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https://hdl.handle.net/2324/1122

出版情報：九州大学工学紀要. 62 (4), pp.207-221, 2002-12-20. 九州大学大学院工学研究院

Memoirs of the Faculty of Engineering, Kyushu University, Vol. 62, No. 4, December 2002

Application of Magnetotelluric Method to Takigami Geothermal Field in Kyushu, Japan

by

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(Received September 25, 2002)

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 promising 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 for data interpretation 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 resistivity structure shows a good correlation to geothermal reservoirs in the area. The 2-D inversion result of the same line (Line-1) was also compared with the temperature logs and lost circulation data obtained during the drilling operations. The result shows a good agreement among them. It is concluded based on the MT sounding 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.

Keywords: Magnetotelluric (MT) method, 1-D and 2-D inversions, Takigami geothermal field, Geothermal reservoir, 3-D resistivity structure

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1. Introduction

The central Kyushu was cut by a volcano-tectonic depression that has developed within a tensile stress field since Neogene time, resulting in the volcanism since Pliocene and Pleistocene times[1]. The northeastern part of central Kyushu, known as the Hohi region shown in **Fig. 1(a)**, is one of the most active geothermal areas in Japan. This geothermal region is associated with a low Bouguer anomaly referred to the Shishimuta basin structure. The Takigami geothermal area is located on the eastern margin of this low-gravity anomalous zone. The northeastern part of the geothermal area extends to a local gravitational high anomaly, while the western portion of the field has a low gravity anomaly (−35 mgal) as shown in **Fig. 1(b)**. A north-south (N-S) striking fault system was thought to exist in the area, related to the large-scale volcano-tectonic depression[2]. 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 methods[3]. However, the subsurface resistivity structure related to the geothermal reservoir is not fully understood in the area. Therefore, detailed MT sounding survey was conducted and advanced techniques such as 1-D and 2-D inversions are applied to interpret the MT data.

The objective of this paper is to interpret the MT data for determining the resistivity structure over the known geothermal reservoir zone in the Takigami geothermal field. Moreover, the 3-D resistivity structure derived from the 2-D inversion analysis can be used for making drilling programs of production and reinjection wells for a further development of geothermal resources in the Takigami geothermal area.

2. Geological Setting and Hydrothermal Alteration

The studied area is mainly covered with volcanic formations of Quaternary age (**Fig. 2**). The oldest volcanic rock is Mizuwake andesite (Pliocene) exposed in the northern part of the

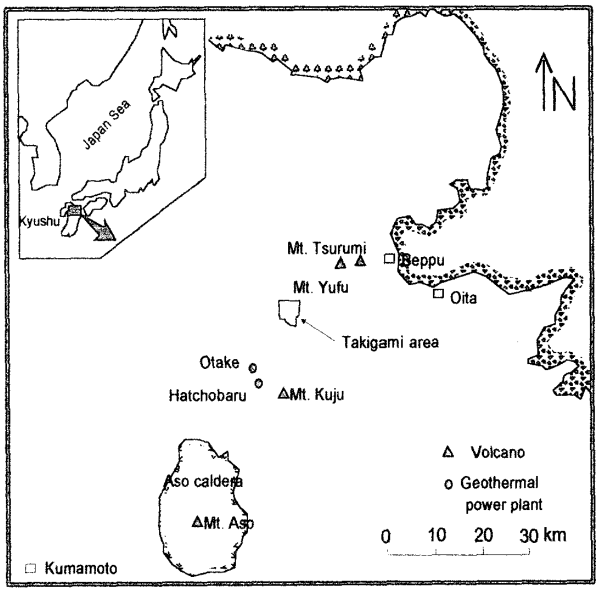

Fig. 1(a) Hohi geothermal area with the location of the Takigami area.

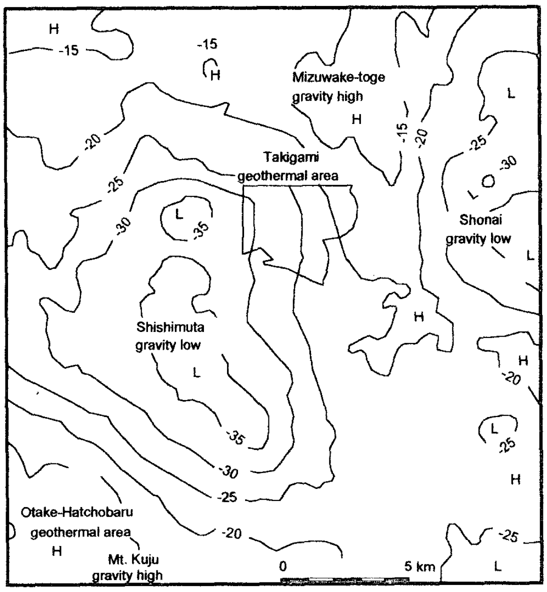

Fig. 1(b) Bouguer gravity anomaly map in and around the Takigami geothermal area.

