

3-D INTERPRETATION OF MAGNETOTELLURIC DATA IN CENTRAL LEYTE AND NORTHERN NEGROS GEOTHERMAL AREAS, CENTRAL PHILIPPINES

Toshihiro Uchida¹, Domingo B. Layugan², David M. Rigor, Jr.², Carlos F. Los Baños²,
Nilo A. Apuada², Rhoel Enrico R. Olivar², and John Patrick L. Catane²

¹Geological Survey of Japan, AIST, Tsukuba 305-867, Japan

²PNOC Energy Development Corporation, Merritt Road, Fort Bonifacio, Taguig City, Philippines

ABSTRACT

A stable three-dimensional (3-D) inversion technique of magnetotelluric (MT) data has been developed and applied to the data obtained in two geothermal fields in the Philippines by PNOC-EDC: Central Leyte and Northern Negros geothermal fields. The inversion method is based on the Gauss-Newton (linearized least-squares) method with smoothness regularization. Static shifts are also treated as unknown parameters in the inversion. A Bayesian criterion ABIC is applied to search the optimum trade-off among the minimization of the data misfit, model roughness and static shifts with an assumption of Gaussian distribution in these quantities. Although the data quantity is large and several parts of the data are contaminated by various noises, the inversion of the two datasets has behaved properly and a stable convergence has been attained. The interpretation of the resultant resistivity models has been still primitive, however, the model of the Central Leyte data indicates a good correlation with the geologic trends of the Philippine Fault and the structure of the nearby volcano.

1.0 INTRODUCTION

The magnetotelluric (MT) method is one of the essential tools for investigating geological structure for geothermal exploration. This is mainly because of its capability to delineate low-resistivity anomalies associated with the reservoir structure. Two-dimensional (2-D) inversion has been a standard technique for MT data interpretation since a decade ago. However, due to complicated geological environments, which we often encounter in geothermal fields, the 2-D interpretation sometimes fails to produce realistic models.

Particularly, the resistivity model of deeper parts of the reservoir structure is often ambiguous.

Sasaki (1999, 2001) developed a 3-D MT inversion technique and tested it with several synthetic datasets. Sasaki (2001) proposed to estimate static shifts simultaneously by the inversion. Uchida et al. (2002) applied the method to the MT data obtained in a geothermal field in Indonesia. The Indonesian MT dataset is a small volume, having only 39 stations. The inversion was performed within a relatively short computation time; and the resultant 3-D models properly indicated the general features of the reservoir structure.

In this paper we have applied the inversion technique to a larger volume MT datasets obtained in two geothermal fields in the Philippines. The MT data was obtained by PNOC-EDC in the Central Leyte and Northern Negros geothermal fields. For this work, we have added a function, to the 3-D MT inversion code, to choose the optimum regularization with regard to the roughness and static shift minimization so that a stable convergence could be attained almost for any MT data which are contaminated by various noises. This work has been conducted as the first step of an informal joint research between the Geothermal Division of PNOC-EDC and the Geological Survey of Japan, AIST.

2.0 INVERSION METHOD

The 3-D inversion scheme used in this work is based on the linearized iterative least-squares (Gauss-Newton) method with smoothness regularization (Sasaki, 1999). The forward modeling for a given arbitrary 3-D earth is by the finite difference method. 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. The electric field is first solved in frequency domain by the finite difference method. Then, the magnetic field is computed from the obtained electric field.

The Jacobian matrix consisting of partial derivatives (sensitivities) of MT responses with respect to block resistivities in the 3-D model should be evaluated from an estimated model at each iteration step in the usual iterative Gauss-Newton procedure. However, in this work, the full sensitivities of the MT responses are computed at only a limited number of iterations; practically at the 3rd and 6th iterations. A Jacobian matrix computed from a homogeneous earth is used at the 1st and 2nd iterations. After the 3rd iteration, except the 6th iteration, the Broyden method is applied to update the Jacobian matrix.

In addition to block resistivities of a 3-D model, static shifts are also treated as unknowns in the inversion (Sasaki, 2001). A 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 estimate from the observed apparent resistivity data. In our inversion, Gaussian-distributed static shifts are assumed. We apply a regularization that the L-2 norm of static shifts is close to zero.

