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Geological Structure Modeling of the Lembang Fault Using 2D AMT (Audio Magnetotelluric) Inversion and Phase Tensor Analysis

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ABSTRACT (9 pt)

The magnetotelluric (MT) method is a geophysical technique that utilizes naturally occurring electromagnetic waves originating from the Earth to measure the intensity of the Earth's electric field (E) and magnetic field (H). The interdependence between electric and magnetic phenomena, particularly in relation to the Earth's electrical properties – mainly conductivity – serves as the fundamental concept of the magnetotelluric method. This is achieved by simultaneously measuring variations in E and H as a function of frequency to determine the subsurface resistivity structure. In this study, field data acquisition was conducted using the AMT (Audio Magnetotelluric) method at the Lembang Fault. This measurement aims to construct a two-dimensional model of the fracture movement patterns and orientations within the fault zone. Based on the study's results, the calculated phase tensor values were obtained and subsequently analyzed to determine the direction of the geoelectrical strike. These data were then subjected to 2D inversion. The results of dimentionality from phase tensor analysis indicate that the model parameters are predominantly characterized by symmetric ellipses (2D) shapes, suggesting that an appropriate inversion model can be constructed in two-dimensional (2D) form. Based on the geoelectrical strike analysis, the subsidiary movement of the Lembang Fault is predominantly oriented in a west-east direction, with a strike angle of 90° or W90°E From the 2D inversion model with supported by geological map, a significant contrast in the anomaly is observed, which suggests the existence of a fault zone within the inversion model. The model reveals two thrust faults that were identified at a depth of approximately 3250 metres, interpreted as a thrust fault is identified at point C-01, trending Southwest–Northeast, while another fault is located at point C-02, oriented Southeast–Northwest an estimated depth of 3125 metres . The resistivity variation is dominated by high values, approximately from 53.97 until 800 ohm-metres., which these caused by active volcanic rocks formation. In addition, this area also associated with magmatic activity, as the Lembang Fault zone is located near an active volcano.

INTRODUCTION

The magnetotelluric (MT) method was first introduced by Tikhonov (1950) and Cagniard (1953). (Syech et al., 2017). The magnetotelluric method is used to determine the resistivity of subsurface rocks by utilizing natural electromagnetic fields. These electromagnetic fields are generated by various physical processes occurring in nature, such as solar wind and lightning. (Febriani, 2014). The solar wind, which contains electrically charged particles, interacts with the Earth's permanent magnetic field, causing variations in the electromagnetic field. These variations form plane waves that propagate to the Earth's surface and induce eddy currents (telluric currents). (Febriani, 2014). The frequency spectrum of this electromagnetic field is very broad, giving the method an advantage, particularly in terms of its depth of penetration. Another advantage of this method is the ease of field measurements. However, its main drawback is its high sensitivity to disturbances (noise) caused by human activities around the survey area. The frequency spectrum used in this method ranges from 10^{-5} Hz to 10^{4} Hz, allowing for deep subsurface imaging. Low frequencies (< 1 Hz) originate from the interaction of charged particles in the solar wind with the Earth's magnetic field, while high frequencies (> 1 Hz) are generated by meteorological activities such as lightning (Hendra, 2013)

The MT method is useful in fault zone investigations because resistivity in the fault zone is significantly lower due to the existence of fluids (Becken et al., 2011). In addition, other researches also revealed that the majority of fault zones is associated with resistor-conductor boundaries, and devastating earth- quakes occurring in or around asperities identified by local resistive areas spatially surrounded by low resistivity zones (Ujihara et al., 2004). Mathematically, the principle of the Magnetotelluric method is explained by the following Maxwell's equations (Maharani et al., 2023):

$$\nabla \times E = -\frac{\partial B}{\partial t} \quad (1)$$

$$\nabla \times H = j + \frac{\partial D}{\partial t} \quad (2)$$

$$\nabla . D = q \quad (3)$$

$$\nabla . B = 0 \quad (4)$$

Where E is the electric field (V/m), B is the magnetic induction (W/m² or T), H is the magnetic field (A/m), j is the current density (A/m²), D is the electric displacement (C/m²), and q is the electric charge density (C/m³) (W. M. Telford, L. P. Geldart & D. A. Keys, 1976).

In addition, there is an assumption that the Earth is considered a conductive medium, allowing the diffusion equation to be applied in analyzing the penetration of the Magnetotelluric method. The depth of electromagnetic wave penetration into the ground, known as skin depth, indicates the distance at which the wave amplitude decreases to 1/e of its original amplitude. As the electromagnetic field penetrates a conductive layer, its energy progressively diminishes with depth. The travel distance of the electromagnetic field also decreases depending on the conductivity of the layers it passes through. In this context, both resistivity and frequency values will affect the skin depth, which can be expressed by the following equation (Maharani et al., 2023):

$$\delta \approx 503 \frac{\sqrt{\rho}}{f} = 503\sqrt{T\rho} \quad (5)$$

where δ is the penetration depth (m), ρ is the resistivity of a homogeneous medium (Ω·m), and f is the frequency of the field (Hz) (Simpson & Bahr, 2005)

In the magnetotelluric method, impedance is expressed in complex form as a quantity consisting of amplitude and phase. This quantity can be represented in terms of resistivity and phase parameters, as shown in the following equations (Simpson & Bahr, 2005):

$$\rho_a = \frac{1}{\omega\mu_0} \, |Z|^2 \qquad (6)$$

$$\varphi = \tan^{-1}\left|\frac{\mathrm{Im}\,(Z)}{Re\,(Z)}\right| \qquad (7)$$

where ρ_a is the apparent resistivity, Z is the impedance (Ω), ω is the angular frequency (rad/s), μ_0 is the magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m), and φ is the phase (°).

