ELECTROMAGNETIC TOMOGRAPHY OF THE GEOTHERMAL ZONES

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KEY WORDS

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ABSTRACT

The thermal horizons have very small electrical resistivity in comparison with the host rocks. This gives grounds to use electromagnetic methods for their remote spatial localization. EM methods enable not only to determine the location of the geothermal reservoirs but also to construct their three-dimensional resistivity models without drilling wells. Such models, in turn, could serve as a reliable basement for estimation of the geothermal potential during the exploitation phase and, correspondingly, for more precise prediction of the reservoir's life-in-service. In order to map the geothermal reservoir and to monitor its boundaries from the earth surface the magnetotelluric sounding method is suggested. It is based on the registration on the earth surface of the electromagnetic field, induced in the earth by natural sources. Such measurements provided over the network of sites enable to construct three-dimensional model of the reservoir, which could be used for estimations mentioned above. The paper presents application of novel technologies developed recently in [5, 7] to construction of 3-D resistivity model of the Minamikayabe geothermal zone by magnetotelluric data [6]. 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 resulting in 3-D mapping of the geothermal reservoir.

1. INTRODUCTION

Electromagnetic fields (in particular, those induced in the earth by natural sources located in the ionosphere - magnetotelluric (MT) fields) are widely used to study the geothermal zones [1-4, 9] 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. It is worth to note that MT study of the geothermal systems is, probably, the only way capable of attacking the problem of the heat budget or hydraulic extraction of heat. However, most of studies provided for mapping the geothermal reservoirs use 1-D or 2-D inversion tools [1-3, 8, 9]. Meanwhile, estimation of the geothermal potential as well as its monitoring during the exploitation phase should be evidently based on the knowledge about deep three-dimensional (3-D) geological structure of the considered target as well as on our ability to interpret properly the measured data. The advanced geophysical interpretation tools developed recently in [5, 7] form a basement for mapping geothermal zones basing on the electromagnetic data collected at the earth surface and taking into account prior geological and geophysical information and the expert estimates [6].

2. BAYESIAN INVERSION OF THE ELECTROMAGNETIC DATA

The resistivity image of the geothermal zone could be obtained using Bayesian statistical inversion [5, 7]. 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 ($c_l, \ldots, c_L$), prior PDF q, and the noise level ε:

$$p(\sigma = a / Y = y) = \frac{f(y/a)q(a)}{\sum_{b \in A} f(y/b)q(b)} \quad , \qquad (1)$$

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

$$f(y/a) = \prod_{i=1}^{I}\prod_{j=1}^{J} p_{i,j}\{y_{i,j} - f\,[\,\vec{E}\ (M_i, \omega_j, a), \vec{H}\ (M_i, \omega_j, a)\,]\}, \qquad (2)$$

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

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 [6] enables to construct 3-D geoelectric models of the geothermal zones by MT data. In the next section I will demonstrate the application of this method to the mapping of the Minamikayabe geothermal zone following [6].

3. CASE STUDY

3.1. Geophysical studies in the Minamikayabe geothermal zone (Hokkaido, Japan)

One principal goal of the operations conducted by NEDO (Japan) in the Minamikayabe geothermal zone in southern Hokkaido, Japan, was 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 (Fig. 1).

