PROCEEDINGS, 23rd Annual PNOC-EDC Geothermal Conference
Hotel Inter-Continental, Makati City, Philippines, March 13-14, 2002

3-D INTERPRETATION OF MAGNETOTELLURIC DATA AT THE ATADEI GEOTHERMAL FIELD, LEMBATA ISLAND, INDONESIA

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ABSTRACT

We conducted an MT survey at the Atadei geothermal field, Lembata Island, Indonesia, and performed a three-dimensional (3-D) interpretation for the detailed investigation of geothermal reservoirs. The 3-D inversion scheme used in this work is based on the linearized iterative least-squares method with smoothness regularization. The forward modeling for a given arbitrary 3-D earth is by the finite difference method. In addition to resistivities of the blocks representing a 3-D earth, static shifts are also treated as unknown parameters in the inversion. Starting from a homogeneous half space, the iterative model refinement by the least-squares method is repeated until the misfit does not change as the iteration proceeds. An optimum smoothness and an optimum weight for the static-shift minimization are searched based on the misfit minimization at each iteration. The inversion worked properly on the field data and reasonably small misfit was achieved. It suggests that the treatment of the static shifts in the inversion is essential. The obtained 3-D resistivity model indicated a low-resistivity shallow layer around the surface manifestations. The deep high-resistivity basement was also delineated beneath the low-resistivity layer. These features preliminary suggested a reservoir Structure in the area.

1.0 INTRODUCTION

The magnetotelluric (MT) method is one of the most common tools for investigating geothermal reservoirs. It is mainly because of its capability to delineate low-resistivity anomalies associated with the reservoir structure. Also, advanced low-noise field instruments and sophisticated two-dimensional (2-D) inversion techniques developed in the past decade have helped to produce detailed resistivity structure around geothermal reservoirs. However, these techniques still require more improvements when we apply them to a geothermal field where the geologic structure is often very complicated. The most difficult tasks are to deal with the three-dimensional (3-D) structure and signal distortion due to shallow inhomogeneous anomalies. For such demands, some new 3-D inversion techniques have been reported in the past few years. In this work, we have carried out MT field measurements in a geothermal field in Indonesia and applied a 3-D inversion technique to the data. This is our second trial of 3-D MT interpretation for geothermal exploration next to the MT data in Flores Island, Indonesia (Uchida et al., 2002).

2.0 INVERSION SCHEME

The 3-D inversion scheme used in this work is based on the linearized iterative least-squares method with smoothness regularization (Sasaki, 1999, 2001; Sasaki and Uchida, 2001). The forward modeling for a given arbitrary 3-D earth is by the finite difference method. The electric field is first salved in the frequency domain. Then, the magnetic field is computed from the obtained electric field. For a finite difference with a staggered grid, the solution region, including both air and earth, is discretized into rectangular cells. The topography is not incorporated.

A Jacobian matrix, consisting of partial derivatives (sensitivities) of MT responses with respect to block resistivities in the 3-D model, is evaluated for a homogeneous earth that is usually the initial model, and is used for the first few iterations. Then, we compute a full Jacobian

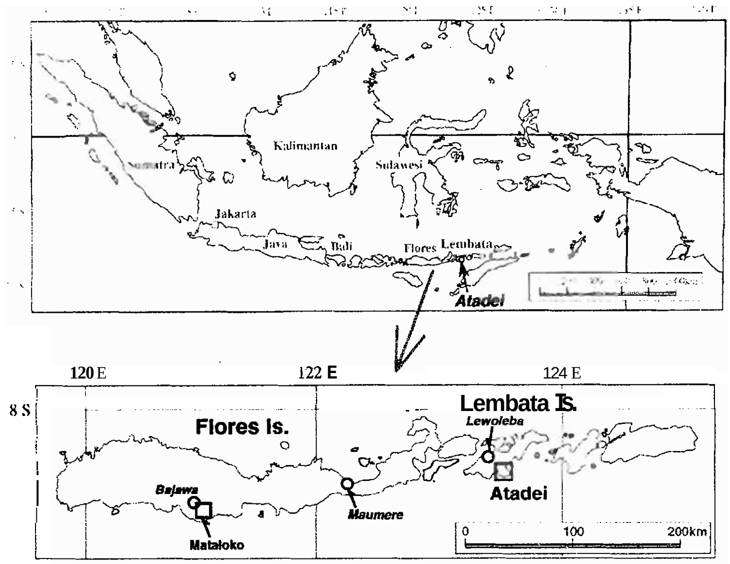

Figure 1. Map of Indonesia and locations of Lembata Island and the Atadei geothermal field.