In MT data processing, specifically using AMT (Audio Magnetotelluric), one of the steps carried out is phase tensor analysis, which involves a complex number phase derived from the ratio between the real part (X) and the imaginary part (Y). Phase tensor analysis of Magnetotelluric (MT) data indicates that galvanic distortion does not affect phase tensor analysis. In this case, the phase tensor can be represented in the form of an ellipse and a skew angle (β) (Caldwell et al., 2004), as shown in the following equation:

$$\alpha = \frac{1}{2}\tan^{-1}\left(\frac{\Phi12 + \Phi21}{\Phi11 -)\Phi22}\right) \qquad (8)$$

$$\beta = \frac{1}{2}\tan^{-1}\left(\frac{\Phi12 + \Phi21}{\Phi11 -)\Phi22}\right) \qquad (9)$$

The inversion used in this study employs the NLCG (Non-linear Conjugate Gradient) method. This inversion utilizes an algorithm to minimize the objective function (ψ) in order to produce changes in model parameters such as resistivity (Rodi et al., 2016). If a model is denoted as m, a mathematical function as F, and d as the data, then the

$$d=(m) + \mathrm{e} \qquad (10)$$

where e is the error value. Thus, the model solution is obtained by minimizing the objective function (ψ) as follows:

$$\psi = (d- F\,(m)){-1}(d- F(m)) + \lambda mTLT\ Lm \qquad (11)$$

where λ is the regularization parameter, a positive value used for weighting, V is the variance of the error, and L is the Laplacian.

Based on phase tensor analysis, the dimensionality and the geoelectrical strike was obtained. The geoelectrical strike refers to a direction that indicates the orientation of electric current flow beneath the Earth's surface, influenced by lateral variations in electrical conductivity. In the context of the subsurface's two-dimensional nature, it is assumed that an electrically conductive zone extends in a direction along which electric current flows. Additionally, the geoelectrical strike provides information about the Earth's stratification and internal structure. The analysis of geoelectrical strike can be visualized using a rose diagram, which is a circular plot showing strike directions based on the phase tensor (Caldwell et al., 2004). This is related to the main structural trends of the study area, allowing for rotation toward the dominant strike direction. This rotation aims to eliminate environmental or instrumental influences on the signal, as well as to help address potential bias and distortion in the data, thereby improving the accuracy and reliability of the interpretation.

This study aims to analyze AMT (Audio Magnetotelluric) data by identifying the direction of the geoelectrical strike based on phase tensor analysis, in order to obtain a 2D model inversion of the subsurface geological structure along the Lembang Fault.

RESEARCH METHOD

This study adopts a geophysical data processing method using the Audio Magnetotelluric (AMT) approach to identify subsurface structures in the Lembang Fault area. The main stages of this methodology include :

1. **Data Acquisition and Static Correction.**
   AMT data were collected through field measurements across the Lembang Fault zone. Prior to further analysis, static correction was applied to the data to minimize the influence of local, non-structural anomalies such as topography and surface heterogeneity.
2. **Phase Tensor Analysis.**
   After correction, the AMT data were analyzed using the phase tensor method to determinant the dimensionality and evaluate the direction of electrical current flow beneath the surface and to characterize lateral geological structures. This approach is immune to galvanic distortion and represents the tensor in terms of an ellipse and a skew angle (β), following (Caldwell et al., 2004).
3. **Geoelectrical Strike Analysis**.
   The geoelectrical strike direction was determined from the phase tensor results to identify the dominant orientation of subsurface conductivity. This direction was visualized using a rose diagram and used to rotate the data toward the dominant strike direction.
4. **Initial Model Construction and 2D Inversion**.
   The identified strike direction served as the basis for constructing the initial model for 2D inversion. The inversion process was carried out using the Non-linear Conjugate Gradient (NLCG) method as formulated by Rodi & Mackie (2001). The objective function (ψ) was minimized to fit the modeled response with the observed data while applying regularization to ensure model stability. The objective function is defined as:

$$\Psi = \| F(m) - d \|^2 + \boldsymbol{\lambda} \| Lm \|^2 \qquad (12)$$

where:

- *F(m)* is the forward model function of resistivity *m*,
- *d* is the observed data,
- λ is the regularization parameter,
- *L* is the Laplacian operator,
- and *e* is the error term.

