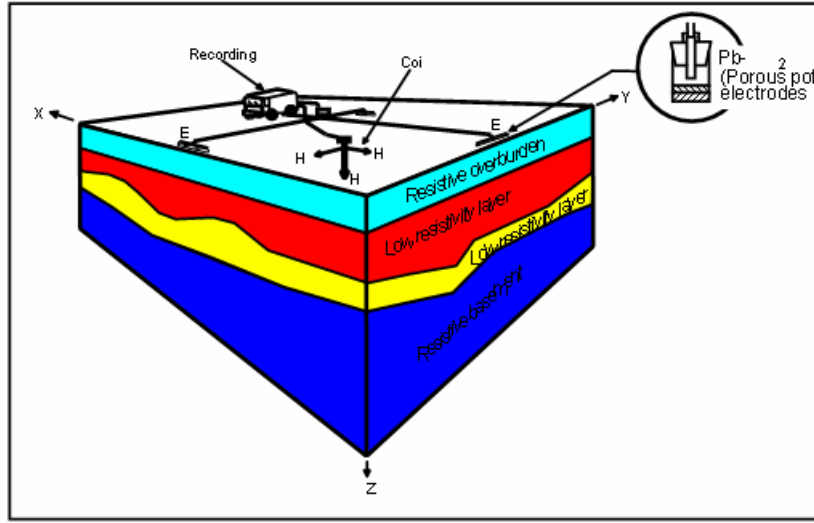
Figure 3: Field layout for MT measurements.

3. MAGNETOTELLURIC (MT) METHOD

3.1 Theoretical Background

In the magnetotelluric method, two orthogonal components of the horizontal electric field and three components of magnetic fields induced by natural primary sources are measured simultaneously as a function of frequency with a field layout of Figure 3. The two apparent resistivity on the earth surface is derived from Maxwell's equation (Cagniard, 1986)

$$\rho_{axy} = \frac{1}{\mu\omega}\left|\frac{E_x}{H_y}\right|^2 \quad \text{and} \quad \rho_{ayx} = \frac{1}{\mu\omega}\left|\frac{E_y}{H_x}\right|^2 \qquad (1)$$

The MT interpretation relies heavily on calculation of forward model for the relationship between observed data and geological fault structure. In this paper, 1-D inversion technique based on the maximum likelihood estimation is applied to the transverse electric (TE-mode) data and 2-D inversion techniques based on a non-linear conjugate gradient method is used for interpreting the transverse magnetic (TM-mode) data.

3.2 1-D inversion

The inversion procedure used in this interpretation is a robust M-estimation procedure method (Sutarno & Vozoff, 1991). The method uses M-estimate instead of least square (LSQ) estimate for minimizing the differences between observed data and computed data using model parameters involved in the inversion problem. The LSQ method assumes a simple Gaussian statistics. However, estimation procedure based on the LSQ would not be statistically optional, as outliers (abnormal data) are frequently superimposed on MT data, which is approximated to Gaussian error. In this situation the estimation of model parameters could be seriously misleading (Mustopa et al., 2000).

In the inversion of magnetotelluric data, we need the initial model parameters, that is resistivities and thicknesses of the formation. We also need apparent resistivity function for

calculating modeling data and observed data. In this case the model function is $g_i^t(p)$ (i=1,2,..,n) where p_j (j=1,2,..,2m-1) is model parameters consisting of resistivities and thicknesses. The observed apparent resistivities data are g_i^{ob} (i=1,2,…,n).

In a robust procedure we minimize the function

$$\chi = \sum_{i=1}^{n} \Gamma(r_i) \qquad (2)$$

where $\Gamma(r_i)$ is loss function and r_i is residue which in MT problem is the difference between observed data and calculated synthetic data theoretically, that is

$$r_i = g_i^{ob} - g_i^t \qquad (3)$$

To achieve scale invariance, a scale parameter s is determined in the following expression.

$$\chi = \sum_{i=1}^{n} \Gamma(t_i) \qquad (4)$$

where $t=r_i/s=(e_i-J\Delta p)$, $r_i=g_i^{ob}-g_i^t(p_o)$ and $e_i=g_i^{ob}-g_i^t(p_o+\Delta p)$.