To stabilize the model correction at each iteration step, smoothness regularization was adopted. The objective function U to be minimized in the inversion is defined as,

$$U = \|\mathbf{W}[\mathbf{d} - F(\mathbf{m}) - \mathbf{G}\mathbf{s}]\|^2 + \alpha^2 (\|\mathbf{C}\mathbf{m}\|^2 + \beta^2 \|\mathbf{s}\|^2) \quad (1)$$

where \mathbf{W} is the weight defined from observation errors, \mathbf{d} is the observed data (apparent resistivity and phase), \mathbf{m} is a 3-D resistivity model, F is a non-linear function that works on the model \mathbf{m} to produce MT responses, \mathbf{C} is a roughening matrix, \mathbf{s} is the static shift, and \mathbf{G} is a matrix that relates static shifts and the MT responses. The first term of the right-hand side is for the misfit minimization and second term is for roughness and static-shift minimization. The α and β are trade-off parameters for roughness minimization and static-shift minimization, respectively, with regard to the misfit minimization.



Figure 1. Location of Central Leyte and Northern Negros geothermal fields in the Philippines; also showing geothermal fields where power plants are in operation.

An optimum regularization for the smoothness, α , and the static shift, β , is searched based on the ABIC minimization at each iteration. To reduce the search procedure, the optimum smoothness is searched every iteration except every 3rd iteration, while the optimum static shift is searched every 3rd iteration, both by minimizing a Bayesian criterion ABIC (Uchida, 1993).

3.0 MT DATA

We have applied the 3-D inversion technique to two MT datasets obtained in Central Leyte and Northern Negros geothermal fields by PNO-EDC (Figure 1). The Central Leyte survey was conducted in 2001 (Rigor et al., pers. comm.). The Northern Negros survey was conducted in 1995 and 2000 (Maneja et al. 2001). The data acquisition was done without the remote reference analysis. Therefore some parts of the data might be contaminated by local noises, especially at lower frequencies. However, overall data quality seems to be fine for further interpretation including 3-D inversion. Very preliminary results by the 3-D inversion are described in the following sections.

4.0 CENTRAL LEYTE GEOTHERMAL FIELD

Figure 2 shows the MT stations in the Central Leyte geothermal field. The survey area is located on the western and southern flanks of Mt. Lobi. Also, the Philippine Fault goes through the western part of the survey area. MT stations are evenly distributed with an average spacing of 1 km, which is suitable for a 3-D interpretation.

For the 3-D inversion, we rotated the MT impedance to north. Directions of x- and y-axes are 90 and 0 degrees clockwise from north, respectively. We used the off-diagonal components of the MT impedance (apparent resistivity and phase) as the observed data. The numbers of MT stations and frequencies used for the inversion are 81 and 11 (from 0.0703 Hz to 72 Hz), respectively. Total number of the observed data is 3468. The noise floor was assumed as 1%. The initial model is a homogeneous half space, whose resistivity is the average of the whole apparent resistivity data, which is 26.2 ohm-m. The number of the resistivity blocks is 2873. The cell size of the finite difference mesh in the interpreted zone is 250 m horizontally. Although the topography is not considered in the forward modeling, we can assume that topography effect is solved as a part of the static shift as far as the skin depth of the highest frequency data is large enough as compared with the amplitude of the topography variation.

Figure 3 shows how the inversion parameters, such as α and β , changed as a function of the iteration step. We started with an initial β as 2 for the first two iterations. The misfit and ABIC decreased as a function of the iteration almost monotonically. The modification step of the parameters became a small after the 17th iteration. We selected the model at the 18th iteration as the final model.

Figure 4 shows depth-slice sections of the final 3-D model. The normalized RMS misfit is 9.98, and the average of the estimated static shifts is 0.688 in the natural logarithmic domain. Figure 5 shows the observed and calculated apparent resistivities and phases for the first 27 stations. Fitting of the data is generally fine. The average amplitude of the estimated static shifts, 0.688, is relatively large. It is probably because of topographic effects or complex changes of the surface resistivity. Large splits between the two

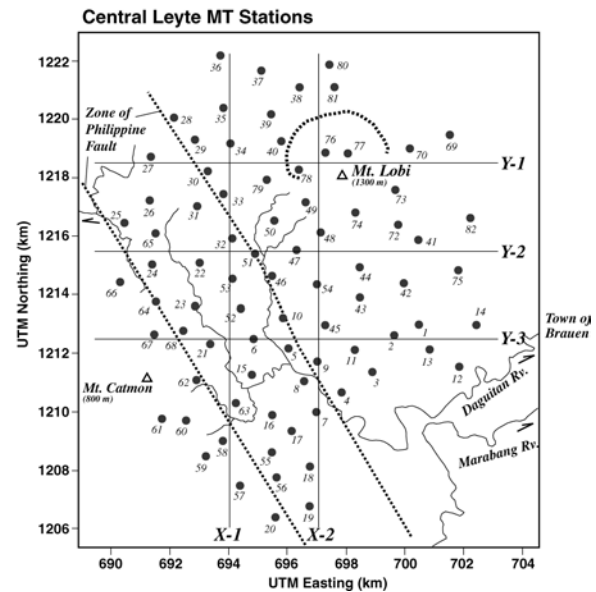


Figure 2. Location of MT stations (dots) with station numbers in the Central Leyte geothermal field. Dashed lines indicate the crater rim of Mt. Lobi and the zone of the Philippine Fault. All MT stations were used for the 3-D inversion.