Through these steps, a 2D resistivity model of the subsurface structure along the Lembang Fault was successfully generated. For a more detailed explanation, the methodology is presented in the flowchart below (Figure 1) :

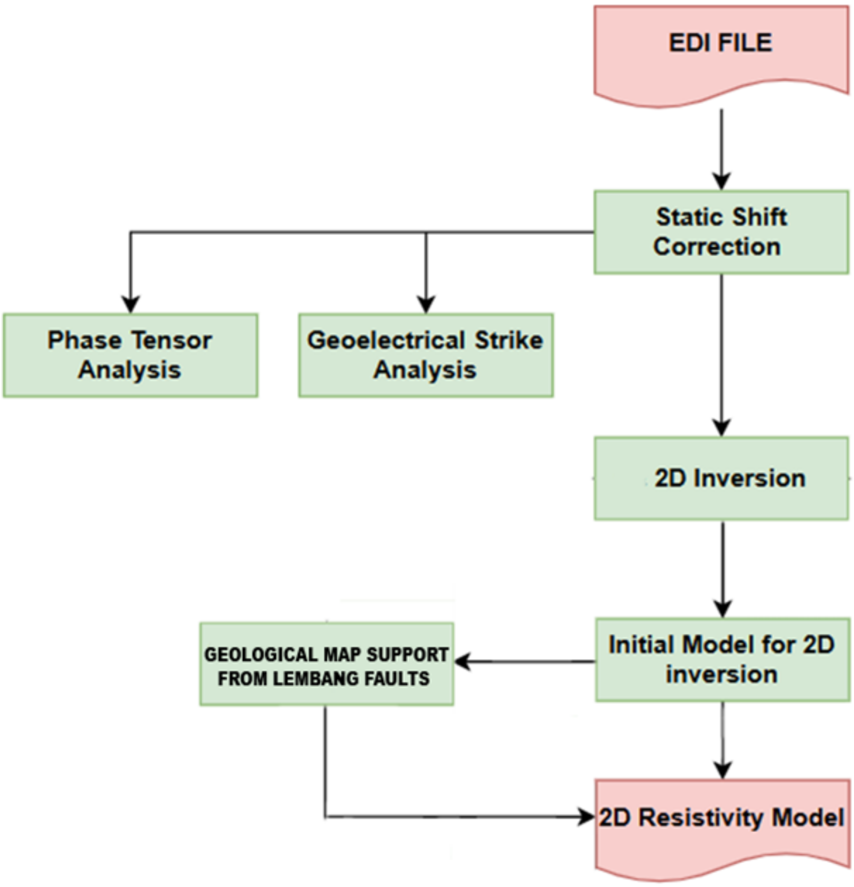

Figure 1. The Flow Chart Diagram for 2D AMT Inversion Model of Lembang Faults

RESULT AND DISCUSSION

The research begins with static correction of the AMT data. The main purpose of static correction in AMT (Audio-Magnetotelluric) data is to eliminate or minimize static effects that may influence the measured data and subsurface interpretation. These static effects can appear as shifts in the resistivity curves, caused by topographic variations, elevation differences, or heterogeneous characteristics of near-surface layers. And then continues with a phase tensor analysis that allows for the preliminary determination of dimensionality. The following is the result of the static correction applied to the AMT data, based on Line 1 from the geological map of the Lembang Fault, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04 (Figure 4) :

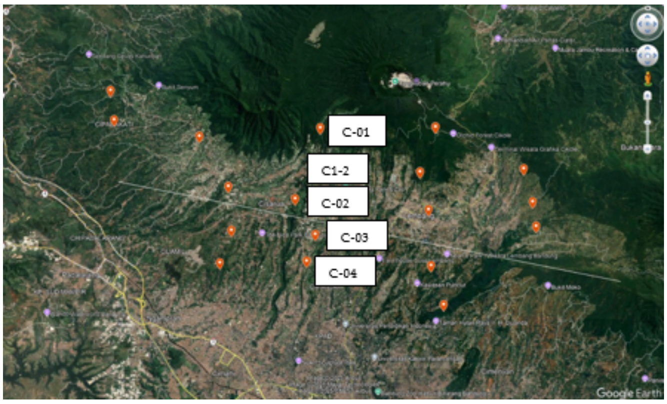

Figure 2. Line 1 Area of Lembang Fault , consisting of five stations: C-01, C1-2, C-02, C-03, and C-04.

