Geothermal Lithology Identification in Air Putih, Lebong, Bengkulu Using Magnetotelluric (MT) Method

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Abstract *- Lebong is one of the areas located in Bengkulu Province and is passed by the Ketaun Segment fault. The fault causes several locations in Lebong to have manifestations such as hot springs, solfatara, and fumarole. This research aims to identify rock lithology with 2D modeling using the magnetotelluric method. The data acquisition process was carried out using a magnetotelluric device with a low frequency of 128 Hz, a medium frequency of 1024 Hz, and a high frequency of 4096 Hz. The sensor in the recording consists of two sensors, namely electric and magnetic. Based on the field survey, the results obtained are several distributions of resistivity values from low, medium, and high. The acquired data was processed using ZONDMT software to obtain 2D modeling. The results of data processing interpret the resistivity value to depth. There are 8 measuring points in one track with a west-southeast direction. Variations in measured resistivity consist of low, medium, and high resistivity. The distribution of low resistivity values (10-25 Ωm) in this area is identified as the response of the caprock, having a depth of <1.5 km, shown in light blue. The distribution of medium resistivity values (40-150 Ωm) shown in green to yellow is identified as a reservoir zone with a depth of >1.8 km. Rocks with high resistivity values (>300 Ωm) shown in red are identified as hot rock zones. Hot rocks are at a depth of 4-6 km. The range of frequency values on the 2D modeling color scale ranges from 1-800 Ωm. The results of this study can be used as a basis for feasibility studies for local governments to develop geothermal energy projects. By knowing the subsurface characteristics, the potential for geothermal energy reserves in Lebong can be evaluated more accurately.*

Keywords*: Lithology; Magnetotelluric; Air Putih; Lebong Regency*

INTRODUCTION

Geologically Indonesia has many areas with the potential for geothermal natural resources that are quite abundant, this is because Indonesia is located at the junction of three plates namely the indo-australian plate, Eurasia and the Pacific plate characterized by the presence of an active ring of fire (Bahri & Ramadhan, 2022).

One area with geothermal potential is Air Putih, Lebong Regency, Bengkulu province. The Ketaun fault that passes through this area creates geothermal manifestations. This fault controls the geothermal system in the area. Manifestations are indicated by the presence of hot springs, fumaroles, ground warm, and solfatara. (Dezayes et al., 2022).

Geothermal systems are formed due to heat propagation by rock convection and conduction (Siregar, Dewi, & Ngatijo, 2021). The geothermal system consists of the main elements: the caprock, reservoir, heat-carrying fluid and heat source (Paais et al., 2021). This heat transfer process also causes hydrothermal fluid in the rock pores to become hot. Hydrothermal fluid that is heated will have a high temperature and pressure to press out the surface. The caprock, which is an impermeable layer, will block the fluid from escaping to the surface (Bahri & Ramadhan, 2022). This trapped hot water and steam is called a reservoir, used as an alternative energy source to replace fossil fuel energy, which is helpful for power generation and transportation (Harahap et al., 2022).

The method that has been used for geothermal exploration activities in the Lebong area is the geomagnetic method conducted by (Purwanto et al., 2024) using geomagnetic method to model the subsurface rock layer. This geomagnetic method can identify total magnetic field anomalies and produce subsurface models up to a depth of 1,2 km. Although effective for mapping at shallow to medium depths, geomagnetic methods have limitations in resolution and penetration depth compared to magnetotellurics. Therefore, magnetotelluric methods are preferred in exploration contexts that require information at depths greater > 4 km, such as the identification of geothermal reservoirs or hydrocarbon basins, due to their ability to provide resistivity images to great depths. Meanwhile, geomagnetic methods are more suitable for studies at shallower depths or as a complement in multi-method geophysical surveys.

The magnetotelluric method is a passive method that uses the interaction of natural electromagnetic waves to interpret the distribution of electrical properties of rocks in the subsurface (Omollo et al., 2022). Because of its deep penetration, the magnetotelluric method is very effective for mapping the deep structure of the earth in the Air Putih, Lebong Regency. This study aims to identify rock lithology based on the distribution of resistivity values in Air Putih, Lebong, using 2D modeling.

Based on the geological map in Figure 1. The structure develops as a horizontal fault (ketaun fault) due to the last tectonic activity around plio-pleiston. The Lebong region is composed of granitic rock formations (T_{mgr}) of the middle Miocene age that break through the Hulusimpang formation (T_{omh}) and Seblat formation(T_{oms}). The formations are composed of breccia minerals, volcanic lava, and tuff with sulfide mineralization and quartz veins, while the Seblat Formation is composed of claystone, siltstone, and siltstone interbedded with sandstone and conglomerate; the formation is of lower-middle Miocene age (Oktarina et al., 2021).