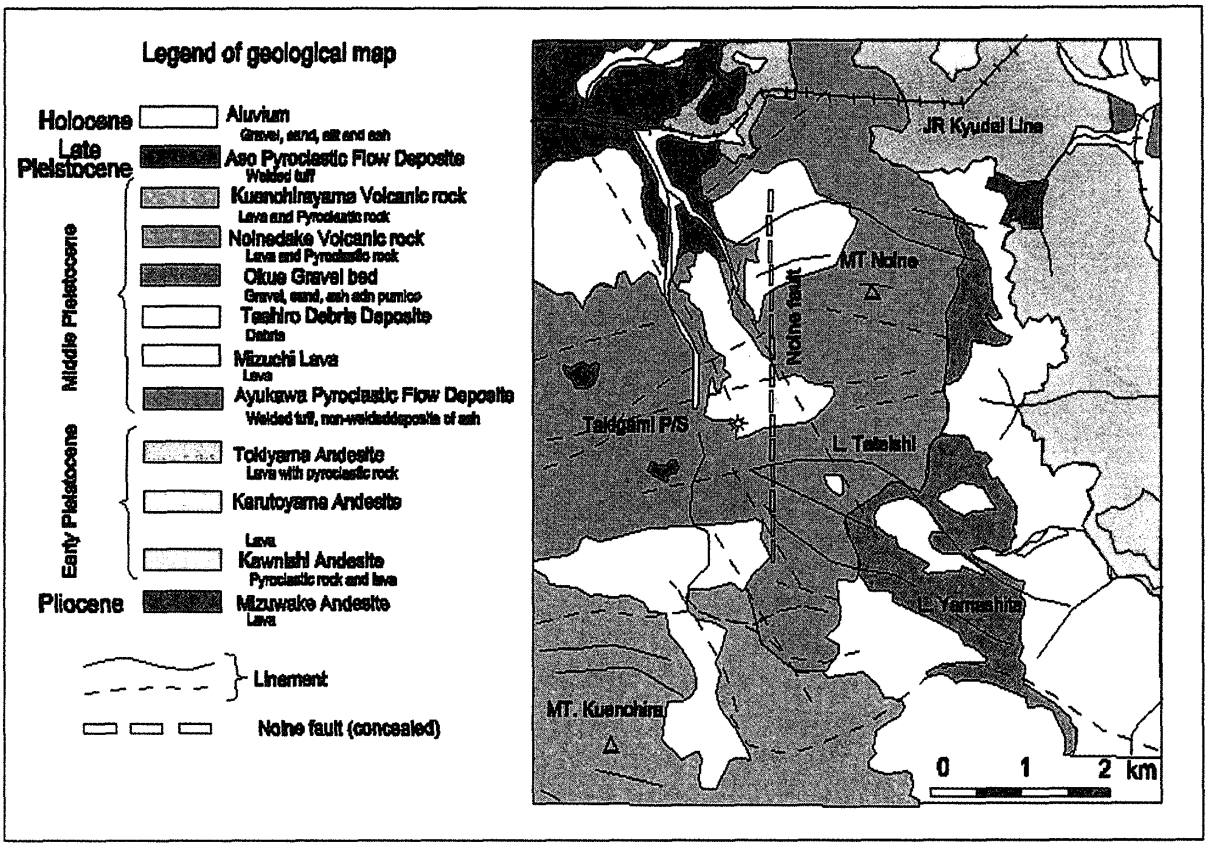

Fig. 2 Geological map of the Takigami geothermal field (Furuya et al., 2000).

area. The formations developed 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 formation and the Noine-dake volcanic rocks. These Quaternary units consist of layers of andesitic or dacitic volcanic rocks. The Mizuwake Andesite (Pliocene) is 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 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 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 as shown in **Fig. 3**.

The east-west (E-W) or northwest-southeast (NW-SE) striking faults were confirmed by a study of surface lineaments using remote sensing data. This type of faults is estimated to have smaller vertical displacements 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

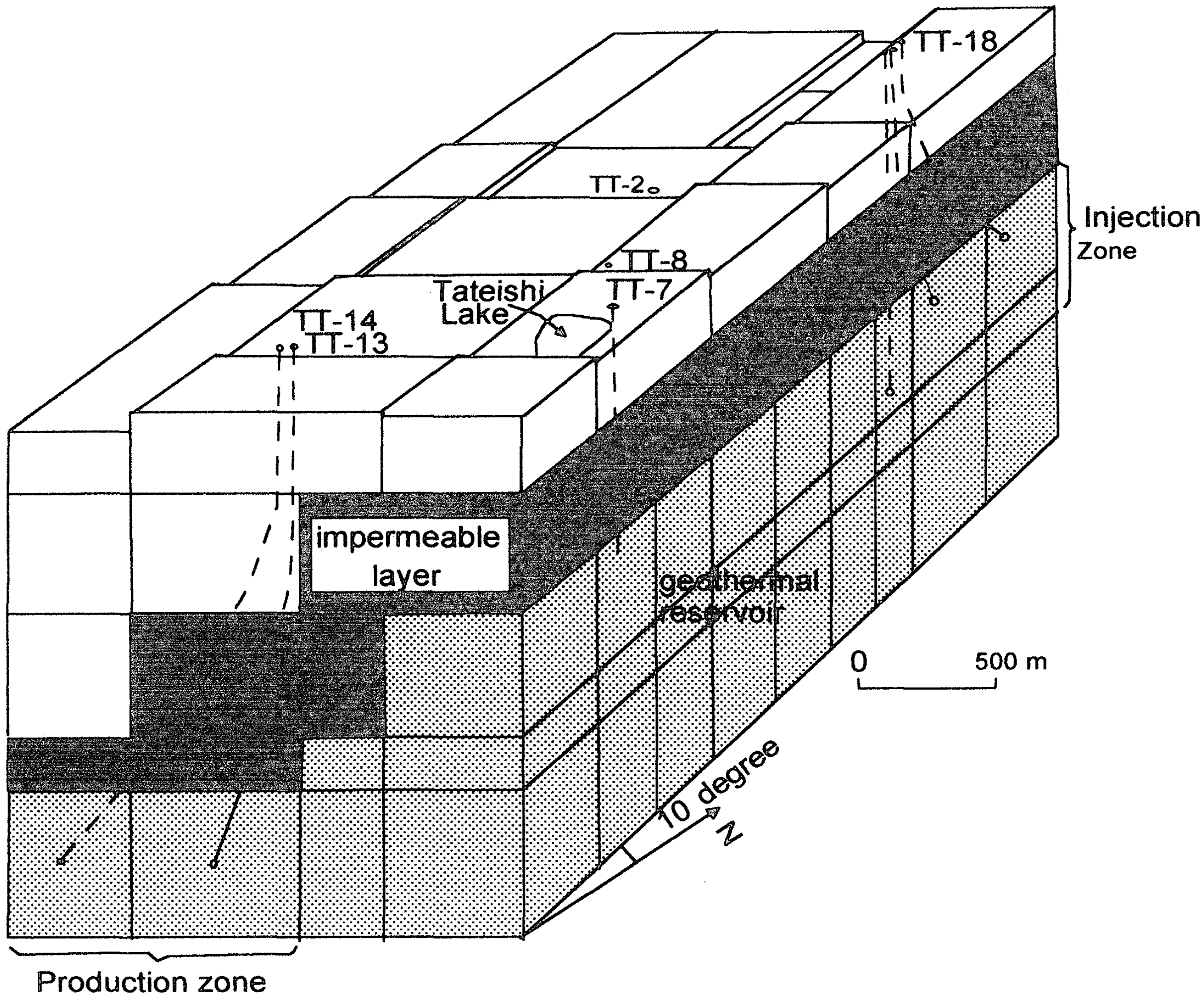

Fig. 3 3-D geological model of Takigami area (Furuya et al., 2000).

andesite and, exists in the shallow depth in the eastern, while deep in the western portion.