matrix for the updated model at the third or fourth iteration. Then, the Jacobian matrix is updated by the Broyden method at later iterations (Sasaki and Uchida, 2001).

In addition to block resistivities in a 3-D model, static shifts are also treated as unknowns in the inversion. The static shift is caused by shallow small inhomogeneities and observed as a frequency-independent bias on apparent resistivity values, without changes in phase values. The amount of the shift is completely arbitrary and impossible to be estimated from the observed apparent resistivity data. In our inversion, we assume that the static shifts follow a Gaussian distribution. Then, we applied a regularization that the norm of static shifts is close to zero. To stabilize the model correction at each iteration step, smoothness regularization is adopted.

The data function is defined as

$$d = F(m) + s + \varepsilon \tag{1}$$

where d is observed data (apparent resistivities and phases), m is a 3-D resistivity model, F is a non-linear function that works on the model m to produce MT responses, s is the static shift, and ε is the observation error. The objective function U to be minimized in the inversion is defined as

$$U = \|W[d - F(m) - Gs]\|^2 + \lambda^2\left(\|Cm\|^2 + \beta^2\|s\|^2\right) \tag{2}$$

where W is the weight defined from observation errors, G is a matrix that relates static shifts and the MT responses, and C is a roughening matrix. The first term of the right-hand side is for the misfit minimization and the second term is for the roughness and static-shift minimization. λ and β are trade-off parameters for the roughness and static-shift minimization, respectively, with regard to the misfit minimization.

Starting from a layered earth or a homogeneous half space, the iterative model refinement by the least-squares method is repeated untif the misfit does not change as the iteration proceeds. An optimum smoothness is searched based on the misfit minimization at each iteration (except every third iteration). Also, an optimum weight for the static-shift minimization is searched based on the misfit minimization at every third iteration.

3.0 MT DATA

The Atadei geothermal field is located in the southern part of Lembata Island, eastern Indonesia (Figure 1). The Volcanological Survey of Indonesia (VSI, August 2001 in order to obtain detailed resistivity structure of the potential area that was delineated by the previous surveys (Figure 2).

The Atadei field is underlain by young volcanic formations. There are several volcanic cones and one active volcano, Mt. Werung, in the study area (Figure 2). There also are a few caldera-like small ring structures. The average elevation of the area is 600 m above sea level. A steaming ground, Watuwawer (Figure 3), and a hot spring, Waiwejak, are located in the center and northwest of the survey area, respectively. The highest temperature measured at the Watuwawer steaming ground is 98 degrees Celsius and the zone is dominant with argillite-type alteration minerals (Aswin et al., 2001).

We set five survey lines, Lines E, F, G, H and I, to cover these surface manifestations (Figure 2). The separation of the lines was generally 600 meters. Station interval was basically 500 meters along each line. However, the survey area was generally of steep terrain and dense vegetation, and only several stations were located on a satisfactory flat place. Many stations were moved from the planned locations to seek a flatter and open place. The number of MT stations in the survey area is 48.

At the beginning of the survey, we tested a remote reference site, which was approximately 5 km to the north of the survey area. We measured at two stations in the survey area and one at the remote simultaneously. We compared two reference results: one is a reference between the two stations in the survey area, and the other is a reference with the remote station. Then, we obtained the exactly same referenced results for these two cases. It means that there is not significant improvement by the remote reference in this area. Therefore, after that, we used all three MT equipments in the survey area and performed a local reference with each other by keeping one station at least 2 km away from the other two stations. Fortunately for the MT measurement, there is no public electricity supply in the Atadei area. During nighttime, we used a small generator to charge batteries and computers at the camp located in a middle of the survey area. The only major noise sources were wind noises. The overall data quality was fine except low-frequency noises at about ten stations.

