The magnetotelluric phase tensor analysis of the Sembalun-Propok area, West Nusa Tenggara, Indonesia

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Abstract. The subsurface structure of the Sembalun-Propok area, NTB, Indonesia, has been investigated using magnetotelluric method (MT). To obtain the information of the dimensionality of the regional structure and determine the regional strike of the study area, the phase tensor analysis has been performed in this study. The results show that most of the skew angle values (β) are distributed within ± 5°. It indicates that the regional structure of the study area can be assumed as two dimensional. In addition, to determine the regional strike of the study area, we also calculated the major axes of the phase tensor. The result presents that the regional strike of the study area is about N330°E. According to the results of the phase tensor analysis, we rotated the impedance tensor to N330°E and performed 2-D inversion modeling. The result presents that the substructure model suits with the geological background of the study area.

1. Introduction

One of the geophysical methods which are useful in geothermal resources investigations is the magnetotelluric (MT) method. The MT is a passive-surface electromagnetic technique to investigate the electrical resistivity structure from the near surface to the upper mantle [1]. The MT method can investigate the lower resistivity anomalies associated with the geothermal resources since they commonly have relatively lower resistivity than initial rocks. Variation in the resistivity is related to the water abundance, temperature, and degree of mineralization [2].
The Sembalun-Propok area is located at the eastern part of Lombok Island, West Nusa Tenggara Province. Geologically, its regional structures are dominated by the normal and strike-slip faults which have the direction of NW-SE [3].

In subsurface structure modeling using MT method, information about dimensionality and regional strike of the study area are important. Without this information, we cannot choose that either 1-D, 2-D or 3-D condition for a study area as the best assumption of the MT data modeling. To obtain this information, one of the methods is the phase tensor analysis which has been proposed by Caldwell (2004). The calculation of the phase tensor does not require an assumption about the dimensionality of the underlying conductivity distribution and is applicable where both the heterogeneity and the regional conductivity structures are 3-D [4]. The method has been applied at the volcanic systems, the geothermal fields, and the fault zone [5-8].

In this study, we analyze the MT data by using the phase tensor analysis to investigate dimensionality and regional strike of the Sembalun-Propok area, West Nusa Tenggara, Indonesia.

2. Observation and Analysis of Audio-Magnetotelluric (AMT) Data

This study was carried out in the Sembalun-Propok area, East Lombok Regency, West Nusa Tenggara Province. Figures 1 (a) and (b) show the topography maps of the Lombok Island and 38 AMT observation points. In AMT exploration, time-series data of electric and magnetic fields were collected by MTU-5A manufactured by Phoenix Geophysics Ltd., in 2007. Duration of the data collection was about a few hours at each site. The data were transformed to power spectra by Fourier Transform, in a frequency range of 0.001 Hz-1000 Hz. All observed data were processed as a single site since we did not have adequate remote reference data.

In this study, we applied the MT phase tensor to obtain information about the dimensionality of the regional structure and to determine the regional strike of the study area [4]. The MT phase tensor can be written in the form of the singular value decomposition (SVD) of a square matrix [4], as follows:

\[
\Phi = R^T (\alpha - \beta) \begin{bmatrix} \Phi_{\text{max}} & 0 \\ 0 & \Phi_{\text{min}} \end{bmatrix} R(\alpha + \beta)
\] (1)

\(R^T\) is the transposed or inverse rotation matrix. \(\alpha\) and \(\beta\) can be expressed by

\[
\alpha = \frac{1}{2} \arctan \left( \frac{\Phi_{12} + \Phi_{21}}{\Phi_{11} + \Phi_{22}} \right), \quad \beta = \frac{1}{2} \arctan \left( \frac{\Phi_{12} - \Phi_{21}}{\Phi_{11} + \Phi_{22}} \right)
\]

(2)

The angle of \(\alpha\) expresses the tensor dependence’s on the coordinate system and with the three coordinate invariants completely defines the tensor. The angle of \(\beta\) is called the skew angle and can be thought of as rotation and is a measure of the tensor asymmetry. The angle of \(\beta\) depends on the tensor’s skew (\(\Phi_{12} - \Phi_{21}\)), which is invariant under rotation but changes sign if the coordinate system is reflected [4].