In an inversion procedure to find a set of earth model parameters $(p_1, p_2,...p_m)$, we minimize equation (8) and by defining the weight function $W(t)=\psi(t)/t$, the m simultaneous equations become

$$J^T W J \Delta p = J^T W r \qquad (5)$$

where J is Jacobian matrix. By adding the damping factor K into solution of equation (5), we get

$$\Delta p = \left(J^T W J + K^2 I\right)^{-1} J^T W r \qquad (6)$$

The solution can be obtained by SVD (Singular Value Decomposition) method. The scale parameter s must also be

estimated. The most commonly used scale estimation is Median Absolute Deviation (MAD)

$$s = \frac{med \left| r_i - med \left| r_i \right| \right|}{\sigma_{MAD}} \qquad (7)$$

One approach to achieving robustness is to choose the loss function $\Gamma(t)$ and thus $\psi(t)$ and the weight function $W(t)$ on theoretical grounds to retain high efficiency over a family of expected distribution in preference to yielding the maximum likelihood estimate for a single distribution. Since most data yield largely Gaussian residuals with a small outliers fraction, it is customary to use a loss function giving efficiency greater than 95 % for normal data but which still provides reasonable protection for noise contaminated data.

3.3 2-D Inversion

The 1-D inversion of MT data is an effective geophysical tool when a regional geological structure is a layered earth, as in a sedimentary basin, and a lateral variation is low. However, when the geological structure is a complicated, the technique may produce error. To overcome the problem, 2-D inversion procedure using TM-mode data is at least an essential tool to interpret the observed data. The 2-D inversion has been used for many years to interpret automatically MT data. This technique makes the interpretation more objective and less time-consuming than the trial-and-error approach, but it does not yield a unique solution. Despite this problem, a common approach to interpret a MT data set is to construct a cross-section of the area by a least-square inversion (Jupp and Vozoff, 1977). The smoothness-constrained least-squares method for 2-D inversion, which finds the smoothest change to the model and the residual error lying within a desired tolerance, was developed by Sasaki (1989), deGroot-Hedlin and Constable (1990), and Uchida (1993). In this paper, we carried out 2-D inversion of MT data of transverse magnetic mode using the algorithm proposed by Rodi and Mackie (2001), that is, a non-linear conjugate gradients (NLCG) algorithm. The NLCG scheme minimizes an objective function that penalizes data residuals and the second spatial derivatives of resistivity. Tikhonov's method defines a regularized solution of the inverse problem to the model m that minimize the object function (Rodi et al, 2001)

$$\Psi(m) = \left(d - F(m) \right)^T V^{-1} \left(d - F(m) \right) + \lambda \left\| L(m - m_0) \right\|^2 \qquad (8)$$

where d is observed data vector, m is an unknown model vector, m_o is a priori model, F is a forward modeling operator, V is an error covariance matrix, L is a linier operator, and λ is a regularization parameter. Each datum d_i is log amplitude or phase of transverse electric (TE) mode or transverse magnetic (TM) mode of tensor apparent resistivities at a particular station. The model vector is also

log resistivity as a function of position ($m(x) = \log \rho(x)$). Laplacian operator can be written as follows:

$$\left\| L(m - m_o) \right\|^2 = \int \left(\Delta(m(x) - m_0(x)) \right)^2 dx \qquad (9)$$

Method of NLCG directly solves to minimize the objective function of equation (8). The model sequence is given by

$$\Psi \left(m_j + \alpha_j h_j \right) = \min_{\alpha} \Psi \left(m_j + \alpha h_j \right) \qquad (10)$$

$$m_{j+1} = m_j + \alpha_j h_j \qquad (11)$$

$$h_j = -C_j g_j + \beta_j h_{j-1} \qquad (12)$$

where α_j is step a step size, h_j is a search direction, C_j is a preconditioner, g_j is a gradient of objective function and β_j is a scalar calculated as

$$\beta_j = \frac{g_i^T C_i \left(g_i - g_{i-1} \right)}{g_{i-1}^T C_{i-1} g_{i-1}} \qquad (13)$$

In NLCG algorithm, the preconditioner has a big impact on efficiency. Two competing considerations in its choice are the computational cost of applying the preconditioner, and its effectiveness in "steering" the gradient vector into productive search direction.

