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Characterization of Geothermal Potential Using 2D Magnetotelluric Inversion at Telaga Tujuh Warna, Lebong Regency, Bengkulu Province, Indonesia

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Abstract

The Telaga Tujuh Warna area in Lebong Regency exhibits geothermal manifestations such as hot water, mud craters, and fumaroles. This research aims to characterize the geothermal potential using 2D Magnetotelluric (MT) inversion. Measurements were conducted with the ADU-07e Magnetotelluric device, involving a 16-hour measurement period. Data collection followed the sounding principle with three frequency levels: high (4096 Hz), medium (1024 Hz), and low (128 Hz), spaced approximately 500 meters apart. Analysis confirms the consistency between 1D and 2D resistivity models, generating a resistivity distribution cross-section. Key findings include: (1) a low-resistivity cap layer (20–40 Ω-m) at approximately 1 km depth; (2) a medium-resistivity reservoir (40–160 Ω-m) at depths of 1–2 km; (3) a high-resistivity geothermal resource (>300 Ω-m) at depths of 1–2.5 km; and (4) a zone with very low resistivity values (2–16 Ω-m) at depths less than 1 km, potentially indicating a fumarole emitting hot water vapor and gas through rock fractures. These findings aim to advance geothermal exploration in Lebong Regency and support Indonesia's renewable energy objectives.

Introduction

Indonesia's growing population and expanding economy continue to drive up national energy demand [1]. To meet this challenge, the government has set ambitious targets to increase the share of renewable energy to 23% by 2025 and 31% by 2050 [2]. Achieving these goals will require the development of energy sources capable of providing reliable baseload power.

Geothermal energy—abundant along Indonesia's volcanic arc—meets this requirement, as it generates electricity with minimal greenhouse gas emissions [3], making it one of the country's most promising clean energy options [4].

Indonesia is one of the leading geothermal energy producers due to its location within the geologically active Ring of Fire [1]. Most areas along the Ring of Fire possess geothermal resources that can be harnessed as alternatives to fossil fuels [2]. Bengkulu Province lies at the intersection of the Indo-Australian and Eurasian tectonic plates and is also traversed by the Sumatra Fault Line [3]. One of the regions in Bengkulu Province that exhibits geothermal features, such as hot springs, is Lebong Regency [4]. Both Lebong and Rejang Lebong regencies possess significant geothermal potential distributed across their territories. Notable geothermal resources in the area include Mount Kaba and Bukit Daun—volcanoes formed during the Tertiary to Quaternary periods [5]

Geothermal energy is derived from volcanic systems that form at active plate boundaries [6]. The geothermal phenomenon involves the circulation of magma beneath the Earth's surface, which transfers heat to the lithosphere and induces movement in the Earth's crust [7]. This magmatic activity plays a critical role in the formation of geothermal systems by heating groundwater, which then forms hot fluids within subsurface reservoirs [8]. A complete geothermal system typically requires three main components: a substantial heat source, a reservoir to store the heated fluids, and a caprock to trap the heat beneath the surface [9].

In geophysics, one of the most accurate methods for detecting geothermal energy is the magnetotelluric (MT) method. The MT method is a passive electromagnetic (EM) technique that measures natural fluctuations in the Earth's electric (E) and magnetic (H) fields, typically in orthogonal directions relative to the surface [10]. This method is suitable for exploring depths of several thousand meters, making it highly effective for deep geothermal investigations [11].

Several studies have been conducted in Lebong Regency using various geophysical methods and research locations. For instance, [12] used the geoelectric method in Pungguk Pedaro Village, [13] applied the same method in Lemeu Village, and [14] employed the magnetotelluric method in Babakan Bogor Village. Research using the geoelectric method generally revealed shallow subsurface features at depths between 20–30 meters. While the geoelectric method effectively characterizes near-surface rock layers, its geothermal insights are mainly limited to lithological conditions. In contrast, the MT method can detect geothermal features at depths of up to 10 kilometers, although it is less sensitive to shallow anomalies starting from around 150 meters. For this reason, MT data are often complemented with other geophysical methods such as magnetic surveys, which enhance detection at shallower depths. This study focuses solely on the analysis of magnetotelluric data using natural electromagnetic signals [6]

Although previous investigations in Lebong Regency employed various methods and study sites, they consistently indicated significant geothermal potential. For example, study [7] produced a 2D resistivity model that revealed the distribution of geothermal features in the surrounding area. Building on these findings, the present research selected a study location in Bioa Sengok Village, within the Telaga Tujuh Warna area, which is believed to be a continuation of the previously explored geothermal zone.

