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Delineating Resistivity Values of Potential Geothermal Areas Along the Bogor Fault Using 2D Magnetotelluric Inversion

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Abstract

Kepahiang Regency, located in an active fault zone, has great geothermal potential with an estimated capacity of up to 154 MW(e), making it a strategic renewable energy source to be developed. This research discusses the geothermal potential in the Kabawetan area, Kepahiang, Bengkulu. The main objective of this research is to evaluate the potential of geothermal resources around the Bogor segment by analyzing the subsurface structure using the Magnetotelluric inversion method and 2D resistivity modeling, in order to identify prospective geothermal reservoir zones. It can evaluate the potential of geothermal reservoirs in Kepahiang. The method used is the Magnetotelluric method, which utilizes the Earth's natural electromagnetic field to determine the distribution of resistivity in the subsurface. The results of 2D modeling with the MT method show potential zones associated with variations in subsurface thermal conditions and the presence of conductive clay minerals with resistivity values between 0.14-1 Ωm. These minerals are thought to be associated with the overburden (reservoir) of the geothermal system that has a depth of 2-4 km. The subsurface layer containing hot water and steam originating from heat emitted from the earth's core with a resistivity value of 2.5-45 Ωm at a depth of 1-4 km is thought to be caprock in the geothermal system, a resistivity value of 120-800 Ωm is thought to be hot rock with a depth between 1.5-10 km. It is estimated that there is a type of andesite rock that has been fractured as a reservoir of geothermal fluid. The findings of this research are expected to contribute to renewable energy as an alternative energy in the future, not only for energy needs but also for regional economic development through tourism and to support sustainable governance.

Introduction

Indonesia has abundant geothermal potential due to its geographical location in the ring of fire [1], so it holds considerable potential for geothermal utilisation, so that it can be used for power generation [1]. Electrical energy from geothermal energy is clean because the emissions produced are very small compared to burning fossil fuels to be converted into electrical energy [2]. The development and utilisation of geothermal energy, which is renewable energy and environmentally friendly, has the potential to be financed under the Kyoto Protocol's 'Clean Development Mechanism' scheme, so that it has an important meaning and is expected to overcome energy and environmental problems [3]. The increasing world demand for energy availability is a problem that must be solved. One way to solve this problem is by utilising alternative energy, namely geothermal energy which is a relatively clean and renewable energy source [4]. This causes Bengkulu Province to have a high level of seismic activity as a result of the plate movement [5]. Another result of the plate movement is that Indonesia is divided into many regions bounded by many active faults [6].

Bengkulu Province has a fault that is divided into 3 segments, namely the Musi, Ketahun, and Manna segments [7]. Kepahiang Regency is located in the area around the Musi Segment which allows geothermal, one of which is in the Kabawetan area. Geothermal manifestations on the surface, such as hot springs and hot water vapour appear on the surface. Research needs to be done to find out how much geothermal heat there is in the Musi segment area. Geothermal reservoirs generally have relatively low porosity, permeability, and density compared to the surrounding environment [8]. Rock formations in the Kepahiang Regency area are Andesite, Breccia Tuff, Scoria and Basalt which are partly the result of alteration by hydrothermal activity [9].

Based on research conducted by [10], The results showed that the geothermal distribution in Kepahiang reaches a depth of between 1.5 km to 5 km and reaches a depth of 3000 meters from Taba Tebelet to Pagar Gunung. Another research conducted by [11] said that geothermal prospects in Kepahiang are spread in several places, such as Babakan Bogor, Barat Wetan, Pematang Donok, Tangsi Duren, Sido Makmur, and Air Sempiang. In these locations, the reservoir depth is estimated to reach 900 meters, and the parent rock is gabbro. Research in the same area has also been conducted by [12], who revealed that in the Babakan area, Bogor, there are hot springs and fumaroles. However, the location is quite far from Kaba Volcano. Realising the existence of this geothermal phenomenon, [13] then conducted research on geothermal distribution in areas far from Kaba Volcano. Meanwhile, research conducted by [14] states that the depth penetration of the Musi Segment Fault in Sumatra, especially located in Kepahiang, reaches a depth of about 20.51 km.

