Proceedings World Geothermal Congress 2000
Kyushu - Tohoku, Japan, May 28 - June 10, 2000

DEVELOPMENT OF THE MULTI-FREQUENCY ARRAY INDUCTION LOGGING (MAIL) TOOL.

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Keywords: Induction logging, Multi-frequency, Array-sensor, Resistivity

ABSTRACT

The New Energy and Industrial Technology Development Organization (NEDO) has been conducting the “Deep-Seated Geothermal Resources (DSGR) Survey” project aiming at deep-seated geothermal resources lying below the depth of 3,000 m. As a part of the DSGR project, a “Multi-Frequency Array Induction Logging (MAIL)” tool has been developed to estimate the resistivity structure accurately around a wellbore.

The MAIL method, which has been developed as a downhole surveying technique, is an approach to estimate the resistivity structure within a few meters from the wellbore by employing an electromagnetic logging approach. The tool has one transmitter and several receivers for magnetic field of multiple frequencies. Observed vertical component magnetic responses are analyzed using one- and two-dimensional inversion methods. The conductivity model is cylindrically symmetrical for the borehole axis. Although there is a similar tool such as the AIT tool of Schlumberger, both sensor arrangement and analyzing method are different.

This paper describes 2D inverse modeling based on a cylindrical model using MAIL logging data obtained from a DSGR well. Result of the inversion showed good correlation with the granite distribution. Thus the MAIL tool was demonstrated to have resistivity resolution for radial and axial directions of a wellbore.

1. INTRODUCTION

Electromagnetic methods such as magnetotelluric (MT) method have been applied for geothermal prospecting. Although the MT method has an advantage for mapping deep resistivity structure analysis, the resolution of the modeled resistivity structure is lower than that of the shallower part. If the surface surveying method such as MT is combined with a downhole EM measurement, it is expected that accurate investigation of resistivity structures should be possible to large depths.

The MAIL tool, which has been developed as an in-hole surveying technique, is an approach to estimate the resistivity structure within a few meters from the borehole wall by employing an electromagnetic logging approach. Also, one- and two-dimensional inversion codes have been developed in our study.

2. OUTLINE OF MAIL SYSTEM

The measurement configuration of the MAIL system is similar to that of induction logging, however, the spatial arrangement of the source and receivers and the depth of penetration are extended by multiplying the vertical magnetic sensors and the frequencies employed for the transmitter (vertical coil). The resistivity structure in the vicinity of the borehole is acquired by analyzing the measured data. For the data analysis, one- and two-dimensional inversion codes are used. Model for the inversion has cylindrically symmetric conductivity structure. In this model, resistivity changes radially from center of the well and/or vertical direction along the well axis. Although similar tools are known well, the MAIL tool has a different sensor arrangement. Also analyzing method is different.

Figure 1 shows a diagram of the tool. It indicates 7 receivers (five Hz components, Hx and Hy) and the transmitter (Tx, four frequencies). As the system is equipped with a 4 channel AD converter, three magnetic field components can be measured simultaneously along with the transmitter monitoring (1 channel). Namely, one logging event enables us to obtain three selected magnetic fields for four frequencies.

3. TWO DIMENSIONAL INVERSION

A preliminary analysis indicates that inversion of cylindrically symmetric conductivity structures can be efficiently carried out using the nonlinear scattering approach proposed by Habashy et al. (1993) for its forward part. The nonlinear scattering method offers good approximation to the electric field inside the inhomogeneity, and this approximation seems far more accurate than the straightforward Born approach. Torres-Verdin and Habashy (1994) successfully implemented the method for investigating the 2.5-D electromagnetic problems.

