Two-Dimensional Inversion Magnetotelluric Investigation of the Pariangan Geothermal Field, Indonesia

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Abstract. Pariangan geothermal field is located in Tanah Datar District, West Sumatera Province, Indonesia. The structure developed in this region is influenced by a large fault that extends through Sumatera from Banda Aceh to the Gulf Semangko in Lampung and also the pattern of radial faults that follow the development of Complex Marapi Volcanism. This study is aimed at delineating the shallow as well as deeper conductive anomalies related to the geothermal system in the Pariangan area. Dimensionality analysis showed a two-dimensional (2D) behavior for the data, and therefore 2D inversion was performed. The result of magnetotelluric (MT) data processing indicates a low resistivity (<15 Ω.m) distribution at depths of 1300-3000 meter, which is interpreted as the caprock. Reservoir rock is indicated by the medium resistivity (15-93 Ω.m) at depths of 1200-3200 m. Below the reservoir the deep reaching conductive anomaly is interpreted as circulating hot fluids which heat up the fluids in the reservoir due to the subduction process. Type of alteration developed in research area are dominated by argillic type characterized by the presence of illite, kaolinite, montmorillonite, dickite, and halloysite; propylitic type characterized by the presence of chlorite, epidote and, quartz; and phyllic type characterized by the presence of sericite, quartz, and chlorite. Basement rock zone is indicated by the high resistivity (93-1000 Ω.m) at the depths of 1500-6000 m. MT in this study shows a powerful geothermal exploration tools because of its sensitivity to image hot saline fluids as zones of high conductivity.

Keyword: Basement rock, Caprock, Complex Marapi Volcanism, Magnetotelluric, Reservoir Rock, Two-dimensional.

1. Introduction
Tectonic processes that occur in Sumatera are controlled by three major fault systems. The first fault system is thrust fault (TF) due to subduction zone, the second fault system is Sumatera fault zone (SFZ) and the third fault system is Mentawai fault (MF). SFZ is a sliding fault with a rightward movement associated with a series of valleys along the row of hills. SFZ are characterized by volcanism and the flow of high-level hydrothermal solutions associated with extension and compressional regimes. And this fault system is interpreted as the magmatic path of the Sumatera tectonic. This has led to the emergence of geothermal manifestations along the path of the SFZ [1]. Geothermal of Pariangan which is administratively located in the Tanah Datar district, West Sumatera Province (Figure 1) was located in the SFZ and active volcanoes, which range from Sabang in the north to Semangko Bay in the south [2].
The parameters measured of magnetotelluric (MT) from natural electromagnetic (EM) signals are magnetic field and electric field in orthogonal directions at the Earth’s surface. While the parameters analyzed are apparent resistivity and phase.

Figure 1. Map of West Sumatera, Pariangan is area in this study indicated by red square

2. Geology Structure

The geological structure that developed in this area was greatly influenced by the tectonic activity of the SFZ and also the radial fault pattern following the development of the complex Volcanism of Marapi. The main pattern of fractures and fault is northwest (NW)-southeast (SE). The second order is the alignment of the southwest (SW)-northeast (NE) and the main fault antitetic. Third order in the form of fractures which are directed almost North and South [2].

3. Data Analysis and Methods

MT method is used to investigate subsurface based on rock conduciviy value depends on the amount of frequency size [3]. The EM wave fluctuations range frequencies of $10^{-3}$-$10^{5}$ Hertz depending on their origin [4]. This can be determined based on how much penetration of EM wave penetrates the subsurface which is formulated as follows [5]:

$$ p(T) = \left(\frac{r}{\pi \sigma \mu}\right)^{1/2} $$

Equation can be approximated as:

$$ p(T) = 500\sqrt{\rho_a T} $$

with $\rho_a$ is apparent resistivity, $\sigma$ is rock conductivity, and $\mu$ is permeability and $p(T)$ is penetration EM wave.

The impedance ($Z$) is a measure characteristic that are analyzed as a function of the MT responses from EM wave which can be written in the following equation [5]:

$$ \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \begin{pmatrix} H_x \\ H_y \end{pmatrix} $$

(3)
Figure 2. Polarizations in MT with two zones of different vertical conductivity structure by Tranverse Electric (TE mode) and Tranverse Magnetic (TM mode) [6].

Based on Figure 2, TE mode is a EM field component which is electric field parallel to the electric strike depends only on magnetic field components perpendicular to the strike. The equation can be written as follows [6]:

\[
\frac{\partial E_x}{\partial y} = \frac{\partial B_z}{\partial t} = i\omega B_z \\
\frac{\partial E_x}{\partial z} = \frac{\partial B_y}{\partial t} = -i\omega B_y \\
\frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} = \mu_0 E_x
\] (4)

TM mode is a EM field component which is electric field perpendicular to strike depends only on magnetic fields parallel to the electric strike. The equation can be written as follows [6]:

\[
\frac{\partial E_x}{\partial y} = \frac{\partial B_z}{\partial t} = i\omega B_z \\
\frac{\partial E_x}{\partial z} = \frac{\partial B_y}{\partial t} = -i\omega B_y \\
\frac{\partial B_z}{\partial y} - \frac{\partial B_y}{\partial z} = \mu_0 E_x
\] (7)