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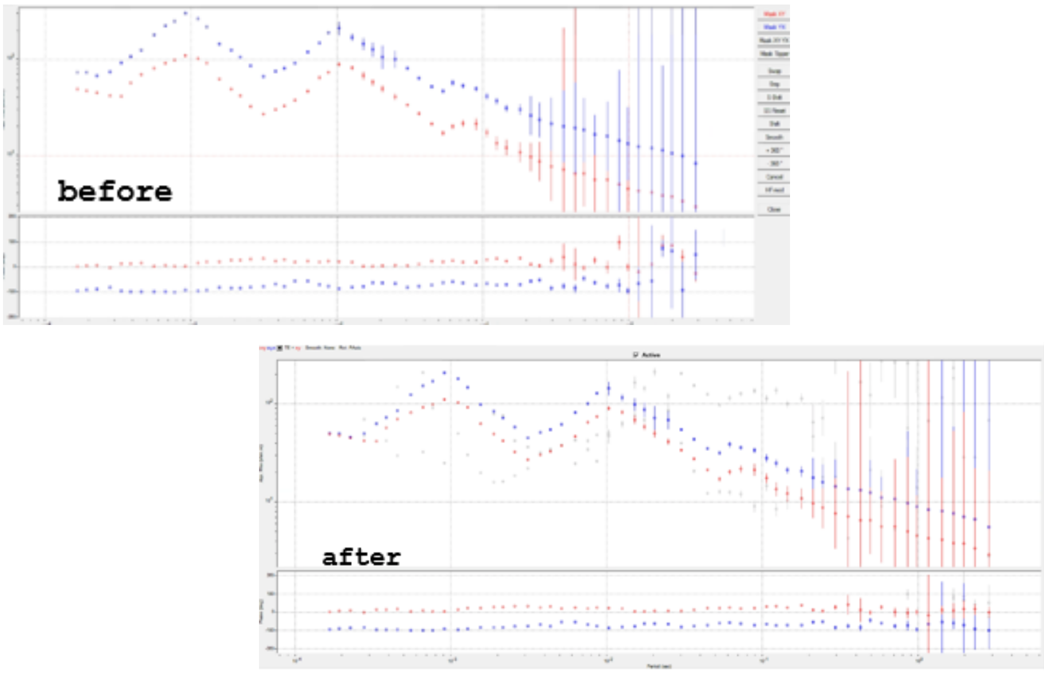

Figure 3. One example of a method for performing static correction on AMT (Audio-Magnetotelluric) data.

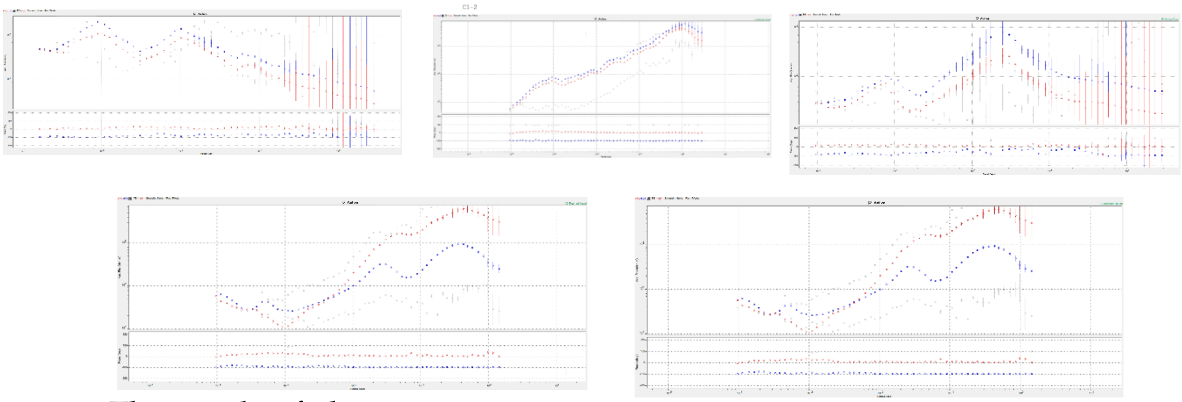

Figure 4. The result of the static correction applied to the AMT data, based on Line 1, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04.

Meanwhile, the results of the phase tensor analysis are shown in the following figure (Figure 5) :

