



A Preliminary Geothermal Prospect Investigation in Lemeu, Northeast Lebong, Indonesia, Using Magnetotelluric Method

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Abstract

The magnetotelluric (MT) field method is an excellent way to generate 2D resistivity cross-sections for mapping geothermal potential. One way to use magnetotellurics is to study how deep the Earth's crust is. This study uses single-point magnetotelluric (MT) measurements to look at the potential for geothermal energy. We used MT magnetotelluric measurements to look at the potential for geothermal energy in the Lemeu area in northeast Lebong in Bengkulu, Indonesia. The magnetotelluric (MT) measurements we selected pass through areas identified as potential sites for hydrothermal activity. This area includes faults and hot springs, which we felt were worthy of investigation. This study collected data from seven magnetotelluric (MT) stations along the profile, which passes through the Lemeu hot springs. Data were collected in the frequency range of 4096 to 128 Hz. This study used a station spacing of approximately ± 1 km for the best resolution. We used Non-Linear Conjugate Gradient (NLCG) for inversion modeling with ZONDMT1D and ZONDMT2D software. ZONDMT1D and ZONDMT2D software. Geothermal resources are located at a depth of 7 km, while geothermal fluid reserves are between 2 and 6 km below.

Keywords: Geothermal; Lebong regency; Magnetotelluric; Resistivity; Indonesia

1. Introduction

Finding and developing clean, low-carbon energy sources has become more important as Indonesia moves towards a low-carbon economy. The sustainable development of Bengkulu Province, Indonesia, holds significant importance, particularly due to numerous settlements that lack access to the energy grid and depend on fossil fuels for electricity generation. Geothermal energy possesses the capacity to generate power while exhibiting low levels of carbon emission, rendering it an exceedingly appealing alternative energy option. Furthermore, its growth necessitates less physical infrastructure (Peng et al., 2023). A region can have the potential for geothermal energy if its geothermal fluids with elevated temperatures ascend through the earth's crust via fault zones or fractures that possess high permeability, ultimately reaching the surface (Muñoz, 2014).

In urban areas, geothermal exploration has received increasing attention in recent years (Yousefi et al., 2019). Renewable energy has the potential to significantly contribute to the energy mix, particularly in densely populated areas where demand is increasing and dependence on fossil fuels needs to be reduced (Schiel et al., 2016). As Kearey and Brooks (2002) note, by decreasing the requirement for drilling and maximizing area coverage, geophysical techniques can increase the efficiency of

exploration. Since geophysical methods make it easier to characterize the subsurface geologically and enable the identification of several changeable circumstances like fault zones, they have shown to be useful instruments for evaluating geothermal systems (Nieto et al., 2019). Hence, to examine the geothermal system, we suggest conducting a geophysical survey employing the magnetotelluric (MT) technique to assess the subsurface properties of the Lemeu geothermal system situated in the Uram Jaya sub-district of northeast Lebong. The resulting physical parameters, such as electrical resistivity, will be employed to characterize the geometry and major fluid ways.

Previous research has identified 265 geothermal sites in Indonesia, with 138 sites (52.07%) currently undergoing preliminary studies to determine potential resource classification. In addition, another 24 sites (9.05%) are currently undergoing studies to see if they can become good sources of geothermal energy (Darma et al., 2021). As observed by Maryanto et al. (2017), only 2.64% of geothermal sites are currently used for energy production, with a total installed capacity of 1,189 MW. Communities often use untapped geothermal sites for various purposes, including tourism, heating and agricultural development such as mushroom cultivation, fertilizer production, and fish farming. However, geothermal resources have not been widely exploited in Indonesia (Hill et al., 2015).

The MT method is frequently employed to investigate the characterization of deep geothermal resources, as it enables the measurement of the resistivity of the subterranean structures that constitute a geothermal system (Maithya and Fujimitsu, 2019; Mitjanas et al., 2021). The resistivity distributions at depth are determined using the MT method, an electromagnetic method that analyses the fluctuations of electric and magnetic fields in the vicinity of the Earth's surface. The MT method has been employed to obtain elasticity distributions in studies of the Earth's crust and even the Earth's mantle due to the significant penetration of electromagnetic fields into the Earth (Grandis et al., 2004). As previously reported in Pavez et al. (2022), there is an inverse relationship between electromagnetic (EM) pulse frequency and penetration depth. MT techniques have been employed to image magma channels or reservoirs (Hill et al., 2015; Di Giuseppe et al., 2017) and hot springs (Peacock et al., 2016) in volcanic environments. The primary objective of utilising MT techniques in geothermal studies is to ascertain the underlying geological characteristics and subsurface fluid distribution, thereby identifying prospective geothermal opportunities (Farid et al., 2021).