3. Magnetotelluric (MT) Method

3.1 Theoretical Background

The basic concept used in MT method can be derived from the solution of Maxwell's equations, in a source free region with assuming time dependence $e^{i\omega t}$ and neglecting the displacement current, as follows

$$\nabla \times \boldsymbol{E} = -i\omega\mu_0 \boldsymbol{H} \tag{1}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + i\omega \boldsymbol{D} \tag{2}$$

$$\nabla \cdot \boldsymbol{D} = 0 \tag{3}$$

$$\nabla \cdot \boldsymbol{B} = 0 \tag{4}$$

where $\boldsymbol{E}$ is the electric field intensity (V/m), $\boldsymbol{B}$ is the magnetic induction (tesla), $\boldsymbol{H}$ is the magnetic field intensity (A/m), ω is the angular frequency, μ_o is the magnetic permeability (H/m).

The apparent resistivity[4)] on the earth surface derived from Maxwell's equation above is

$$\rho_{axy}=\frac{1}{\mu\omega}\left|\frac{E_x}{H_y}\right|^2 \text{ and } \rho_{ayx}=\frac{1}{\mu\omega}\left|\frac{E_y}{H_x}\right|^2 \tag{5}$$

The MT interpretation relies heavily on forward model calculation into the relationship between observed data and real geological structure and to obtain a reliable solution. In this paper, 1-D inversion technique based on the maximum likelihood estimation (M-estimate) is applied to the TE-mode data and 2-D inversion technique based on a non-linear conjugate gradient method is used for interpreting the TM-mode data.

3.2 1-D inversion

The inversion procedure used in this interpretation is a robust M-estimation procedure method[5]. The method uses M-estimate instead of least square (LSQ) estimate for minimizing the differences between observed data and computed data using model parameters (resistivity and phase) 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[6].

In the inversion of magnetotelluric data, we need the initial model parameters, that is resistivities ρ_j $(j=1,2,...,m)$ and thicknesses h_j $(j=1,2,...,m-1)$. We also need apparent resistivity function for calculating synthetic 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 ρ_j $(j=1,2,...,m)$ and thicknesses h_j $(j=1,2,...,m-1)$. The synthetic or the observed apparent resistivities are is g_i^{ob} $(i=1,2,...,n)$.

In a robust procedure we minimize the function

$$\chi=\sum_{i=1}^{n}\Gamma(r_i) \tag{6}$$

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

$$r_i=g_i^{ob}-g_i^t \tag{7}$$

To achieve scale invariance, a scale parameter s is determined in expression of equation (6). Thus the equation (6) becomes

$$\chi=\sum_{i=1}^{n}\Gamma(t_i) \tag{8}$$

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

$$J^TWJ\Delta p=J^TWr \tag{9}$$

By adding the damping factor K into solution of equation (4), we get

$$\Delta p=(J^TWJ+K^2I)^{-1}J^TWr \tag{10}$$

The solution is 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)

$$s=\frac{med|r_i-med|r_i||}{\sigma_{MAD}} \tag{11}$$

One approach to achieving robustness is to choose the loss function $\Gamma(t)$ and thus $\psi(t)$ and $W(t)$ 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 loss function giving efficiency greater than 95% for normal data but which still provide reasonable protection for noise contaminated data. On this base, in this paper, we use Huber hybrid method that is

$$\Gamma(t)=\begin{cases}\frac{1}{2}t^2, & |t|\le t_o\\ t_o|t-\frac{1}{2}t_o, & |t|\ge t_o\end{cases},\quad \psi(t)=\begin{cases}t, & |t|\le t_o\\ t_o\mathrm{sign}(t), & |t|\ge t_o\end{cases},\quad W(t)=\begin{cases}1, & |t|\le t_o\\ \frac{t_o}{|t|}, & |t|\ge t_o\end{cases} \tag{12}$$

where t_o is called tuning constant, and it has value 1.5 for Huber hybrid.

3.3 2-D inversion

The 1-D inversion of MT data is good to be used when a regional structure is approximately horizontal, as in a sedimentary basin, and a lateral variation is low. However, when the structure is not approximately layered, the technique may be serious error. To overcome the problem, 2-D inversion procedure is an essential tool to interpret the MT 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 then the trial-and-error approach but it does not yield a unique solution. Despite this, a common approach to fitting a 2-D MT data set is to construct a cross-section of the area based on prior geological knowledge and the model parameterization to solve for the conductivities by least-squares inversion[7]. The smoothness-constrained ("regularized" solution) least-squares method for 2-D MT inversion, which finds the smoothest change to the model and the residual error lies within a desired tolerance, was developed by Sasaki[8], deGroot-Hedlin and Constable[9], and Uchida[10].

