RGNZ/MGPB

Rudarsko-geološko-naftni zbornik
(The Mining-Geology-Petroleum Engineering Bulletin)
DOI: 10.17794/rgn.2025.4.2

Original scientific paper

Assessment of Geothermal Potential in Kepahiang District Using the Magnetotelluric Method for Renewable Energy Development

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Abstract

Indonesia, located on the Pacific Ring of Fire, has 147 volcanoes, with 76 still active, creating optimal conditions for geothermal energy development. Kepahiang Regency in Bengkulu Province is particularly promising for geothermal exploration, evidenced by hot springs, fumaroles, and other geothermal phenomena. This study aims to enhance subsurface analysis through a detailed Magnetotelluric (MT) survey, utilizing 17 strategically placed stations near geothermal manifestations and fault zones. The MT method is highly effective for deep geothermal resource exploration, as it measures natural geomagnetic field variations to assess subsurface electrical resistivity. Data were collected over 16 hours at different frequencies (128 Hz, 1024 Hz, 4096 Hz) and analyzed using MAPROS, ZONDMT1D, and ZONDMT2D software, producing detailed subsurface resistivity models. The results identified low-resistivity zones at various depths, indicating potential geothermal reservoirs with hot fluids and thermally altered stones. Notably, the measurements revealed a heat source in the upper layer with a resistivity of over 350 ohm-m, and at point 3L1, the presence of a cap rock beneath the manifestation at a depth of 1-2 km with a resistivity of 0.7-1.6 ohm-m. Below this cap rock, a hot rock layer with a resistivity exceeding 350 ohm-m was detected. These findings highlight promising targets for further exploration, including directional drilling to confirm the presence and feasibility of geothermal resources. Developing geothermal energy in Kepahiang could offer a sustainable energy source, reduce fossil fuel dependence, and support regional economic growth by creating jobs and lowering greenhouse gas emissions.

Keywords:

Kepahiang, magnetotelluric, geothermal, resistivity

1. Introduction

Indonesia is one of the countries located in the Pacific Ring of Fire (**Masum and Ali Akbar, 2019**), with 147 volcanoes, 76 of which are still active (**Bhaskara, 2017; Hamna et.al., 2024**). Indonesia's position on the Pacific Ring of Fire, combined with its many active volcanoes, supports significant geothermal energy potential. Kaba Volcano is one such active volcano. Bengkulu Province, Sumatra, the geological and historical background of Mount Kaba reflects the dynamic processes that characterize this seismically active region (**Azhari Aziz Samudra, 2024**). The region is known for its high tectonic and volcanic activity, which creates ideal geological conditions for the formation of geothermal energy sources. Mount Kaba is part of the Sunda Arc, a volcanic arc formed by the subduction of the Indo-Australian Plate beneath the Eurasian Plate. This tectonic boundary creates intense geological forces, leading to the formation of stratovolcanoes like Mount Kaba. The mountain features several craters and is primarily composed of volcanic stones and pyroclastic deposits from previous eruptions. Mount Kaba has a recorded history of eruptions. Most of these eruptions are phreatic or explosive, caused by the interaction of magma with water. The eruptions have been relatively small, with ash emissions impacting surrounding areas. Historical data indicates that eruptions occurred periodically, with moderate impacts on local communities and ecosystems (**Fahmi et al., 2015**). Mount Kaba is considered active, as it has exhibited eruptions and volcanic activity in recent history. Its most recent eruption occurred in 2000, which involved ash emissions. Monitoring systems are in place to observe any signs of renewed activity, given its potential hazards. High tectonic activity refers to frequent movements of the Earth's lithospheric plates, including subduction, collision, and faulting. Indonesia's position within the Pacific Ring of Fire makes it prone to high tectonic and volcanic activity. Mount Kaba, as an active

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Received: 17 September 2024. Accepted: 14 February 2025.
Available online: 27 August 2025

stratovolcano, exemplifies this dynamic geological environment, with its history of eruptions and ongoing potential for future activity (**Mather, 2015**). According to **Veloso et al. (2020)** and **Jolie et al. (2021)**, the most productive geothermal wells are found in Tertiary volcanic or volcaniclastic systems. One of the areas in Indonesia that shows indications of geothermal resources is the Kepahiang Region, Bengkulu Province (**Maghfira et.al., 2023**). Kepahiang Regency is known to have promising geothermal potential, characterized by the appearance of manifestations of hot springs, fumaroles, and other geothermal phenomena around the area.

Geothermal energy offers excellent potential to be developed as a renewable energy source in the Kepahiang Region to fulfil energy needs sustainably. The heat source within the Earth is inexhaustible and can guarantee a consistent supply of energy with high efficiency and minimal environmental impact (**Jannat et al., 2022; Zaher et al., 2023**). In addition, geothermal energy has lower electricity production costs and higher capacity factors (>95%) compared to other renewable energy production (**Vonsée et al., 2019; Amoatey et al., 2021**).

Therefore, the utilization of geothermal energy in the region can make a significant contribution towards reducing dependence on fossil fuels and reducing greenhouse gas emissions (**Ball, 2021**). If this potential can be optimized, geothermal energy can be used as an energy source for Geothermal Power Plants. Some previous studies, such as those conducted by **Lase et al. (2024)** and **Purba et al. (2024)** have included geothermal surveys in the Kepahiang area with several methods and different points. The principal advantage of this research is that it is conducted by installing a substantial number of stations across a broad area, thereby facilitating the acquisition of more comprehensive and detailed information on subsurface structures through the Magnetotelluric (MT) method.

The Magnetotelluric (MT) method is commonly used to investigate deep geothermal resources as it can characterize the electrical resistivity of deep geothermal system structures (**Pellerin et al., 1992; Spichak and Manzella, 2009; Muñoz, 2014; Mitjanas et al., 2021; Pace et al., 2022**). MT is a passive geophysical technique that utilizes naturally occurring geomagnetic variations as a resource. In MT surveys, two electric field components (Ex and Ey) and three magnetic field components (Hx, Hy, and Hz) are measured (**Saibi et al., 2021**), which can provide comprehensive information about the geological structure and thermal conditions in the area in 1D and 2D. Using MT can explore geothermal by showing the associated conductivity anomaly and its thermal gradient (**Everett and Hyndman, 1967; Yadav et al., 2020**). It is anticipated that this will be employed in the construction of wind farms, which not only offer a sustainable source of energy but also enhance the welfare of local communities by creating new employment opportunities and stimulating the regional economy.

2. Geological and geothermal settings

The Kepahiang Region of Bengkulu Province is renowned for its substantial geothermal potential, situated within the Bukit Barisan Mountain zone, specifically in the Kaba Volcano Complex. The area is home to a diverse range of volcanic landscapes, encompassing volcanoes of both Tertiary and Quaternary age (**Larasati et al., 2023**). The existence of volcanoes along this zone is followed by the emergence of geothermal systems scattered in several areas, one of which is the Kepahiang Geothermal Field. Apart from volcanoes, activity in the subduction zone also produces fractures or long faults on the island of Sumatra, which are called the Sumatra Fault. The geological characteristics of this area are dominated by volcanic and sedimentary formations formed from volcanic activity due to the proximity of Mount Kaba. Mount Kaba is classified as an active volcano where apart from the geothermal activity around it, volcanic activity and earthquakes still occur with moderate frequency of occurrence so that Kaba volcanic activity is monitored by the Indonesian volcano monitoring agency. Geologically, the stones around Mount Kaba are generally of Early Quaternary age. According to **Nurdiyanto et al. (2014)**, the geological data of the Kepahiang Geothermal Area indicates the presence of impermeable stones with clay mineral properties belonging to the montmorillonite and kaolinite types, which are particularly abundant in the area surrounding the Sempiang alteration manifestation. The alteration process produces argillic to advanced argillic alteration types, indicating high temperature and acidity conditions. This zone functions as an impermeable layer (cap rock) that is important for trapping geothermal fluids underneath, thus supporting the potential for geothermal energy development. These alteration stones exhibit characteristics of argillic to advanced argillic types.