Despite ongoing geothermal research in Lebong Regency, no detailed study has yet focused on the geothermal manifestations in the Telaga Tujuh Warna area. These manifestations include hot springs, hot mud pools, geysers, sulfur deposits, and visible steam emissions around the lake—all of which strongly suggest the presence of geothermal sources in the area [15]. The subsurface structure can be analyzed and interpreted as part of a geothermal system by generating a cross-sectional model of subsurface resistivity distribution [16]. The results of this study are expected to provide valuable information on the subsurface structure of the Telaga Tujuh Warna area, contributing to future geothermal exploration efforts.

Regional Geology

Bengkulu Province is located within the Bukit Barisan mountain range, with elevations ranging from 400 to 1,900 meters above sea level. According to [17], Lebong Regency features diverse topography, ranging from lowland plains to hilly and mountainous terrain, with the latter dominating the region. This mountainous physiography significantly contributes to the utilization of the region's natural resources. The area also exhibits a wide variety of soil types, with six major rock formations and five types of magmatic lithologies identified. The research area shows notable variations in elevation, influenced by several volcanic features, including Mount Kaba, Bukit Daun, Bukit Kumayan, Bukit Lalang, Bukit Mucung, Bukit Kelang, and others. The geological conditions of Lebong Regency are illustrated in Figure 1 [18].

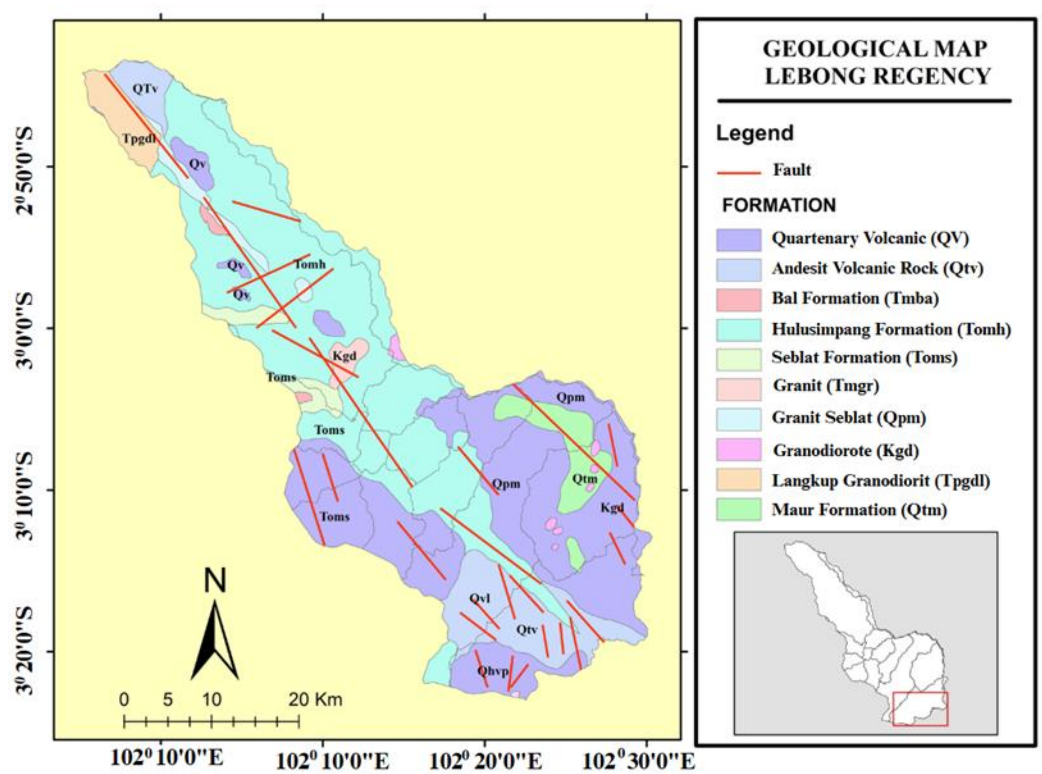

Figure 1. Modified Regional Geological Map of Lebong Regency [18]

