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# Three-Dimensional Resistivity Structure of the Minamikayabe Geothermal Zone Revealed by Bayesian Inversion of MT Data

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## ABSTRACT

The paper presents application of the Bayesian inversion methodology to construction of 3-D resistivity model of the Minamikayabe geothermal area by magnetotelluric (MT) data. In order to obtain an initial image of the geoelectric structure of the survey area, Bostick transformation of the determinant apparent resistivity is used. Further refinement of the model is accomplished by full-range 3-D inversion of all elements of the impedance tensor. Two-stage procedure results in 3-D geoelectrical model of the studied area, from which a highly conductive zone associated with geothermal reservoir is picked out.

## 1. INTRODUCTION

MT fields are widely used presently to study geothermal zones due to their deep penetration into the earth and ability to resolve the parameters of complex geological media in the cases when other methods do not give adequate results (Pellerin et al., 1996). However, most of studies provided use 1-D or 2-D interpretation tools. Meanwhile, the mapping of the reservoir boundaries in the process of the heat extraction as well as a precise forecast of the remaining potential should be evidently based on the knowledge about its three-dimensional structure as well as on our ability to interpret properly the measured data.

The advance 3-D MT imaging, inversion and recognition tools developed recently in (Spichak, 1999; Spichak et al., 1999; Spichak and Popova, 2000; Spichak, 2001) form a basement of a new paradigm of the electromagnetic data interpretation, which takes into account the geological information known, noise level in the data, prior estimates of unknown parameters based on the results of past interpretations, hypotheses formulated in probabilistic terms, data available from other methods and formalized interpreter's experience. The objective of this paper is to demonstrate the results of the application of the developed methods to 3-D interpretation of the MT data collected in the Minamikayabe geothermal zone.

## 2. PREVIOS STUDIES

The New Energy and Industrial Development Organisation (NEDO) has conducted geologic, gravity, geochemical, MT, and other surveys in the Minamikayabe area of over 9 km$^2$ in the southern Hokkaido, Japan, in order to detect and subsequently develop geothermal energy sources. For this purpose, seven wells were drilled in a selected region, and an area of over 9 km$^2$ was covered by geologic, gravity, geochemical, magnetotelluric, and other surveys. In the immediate vicinity of the wells MK-2 and MK-6, over an area of 1.2 x 1.2 km$^2$, a high accuracy magnetotelluric survey was performed (Takasugi et a1., 1992a) with an electrode separation of 100 m in a frequency range from 0.001 to 20 000 Hz and with one side of the survey area parallel and the other perpendicular to the coast (Fig. 1).

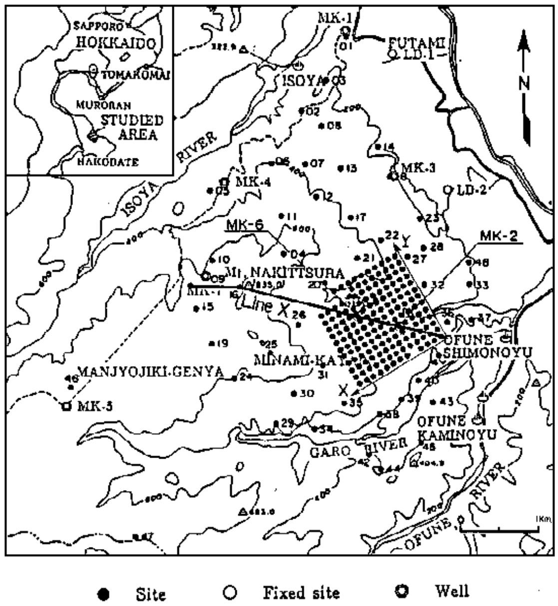



**Figure 1: Location scheme of the Minamikayabe survey area (after Takasugi et a1., 1992a).**

**Solid dots, MT sounding sites; double circles, wells.**

The processing of the MT data has shown that for a number of reasons only those measurements in the range from 1 Hz to 250 Hz can be deemed reliable (Takasugi et a1., 1992b). This paper presents an estimation by means of two-dimensional numerical modeling of how the coast effect bears on the interpretation results. Computations have shown the apparent resistivities to be scarcely affected by the sea in the TE mode at frequencies of more than 0,01 Hz, whereas the TM mode is affected, with the result that the respective resistivity values are overstated. On this basis, the authors consider two-dimensional interpretation to be fully justified in the TE mode alone. Another conclusion drawn in this paper from an analysis of how the induction vector amplitude depends on the frequency (0,1; 1, and 10 Hz), is that the near-surface electric conductivity distribution in the survey area is markedly two-dimensional, with the respective contours aligned NW–SE, whereas the deep conductivity pattern has a complex three-dimensional character.

Based on well logging data, the authors conclude that the horizontally layered section has a three-layer structure, although on the same grounds, Takasugi (1992b) considers this section to be four-layered. Lastly, logging data from certain wells reveal a high electric conductivity in the depth range from 100 to 600 m, suggesting the presence of a geothermal reservoir there (Takasugi et al., 1992b).