Previous research on geothermal energy (Al Ansory et al., 2023) examined the Air Putih tour of Lebong Regency, utilizing the 2D Magnetotelluric method. The results indicated identifying the resistivity value of the Mine Sawah Village area, Lebong Regency, which was divided into three layers. The resistivity value between 20 and 50 $\Omega\cdot m$ was observed in the first layer, while the second layer exhibited a resistivity value between 50 and 100 $\Omega\cdot m$. The third layer exhibited a resistivity value between 100 and 200 $\Omega\cdot m$. The caprock layer is interpreted as having a resistivity value of 0.26-0.8 $\Omega\cdot m$ with a depth of > 0.8 km and a high resistivity value of > 300 $\Omega\cdot m$ is interpreted as a heat source rock with a depth from 1.8 km to 6.5 km. Research that has been conducted in the same area has been conducted by Kausari et al. (2024) identifying the distribution of hydrothermal below the surface in Lemeu Village, Lebong Regency. The resistivity value ranges from 1.3 $\Omega\cdot m$ - 7.21 $\Omega\cdot m$ which is identified as hydrothermal at a depth of 1-30 meters. Further research is needed to explore the geothermal potential at deeper depths. The next research is expected to use the Magnetotelluric (MT) method to map the distribution and depth of the geothermal potential.

This research identifies geothermal activities mainly focused on the Hululais site and its surrounding area. These investigations have indicated the potential for the presence of conductive heterogeneities beneath the active volcanic mountain Hululais, as well as the possibility of resistive structures in the top crust at depths greater than 10 km. This research proposes a resistivity model that uses MT data to map the electrical resistivity structure below the surface at depths of 5 to 10 kilometers, providing a deeper understanding of the geothermal potential in the Lebong Regency. With a focus on Lemeu, Uram Jaya sub-district, and Lebong Regency specifically, we believe that the application of a

two-dimensional modeling approach could be a valuable tool to facilitate and expand the understanding of geothermal resources in the region mentioned above.

This study is an initial step to explore the potential of geothermal resources in Lemeu Village, located in the northeast of Lebong Regency, Bengkulu Province, Indonesia. In order to achieve this goal, a 2D cross-sectional Magnetotelluric (MT) inversion model is used to analyze the MT data that has been collected in the area. These data include the vertical magnetic transfer function and total impedance tensor, which are important foundations in this study. The geothermal system in this area not only opens up opportunities for renewable energy but also brings various direct benefits to the local community. These benefits include increasing the tourism sector and utilizing geothermal energy as a sustainable energy resource. Lemeu Village, which is known as one of the geothermal spring locations, is a clear indication of the great potential of geothermal energy stored below the surface. Utilization of this energy provides a golden opportunity to support regional development, both in the form of energy development and tourism.

2. Geological Setting

The regional physiography of Sumatra Island, Lebong Regency, is mostly made up of volcanic and partially altered rocks (Bemmelen, 1969). The Lemeu Village area is part of the Barisan Mountains Zone, where at its heart there is a hulusimpang rock formation (Tomh), which shows that magma is active in the area. The sediments in the Bengkulu Basin are affected by the activity of dextral strike-slip fault systems, which are collectively known as the Mentawai Fault Zone (MFZ) and the Sumatra Fault Zone (SFZ). It's thought that fault activity affects the formation of Tertiary sedimentary basins. However, it can also act as a separator between basins, which occurs long after the sedimentation process takes place. So, we can say that the horizontal faults on the island of Sumatra are pretty deep, going right through the bedrock. This means that magmatism and volcanic activity occur on the surface. The geological structure of the study area is the oldest rock unit in the Bengkulu Basin, formed in the Oligocene-Early Miocene. The main force direction is roughly southeast to northwest. The Lebong area is made up of hills and undulating plains. The steep hills are made up of rocks from the Quaternary period, which was about 2.6 million years ago. These rocks are made up of lava, volcanic breccia, and tuff. The undulating plains are made up of Quaternary-age deposits, which are made up of river alluvial deposits and alluvial deposits that the weathering of volcanic rocks has formed. The study area is located along the Ketahun fault, which is characterized by valleys and cliffs that can be identified by the straightness of the river (Gafoer et al., 2007).

The Bengkulu Region encompasses the Bengkulu Basin and the Bukit Barisan Range (Indarto et al., 2009). Sedimentation of the Bengkulu Basin resulted in the formation of a stratigraphic series comprising the Hulusimpang Formation, Lemau Formation, Simpangaur Formation, and Bintunan Formation. This tectonic process gave rise to the intermontane basin (Zulkarnain, 2008). The Lebong Regency is a hill range with an altitude between 500 and 1.000 meters above sea level. The geological structure of the study area is characterized by the presence of fault structures, including kinks, slip faults, and Ketahun faults, which have a late Miocene age. This is the period during which the geological structures in the study area were formed (Arief et al., 2018). The study area is characterized by the Hulusimpang Formation (Tomh) (Fig. 1), which is composed of lava, altered tuff, and volcanic breccia and comprises andesite to basalt rocks in the shallow land-sea transition area.

3. Material and Methods

The region's structure and geological features were considered when configuring the locations. As seen in Fig.2, the spatial arrangement of the sites has been deliberately designed to mimic a single

crossing. The normal range of distance between sites is 1.2 km to 2.5 km, with the limitations imposed by the inaccessibility of a measurement site influencing the variation.