The geological structure found in this region is a fault that trends northwest to southeast, as shown by the numerous fumarole occurrences, hills, waterfalls, faults, and igneous stone breakouts. Active tectonic circumstances are indicated by the features of the developed geological formations (**Li et al., 2019**). The term “developed geological formations” is used to describe the results of the formation of stone layers and geological structures that continue to change or experience new formation due to various geological factors, including tectonic activity, volcanism, and sedimentation. In the context of active tectonics, evolving geological formations indicate that the area is still experiencing dynamic processes that affect its geological structure and composition. Kepahiang Regency’s stratigraphy is made up of Quaternary and Tertiary eras. The Hulusimpang Formation (Tomh), Seblat Formation (Toms), Granite (Tmgr), Lemau Formation (Tml), and Simpangaur Formation (Tmps) are the units that make up the tertiary stratigraphic units. The Bintunan Formation (QTb), Old Volcanic Stones (Qv), Bukit Kaba Volcanic Breccia Unit

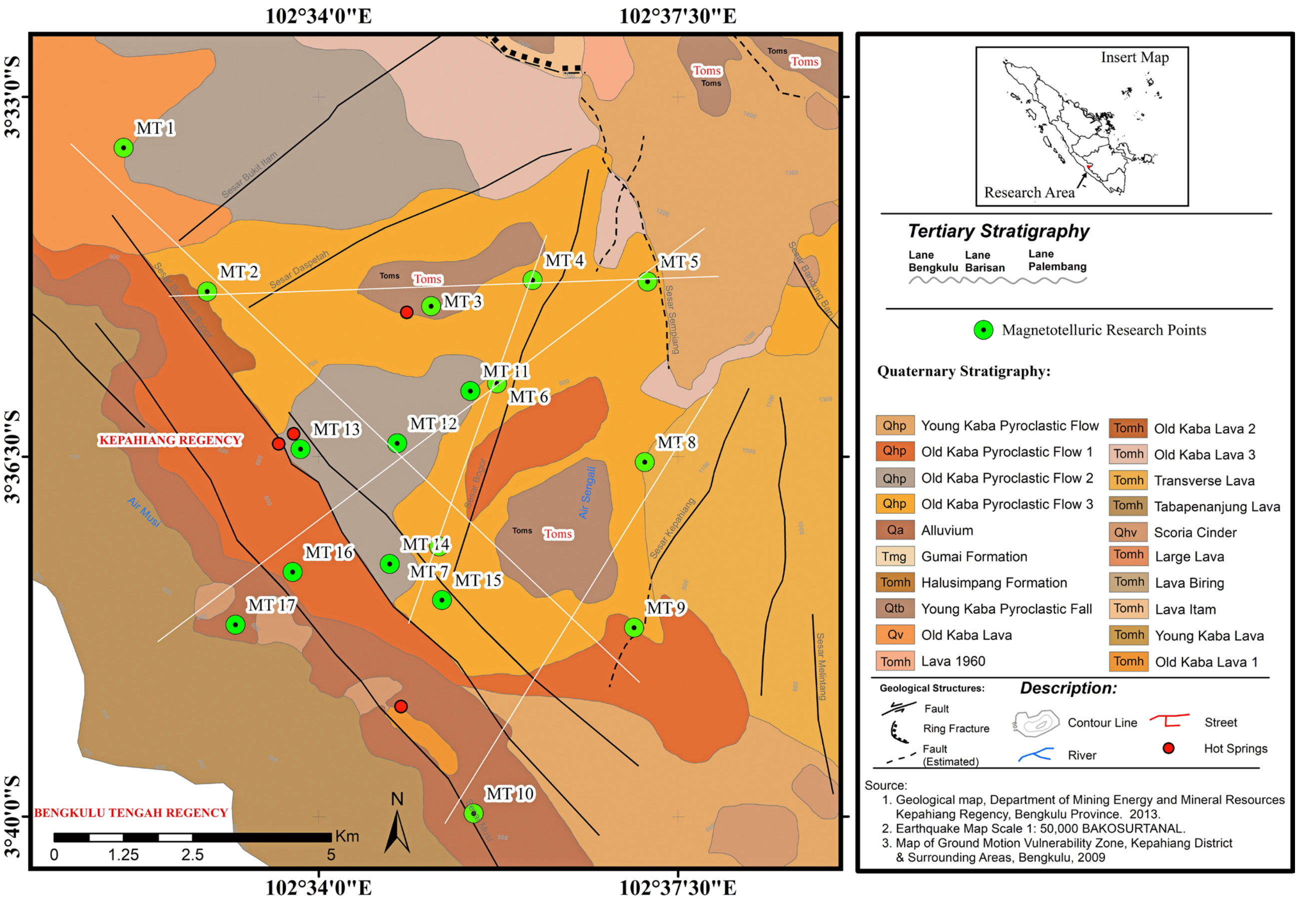

Figure 1. (a) Geological map of the study area modified from **Gafoer et al., 2007** and **Irwanto et al., 2013**

(Qhvk), Swamp Deposits (Qas), and Alluvial (Qal) are the quaternary stratigraphic units that make up this group (**Hadi et al., 2024**). The earliest Tertiary sedimentary stone in the Bengkulu Basin is called the Hulusimpang Formation (Tomh). It is made up of sedimentary stones that were regressively deposited in the late Oligocene to late Miocene ages (**Heryanto, 2006; Farid et al., 2021**). The andesitic to basaltic lavas, volcanic breccias, and tuffs that make up the Hulusimpang Formation lithology (Tomh) are often altered and include quartz, veins, and sulfide minerals (**Sihombing et al., 2018**). The Old Volcano Unit Formation (Qv) is a Holocene – Pleistocene geological age formation composed of lithologies of andesite-basalt lava, tuff, and volcano breccia. The thickness of this formation is about 300 m spread in the northwest corner of the Bukit Barisan zone. The depositional environment is terrestrial to shallow marine (**Firdasari and Idarwati, 2017**).

The Figure above consists of two parts that provide scientific information about the geothermal potential in Kepahiang Regency, Bengkulu Province. **Figure 1** is a detailed geological map depicting various stone formations, faults, and other geological structures. On this map, magnetotelluric measurement locations marked with codes (MT1 – MT17) indicate essential points in the study of geothermal potential. The map also shows significant faults, such as the Musi Fault and Ketahun Fault, which have a substantial role in the formation of geological structures in the region.