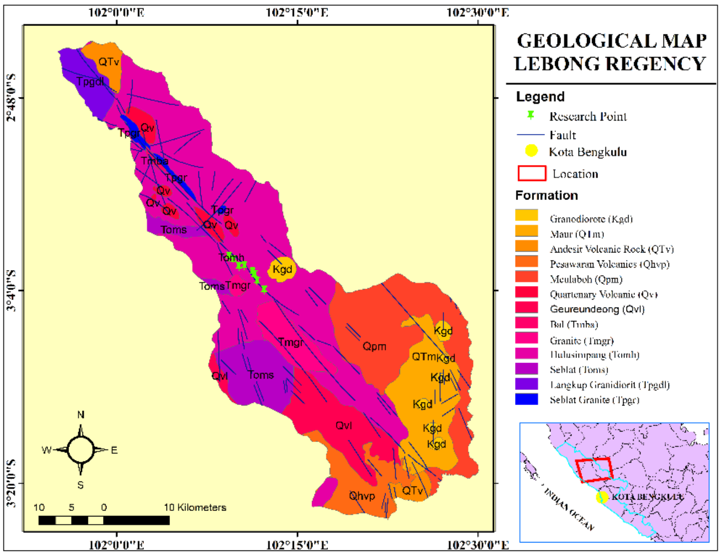


Figure 1. Geologic Map of Lebong Regency

RESEARCH METHODS

Data Acquisition

This research was conducted using the magnetotelluric method. The research location was in Air Putih, Lebong Regency. Measurements were made at 8 measuring points with 1 track in the West-Southeast direction. The data acquisition process was carried out using a magnetotelluric tool. Data recording lasted 16 hours with a depth range of up to 10 km. The selection of exploration depths of more than 4 km using the magnetotelluric method is based on the need to obtain detailed information about deeper subsurface geological structures, especially in the context of exploration for energy resources such as geothermal and hydrocarbons. The primary heat sources are deeper, usually at depths >3-5 km, often in the form of hot granites or intrusive magmas (Hoerunisa & Sismanto 2020).

The measurement process was carried out with a low frequency of 128 Hz, a medium frequency of 1024 Hz, and a high frequency of 4096 Hz. Data recording at low frequencies can achieve deeper penetration (Pahri, Paembonan, & Irawati, 2023). Sensors in data acquisition consist of two sensors, namely electrical and magnetic sensors. In the magnetic sensor, there are three coils (H_x, H_y, and H_z). The coil acts as a magnetic sensor. The coil (H_x) is placed in a position facing north-south, the coil (H_y) is placed in a position facing east-west, and the coil (H_z) is placed vertically. These three coils are positioned at a distance of 30 m from the main unit. In the electrical sensor using 4 porospots positioned at a distance of 50 m from the main unit based on the cardinal directions (north, south, west and east) orthogonally ($E_x$and E_y). GPS is placed at a height of ± 2 m and connected to the main unit.

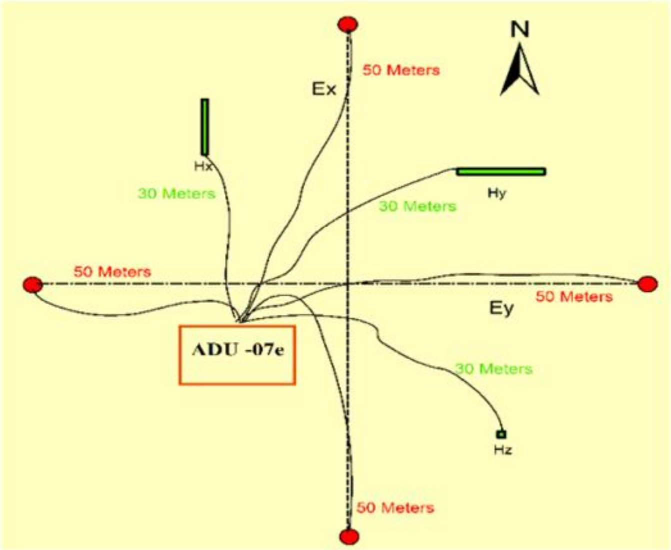
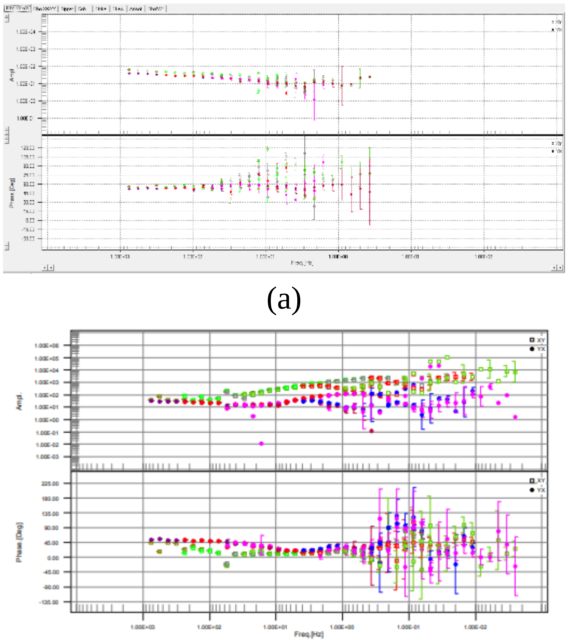