Geologically, Lebong Regency is situated within the Sumatran Fault Zone, a dextral (right-lateral) shear fault that extends from south to north. This fault system has generated various derivative structures and distinctive morphologies along its length [19]. The research site in Bioa Sengok Village, within the Telaga Tujuh Warna area in South Lebong, lies within this fault zone. The area is characterized by intermontane basins—elongated and narrow depressions composed of rocks from the Tertiary to pre-Tertiary periods [20]. According to [4], geothermal reservoirs in Sumatra often consist of sedimentary rocks affected by tectonic activity and faulting. These geological conditions suggest significant geothermal potential at the study location. Therefore, this research applies the magnetotelluric method to determine the subsurface distribution of geothermal resistivity values in the area.

Theory and Calculation

The magnetotelluric (MT) method operates based on the principles of wave propagation and electromagnetic induction that occur in subsurface anomalies. Electromagnetic fields penetrate the Earth's surface and induce secondary electric and magnetic fields (such as eddy currents or geothermal currents) within conductive materials underground, which are then recorded by geomagnetic sensors [21].

The primary data used in magnetotellurics are natural electromagnetic (EM) waves. A key parameter used to describe the medium's response to EM waves is impedance (Z). Impedance is a tensor that relates the electric field to the magnetic field, as expressed in the following equation [22]:

$$\mathbf{E=ZH} \tag{1}$$

Maxwell's equations describe the behavior of electromagnetic (EM) fields and represent a unification of the fundamental laws governing electric and magnetic phenomena. These equations state that any change in the magnetic field **H** will induce an electric field **E**, and vice versa. The electromagnetic field can be represented by the following four Maxwell equations [23]:

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}, \text{ (Faraday's Law)} \tag{3}$$

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial t}, \text{ (Ampere's Law)} \tag{4}$$

$$\nabla \cdot D = q, \text{ (Coulomb's Law)} \tag{5}$$

$$\nabla \cdot B = 0, \text{ (Law of Magnetic Flux)} \tag{6}$$

With E is the electric field intensity (*Volts/m*), D is the electric flux density (*Coulomb/m²*) H = magnetic field intensity *(Ampere/m)*, B = magnetic flux density (*Weber/m²*), J = electric current density (*Ampere/m²*), and ρc = electric charge density (*Coulomb/m²*).

Magnetotellurics (MT) is a passive geophysical method of measuring variations in the earth's natural electromagnetic field to detect the earth's subsurface structure at depths of 10 meters to 10 kilometers based on subsurface resistivity properties [24]. Natural sources of electromagnetic fields at frequencies (less than 1 Hz) come from signals emitted by the sun, while frequencies (more than 1 Hz) come from thunderstorms [25]. To calculate the penetration range of electromagnetic waves using skin depth. Skin depth is the depth of a homogeneous medium where the amplitude of the electromagnetic wave has been reduced [26]. Skin depth can be formulated with the equation:

$$\delta = \sqrt{\frac{2\rho}{\omega\mu_o}} \tag{7}$$

With δ in meters, ρ is the specific resistivity of a homogeneous medium in Ωm , μ_o is the magnetic permeability in vacuum (4π x 10^{-7}), and ω is the angular frequency [27].