Obviously, the interpretation of the array MT data collected in this area should be three-dimensional. The first 3-D resistivity model of the Minamikayabe zone was published by Zhdanov (1998). It was obtained using quasi-linear inversion and based on the assumption that the basement is four - layered. Further, Spichak has published the result of 3-D imaging of this structure by means of Bostick transformation followed by Bayesian inversion (Spichak, 1999, 2002). Sections 3 and 4 briefly outline the methods used to this end according to Spichak et al. (1999) and Spichak (2001), respectively.

## 3. 3-D BAYESIAN INVERSION

In the context of the Bayesian approach, both observations and model parameters (resistivities) are considered as random variables. Bayesian analysis determines the posterior probability density function (PDF) of the conductivity - i.e., the conditional probabilities of its values given the data $y$, prior information in terms of a conductivity palette ($c_l,...,c_L$), prior PDF $q$, and the noise level $\varepsilon$:

$$p(\sigma = a / Y = y) = \frac{f(y/a)q(a)}{\sum_{b\in A} f(y/b)q(b)} \ ,$$

where $q(a)$ is the prior probability of the image $a$ and $f(y/a)$ is a conditional probability of the variable $y = (y_{i,j,}; i = 1,2,..., I; j = 1,2,..., J)$ given the values of the unknown parameters. If the probability densities $p_{i,j}$ are Gaussian with zero mean and covariances $(\zeta_{i,j})^2$, we obtain:

$$f(y/a) = Z \exp(-\sum_{i,j} \frac{\left\{y_{i,j} - F\left[\vec{E}(M_i, \omega_j, a), \vec{H}(M_i, \omega_j, a)\right]\right\}^2}{2(\varsigma_{i,j})^2} \ ,$$

where $\vec{E}$ and $\vec{H}$ are the values of the electrical and magnetic field, correspondingly, measured at the earth surface; Z is a normalizing constant.

Let $A(k, c_j)$ be a set of images that have the resistivity $c_j$, in the domain $P_k$, then the $k$th marginal posterior probability $p_k$ is

$$p_k(c_j) = P\left[\sigma \in A(k.c_j) / Y = y\right] = \frac{\sum_{a\in A(k,c_j)} f(y/a)q(a)}{\sum_{b\in A} f(y/b)q(b)} \ .$$

The outer cycle of the iteration process scans all $K$ homogeneous domains in the regions of search while the inner cycle solves the forward problem for $L$ prior values of the resistivity.

It can be proved that in each domain of the region of search, the sequence of the mean conditional probabilities converges toward the corresponding marginal probability:

$$p_k(c_j) = \lim_{N=\infty} \frac{1}{N+1} \sum p_k^n(c_j) \ .$$

This gives an estimate of the mean posterior resistivities in each homogeneous domain of the region of search:

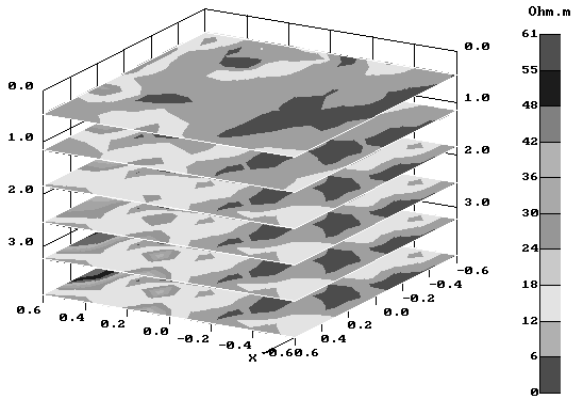
$$\rho_k = \sum_{j=1}^{L} c_j \, po_k(c_j) \quad k = 1,..., K \ .$$

Thus, the solution of the inverse problem is reduced to the search for the posterior conductivity distribution by means of successive solution of the forward problem for the prior values of the conductivity values in all domains of search. The effective algorithm developed basing on this approach (Spichak et al., 1999) enables to construct 3-D geoelectric models of faults, volcanoes, geothermal zones, etc. by MT data (Spichak, 1999).

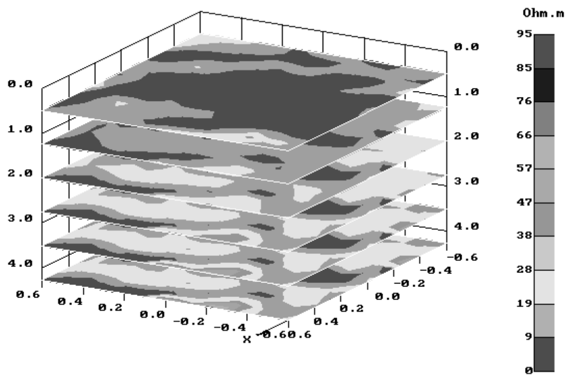
## 4. 3-D RESISTIVITY MODEL

In order to obtain a reliable image of the resistivity structure of the Minamikayabe area, fast imaging and full-range 3-D inversion were applied successively (Spichak, 2002). First, fast Bostick transformation of the apparent resistivity data has resulted in a 3-D resistivity image of the region of search, which provided an initial approximation for the Bayesian statistical inversion. The latter was used then for refinement of the resistivity distribution in the regions of a special interest taking into account the supplementary information.

