



Investigation of Geothermal Using Magnetotelluric Method in Babakan Bogor, Bengkulu Province, Indonesia

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Abstract - Bengkulu Province, due to be crossed by Bukit Barisan Mountains has relatively large geothermal reserves. This study aims to investigate the geothermal reserves in Babakan Bogor Village, Kepahiang Regency, Bengkulu Province. The magnetotelluric (MT) method with electric and magnetic sensors was used to record data in the fields. The electric sensor consisted of three porous pots, two of which were placed horizontally (E_x , E_y) and the other one vertically (E_z) as the ground. Magnetic sensors with two coils were placed horizontally (H_x , H_y) and one vertically (H_z). The data obtained in the field are in the form of rock resistivity values which are correlated with geothermal potential, so that the reservoir could be determined. Data recording in the fields used low frequencies, *i.e.* 128 Hz. Data processing was done using MAPROS software to convert time-series data to EDI file types. Input data in the MAPROS software is in the form of apparent resistivity *vs.* depth values. Furthermore, an inversion was carried out to obtain the true resistivity value as the output of the software. ZONDMT1 and ZONDMT2 were used to model the resistivity values in one dimension (1D) and two dimensions (2D). The results showed that there were geothermal reserves in the Babakan Bogor Village, Kepahiang Regency, at a depth of 1,500 to 5,000 m.

Keywords: geothermal, magnetotelluric, electric sensors, magnetic sensors, resistivity, Bengkulu

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INTRODUCTION

Background

In the future, geothermal could become the main choice of energy source to meet the energy needs in Indonesia. It is due to some reasons such as the very large geothermal reserves, approximately 29,000 MW (ESDM, 2016), and that geothermal energy is environmentally friendly (Setyaningsih, 2011). Until 2030, Indonesia needs

an additional energy supply of 35,000 MW to meet the needs of industry and households. Such large energy needs must be met from fossil energy and nonfossil energy, such as geothermal. Since fossil energy reserves are decreasing, the chance of meeting the energy need from geothermal is very large. Geothermal is renewable energy, so it can be used on a sustainable basis at a low cost, affordable by all economic classes of society. The 7th goal of the Sustainable Development

Goals is to maintain clean and affordable energy availability. The choice of geothermal energy to fulfill the 7th goal is very promising, because the geothermal reserves are large and investment on this energy is very profitable.

The Province of Bengkulu is one of the provinces on Sumatra Island, Indonesia, crossed by the Bukit Barisan Mountains. According to the structural geological theory, the Bukit Barisan Mountains were formed by the subduction pressure of the Indo-Australian Tectonic Plate on the Eurasian Tectonic Plate called the volcanic arc (Zulkarnain, 2011). This subduction pressure resulted in an elongated fracture called the Sumatran Fault (Kerry, 2000). This fault magma seeps form geothermal reservoirs around the fault (Hirofumi *et al.*, 2010). One of these reservoirs is located on a slope of Mount Kaba, Kepahiang Regency, precisely in Babakan Bogor Village (Lusi, 2017), and Lemau Village, in Lebong Regency. The map of the studied area and magnetotelluric data points are shown by the administrative map in Figure 1.

The source of the geothermal reservoir is known by applying the magnetotelluric (MT) method (Heny, 2018). With this method, a researcher can reach the geothermal sources, up to a depth of 10 km below the earth surface. With this deep range, the MT method is the best choice to determine the potential of geothermal resources of an area. The novelty of this study is the use of low, medium, and high frequency bands, namely 128 Hz, 2048, and 4096 Hz, so that the depth penetration range can be covered from shallow to deep level.

Theoretical Framework

Geothermal energy is stored energy in the form of hot water or hot steam under certain geological conditions and depths in the earth crust (Grant and Bixley, 2010). In Indonesia, the geothermal reserves are very large, *i.e.* 29,038 MW, sufficient to meet energy needs in the future (Andiesta *et al.*, 2014). In this country, the geothermal reserves are located in western Sumatra, Maluku,