4. INTERPRETATION OF MT RESULTS

The MT method has been successfully used for exploring a geothermal reservoir both theoretically and practically. For instance, Johnston et al. (1992) evaluated the MT method for detecting a geothermal reservoir theoretically. The result indicated that the method is very powerful tool for a reservoir exploration. Ushijima et al. (2000) used the method for detecting the promising production area in Hatchobaru geothermal field. The result showed very good correlation with the known geothermal reservoir, which provides steam and hotwater mixtures for the 55 MW geothermal power plant in Hatchobaru geothermal area.

The MT field survey in Takigami area have was carried out by Phoenix Geophysics Ltd. under a project of Idemitsu Geothermal Co. in the Takigami area. The measurements sites shown in Figure 4 were not regularly spaced.

A remote-reference technique was used in these measurements to overcome bias to the estimate of electrical impedance caused by the presence of noise. The data interpretation used here is 1-D and 2-D inversion procedures as described in the sections 3.2 and 3.3.
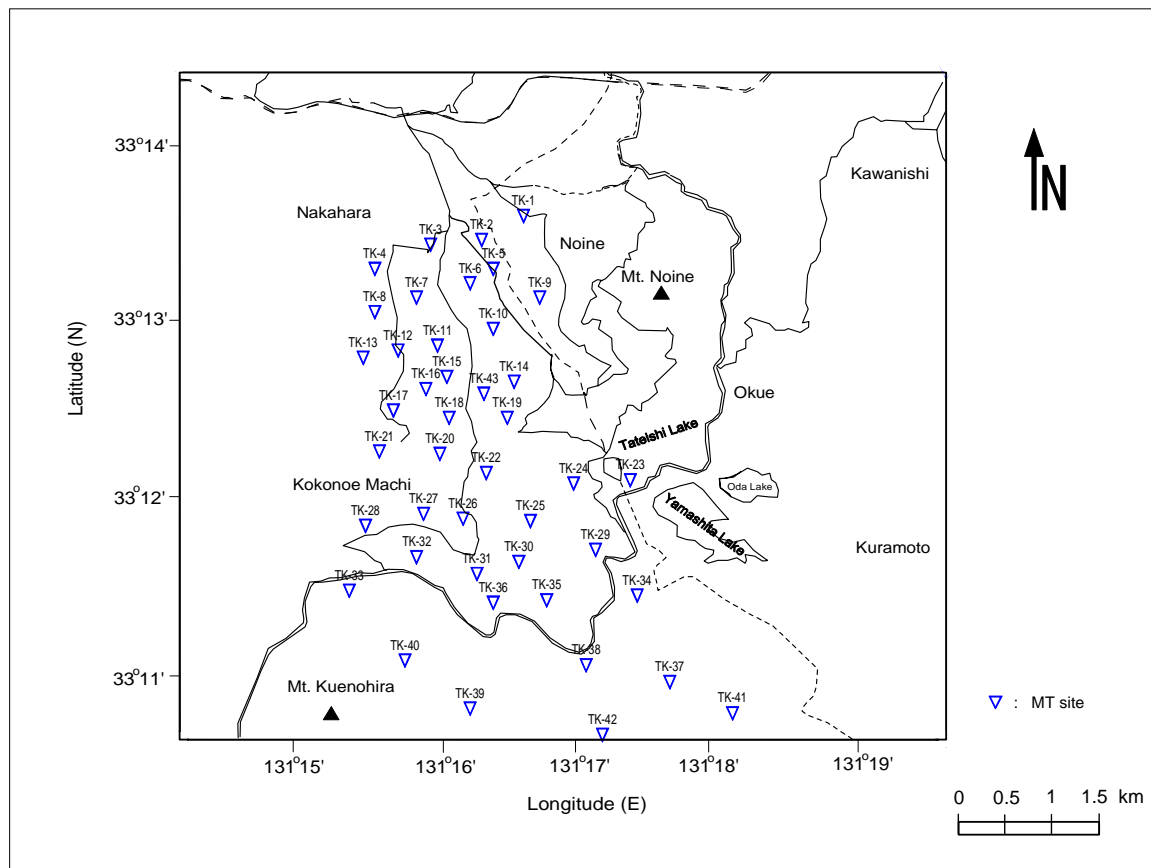
Figure 4: Location map of MT sounding survey.