Table 1. Coordinates of measurement point MT

No	Site	UTM Easting	UTM Northing
1	MT1	226145	9606337
2	MT2	227660	9603763
3	MT3	231702	9603510
4	MT4	233533	9603982
5	MT5	235606	9603964
6	MT6	232895	9602127
7	MT7	231857	9599201
8	MT8	235565	9600725
9	MT9	235379	9597755
10	MT10	232494	9594415
11	MT11	232414	9601991
12	MT12	231096	9601048
13	MT13	229352	9600942
14	MT14	230968	9598886
15	MT15	231911	9598240
16	MT16	229216	9598736
17	MT17	228187	9597789

Figure 2 is a topographic map that uses colour grading to show the elevation variations in the area, focusing on

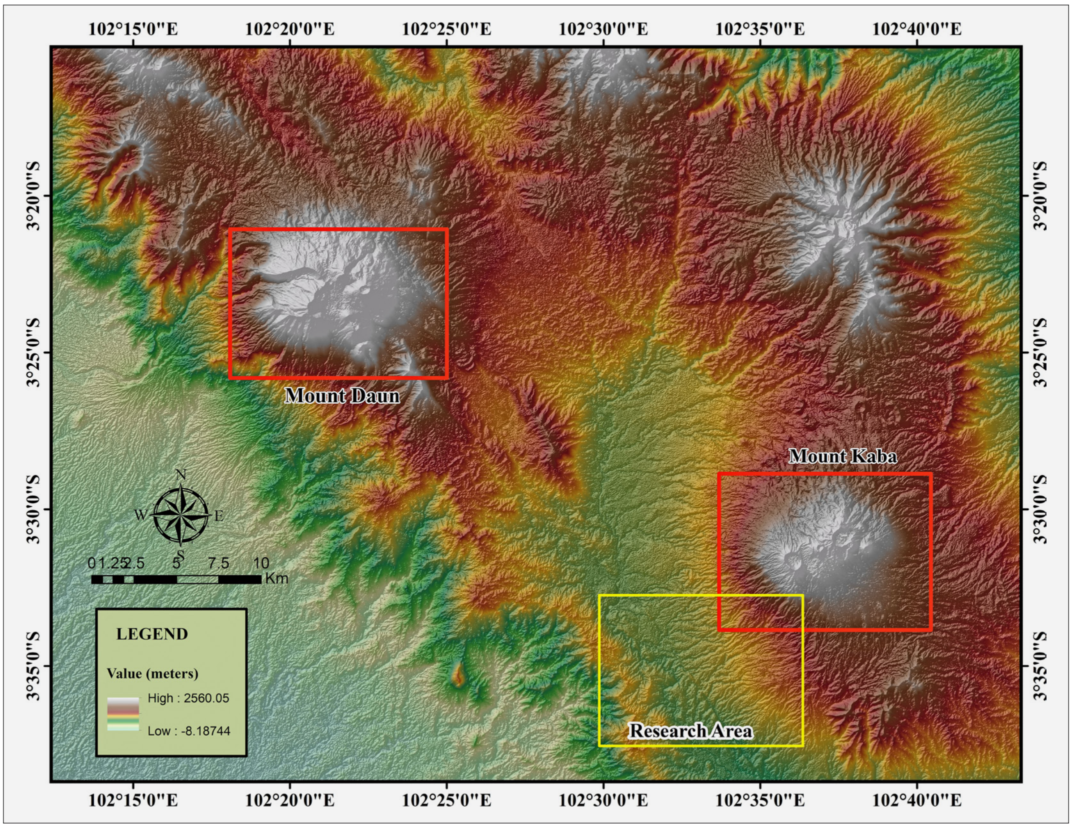

Figure 2. Elevation Map showing the study area in Kepahiang Regency, Bengkulu Province, Indonesia

two main topographic features, namely 'Gunung Daun' and 'Gunung Kaba'. These two areas are mapped in greater detail as they are considered to have significant geothermal potential. The yellow area is a correlation between the geological and topographic data displayed on this figure providing a strong scientific basis to support the exploration and development of geothermal resources in Kepahiang Regency. The research area is adjacent to Mount Kaba, indicating that the geothermal potential of the research area comes from Mount Kaba, but in **Figure 2** there is Mount Daun, which is located not too far from the area. Mount Daun is also a volcano. The formation of heat sources on Mount Kaba and Mount Daun is due to the influence of the Musi segment.

3. Method

a. Magnetotelluric (MT) survey at Kepahiang Regency

Magnetotelluric (MT is a passive geophysical method that uses the normal temporal fluctuations (Hx, Hy, and Hz) of the magnetic field and the Earth's electric field (Ex and Ey) (**Singh, 2023**). Geographic north, east, and vertical depth are all congruent with the x, y, and z directions (**Ishizu et al., 2021**). Electrical and magnetic sensors were used in MT data acquisition to capture data in the field. The five porous pots that make up the electrical sensor are arranged as follows: two are positioned horizontally (Ex, Ey), and one is positioned vertically (Ez) as the ground. Magnetic sensor with 2 coils placed horizontally (Hx, Hy) and 1 vertically (Hz) (see **Figure 3**). To measure the electric field component at the Earth's surface, unpolarized electrodes are positioned in four primary directions (west, east, south, and north) as part of the equipment setup for the magnetotelluric technique measurement.

Furthermore, the magnetic field component is measured in three directions using magnetic sensors: vertical, east-west, and north-south. A data logger device records the data from these electrodes and sensors, which is then examined in more detail. The gadget runs on a battery and has a GPS and GSM connection for precise measurement and location recording, as well as real-time data transfer. This arrangement is commonly used in magnetotelluric surveys, which aim to understand underlying characteristics and aid in the finding of geothermal resources in Kepahiang Regency.

Geothermal exploration in Kepahiang District was conducted at 17 spatially distributed measurement stations (see **Figure 3**). The location of hot water manifestations that surfaced and the separation between the measurement locations and the faults were taken into consideration while allocating measurement stations (see **Figure 3**). MT signals were recorded for 16 hours with three signal frequencies, namely low frequency (128 Hz), medium frequency (1024 Hz), and high frequency (4096 Hz) with the Metronix/ADU-07e device.

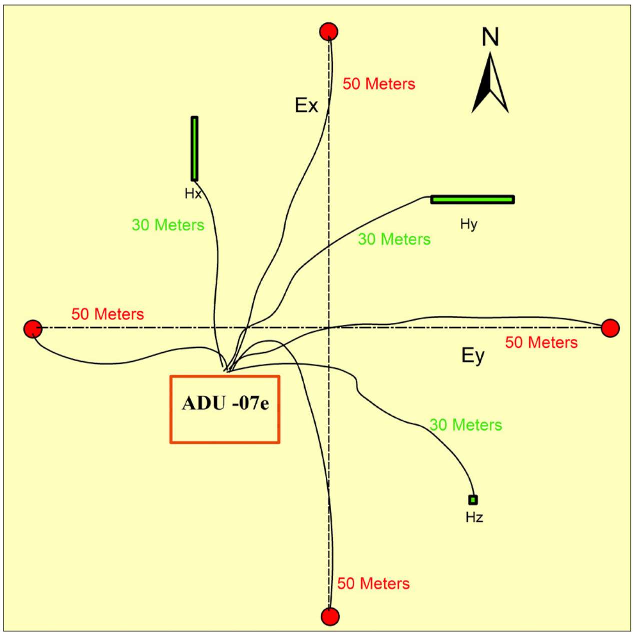

Figure 3. A typical layout for a standard MT recording station (re-drawn) (**Saibi et al., 2021**)

b. Data analysis

The derivation of equations for the MT method was developed following the Cagniard approach (**Hadi, 2007**). The basic assumptions used in the Cagniard approach are that the Earth is considered a horizontal layer where each layer has homogeneous isotropic properties, and natural electromagnetic waves interacting with the Earth are plane waves. By assuming that the Earth is homogeneous isotropic (**Hadi et al., 2009**), the physical properties of the medium do not vary with time, and there is no source of charge in the medium under review, so Maxwell equations are obtained in the form:

$$\nabla x\boldsymbol{E} = -\mu \frac{\partial H}{\partial t} \quad (1)$$

$$\nabla X\boldsymbol{H} = \sigma E + \varepsilon \frac{\partial E}{\partial t} \quad (2)$$

$$\nabla \cdot \boldsymbol{E} = 0 \quad (3)$$

$$\nabla \cdot \boldsymbol{H} = 0 \quad (4)$$

Where:

E = Electric Field (Volt/m),
H = Magnetic Field (Ampere/m^2),
∂t = Change in time (second).