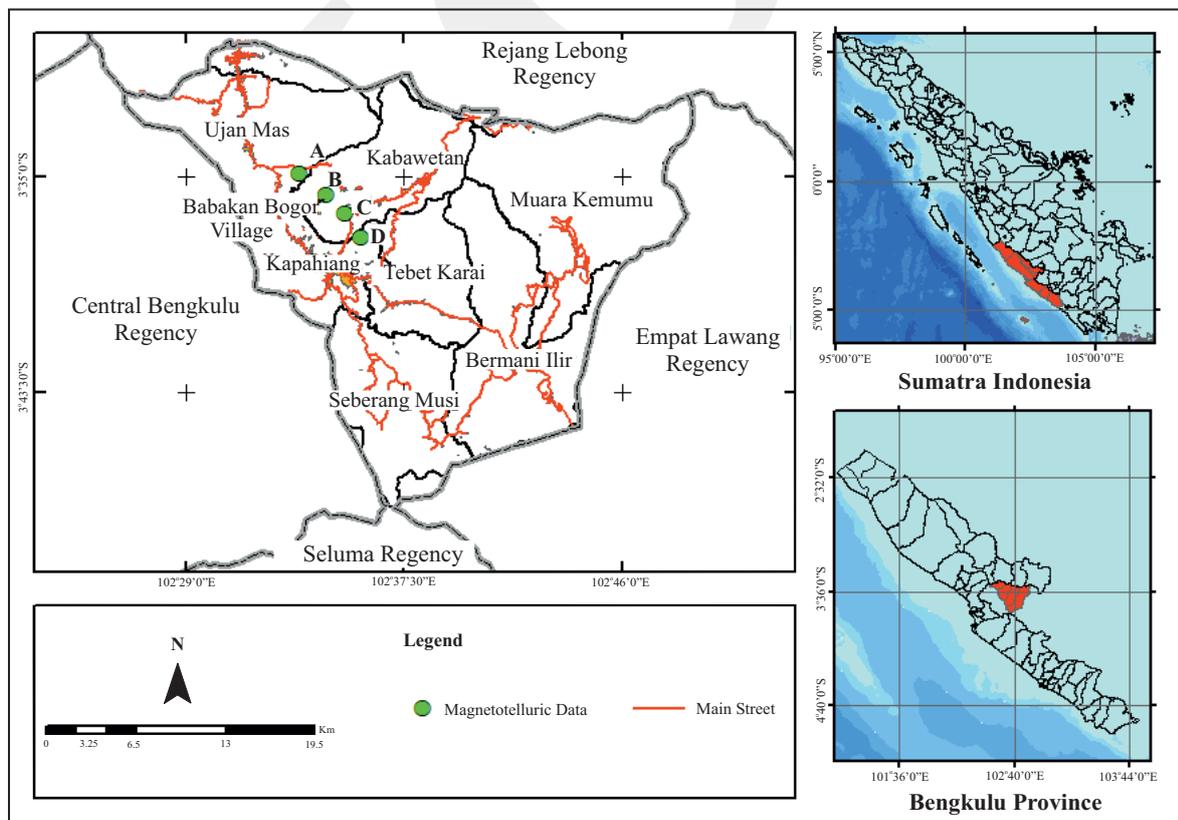


Figure 1. Administrative map of the studied areas and magnetotelluric data points.

Southern Java, Bali, Nusa Tenggara, Maluku, and Sulawesi (Saptadji, 2001). On the Sumatra Island, geothermal reserves are produced by the Bukit Barisan Mountains (Bambang *et al.*, 2010), which cross the Bengkulu Province, so this province has geothermal reserves. The geothermal system in Indonesia, especially in the Bukit Barisan area, is generally a hydrothermal system that has a temperature of more than 225 °C (Dickson and Fanelli, 2003), which is very potential for power generation. The existence of geothermal is often known by the presence of hot springs on the surface of the earth.

Basic Principles of MT Method

MT is an electromagnetic geophysical survey method using electromagnetic (EM) systems originating from natural sources with frequencies of less than 1 Hz from current systems in the ionosphere, magnetosphere, and electrical storms in the atmosphere (Akmam, 1997). This MT method can be used to determine the resistivity of subsurface rocks by measuring the magnitude of the electric and magnetic fields for various frequencies. The MT method is based on the concept that waves originating from the source will be emitted to all directions, and when they reach the surface some is reflected and some are transmitted. If the transmitted wave hits an anomaly in the form of a conductive material it will make a field which is then recorded by the receiver. Because there are some reflected waves, the fields recorded at the receiver are the total fields, *i.e.* the primary field that originates from the source and the secondary field that comes from induction by an anomaly.

The principles of EM waves can be explained by Maxwell Equation, which states that any change in the H magnetic field will cause an electric field of E or vice versa. An EM field can be expressed in four Maxwell that shows the equation (1) - (4) (Zonge and Hughes, 1988):

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \dots\dots\dots(1)$$

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \dots\dots\dots(2)$$

$$\nabla \cdot \mathbf{D} = \rho_c \dots\dots\dots(3)$$

$$\nabla \cdot \mathbf{B} = 0 \dots\dots\dots(4)$$

Where:

- E** is electric field intensity (V / m),
- B** is magnetic flux density (Wb / m²),
- H** is magnetic field intensity (A / m),
- J** is electric current density (A / m²),
- D** is electric flux density (C / m²), and
- ρ_c is electric charge density (C / m³).