4.1 MT soundings in Takigami area.

Typical observed MT sounding curves are illustrated in Figure 5.

As shown in the Figures that the geoelectrical sections are characterized by a high resistivity layer in shallow level (300-700 m) overlying a low resistivity zone (3-30 ohm-m), which has thikiness of 50 to 1000 m. These anomalous low resistivity and lateral discontinuity of apparent resistivity curve may be due to faulting and hydrothermal alteration zone. The low resistivity distribution of the MT sites becomes deeper and thicker to the southwest. This characteristics is in agreement with geological model confirmed by drilling results in Takigami area. In order to investigate a lateral distribution of resistivity, a contour map of the 1-D inverted resistivity at 300 m from sea level and at sea level are developed. The distribution of the low resistivity is relatively the same in the eastern part and western part. On the other hand, at the sea level the resistivity in the western part is low while high in the eastern

part. Therefore, it is evaluated that the reservoir is shallower in the eastern part than that in the western part. The boundary is probably the Noine fault zone. From the depth-sliced resistivity-contoured maps, we could evaluate the general fault trend and structural trend. Generally, the most favorable areas for geothermal development within the surveyed areas are the intersection zones of faults, which would provide sufficient fracturing. This fracturing is a requirement for a promising reservoir and to maintain well capacities through the life of a geothermal power plant. Minor faulting, generally perpendicular to the trend of the interpreted faulting, intersects these faults providing a more favorable environment for geothermal fluid circulation.

