JPPIPA 9(8) (2023)

Jurnal Penelitian Pendidikan IPA

Journal of Research in Science Education

http://jppipa.unram.ac.id/index.php/jppipa/index

Integrative Analysis of the Geothermal Structure in Kepahiang: Insights from Magnetotelluric, Gravity, and Remote Sensing Techniques

Nindia E. Larasati[1*], Agus Laesanpura[1], Asep Sugianto[2]

[1] Department of Geophysics Engineering, Faculty of Mining and Petroleum Engineering, Institute of Technology Bandung, Bandung, Indonesia.
[2] Center for Volcanology and Geological Hazard Mitigation, Bandung, Indonesia.

Received: June 6, 2023
Revised: July 17, 2023
Accepted: August 25, 2023
Published: August 31, 2023

Corresponding Author:
Nindia E. Larasati
nindia3097@gmail.com

DOI: 10.29303/jppipa.v9i8.4576

Abstract: This research was conducted to determine the structure and depth of the reservoir using remote sensing as an initial survey to assess the geological alignment direction, employing ALOS PALSAR radar imagery. Subsequently, further surveys were conducted using the magnetotelluric and gravity methods to analyze the structure and depth of the geothermal reservoir. The magnetotelluric data were processed using Phoenix software, where the data was transformed from the time domain to the frequency domain using Fourier transformation, and processed to obtain apparent resistivity and phase. The MT data was integrated with gravity data, and the gravity data underwent standard correction procedures to obtain the Complete Bouguer Anomaly (CBA) map. Two-dimensional (2D) inversion using the NLCG algorithm and 2D forward modeling of the gravity data were performed. The dominant alignment pattern obtained was northwest-southeast, with an orientation of 320° NW or 140° SE. Based on the results of geological alignment, a profile is produced that is perpendicular to the straightness. The results from the 2D inversion and gravity forward modeling indicated that the geothermal reservoir is likely located beneath the caprock at an estimated depth of approximately 1800 m, with resistivity values ranging from 32 to 256 Ohm-m and a density value is 2.6 gr/cc.

Keywords: Geothermal; Kepahiang; Lineament; Magnetotelluric; Reservoir

Introduction

The Kepahiang geothermal area is on the subduction route in the western Sumatran magmatic arc area. The Kepahiang geothermal system is closely related to the volcanic activity of Mount Kaba which still retains heat from remnant magma with manifestations on the surface such as hot springs, solfatara, fumaroles, and alteration rocks. In general, the rocks in this area are dominated by volcanic rock products from Bukit Itam and Bukit Kaba. The youngest product is basalt lava from Mount Kaba Muda which is estimated to be 500,000 years old. The formation of Mount Kaba is strongly influenced by tectonic activity which generally has a northwest-southeast direction and is related to the Sumatran fault. Geothermal fluids are strongly influenced by surface water with upflow zones around the Sempiang springs and flowing around Babakan, Bogor (Sugianto et al., 2012). Hot springs are one indication of the existence of a geothermal system beneath the surface.

The geothermal system has requirements such as the availability of water, caprock, reservoir and heat source. The heat source trapped beneath the earth's crust is known as geothermal. Volcanoes, fumaroles, hot springs and other hot geological phenomena on the earth's surface are manifestations of the location of geothermal points (low or high temperature) below the surface (Kasbani, 2009; Bayer et al., 2019; Hochstein & Sudarman, 1993; Qin et al., 2011; Taqiuddin et al., 2016;

How to Cite:
Larasati, N. E., Laesanpura, A., & Sugianto, A. (2023). Integrative Analysis of the Geothermal Structure in Kepahiang: Insights from Magnetotelluric, Gravity, and Remote Sensing Techniques. *Jurnal Penelitian Pendidikan IPA*, *9*(8), 5971–5978. https://doi.org/10.29303/jppipa.v9i8.4576

Risdianto & Kusnadi, 2010; Silva-Fragoso et al., 2021). Geothermal reservoirs are subsurface rock formations that can store and transmit thermal fluids. Reservoirs tend to be rocks with good porosity and permeability. Geothermal reservoirs are surrounded by rock layers with very low permeability (impermeable). This layer is known as caprock and usually consists of clay minerals that bind water but are difficult to remove (swelling). In general, permeability is related to geological structures such as faults, joints and fractures. To analyze the structure, a geophysical survey is carried out which is able to interpret the subsurface based on physical parameters. The suitable geophysical method for geothermal exploration is the magnetotelluric (MT) method (Saptadji, 2001).