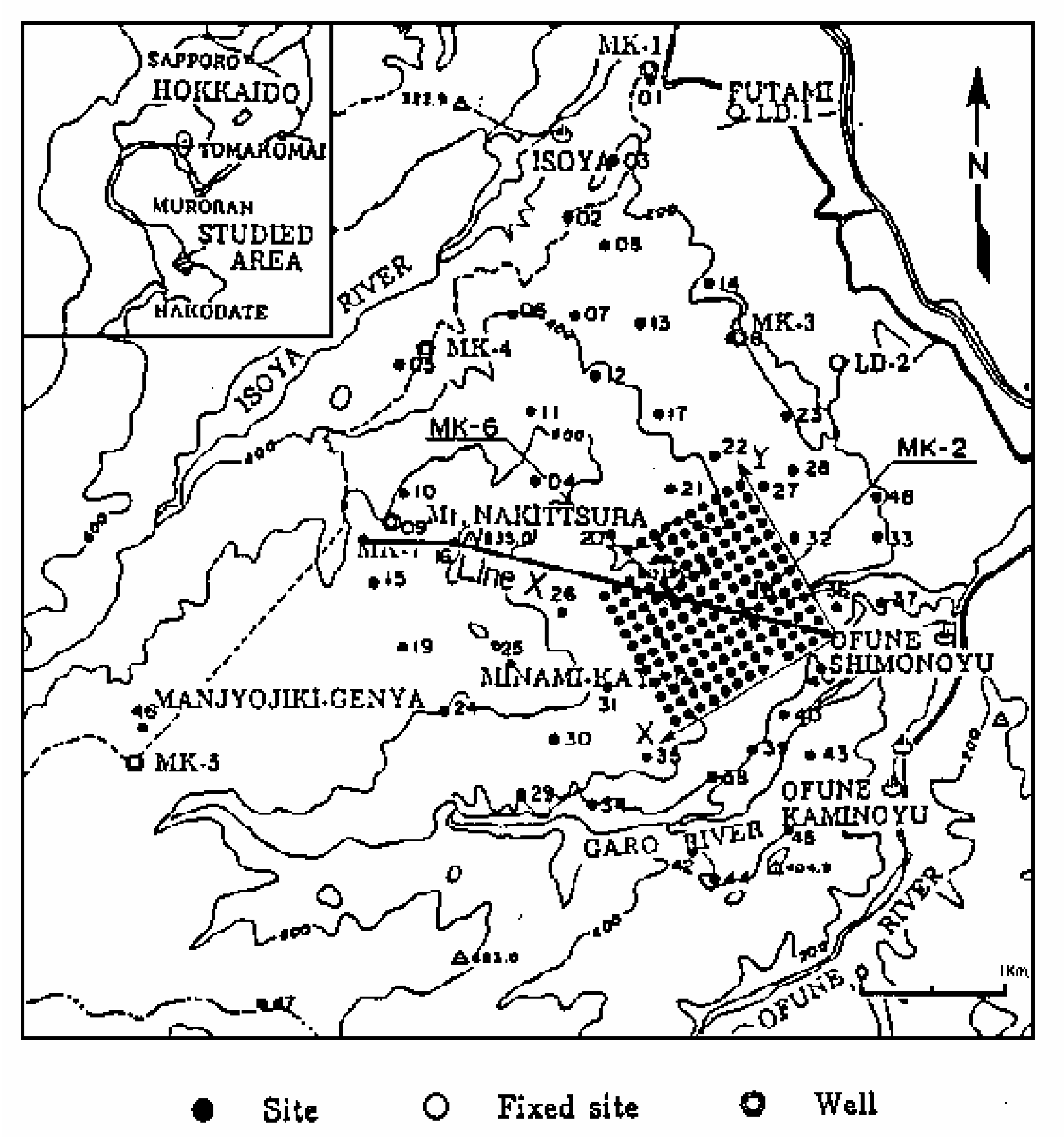


Figure 1. Location scheme of the Minamikayabe survey area (after [8]). Solid dots, MT sounding sites; double circles, wells.

3.2. 2-D MT data interpretation

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 [8] 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).

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 [8]. 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. Fig. 2 depicts the pseudo-section ρ^{TE}, constructed along a profile through the MK-2 and MK-6 wells.