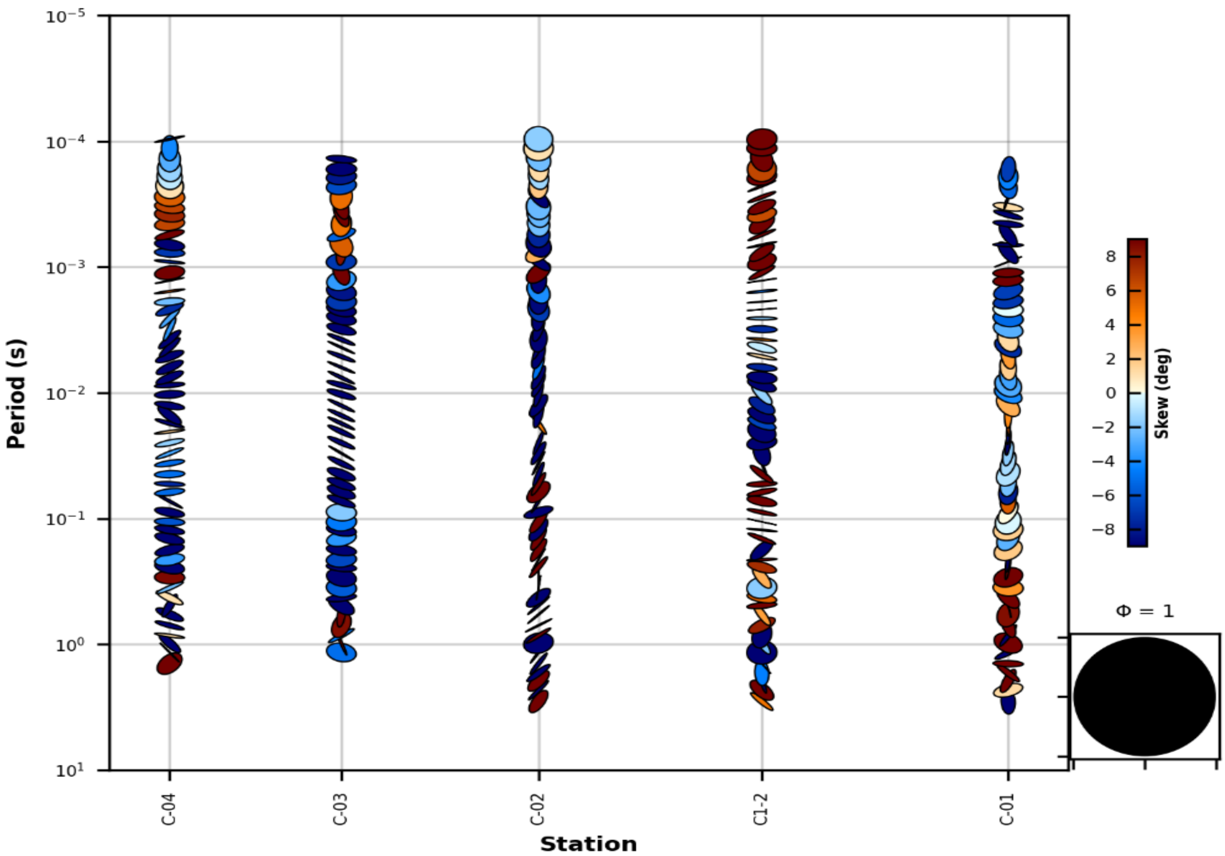

Figure 5. The result of phase tensor analysis from AMT data, based on Line 1, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04.

In Figure 5, the phase tensor across all data from the low period range (10^{-4} s), medium (10^{-2}), and high period (10^{1} s) shows a dominant symmetric ellipses, and also presents color mapping based on the skew angle values ($-8° < \beta < 8°$), which are associated with intermediate depths, where the major and minor axes are not equal ($\Phi_{max} \neq \Phi_{min}$), indicating a tendency toward 2D dimensionality with a consistent geoelectrical strike direction. This is also associated with 2D characteristics, namely variations in resistivity with depth and laterally.
Then, the geoelectrical strike is examined by plotting a rose diagram. This is done to determine the orientation of subsurface structures and conductivity, which are used for rotating the AMT data. Figure 6 below shows the results of the geoelectrical strike :

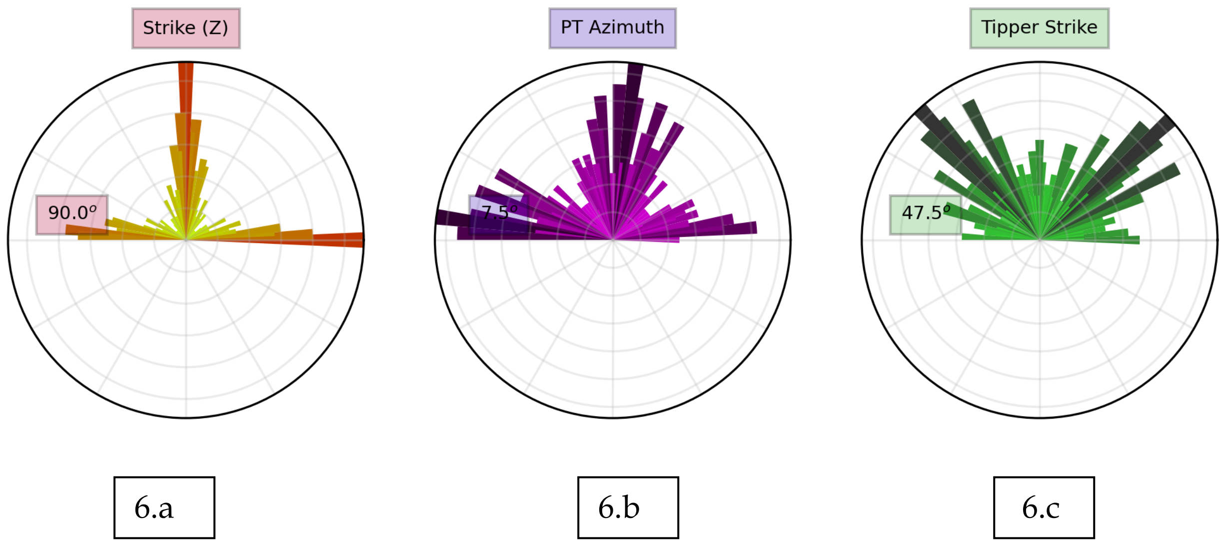

Figure 6. The result of geoelectrical strike analysis from AMT data, based on Line 1, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04.

