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RESEARCH ARTICLE

Estimation Top and Bottom of Bogor Fault, Kepahiang Regency Based on 2D Magnetotelluric Data Analysis

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Abstract

Kepahiang Regency, Bengkulu Province, is an area crossed by the Musi segment of the Sumatra Fault and a number of secondary faults, including the Bogor Fault, which contribute to the high level of seismic activity in the region. The presence of these active faults, combined with a relatively high population density, poses a potential threat to infrastructure and public safety. This study aims to identify the subsurface geometric characteristics of the Bogor Fault, particularly its upper and lower depths, as part of earthquake disaster mitigation efforts. The Magnetotelluric (MT) method was used in this survey with the ADU-07e system, which utilizes natural electromagnetic fields, with two horizontal electrical sensors (Ex, Ey) and three horizontal sensors (Hx, Hy), as well as a vertical magnetic sensor (Hz). Data collection was conducted at six measurement points with a 1 km interval along the Northeast–Southwest transect that crosses the Musi Fault and the Bogor Fault. Data processing was performed using *MAPROS* software for time-domain to frequency-domain conversion, and *ZONDMT2D* for subsurface modeling. The modeling results showed a low resistivity zone at point T6, with values between 0.21–1.6 Ωm, which was interpreted as the presence of the Bogor Fault. This zone was identified at a depth of approximately 2 km and was estimated to extend more than 8 km in the north–south direction. This finding provides important indications of the presence of an active fault in the area and can serve as a basis for earthquake risk mitigation efforts in Kepahiang.

Keywords: Faults, Kepahiang, Magnetotelluric, Resistivity.

1. Introduction

Indonesia is a tectonically active region that is highly vulnerable to tectonic disasters due to the connection between tectonic plates. Thus, Indonesia must remain vigilant against tectonic disasters that can occur on convergence or transformation paths. Tectonic disasters mostly cause material losses and human deaths (Lestari et al., 2020). People living on the island of Sumatra, which is very close to the Sumatra Fault line, including the area in Bengkulu Province, is one of the tectonic threats (Ardiansyah, 2017).

The Bukit Barisan Mountains cross several provinces, including Bengkulu. According to geological science, the subduction pressure of the Indo-Australian Tectonic Plate penetrates under the Eurasian Tectonic Plate and moves at a speed of 50 to 70 mm per year, which causes the formation of the Bukit Barisan Mountains (Sihombing et al., 2024). As a result of this plate movement, Bengkulu Province has a high level of seismicity, especially in the area where the Musi segment of the Sumatra fault crosses Kepahiang Regency. This region is part of the Sunda crust, or sundalanda, which is part of the Eurasian continental plate (Mulyana, 2006). Kepahiang belongs to an area that is rather far from the subduction zone. Nonetheless, tectonic processes cause the formation of geological structures such as folds and faults. Some of these faults are active faults, which often cause earthquakes. The morphology of Kepahiang consists partly of hills to steep hills and partly of plains to undulating plains. The hilly to steep hilly morphology consists of Quaternary-aged volcanic rocks consisting of lava, volcanic breccia and tuff. The morphology of the plains to undulating plains also consists of Quaternary aged deposits consisting of river alluvial deposits, alluvial deposits resulting from weathering (Supartoyo et al., 2019).

The Sumatra Fault is one of the active faults located on the island of Sumatra. The Sumatera fault is a 1900 km long dextral strike-slip fault that splits the island of Sumatra in two from the Gulf of Andaman in the north to Semangko Bay in the south, parallel to the alignment of the subduction zone (Lubis et al., 2019). Bengkulu Province, especially Kepahiang Regency, is crossed by one of the segments, namely the Musi segment, which is one of the segments on the Sumatra fault. According to data from one of the studies on the Musi segment, the Musi segment is directly bounded by the Ketahun segment in the north and the Manna segment in the south, has a length of about 70 km, the width of the dilatational step over zone is about 5.6 km, the geomorphic appearance is a valley depression, the distance from the face deformation or subduction zone is about 260 km, the depth of the Benioff zone subduction is about 15 km (Natawaidjaja and Triyoso, 2007). And the slip rate value based on the river offset is about 15 mm / year (PUSGEN, 2022). The Musi segment line of the Sumatra fault is not located directly on the Musi River in the Kepahiang area, but east of the Musi River with a distance ranging from 1.2 km to 3.1 km. The fault line is located on volcanic rock deposits in the form of volcanic breccia (Putri, 2023).