4.2 2 -D inversion

According to the results obtained through the inversion procedure, we could construct the 2-D resistivity cross-section for each profile. Figure 6 show an example of geoelectrical cross-section of 2-D inversion of the SW-NE survey line across the present steam production zone.
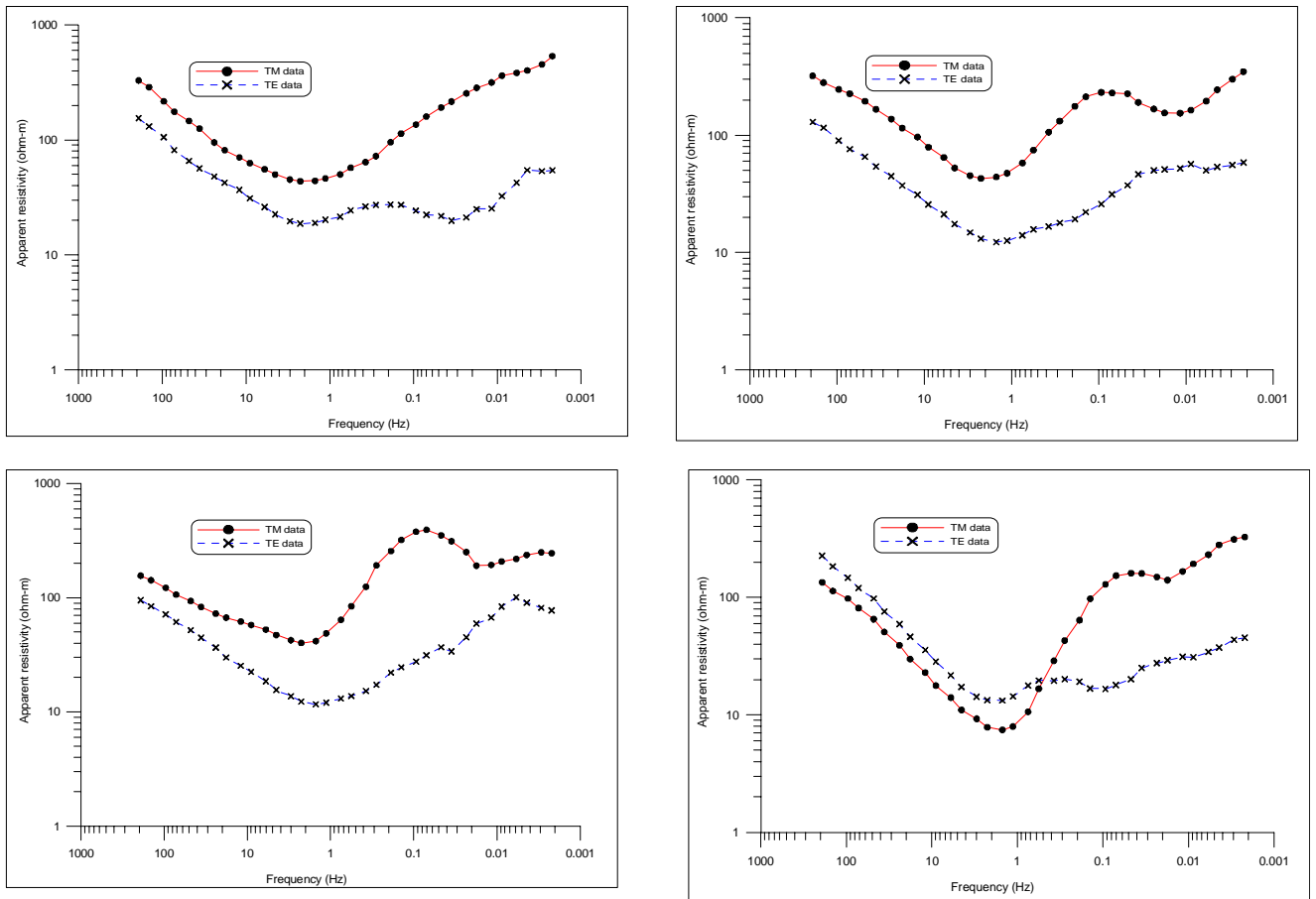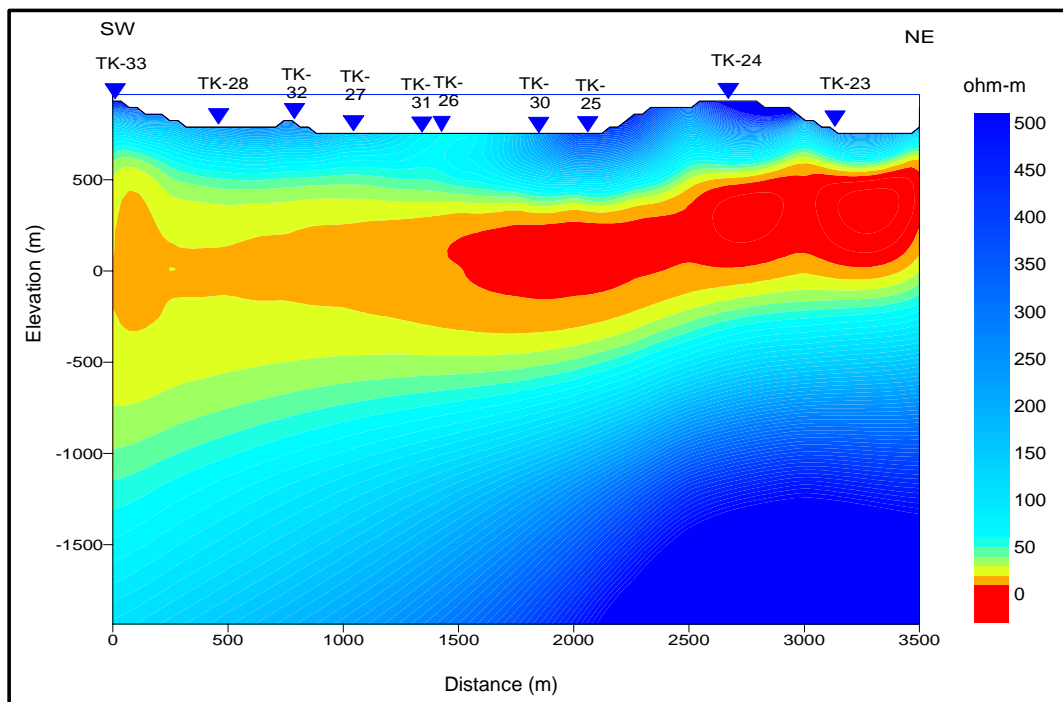
Figure 5: Some observed MT sounding curves.