If the variation with time is expressed as a sinusoidal function, then the equation will be obtained (**Grant and West, 1965**):

$$E(r,t) = Re\boldsymbol{E}(r,\omega)e^{i\omega t}$$

$$H(r,t) = \mathrm{Re}\,\boldsymbol{H}(r,\omega)e^{i\omega t} \quad (5)$$

Where:

$E(r,t)$ = the electric field as a function of position r and time t,
E(r,ω) = the electric field in the frequency domain, where ω is the angular frequency. This function typically describes the spectrum of the field at different frequencies,
Re = this denotes the real part of the expression, since the electric field is a real physical quantity,
$e^{i\omega t}$ = a complex exponential that oscillates in time with frequency ω.

Then **Equation 5** becomes:

$$\nabla^2 \boldsymbol{E} = i\sigma\mu\omega\boldsymbol{E} - \varepsilon\mu\omega^2\boldsymbol{E}$$

$$\nabla^2 \boldsymbol{H} = i\sigma\mu\omega\boldsymbol{E} - \varepsilon\mu\omega^2\boldsymbol{H} \quad (6)$$

Where:

∇^2 = the Laplacian operator, which represents spatial derivatives (typically the second spatial derivatives),
E = the electric field (Volt/m),
σ = the electrical conductivity of the material,
μ = the permeability of the material,
ω = the angular frequency of the electromagnetic wave,
ε = the permittivity of the material,
H = the magnetic field (Ampere/m^2).

Skin Depth is the distance of attenuation of electromagnetic waves in a homogeneous medium such that it becomes 1/e (~37%) of the amplitude at the surface. By using a quasi-static approach and assuming a permeability value $\mu = \mu 0 = 1,256x10^{-6}$ H/m, and inputting the frequency $(\omega 2\pi f)$ (**Zonge and Hughes, 1988**), it is obtained:

$$\delta = 503\left[\frac{\rho}{f}\right]^{\frac{1}{2}} \quad (7)$$

where:

δ = skin depth (m),
ρ = resistivity of homogeneous medium (Ωm),
f = electromagnetic wave frequency (Hz).

The inversion technique, which models and determines the connection between apparent resistivity and genuine resistivity, may be used to find the real resistivity value when resistivity values on Earth are heterogeneous. Time series data from 17 measurement locations were analyzed with MAPROS software. Station points were taken in 2022 and processed and analysed using MAPROS software (**Lubis et al., 2021**). The most recent section and subsurface information was then obtained by reprocessing the data using station data from 2024. The time series data from the MT survey were processed using the software programs MAPROS (see **Figure 3**), ZONDMT1D, and ZONDMT2D to create a subsurface model. After

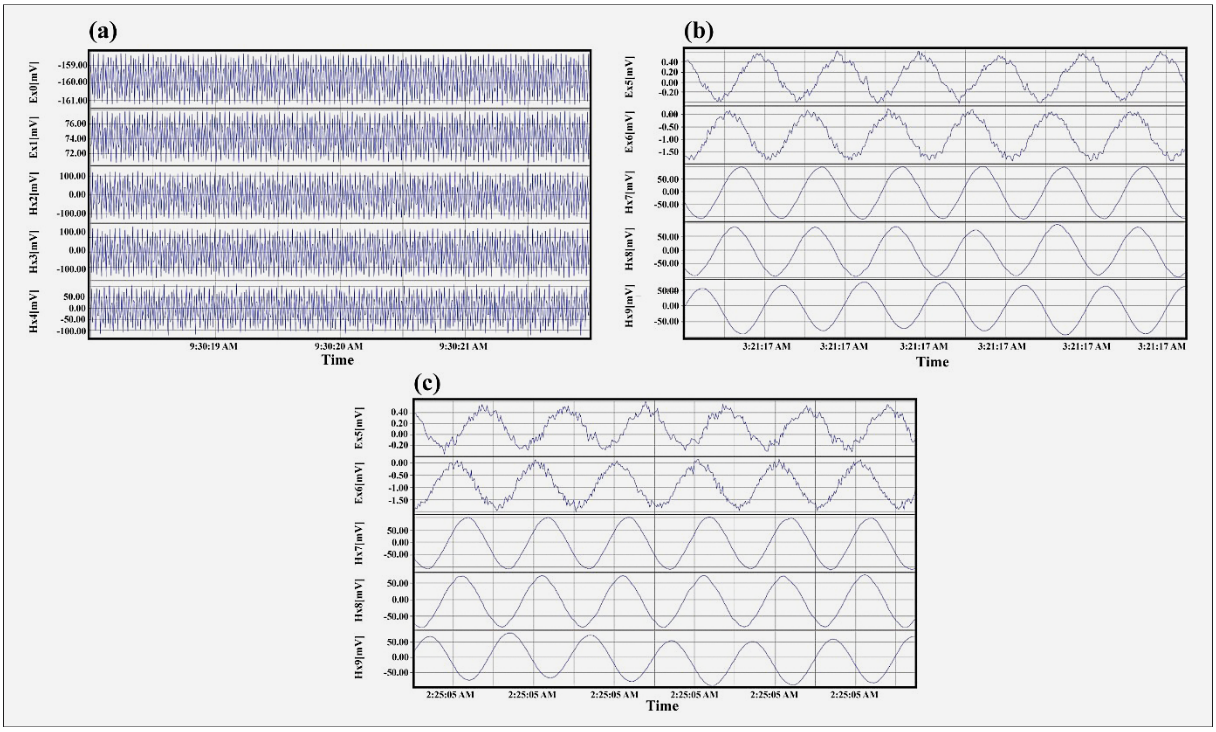

Figure 4. (a) Time Series Data Frequency 128 Hz, (b) Time Series Data Frequency 1024 Hz, (c) Time Series Data Frequency 4069 Hz.

noise in the E and H time series has been eliminated, Mapros is utilized for the Fast Fourier Transform (FFT) approach to transform MT time series data into apparent resistivity and phase-amplitude. Using the produced EDI files from the MAPROS processing, subsurface structures are built in the ZONDMT1D and ZONDMT2D processing. Electronic Data Interchange (EDI) is a standard file format for storing and sharing MT survey data. It is used to store comprehensive information about electric and magnetic field measurements, including location parameters, impedance data, and other metadata. The underlying structure of the Earth is displayed by the inverse ZONDMT1D and ZONDMT2D processing outputs, which exhibit the resistivity (ρ) model (Ωm) as a function of depth Z (m) (**Suhendra et al., 2024**). Interpretation of this resistivity data makes it possible to identify stone layers with conductive properties that may signal the presence of geothermal fluids (**Ars et al., 2024**). Thus, areas with consistently low resistivity can be identified as target zones for further exploration.