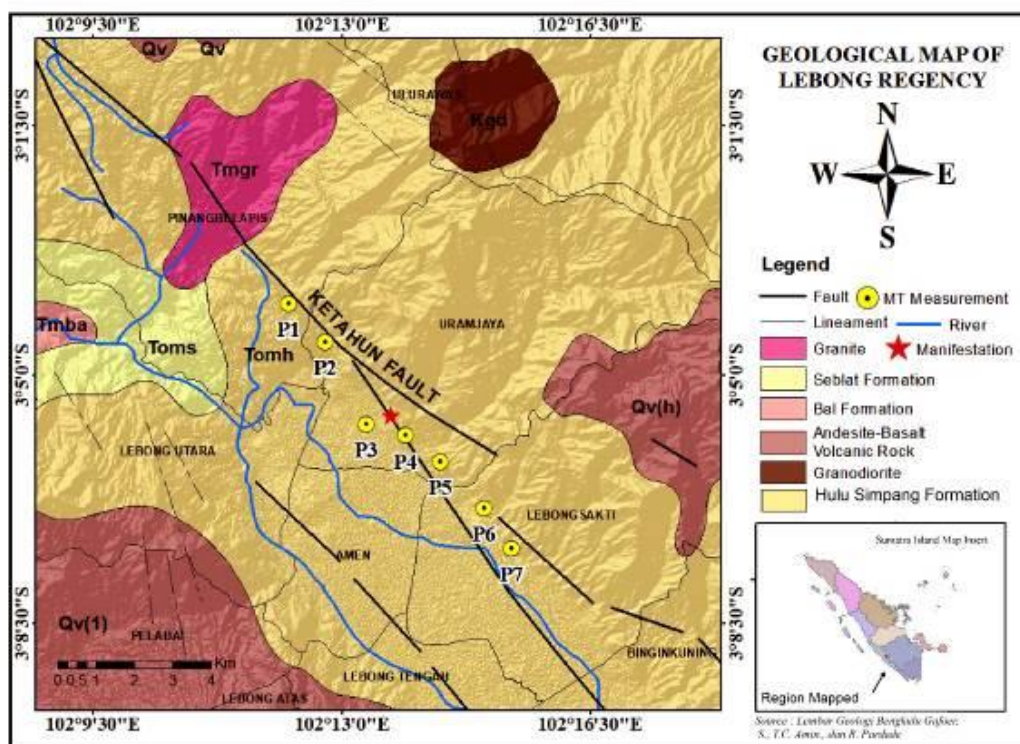


Fig. 1. A geological map of Lebong Regency (Gafoer et al., 2007)

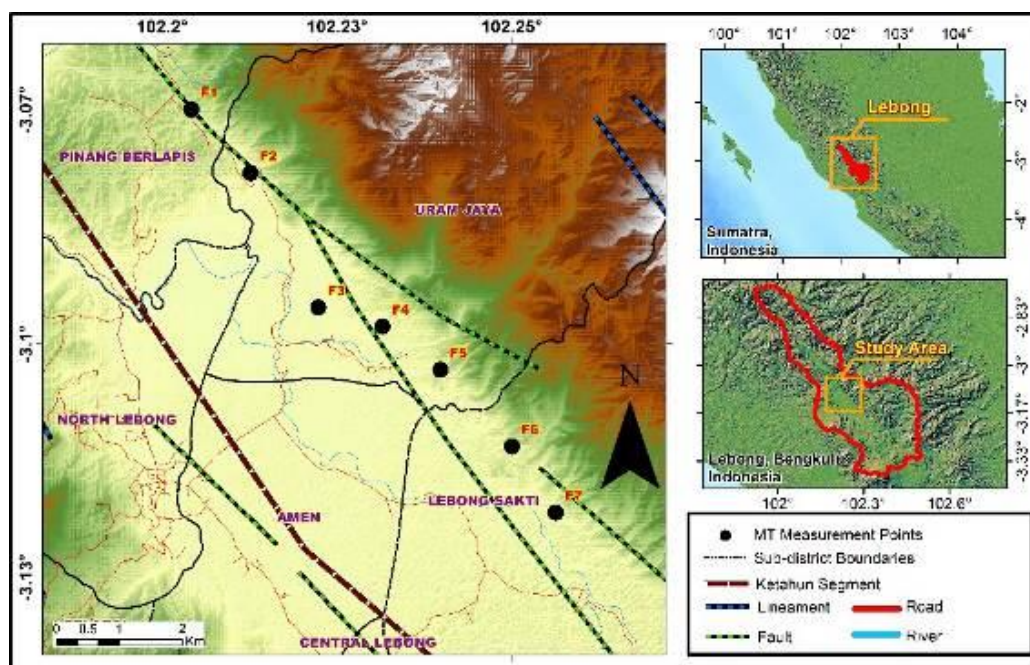


Fig. 2. A map of the measurement location, overlaid with topography from the Digital Elevation Model of the National Aeronautics and Space Administration (DEMNAS)

<https://tanahair.indonesia.go.id/demnas/#/>.