The equations connecting the physical properties of the medium with the fields that arise in the medium are shown in equations (5) to (7) :

$$\mathbf{D} = \varepsilon \mathbf{E} \dots\dots\dots(5)$$

$$\mathbf{B} = \mu \mathbf{H} \dots\dots\dots(6)$$

$$\mathbf{J} = \sigma \mathbf{E} \dots\dots\dots(7)$$

Where:

- ε is electrical permittivity (F / m),
- μ is magnetic permeability (H / m), and
- σ is medium conductivity (S / m).

If it is assumed that the earth has homogeneous isotropic properties (Sharma, 1997), the physical properties of the medium do not vary with time, and there is no source of charge in the medium being examined, then Maxwell Equations are present in equation (8) to (11) :

$$\nabla \times \mathbf{E} = -\mu \frac{\partial \mathbf{H}}{\partial t} \dots\dots\dots(8)$$

$$\nabla \times \mathbf{H} = \sigma \mathbf{E} + \varepsilon \frac{\partial \mathbf{E}}{\partial t} \dots\dots\dots(9)$$

$$\nabla \cdot \mathbf{E} = 0 \dots\dots\dots(10)$$

$$\nabla \cdot \mathbf{H} = 0 \dots\dots\dots(11)$$

By performing curl operations on equations (Grant and Bixley, 2010; Andiasta *et al.*, 2014) and substituting the quantities, there comes wave equations for the electric and magnetic fields. Furthermore, by applying the vector identity, there comes the equations for electric field and

magnetic field wave as a function of time and distance (12) and (13) as follows :

$$\nabla^2 \mathbf{E} - \sigma\mu \frac{\partial \mathbf{E}}{\partial t} - \varepsilon\mu \frac{\partial^2 \mathbf{E}}{\partial t^2} = 0 \dots\dots\dots(12)$$

$$\nabla^2 \mathbf{H} - \sigma\mu \frac{\partial \mathbf{H}}{\partial t} - \varepsilon\mu \frac{\partial^2 \mathbf{H}}{\partial t^2} = 0 \dots\dots\dots(13)$$

If variation because of time is expressed in sinusoidal functions, there comes the following equations 14–15 (Grant and West, 1965):

$$\mathbf{E}(\mathbf{r},t) = \text{Re } \mathbf{E}(\mathbf{r},\omega)e^{i\omega t} \dots\dots\dots(14)$$

$$\mathbf{H}(\mathbf{r},t) = \text{Re } \mathbf{H}(\mathbf{r},\omega)e^{i\omega t} \dots\dots\dots(15)$$

where ω = angular frequency ($\omega = 2\pi f$), then we get:

$$\nabla^2 \mathbf{E} = i\sigma\mu\omega \mathbf{E} - \varepsilon\mu\omega^2 \mathbf{E} \dots\dots\dots(16)$$

$$\nabla^2 \mathbf{H} = i\sigma\mu\omega \mathbf{H} - \varepsilon\mu\omega^2 \mathbf{H} \dots\dots\dots(17)$$

Skin Depth, Wave Impedance, And Pseudo Resistivity

By entering the conductivity constant or k , into equations (Kaufman and Keller, 1981; Hadi, 2007), it will be obtained :

$$\nabla^2 \mathbf{E} + k^2 \mathbf{E} = 0 \dots\dots\dots(18)$$

$$\nabla^2 \mathbf{H} + k^2 \mathbf{H} = 0 \dots\dots\dots(19)$$

where:

$$k^2 = \mu\varepsilon\omega^2 - i\mu\sigma\omega = \mu\omega(\varepsilon\omega - i\sigma), \text{Re}(k) > 0 \dots\dots(20)$$

$$k^2 = -i\mu\omega(\sigma + i\omega\varepsilon), \text{Im}(k) < 0 \dots\dots\dots(21)$$

$$k = \alpha - \beta = [-i\mu\omega(\sigma + i\omega\varepsilon)]^{1/2} \dots\dots\dots(22)$$

phase constant α , is formulated as:

$$\alpha = \omega \left[\frac{\mu\varepsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\varepsilon\omega} \right)^2} + 1 \right) \right]^{1/2} \dots\dots\dots(23)$$

attenuation constant β :