Based on the earthquake records of the Musi segment, this segment had caused a strong earthquake on 15 December 1979 with a magnitude of Mw=6.0 located at coordinates 3.5 LS, 102.4 East at a depth of 25 km. Another earthquake occurred on 15 May 1997 with a magnitude of Mw=5.0. Thus it can be expected that considerable energy storage is taking place in this segment after the earthquakes of the past few decades (Ardiansyah, 2017). The Musi segment fault is also divided into several sub-faults, one of which is the Bogor fault. Based on the geological map, the Bogor fault is located in Kabawetan sub-district, which is an agro-tourism area and also near residential areas and population activities. Therefore, with the lack of information about the Bogor fault which is a sub-fault of the Musi, it is necessary to conduct further research on the existence as well as the Top and Bottom of the unknown Bogor fault as one of the disaster mitigation efforts to minimise the risk of fatal damage. Previous studies have only focused on the development, movement, slip rate value of the Sumatra Musi segment fault and did not go further into the Musi sub-fault. One example is a study to determine the movement of the fault on the Musi segment using geological methods.

One of the geophysical methods used to determine the existence of sub-faults is the Magnetotelluric (MT) method because it is considered capable of detecting subsurface structures to a depth of approximately 8,000 m (Jasmine et al., 2014). This is because MT method measurements use low frequencies to detect to a greater depth than other methods (Rahmawati et al., 2024). Studies that have been conducted using the MT method to identify the existence of sub-faults have been conducted by ilmi et al. (2024) to identify the presence of sub-faults in Lemeu Village, Lebong Regency, Bengkulu. Based on research done by Ilmi, et al. (2024) obtained the results of the Magnetotelluric 2D cross section which shows a zone with low resistivity values between the research points, which is thought to be a new fault zone with resistivity values ranging from 1.3 - 6.1 Ωm starting from a depth of 2.5 km and above so that this zone can be thought to be a secondary fault which is a branch of the Ketaun fault. This shows that this research can map geological structures that are suspected to be new faults. This study aims to determine the value of the top depth and bottom depth of the Bogor fault. The problem in this research is the lack of research information about the Musi sub-fault.

This research is expected to provide comprehensive information about the existence of the Musi sub-fault, more specifically the Bogor fault, which has not been known to monitor the existence of the plate so as to minimise the losses and impacts caused by earthquake natural disasters and also to know the value of the top depth and bottom depth of the Bogor fault. It can also help further research on the Musi sub-fault.

2. Literature Review

2.1 Detailed Geology of Kepahiang

Based on a detailed Geological Map of the study area (Figure 1) Kepahiang is surrounded by hills to steep hills and partly plains to undulating plains. The hills to steep hills are composed of young volcanic rocks of Quaternary age, consisting of lava, volcanic breccia and tuff. While the plains to undulating plains are composed of Quaternary aged deposits in the form of river alluvial deposits, alluvial deposits resulting from weathering of young volcanic rocks (Sihombing et al., 2024). The geological structure shows that the Kepahiang area is dominated by faults. In general, the faults found in the Kepahiang area are active faults that follow the structural pattern of Sumatra Island which is northwest-southeast orientated. Some other faults have north-south and northeast-southwest directions. The geological structure pattern was formed as a result of previous tectonic activity (Supartoyo et al., 2019). One of the faults affecting the geology of Kepahiang is the Musi segment of the Sumatra Fault, which runs north-south and is right in the Kepahiang area (PUSGEN, 2017).