To analyze the quality of the data acquired, time series measurements were conducted at different frequencies in the Kabawetan sub-district. The data findings from the Kepahiang inquiry into time series analysis and impedance linear system theory, as interpreted by numerical modelling approaches, are shown in **Figure 4**. As the data is collected over time, time series analysis represents an essential method for its processing. The integration of time series analysis and linear impedance theory facilitates a more precise and efficacious interpretation of subsurface structures. Data compression Noise that was observed during data capture was eliminated using MT processing. To see the properties of the signal and the recorded noise, time series data was acquired from the acquisition of the electric field on the x and y axes and the trailer signal's magnetic field on the z, y, and x axes for each sound. The time series data was converted into the frequency domain of the spectrum via Fourier transform, which allowed further processing to be performed. At a low frequency of 128 Hz (see **Figure 4a**), data taken for 13 hours showed very minimal noise with a stable voltage between 500 mV and -500 mV, indicating excellent data quality. At a medium frequency of 1024 Hz (see **Figure 4b**), the Hx2, Hy3, and Hz4 magnetic field measurements with voltages between 40 mV to 50 mV showed stable data without interference from magnetic storms or other H and E field sources. This measurement was conducted for 2 hours on 09 May 2024, starting from 05:20 to 07:20 UTC, which was converted to 12:20 to 02:20 AM. At a high frequency of 4096 Hz (see **Figure 4c**), the resulting signal in the form of sinusoidal waves also shows good data quality with a relatively stable saturation level, as evidenced by the lack of noise and the stability of the positive and negative numbers produced. These overall measurement results indicate that the data obtained are of excellent quality, which can be used as a basis for further analysis. Study of impedance values estimated using the least squares method.

c. Inversion

One-dimensional (1D) inversion is used to analyze Magnetotelluric (MT) data and generate sounding curves that show the variation of earth resistivity with depth. The variation of the earth's resistivity with depth refers to the change in the resistivity (electrical resistance) of materials under the earth's surface as depth increases. This resistivity is influenced by various factors, such as stone type, mineral content, temperature, porosity, and the presence of fluids (such as water, oil, or geothermal fluids) in it. In this study, all MT stations were processed with the 1D inversion method using eight different data sets of apparent resistivity (ρ) and layer thickness. The iteration process was performed 20 times until an RMS (Root Mean Square) value of less than or equal to 15% was obtained. Root Mean Square (RMS) is a statistical measure used to evaluate how well the inversion model results match the actual measurement data. In the context of geophysical inversions such as Magnetotelluric (MT), RMS is used to assess the error or difference between observed data (real data) and synthetic data (modelled data).

4. Results and discussion

Resistivity distribution in high-enthalpy geothermal fields usually depends on clay minerals, temperature, and lithology of volcanic deposits (**Saibi et al., 2021**). The primary purpose of this 2D MT model is to clarify the geometry of formation boundaries and the central resistivity anomalies (**Pavez et al., 2022**). This research shows that the geothermal potential found comes from the volcanic system of Kaba Volcano, which is located to the southwest of the geothermal manifestation in the Kepahiang Area, Kabawetan District (see **Figure 2**). The Kaba Volcano Complex System includes the Kepahiang Geothermal Area. In addition to other volcanic products like Bukit Lumut in the northwest, Taba Panan-jung in the southwest, and Bukit Malintang in the southeast, the mountain generates two primary types of eruption products: those of Old Kaba and those of Young Kaba. The stone units are made up of surface deposits, pyroclastic tumbles and flows, lahars and dacitic, andesitic, and basaltic andesitic lavas (**Nanang Sugianto et al., 2022**). Geothermal manifestations can be interpreted as outflow areas in geothermal systems because the research location is quite far from the volcanic system of Kaba Volcano. The volcanic system of Kaba Volcano is what creates the formation of geothermal reservoir systems around the Kepahiang Area (see **Figure 1**). The existence of this geothermal resource can be attributed to the presence of the active Musi Fault in the Sumatra Fault Zone (**Hochstein and Sudarman, 1993**). Activation of conductivity along faults represents heat transmission between the reservoir and the heat source (**Saraswati et al., 2019**). Fault information is characterised by significant changes in resistivity values, these faults are usually seen as zones of low resistivity due to fractures filled with fluid or conductive minerals. Hot fluids in the Kepahiang Geothermal System are bicarbonate and sulfate types in the immature water zone (**Shalihin et al., 2024**). The presence of hot springs and altered stone near the Air Sempiang and Babakan Bogor Regions of Kepahiang Regency is indicative of the presence of geothermal systems in the area. Kaba Volcano is the source of the geothermal energy. The changed section of the manifestation has a high concentration of kaolinite and montmorillonite clay minerals, indicating the presence of impenetrable stones in this location. The modified stones belong to the advanced argillic to argillic class. Kaba Volcano's pyroclastic flows and lava products revealed the change (**Raharjo et al., 2022**).

The geothermal manifestation of the research area is situated at an outflow location in the geothermal system, close to the Kaba volcanic system. The geothermal manifestation, which is close to the Kaba volcanic activity's upflow activity, shows how the geothermal system at Kepahiang is coherent with the modern volcanic system (**Lubis et al., 2021**). The geothermal resources in the Kepahiang Region closely resemble the scenario put forward by (**Nicholson, 1993**), according to which the fluid originates in the infiltration region. Here, the lateral movement of the Sumatra Fault Zone seems to have broken up the area around Babakan Bogor and Air Sempiang, resulting in the formation of a fumarole system due to the heat source from the volcanic system at Kaba volcano (see **Figure 1**). Data interpretation is based on comparisons of stone resistivity. These substances have the power to alter stone's resistivity. The resistivity value range in stones will widen due to the overlap brought on by water-filled stone pores, making it more challenging to differentiate between different types of stones (**Hadi et al., 2009**).

1D Modelling in MT research is an important tool for understanding the vertical structure of subsurface resistivity. This method is highly beneficial in geothermal exploration, helping to efficiently identify reservoir layers, overburden and other geological structures. Despite its limitations, 1D Modelling remains a crucial first step before moving on to more complex analyses. These results provide an overview of the subsurface resistivity distribution, as generated from the Kepahiang geothermal field measurement site, to identify potential geothermal resources. Geothermal systems depend on the interaction between reservoirs, overburden, faults, and stones within a geological framework. Each of these elements has an important role in supporting the existence and sustainability of geothermal resources (**Wallis et al., 2018**). At the Kepahiang Geothermal Field measurement site, 1D Modelling results are used to map the subsurface resistivity distribution. Resistivity is closely related to the properties of stones and geothermal fluids, such as mineral content, temperature, and salinity.