In this paper, we carried out 2-D inversion of MT data of transverse magnetic mode using the algorithm proposed by Rodi and Mackie[11] that is a non-linear conjugate gradients (NLCG) algorithm. The NLCG scheme is to minimize 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 is

$$\Psi(m)=(d-F(m))^T V^{-1}(d-F(m))+\lambda\|L(m-m_0)\|^2 \tag{13}$$

where d is an 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) or transverse magnetic (TM) mode of complex apparent resistivity at a particular station and frequency. The model vector is also log resistivity as a function of position $(m(x)=\log\rho(x))$. Laplacian operator can be written as follows

$$\|L(m-m_o)\|^2=\int(\Delta(m(x)-m_0(x)))^2dx \tag{14}$$

NLCG directly solves to minimize the objective function ψ of equation (13). The model sequence is given by

$$\Psi(m_j+\alpha_j h_j)=\min_{\alpha}\Psi(m_j+\alpha h_j) \tag{15}$$

$$m_{j+1}=m_j+\alpha_j h_j \tag{16}$$

$$h_j = -C_j g_j + \beta_j h_{j-1} \tag{17}$$

where α_j is 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

$$\beta_j = \frac{g_l^T C_l (g_l - g_{l-1})}{g_{l-1}^T C_{l-1} g_{l-1}} \tag{18}$$

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 data

The MT method has been successfully used for exploring a geothermal reservoir both theoretically and practically. For instance, Johnston et al.[12] evaluated the MT method for detecting a geothermal reservoir theoretically. The result indicated that the method is very powerful tool for a reservoir exploration. While Ushijima et al.[13] used the method for detecting the promising area in Hatchobaru geothermal field. The result was very good correlation with the known geothermal reservoir, which provides steam of the 110 MW for

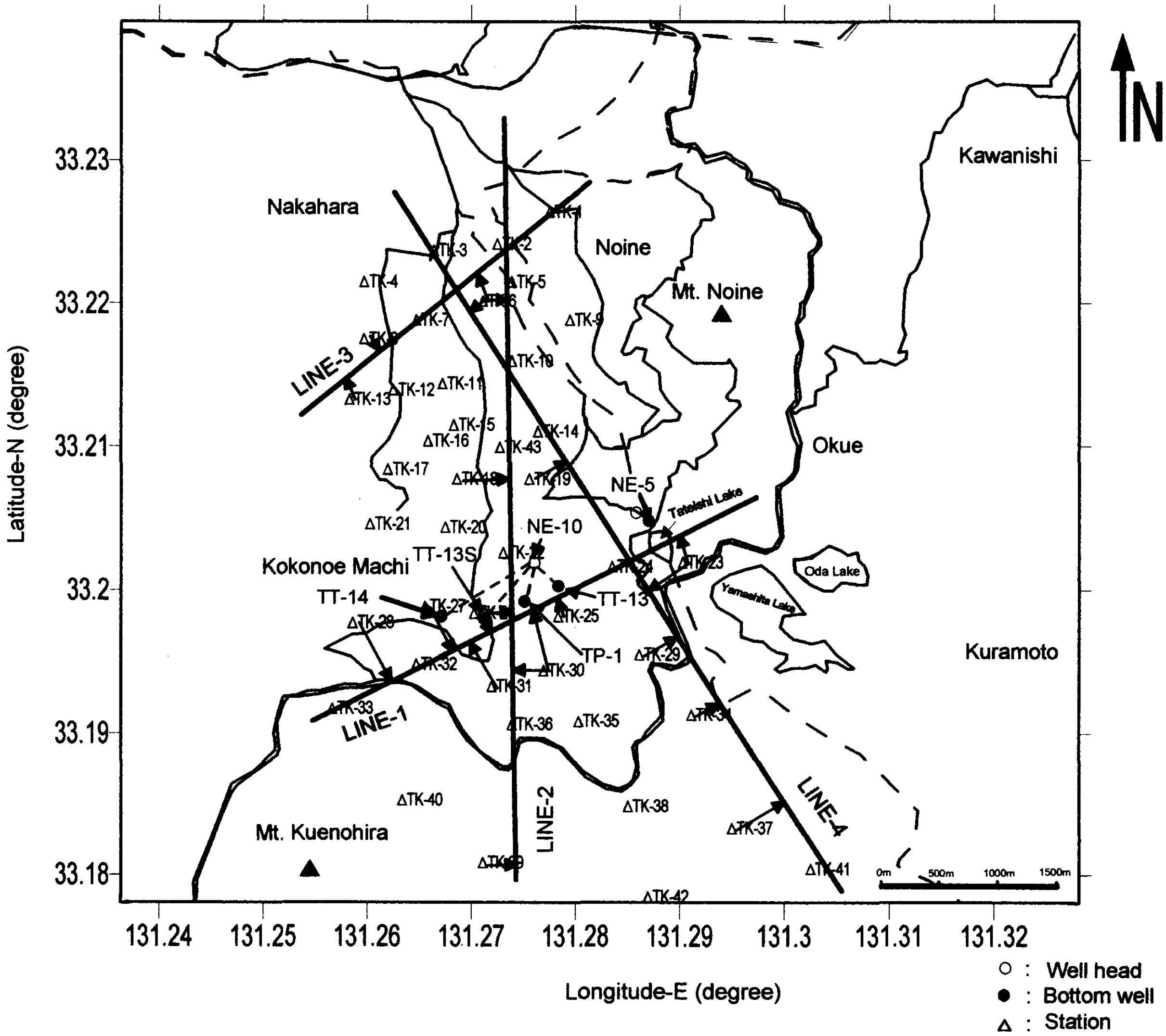

Fig. 4 Location of MT sites and some boreholes.