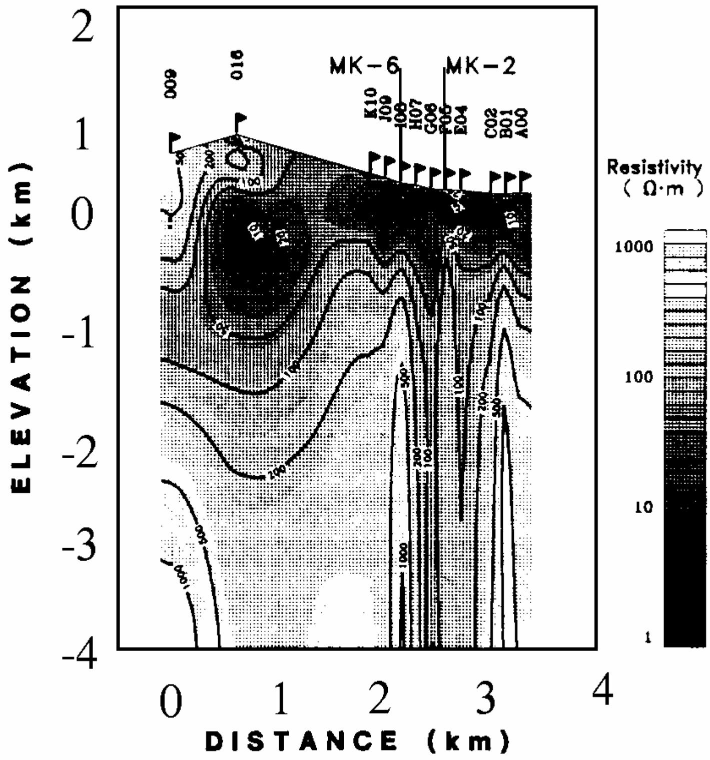


Figure 2. Pseudo-section ρ^{TE}, constructed along the profile through the wells MK-2 and MK-6 (after [8]).

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, this paper concludes that the horizontally layered section has a three-layer structure, although on the same grounds, Takasugi et al. [8] considers this section to be four-layered. Lastly, logging data from certain wells (Figs. 3, 4) reveal a high electric conductivity in the depth range from 100 to 600 m, suggesting the presence of a geothermal reservoir there [8].

3.3. Constructing a three-dimensional resistivity model

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 their transformations. However, the "contraexample" given in [5], shows that an interpretation based on a single polarization can lead to errors, even using the TM mode in the input data, especially when the prior notion of the section is far from the reality.
As was shown by the case study of the model problem in [1], the most correct approach is to interpret monitoring data with due account not only for the TE and TM modes, but for all the

