

# ADVANCED THREE – DIMENSIONAL INTERPRETATION TECHNOLOGIES APPLIED TO THE MT DATA IN THE MINAMIKAYABE THERMAL AREA (HOKKAIDO, JAPAN)

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## SUMMARY

The paper presents application of novel technologies for 3-D interpretation of geophysical data developed recently in Geoelectromagnetic Research Institute RAS (GEMRI RAS) to construction of 3-D resistivity model of the Minamikayabe geothermal zone by magnetotelluric data collected by NEDO. In order to obtain an image of the geoelectric structure of the survey area, fast imaging and full-range 3-D inversion are applied successively.

First, a fast Bostick inversion of the apparent resistivity data yields a 3-D resistivity image of the region, which provides a basis for assessing the horizontal and vertical dimensions and depth of occurrence of the high conducting zone (with resistivity of less than 6 Ohm-m), which could be associated with the reservoir of geothermal energy. Second, a Bayesian statistical inversion is used aimed at refinement of the resistivity distribution in the regions of a special interest taking into account the supplementary information that comes from other methods and drilled wells.

## 1. INTRODUCTION

Magnetotelluric 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. 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<sub>a,b</sub>; 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, new hypotheses formulated in probabilistic terms, data available from other methods and formalized human experience. This study is aimed at 3-D interpretation of MT data in a geothermal field Minamikayabe (Hokkaido, Japan) using the approaches to the data interpretation mentioned above.

## 2. 2-D MT STUDIES IN THE MINAMIKAYABE AREA

The New Energy and Industrial Development Organisation (NEDO) has conducted geologic, gravity, geochemical, magnetotelluric, and other surveys in the Minamikayabe area of over 9 km<sup>2</sup> in the southern Hokkaido, Japan, in order to detect and subsequently develop geothermal energy sources. In the immediate vicinity of the wells MK-2 and MK-6, over an area of 1.2 x 1.2 km<sup>2</sup>, a high accuracy magnetotelluric survey was performed (Takasugi et al., 1992) 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).

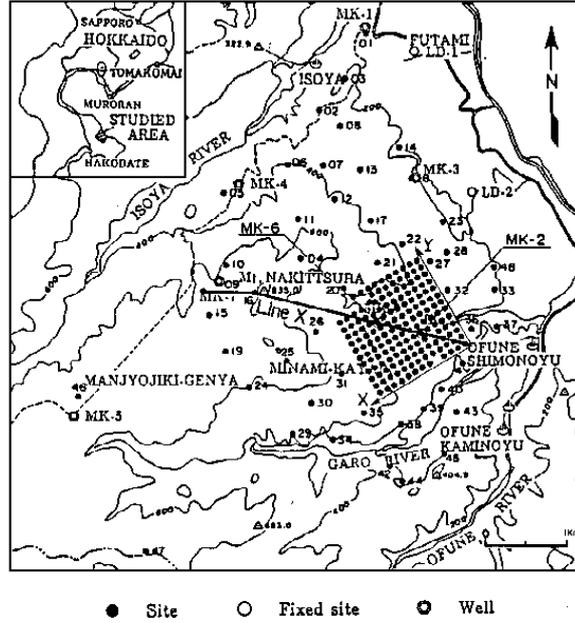


Figure 1. Location scheme of the Minamikayabe survey area (after Takasugi et al., 1992). Solid dots, MT sounding sites; double circles, wells.

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 al., 1992). 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 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, it is concluded that the horizontally layered section has a three-layer structure, although on the same grounds, (Takasugi, 1992) considers this section to be four-layered. Lastly, logging data from the wells MK-2, MK-6 (Fig.1) reveal a high electric conductivity in the depth range from 100 to 600 m, suggesting the presence of a geothermal reservoir.

### 3. 3-D MT IMAGING

The above deductions concerning the geoelectric structure of the region were made in the context of the commonly accepted concept of MT data interpretation, using the “least screwed” field components or modes. However, the “contraexample” given in (Spichak et al., 1999<sub>b</sub>) shows that two-dimensional interpretation based on a single polarization (even using the TM mode) can lead to errors, especially when the prior notion of the section is far from the reality.

Despite the development of two-dimensional inverse methods, to this day, the approach based on the synthesis of one-dimensional conductivity profiles has remained an effective tool for imaging in the absence of prior information. The necessity of such an approach increases in 3-D case, when the measured data is often deficient, and prior information is too scanty. In this situation, a unique practical recourse, which is especially helpful for a prompt tentative estimation of the resistivity distribution, lies in constructing a 3-D resistivity image of the medium based on the MT fields or their transformations:

$$\tilde{F}_i(\vec{r}, (z_{app})_j) = \hat{T}F_i(\vec{r}, \omega_j) \quad (j=1,2,\dots,N_\omega), \quad (1)$$

where  $F_i$  are the components of the MT field measured on the surface for  $N_\omega$  frequencies,  $\hat{T}$  is the transforming operator,  $\tilde{F}$  is the MT field image,  $\vec{r}$  is the radius vector of the observation point,  $\omega_j$  is the frequency, and

$(z_{app})_j$  is the apparent depth corresponding to this frequency. Note that for Bostick transformation ( $\hat{T}F = \frac{1}{\mu_0 \omega} |\hat{Z}|^2$ , where  $\hat{Z}$  is the impedance)  $\hat{F}$  takes on the meaning of the apparent resistivity.

For imaging the geoelectric structure of the survey area, the above technique 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., 1992).