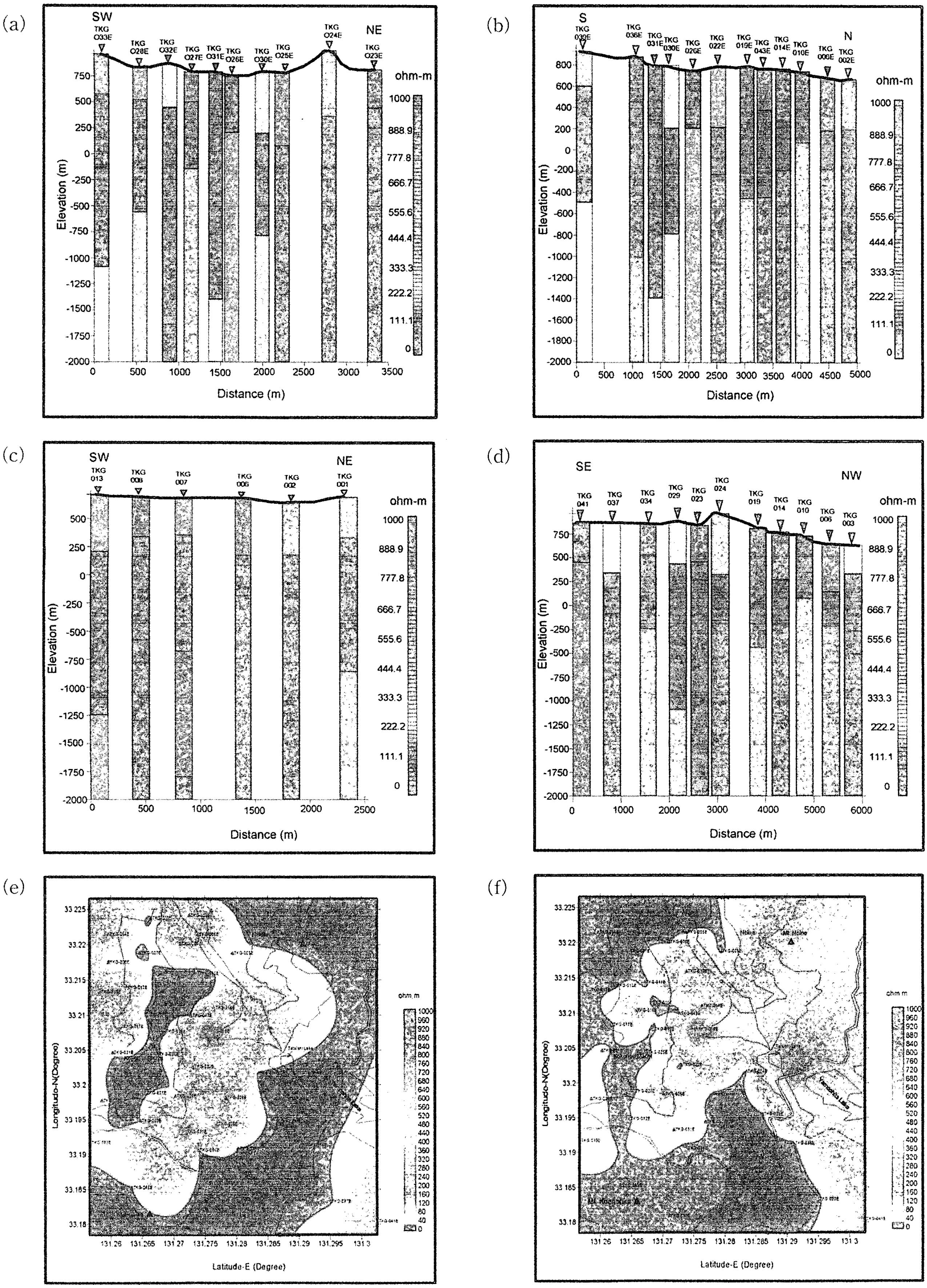

Fig. 5 Resistivity layer sections of Lines 1–4 and depth sliced resistivity contour maps at 300 m above sea level and sea level in the Takigami geothermal area.

two power plants. The MT measurements have been carried out by Phoenix Geophysics Ltd. under project of Idemitsu Geothermal Co. in the Takigami area of northeastern Kyushu, Japan. The measurements were not in a regularly spaced station shown in the **Fig. 4**.

A remote-reference technique was used in these measurements to overcome a bias into 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 above sections **3.2** and **3.3**.

4.1 1-D inversion

The 1-D inversion results are displayed as a geoelectrical cross-section along four lines (**Fig. 5(a)~5(d)**). As shown in the Figures that the geoelectrical sections are characterized by a high resistivity (50 to 1000 ohm-m) layer in shallow level (300-700 m) and overlying a low resistivity zone (3-30 ohm-m), which has thicknesses of 50 to 1000 m. These anomalous low resistivity and lateral discontinuity of resistivity structure may be due to faulting and hydrothermal alteration zone. The interesting point is found in the cross-section of Line-1 shown in **Fig. 5(a)** that is characterized by shallow and thin of the low resistivity zone in the northeast. The low resistivity distribution of the line becomes deeper and thicker to the southwest. This phenomenon is in agreement with 3-D geological model as shown in **Fig. 3**. 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 (**Fig. 5(e) and 5(f)**). The distribution of the low resistivity is relatively the same in the eastern part and western part (**Fig. 5(e)**). On the other hand, at the sea level the resistivity in the western part is low while high in the eastern part (**Fig. 5(f)**). 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 resistivity-contoured maps as shown in **Fig. 5(e)** and **5(f)**, 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. **Fig. 6(a)~6(d)** show geoelectrical cross-sections of 2-D inversion results of each survey line.

The cross-sections 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. Like as in the 1-D inversion result, the 2-D cross-sections of inversion results of Line-1 and Line-3 (**Fig. 6(a) and 6(c)**) show 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 as shown as a three-dimensional geological model in the area (**Fig. 3**).