Figure 2. Sensor configuration during data acquisition (Al Ansory et al., 2023)

Data Processing

The result of magnetotelluric data acquisition in the field is raw data in the form of a time series that provides information about the electromagnetic field data recorded against time. Data transformation is performed to convert magnetotelluric data from the time domain to the frequency domain. After the data is in the frequency domain, the next stage is robust processing, which eliminates the influence of data from noise. The output of robust processing is the apparent resistivity and phase data. This process is carried out using the MAPROS software. The results of data processing in MAPROS are stored in the form of edi file (Maryanto et al., 2017).



(a)

(b)

Figure 3. (a). Magnetotelluric curve before data editing (b). Magnetotelluric curve after data editing.

2D inversion is carried out using ZONDMT software to obtain the distribution of subsurface resistivity values by adjusting the mathematical model curve to the measurement data in the field (Pratama et al., 2021). The results of the 2D inversion modeling are subsurface conditions interpreted with resistivity that varies with depth and distance in the direction of the cross-section profile.

Magnetotelluric Method

The resistivity distribution is used to determine the types of lithology that exist in the subsurface of the study area. The magnetotelluric method is one of the geophysical methods that uses electromagnetic fields to conduct sounding for estimating subsurface structures by looking at subsurface resistivity values. Electromagnetic fields have a frequency range from 1 – 10.000 Hz, which is able to reach depths of up to thousands of kilometers below the earth's surface (Wulandari, Gaffar & zulaikah, 2017).

Electromagnetic waves induced into the earth's surface are generated by increasing the period when sounding. This concept is the skin depth equation that calculates the penetration of electromagnetic waves when diffusing into the earth.

$$\delta \approx 503\sqrt{\frac{p}{f}} \qquad (1)$$

δ is skin depth, ρ is resistivity, and for f is frequency (Simpson and Bahr 2005).

A fundamental differential equation to explain the behavior of electromagnetic waves is described in Maxwell's equations regarding electromagnetic waves which are the Laws of Faraday, Ampere, Gauss, Coulomb, written in the following equation.

$$\nabla \times E = -\frac{\partial B}{\partial t} \qquad (2)$$

$$\nabla \times H = j + \frac{\partial D}{\partial t} \qquad (3)$$

$$\nabla . D = q \qquad (4)$$

$$\nabla . B = 0 \qquad (5)$$

E is the electric field (Volt/m), H is the magnetic field (Ampere/m), B is the flux or magnetic induction (Weber), D is the electric displacement (Coulumb), and q is the electric charge density, j is the current (Telford, Geldart, & Sheriff 1990).

Data Analysis

To transform the resistivity form into a geological form, knowledge of the resistivity value for each type of material and geological structure of the research area is required. The resistivity value of rocks is based on several factors, namely clay content, fluid content, groundwater availability, rock mineralogy and so on. If there is a liquid in a rock, it can reduce the value of the rock's resistivity. The difference in rock resistivity values can be seen in Table 1.

Table 1. Resistivity values of some rocks (Reynolds 1997)

Material	Resistivity
Granite	200-10000
Andesite	1.7×10^{2}-45×10^{4}
Basal	200-100000
Limestone	500-10000
Sandstone	200-8000
Slatestone	20-200
Sand	1-1000
Clay	1-100
Alluvium	10-800
Laterite	800-1500
Kalsit	1×10^{12}-1×10^{13}

RESULTS AND DISCUSSION

2D inversion modeling is used in geophysical surveys to analyze resistivity variations in the subsurface. One of the approaches used in this modeling is pseudosection, which provides a 2D model of resistivity variations in the subsurface along a specific measurement path. Pseudosections are particularly useful in identifying areas where there are horizontal changes in soil or rock properties, characterized by the presence of sharp resistivity gradients (Joel et al., 2022). The selection of an appropriate model can also be adjusted to the geological information of the study site.