Research on geothermal reserves can be known by using geophysical methods [15]. One of the most popular geophysical methods used for geothermal exploration is the Magnetoteluric method [16]. Magnetoteluric is a method to describe the distribution of resistivity or electrical conductivity under the earth's surface by passively measuring the sources of electric and magnetic fields found in nature on the earth's surface [17]. The purpose of this research is to determine the potential of geothermal resources in the area around the Bogor segment with magnetoteluric inversion through 2D resistivity modelling and to determine the potential of geothermal reservoirs in Kepahiang which will hopefully contribute to the community and government as a reference in providing information about renewable energy as an alternative energy in the future for the construction of Geothermal Power Plants (PLTP) which not only provide a sustainable source of energy but can also improve the welfare of local communities for local economic development through geotourism.

Geothermal and regional geology

The Kepahiang region has geothermal potential that is very interesting to study, which is found in several places, including Mount Kaba and Bukit Daun which are Tertiary-Quaternary volcanoes [18]. This is based on geological information [18]. Hot springs, fumaroles, alteration rocks, solfatara, and teralterated rocks are manifestations that indicate the presence of geothermal reserves [19]. The heat source is a crucial component of a geothermal system [20]. Generally, the heat source is underground magma connected to rocks that are denser than the surrounding rocks [21]. Kepahiang is surrounded by young Quaternary volcanic hills consisting of lava, tuff and weathered volcanic sediments, forming undulating plains [22].,[23]. The alteration area near the Air Sempiang manifestation consists of impermeable rocks containing clay minerals such as kaolinite and montmorillonite. Argillic to advanced argillic alteration is found in pyroclastic flows and lavas of Mount Kaba. The Sempiang fault zone, which runs north-south, is the main location of the host rocks [21]. The young lavas of Kaba products serve as the overlying rocks, while Tertiary sedimentary and volcanic materials cover Quaternary deposits. The history of Mount Kaba is characterised by explosive eruptions that produced Old Kaba I-III lavas and pyroclastic flows and falls [24].,[25]. The Semangko Fault, which runs from Aceh in the north to Teluk Semangka in Lampung in the south of Sumatra Island, is one of the faults influencing the geology of Kepahiang [26]. The Great Sumatran and the Sumatra Fault are other names for this fault [26]. Figure 1 depicts the Kepahiang Regency's regional geology.

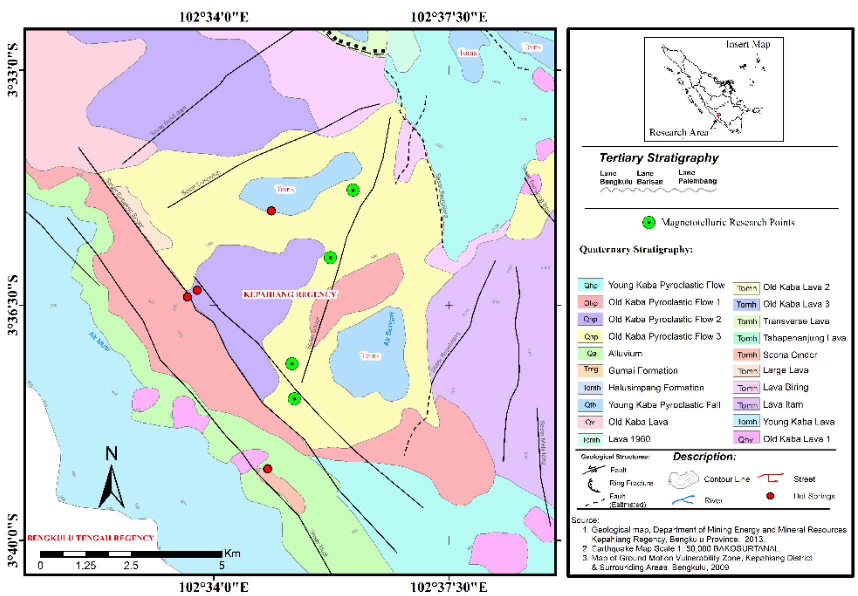

Figure 1. Detailed geological map of the study area modified from [27]

Numerous rock types in Kepahiang Regency change as a result of hydrothermal activity. Geological formations include the Quaternary Volcano Formation, Diorite, Gumai Formation, Hulusimpang Formation, Sebelat Formation, and Kaba Volcano Formation in the area [28]. There are other types of rocks, including Scoria, Andesite, Tuff Breccia, and Basalt. Veil rocks with a high concentration of montmorillonite and kaolinite clay minerals can be found in the alteration area where Mount Kaba's pyroclastic flows and lava erupted [28]. The Sempiang fault zone, which stretches nearly north-south, is where these host rocks are [21].