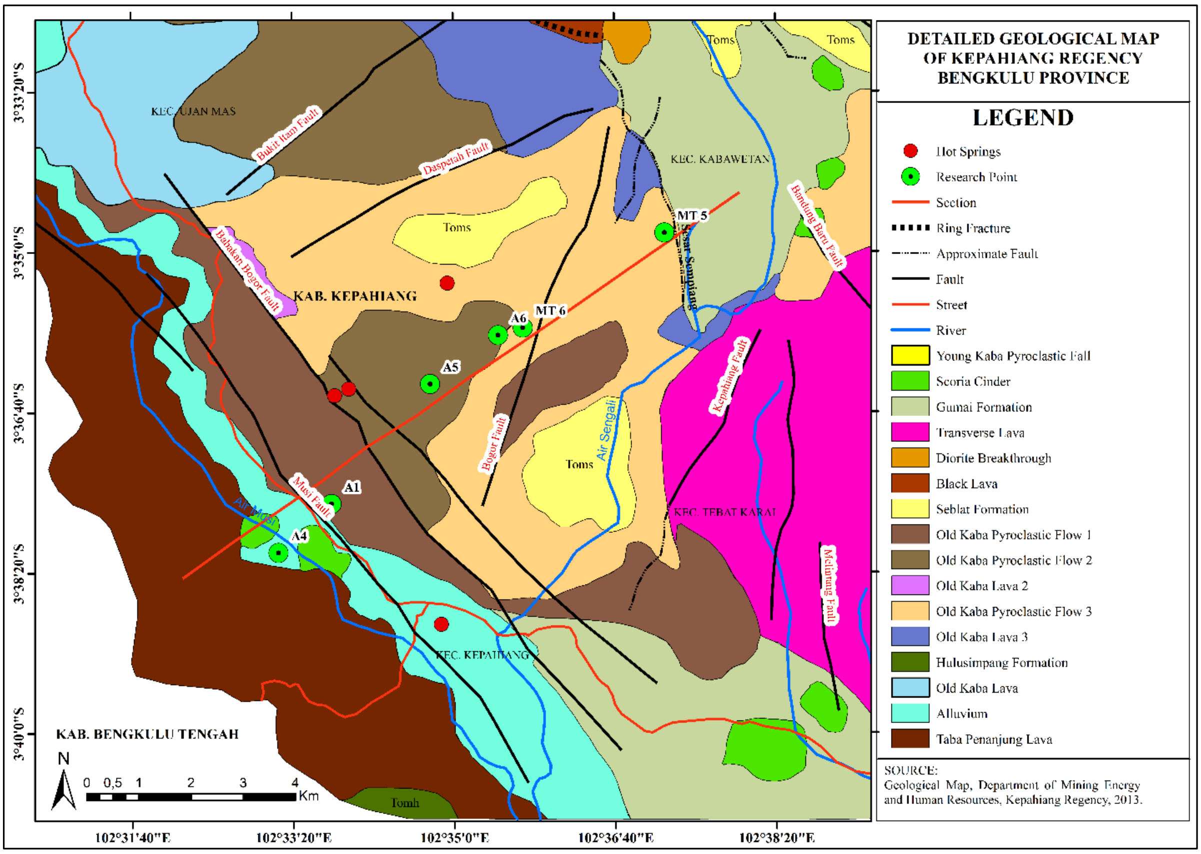


Fig. 1. Research of Geological Maps (Modified from (Gafoer, Amin and Pardede, 2007) dan (Irwanto *et al.*, 2013)).

2.2 Fault

In general, fractures or fracture systems in rocks undergoing movement are referred to as faults. Faults usually form paths or lines, but faults can also take the form of fault planes or single fractures (Supartoyo et al., 2019). In geological terms, a fault is a planar fracture or discontinuity in a rock volume caused by significant displacement due to rock mass movement. There are three types of faults: normal (descending), strike-slip (horizontal) and strike-slip faults. Based on their activity level, faults are classified into two: active faults and inactive faults (Firdaus, Setyawan and Yusuf, 2016).

One of the active faults in Indonesia is the Sumatra fault. The Sumatra fault or Semangko fault is a geological fault that is approximately 1,900 km long, stretching from North Aceh to Semangko Bay in South Lampung (Kurniawan and Rasmid, 2016). This fault is a strike-slip fault that moves horizontally, both right and left, and is part of a large fault complex in the subduction zone between the Indo-Australian Plate and the Eurasian Plate (Natawaidjaja and Triyoso, 2007). As one of the most active faults in Indonesia, the Semangko fault has repeatedly caused large earthquakes with a magnitude of 7.5 M such as those that occurred in Padang Panjang in 1926 and in the Sumatra region in 1933, indicating a potentially serious threat to the island of Sumatra (Sakdiyah and Choiruddin, 2021). One of the active segments of the Sumatra fault system is the Kepahiang Fault, also known as the Musi Fault. This fault is located in Kepahiang Regency, Bengkulu Province and has the potential for high seismic activity. The Musi segment has a significant earthquake history. The magnitude 6.0 earthquake in 1979 and 5.0 earthquake in 1997 are evidence of high seismic activity in this area. Geo-electrical analyses have been conducted to determine the angle (dip) of fault movement in the Musi segment. The results show that the fault movement in this segment ranges from 45°-90°. The considerable level of energy accumulated after previous earthquakes indicates the potential for earthquakes with larger magnitudes to occur in the future (Lubis et al., 2019). The study showed that the 85km-long Musi Fault, which passes through residential areas in Kepahiang, is a potential source of earthquakes that can have a significant impact on the surrounding communities (Ardiansyah, 2014). The Musi fault has several sub-faults, one of which is the Bogor fault located in Kabawetan sub-district, where this area is an agro-tourism area and is also close to settlements and activities of the surrounding community. The lack of information about the Bogor fault makes it necessary to conduct further research on this Musi sub-fault which has the potential to become an earthquake hazard in the future, as well as being one of the disaster mitigation efforts to minimise the risk of fatal damage. This research focuses on identifying the top and bottom depths of the Bogor fault of the Musi sub-fault.