Potential zones for geothermal exploration are in the range of 5-800 Ωm and obtain information on the rock structure below the surface to a depth of up to 10 km. This range adequately describes the resistivity variations that may appear in geothermal systems.

There are 3 cross-section results, namely cross-section 1 shows field data with apparent resistivity values, cross-section 2 shows the calculation model between field data and model data generated by the software, and cross-section 3 shows the true resistivity value results. The resistivity cross section shows resistivity values that can be classified into 3 groups, namely low, medium and high resistivity. Low resistivity (10-25 Ωm) shown in light blue is thought to be associated with the caprock layer of the geothermal system. Medium resistivity (30-150 Ωm) shown in green to yellow is thought to be associated with the reservoir layer of the geothermal system. High resistivity (>300 Ωm) shown in red is thought to be associated with the heat source rock of the geothermal system.

Table 2. Resistivity Distribution and Lithology Characteristics in the Air Putih Area.

Resistivity (Ωm)	Litology	Colour	Depth
10-25	Caprock	Light blue	<1,5 km
30-150	Reservoir	Green-yellow	>1,8 km
>300	Hotrock	Red	4-6 km

Based on the 2D inversion modeling results in Figure 4, the layer with a resistivity value of 10-25 Ωm is shown by the light blue color range, which is associated with a layer of host rock in the geothermal system at a depth of <1.5 km. This layer is identified as a volcanic rock that undergoes hydrothermal alteration (Irawati, Paembonan, & Fernanda, 2024). Based on the geological structure in Air Putih, the Hulusimpang Formation, which is of Tertiary age (Oligocene-Miocene), is part of the Bengkulu basin and consists of andesitic volcanic deposits that have undergone alteration and mineralization (Oktarina et al., 2021). The hydrothermal alteration process in these volcanic rocks is dominated by clay minerals. These clay minerals are composed of chlorite, pyrite, quartz and calcite, indicating mineralogical changes due to interaction with hot fluids (Oktarina & Eddy 2022). This alteration process plays an important role in geothermal systems, because the clay rocks formed are generally weathered so that they can function as a buffer layer that inhibits the migration of hot fluids to the surface (Sapulete, Souisa, & Jubaedah, 2019). In general, the salinity and conductivity of claystone resulting from hydrothermal alteration associated with geothermal activity will result in low resistivity in geothermal systems (Dewi, Maryanto, & Rachmansyah, 2015).