The nonlinear scattering approach involves reformulating the electric field integral equation as

$$E_\theta(r) = E^i_\theta(r) + E_\theta(r)\int_V G_E(r,r')\,\Delta\sigma(r')\,dx'dz' + \int_V G_E(r,r')\,\Delta\sigma(r')\left\{E_\theta(r') - E_\theta(r)\right\}dx'dz' \qquad (1)$$

where we added and subtracted one integral involving the electric field, *E*(*r*), at observation point. As can be seen in the first integral of this equation, we can take this electric field to the outside of the integral, because it is independent from the integral variables (primed coordinate). If and when the electric field is smooth and continuous, the second integral can be neglected (Habashy et al., 1993), and as a result equation (1) can be approximated by

$$E_q^N(r) = E_q^i(r) + E_q(r)\int_V G_E(r,r') \cdot \Delta\sigma(r')dx'dz' \qquad (2)$$

from which one can derive for the electric field inside the inhomogeneity as

$$E_q^N(r) = \Gamma(r)E_q^i(r) \qquad (3)$$

with the 'scattering coefficient' Γ (r) defined as

$$\Gamma(r) = \left(1 - \int_V G_E(r,r') \cdot \Delta\sigma(r')dx'dz'\right)^{-1} \qquad (4)$$

The superscript 'N' in equation (2) and (3) indicates nonlinear approximation. Assuming that the inhomogeneity is divided into N cells of constant conductivity, the magnetic field equation can be written as

$$H_z^N(r) = H_z^i(r) + \sum_{i=1}^{N} \Delta\sigma_i \int_{V_i} G_H(r,r_i') \cdot \Gamma(r_i')E_q^i(r_i')dx'dz' \cdot$$

(5)

Now, taking variation of this equation with respect to the conductivity, we obtain

$$\delta H_z^N(r) = \sum_{i=1}^{N} \delta\sigma_i \int_{V_i} G_H(r,r_i') \cdot \Gamma(r_i')E_q^i(r_i')dx'dz' + \sum_{i=1}^{N} \Delta\sigma_i \int_{V_i} G_H(r,r_i') \cdot \delta\Gamma(r_i')E_q^i(r_i')dx'dz' \qquad (6)$$

where the variation of the nonlinear scattering coefficient is given by

$$\delta\Gamma(r_i') = \frac{\sum_{j=1}^{N} \delta\sigma_j \int_{v_j} G_H(r_i',r_j'')dx''dz''}{\left(1 - \sum_{k=1}^{N} \Delta\sigma_k \int_{v_k} G_H(r_i',r_k'')dx''dz''\right)^2}. \qquad (7)$$

The data variation on the left of equation (6) is the difference between measurement in the borehole and numerically computed field approximated by equation (5).

Inversion for the electrical conductivity is actually carried out by solving the normal equation with regularization

$$A^T A\delta\sigma + \lambda R(\sigma) = \delta H \qquad (8)$$

where elements of matrix A comes from the elementary volume integral

$$a_{ji} = \int_{V_i} G_H(r_j,r_i') \cdot \Gamma(r_i')E_q^i(r_i')dx'dz' \qquad (9)$$

where the subscript ji indicate j-th data related to the i-th cell of the model. λ is the regularization parameter and $R(\sigma)$ is used to make sure that inverted conductivity distribution is smooth in some sense to reduce the non-uniqueness of the solution. Usually we use something like Laplacian for this purpose. The right hand side of equation (8) is the difference between data and model generated magnetic field. In case of the first order approximation, the initial model is homogeneous, so this term is just the data itself. At the end of first order approximate inversion the conductivity model is updated. So the model is not homogeneous anymore, and we have completed the extended Born inversion (Habashy et al., 1993). In this development we need to re-evaluate the scattering coefficient

$$\Gamma(r) = \left(1 - \int_V G_E(r,r') \cdot \Delta\sigma(r')dx'dz'\right)^{-1} \qquad (10)$$

and the source term at the j-th data point will be updated using

$$\delta H_j = \delta H_z^N(r_j) + S_j$$

with

$$S_j = \sum_{i=1}^{N} \Delta\sigma_i \int_{V_i} G_H(r_j,r_i') \cdot \delta\Gamma(r_i')E_q^i(r_i')dx'dz', \qquad (11)$$

for which the variation in the scattering coefficient, given by equation above as

$$\delta\Gamma(r_i') = \frac{\sum_{j=1}^{N} \delta\sigma_j \int_{v_j} G_H(r_i',r_j'')dx''dz''}{\left(1 - \sum_{k=1}^{N} \Delta\sigma_k \int_{v_k} G_H(r_i',r_k'')dx''dz''\right)^2}, \qquad (12)$$

needs to be re-evaluated also.