Figure 6: Resisitivity section derived from 2-D inversion of MT data across the production zone.
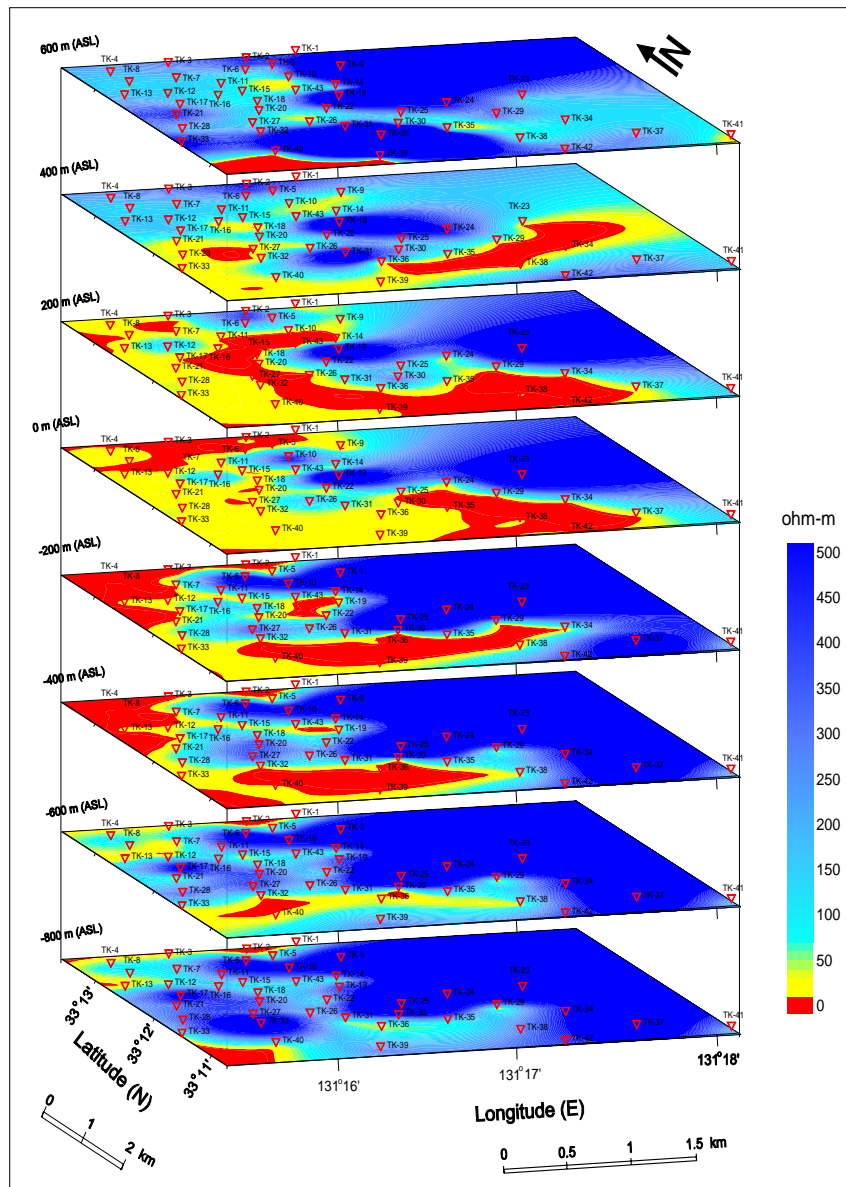
Figure 7: Depth-sliced resistivity distribution in the Takigami area.

The cross-section indicate a high resistivity (50 to 500 ohm-m) zone in a shallow section with 300 to 550 meters depth overlying a lower resistivity zone (3-20 ohm-m) with 850 meters thickness. These anomalous features may be due to faulting, fracturing, and hydrothermal alteration along a significant fracture. The 2-D cross-sections of inversion result shows that the low resistivity zone in the northeastern part is intensive and shallower than that in the southwestern part. Accordingly, the underlain resistive layer correlated to the reservoir zone is shallower in the northeastern part. This inversion result also has a good agreement with the geological feature.

4.3 Three-dimensional View

To understand the resistivity distribution in term of 3-D geological structure, we construct a 3-D view of resistivity distribution from the 1-D inversion results with 100 m depth intervals.