Method

This research uses the adu-07e metronics tool in Kabawetan District, Kepahiang Regency. Field measurements were conducted on 05-08 May 2024, with 4 measurement stations scattered around the Bogor fault. The bogor fault is one of the active faults located on the island of sumatra. Such active faults are often indicative of tectonic movements that can affect geothermal formation and potential. kepahiang district is located in an area on the bogor fault, which has high geothermal potential. Researching the area around the Bogor fault can open up opportunities for more efficient geothermal utilisation in the area, as well as contributing to the development of geothermal energy in Indonesia. To support this research, using the ADU-07e MT method with an estimated range of 10 Km. Each measurement station is correlated to obtain a 2D model. The 2D results are used to see the geothermal distribution and depth. Magnetotelluric method is an effective geothermal exploration technique, which measures the variation of natural magnetic and electric fields in the time domain using magnetic and electric sensors [17]. Due to its advantage in detecting the different resistivity or conductivity of different types of rocks and fluids below the earth's surface, Magnetotellurics is a frequently used technique in geothermal exploration. This method is effective in determining the depth of heat sources in geothermal systems [29].

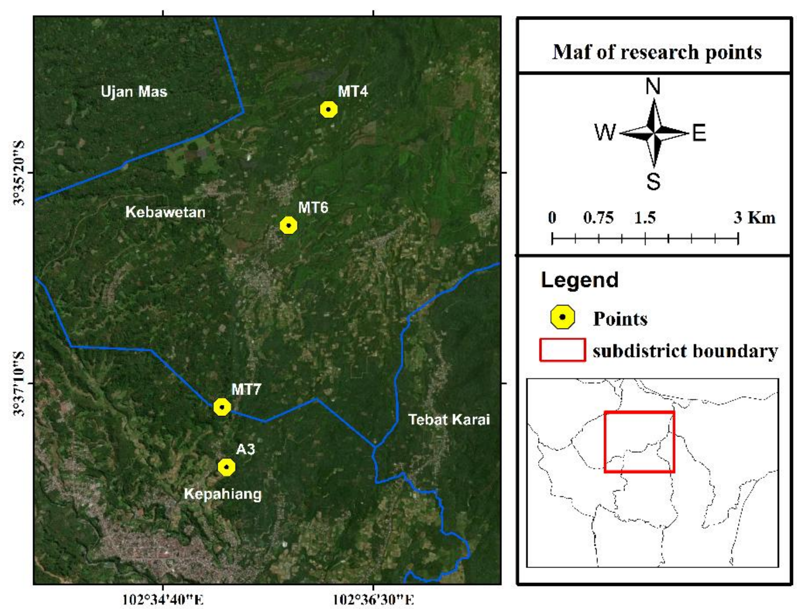

Figure 2. Location of the research point

MT data acquisition is carried out with electrical sensors and magnetic sensors to record data in the field (Figure 3). The electrical sensor consists of 4 Porous pots, where the pots are placed according to the 4 cardinal directions (north, south, west, east). The Porous pots are important in MT data acquisition as they ensure a stable signal and minimal noise when measuring the natural electric field, with the electrolyte solution and porous walls facilitating ion exchange with the soil. The magnetic sensor consists of Coils placed parallel to the X, Y, and Z axes to capture the horizontal and vertical components of the magnetic field at the Earth's surface in the time domain [24]. The purpose of the Coils is to measure variations in the earth's magnetic field with high sensitivity, aiding the identification of rock conductivity, mineral resources, and geological structures. MT signals were recorded for 16 hours, the results were taken with Low frequency (128 Hz) requires 13 hours of recording because it is prone to noise, but can penetrate deeper and is suitable for materials with high resistivity. medium frequency (1024 Hz) with a recording duration of 2 hours, aiming to transition from low frequency to high frequency. high frequency (4096 Hz) with a recording time of 1 hour because High frequency is used to investigate shallow layers and detect materials with low resistivity. Frequency selection in MT is important to control signal penetration, adjust subsurface resistivity, reduce noise, and obtain an accurate geological picture. The combination of frequencies enables mapping of layers from shallow to deep, supporting natural resource exploration.