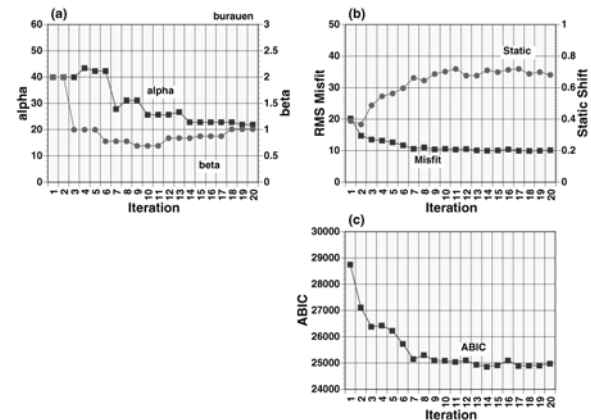


Figure 3. Inversion parameters as a function of the iteration: a) smoothing factor α and static shift parameter β , b) RMS misfit and the norm of static shifts in natural logarithmic domain, and c) ABIC.

curves at higher frequencies, for example, at stations 8 and 17, are well estimated by the inversion. However, there are some discrepancies in detailed portions of the curves: e.g., the phase data at stations 23 and 24 were not well recovered. Also, noisy curves that might be due to near-field noise sources can be recognized at stations 6, 27, etc. These resulted in a relatively large RMS misfit of 9.98.

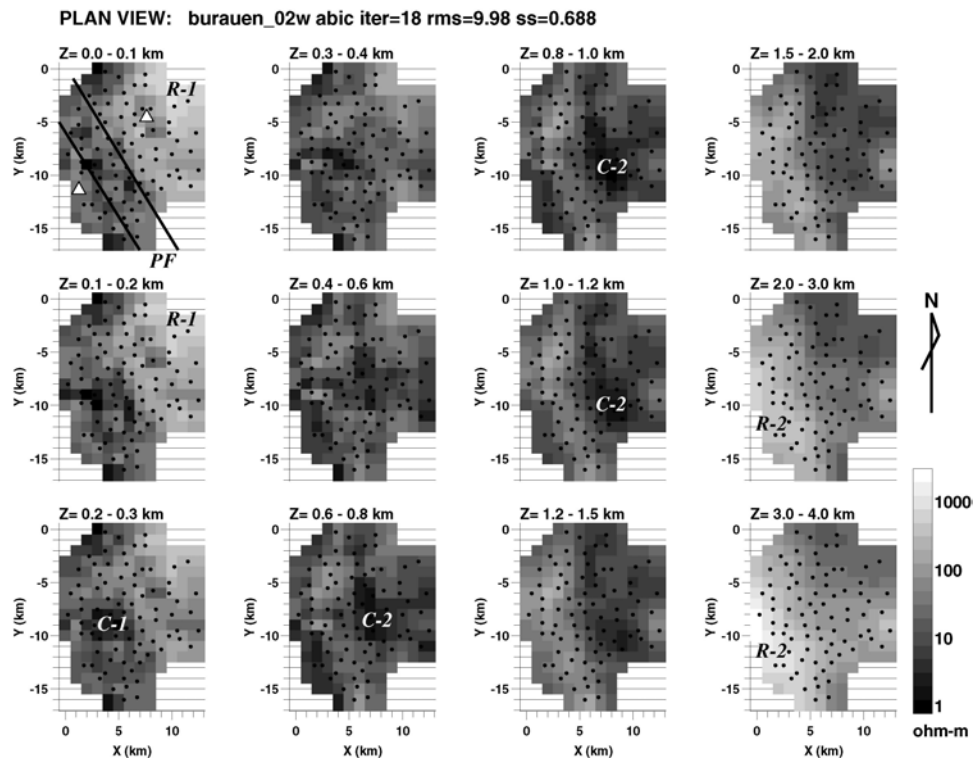


Figure 4. Depth-slice resistivity sections of the 3-D model. Black dots indicate the MT sites. Dominant low-resistivity (C-1, C-2) and high-resistivity (R-1 and R-2) anomalies are shown. On the top left panel, triangles indicate Mt. Lobi and Mt. Catmon, and solid lines indicate the zone of Philippine Fault.