In Figure 6.a, the result of strike (Z) shown directed to the left, with a reddish-yellow color, represents the dominant horizontal electric field direction based on the impedance tensor (Z). From its figure shown the dominant structure, with a value of W90°E which is indicates that the structure trends in an west to east direction. The red color indicates the direction that appears most frequently or dominates across all measured frequency periods. Meanwhile, the azimuthal phase tensor in Figure 6.b, shown in purple at the center position, indicates the direction of distribution anisotropy of the phase tensor, which is generally more stable against distortion and is often used as an alternative reference for strike direction. Based on figure (6.b) above, The distribution value is 7.5^0, indicating that the distribution is nearly symmetrical with a dominant direction close to 0°/180°, which is almost aligned with the Z strike direction but with a slight rotation. This may suggest the presence of local variation effects or galvanic distortion. As for the tipper strike direction (Figure 6.c), it is oriented to the left and shown in green colors, representing the Tipper vector (T), which is the ratio between the vertical (Hz) and horizontal (Hx) components of the magnetic field. This analysis is used to assess the direction of lateral resistivity contrast in the subsurface structure. In Figure 6.c, the Tipper Strike value is 47.5^0, indicating a strong lateral contrast in that direction.

After the data were rotated and the survey lines were adjusted based on Geoelectrical strike analysis, a 2D inversion was performed using the Nonlinear Conjugate Gradient (NLCG) approach. This inversion method applies a differential function within the objective function to minimize outliers, aiming to produce an optimal model, thus a sensitivity analysis of the model inversion parameters was required. The results of the parameter inversion are presented in the L-curve shown in Figure 7 below :

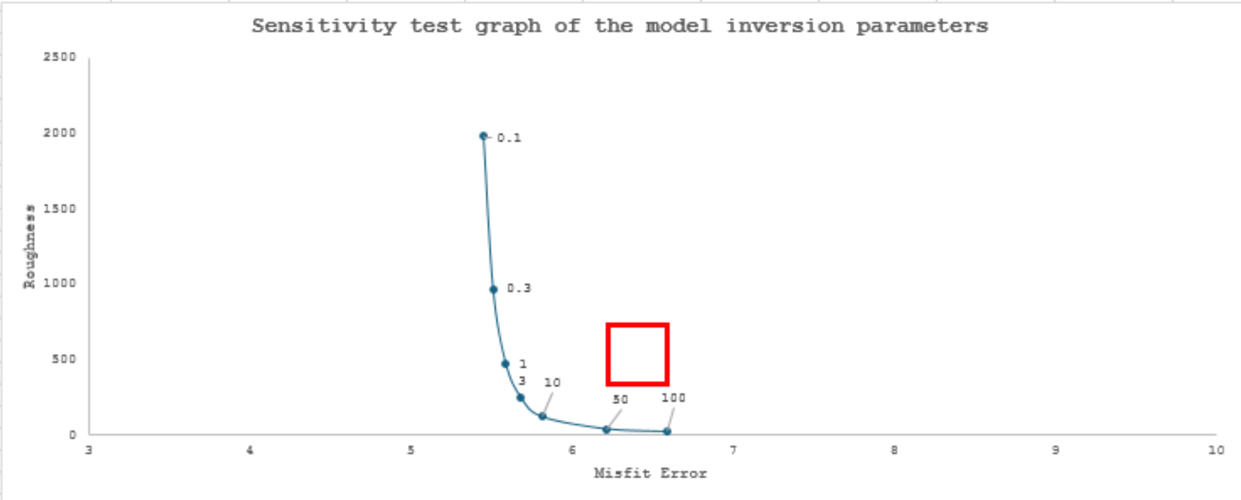

Figure 7. The result of Sensitivity test graph of the model inversion parameters

Based on Figure. 7 above, It can be observed that the RMS misfit value changes significantly. The optimal parameter inversion occurs at tau = 3, with an RMS misfit of 5.68 % and a roughness value of 254.6. This indicates that although a certain level of roughness remains, the low RMS misfit value suggests that the 2D inversion modeling can be performed effectively.

Subsequently, 2D inversion modeling was carried out for the AMT data, based on the parameter inversion value at tau = 3. In this 2D inversion modeling, the observed pseudosection data were also compared with the model response. With the support of the Lembang Fault geological map, the 2D AMT inversion results along line 1, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04 reveal the following features of the Lembang Fault geological structure (Figure 8) :