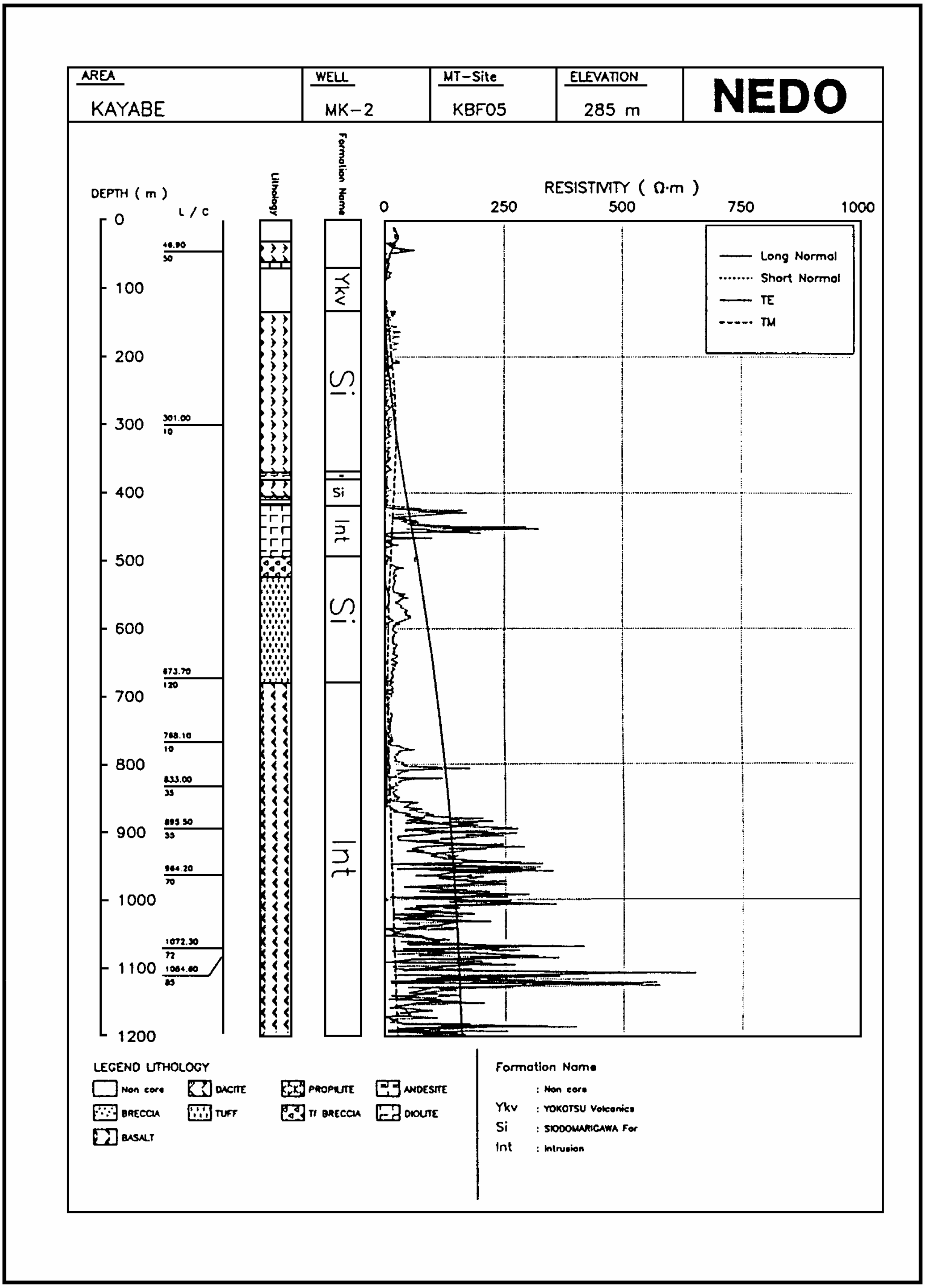


Figure 3. Resistivity logging data from the MK-2 well (after [8]).