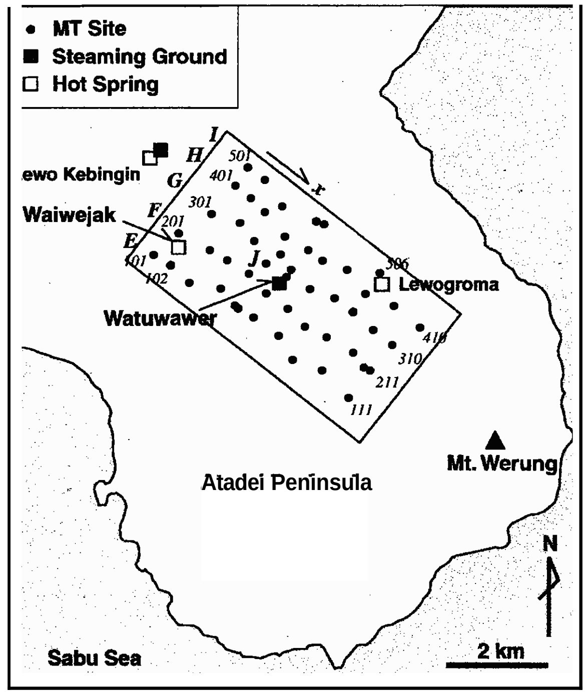

Figure 2. The MT stations in the Atadei geothermal field (solid circles). Five lines (E, F, G, H and I) were arranged. The zone of 3-D interpretation is shown by a rectangle. Solid squares are steaming grounds, open squares are hot springs, a solid triangle is an active volcano.

Figure 3. Watuwawer steaming ground. Setting up an MT site at an eastern side of the manifestation.