Experimental Method

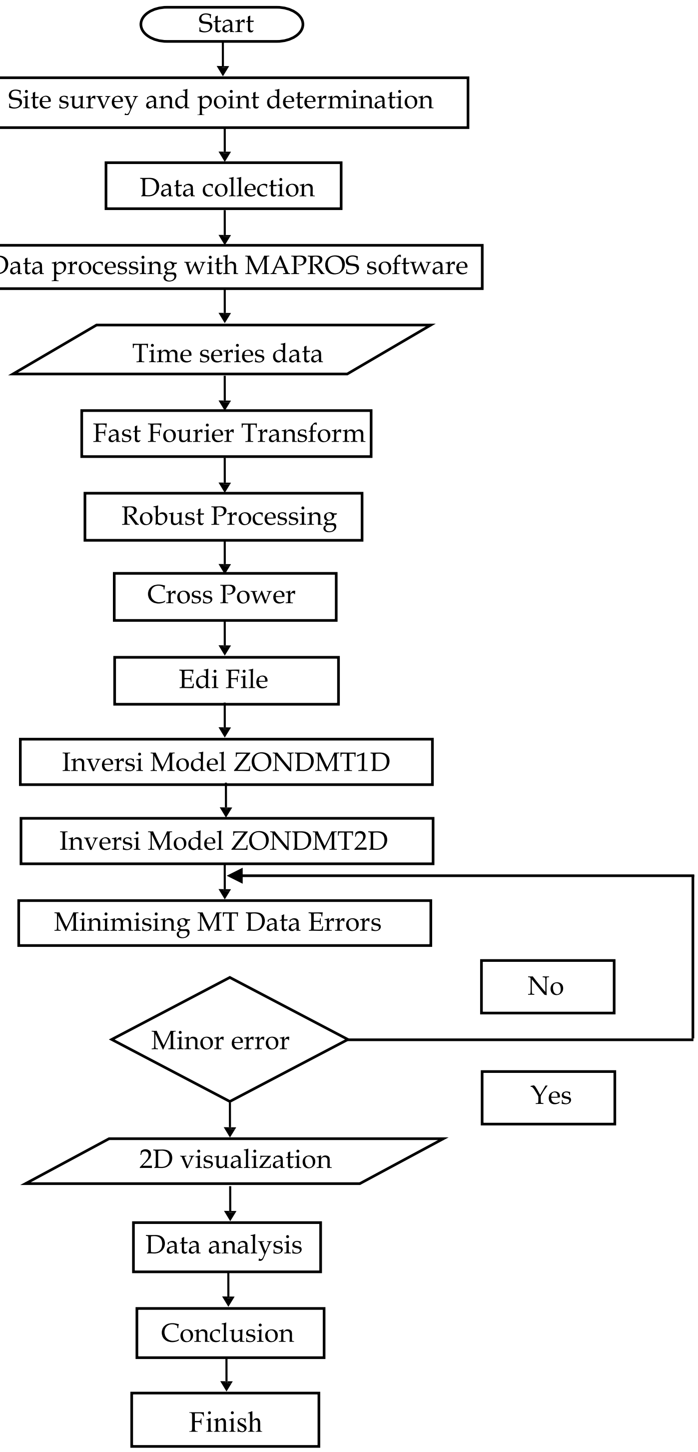

Figure 2. Research Flow Chart

This study utilized the magnetotelluric (MT) method, with the data collection process illustrated in Figure 2. The method employs three frequency ranges: high frequency (1024 Hz), which serves as the medium frequency in this context and is measured over a 2-hour period; and low frequency (128 Hz), recorded over a 13-hour period to obtain deeper and more extensive subsurface data. In general, the lower the frequency used, the deeper the penetration depth achieved [27]. Three measurement points were established, each spaced 500 meters apart. The study location is shown in Figure 2. Measurement data were recorded continuously for 16 hours at each point.

According to [12], alteration zones identified around the study area include potassic, prophylitic, and silicate types. The hydrothermal system is controlled by geological structures composed of sandy gravel, volcanic breccia, tuff, andesite, basalt, basaltic-andesite sand, sandy silt, and clay—predominantly rocks originating from acidic magma.