4.3 3-D View

To understand the resistivity distribution in terms of 3-D geological structure, we construct the 3-D view of resistivity distribution from the 1-D inversion results with 100 m

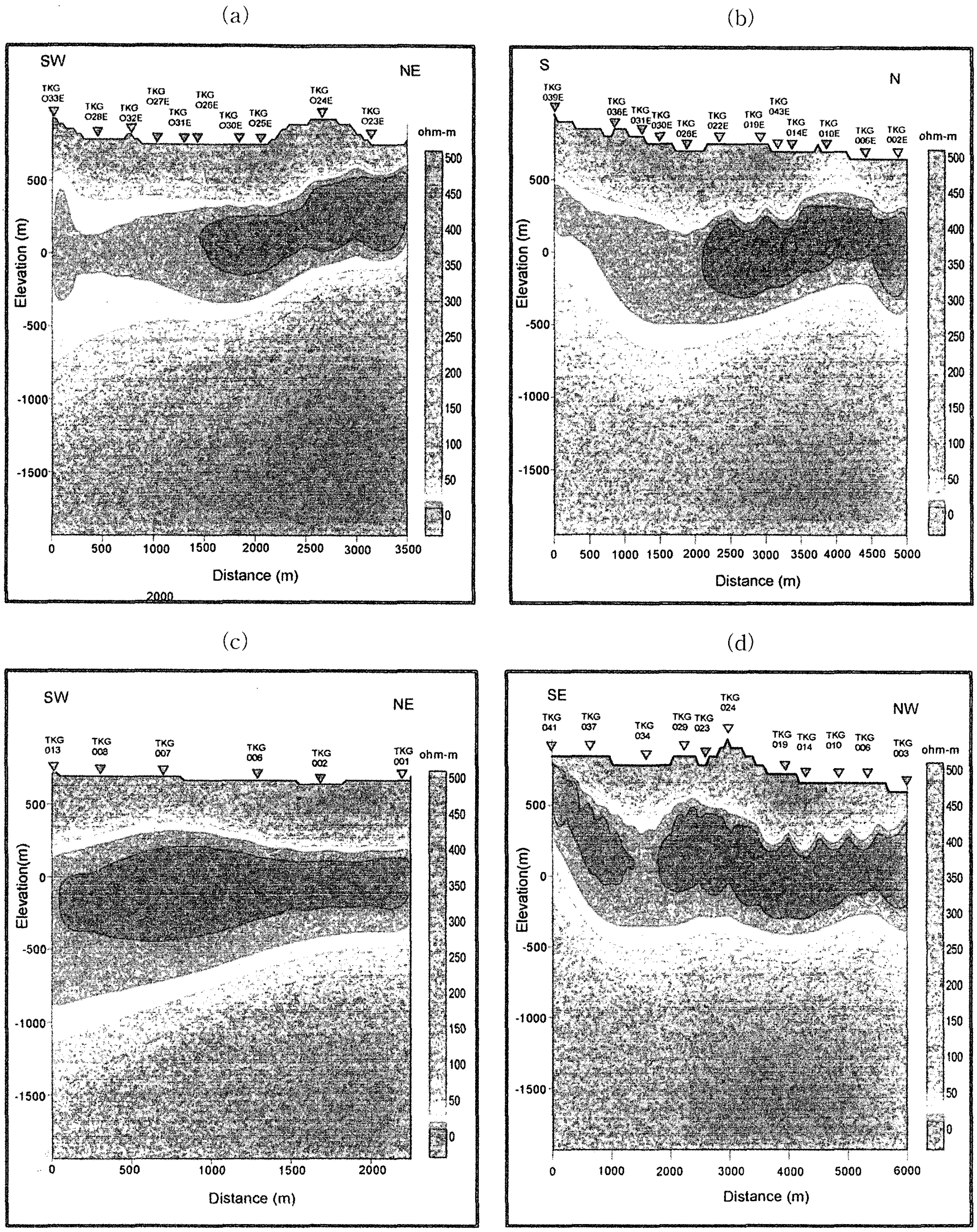

Fig. 6 Resistivity cross-section derived from 2-D inversion of MT data.

depth. **Figs. 7(a)~7(d)** 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 geological feature derived from 3-D geological model and the strike of the Noine fault in the area (**Fig. 3**).