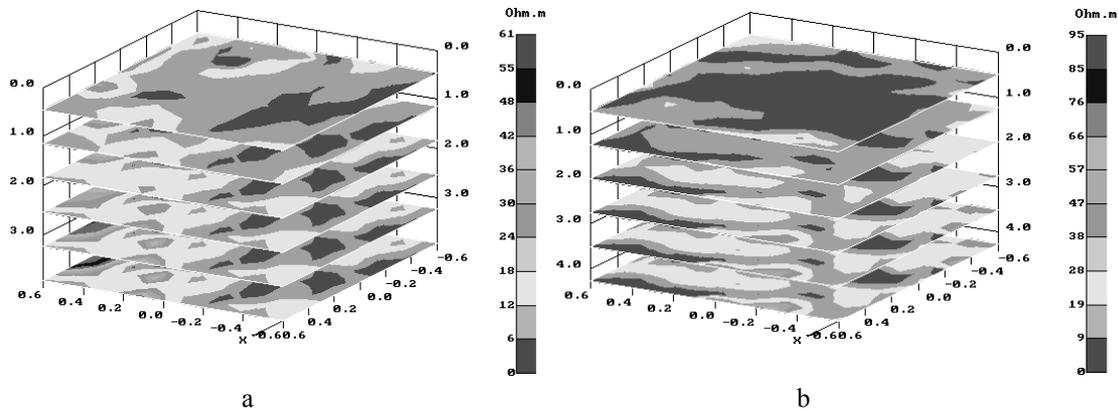


Figure 2. Horizontal slices of 3-D apparent resistivity distribution obtained from  $\rho^{TM}$  (a) and  $\rho^{TE}$  (b) data.

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 units 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 geoelectric 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.

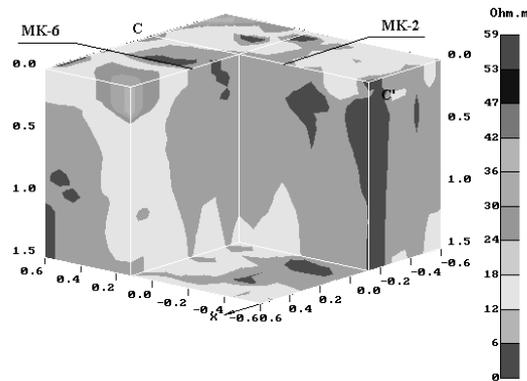


Figure 3. Volume apparent resistivity  $\rho_{det}$  map.

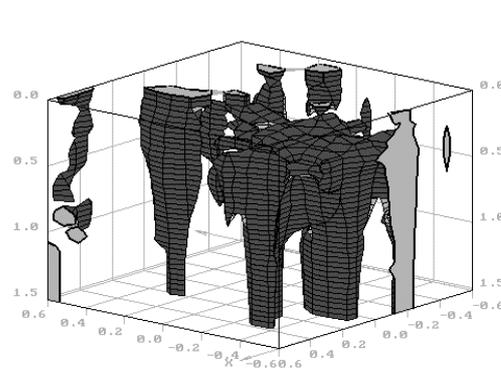


Figure 4. Highly conductive zone (resistivity is less than  $6 \Omega \cdot m$ ) revealed by 3-D inversion of MT data.

#### 4. REFINEMENT OF THE RESISTIVITY IMAGE BY MEANS OF THE BAYESIAN STATISTICAL INVERSION

The resistivity image obtained at the first stage was further refined using Bayesian statistical inversion (Spichak et al., 1999b). In the context of this approach, both observations and model parameters (resistivities) are considered as random variables. Bayesian analysis determines the posterior probability density function (PDF) of

the resistivity - i.e., the conditional probabilities of the resistivities given the data  $y$ , prior information in terms of a resistivity palette  $(c_1, \dots, c_L)$ , prior PDF  $q$ , and the noise level  $\mathcal{E}$ :

$$p(\sigma = a / Y = y) = \frac{f(y/a)q(a)}{\sum_{b \in A} f(y/b)q(b)}, \quad (2)$$

where  $q(a)$  is the prior probability of the image  $a$  and  $f(y/a)$  is a conditional probability of the variable  $y = (y_{i,j}; i = 1, 2, \dots, I; j = 1, 2, \dots, J)$  given the values of the resistivities. It is a function of  $a = (a_k; k = 1, 2, \dots, K)$  through  $\vec{E}$  and  $\vec{H}$  and could be calculated directly as follows:

$$f(y/a) = \prod_{i=1}^I \prod_{j=1}^J p_{i,j} \{y_{i,j} - f[\vec{E}(M_i, \omega_j, a), \vec{H}(M_i, \omega_j, a)]\}, \quad (3)$$

where  $p_{i,j}$  is the probability density of the noise  $\mathcal{E}_{i,j}$ .

The solution of the inverse problem is reduced to the search for the posterior resistivity distribution by means of successive solution of the forward problem for the prior values of the resistivities in all domains of search. The effective algorithm developed basing on this approach (Spichak et al., 1999<sub>b</sub>) enables to construct 3-D geoelectric models by MT data (Spichak, 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. 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

Thus, two-stage inversion of the invariant apparent resistivity data based on rough imaging followed by refinement of the resistivity distribution by means of the Bayesian statistical inversion enabled to re-construct a 3-D geoelectric structure beneath the Minamikayabe region and to delineate a highly conductive zone that can be associated to the geothermal reservoir.

## ACKNOWLEDGEMENTS

The author is grateful to the NEDO (Japan) and Dr. Takasugi who kindly provided the MT data collected in the Minamikayabe area.

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