The purpose of this research is to calculate the geothermal distribution in the Lemeu area, Uram Jaya, Lebong Regency, using the magnetotelluric method between 1 and 12 June 2023. Magnetotellurics is an electromagnetic approach that records changes in electric and magnetic fields near the surface of the Earth to get information about the distribution of resistivity values with depth. Magnetotellurics, or MT for short, is also known as magnetogradiometry. MT is utilized to create images/models of the resistivity distribution in the crust and even the mantle in order to account for the fact that electromagnetic fields are capable of penetrating vast depths into the Earth. According to research by Pavez et al. (2022), the penetration depth reduces as the frequency of the electromagnetic pulse increases. In volcanic regions, magnetic tomography (MT) can be utilized to detect magmatic conduits or reservoirs (Di Giuseppe et al., 2017), hydrothermal fluids (Peacock et al., 2016), geothermal reservoirs (Pavez et al., 2022), fluids (Pavez et al., 2020), and crustal conductors (Reyes-Wagner et al., 2017). At seven different MT stations, measurements were collected, and the data was recorded using a Metronix ADU-07e. In order to measure magnetic fields, three MSF-07e coil magnetometers were buried in the ground for thermal and mechanical stability. These magnetometers were pointed in the northeastern, eastern, and vertical directions, respectively. We were able to calculate the electric field by monitoring the voltage differences between four EFP-06 electrodes that were arranged in a north-south and east-west pattern. For 16 hours, time series of the horizontal and vertical components of the electric and magnetic fields, as well as the vertical components of the magnetic field, were recorded. Three magnetic field components (represented as H_x , H_y , and H_z) and two perpendicular electric field components (E_x and E_y) can be measured using the ADU-07e device (Ahmed et al., 2024). At every location, three magnetic sensors were employed to guarantee precise measurements of these fields. Furthermore, as illustrated in Fig.3, four porous vessels with electrodes oriented in the east-west and north-south directions were used to quantitatively measure electric fields. For this study, three frequency levels were used: high frequency (4096 Hz), low frequency (128 Hz), and medium frequency (1024 Hz). To make processing the resultant data easier, it was converted. Three distinct sets of frequency band data were produced as a result, each of which matched a certain sampling frequency.

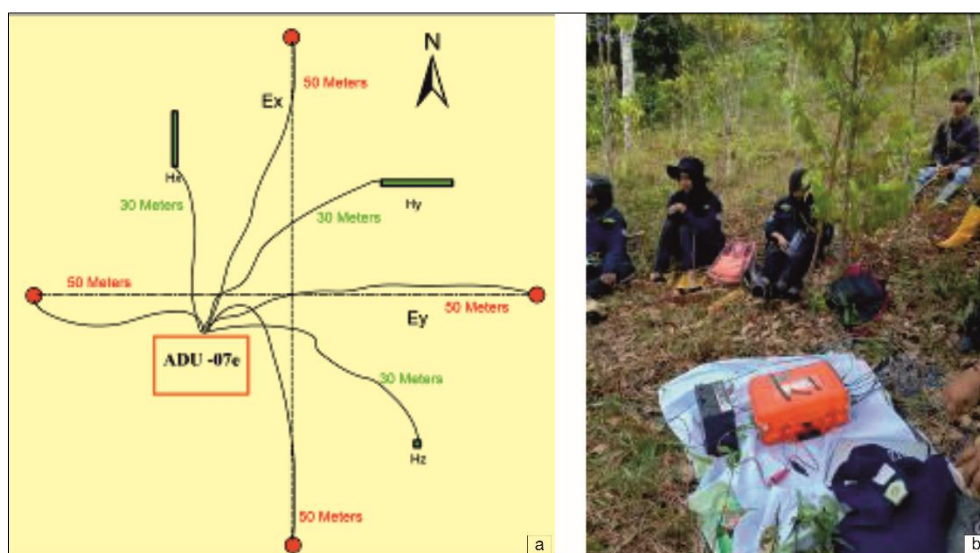


Fig. 3. a) The configuration of the data acquisition system for MT is presented in section, b) deals with the same topic from a different perspective. A survey of the MT area in Lemeu is scheduled for June 2023.

The software MAPROS, ZondMT1D, and ZondMT2D were employed to process all of the MT data. The time series data was transformed into frequency domain data via a Fourier transform. A variety of data types, including apparent resistivity and phase impedance, might be analyzed thanks to this

transformation. A resistivity model ($\rho(\Omega.m)$) and depth model Z (km) were obtained using the ZondMT1D program, which then produced a one-dimensional curve. After that, a two-dimensional transect model was produced by processing the data using an inverse modeling technique with ZondMT2D. A thorough review of the use of nonlinear conjugate gradient inversion (NLCG) algorithms on MT data is given by Rodi and Mackie (2001). Optimization techniques that involve directly minimizing a non-quadratic objective function on a Cartesian orthogonal rectilinear grid are the most common.