The MT response of high-temperature reservoirs suggests resistivity as an indirect indicator of geothermal fluids, in response to altered rock (Pellerin et al., 1996). If mapped, resistivity can be used to deduce untapped high permeability fracture zones filled with hot fluids (Gasperikova et al., 2015). In addition to the MT method, other geophysical methods are also needed to support the results from the MT data, namely the gravity method. The gravity method is one of the most economical geophysical methods for modeling geothermal systems. Gravity data in the form of a Bouguer anomaly map is used to infer geological characteristics and describe the subsurface structure of the study area based on its density value. Observations of gravity at the Earth's surface reflect the overlapping effects of wider and deeper mass variations as well as shallower and more localized changes near the point of observation (Maithya et al., 2020).

Many studies have been conducted to study geothermal systems in Kepahiang, Bengkulu. According to Herlambang et al. (2016) and Arsadipura et al. (2011), the upflow flow of the Kepahiang geothermal system includes the location of the Mount Kaba caldera rim to the location of the fumaroles and Sempiang hot springs (sulfate water), while the outflow flow heading towards the Babakan Bogor hot spring which is to the southwest of Mount Kaba. BOC as the peak position of the Kepahiang geothermal system reservoir is at an elevation of around 300 m. The heat source is described around the peak of Mount Kaba which indicates that the Kepahiang geothermal system is associated with the volcanic activity of Mount Kaba.

Remote sensing method is a technology that is used to obtain information about objects and other things without the need to take direct physical action (Lillesand et al., 2004). Remote sensing methods are an alternative in facilitating exploration challenges, namely in terms of time effectiveness, economy and accessibility to exploration sites (Isa et al., 2020). According to Iswahyudi et al. (2014), lineament features expressed in remote sensing satellite imagery can be observed and mapped. This alignment can reflect the geological structure. Geological structures (faults and fractures) can function as permeable zones where fluids circulate and form a geothermal system.

In addition, Novranza et al. (2018) conducted a survey using remote sensing to increase survey effectiveness and efficiency in geothermal exploration using Landsat 8 OLI imagery. The results of the study show that the main directions of lineament developing in the KMS geothermal field are Northwest-Southeast and North-South. The appearance of some surface manifestations is correlated with straightness.

Based on research by Kusnadi et al. (2014), geologically the study area is located in the Sumatran magmatic arc with a quaternary volcanic environment. The morphology consists of four geomorphological units, namely Kaba Peak geomorphological unit, Body geomorphological unit (Taba Pananjung, Malintang, and Kaba), Kaba Foot geomorphological unit, and Plains Geomorphology Unit. The Kepahiang geothermal area is part of the Kaba Volcano complex system. The products of this mountain are broadly divided into two parts, namely the products of the Kaba Tua eruption and the products of the Kaba Muda eruption which are surrounded by other volcanic products, such as Bukit Lumut in the northwest, Taba Pananjung in the southwest, and Bukit Malintang in the southeast. The rock unit consists of lava composed of dacitic, andesitic, and basaltic andesite, pyroclastic falls and flows, lava and surface deposits.

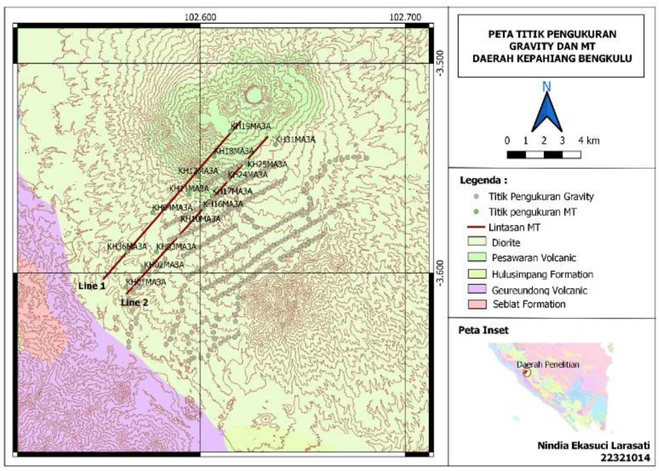

Figure 1. The research location is in the southern part of Mount kaba where MT and gravity trajectories are made in a southwest-northeast direction. There are 15 MT measurement points and 272 gravity measurement points

To find out more about the subsurface structure, an initial geological lineament survey was carried out using remote sensing. After that, a geophysical study was carried out on the Kepahiang geothermal area, Bengkulu using the MT and gravity methods (Sihombing & Rustadi, 2018). The measurement map can be seen in Figure 1. The results of the three methods are then integrated to better display the subsurface structure. In addition, the results from the MT and gravity methods were also validated with geological cross-sections in the study area. Where for the MT method a two-dimensional inversion process is carried out and for the gravity method a forward modeling is carried out. The final results aim to estimate the depth of the caprock, a geothermal reservoir and understand the subsurface structure of the geothermal system in the study area.