$$\beta = \omega \left[\frac{\mu\varepsilon}{2} \left(\sqrt{1 + \left(\frac{\sigma}{\varepsilon\omega} \right)^2} - 1 \right) \right]^{1/2} \dots\dots\dots(24)$$

skin depth δ is defined as:

$$\delta = 1 / \beta \dots\dots\dots(25)$$

wavelength of signal:

$$\lambda = 2\pi\delta \dots\dots\dots(26)$$

conductivity velocity:

$$v = \lambda f \dots\dots\dots(27)$$

In the conductive medium, the amplitude decreases with the decreasing attenuation constant β , whereas the field phase difference depends on the phase constant α . Medium conductivity is an important parameter in determining subsurface structures. The assumption of the quasi-static field can be used if the rock conductivity is sufficiently large. Usually, earth material has conductivity $\sigma > 10^{-4}$ S / m ($\rho < 104 \Omega.m$) and permittivity $\varepsilon < 10^{-11}$ F / m. For frequencies below 100 kHz, σ is much bigger than $\varepsilon\omega$, so the displacement current effect is much smaller and negligible compared to the conduction current. In this case, α equals β , and the constant conductivity k is given by (Zonge and Hughes, 1988):

$$k = (1 - i) \left[\frac{\mu\sigma\omega}{2} \right]^{1/2} \dots\dots\dots(28)$$

Skin depth is the distance of EM wave attenuation in a homogeneous medium, so it becomes 1/e (~37%) of the amplitude on the surface. With the quasi-static approach, the (26) becomes (Zonge and Hughes, 1988):

$$\delta = \left[\frac{2}{\mu\sigma\omega} \right]^{1/2} \dots\dots\dots(29)$$

The skin depth in the conductive medium depends on the permeability of the medium, resistivity, and the frequency of EM waves crossing through the medium. If the permeability value μ equals $\mu_0 = 1,256 \times 10^{-6}$ H/m, and the frequency

($\omega = 2\pi f$) is entered, then (29) becomes (Zonge and Hughes, 1988):

$$\delta = 503 \left[\frac{\rho}{f} \right]^{\frac{1}{2}} \dots\dots\dots(30)$$

Where:

- δ is skin depth (m),
- ρ is homogeneous medium resistivity ($\Omega.m$),
- f wave frequency of EM (Hz).

Wave impedance is defined as the ratio between the electric and magnetic fields. Meanwhile, pseudo resistivity is the measured resistivity on a multilayered medium, which has a different resistivity, and the thickness of the layers is considered homogeneously isotropic. The relationship between pseudo resistivity and wave impedance is stated in this equation (Kaufman and Keller, 1981):

$$\rho_a = \frac{1,27 \times 10^5}{f} \left| \frac{E}{H} \right|^2 \dots\dots\dots(31)$$

Where:

- ρ_a is pseudo resistivity and
- E/H is wave impedance.

Because the earth has heterogeneous resistivity, the actual resistivity is obtained through the inversion method by making models derived from the relationship between the pseudo resistivity and the actual resistivity (Hadi, 2007).

METHODS

The investigation of geothermal energy reserves was carried out through the following stages:

Study of Literature

Literature study was carried out by collecting maps and data from survey reports that have been conducted previously in the area under investigation with the aim of obtaining an overview of the regional geology, the locations where surface

manifestations and volcanic, geological and hydrological phenomena were found in the area under investigation.

Field Surveys

The field surveys consisted of geological, hydrological, and geochemical surveys. The area surveyed at this stage was approximately 5–20 km². The surveys were conducted in: 1) places that have surface manifestations and the surrounding areas, 2) other places that have been determined based on the results of studies on interpretation of topographic maps, landsat images and remote sensing, and on the reports of previous surveys.

Data Analysis and Interpretation

The existing references and the results of the field surveys were analyzed to obtain models regarding regional geology and hydrology in the area to determine the prospective areas that showed signs of geothermal resources. The results of data analysis and interpretation were also used to determine the type, temperature, and rock type of reservoir, and the origin of water sources.

Detailed Geological Surveys

Geological surveys are generally carried out primarily to understand geological and stratigraphic structures, so a detailed geological survey must be carried out over a fairly wide area (Teguh and Farrel, 2016). The geological surveys were done to determine the distribution of rocks horizontally and vertically, the geological and tectonic structure, and the geological history in relation to the formation of geothermal systems, the approximate area of prospective area, and their heat sources, as shown in Figure 2.