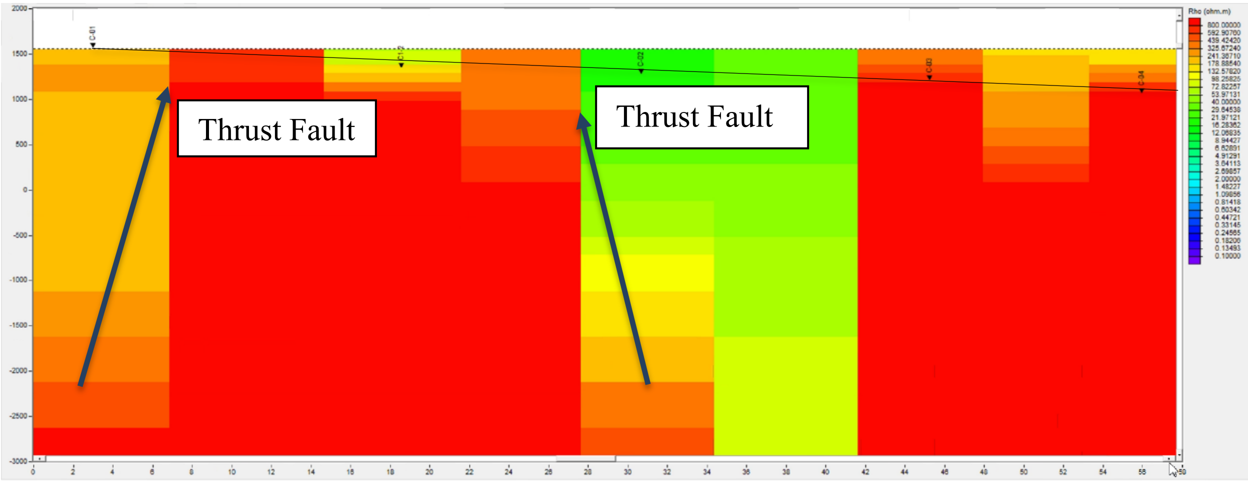

Figure 8. The 2D AMT inversion results along line 1, consisting of five stations: C-01, C1-2, C-02, C-03, and C-04