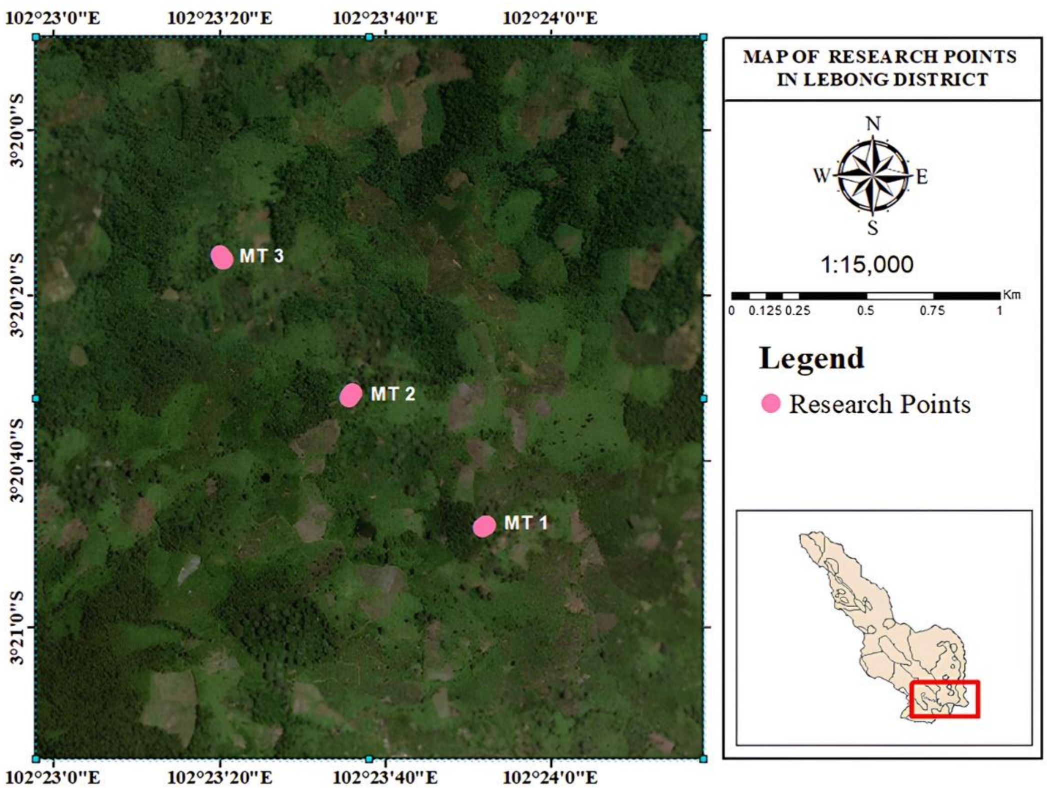

Figure 3. Map of the Distribution of Research Points

Magnetotelluric (MT) fields are divided into two polarization modes: Transverse Magnetic (TM) mode and Transverse Electric (TE) mode. These are commonly referred to as H-polarization (where the magnetic field is polarized along the model direction) and E-polarization (where the electric field is polarized along the model direction) [28]. In the survey area, MT data were collected by measuring the horizontal components of the electric field (*Ex, Ey*) and the magnetic field (*Hx, Hy*); Additionally, the vertical component of the magnetic field (Hz) was measured to complement the dataset. The propagation of electromagnetic waves is illustrated in Figure 4.

The magnetotelluric measuring system consists of three magnetic field sensors (magnetometers), two pairs of electric field sensors (electrodes), a PC, and a receiver unit that functions as the signal processor and data recorder [29].

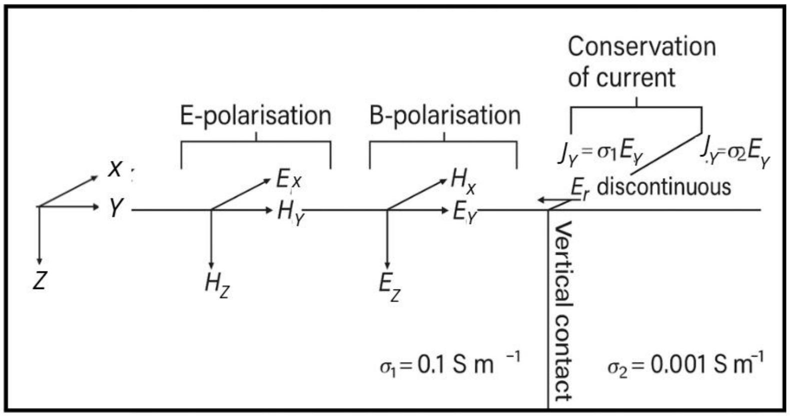

Figure 4. Electromagnetic Wave Propagation [30]

The data acquired in the field are raw time-series recordings, which do not yet display resistivity variations. These time-series data are initially processed using MAPROS software, which functions by selecting the highest-quality segments of the time-series to produce optimal results. After preliminary processing, static shift correction is applied to remove unwanted noise caused by near-surface local variations and topographic influences [23]. The processed output is then saved in the form of an EDI file. This file is subsequently processed using ZONDMT software to generate both 1D and 2D inversion models. In the 1D modeling stage, the geological interpretation is still limited and may not accurately reflect the complexity of the subsurface, necessitating further refinement through ZONDMT2D software. The 2D modeling phase produces a cross-sectional image of the subsurface, illustrating resistivity variations with depth and lateral distance along the profile line. The modeled depth is limited to a maximum of 10 km.