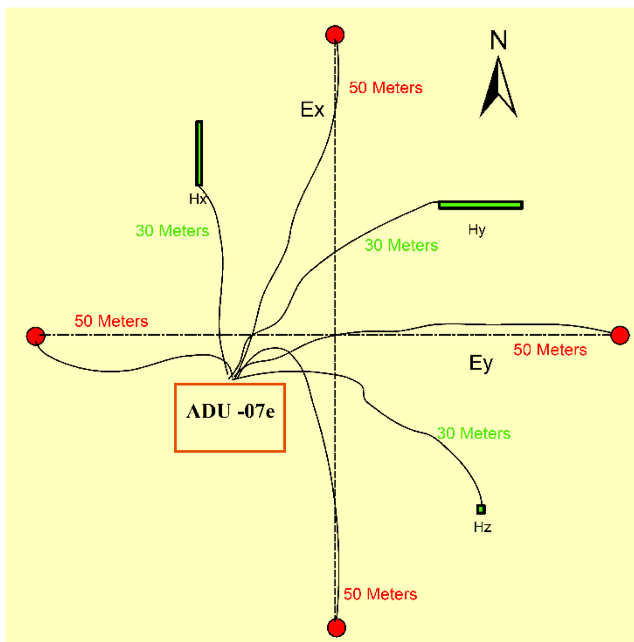

Figure 3. Magnetotelluric arrangement in the internal coordinate system [30].

The signal source of the Magnetotelluric method comes from a time-varying electromagnetic field that comes from lightning and solar wind. Large electromagnetic fields with frequencies above 1 Hz come from lightning. Lightning is a very large and sudden electrical phenomenon, which produces very rapid changes in electric and magnetic fields. This sudden change creates electromagnetic waves at various frequencies, including low to high frequencies due to rapid changes in current and voltage and large energy. while the frequency below 1 Hz comes from the interaction of the solar wind with the Earth's magnetic field caused by the process of the Earth's magnetosphere which is affected by highly charged particles coming from the solar wind solar wind due to magnetic field fluctuations that occur at a very slow rate [30]. the penetration range of EM waves is used to determine skin depth. EM electromagnetic waves in the MT method are used to map subsurface structures by sending signals that propagate through geological layers with different resistivities. The frequency response of the signal received at the surface provides information about the geological structure and distribution of underground materials, The nature of electromagnetic wave propagation into the subsurface of the earth satisfies Maxwell's equations in relation to the magnetic field and Electric field [31]. Here is how the equation is put together:

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

$$\nabla x H = j + \frac{\partial D}{\partial t} \quad (2)$$

$$\nabla . D = q \quad (3)$$

$$\nabla . B = 0 \quad (4)$$

where j is the electric current density (A/m²), D is the electric field (V/m), B is the magnetic induction (W/m²), H is the magnetic field (A/m), and D is the electric charge transfer (C/m²). Many electromagnetic fluxes, including wind and solar lightning, provide signals generated by the Magnetotelluric approach [32].

Data processing was performed using Mapros, ZondMT1D, and ZondMT2D software. Time series is the raw data from the MT tool, collected in regular time intervals (Figure 4).