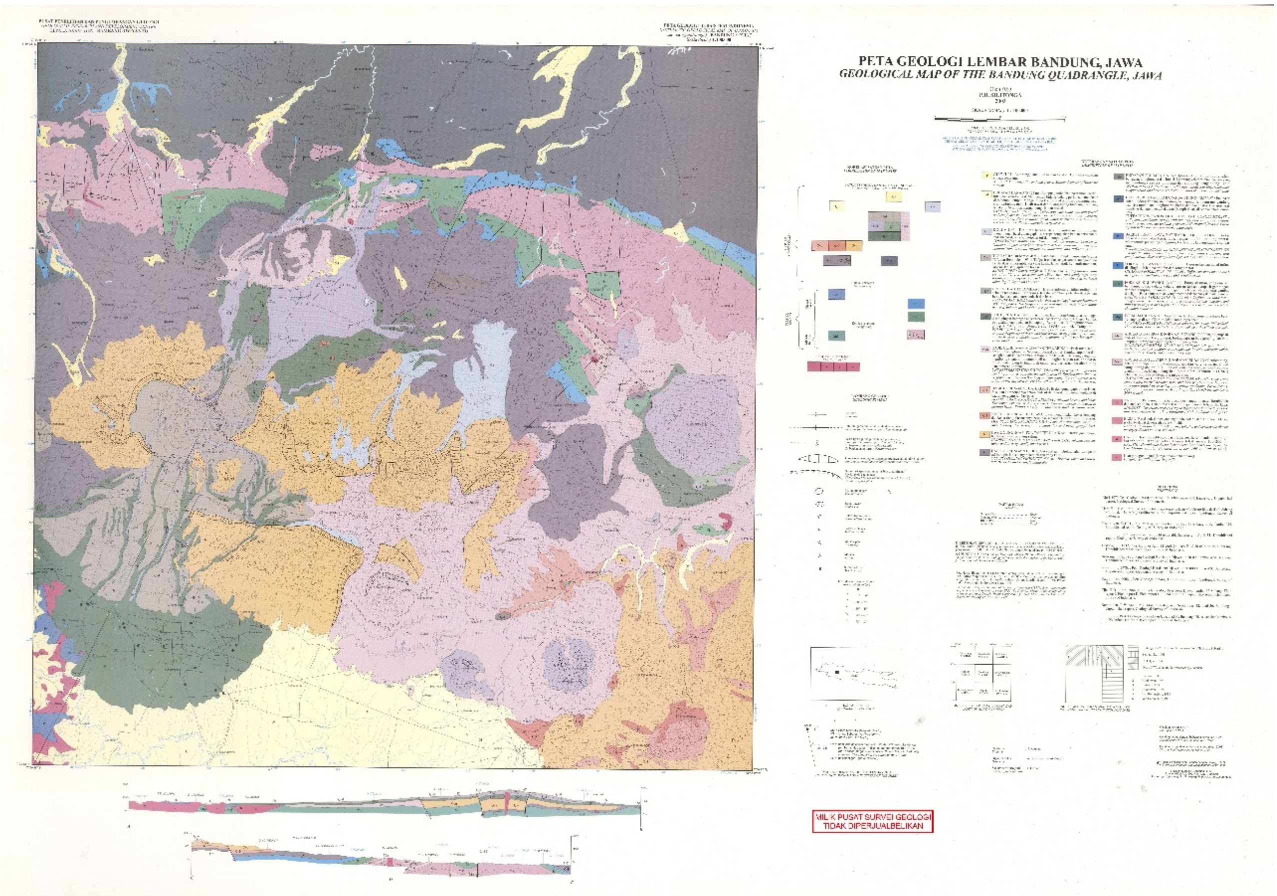

Figure 9. The Geological map of Lembang Fault

Based on Figure 8 dan Figure 9 above, This is Line 1, which consists of five AMT measurement points and is oriented in an West to East direction. A significant contrast in the anomaly is observed, which suggests the existence of a fault zone within the inversion model. The model reveals two thrust faults that were identified at approximately 3250 metres depth, at point C-01, trending Southwest–Northeast. Than another fault is located at point C-02, oriented Southeast–Northwest with approximately 3125 metres depth. The resistivity variation is predominantly characterized by high values. At points C-01, C-02, and C1-2, the resistivity ranges from moderate to high, approximately 53.97 to 800 ohm-metres. Similarly, points C-03 and C-04 also exhibit high resistivity values, ranging from 241.367 to 800 ohm-metres. These high resistivity values are likely dominated by volcanic rocks formation. In addition, this area is associated with magmatic activity, as the Lembang Fault zone is located near an active volcano.

CONCLUSION

Based on the discussion above, the following conclusions can be drawn :

1) The magnetotelluric (MT) method is a geophysical technique that utilizes naturally occurring electromagnetic waves originating from the Earth to measure the intensity of the Earth's electric field (E) and magnetic field (H). This is achieved by simultaneously measuring variations in E and H as a function of frequency to determine the subsurface resistivity structure. In this study, field data acquisition was conducted using the AMT (Audio Magnetotelluric) method at the Lembang Fault. This measurement aims to construct a two-dimensional model of the fracture movement patterns and orientations within the fault zone.
2) Based on the results of the study, the calculated phase tensor values were obtained and subsequently analyzed to determine the direction of the geoelectrical strike. These data were then subjected to 2D inversion.
3) The results of dimentionality from phase tensor analysis indicate that the model parameters are predominantly characterized by a symmetric ellipse (2D) form.
4) Based on the geoelectrical strike analysis, the subsidiary movement of the Lembang Fault is predominantly oriented in a West to East direction, with a strike angle of 90° or W90^0E.
5) From the 2D inversion model supported by the geological map, a significant contrast in the anomaly is observed, which suggests the existence of a fault zone within the inversion model. The model reveals two thrust faults that were at point C-01 with 3250 metres depth, trending Southwest–Northeast, and another fault is located at point C-02, oriented Southeast–Northwest with 3125 metres depth. High values predominantly characterize the resistivity variation. At points C-01, C-02, and C1-2, the resistivity ranges from moderate to high, approximately 53.97 to 800 ohm-metres. Similarly, points C-03 and C-04 also exhibit high resistivity values, ranging from 241.367 to 800 ohm-meters. These high resistivity values are likely dominated by volcanic rocks formation. In addition, this area is associated with magmatic activity, as the Lembang Fault zone is located near an active volcano.

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REFERENCES

Becken, M., Ritter, O., Bedrosian, P. A., & Weckmann, U. (2011). *Correlation between deep fluids , tremor and creep along the central San Andreas Fault*. https://doi.org/10.1038/nature10609

Caldwell, T. G., Bibby, H. M., & Brown, C. (2004). *The magnetotelluric phase tensor*. 457–469. https://doi.org/10.1111/j.1365-246X.2004.02281.x

Febriani, F. (2014). *Subsurface structure of the Cimandiri fault zone, West Java, Indonesia*.

Hendra, G. (2013). *Magtetotulleric Method*. Program Studi Teknik Geofisika, FTTM ITB, Bandung.

Maharani, L., Paembonan, A. Y., & Irawati, S. M. (2023). *Dimensionality Analysis Using Phase Tensor and 2D Modeling of the Camas Prairie Geothermal System, Idaho, USA Based on Magnetotelluric Data*. *9*(3), 167–175.

Rodi, W. L., Rodi, W., & Mackie, R. L. (2016). *Nonlinear Conjugate Gradients Algorithm For 2-D Magnetotelluric Inversion Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion*. *January 2001*. https://doi.org/10.1190/1.1444893

Simpson, F., & Bahr, K. (2005). Practical magnetotellurics. *Practical Magnetotellurics*, *9780521817*(July), 1–254. https://doi.org/10.1017/CBO9780511614095

Syech, R., Juandi, & Sugianto. (2017). *Numerical Modeling of a Natural Electromagnetic Wave Measurement Instrument for Mineral Exploration Using the Finite Element Method* (pp. 7–11).

Ujihara, N., Honkura, Y., & Ogawa, Y. (2004). *Electric and magnetic field variations arising from the seismic dynamo effect for aftershocks of the M7 . 1 earthquake of 26 May 2003 off Miyagi Prefecture , NE Japan*. *May 2003*, 115–123.

W. M. Telford, L. P. Geldart, R. E. S., & D. A. Keys. (1976). Applied Geophysich. *Geological Magazine*, *113*(5), 492–493. https://doi.org/10.1017/S0016756800050858