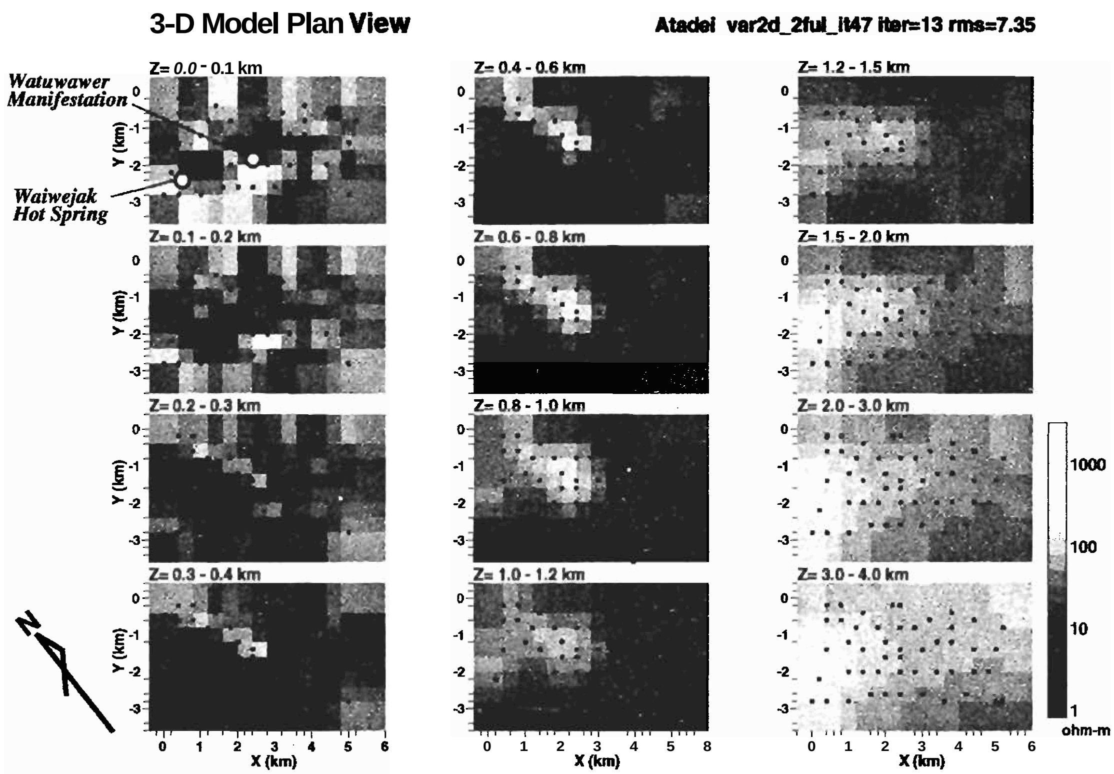

Figure 4. The depth slice sections of the 3-D resistivity model of the MT data, from surface (upper-left panel) to a depth of 4 km (lower-right). Small black dots indicate MT stations.

4.0 3-D INTERPRETATION

We have applied 3-D inversion to the data at the 48 stations. The impedance was rotated to the direction of survey lines; x- and ydirections are 128 and 38 degrees clockwise from north, respectively. Then, off-diagonat components of the impedance, Z_{xy} and Z_{yx}, were computed.

Eleven frequencies, from 0.07 Hz to 60 Hz, were used for the inversion. The size of the cells at the surface in the interpreted zone (shown by'a rectangle in Figure 2) was 200 m horizontally and 100 m vertically. Gradually coarser cells were added outside the interpreted zone. The number of finite difference cells was 57, 45 and 33 in x, y and z directions, respectively. The number of blocks for the inversion is 14, 8 and 13 in x, y and z directions, respectively. The MT responses used for the inversion were apparent resistivities in the natural logarithmic domain and phases. For the weighting matrix W, a noise floor of 1 % was assumed.

Starting from a homogeneous half space of a resistivity that is the average of observed apparent resistivities, the iteration converged at about 10 - 13 iterations. Figure 4 shows an obtained 3-D model, and Figure 5 shows observed and modeled apparent resistivities and phases at the stations on Line G. The final normalized root-mean-squares (rms) error was approximately 7. It is not small enough, however, the fitting is visualty very fine (Figure 5). It seems that this level of the rms error is the smallest that we can achieve at this moment. The average estimated static shift is 0.71 in the natural logarithmic domain. This is a large number because the observed apparent resistivities contain large static shifts that are due to strong topography effects.

At the shallow layer, depths of 0 - 100 m, low-resistivity anomalies are limited around the Watuwawer manifestation and Waiwejak hot spring. Then, at depths of 100 - 400 m, the low-resistivity zone between Watuwawer and Waiwejak becomes dominant. Another low-resistivity zone is recognized in the southeast of the survey area. At depths of 400 - 1200 m, high-resistivity anomaly beneath the Watuwawer manifestation becomes dominant. At a depth