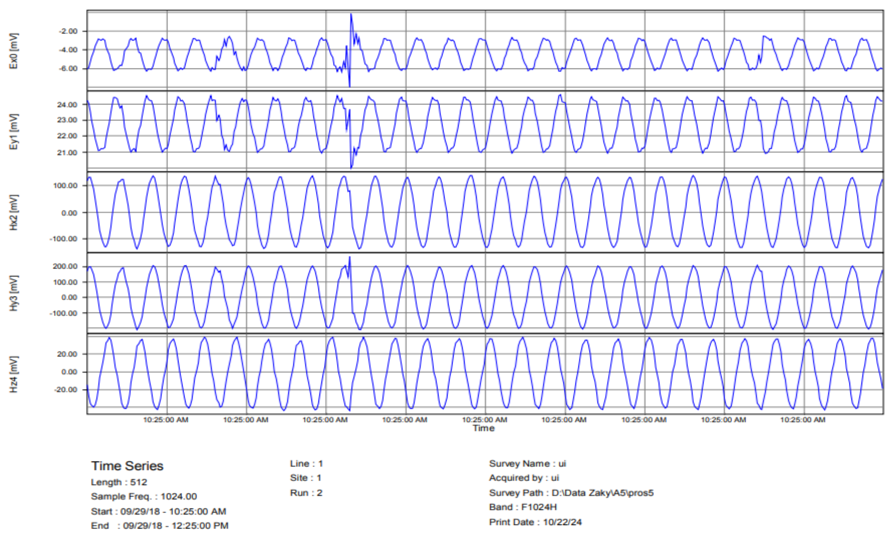

Figure 4. Time series data

ZondMT2D to convert, visualise and analyse subsurface resistivity parameters. Mapros was used to transform the survey data to EDI format, starting with file management, survey and traverse creation, and data import using Easy ATS Import Files. After data editing and filtering, the resulting EDI files were processed in ZondMT1D for resistivity (ρ) and depth (Z) modelling, which were then visualised in Interpretation Mode with specific inversion parameters. Next, processing in ZondMT2D involved dongle installation, file opening and Mesh Constructor activation to improve interpretation resolution. The final stage involves applying various processing options, such as Apply, Pseudosection, and Inversion, before saving and exporting the final results in Save Mod3D format, resulting in a more accurate and structured geophysical model. Inversion methods are indispensable for producing models that can reconstruct the Earth's subsurface data [9].

Result and Discussion

1D modelling is one of the basic approaches in geophysical analysis that is useful for understanding subsurface structures. The graph of resistivity vs. depth shows varying values of resistivity (0-800 Ωm) and depth ranges (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 the resissivity value and the depth of the ground surface. 1D modelling is a rare and important aspect of geothermal research, serving as an efficient method for analysing reservoir systems, overburden, and segment-related structures. In Figure 4, the data is in time data format so the data must be converted or transformed into the frequency domain using the fast fourier transform (FFT). The next step is to correlate the resistivity value and depth from the ground surface. 1D modelling at each sonding point can be used in 2D modelling to obtain the distribution of resistivity values in geothermal areas through the inversion stage, can be seen in Figure 5.

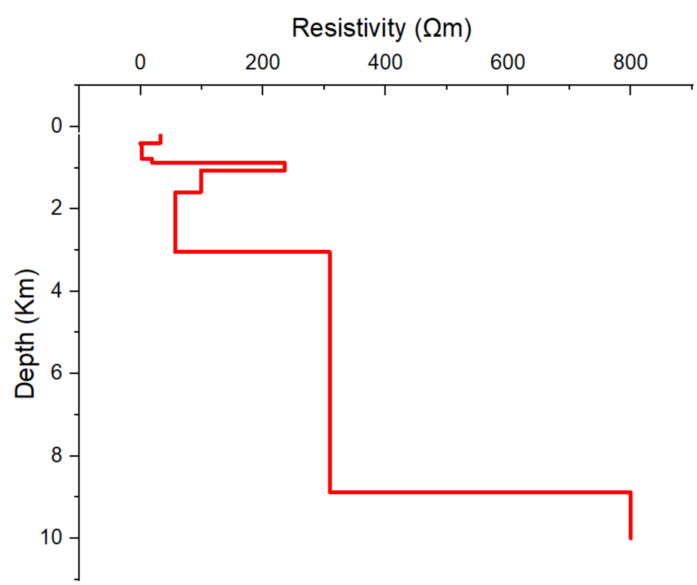

Figure 5. Graph of resistivity against depth in 1D at point A3

The 2D resistivity model was created by inputting MT data used to explore the geothermal resources in Kepahiang district (Figure 6). Changes in subsurface resistivity values to a depth of 10 km with different distances per point. The value of the research results obtained varies, including low resistivity with a value of 20-50 Ωm, medium resistivity of 50-200 Ωm, and high resistivity> 200 Ωm, high resisitivity value is estimated as a heat source [33]. Based on the results of research [34], In the northwest, north, and northeast areas of Kabawetan District, medium-sized total anomalies with values between 0 nT to -1500 nT dominate. The intensity of the most dominant total magnetic anomalies on the distribution map is low, ranging from 0 nT to -1500 nT, indicating that there is geothermal heat in the area. This data shows that the research location is in an area with significant geothermal potential characterised by the presence of manifestations in the research area. The low resistivity zone (0.14-1 Ωm), shown in blue is analysed as a trapped reservoir containing hot water and steam derived from heat emitted from the earth's core at 2-3 km depth. Reservoir layers usually contain rock types that have high porosity and permeability, which allows the flow and movement of fluids such as oil, gas, or water. Rock types that are often found in reservoir layers are Sandstone, Limestone, Limestone and Igneous [35]. The medium resistivity zone (2.5-45 Ωm), shown in green to yellow colour, is thought to be cap rock. Cap rock is a cap rock composed of rock layers consisting of conductive clay minerals and has impermeable properties, which makes it very effective in trapping fluids in the reservoir at a depth of 1-4 Km. This rock also functions as a cover or baffle layer for the underlying reservoir layer, which prevents fluids such as oil, gas, or water from moving up to the surface. Caprock has high conductivity and acts like a hat in retaining heat and hot fluids. high resistivity zones (120-800 Ωm), Ωm shown in orange to red colour are suspected to be hot rock with depths between 1.5-10 km. consists of granitic rocks that have high temperatures but very low permeability and little stored fluid. This hot rock system utilises the heat stored in low-porous and non-permeable rocks [35]. Shown in Figure 6 is a cross-sectional model of restisivity.