Root mean square error (nRMS) is obtained static shift correction and two-dimensional inversion process from the response of the MT model with \( \tilde{r} \) is the residual between calculated and observed data, can be written [8]:

\[
nRMS = \sqrt{\frac{1}{N} \sum_{i=1}^{N} \tilde{r}_i^2}
\] (10)

In two-dimensional inversion process, general form of relationship between data and model parameters are searched can be written with [9]:

\[
d = F(m) + e
\] (11)

With \( F \) is forward function which theoretically predicts \( d \) (data) for give \( m \) (model), \( \lambda \) is regularization parameter and \( e \) is error function. A suitable model is usually defined as one minimizing the objective function \( \Psi(m) \) measured by the difference between \( d \) and \( F(m) \). Damped least square requires specifications regularization parameters. This parameters minimize data mismatch respect forward model and stability functions \( \Omega(m) \).

\[
\Psi(m) = (d - F(m))^T V^{-1} (d - F(m)) + \lambda m^T L^T L m
\] (12)

With \( V \) is vector covariance matrix, \( L \) is linear operator (smoothness).
Data measured in the Geothermal Field which are directed SW-NE were 9 measurements points, cutting (perpendicular) to the regional structure of the study area with distances between measuring points around 1200-1500 m [2]. Processing of MT data is done from raw data in the form of time series. The initial principle processing the data is to change the time domain data into frequency domain by FFT (Fast Fourier Transform) method. The transformation process to frequency domain is done because physical parameters such as impedance, apparent resistivity, and phase are frequency functions. After that, robust processing to damped the noise and make the smooth curves by editing process. We can calculate the value of impedance, apparent resistivity and phase. Then a static process and processing two-dimensional inversion modelling for the subsurface model of the measurement results (calculate and observation data).

4. Results and Discussion

The editing process aims to eliminate the noise signal and get the smooth curves. Curves the match the trendline during observation will describe the subsurface conditions. This process result by FFT in robust processing form high frequency (.MTH) and low frequency (.MTL) shown in Figure 3.

![Figure 3. Cross Power Selection of measurement points MTPR-33 Line 4](image)

Static Shift Correction can be done with the smoothing curve process. The data entered is the editing result data apparent resistivity and phase respect to frequency that is already in the format *.edi. This correction aims to obtain smooth data apparent resistivity and phase respect to period and damped the amount of noise due to influence of subsurface topography. Based in the Figure 4, showed TE+TM calculate dan observation data coincide with each other indicating the value of noise is getting smaller with rms 1.4374.

![Figure 4. Comparison Static Correction Results Of TE and TM Calculate and Observation of measurement points MTPR-33 on Track 4](image)
Two-dimensional inversion model is a model that describes the investigation of the subsurface structure conductivities laterally and horizontally. The color represents the resistivity value and the type of rock concerned in the geothermal system. After two-dimensional inversion modeling obtained results from inversion with a value of 2.0951 error rms as shown in Figure 5. Distribution of Track 4, shows low resistivity <15 $\Omega \cdot m$ at depth of 1300-3000 meters below the measurement point MTPR-32, MTPR-33, MTPR-34, MTPR-35 indicated as Caprock zone. The value of this type of low resistivity is estimated to be associated with rock products of Complex Marapi Volcanism in the form of lava and pyroclastic falls. Medium resistivity ranges from 15-112 $\Omega \cdot m$ at depth of 1200-3200 meters below the measurement point of MTPR-35 and MTPR-34 which is interpreted as a reservoir zone which is estimated to be associated with volcanic product rocks from Complex Marapi Active Volcano. High resistivity ranges from 112-1000 $\Omega \cdot m$ at depth of 1500-6000 meters which is interpreted Basement rock. High resistivity is thought to be associated with metamorphic rocks.

5. Conclusions

Low resistivity values <22 $\Omega \cdot m$ are interpreted as caprock zones (red to yellow). The caprock zone has a low resistivity type (conductive) because in this zone there are impermeable rocks, so that the fluid is trapped in this stamp both physically and minerals. Medium resistivity ranging from 22-112 $\Omega \cdot m$ (green color) is interpreted as a reservoir zone. The reservoir zone has permeable rock because the fluid in this zone evaporates as a result of its position closer to the heat source. While the blue color is interpreted as impermeable zone which is suspected as metamorphic rock which acts as basement rock from the study area with high type of resistivity ranging from 112-1000 $\Omega \cdot m$.

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Acknowledgments

First, praises and thanks for the presence of the God, the Almighty, the Lord of the Worlds for the abundance of His mercy and guidance, the author can be complete the research successfully. Gratefully acknowledge the Resources Center for Mineral, Geothermal and Coal which is located in Bandung, West Java for the opportunity given to publish this paper at once to Mr. Wiwid Joni, S.Si, MT as mentor. Especially to Mr. Sabrianto Aswad, S.Si, MT and Mrs. Dra. Maria, M.Si as a supervisor provide knowledge and motivation to the author. And most importantly, both parents the writer who always gives prayers and endless motivation for the author.