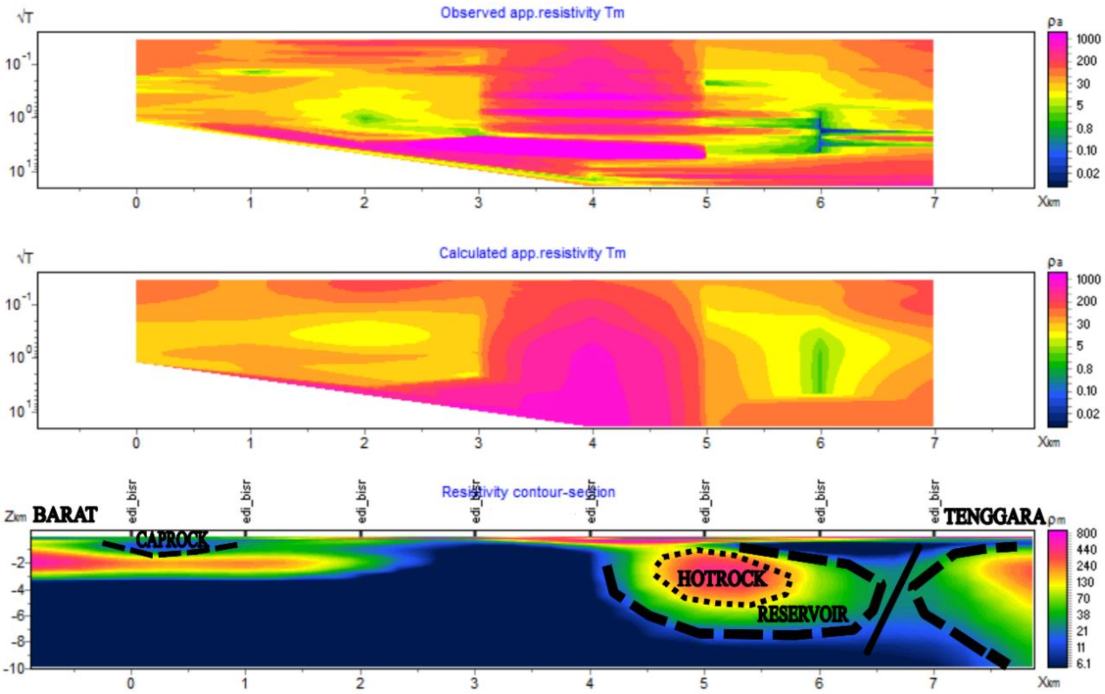


Figure 4. 2D inversion modeling

Below the low resistivity distribution, there is a zone with medium resistivity (30-150 Ωm), which is shown in green-yellow color. This zone is associated with the reservoir layer in the geothermal system at a depth of >1.8 km and is identified as fractured andesite rock, thus acting as a place of accumulation of geothermal fluids (Salam and Harmoko 2017). The fluid in the reservoir is heated and produces hot water and fumaroles which then appear on the surface as geothermal manifestations through fractures (Pratama et al. 2021). The andesite rock is composed of volcanic breccia and tuff, which is the result of past volcanic activity (Oktarina, Mia. 2022).

Rock response with high resistivity value (>300 Ωm) is shown in red color associated with heat source rocks in geothermal systems at a depth of 4-6 km. Hot rock found in the geothermal system in the Air Putih area is composed of metamorphic and igneous rocks (Salam and Harmoko 2017). The igneous rocks are deep breakthrough rocks (Granite and diorite) of the Middle Miocene age that break through the Upper Simpang Formation and Seblat Formation. Granite Formation(T_{mgr}), middle Miocene in age (Atimi, MT. and Sartika 2022).

Around the MT7 location, there are indications of fractures that act as hot fluid migration paths to the surface. 2D modeling interpretation indicates the presence of a fault between points MT7 and MT8. These faults are closely related to the regional geological structure, as shown in the geological map in Figure 1. These faults are considered the main factor that allows hot fluid infiltration into the Granite rock, which changes due to hot fluid intrusion from the magma system at depth. Based on research by (Mulyani et al. 2022), stated that fault structures have rocks that are easily deformed so that they become intrusion locations related to heat sources, and act as fluid flow paths to the surface.

Based on the research of (Al Ansory et al. 2023) in the same area using the magnetotelluric method of subsurface structure, the resistivity cross section in 2D inversion of potential hot rock in the research area is at a depth of 1.8 km to 6.5 km, composed of igneous and metamorphic rocks.

2D magnetotelluric modeling has several limitations compared to 3D models, especially in describing complex subsurface geological structures. 2D models assume that resistivity variations only occur in two directions, whereas actual conditions exhibit 3D heterogeneity that can lead to errors in interpretation (Wannamaker 2005). In addition, these models are less able to capture significant lateral induction effects and often oversimplify the data, so the results obtained can be less accurate compared to 3D modeling (Siripunvaraporn and Egbert 2000).

CONCLUSION

The 2D resistivity model of the Air Putih Geothermal area, Lebong, shows that the study area has 3 groups of resistivity values, namely low, medium, and high resistivity. The low resistivity of 10-25 Ωm is associated with the caprock layer with a depth of < 1.5 km, this layer is identified as a volcanic rock is dominated by clay minerals. Medium resistivity of 40-150 Ωm is associated with the reservoir layer with a depth of >1.8 km identified as fractured andesite rock. Resistivity >300 Ωm is associated with hot rocks with a depth of 4-6 km below the surface, identified as the igneous rocks are deep breakthrough rocks (granite and diorite). The results of this study identified geothermal potential in the form of hot rock at point MT5, with a thickness of 2 km. The results of this research can serve as a basis for the local government to conduct feasibility studies for developing geothermal energy projects in Lebong. By understanding the subsurface characteristics, potential geothermal energy reserves can be evaluated more accurately, thus supporting more effective decision making in exploring and utilizing geothermal resources. To improve the accuracy in identifying subsurface structures, future research is recommended to use the refraction seismic method. This method can provide a more detailed model of fracture zones and hot fluid migration pathways and help confirm the presence of geothermal reservoirs. In addition, refraction seismic can also be used to detect the presence of faults that act as the main pathway of the fluid to strengthen the analysis results from other geophysical methods.

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