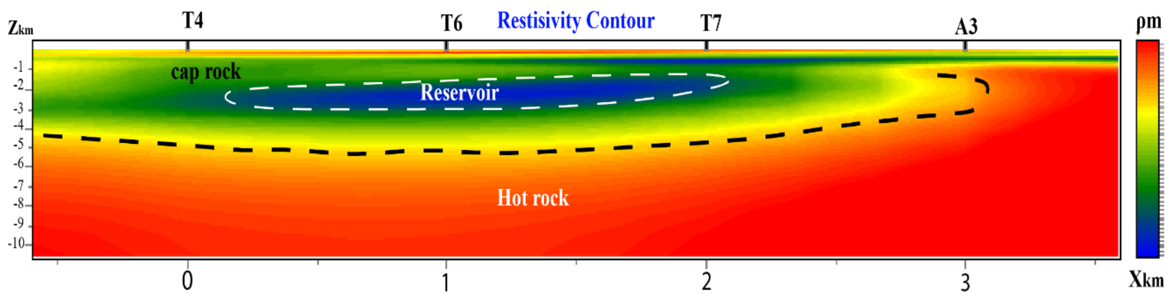

Figure 6. 2D resistivity cross section model

Table 1. Grouping of Resistivity Values (Ωm) according to [36].

No	Resistivity (Ωm)	Depth (Km)	Description
1	0,14-1	2-3	*Reservoir*
2	2,5-45	1-4	*Caprock*
3	120-800	1,5-10	*Hot Rock*

The relationship between resistivity cross sections generated from geophysical data processing and geothermal manifestations at the surface is very important in the interpretation of geothermal data. Geothermal manifestations, such as hot springs, are generally located directly above or very close to zones of low resistivity in the subsurface. These zones of low resistivity indicate the presence of hot fluids flowing within altered rock layers, which are often directly related to active geothermal systems in the subsurface [37]. This suggests a close relationship between subsurface geological conditions and geothermal phenomena visible at the surface, which is important for understanding the potential for geothermal resources in the region.

The results of research conducted in this area show that the existing geological structure consists of dominant volcanic rock units, with the main formation being andesite volcanic deposits. These andesitic rocks have undergone significant alteration and mineralisation processes, which play a role in the formation of hot fluid recharge zones. This alteration, which involves changes in the mineralogy of the rocks due to contact with hot fluids, can reduce the resistivity of the rocks, making them visible as zones of low resistivity on geophysical resistivity cross sections.

The discovery of these resistivity cross sections provides a clearer picture of the distribution and depth of geothermal zones present in the subsurface, which is essential as a basis for further exploration. The knowledge gained from this resistivity interpretation is expected to confirm the existence of geothermal reservoirs that have great potential to be utilised as alternative energy sources in the future. The utilisation of geothermal energy is not only important to support sustainable energy needs, but also to support local economic development. The development of Geothermal Power Plants (PLTP) in the region can provide significant economic benefits to the surrounding communities, through job creation, infrastructure improvement, and contribution to the sustainability of environmentally friendly energy resources. Thus, further exploration of the geothermal potential in the region will not only fulfil energy needs, but can also be a driving force in sustainable clean energy-based economic development.

Conclusion

The 2D modelling results show that the caprock zone at a depth of 1-4 km consists of andesitic lava rock types that have been transformed into impermeable layers and clays. This zone has resistivity values ranging from 2.5 to 45 Ωm. The reservoir layer, which is believed to store geothermal fluids, is located at a depth between 2-3 km and has a resistivity value between 0.14 to 1 Ωm. This layer mainly consists of fractured andesite rocks. Finally, the hot rock layer, which is found at a depth of 1.5 to 10 km, consists of granitic rocks and has resistivity values between 120 to 800 Ωm.

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