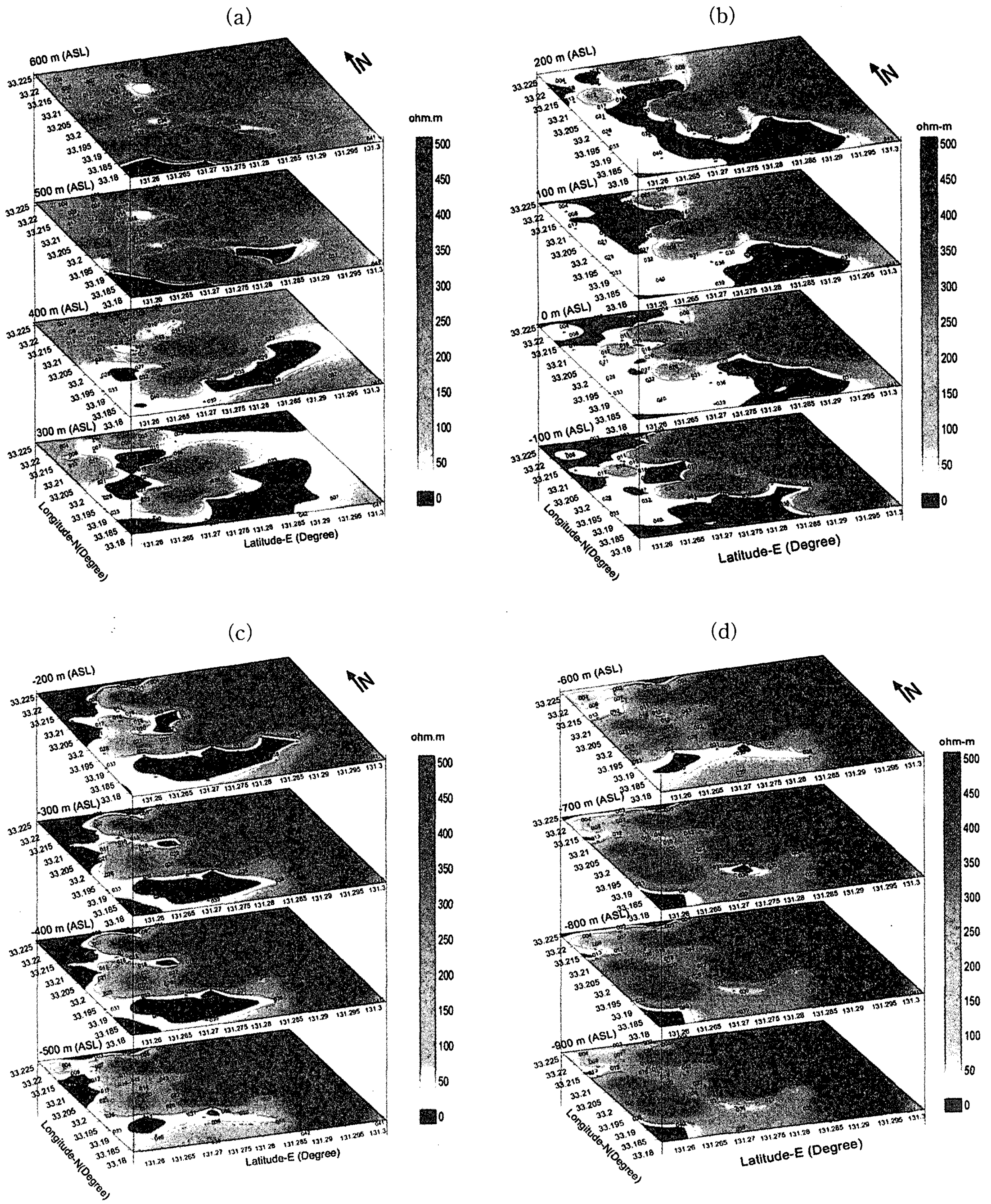

Fig. 7 Imaging 3-D resistivity structure derived from 1-D inversion of MT data.

5. Comparison of MT results with well logging data

Figure 8 shows a representative geoelectrical cross-section of 1-D inversion result of Line-1 together with resistivity logging data[14] in the same direction (SW-NE).

There are five wells displayed in the **Fig.** 8 compared with six MT sounding sites. The site TKG-028E and 033E correlate with well TT-14, where the low resistivity layer (approximately 30 ohm-m) becomes thicker towards site TKG-033E. The site TKG-031E correlates

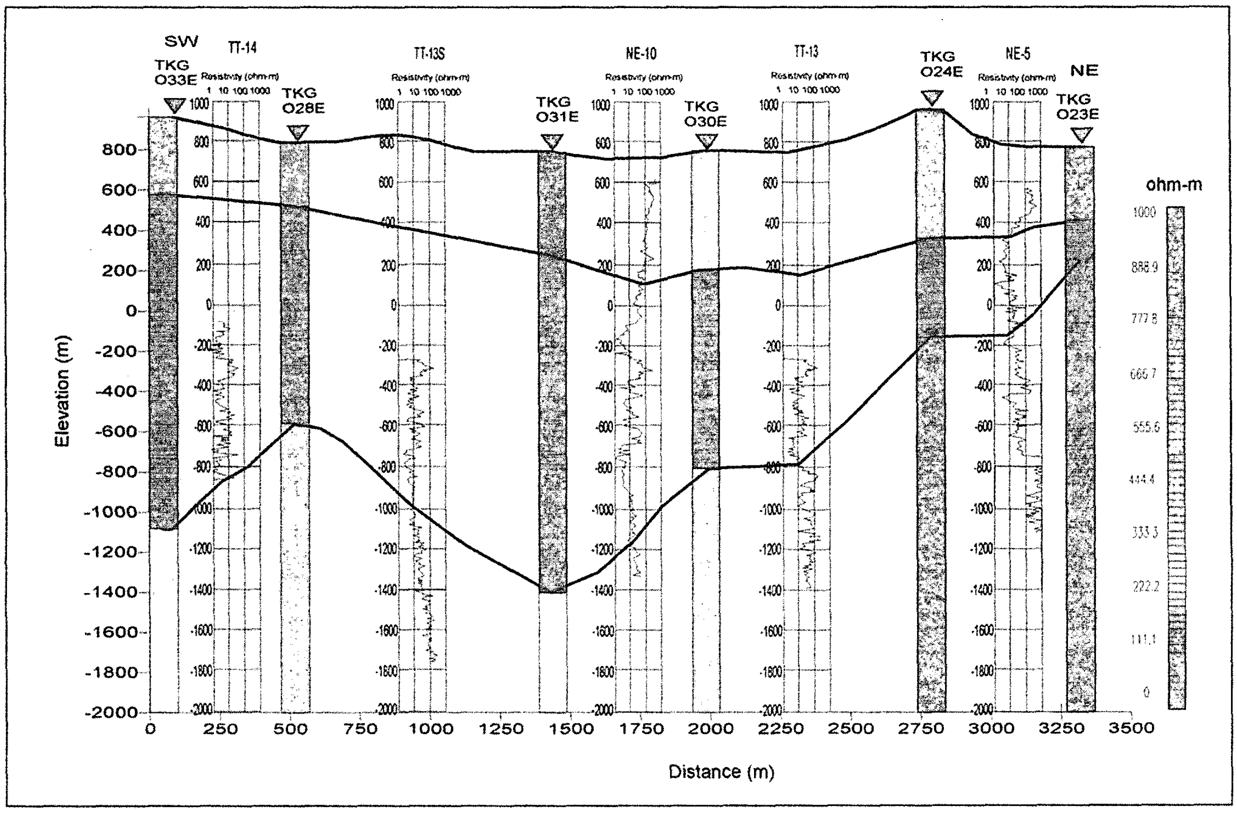

Fig. 8 Comparison of 1-D inversion result with electrical logging data.