Geophysical Surveys

From the results of geological and geochemical surveys, the areas for geophysical surveys were determined. Geophysical surveys were conducted to determine the physical properties of rocks ranging from the surface to a depth of several kilometers below the surface. The data of physical properties of rocks such as resistivity were used to find the area where anomalies

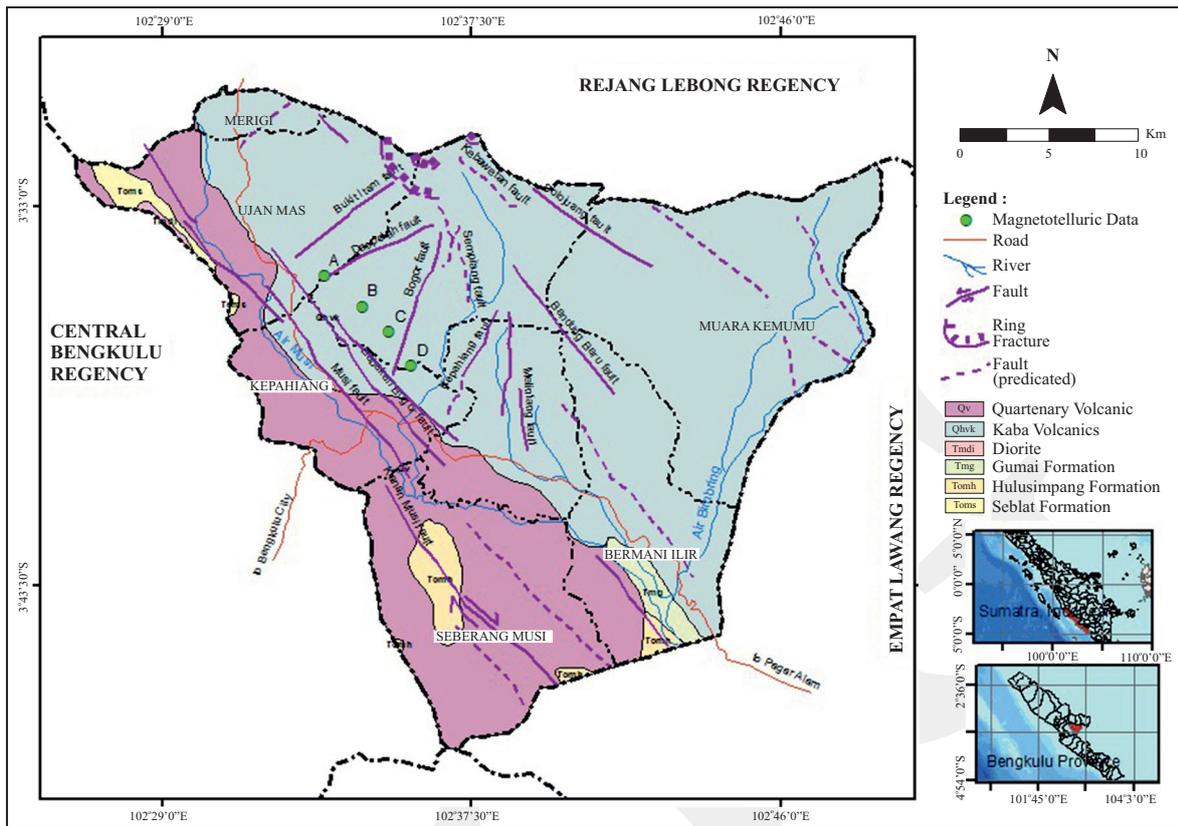


Figure 2. Geological map and magnetotelluric data of Kepahiang Regency, Bengkulu Province (Gaføer *et al.*, 2000 and Hadi *et al.*, 2018).

occur due to geothermal systems. In this survey the MT method was started to be used.

Surveys Using the MT Method

MT method is a passive electromagnetic method that measures the orthogonal components of the electric and magnetic fields on the surface of the earth as shown in Figure 3.

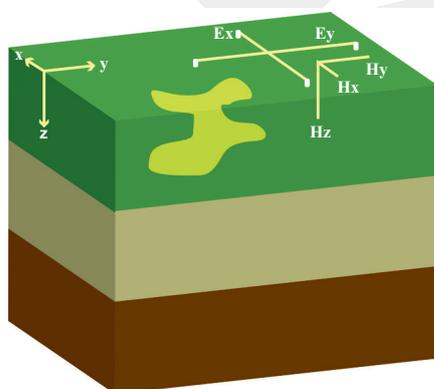


Figure 3. MT arrangement in an internal coordinate system (Rosenkjaer, 2011).