Results and Discussion

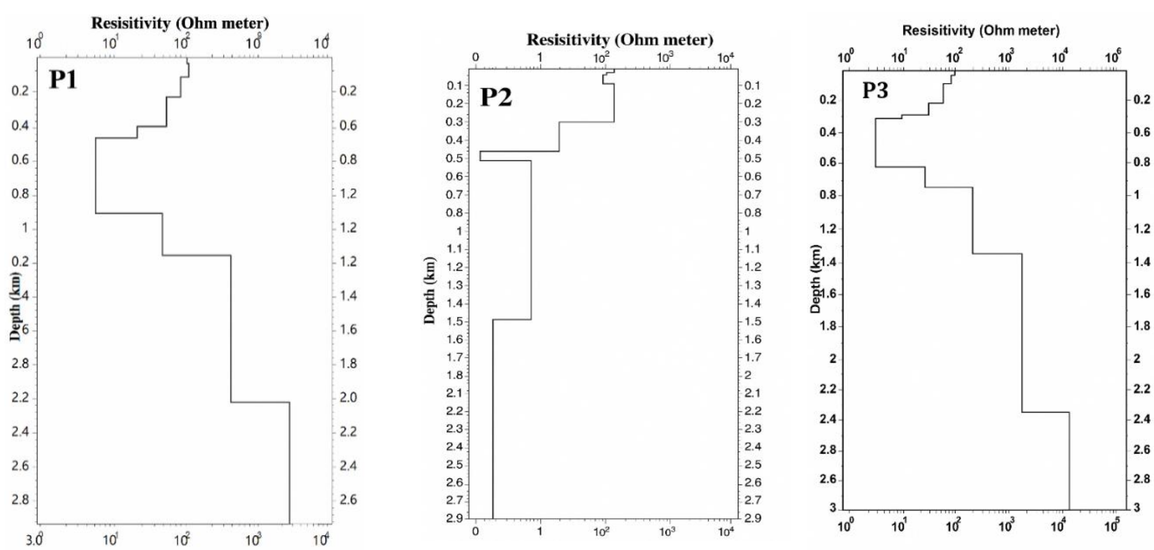

Figure 5. Modeling of 1D Resistivity Inversion with Depth

In the inversion process, 1D magnetotelluric data were processed using ZONDMT1D software. This software produces results that closely approximate the actual subsurface conditions, with interpretations presented in the form of depth-resistivity curves, as shown in Figure 5. The 1D interpretation primarily serves to validate the relationship between resistivity and temperature, which are generally directly proportional—meaning that greater depths often correspond to higher resistivity values, and potentially, higher temperatures. As shown in Table 1, peak resistivity values exceeding 300 Ωm at depths of 1.5–3 km indicate the presence of significant geothermal resources, particularly at measurement points 1 and 3. Moderate resistivity values ranging from 40–180 Ωm suggest the presence of reservoir layers, while low resistivity values below 40 Ωm are interpreted as caprock layers, especially at measurement point 2. The results from the 1D inversion modeling will be correlated with the 2D modeling outcomes to develop a more accurate and realistic subsurface model. Further refinement is conducted using ZONDMT2D software.

Table 1. Estimated Resistivity Value (*Ωm*)[31]

No	Clay Mineral	CEC Range (Ωm)	CEC Average (Ωm)
1.	Kaolinite	3-15	10
2.	Smektite (Montmorillonites)	40-150	120
3.	Illite	10-40	20
4.	Chlorite	10-40	20
5.	Heat Source	>300	>300