The other critical element for the improved resolution is the choice of the regularization parameter λ. At the moment this parameter is fixed within data standard deviation, but it is not certain that this bound provides the optimum resolution.

4. MAIL TEST USING ACTUAL WELL

The test of the MAIL tool was conducted using an actual well that was drilled by NEDO in the DSGR project. This well, WD-1b, is located in the Kakkonda geothermal area, Iwate Prefecture. The pilot survey well WD-1a reached 3,729m and encounterd temperature of over 500 degrees C in fiscal year (FY) 1995. In FY 1996, NEDO drilled a side-tracking well WD-1b and hit several high permeability zones.

In the logging by the MAIL tool, four frequencies, 3, 12, 24 and 42 kHz and three sensors set at positions of 4, 5, 6 m spacings were used for the logging. Logging depth was from 2250m to 2880m. Figure 3 shows apparent resistivity caculated using 42 kHz data. Also apparent resistivity of normal electrical logging is compared with the MAIL data. Apparent resistivity of MAIL is calculated as follows.

$\rho a = 2/(\mu\omega R^2) * Hr/Hi$

ρa: Apparent resistivity.
μ: Magnetic permeability (=4πE-7).
ω: 2πf.
R: Distance from transmitter to receiver.
Hr: Real part of magnetic response.
Hi: Imaginary part of magnetic response.

Figure 3 shows that correlation between MAIL and normal logging data is good. This shows the MAIL tool can detect the resistivity response around wellbore.

5. TWO DIMENSIONAL INVERSION.

We analyzed the MAIL data using a two-dimensional inversion code. Figure 4 shows the result of MAIL 2D analysis.

In this analysis, we used the following data.

1. Frequency: 12, 24, 42 kHz
2. Receiver: 4, 5, 6 m from the transmitter

Initial model for inversion is as follows.

3. Block size: 2m (vertical direction)
   1 m (radial direction)
4. Number of blocks: 30 (vertical direction)
   8 (radial direction)
5. Initial resistivity : 50 ohm-m
   Background resistivity : 200ohm-m

We can recognize a good relationship between the MAIL result and the geologic structure as follows.

1. Boundary of granite is located at 2850 m depth. MAIL results indicate high resistivity contrast at the depth.
2. At 2740m and 2810m depths, there are lost circulation zones. At each depth, the MAIL result indicate low resistivity structure.
3. There is low resistivity distribution near the well wall. It was estimated as an effect of drilling.

6. CONCLUSION

The conclusions that can be drawn from the present study are summarized as follows.

1. Results of two-dimensional inversion analysis using the DSGR data show good relationship between resistivity and granite distribution.
2. In the two-dimensional analysis, it was verified that MAIL tool had a certain resistivity resolution for radial direction and axial direction of well bore.
3. If homogeneous resisitivity structure was used for initial model, there was good convergence for two-dimensional inversion analysis.
4. There is low resistivity distribution near the well wall. But MAIL tool didn't have short distance sensor from transmitter. So, it is possible that low resistivity indicated near the borehole was not true.