1D Model is one of the basic approaches in geophysical analysis that is useful for understanding the subsurface structure (**Chandran and Anbazhagan, 2017**). Resistivity vs depth graph showing varying resistivity val-

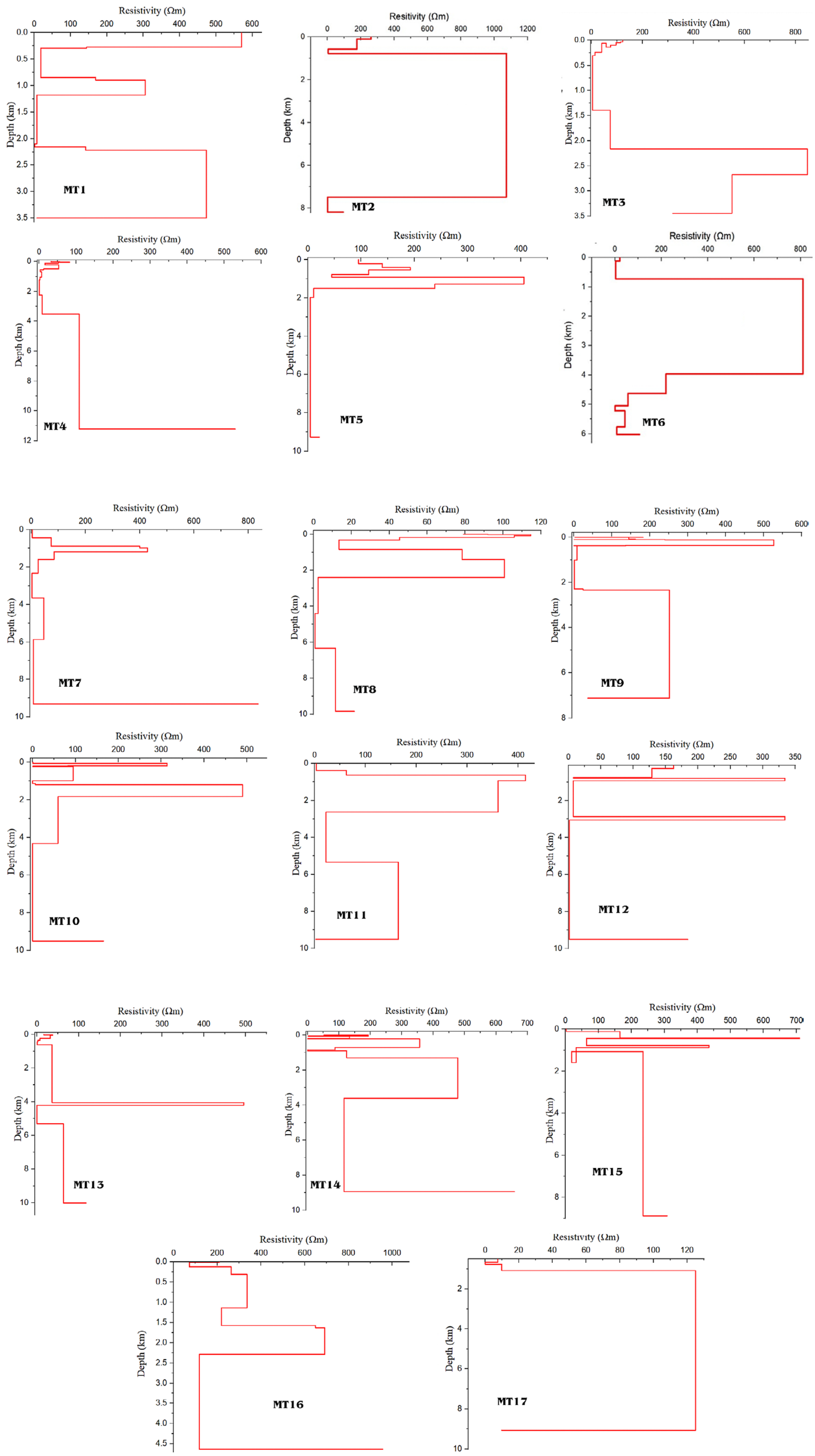

Figure 5. This is the 1D curve from the inversion result

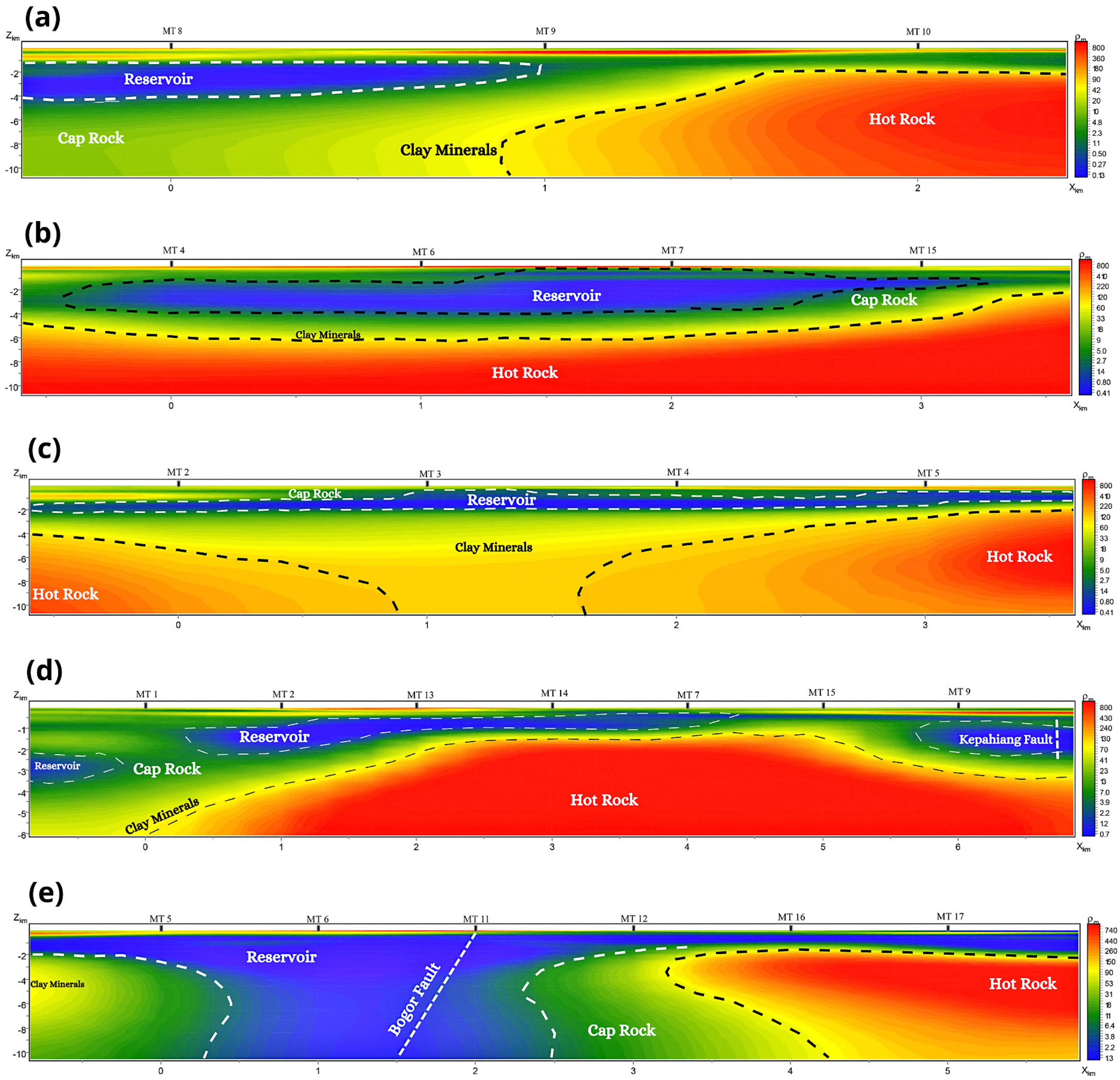

Figure 6. 2D modelling of 5-line Magnetotelluric Method Inversion

ues (0.13-800 Ωm) and depths ranging from (0-10 km) in each MT data measurement. The red line shows the depth range, which aims to determine whether there is a relationship between resistivity values and the depth of the ground surface. The graph also displays a red line that shows a certain depth range, with the aim of identifying the relationship between resistivity values and depth from the ground surface. **Figure 5** illustrates the relationship between resistivity and depth as a result of 1D Inversion of MT data. 1D modelling is a very important tool in geothermal research, which serves as an efficient method for analyzing reservoir systems, cap rocks, and structures related to faults. This analysis provides important information about the vertical resistivity distribution, which can be used to: Identify reservoirs, namely stone layers that have moderate to low resistivity values, indicating hot fluid content; determining the presence of cap rock layers, which typically have high resistivity due to their dry and non-permeable nature; detecting fault-related geological structures that may act as pathways for hot fluid migration. Although limited to vertical interpretation, its ability to provide rapid insight into subsurface properties makes it indispensable for guiding further exploration efforts.

Variations in the graph were observed at each measurement point. This disparity arises due to different resistivity readings indicating variations in the constituent materials at each measurement location. The presence of manifestations in Air Sempiang and Babakan Bogor, as well as the Musi Fault, can accommodate many measurement stations for magentotelluric (MT) surveys that use a variety of resistivity values. The interaction of the Musi Fault results in the formation of structural weak zones or fracture zones. This zone is formed by tectonic activity that creates fractures, faults, and cracks in the stone. The combination of permeable fractures and hydrothermal activity makes this zone important for geothermal exploration. In this study, the subsurface structure of the Kepahiang Regency geothermal field area has varied characteristics, reflecting the geological complexity of the area.

The output of five geophysical sections created by inverting magnetotelluric (MT) data was used to explore geothermal resources in Kepahiang Regency (see **Figure 6**). The change in subsurface resistivity to a depth of 10 km with different horizontal distances is shown in each of the sections (a, b, c, d, and e) with five lines (see **Figure 1**). More conductive materials, denoted by lower resistivities and seen in blue, are frequently found near hot fluids or in stones that are saturated with water. On the other hand, more resistant materials, such as solid or dry stone, have greater resistivities, which are shown in red.

The resistivity pattern in the research region is quite similar to the resistivity expected for geothermal systems. The zone of relatively low resistivity (0.13-2.9 Ωm) is simulated as a hot water region (geothermal reservoir) with the geothermal section located deeper than 2 km. It is believed that this zone has a porous, permeable geothermal reservoir with the ability to transport and hold fluids (**Larasati et al., 2023**). The underlying metamorphic rocks are accompanied by carbonate conglomerates and limestone (**Relindo, 2021**). By using geometry analysis, the geothermal reservoir's depth has been determined. According to **Saibi (2018)**, the reservoir is below (2-4 km) in depth. The hot rock region, which is located at a depth of 2-10 km, might be represented by the reported zone of moderate to relatively high resistivity (130-800 Ωm) at the lower level of the model.