The values of E_x , E_y , H_x , H_y , and H_z can be recorded using a set of MT measuring instruments, consisting of one magnetotelluric, two sets of electrodes, E_x and E_y , and three pieces of magnetometer coils, H_x , H_y , and H_z as shown in Figure 4.

The values of E_x , E_y , H_x , H_y , and H_z recorded in the field were MT data in time series which can

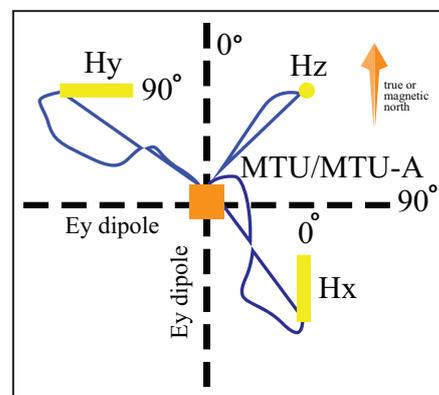


Figure 4. Field layout for a 5-channel MT acquisition system (Phoenix Geophysics, 2009).

be converted into 2D resistivity models through several processing stages, *i.e.* time series, spectra, fast Fourier transform, start processing, and cross power selection to get rho (P) phase. The process of changing data from the time domain to the frequency domain was conducted using the Fast Fourier Transform (FFT) technique. This technique is already available in MAPROS software, so creating functions for FFT is no longer needed. Statistical processing of magnetotelluric data is to reduce data that deviates from the main data pattern, while cross power is a step to modify the curve so that it becomes smooth (Sintia *et al.*, 2015).

The sources of the MT signal are the magnetic fields from inside and outside the earth that have a varying frequency range. The magnetic fields from inside the earth occur due to the movement of the earth mantle against the earth core. Magnetic fields originating from outside the earth are those generated in the atmosphere and magnetosphere (Kadir, 2011).

RESULT AND DISCUSSION

The results of the investigation in Babakan Bogor Village are shown in the time series in Figure 3, the graph model of relationship between resistivity and depth in Figure 4, and the 2-dimensional resistivity contour model in Figure 5. The time-series data of electric fields, E_x0 , E_y1 , and the magnetic fields, H_x2 , H_y3 , and H_z4 (Figure 5) have good quality, because the measurements were taken at deep soil layers, so the data were far from noise. In the MAPROS software, there are facilities to reduce data that deviates from the main data pattern, so that the data processed is only data that has a good quality.

The large data in Figure 5 were obtained from thirteen-hour measurement with a frequency of 128 Hz from a deep layer. During the thirteen-hour measurement with a frequency of 128 Hz, the resulting voltage was stable, from 100 (mV) to -100 (mV). The stable voltage indicates that the data taken at the time of measurement has a