Magnetotelluric (MT) data can be converted into one-dimensional and two-dimensional with the ZONDMT1D and ZONDMT2D programs. The subsurface profile generated from the inversion process shows the resistivity ($\Omega.m$) as a function of depth Z (m). One popular technique for identifying key characteristics of subsurface geoelectric structures, like directional orientation and the existence of shallow fault zones, is the application of dimensional analysis to MT data. The best modeling approach for a certain data set can also be found using this analysis method (Martí et al., 2010). The purpose of the MT data analysis process is to allow the collected data to be used to build a subsurface resistivity model based on the observed MT data. Therefore, the MT response must be developed to determine whether the data requires a three-dimensional resistivity model, a one-dimensional gridded curve model, or a two-dimensional resistivity model with directional constants (Maithya and Fujimitsu, 2019).

Regarding 2D inversion, it is considered that the medium's resistivity can change with depth in one of its lateral directions while staying constant in the other. Electric shock is the term typically used to describe this event. A survey that is conducted along a profile that is roughly perpendicular to the electric shock is subjected to the inversion method. If the field configuration's coordinate system is not parallel to and perpendicular to the electric shock, The application of a mathematical rotation to the MT impedance tensor data is suggested by Maithya and Fujimitsu (2019). This rotation guarantees that the tensor's two axes are parallel to and perpendicular to the electric shock, respectively. An inversion procedure is then used to balance the resistivity and apparent phase values obtained from the element impedance. According to Maithya and Fujimitsu (2019), the impedance can be achieved by applying an electric field parallel to the shock (known as TE mode), perpendicular to the shock (known as TM mode), or both simultaneously.

4. Results

An electromagnetic technique known as magnetotellurics is used to collect data on the distribution of resistivity values at different depths by observing changes in electric and magnetic fields near the Earth's surface. Magnetotellurics is also known as magneto-gradientometry or MT. MT is used to build models and images of resistivity distributions in the Earth's crust and even in the mantle because electromagnetic waves can penetrate great depths in the Earth. The research conducted by Pavez et al., (2022) the results demonstrated that the depth of penetration decreased as the frequency of electromagnetic pulses increased. In areas of volcanic activity, magnetic tomography (MT) can be employed to identify the presence of magma channels or reservoirs (Di Giuseppe et al., 2017), hot springs (Peacock et al., 2016), geothermal reservoirs (Pavez et al., 2022), fluids (Pavez et al., 2020), and conductors in the Earth's crust (Reyes-Wagner et al., 2017). The data were acquired using a Metronix ADU-07e, and measurements were taken at seven distinct MT stations. To ensure mechanical and thermal stability, three MSF-07e coil magnetometers were buried to measure the magnetic field. The magnetometers were oriented vertically, eastward, and northeast. By tracking the voltage difference between four EFP-06 electrodes placed in an east-west and north-south pattern, the electric field was determined. For 16 hours, time series of the magnetic field's vertical component, as well as the electric field's horizontal and vertical components, were captured.

A time series plot of the findings from the Lemeu study is displayed in Fig.4. As the measurements were taken in deep layers of soil, the time series data for the magnetic field of the H_{x2} , H_{y3} , and H_{z4} , and the electric field, E_{x0} , E_{y1} (Fig.3.a), are of high quality since they are noise-free. Data that diverge from the primary data pattern can be subtracted using a feature in the MAPROS software. As a result, this software can only process data of the highest quality.

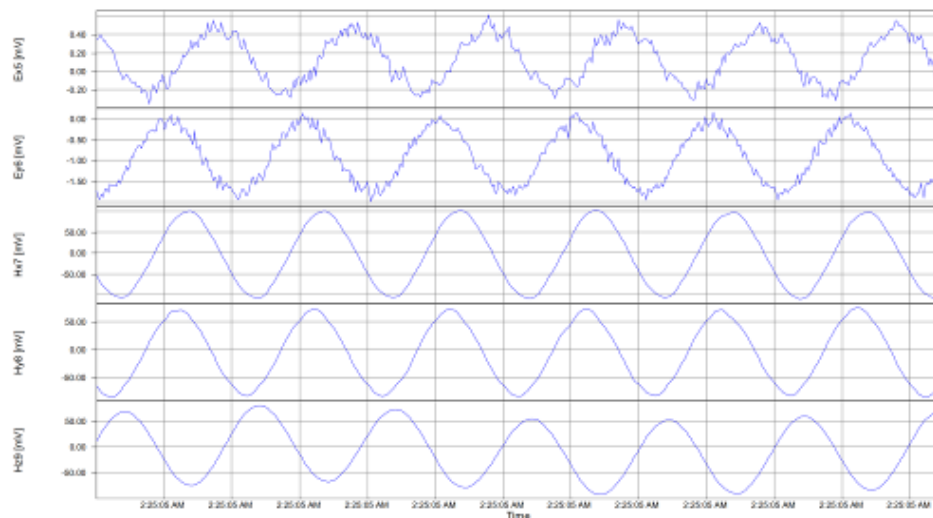


Fig. 4. The data set comprises time series data of electric and magnetic fields, derived from measurements obtained via the MT method.