Line (a) shows that the first (uppermost) layer (1) is the saturated geological layer that is shallow and has a resistivity range from (29-90 Ωm), indicating clay stone (clastic sedimentary stone) (**Murad et al., 2012**), The second layer (2) is conductive and has a resistivity of 1.1–10 Ωm. It reaches depths of 2–4.2 km and a low resistivity zone of 0.1–2.38, which may suggest the presence of hot fluids or geothermal heat-affected stones. At a depth of 5 to 10 kilometers, the third layer (3) is a medium to high resistive zone (250-800 Ωm). Line (b) shows a transition zone at a depth of (2-4 km) that may be connected to variations in subsurface heat conditions as well as conductive clay minerals (45-120 Ωm). The geothermal system cover stone, or cap rock, is characterized as the resistivity zone (2.7–18 Ωm). Cap rock acts as a reservoir cover to stop geothermal fluids from leaking or escaping (**Suhaidi et al., 2022**). Caprock functions as a seal over the reservoir to prevent the migration of fluids such as oil, gas, or water out of the reservoir. However, under some conditions, caprock can lose its effectiveness as a seal, leaving the reservoir vulnerable to leakage. Tectonic activity, overpressuring, or weathering can cause cracks to form in the caprock, which become pathways for fluid migration to the upper layers or even to the surface. In addition, if the caprock has high permeability due to the presence of fine sand or natural fractures, its ability to hold fluid is limited, allowing fluid to seep out. Fault movement due to geological or operational stresses can also open up migration pathways within the caprock, resulting in fluid leakage. To minimise such risks, an in-depth analysis needs to be conducted, including an evaluation of caprock integrity, reservoir pressure and potential geomechanical risks. To prevent fluids from migrating out of the reservoir, cap rock can also create a seal or barrier over the reservoir stone (**Alviandari et al., 2018**). According to the information that the depth and temperature functions are directly proportional, line (c) has a zone of medium to high resistivity with the highest temperature, ranging from 130 to 800 Ωm. This zone is identified as hot rock and is composed of granite, which has a high temperature but very low permeability and little fluid stored. Under impermeable stones, the lowest resistivity zone (0.41-1.1 Ωm) is studied as a reservoir. The resistivity zone (2.7–45 Ωm) serves as a cap rock to keep the reservoir's heat accumulation process going. Vapor condensation at shallow levels or lower temperature fluids can be the source of cap rock generation in geothermal systems (**Pavez et al., 2020**), which will result in the formation of a condensate layer. According to (**Clarissa et al., 2020**), cap rock retains heat and hot fluids in the system like a hat because of its high conductivity. Hot rock is defined as a high resistivity zone (120-800 Ωm). This technology makes use of the heat that is stored in non-permeable, low-porosity stones.

The relationship between these resistivity cross-sections and surface geothermal manifestations is also critical to the interpretation of the data. There appears to be a direct relationship between the geological conditions below the surface and the surface-level geothermal manifestations; hot springs are one example of geothermal manifestations that are located above or next to underlying zones of low resistivity. This demonstrates that the low resistivity zone at a depth of around 4–8 km may be the heat source or fluid movement channel that generates the geothermal manifestations, such as hot springs if they are discovered above line (d). The measurement findings show that there is a heat source with resistivity >350 Ωm in the top layer. The finding of fumarole manifestations that come to the surface, which appear due to groundwater breaking through fractures in contact with volcanically heated stones (**Wulandari et al., 2018**), point MT13 indicates the presence of host stone connected to the reservoir, which implies the presence of conduction channels that function as fluid channels, and point MT9 indicates the suspicion of the Kepahiang Intermediate Fault. This cap rock has a resistivity of 0.7–1.6 Ωm and is found at a depth of 1-2 km. The overlying layer is typically made up of stone layers that have changed as a result of fluid interaction with the stones it passes through, and hot rocks with a resistivity of >350 Ωm have been found beneath the overlying stone.