Central Leyte

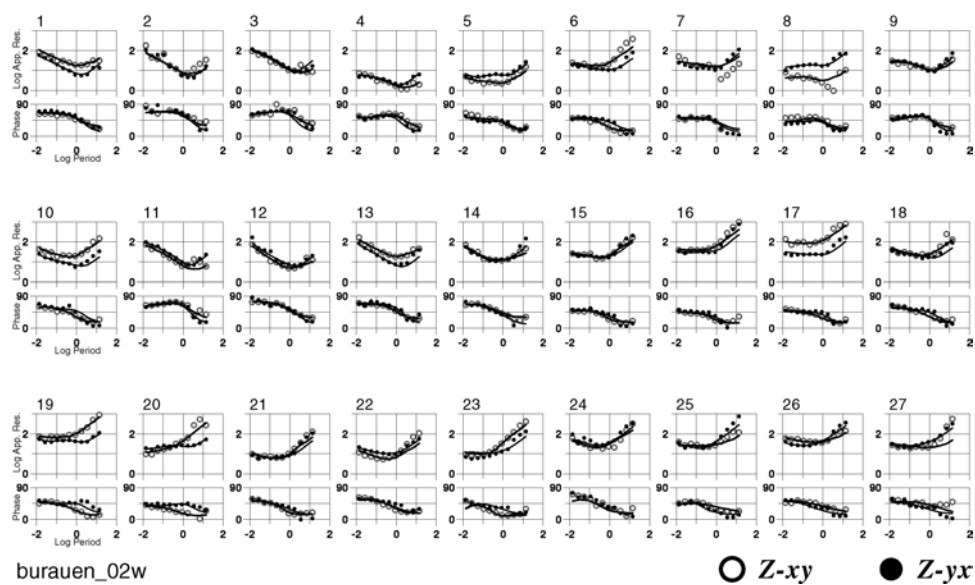


Figure 5. Observed (circles) and computed (solid lines) apparent resistivities and phases of the sites on the first 27 stations. Open circles are Z_{xy} and solid circles are Z_{yx} . Static shifts are included in the computed apparent resistivity curves.

From the depth-slice sections in Figure 4, the following features can be observed in the resistivity model (Figure 4):

- 1) High-resistivity zone (R-1) exists in the shallow layer around Mt. Lobi. This is interpreted as unaltered volcanic rocks around the volcano.
- 2) In the western area, a shallow low-resistivity anomaly (C-1) is recognized. Because it is a local anomaly with a depth of 200 – 400m, it might be associated with a shallow alteration zone.
- 3) A large low-resistivity zone (C-2) is recognized at depths of 600 – 1500 m in the eastern half of the survey area. The lowest resistivity is approximately 1 – 2 ohm-m. This is the biggest conductive zone in this area.
- 4) A large high-resistivity layer (R-2) is situated at depths greater than 1.5 km in the western half of the area. The strike direction of this resistive body is NNW-SSE, which is consistent with the direction of the Philippine Fault in Leyte Island.

Figure 6 shows three west-east cross sections, Y-1, Y-2 and Y-3, and Figure 7 shows two north-south sections, X-1 and X-2, extracted from the 3-D model shown in Figure 4. A clear contrast of the low-resistivity zones, C-2 and C1, against the deeper resistive body, R-2, can be recognize along Line Y-3. This corresponds to the location of the Philippine Fault. In the north-south lines, the low-resistivity zone C-2 is dominant to the south of Mt. Lobi.

5.0 NORTHERN NEGROS GEOTHERMAL FIELD

Figure 8 shows the MT stations in the Northern Negros geothermal field. The survey area is located on the northwestern flank of the Canlaon Volcano. For the 3-D inversion, we rotated the MT impedance to the direction of 45 degrees from north. Directions of x- and y-axes are 135 and 45 degrees clockwise from north, respectively. The numbers of MT stations and frequencies used for the inversion are 92 and 11 (from 0.0703 Hz to 72 Hz), respectively. Total number of the observed data is 3942. The initial model is a homogeneous half space, whose