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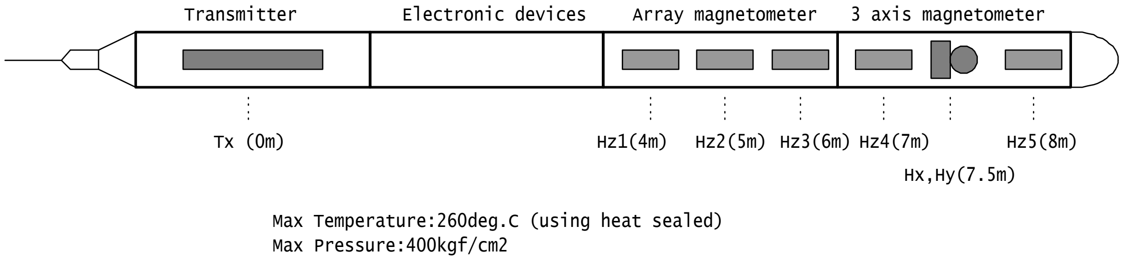

Figure 1 MAIL tool. It includes five vertical-component magnetometers and two horizontal component magnetometers. Measurement is conducted in such a way that the magnetic fields of frequencies 3, 12, 24, 42 kHz are received by any of the three magnetometers.

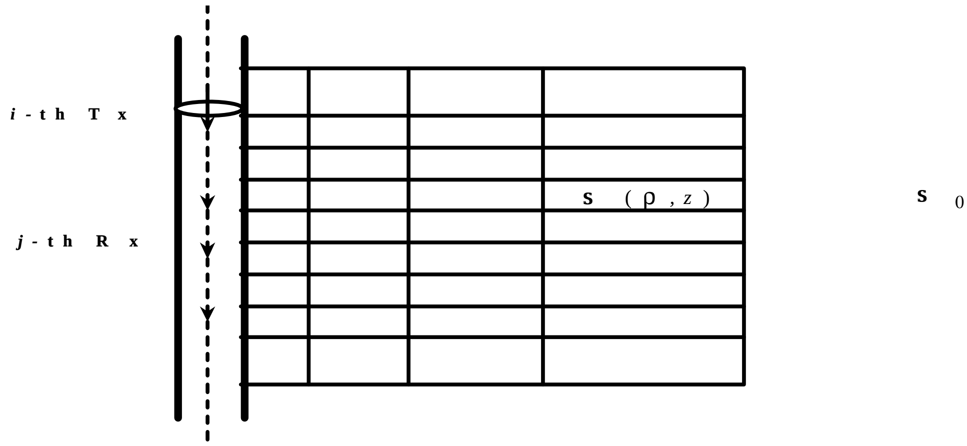

Figure 2. A MAIL tool going through a cylindrically symmetric medium.

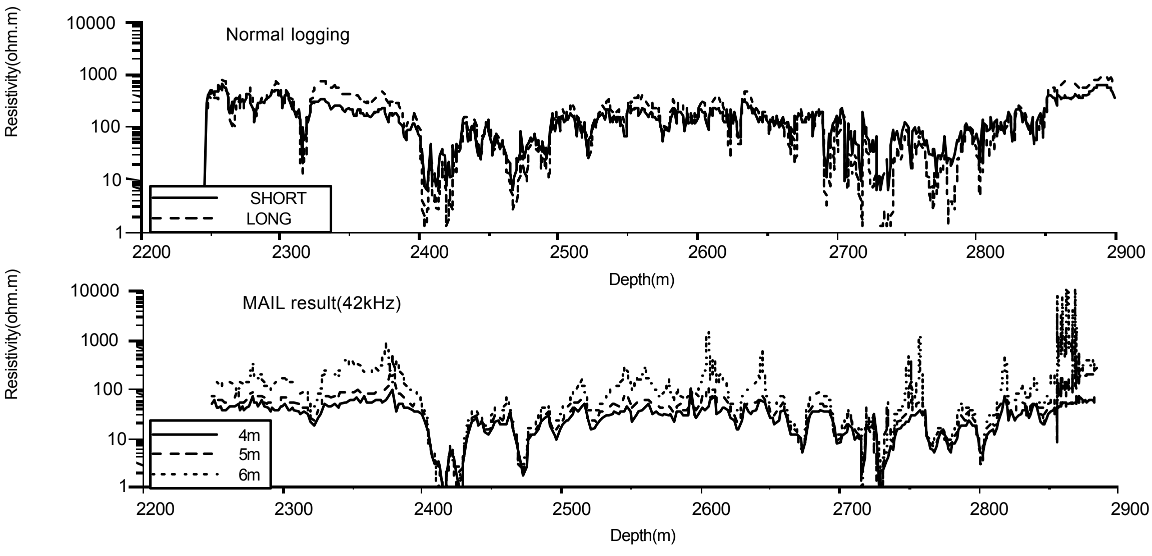

Figure 3. Apparent resistivity at 42kHz calculated using MAIL response.