3. Methods

This study used six measurement points with a distance interval of 1 km located extending from the Musi fault to the Bogor fault of the Musi sub-fault, located in Kabawetan Sub-district, Kepahiang Regency (Figure 2). This study aimed to identify the existence of the Musi sub-fault using the magnetotelluric method. This method is used to determine the resistivity distribution in the subsurface, using measurements of electric and magnetic fields at the surface. The Magnetotelluric method has a deep penetration of up to 8,000 metres, which is why it can be used to determine the subsurface structure (Rizal et al., 2019).

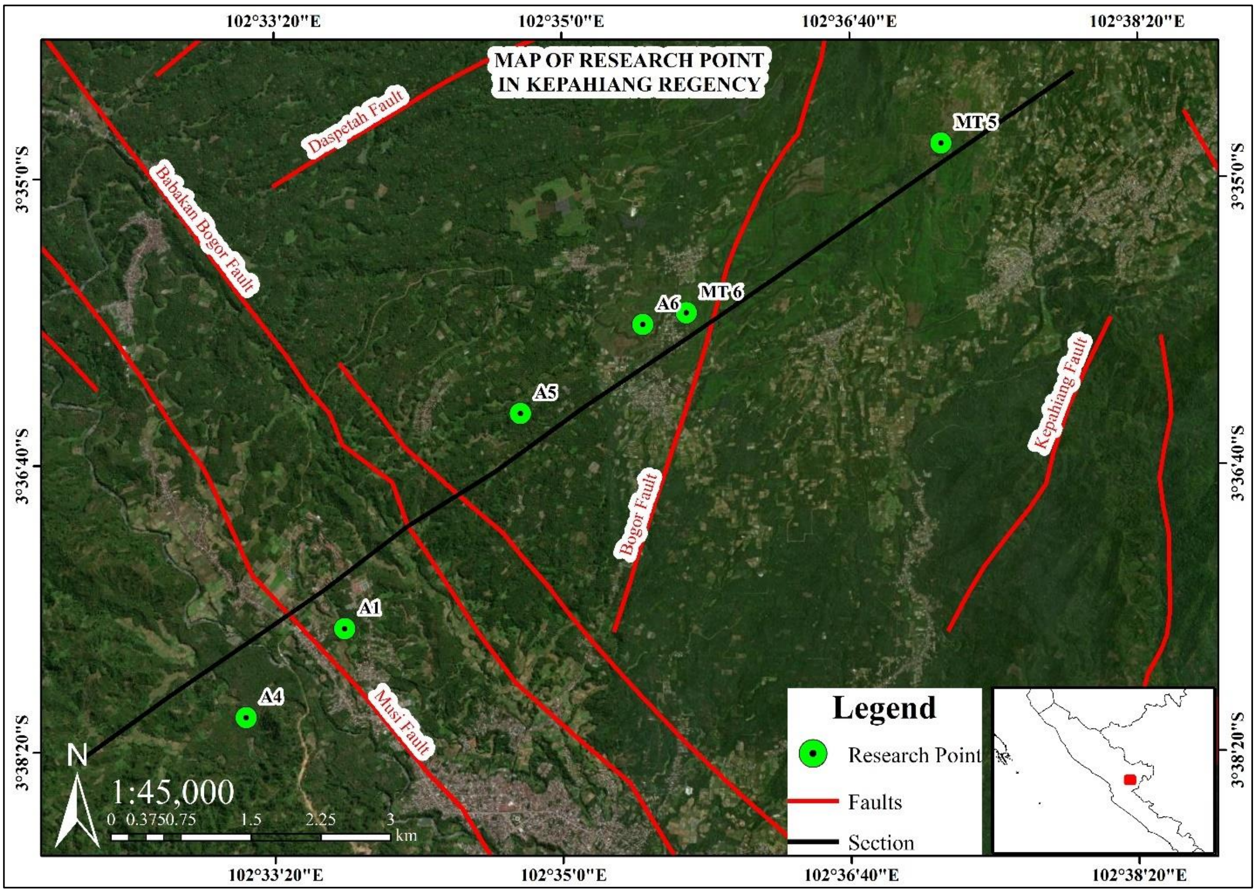


Fig. 2. Maps of Research Point

The Magnetotelluric method measures the orthogonal or perpendicular components of the Electric (Ex, Ey) and magnetic (Hx, Hy, Hz) fields at the Earth surface in the time domain (Setyani, 2017). Figure 3 shows a typical Magnetotelluric setup, with the Earth's naturally varying magnetic field as the source of a wide and continuous spectrum of electromagnetic waves. The internal coordinate system measures the electric field horizontally orthogonally and the magnetic field vertically and horizontally orthogonally (Al Ansory et al., 2023).