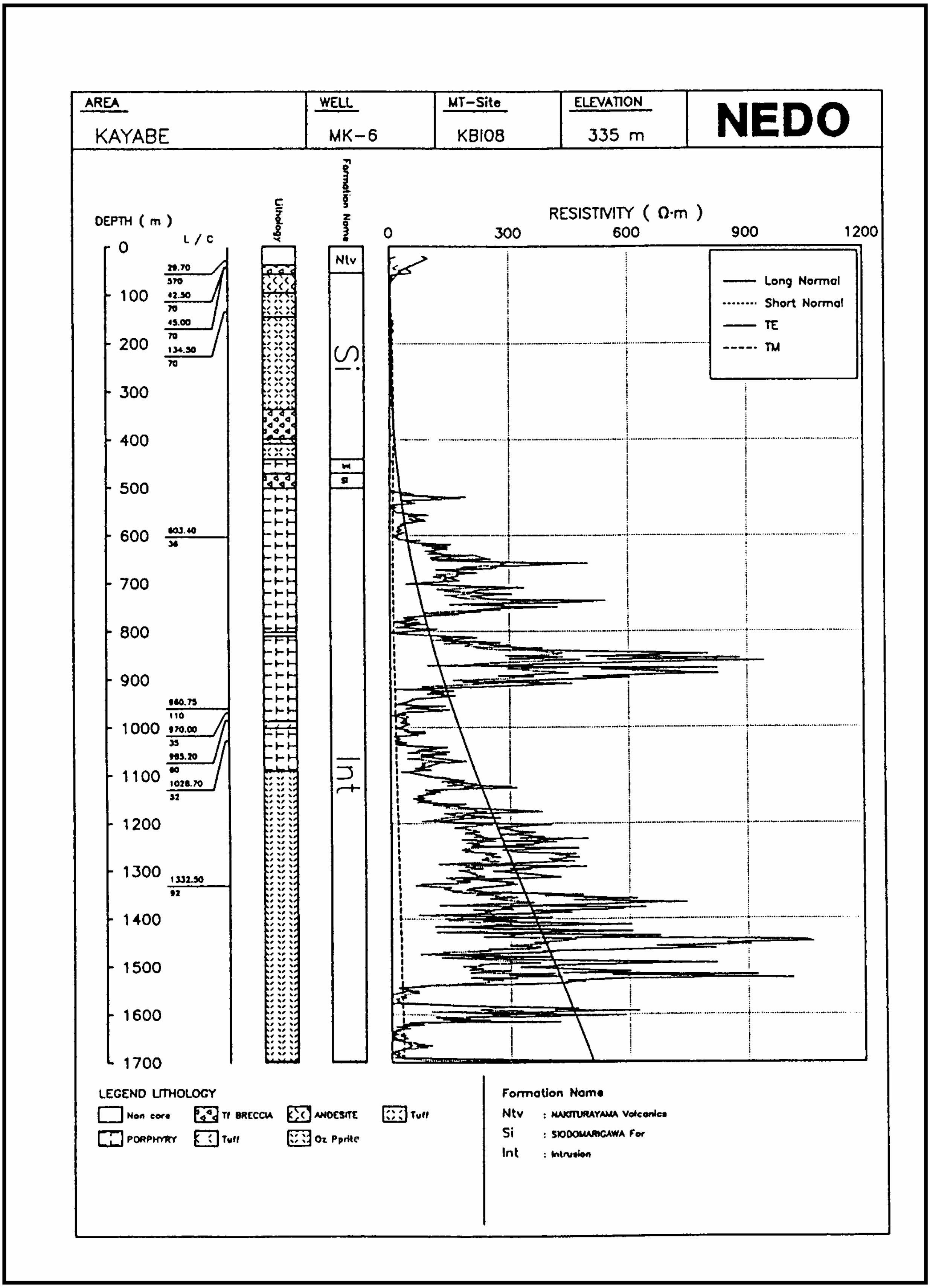


Figure 4. Resistivity logging data from the MK-6 well (after [8]).

components of the MT field, which amounts to accounting for diagonal units of the matrix as well when interpreting apparent resistivities. Such an approach to data interpretation can be realized not only within the framework of the concept of the “complete solution of the three-dimensional inverse problem”, but also, e.g., using the technique proposed in [5]. 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 notion of the three-dimensional geoelectric structure, which can then be refined using one or another regular method of MT data inversion in a three-dimensional medium.

For imaging the geoelectric structure of the survey area, the above technique was applied in [6] to the apparent resistivity components $\rho_{xx}, \rho_{xy}(\rho^{TM}), \rho_{yx}(\rho^{TE}), \rho_{yy}$ and to the $\rho_{\det}$ calculated on their basis.

Figure 5 *a* shows a contour map of the ρ^{TE} distribution at a depth of 1,5 km [8], and Fig. 5 *b* depicts a horizontal slice of the three-dimensional ρ^{TE} distribution at the same depth. Comparison shows the distribution patterns of the apparent resistivity to be very similar, although in the latter case the slice is more highly conductive.

Figs 6 and 7 depict three-dimensional resistivity distributions based on the ρ^{TM} (Fig. 6.6 *a*), ρ^{TE} (Fig. 6 *b*), and $\rho_{\det}$ (Fig. 7) inversions. A comparison of Fig. 6 *a* and Fig. 6 *b* shows that the TM mode interpretation does yield a more highly resistive section, just as was inferred in [8]. At the same time, a comparison of Fig. 6 *b* and Fig. 7 shows that taking into account diagonal units of the apparent resistivity matrix in the inversion somewhat affects the overall picture, although the resistivity distribution at separate sites remains almost unchanged.

Lastly, Fig. 8 presents highly conductive areas with apparent resistivity values not exceeding 6 Ohm$\cdot$m, obtained on the basis of the $\rho_{\det}$ full-range inversion [7]. 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.

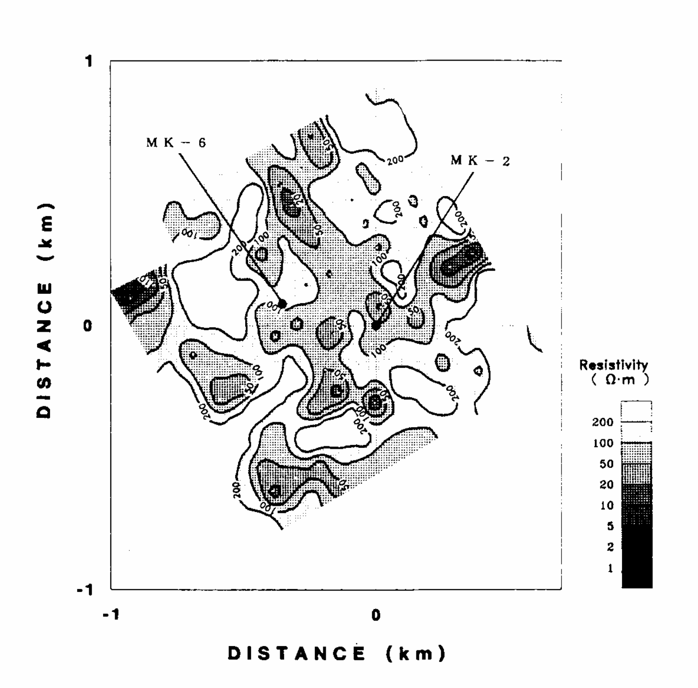
Therefore, the fast inversion of apparent resistivity data followed by its refinement using the Bayesian inversion, yields a three-dimensional resistivity image of the geoelectric structure beneath the Minamikayabe region and delineates a highly conductive zone that can be interpreted as a geothermal reservoir.