Figures 7 show that there are three layers of distribution of resistivity in the area. The conductive (second) layer, which correlates to the layer of pyroclastic rocks and a zone of strong hydrothermal alteration, is shallow and thin in the east and becomes deeper and thicker to the west. The boundary is probably the Noine fault zone. This trend is in agreement with the strike of the Noine fault in the area.

5. COMPARISON OF MT INVERSION RESULTS WITH WELL LOGS AND PRODUCTION DRILLING DATA

Figure 8 shows a representative geoelectrical cross-section of 2-D inversion result of MT survey line (Line-1) together with resistivity logs, temperature logs and lost circulation data during the drilling of production wells in the same direction (SW-NE).
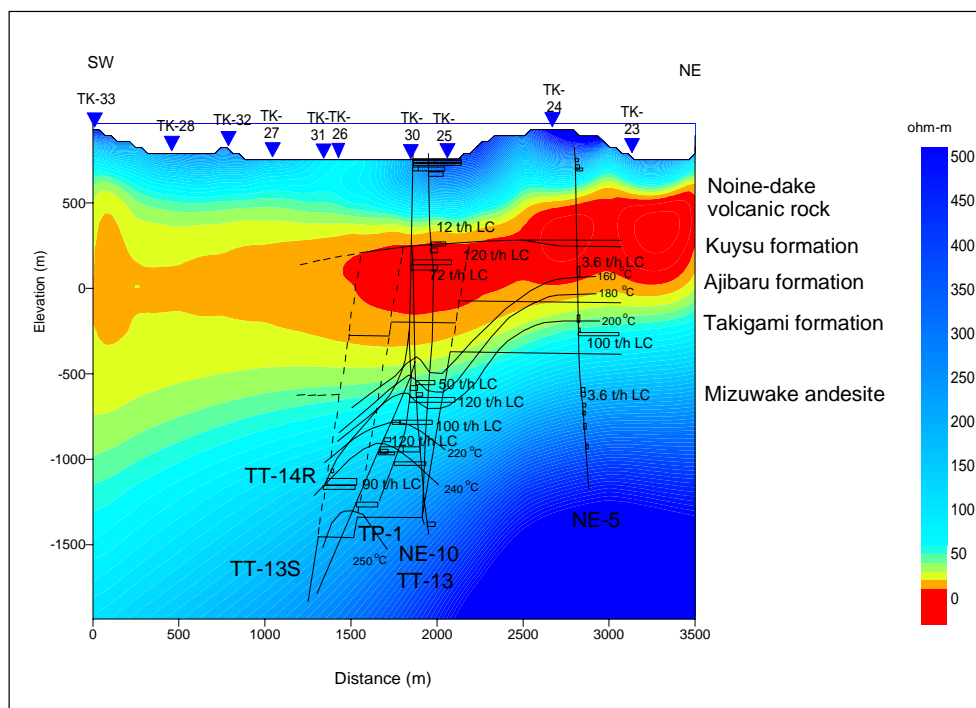
Figure 8: Comparison of MT results with well data of five production wells.

There are five wells displayed in the Figure 8 compared with ten MT sounding sites. The site TK-28E and 33E correlate with production well TT-14, where the low resistivity layer (approximately 30 ohm-m) becomes thicker towards site TK-33E. The site TK-31E correlates with production well TT-13S, which the low resistivity layer (approximately 32 ohm-m) is thick (approximately 1500 m). The site TK-30E correlates with the production wells of TT-13 and NE10, where the low resistivity layer (approximately 24 ohm-m) becomes thicker towards NE-10. The site TK-23E and TK-24E correlate with exploratory well NE-5 where the low resistivity (approximately 6 ohm-m) is shallow and thin. Generally, the resistivity distribution in each MT sounding obtained is almost similar to the resistivity obtained from electrical resistivity logging.