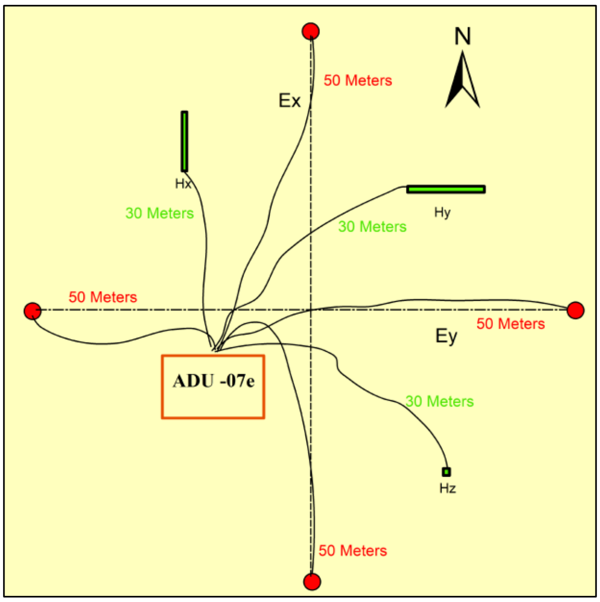


Fig. 3. Magnetotelluric Arrays in Internal Coordinate System (Al Ansory et al., 2023).

The Magnetoteluric method utilises natural Electromagnetic (EM) fields to determine the Earth's subsurface structure based on the electrical properties of rocks at relative depths (including the Earth's mantle) within the Earth (Hidayat, Junursyah and Asep, 2016). Complex physical processes generate electromagnetic fields that have a very wide frequency spectrum, ranging from 10^{-5} Hz to 10^{4} Hz. Variations in the electromagnetic field at low frequencies of less than 1 Hz are caused by the interaction of the Earth's permanent magnetic field with wind containing electrically charged particles, causing variations in the electromagnetic field. Furthermore, variations above 1 Hz are caused by meteorological activity such as lightning, which creates electromagnetic waves that travel between the ionosphere and the earth (Fitrida et al., 2015).

To find out the nature of electromagnetic waves, the general equation is used, namely Maxwell's equations (Fitzpatrick, 2008) :

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \qquad (1)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \qquad (2)$$