Fig. 4 displays the results that were acquired after sixteen hours of inner layer measurements at 128 Hz. The voltage that results is between 100 mV and -100 mV and is constant. Kanyar's study from 1953 demonstrated that a steady voltage is a great way to gauge how accurate the data from a measurement is. The data displayed in Fig. 4 is raw and original in the temporal domain. A Fast Fourier Transform (FFT) is then used to convert the data into the frequency domain so that additional processing can be done. A one-dimensional inversion approach is the next stage. This method's goal is to ascertain whether the resistivity value and the depth to the ground surface are correlated. The relationship between resistivity and depth to ground is depicted in Fig.5.

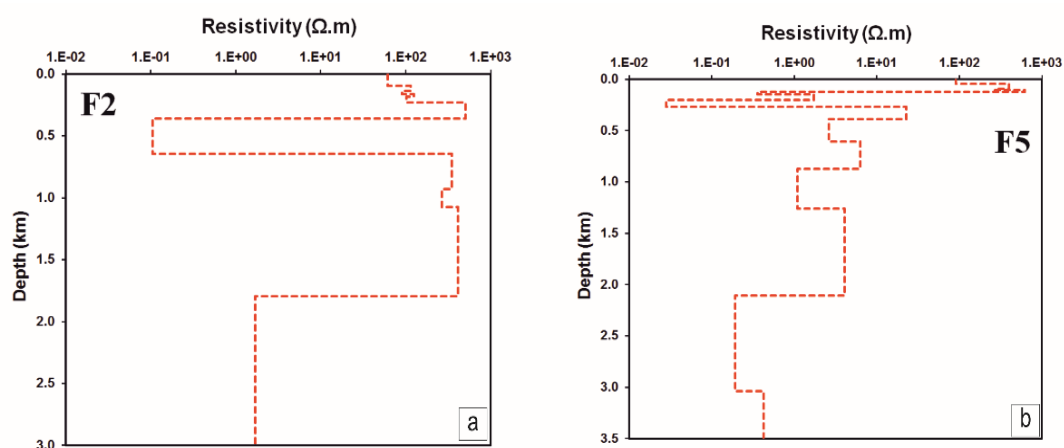


Fig. 5. 1D curve from the inversion result

The goal was to create a 2D resistivity cross-section of Lemeu. Comparing the data with existing geological knowledge would enable us to learn more about the island's hydrothermal and magmatic

systems. To accomplish this, an inversion approach was used, in which the resistivity values estimated using the least squares method were compared to the measured resistivity data. For each MT study, the resistivity-depth plot shows a range of resistivity values from 10^{-2} to $10^3 \Omega.m$ and depths from 3 to 3.5 km. The red dashed line shows the depth range. Subsequently, resistivity cross-sections were made at each site using field data, and these cross-sections were utilized to make resistivity contours in two dimensions (2D). This two-dimensional (2D) resistivity model (Fig.6) represents the geothermal distribution at Lemeu. After inversion, the resistivity predicted by the model and the apparent resistivity observed in the field can be used to evaluate the true resistivity. The purpose of this inversion is to make using real resistivity data easier. The relationship between resistivity values and the types of rocks present is demonstrated by the two-dimensional resistivity model, which is shown in Fig.7. A section devoted to debate provides a more thorough analysis.

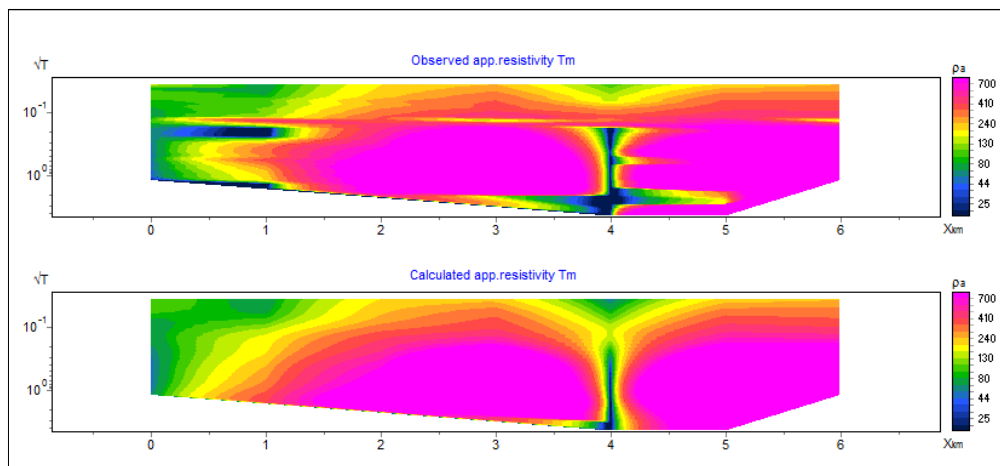


Fig. 6. The data set comprises time series data of electric and magnetic fields, derived from measurements obtained via the MT method.