Graphically, the MT phase tensor can be represented as an ellipse where the major \(\Phi_{\text{max}}\) and minor axes \(\Phi_{\text{min}}\) of the ellipse depict the principal axes and values of the tensor with the orientation of the major axes specified by the angle (\(\alpha-\beta\)). In general, where the regional conductivity distribution is 3-D, the skew angle \(\beta\) is non-zero. If the phase tensor is symmetric \(\beta = 0\), this situation occurs where the regional conductivity distribution is 1-D or 2-D [4]. The information of the dimensionality and regional strike are very important as the preliminary analysis in 1-D, 2-D or 3-D MT data modeling.
3. Results and Discussion

To obtain information about the dimensionality of the regional structure, the MT phase tensor was applied on the three profiles, as presented by the white lines on the topography map in figure 1(b). The dimensionality, D, is indicated by the skew angle of the phase tensor (β value) [4]. For idealized condition, D = 1 or 2 when β = 0.

Figure 2 shows the skew angle β plot of the observation points along the Line 1, Line 2, and Line 3 for all frequency ranges. The results show that most of the β values are distributed within ±5° for frequency higher than 0.1 Hz. For lower frequency (0.001 Hz-0.1 Hz), the β values are distributed in -10° ≤ β ≥ 10°. This result confirms that the resistivity structure can be assumed as 1-D or 2-D for the higher frequency. Therefore, it is safe to perform 2-D modeling for the MT data with frequency range of 0.1 Hz - 1,000 Hz.
In the next step, we estimated the regional strike of the study area by calculating the major axes of the phase tensor \((\alpha - \beta)\). Figure 3 shows the rose diagram of the \((\alpha - \beta)\) value for all frequency ranges. The estimated values have 90° ambiguity. The results of the phase tensor major axes agree well with...
the general regional strike. It shows that the dominated strikes are NW-SE and NE-SW directions for all frequency ranges. Using this information, we applied 2-D inversion modeling of the MT data using Ogawa and Uchida's code [9]. In this paper, we chose the Line 2 data that has frequency range of 0.1 Hz - 1,000 Hz for the modeling. Since we assumed the regional strike of the study area is NW-SE, we selected N330°E as the best value of the regional strike and rotated the impedance tensor of Line 2 to this direction.

Figure 3. The rose diagram that presents the regional strike determined by the phase tensor for all sites.

Figure 4. The result of the 2D inversion modeling of the MT observation points along the Line 2. The labels on the triangles indicate the observation sites that correspond to the Figure 1.

Figure 4 shows the result of the 2D inversion modeling of the MT data along the Line 2. The near surface along the Line 2 is dominated by high resistivity layer (> 500 Ωm). It is highly associated with the surface geology of the study area, which is characterized by the Old Quaternary volcanic of Sembalun, the permeable rocks of Sembalun-Propok and the Young Quaternary Propok-Rinjani volcanic [10]. The products mostly consist of andesitic to dacitic rocks of a calc-alkaline suite [10]. Below the resistive layer at the near surface, along the Line 2 the inversion modeling shows the layer with low-moderate resistivity layer (5 - 80 Ωm). Low - moderate resistivity zone is down to 4 km deep in the northwest and southeast regions and to 2 km deep below MT33 - MT35. It is possibly a cap rock layer of geothermal system of the Sembalun-Propok area. The result also shows that this layer is also at the near surface below the MT33 observation point. It is possibly associated with the hot spring which is located near the MT33. The third layer is the very conductive layer and possibly associated with the presence of thermal fluids.
This result confirms that the MT phase tensor can be useful as the preliminary analysis before applying 2-D inversion modeling. It helps us to obtain information about the dimensionality of the regional structure and to estimate the regional strike of the study area.

4. Conclusion
To obtain the information of the dimensionality of the regional structure and the regional strike, the MT phase tensor has been applied as the preliminary analysis in the Sembalun-Propok area, NTB, Indonesia. The result shows that the resistivity structure of the Sembalun-Propok can be assumed as 2-D for the higher frequency and the regional strikes are dominated to be NW-SE and NE-SW directions for all frequency ranges. Therefore, it is safe to rotate the impedance tensor to N330°E direction and perform the 2-D inversion modeling for the MT data with frequency range of 0.1 Hz - 1000 Hz. In the following step, we applied the 2-D inversion modeling to Line 2. The result shows that the substructure model supports the geological background of the study area.

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