Line (e) is a 2–10 km deep zone of low resistivity (1.3–2.9 Ωm). Faults are present, according to the measurement findings. A fault is a zone or plane of fracture in stones that has experienced movement. The Sumatra Fault System, which is northwest-southeast orientated and moves dextrally, is where the regional geological structure of the study area is situated (**Khoirunnisa et al., 2024**). Due to the Indian Ocean Plate pushing against the Eurasian Plate, creating a thrust zone along Sumatra Island's West Coast, this fault is still actively moving (**Hadi, 2009**). The interaction of these faults results in some compression zones experiencing folding and thrust faulting, while the stretch zones experience depression and normal faulting (**Saputra, 2024**). One of the sites inside this depression zone is the Kepahiang region in the Kabawetan Subdistrict. A portion of these common faults serves as a conduit for magma that rises to the surface to create volcanoes. Geological data (see **Figure 1a**) confirms that this track section is situated close to the fault. The Bogor Fault is present, as shown by Point A6. Geological data refers to the Bogor Fault as the Sub-Musi Fault, which forms the incursion and volcanic region of Mount Kaba. A cap rock that is linked to the reservoir is seen in line (e), suggesting the existence of a deep conduction channel that serves as a fluid conduit. This cap rock is situated in the area of the almost north-south Bogor Fault System. Apart from the data on modification, young and old lavas of the Kaba product that have not undergone substantial agglomeration can also be considered as host stone (**Ilmi et al., 2020**). Deeper-level fluids often follow the most permeable paths to the surface, which are primarily faults (**Sihombing et al., 2024**). Between the heat source and the reservoir, one possible route for heat transport is through conductive processes along fault lines (**Farid et al., 2023**). The results show that the stone structure in the study area consists of volcanic stone units, the primary formation of which is alternated and mineralized andesitic volcanic deposits. The findings from this resistivity cross-section provide a solid basis for further exploration, including directional drilling, to confirm the presence and feasibility of geothermal reservoirs, which could support the development of geothermal energy in Kepahiang**.**

5. Conclusions

This research shows that there's a lot of potential for geothermal resources in Kepahiang Regency, Bengkulu Province. We did a full magnetotelluric (MT) survey at 17 measurement stations to find out more. The data inversion results show that there are low resistivity zones at specific depths that could be geothermal reservoirs. The resistivity vs. depth relationship in 1D modelling is crucial for identifying and characterizing geothermal systems. By serving as a stepping stone for 2D modelling, 1D data provides accurate vertical information that, when interpolated across multiple locations, enhances spatial understanding and ensures robust, multi-dimensional geothermal analysis. This is in line with what we're seeing at the surface in the form of hot springs. The low resistivity zone at about 4-8 km deep could be linked to hot fluids or geothermal-affected stones, as well as the presence of host stones at 1-2 km deep. The study found that there is a fault in the area, which is the Sub-Musi Fault or, more specifically, the Bogor Fault and estimate of Kepahiang Fault. This is because this area is prone to fracturing due to the lateral movement of the Sumatra Fault Zone. The Sumatra Fault zone (Musi Segment) is active. It is thought to be the reason behind the formation of geothermal systems, including the emergence of hot springs in the Air Sempiang and Babakan Bogor Areas of Kepahiang. The 2D modelling results show that the high-density stones are likely to be Kepahiang geothermal sources, while the low-density stones are probably fault zones and porous stones. This suggests there's a strong possibility of a geothermal system with great potential for further exploration. All components (host stone, reservoir, migrating fluid, and hot rock) are commonly found in conventional geothermal systems, but their nature and presence vary depending on the type of system (volcanic, non-volcanic, or enhanced geothermal systems). An understanding of the relationship between these elements is essential for sustainable geothermal energy development. The findings of this research provide a robust scientific foundation for the advancement of geothermal energy as a sustainable and renewable energy source. This development has the potential to reduce the reliance on fossil fuels, mitigate greenhouse gas emissions, and enhance the economic well-being of surrounding communities. However, further exploration, including directional drilling, is necessary to confirm the presence and viability of identified geothermal reservoirs. This will facilitate the development of geothermal power plants in the region.

Acknowledgement

The research team expresses gratitude to LPPM Bengkulu University for funding this study through PNBP, under contract number 2962/UN30.15/PT/2024. The Metronix ADU-07e Geophysical Laboratory Equipment was used in this study. The authors also extend their appreciation to the Farid Research Group (FRG) team for their assistance with data collection

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SAŽETAK

Procjena geotermalnoga potencijala u okrugu Kepahiang magnetotelurskom metodom za razvoj korištenja obnovljivih izvora energije

Indonezija, smještena na Pacifičkome vatrenom prstenu, ima 147 vulkana, od kojih je 76 još uvijek aktivno, što stvara optimalne uvjete za razvoj korištenja geotermalne energije. Okrug Kepahiang u pokrajini Bengkulu posebno je prikladan za istraživanja geotermalnoga potencijala, o čemu svjedoče vrući izvori, fumarole i drugi geotermalni fenomeni. Cilj je ovoga istraživanja poboljšati analizu podzemlja putem detaljnoga magnetotelurskog (MT) istraživanja 17 strateški postavljenih postaja u blizini manifestacija geotermalnih pojava i rasjednih zona. MT metoda vrlo je učinkovita za istraživanje dubokih geotermalnih resursa s obzirom na to da mjeri prirodne varijacije geomagnetskoga polja za procjenu podzemnoga električnog otpora. Podatci su prikupljani tijekom 16 sati na različitim frekvencijama (128 Hz, 1024 Hz, 4096 Hz), a analizirani su korištenjem softvera MAPROS, ZONDMT1D i ZONDMT2D stvarajući detaljne modele otpornosti. Rezultati provedenih analiza otkrili su zone niskoga otpora na različitim dubinama upućujući na potencijalna geotermalna ležišta i termičke anomalije u stijenama. Naime, mjerenja su otkrila izvor topline u gornjemu sloju s otporom od preko 350 Ohm-m, a u točki 3L1 prisutnost krovine ispod manifestacije na dubini od 1 do 2 km s otporom od 0,7 do 1,6 Ohm-m. Ispod navedene krovine detektiran je sloj vruće stijene s otporom većim od 350 Ohm-m. Ovi rezultati poticajni su za daljnja istraživanja uključujući usmjereno bušenje kako bi se potvrdila prisutnost i iskoristivost geotermalnih izvora. Razvoj korištenja geotermalne energije u Kepahiangu mogao bi ponuditi održivi izvor energije, smanjiti ovisnost o fosilnim gorivima i podržati regionalni gospodarski rast stvaranjem radnih mjesta i smanjenjem emisije stakleničkih plinova.

Ključne riječi:
Kepahiang, magnetotelurska metoda, geotermalno, otpornost

Author's contribution

Muchammad Farid (Prof, Full Professor, Disaster Mitigation) provided analysis and interpretation of the 2D Magnetotelluric Method of Geothermal Potential. **Hery Suhartoyo** (PhD, Associate Professor, Mined Land and Forest Rehabilitation) created digital geological maps and analyzed geological maps. **Arif Ismul Hadi** (Prof, Full Professor, Seismic Hazard Analysis) analyzed the results of geological maps and inversion results of geothermal modelling. **Refrizon** (Chief Professor, Geophysics) analyzed field data. **Andre Rahmat Al Ansory** (Researcher, Geophysics) retrieved and processed data. **Hana Raihana** (Researcher, Geophysics) wrote and edited the manuscript.
All authors have read and agreed to the published version of the manuscript.