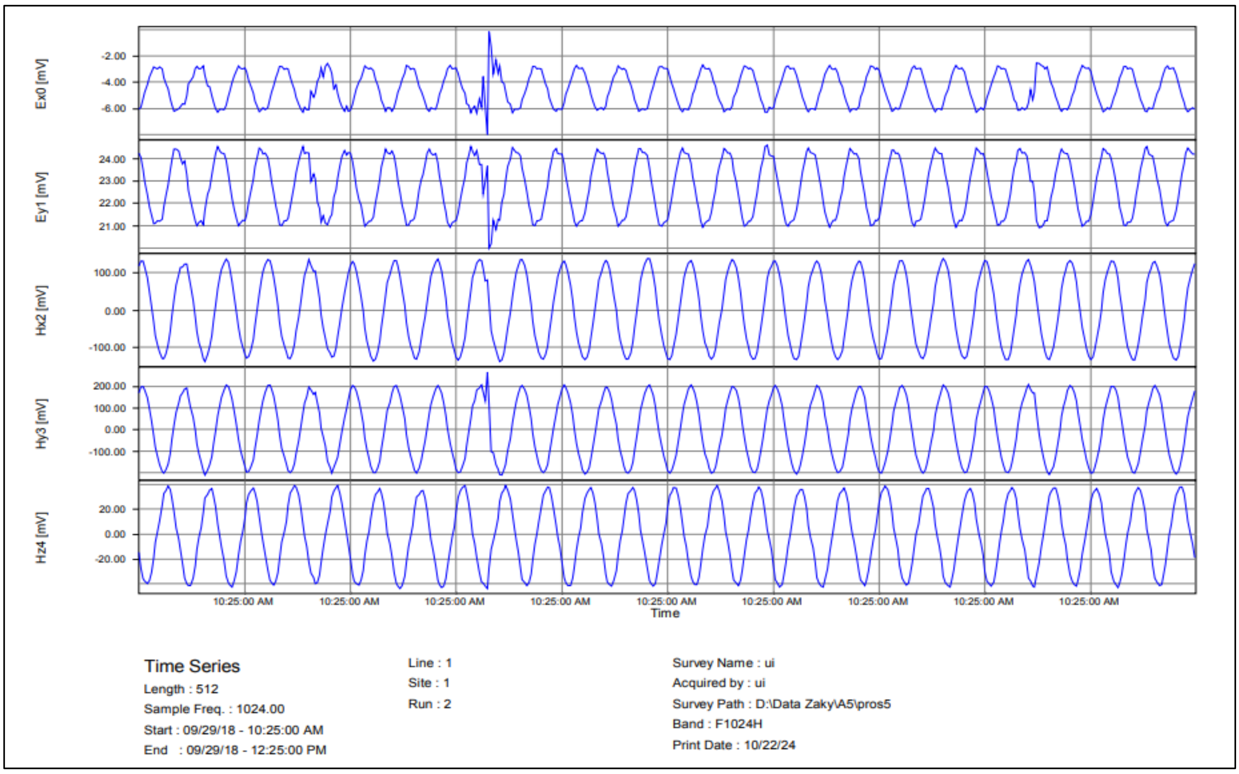
$$\nabla \cdot D = q \qquad (3)$$

$$\nabla \cdot B = 0 \qquad (4)$$

Where :

$\vec{E}$:Electric Field (Volt/m)
B :Magnetic Flux or Induction(Weber/m^{2})
H :Magnetic Field (Ampere/m)
J :Current Density (Ampere/m^{2})
D :Electric Displacement (Coulomb/m^{2})
q :Current Charge Density (Coulomb/m^{3})
t :Time (s)

Data processing was performed using *Mapros*, *ZondMT1D*, and *ZondMT2D* software. The results of measurements using the magnetotelluric method are in the form of time series of electric field data that have good quality with regular time intervals (Figure 4).



Time Series
Length : 512
Sample Freq. : 1024.00
Start : 09/29/18 - 10:25:00 AM
End : 09/29/18 - 12:25:00 PM

Line : 1
Site : 1
Run : 2

Survey Name : ui
Acquired by : ui
Survey Path : D:\Data Zaky\A5\pros5
Band : F1024H
Print Date : 10/22/24

Fig. 4. Time Series Data.

Figure 4 shows the measurement results for 16 hours taken with a low frequency (128 Hz) with a recording time of 13 hours because small frequencies are more susceptible to noise, therefore the recording time is longer, medium frequency (1024 Hz) with a recording duration of 2 hours, high frequency (4096 Hz) with a recording time of 1 hour because the frequency used is large. Further data processing began with processing in *Mapros* software by converting the survey time series data to edi file format in Mapros. First, moving the time series data into a special folder, followed by importing with the 'easy ats import file' command, by monitoring the sampling time, and processing and exporting edi data. Then, process the edi file data in *ZondMT1D* software to produce a resistivity and depth model, then analyse it using *ZondMT2D* to produce a 2D cross section of resistivity values.

4. Results and Discussion

This research was conducted in Kabawetan District, Kepahiang Regency using the magnetettotelluric method with six points (MT5, MT6, A6, A5, A1, A4) of measurement to obtain the apparent resistivity value of the measurement results. Figure 3 shows the map of the research location. Magnettotelurik measurement results are shown in the time series results in Figure 4. Furthermore, data processing in Mapros Software, data that is still in time format must be converted or transformed into the frequency domain using fast fourier transform (FFT). Then correlate the resistivity value and the depth of the ground surface and the relationship between the resistivity value and depth can be seen in Figure 5. The changing lines on the graph of the 1D Magnettotelurik results show the change in resistivity value with depth.

The results of the 2D resistivity cross section can be seen in Figure 6 which shows three 2D cross sections of the resistivity value of cross section 1 is field data which is a pseudo resistivity value, cross section 2 is a calculation model between field data and model data generated by ZondMT2D software, and cross section 3 is the result of the actual resistivity value, the results of the 2D cross section show that the resistivity value is related to the type of rock that is there.