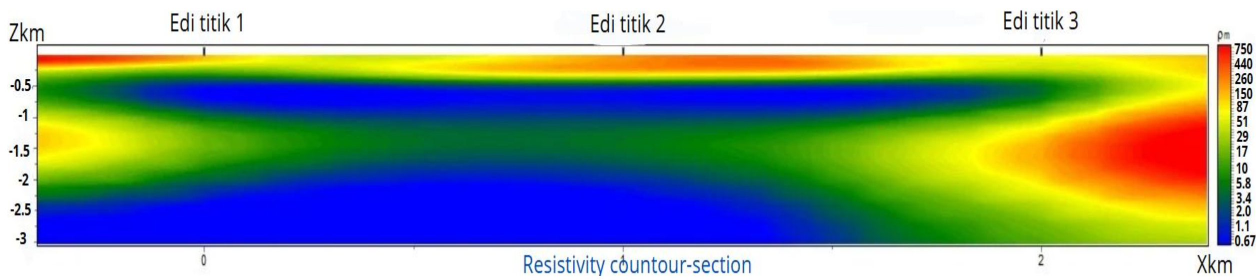

Figure 6. 2D Inversion Modelling

Previous research conducted in the same area [15] revealed that the 2D cross-sectional model identified a subsurface rock structure consisting of alteration tuff, interpreted as reservoir rock, located at depths of 400 to 800 meters. These altered rocks are indicative of geothermal potential. The resistivity distribution in two dimensions is presented in Figure 6. Figure 6 shows the results of 2D inversion modeling, interpreting the resistivity values of the geothermal system based on three measurement points around the Telaga Tujuh Warna area in Lebong Regency. The results of the 2D modeling are consistent with the 1D modeling, where measurement points 1 and 3 exhibit high resistivity values, while point 2 displays low resistivity. According to [32], geothermal systems can be conceptualized through three resistivity zones: low resistivity values indicating conductive clay caps, medium resistivity values associated with reservoir zones, and high resistivity values that typically represent the heat source or hot rocks.

The 2D inversion results reveal a low resistivity zone, shown in green, suspected to be altered volcanic rock with high clay mineral content, with resistivity values ranging between 20 Ω·m and 40 Ω·m at an approximate depth of 1 km. These clay-rich rocks are impermeable and act as caprock, preventing the upward migration of geothermal fluids, thereby trapping heat in the reservoir [30]. This caprock layer plays a crucial role in maintaining heat accumulation within the geothermal system [23]. The medium resistivity zone, shown in yellow, is interpreted as fractured andesitic lava with resistivity values between 40 Ω·m and 160 Ω·m, located at depths greater than 1 km. The fractures in this layer serve as conduits for geothermal fluids to move via conduction and convection, allowing them to reach the surface and form geothermal manifestations such as hot springs [26]. The high resistivity zone, marked in red, is presumed to represent the geothermal heat source. This zone, with resistivity values exceeding 300 Ω·m, is associated with intrusive rocks composed of andesitic to basaltic lava. Based on measurement data, the heat source is located at measurement point 3, extending northward at a depth of approximately 2.5 km [23]. These findings provide valuable insights into the geothermal structure of the Telaga Tujuh Warna area and can be applied to support further exploration and development.

A zone with very low resistivity values, shown in blue and ranging from 2 to 16 Ωm, is identified in the model. This zone is interpreted as a fumarole, as its geological structure allows hot water vapor mixed with gas to escape through fractures in the rock, forming steam. Fumaroles are typically associated with volcanic hydrothermal systems and are characterized by the emission of steam and volcanic gases [33]. The relationship between resistivity cross-sections and geothermal manifestations on the surface is also very important in analyzing geothermal data. Manifestations such as hot springs are usually located above or near areas of low resistivity beneath the surface, indicating a direct link between the geological conditions beneath the surface and the presence of geothermal manifestations that emerge to the surface. This study provides information that point 3 has the potential for geothermal distribution located at a depth of 2.5 km below the Earth's surface. However, further investigation is needed to determine the prospects of this area for use in geothermal exploration in the future.

Conclusion

The integration of 1D and 2D resistivity models has successfully identified subsurface geological structures and thermal anomalies within the study area. The 1D resistivity model provides localized vertical information related to lithological layers and temperature effects, while the 2D resistivity model offers a more comprehensive interpretation of both vertical and lateral variations. Interpretation of the 2D resistivity model reveals that low resistivity values (20–40 Ω·m) at depths of approximately 1 km correspond to the cap layer, likely composed of altered volcanic rocks rich in clay minerals, shown in green. Medium resistivity values (40–160 Ω·m) at depths of 1–2 km indicate potential geothermal reservoir zones, identified as fractured andesitic lava, illustrated in yellow. High resistivity values (>300 Ω·m) at depths of 1–2.5 km particularly near measurement point 3 toward the north are interpreted as potential heat sources (hot rocks). Furthermore, the presence of surface manifestations such as hot springs and fumaroles supports this interpretation. These features are characterized by very low resistivity values (2–16 Ω·m) at shallow depths (<1 km), which may represent clay-rich mineralized cap layers or hydrothermally altered zones associated with the geothermal system.

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