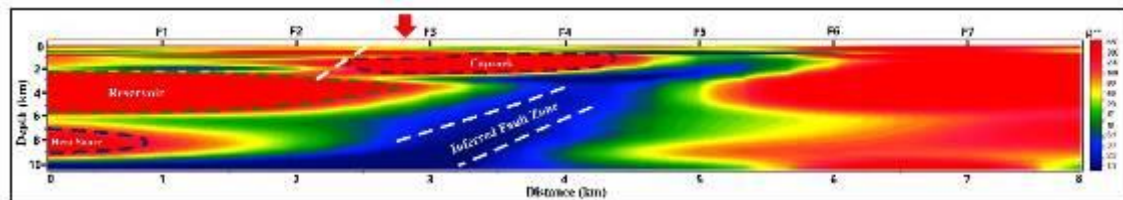


Fig. 7. The objective of this study is to utilize subsurface 2D inversion modeling of MT observation points

Three key elements make up an ideal geothermal system, according to Gupta (2014) three things: a reservoir rock layer that has high enough porosity and permeability to store and flow fluids (hot water or steam), a cap rock layer that has very low permeability, which acts as a seal to prevent hot fluids from escaping the reservoir, and a heat source in a geothermal system usually originating from geothermal activity below the surface (Ahmed and Al- haleem, 2024). The cap rock layer is most likely located one to two kilometers below the surface, or between $110 \Omega.m$ and $300 \Omega.m$, according to a two-dimensional cross-section. Where the geothermal reservoir is estimated to be located, at a depth of two to six kilometers, the resistivity is expected to be between $300 \Omega.m$ and $400 \Omega.m$. However, the heat source will have a high resistance of $600 \Omega.m$ at a depth of 7 km. The fact that this geothermal potential is visible on the surface, especially in the form of hot springs close to well F3, allows for its identification.

The subsurface in the southern region of the study area has moderate to low resistivity and a homogeneous structure (Fig. 7). These features are present throughout the subsurface of this region.

Therefore, in this area, the model is less bound. As a result, the large disturbances observed during the MT data measurements may explain the lack of low resistivity structures beneath the study area in our model. These formations may be related to the potential of shallow magmatic sources. The presence of magma at shallow depths produces high temperatures below the surface, which can heat groundwater to form a hydrothermal system (Simmons and Kirby, 2024). This process often produces phenomena such as hot springs, fumaroles, or hot mud pools. In the study area of Lemeu Village, this potential is likely to exist, with indications of the presence of shallow magmatic sources that act as heat sources, rocks that allow reservoirs, and a capping layer that keeps the system stable.

5. Discussion

The magnetotelluric method uses an electromagnetic approach to collect data on the distribution of resistivity values with depth. The MT method creates a model of resistivity distribution in the Earth's crust, even in the Earth's mantle, to show that electromagnetic fields can reach great depths to the surface of the Earth's core. MT utilizes natural sources to obtain variations of the magnetic and electric fields at the surface of the earth. The MT data appear to indicate the presence of geothermal reservoirs, which could be explained by the way electricity flows through the materials. On the other hand, the MT results only provide information on the resistivity values of the rocks and the depth of occurrence. We were fortunate to have access to geological information from (Gafoer et al., 2012). A graph was used to create a 2D resistivity cross-section, which showed that there are three main resistivities in the study area extending downwards for a distance of 10 kilometers. The MT F3 and F4 survey points are located below the strange structure seen in the inversion and 2D interpretation (Fig.7). The structure in question is covered in a layer of conductive silt and has a comparatively low resistance.

The formation of an Inferred Fault Zone (IFZ) is thought to occur when magma intrusion interacts with active faults, primarily the Ketahun section. The formation of Inferred Fault Zones (IFZ) is thought to occur as a result of complex interactions between magma intrusions and active faults (Wibberley et.al., 2008). This process begins when magma rising from depth encounters a weak zone in the Earth's crust, such as an active fault. This fault, which already has fractures and cracks due to tectonic movements, becomes a preferential pathway for magma to flow or compress (Li et al., 2022).

During the interaction, the pressure from the magma intrusion can widen existing fractures or even create new fractures around the fault, enlarging the fault zone. This activity can change the geometry and behavior of the fault, creating a new fault zone that is difficult to observe directly, which is then referred to as an Inferred Fault Zone. These zones play an important role in subsurface dynamics, including as a pathway for hydrothermal fluid migration, which can contribute to the formation of geothermal resources or certain mineralization. Identification of IFZ often requires analysis of geophysical data, such as resistivity or gravity, as well as interpretation of geological structures based on deformation patterns. The pool is then heated by rainfall and water infiltration from the Lebong River, so that it has a relatively low resistivity which can be assumed that there is magma activity on the surface. Geological evidence and surface manifestations indicating the presence of magma strengthen this assumption. Further explanation for this statement is the existence of hot water swimming pools built by local residents in the northeastern part of the area, where hot water manifestations are present on the surface.