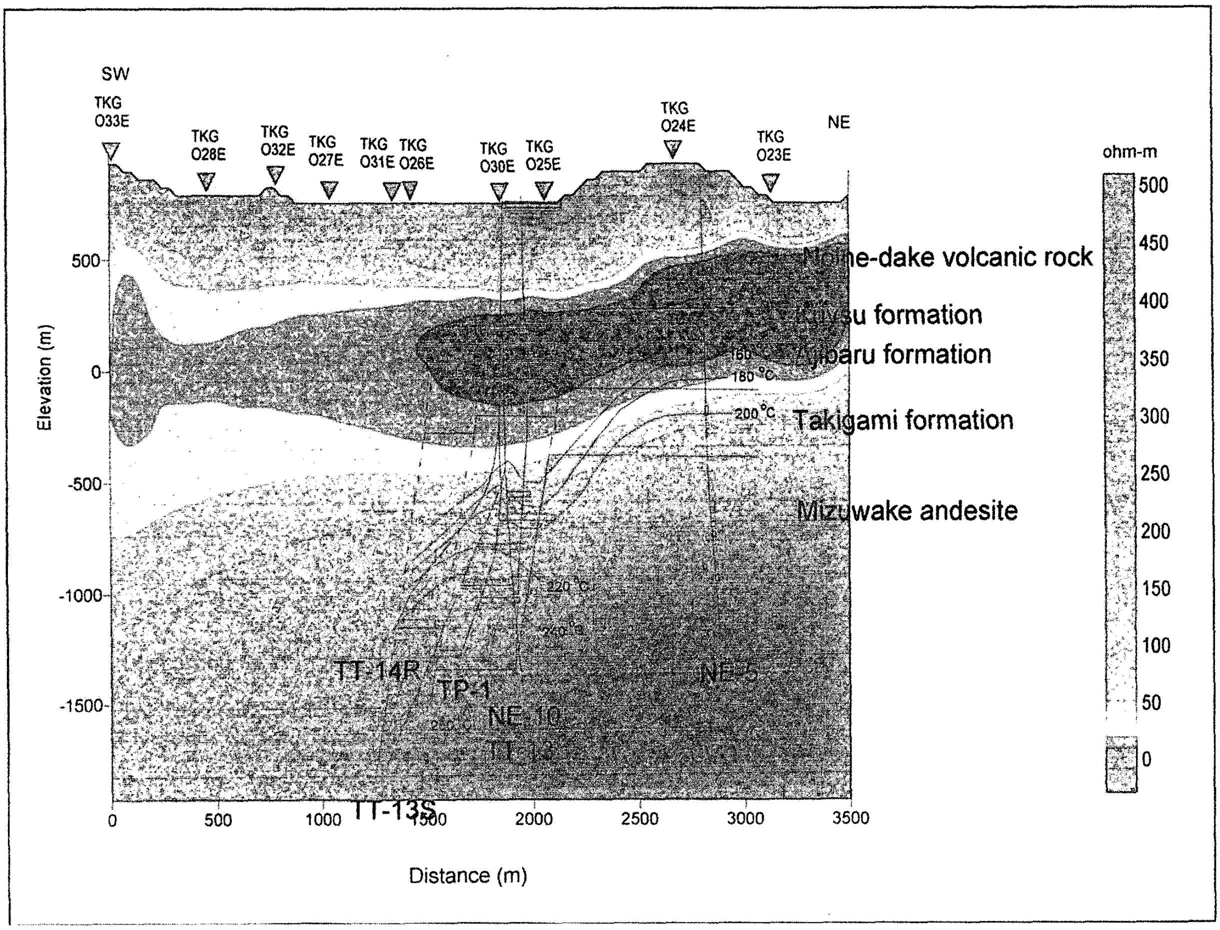

Fig. 9 Comparison of 2-D inversion result with lost circulation zones (geothermal reservoirs) and temperature logging data.

Table 1 Stratigraphy and formation in the Takigami area. (Furuya et al., 2000)

Age		Formation	Lithology
Quaternary	Pleistocene	Noine-dake volcanic rocks	pyroxene-hornblend andesite/dacite lava and pyroclastic
		Kusu formation	pumice/sandy tuff
		Ajibaru formation	hornblend andesite lava/brecciated lava
		Takigami formation	plagioclase megacrystic dacite lava/pyroclastic andesite lava/pyroclastics tuffaceous sandstone/siltstone
Neogene	Pliocene	Mizuwake Andesite	andesite lava/pyroclastics

with TT-13S, which the low resistivity layer (approximately 32 ohm-m) is thick (approximately 1500 m). The site TKG-30E correlates with the well TT-13 and NE10, where the low resistivity layer (approximately 24 ohm-m) becomes thicker towards NE-10. The site TKG-023E and TKG-024E correlate with well NE-5 where the low resistivity (approximately 6 ohm-m) is shallow and thin. Generally, the resistivity distribution in each sounding obtained from the 1-D MT data inversion is almost similar to the resistivity obtained from well 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 geophysical well logging.

The comparison of 2-D inversion result in Line-1 with drilling data as shown in **Fig. 9** 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. This condition is similar to geological condition mentioned in section **2**. The composition of each type of rock is described in **Table 1**[15].

It was recognized from the **Fig. 9** that the electrical discontinuity is found in MT stations of TKG-026E, TKG-030E and TKG-025E in the depth of 800-1000 m below sea level. In this depth the lost circulation has occurred during the drilling of boreholes (TT-14R, TT-13S and TP-1). It was confirmed that the result of 2-D 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 **Fig. 9**. The correlation between distribution of the subsurface resistivity and distribution of the temperature from the **Fig.9** 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. While the bottom layer is more resistive than the second layer 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 east and becomes thicker to the west. The discontinuity of electrical resistivity is clearly shown in 1-D inversion result of Line-1 beneath the MT sites of TKG-030E and TKG-031E in the depth of 800-1000m below sea level. It means that this zone corresponds to a fracture zones correlated with a geothermal reservoir. In the drilling data of production boreholes TT-14 R, TT-13S and TP-1, which approximately coincide with MT sites of TKG-026E and TKG-030E, 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 TKG-026E, TKG-030E and TKG-025E obtained from 2-D inversion result as shown in **Fig. 9**.

7. Conclusions

The MT method 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 Takigami area mainly composed by 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 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. This 3-D resistivity structure is good agreement with the geological feature and the Noine fault in the Takigami area.

Acknowledgments

We would like to express our gratitude to Idemitsu Oita Geothermal Co., Ltd. for permission of the MT data. We thank to Dr. Yunus Daud for carefully reviewing the manuscript and for his many helpful improvements to the paper.

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