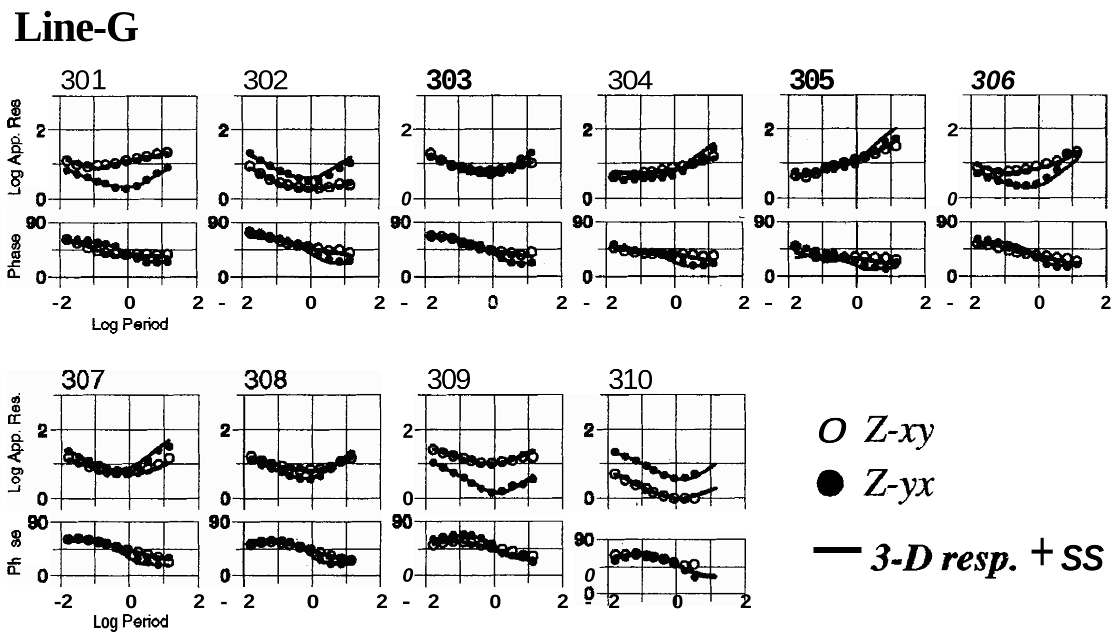

Figure 5. 3-D responses at the stations on Line G. Open and solid circles are observed data in the xy- and yx-components, respectively. Lines are computed data including static shifts.

greater than 2 km, the entire area becomes high-resistivity.

Figure 6 shows three NW-SE cross-sections that are near Watuwawer and Waiwejak. The high-resistivity basement is very shallow beneath Watuwawer. There is a shallow low-resistivity zone between Watuwawer and Waiwejak. As a very preliminary geological interpretation, we estimate that the shallow basement beneath Watuwawer indicates an existence of a geothermal reservoir. There probably is a heat source at far deep. The shallow low-resistivity layer may correspond to a clay-alteration zone. The reconnaissance survey by DMRI recognized the existence of smectite around the Watuwawer manifestation. Based on these results, DMRI is planning the first shallow drilling in this zone near future.

5.0 CONCLUSIONS

We carried out an MT survey over the Atadei geothermal field, Lembata Island, Indonesia, and performed a 3-D interpretation. The inversion worked properly with a full Jacobian computation and the inclusion of the static shift in the inversion. The 3-D resistivity model preliminary suggested a reservoir structure in the area.

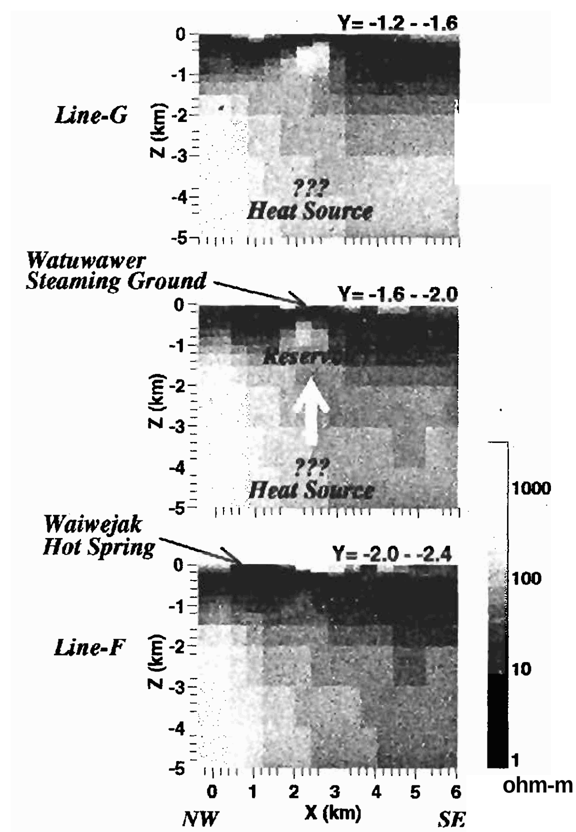

Figure 6. Vertical cross sections of the 3-D MT model and very preliminary interpretation of the reservoir model.

ACKNOWLEDGMENTS

The authors are grateful to Y. Sasaki, Kyushu University, for the 3-0 MT inversion code. TU and TJL used a computer system at the Tsukuba Advanced Computer Center, AIST, Tsukuba, for this work.

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