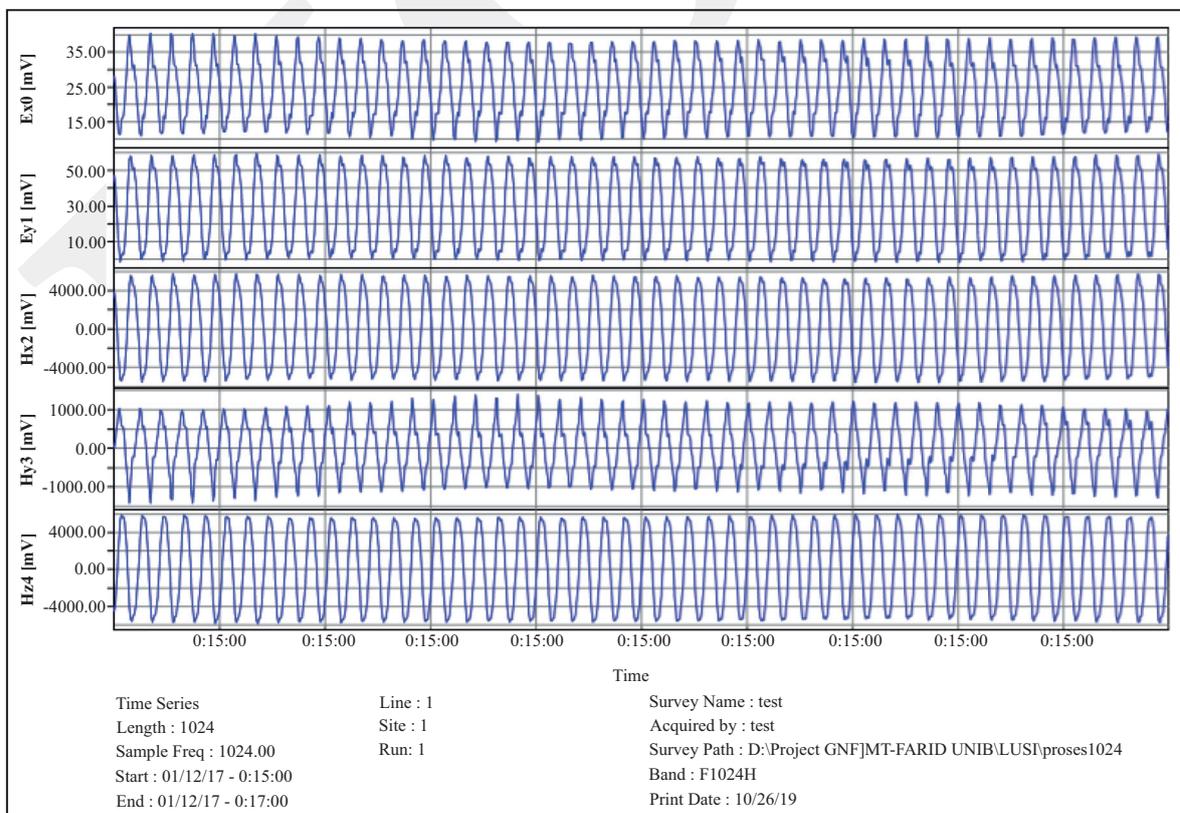


Figure 5. Time series data of electric fields; E_x , E_y , and magnetic fields, H_x , H_y , and H_z from field measurements.

high level of accuracy (Cagniard, 1953). The data in Figure 5 were still raw in the time domain. For further processing, the data must be transformed into the frequency domain using FFT. The next step was to correlate the resistivity values and depths from the ground surface. The relationship between resistivity and depth is shown in Figure 6.

The resistivity and depth graph shows the resistivity values from 10^{-4} Ohm-m to 10^4 Ohm-m and depths of 1,000 to 5,000 m at each measurement sounding, which is shown by the red line. This layer is predicted to be composed of a capstone which is usually located in the depth of 500 m below the earth surface. At a depth of 1,000-5,000 m, where the geothermal reservoir is estimated to be located, the resistivity is moderate (20-200 Ohm-m), while at a depth of 1,500-5,000 m where the heat source is estimated to be located, the resistivity is high (800 Ohm-m). The 2 D resistivity contour models were obtained from data acquisition in the field at each different sounding point. These 2 D resistivity models show the distribution of geothermal energy in the Babakan Bogor Village, Kepahiang Regency.

In Figure 7, the upper part is the apparent resistivity value obtained in the field as a function of depth, while Figure 7 in the middle is the model resistivity value as a function of depth. The results of the inversion between the apparent resistivity values obtained in the field against the model resistivity value will obtain the true resistivity values that are ready to be interpreted. Figure 7 shows 2D resistivity models which indicate that the resistivity value is related to the type of rock. Low resistivity is estimated to be resulted from a caprock with a depth of 500 m, medium resistivity from a geothermal reservoir with a depth of 2,000–5,000 m, and high resistivity from a heat source with a depth of 1,500-5,000 m (Dewashish, 2012; Falae, 2014). The existence of this geothermal potential can be shown by the presence of manifestations that appear on the surface, namely in the form of hot springs located in the Babakan Bogor Village.

The data generated always have noise that can be caused by several factors including the presence of conductives materials, and errors when installing tools. Noise on time series data can be minimized by removing some of the data having noise, so that the quality of data obtained