CONCLUSIONS

Thus, magnetotelluric sounding of the geothermal zones allows three - dimensional mapping of the geothermal reservoir basing on the data measured at the earth surface and serve as an efficient tool for indirect estimating of the geothermal potential without drilling wells.

The two-stage interpretation of the electromagnetic data based on rough imaging followed by refinement of the resistivity distribution by means of the Bayesian statistical inversion enables to re-construct a 3-D geoelectric structure of the geothermal system and to delineate a highly conductive zone that can be associated to the geothermal reservoir.

It is important to note that regular magnetotelluric sounding supplemented by geophysical information available in situ from the drilled wells allow to carry out a remote spatial monitoring of the thermal waters, which might increase the effectiveness of the geothermal plant operation.



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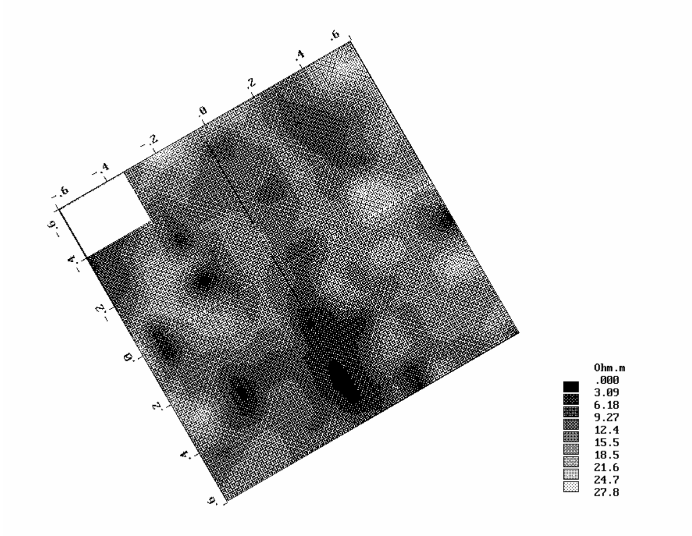
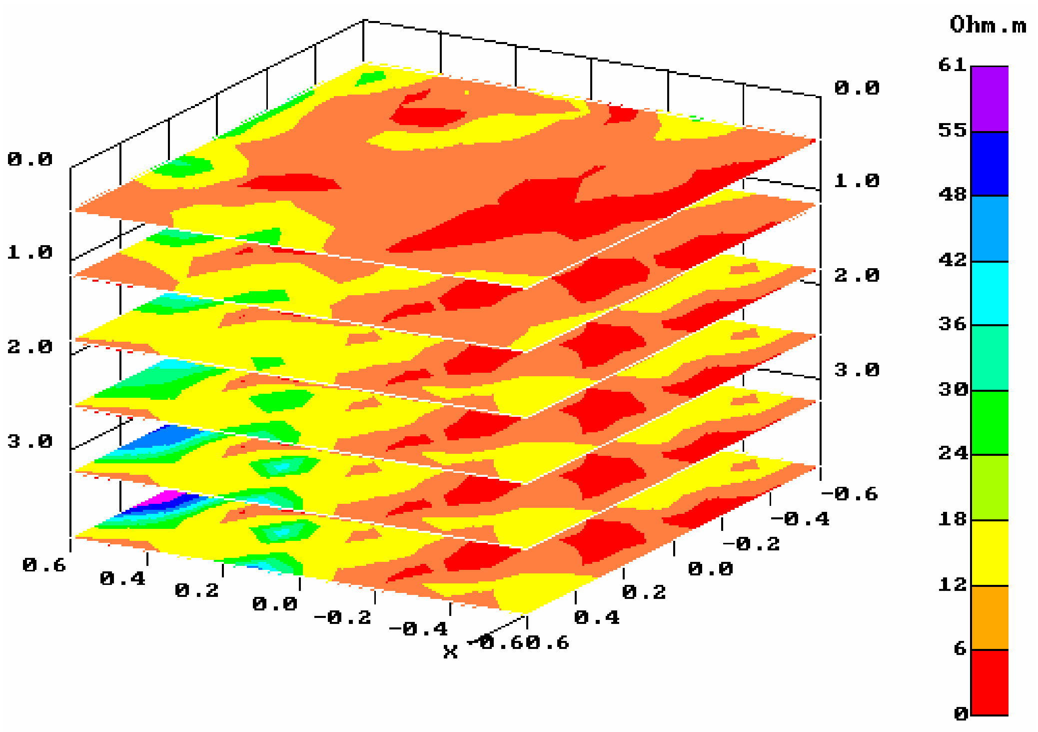