The electrical structure is composed mainly of three layers: the surface layer (resistive layer), the intermediate (conductive layer) and the bottom layer (resistive layer). The conductive layer is shallow and thin in the east and deepens and becomes thicker to the west. The 1-D inversion of MT data is very good to be used for layered earth structure which has a good correlation with resistivity obtained from well logging. The comparison of 2-D inversion result with drilling data shows that there are four resistivity zones correlate with four primary rock units: first, the surface high resistivity zone correlates with Noine-dake volcanic rock as non altered zone; second, the low resistivity zone correlates with Kusu and Ajibaru formation as smectite layer minerals; third, intermediate low resistivity zone correlates with Takigami formation as mixed layer minerals; and fourth, high resistivity 'basement' correlates with Mizuwake andesite rock as illite-chlorite layer. The composition of each type of rock is described in Table 1. It was recognized from the Figure 8 that the electrical discontinuity is found in MT stations of TK-26E, TK-30E and TK-25E in the depth of 800 - 1000 m below sea level. At this depth the lost circulation has occurred during the drilling of production boreholes (TT-14R, TT-13S and TP-1). It was confirmed that the result of resistivity inversion correlates with fracture zones corresponding to geothermal reservoirs. The subsurface temperature distributions of Takigami area obtained from fluid inclusion measurement using samples from some wells are also displayed in the Figure 8. The correlation between distribution of the subsurface resistivity and distribution of the temperature can be concluded as follows: first, the surface high resistivity zone (50-500 ohm-m) correlates with low temperature zone due to cold meteoric circulation that corresponds to fresh and quaternary volcanic rocks; second, the low resistivity zone (1-20 ohm-m) correlates with impermeable layer and has a steep and constant thermal gradient of about 20°C/100 m, which corresponds to montmorillonite and mixed clay zones; and third, high resistivity 'basement' (50-500 ohm-m) correlates with high temperature zone (160-250°C) which corresponds to the tertiary andesite lava flow and the illite-chlorite zone. The low resistivity zone (second layer) is shallow in the NE and deepens in the SW, which correlates with the temperature distribution of 180°C. In general, the distribution of the three-layer resistivity structure has a good correlation with the distribution of temperature.

6. DISCUSSIONS

The MT data obtained from Takigami geothermal field have been reinterpreted in order to derive a new insight of the geothermal structures in the Takigami geothermal field. The results of 1-D and 2-D inversion of MT data revealed that the resistivity structures in this area composed mainly of three layers. The surface layer has a resistivity of 50 - 500 ohm-m and low temperature zone as a normal layer. The intermediate layer has an extremely low resistivity of 1 - 20 ohm-m with a steep geothermal gradient of about 20°C/100 m due to strong hydrothermal alteration zone of smectite and mixed layer minerals. The bottom layer is more resistive than the second layer and has resistivity of 30 - 500 ohm-m with a high temperature zone (160-250°C) as illite-chlorite layer. The three-layer structure extends laterally in the Takigami area. The conductive (second) layer, which correlates with a layer of pyroclastic rocks and a zone of

strong hydrothermal alteration, is shallow and thin in the discontinuity of electrical resistivity is clearly shown in the inversion result beneath the MT sites of TK-30E and TK-31E in the depth of 800 - 1000 m below sea level. We suggest that this zone corresponds to promising fractured zone correlated with a potential geothermal reservoir. In the drilling data of production boreholes TT-14R, TT-13S and TP-1, which approximately coincide with MT sites of TK-26E and TK-30E, were found as good lost circulation zones in the depths of 800 – 1000 m. This condition correlates with discontinuity of electrical resistivity below the MT sites of TK-26E, TK-30E and TK-25E as shown in Figure 8.

7. CONCLUSIONS

The MT soundings applied in the Takigami geothermal area is a powerful tool for determining areas of anomalously low resistivity zones indicating a potential geothermal reservoir beneath the volcanic area. The interpretation results show that the resistivity structure of the Takigami area mainly is composed of three layers, high resistivity in the fist layer, low resistivity in the second layer and high resistivity in the third layer. The results also show that the geothermal reservoir of the Takigami geothermal field is located in the different depths separated by the Noine fault zone. The eastern reservoir zone is shallower than the geothermal reservoir in the western part. The MT results show a good agreement with electrical resistivity logs, lost circulation zones during drilling operations and temperature distributions observed by temperature logging. This 3-D resistivity structure is good agreement with the geological feature, and the Noine fault in the Takigami area.

ACKNOWLEDGMENTS

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