For imaging the geoelectric structure of the survey area, the Bostick transformation was applied to the apparent resistivity components $\rho_{xx}, \rho_{xy}(\rho^{TM}), \rho_{yx}(\rho^{TE}), \rho_{yy}$. Fig. 2 depicts three-dimensional resistivity distributions based on the $\rho^{TM}$ (Fig. 2 *a*) and $\rho^{TE}$ (Fig. 2 *b*) inversions. A comparison of Fig. 2 *a* and Fig. 2 *b* shows that the TM mode interpretation does yield a more highly resistive section, just as was inferred in (Takasugi et al., 1992b).




**a**




**b**

**Figure 2: Horizontal slices of 3-D apparent resistivity distribution obtained from $\rho^{TM}$ (*a*) and $\rho^{TE}$ (*b*) data (after Spichak (2002)).**

As it was shown in (Spichak, 1999), the most correct approach is to interpret MT data with due account not only for the TE or TM modes, but for all the components of the MT tensor, which amounts to accounting for diagonal elements of the matrix as well when interpreting apparent resistivities. Indeed, all the components of the tensor just mentioned can be taken into account by considering the determinant constructed on their basis. The subsequent Bostick transformation of its frequency dependence into a depth function in fact yields the least screwed image of the three-dimensional resistivity structure (Fig. 3). A comparison of Fig. 2 *a*, *b* and Fig. 3 shows that taking into account diagonal units of the apparent resistivity matrix in the inversion affects the overall resistivity distribution in the domain of search.

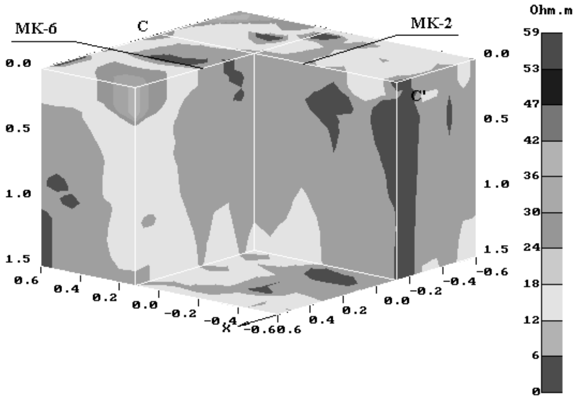



**Figure 3: Volume resistivity image of the Minamikayabe geothermal zone.**

It is interesting to note in this connection that 3-D quasi-linear inversion of the TE and TM data (Zhdanov et al., 1998) gives the results similar to those obtained by 2D TM mode inversion (Takasugi et al., 1992b) and different to the results obtained by 3D inversion using information on all impedance components.

The resistivity image obtained at the first stage was further refined using Bayesian statistical inversion of the impedance components (Spichak et al., 1999). Fig. 4 presents highly conductive areas with resistivity values not exceeding 6 Ohm · m, obtained on the basis of the Bayesian inversion taking into account the resistivity profiles from the wells MK-2 and MK-6.

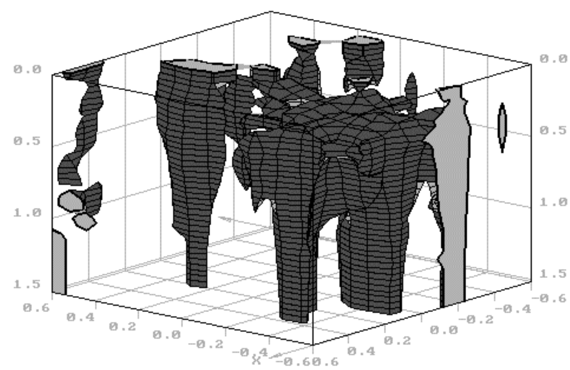



**Figure 4: Highly conductive zone (resistivity is less than 6 Ω ·m) revealed by 3-D inversion of MT data .**

It is easy to see that, firstly, they cluster in the southern part of the zone in question, and, secondly, that their horizontal dimensions at first increase with depth, reaching a maximum in the depth range from about 200 to 800 m, and then decrease again.

## 5. CONCLUSIONS

3-D Bayesian inversion of MT data is applied to mapping Minamikayabe geothermal zone. Interpretation methodology suggested consists from 3-D imaging geothermal zone basing on apparent resistivity determinant followed by full-range Bayesian inversion of the impedance components. It is demonstrated that developed methodology enables to construct a 3-D geoelectric structure of the geothermal area and to delineate a highly conductive zone that can be associated to the geothermal reservoir.

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