b

Figure 5. Contour map for the apparent resistivity transformation at a depth of 1,5 km: *a* - ρ^{TE} [8] and *b*- $\rho_{\det}$ [6].



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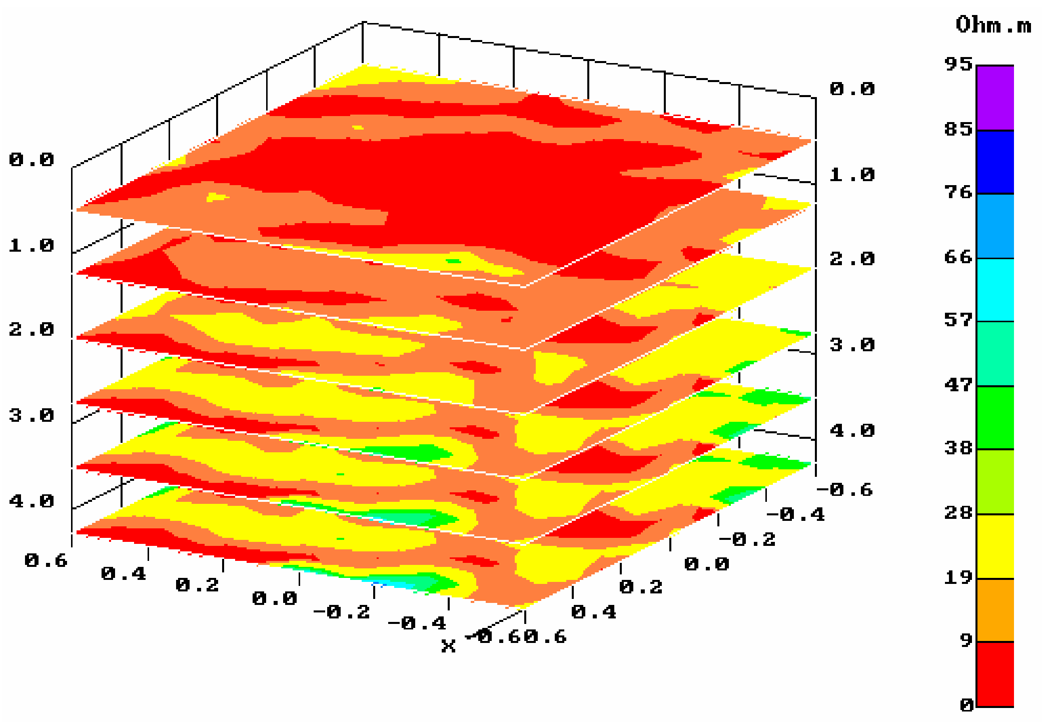

b

Figure 6. Horizontal slices of 3-D apparent resistivity distribution obtained from ρ^{TM} (*a*) and ρ^{TE} (*b*) data (after [6]).