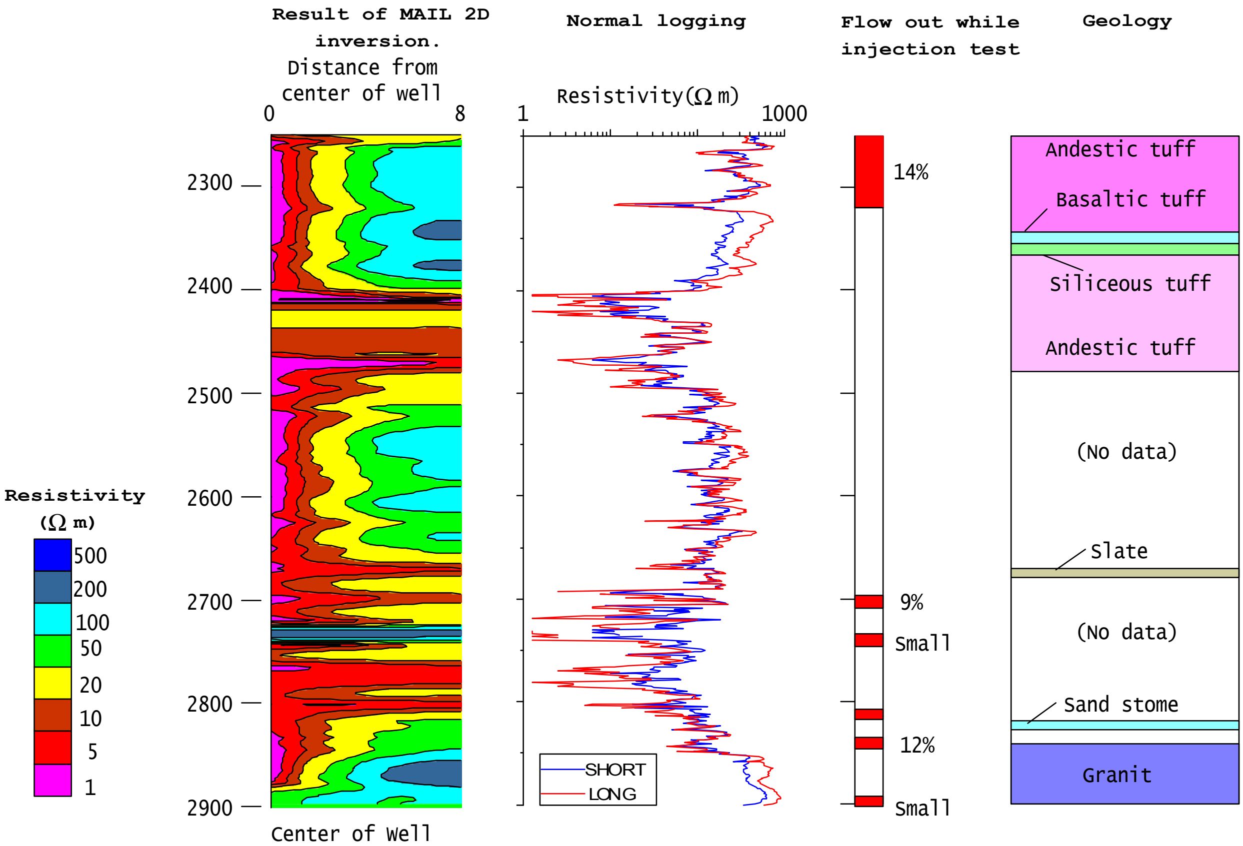

Figure 4. Result of two-dimensional analysis