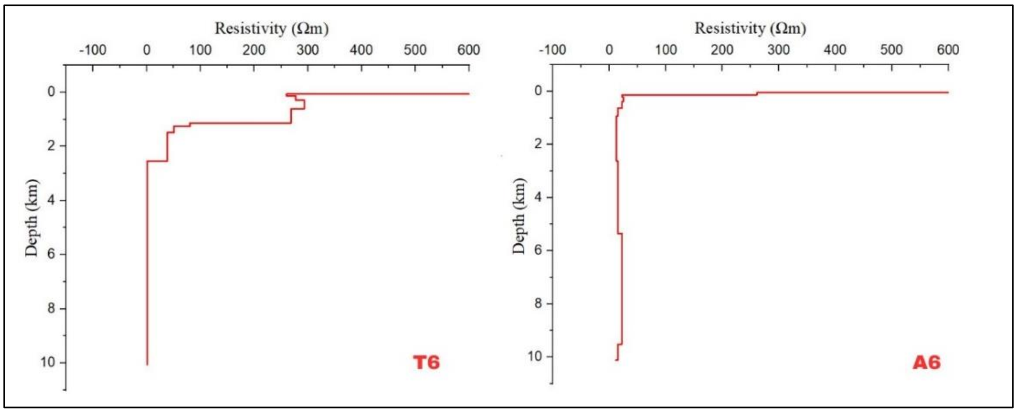


Fig. 5. Relationship between Resistivity Value and Depth (Point T6 and Point A6).

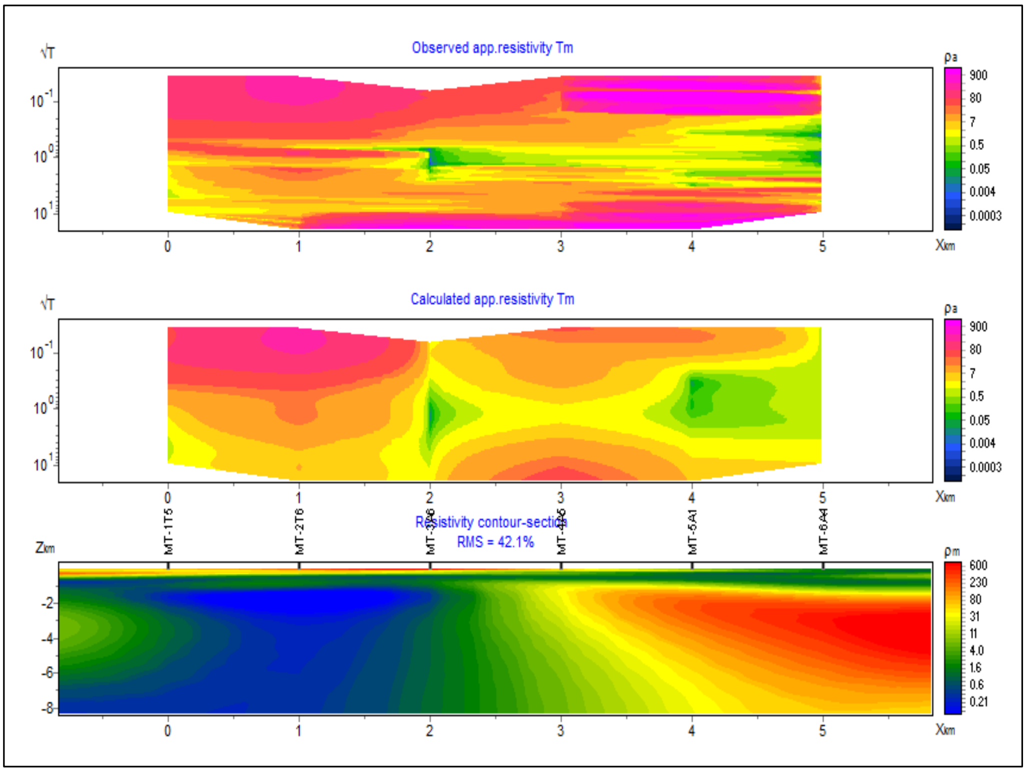


Fig. 6. 2D Cross Section Model of Resistivity value with 6 measurement points.

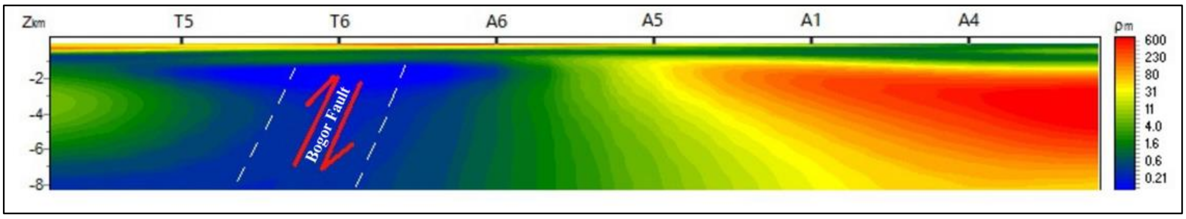


Fig. 7. Results of 2D cross-section showing the presence and depth of the Bogor Fault.