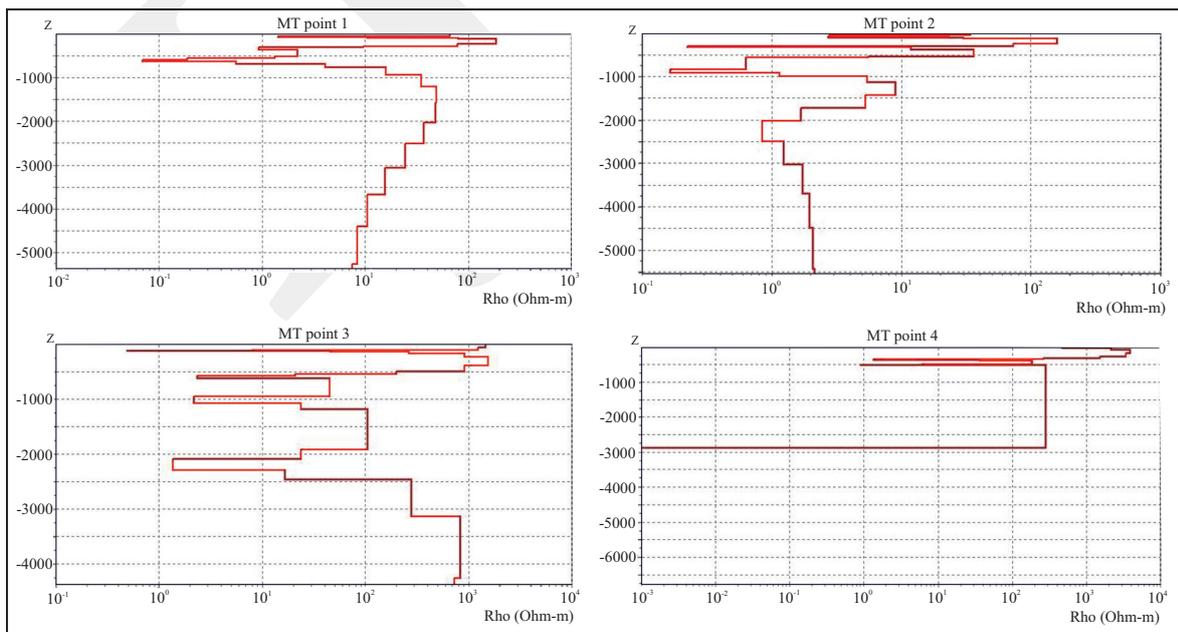


Figure 6. Resistivity values at different depths.

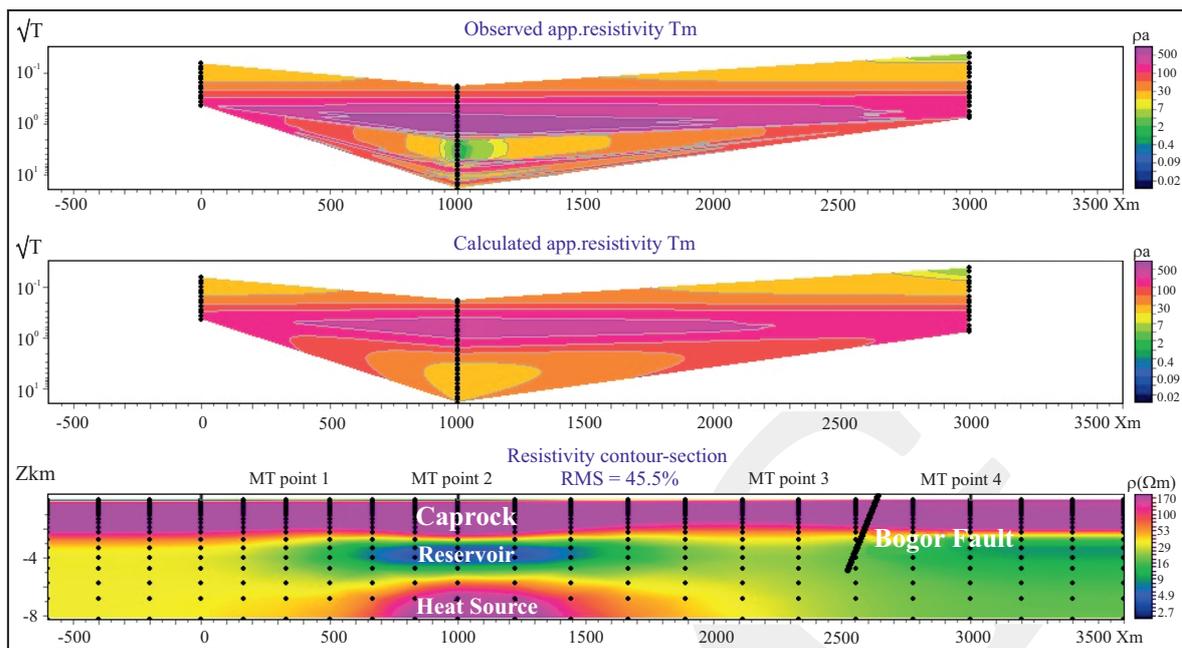


Figure 7. 2-D resistivity models resulted from the data analyses.

is still good. The process of deleting data can be done during the data processing using MAPROS software. Bad data due to noise can be reduced through Robust processing, so that the data obtained in the field are data that have been selected well.

CONCLUSIONS

Geothermal energy reserves in Kepahyang District have very promising prospects. These surveys need to be expanded to give confidence to all parties that there are great reserves of geothermal energy in Bengkulu.

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BOGOR