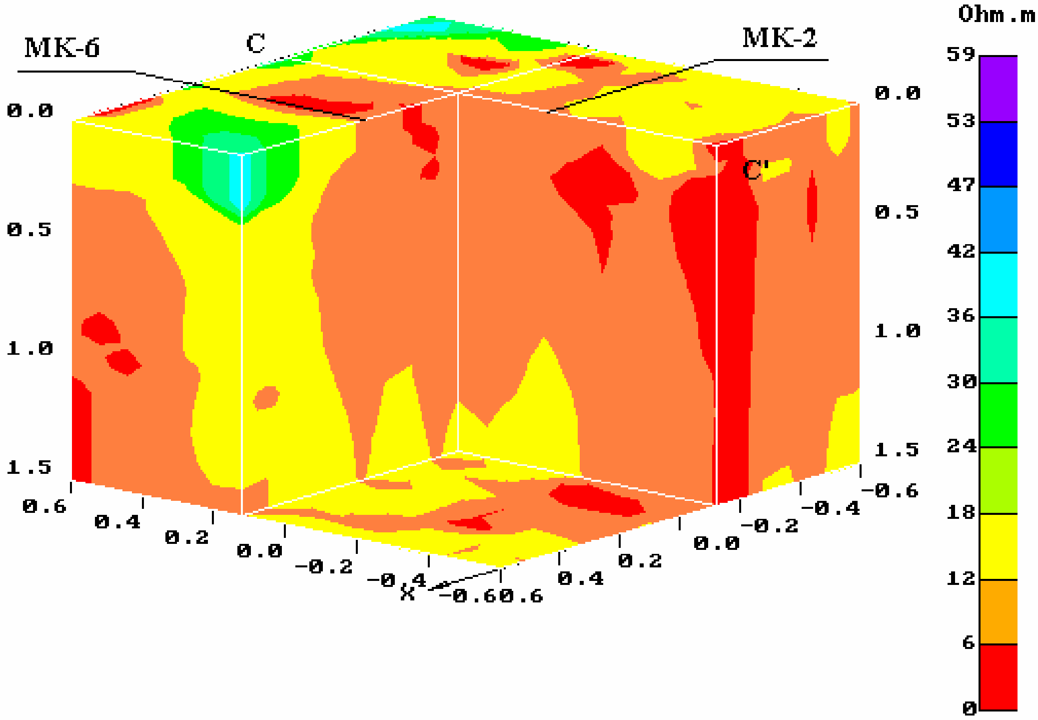

Figure 7. Volume apparent resistivity ρ_{det} map (after [6]).

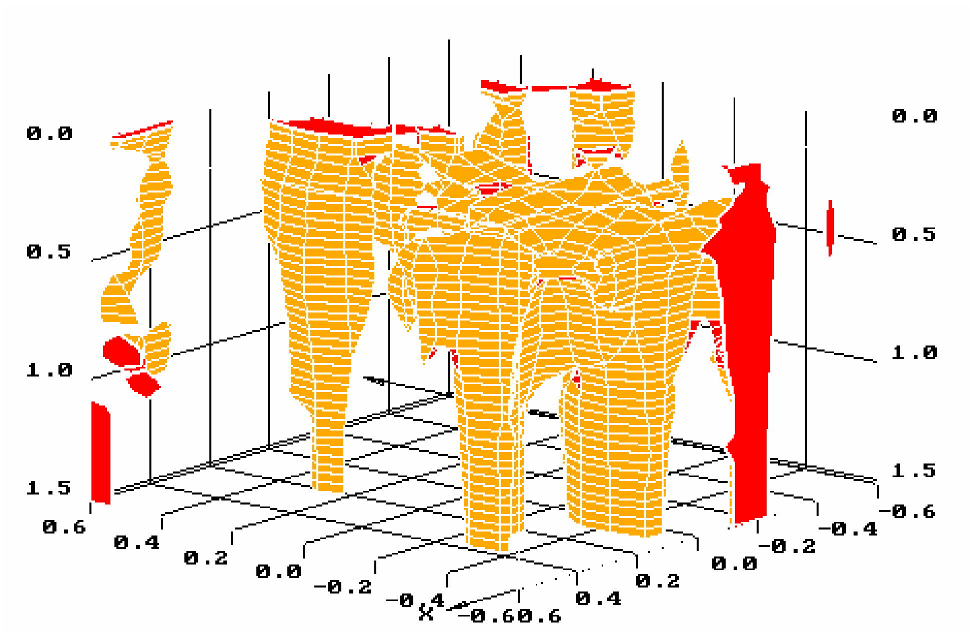

Figure 8. Well conducting zone (apparent resistivity is less than 6 Ω ·m) (after [6])

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