The 2D resistivity cross section model shows varying resistivity values, starting from 0.21 Ωm to 600 Ωm. based on Gafoer (2012) the resistivity value can be classified into 3 groups, namely low resistivity (0.21 - 4.0 Ωm) shown in blue which is thought to be a reservoir layer which is a container where geothermal fluid accumulates (Manyoe, 2018). This reservoir zone area is also influenced by the northeast-southwest trending fault, the Bogor fault. In this research area, it is identified that there is a type of basalt lava rock consisting of secondary clay minerals as a result of alteration due to fluid interaction with the rocks that are passed through so that they experience fractures (Nidya et al., 2013). This layer is composed by basalt rock, and andesite rock. Medium resistivity with values ranging from 11 - 80 Ωm is green to yellow in colour and is thought to be a caprock or overlaying layer at a depth of 2 km which is an impermeable layer that functions as a reservoir cover (Wote et al., 2023). This layer is composed of altered rocks (granite, etc.) andesite and claystone. The red colour indicates a high resistivity value with values ranging from 230 - 600 Ωm which is thought to be a hot rock layer that functions as a heat source, which can take the form of granite breakthrough bodies or other forms of batholith (Salam and Harmoko, 2017). This layer is composed by igneous and rocks metamorphic.

The 2D cross section shows an anomalous structure in the measurement at point T6. This structure has a resistivity value that changes significantly and shows a low resistivity value of 0.21 - 1.6 Ωm which is thought to be the Bogor fault zone located at a depth of 2 km to more than 8 km. The presence of a fault zone can generally be identified as a conductive zone by the presence of a fracture that has 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 is characterised by a resistive zone (Pratama et al., 2021). The results of the 2D cross section processing show that when the measurement is at a depth of 2 km, the layer is fractured which is indicated by a change in the resistivity value that leads to the Bogor fault which is a sub-fault of the Musi fault located in the study area which can be seen in Figure 1. This fault zone is a sub-fault of the Musi fault that has long been constructed with magma which causes fluid to seep into the fractures heated by the hot rock layer and produces low resistivity values (Figure 7). From the 2D cross section results, it is known that the uppermost depth of the Bogor fault is 2 km as indicated by the change in resistivity values and the lowest depth of this fault is estimated to be deeper than 8 km as can be seen in Figure 7. It is also suspected that the constituent layers around the Bogor fault area are composed of andesite and sedimentary rocks (clay) as indicated by resistivity values ranging from 4.0 - 31 Ωm as well as igneous and metamorphic rocks which can be seen from resistivity values ranging from 80 - 600 Ωm. Geological data refers to the Bogor Fault as the Sub-Musi Fault, which forms the subduction and volcanic area of Kaba Mountain. A caprock connected to the reservoir is shown in Figure 7, indicating the presence of a deep conduction channel that serves as a fluid conduit. This caprock is located in the north-east - south-west area. From the 2D cross section results in Figure 7, it is known that point T6 is an area directly crossed by the Bogor fault with a shallow upper depth and a very deep lower depth, so that it can provide information to the people in the surrounding area to always be aware of the threat of earthquake disasters that will occur at any time and the need for disaster mitigation efforts carried out by the government such as the creation of evacuation routes in the area around the fault in the event of an earthquake. It is hoped that this research can be a reference for further studies that are more detailed about the Bogor fault and other Musi sub-faults.

5. Conclusion

Based on the results of research in Kabawetan Subdistrict, Kepahiang Regency, conducted at six measurement points using the magnetotelluric method, a two-dimensional subsurface cross-section was obtained that indicates the presence of the Bogor Fault. This zone was identified at point T6 with low resistivity values ranging from 0.21 to 1.6 Ωm, starting from a depth of approximately 2 km below the surface and estimated to extend vertically to more than 8 km. This finding indicates that the Bogor Fault has an upper depth of approximately 2 km and a lower depth that is not yet precisely defined, but is more than 8 km. Thus, this study shows that the magnetotelluric method is effective in identifying fault structures and subsurface geological conditions in the surrounding area. However, there are several limitations to this study. The limited number of measurement points (six points) with a distance of 1 km between points can affect the spatial resolution of the resulting model. Additionally, the interpretation of the maximum depth of the fault is estimative due to the limited penetration of data at low frequencies. Therefore, further studies with a larger number of points and a combination of other geophysical methods are recommended to obtain more comprehensive and accurate results.

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