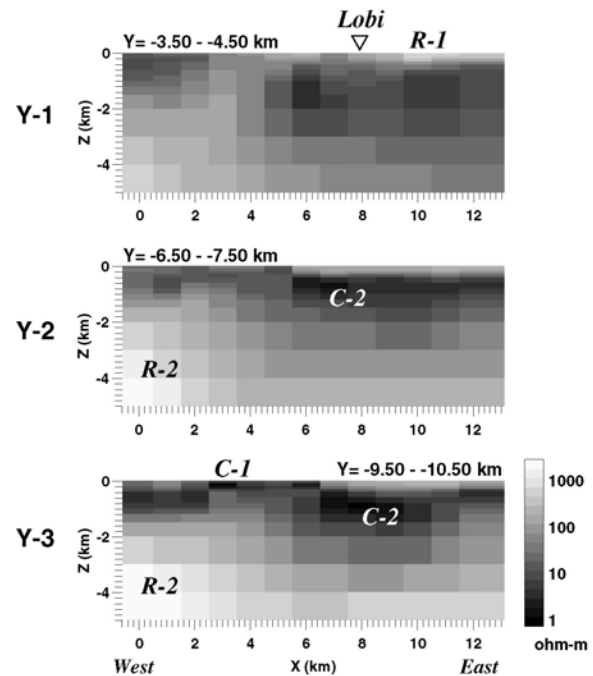


Figure 6. Vertical sections of three east-west lines extracted from the 3-D model shown in Figure 4. Location of lines is shown in Figure 2.

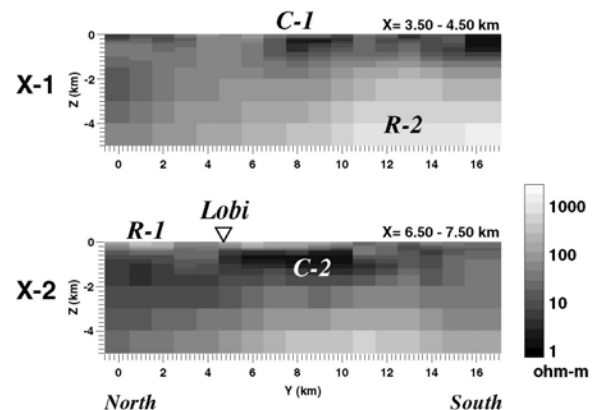


Figure 7. Vertical sections of two north-south lines extracted from the 3-D model shown in Figure 4. Location of lines is shown in Figure 2.

resistivity is 11.2 ohm-m. The number of the resistivity blocks is 2912. The cell size of the finite difference mesh in the interpreted zone is 200 m horizontally. The same parameter setting was applied for the inversion as the case of the Central Leyte data. At the time of writing this manuscript, we found minor errors in the data file when it was modified from the original file.

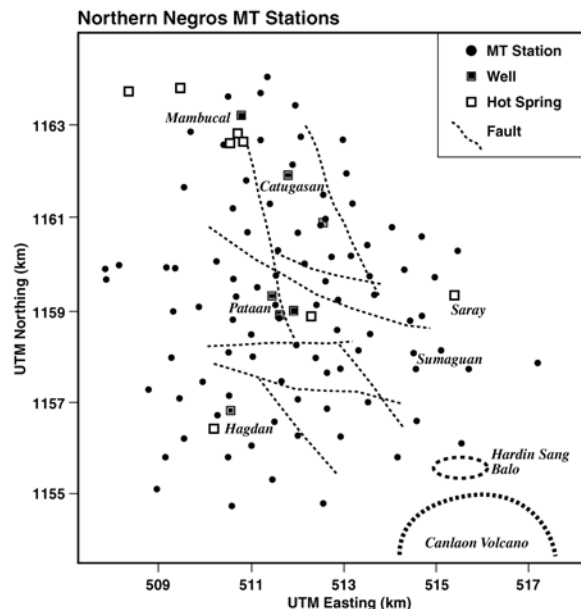


Figure 8. Location of MT stations (dots) in the Northern Negros geothermal field. Thin dashed lines are estimated faults, open squares are hot springs, solid squares are geothermal wells, and thick dashed lines indicate volcano summit or crater rim.

6.0 CONCLUSIONS

The 3-D inversion technique based on the finite-difference forward modeling and the Gauss-Newton inversion scheme with smoothness regularization has worked very well on a large volume MT field data obtained over the Central Leyte and Northern Negros geothermal fields. Static shifts were solved simultaneously during the inversion. The optimum trade-off with regard to the roughness minimization and the static shift minimization was determined by a Bayesian criterion ABIC.

The inversion has behaved very stably and a convergence has been usually attained easily. The final 3-D models seem to be more realistic for the entire resistivity model than 2-D models. In the case of the Central Leyte data, the 3-D

model show a good correlation with the major trends of the Philippine Fault and the structure of Mt. Lobi. Therefore, the 3-D interpretation is essential for geothermal exploration, and more reliable 3-D inversion technique is necessary for accurate imaging of deep resistivity structure around geothermal reservoirs.

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