This study shows that the geothermal potential detected comes from the Hululais volcanic system, which is located to the southwest of the geothermal manifestation in the Lemeu region, Lebong Regency. The geothermal manifestation can be interpreted as a flow zone of a geothermal system, as the study site is quite far from the Hululais volcanic system. In this case, the heat source comes from the Hululais volcanic system, which has created a system of geothermal reservoirs around the Lemeu zone (Fig.1). The lateral migration of the Sumatra fault zone is responsible for the presence of ZIF in this region. The

presence of hot springs in the Lemeu, Uram Jaya, and Lebong areas is one of the driving factors for the development of geothermal systems due to the active annual nature of the Sumatra rift. Considering the presence of hot springs in the study area, geothermal system development could be stimulated by the active Ketahun sector of the Sumatra Fault Zone. A resistivity cross-section showing three distinct conductive zones was created using a 2D model (Fig.7).

In the geothermal system in this research area, there are three main components, namely, Heat source, Reservoir, Caprock, and Fault. The 2D Inversion Modelling results (Fig.7) show that the blue layer has a low resistivity value (1.3-3.7 $\Omega.m$), which is indicated as the Fault Zone area. The existence of a fault zone can generally be identified as a conductive zone with the presence of fractures that have the potential to be filled with fluid, causing the resistivity value in the fracture to have a low resistivity value, while the bedrock or basement rock is characterized by a resistive zone (Pratama et al., 2021). When the measurement depth is at 3 km, the layer experiences a fracture that has the potential to be the Ketaun subfault zone that has not been mapped (Fig.7). This fault zone can be formed from the parent fracture, namely the Ketaun fault, which interacts with magma intrusion, causing fluid to enter the fracture which is then heated by the hot rock layer, resulting in a low resistivity value (Rahmawati et al., 2024). The layer that has a low resistivity value near the surface is indicated as a cap rock area or can also be suspected as a rock undergoing alteration, which has a resistivity value of around (6.21-29 $\Omega.m$), (Al Ansory et al., 2023) at a relatively shallow depth of between 1 km which is marked in green.

The low-temperature conductive alteration minerals, considered to be the host rock of the geothermal system, lie between one and two kilometers below the surface and are thought to dominate the study area (Moore et al., 2008). Most people believe that these minerals come from rocks that form geothermal systems. The cover layer in a geothermal system can be formed due to condensation of fluids or vapors at low temperatures at shallow depths, forming layers of condensation. Zones that have moderate resistivity values that have a resistivity value range (140-230 $\Omega.m$) are generally spread at depths of more than 2-6 km with varying thicknesses marked in red. This zone is thought to be a geothermal reservoir. Reservoirs usually consist of rocks such as sandstone, limestone, or volcanic rocks that have been fractured, allowing fluids to move easily.

The last zone is a zone that has a high resistivity value and is commonly called a resistive layer marked in dark red. Its resistivity value ranges from 390 to 650 $\Omega.m$. This zone is spread at depths below 7-9 km, which is the heat source zone. The heat source heats the fluid (water or vapor) trapped in the reservoir, creating a high-temperature gradient that is the basis of geothermal energy. The red arrow in (Fig. 7) shows that the cap rock is connected to the reservoir; it can be assumed that the conductivity is in the rock and acts as a fluid. The fluid in it usually rises to the surface through rocks that are rich in permeability, most of which are faults. Conduction activity along the fault is one of the possibilities for heat transmission between the reservoir and the heat source. Based on the geological map (Fig.2), the research area is located in the strain zone formed by the Ketahun Fault. The results of the study show that the rock structure in the research area consists of volcanic rock units; the main component of the formation is altered andesite volcanic deposits that have undergone vitrification alteration and mineralization.

MT measurements to improve model resolution are an important step in improving the results obtained. At this stage (Fig. 7), the resulting 2D resistivity model only includes seven MT measurement points. With the addition of MT points, it is expected that the resulting subsurface structure model will be more accurate and detailed. In addition, further development can be done by creating more 2D profiles or even compiling a 3D model through the integration of several 2D profiles. MT data has the potential for rich information, which can improve model resolution, especially in identifying the direction and source of geothermal energy more clearly. This will support a more accurate interpretation of the distribution and origin of geothermal energy, while providing deeper insights for scientists.

6. Conclusions

The MT data was inverted in 2D to produce initial resistivity structures. The 2D model suggests that resistivity values could range from 10 to 650 $\Omega.m$, which could indicate the presence of surface layers. The 2D model suggests that the first layer may be a cover rock, as it is conductive and has a resistivity of less than 80 to 140 $\Omega.m$. This conductive zone may extend to a depth of two to three kilometers. Below the top layer, at a depth of two to six kilometers, there appears a zone of moderate to high resistivity of 230 to 650 $\Omega.m$. Despite the application of novel structural and geological methods, the final two-dimensional model appears to be consistent with the prevailing geological data for the region. Geological evidence and magnetotelluric data have verified the Lemeu geothermal system. This theory is supported by hot springs located close to MT F3, which is a flow zone. This study is the initial effort to use the magnetotellurics technique to analyze this geothermal system. It would be beneficial for future research aims to fill the remaining gaps in our knowledge.

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