Method

Remote Sensing

This study uses the application of remote sensing technology as a preliminary study to determine the geological alignment in the local area with manual observations. The processed data is in the form of ALOS PALSAR Radar Imagery. The ALOS PALSAR image is a radar image obtained from the results of recording the reflection of microwaves back by objects. ALOS PALSAR image data contains the appearance of the level of backscatter characteristics of objects on the earth's surface. The advantage of this image is that the results of the image recording are not affected by the recording time either day or night and the weather conditions of the Earth's atmosphere (fog and clouds) (Sarjani et al., 2017). ALOS PALSAR images are orthorectified using SNAP (Sentinel Application Platform) software to correct ALOS PALSAR data. Initial data processing includes radiometric calibration, multilook, speckle filter, deskew, and terrain correction processes. The geological lineament analysis was carried out using QGIS software. After making the alignment manually the resulting alignment is also used to make a rosette diagram which is useful for seeing the direction of the spread of the alignment. The diagram is made by taking into account the length of the alignment in a certain direction compared to the total existing alignment (Iqbal & Juliarka, 2019).

Magnetotelluric

MT measurement data obtained from PSDMBP in the form of 15 measurement points. The initial data is still in the form of a time series. The time series obtained from the five MT components (electricity and magnetism) are processed using a Fourier transform algorithm so that the relationship between the magnetic and electric fields at each MT point can be represented in the frequency domain (Budiraharjo et al., 2017; Saibi et al., 2021; Chave & Jones, 2012). The resulting impedance tensor is converted into resistivity and phase angle which produces an electrical resistivity model. During acquisition, all four instruments used were run synchronously to estimate the impedance tensor using remote reference processing, if needed, and to improve the apparent resistivity and phase curves (Gamble et al., 1979).

Data processing from time series to resistivity and phase angle using SSMT2000 and MTEditor. The resistivity is obtained from a comparison of the values of the electric and magnetic fields which is also known as the Cagniard equation (Cagniard, 1953). This equation is the result of Maxwell's equations assuming plane waves:

$$\rho_\alpha = \frac{1}{s} f \times \left|\frac{\mathbf{E}}{\mathbf{H}}\right|^2 \quad (1)$$

$$\phi = \tan^{-1}\left(\frac{\mathrm{Im}\,\mathbf{Z}}{\mathrm{Re}\,\mathbf{Z}}\right) \quad (2)$$

where ρ_α is the apparent resistivity (ohm.m), f is the frequency (Hz), $\mathbf{E}$ is the electric vector field (mV/km), $\mathbf{H}$ is the magnetic vector field (nT), $\mathbf{Z}$ is the impedance ($\mathbf{Z} = \mathbf{E}/\mathbf{H}$).

The next step is the inversion process. To display the subsurface profile from measurement data. In this study using 2D inversion using WinGlink software where this software uses a nonlinear conjugate gradient (NLCG) algorithm. The NLCG algorithm does not need to calculate and store the sensitivity matrix directly, and the calculation speed is fast, with small memory requirements (Rodi & Mackie, 2001), so it is the most commonly used algorithm for 2D and 3D MT inversion.

Gravity

Before taking gravity measurements, it is necessary to carry out a field survey to determine the geological conditions in the area. In addition, standard corrections must also be applied to the recorded data (Abdel Zaher et al., 2018). These corrections include drift correction, free air correction, Bouguer correction, latitude correction and terrain correction. Two opposite effects are involved: a decrease in gravity due to an increase in the distance of the observation point from the center of the earth (free-air correction) and an increase due to the gravitational pull of dense material between this point and sea level (Bouguer correction). In the form of synthesis, Bouguer anomaly (BA) in units of mGal at a certain position is estimated by the equation (Yamamoto, 1999):

$$\mathrm{BA} = \mathrm{g} - \gamma + \beta \mathrm{h} - 2\pi \mathrm{G} \rho \mathrm{h} + \rho \mathrm{T} \quad (3)$$

where BA is the Bouguer anomaly (mGal), g is the absolute gravity measurement value (mGal), γ is the normal gravity value, βh is the free air correction (mGal/m), T is the terrain correction and h is the altitude (m).

Gravity measurements were carried out at 272 points. Standard corrections were applied to the gravity data to obtain a complete Bouguer anomaly (2.53 g/cm^3). A forward modeling process is carried out to analyze the subsurface based on residual anomalies.

Result and Discussion

Remote Sensing

The results of ALOS PALSAR image processing on the SNAP software can be seen in the image and then the lineaments are drawn manually using QGIS. Lineaments can be drawn by looking at several morphological lineaments such as lineaments of valleys, rivers, ridges, fault zones, and fractures on the surface. The alignment data is then made a rose diagram to show the alignment direction in the study area.

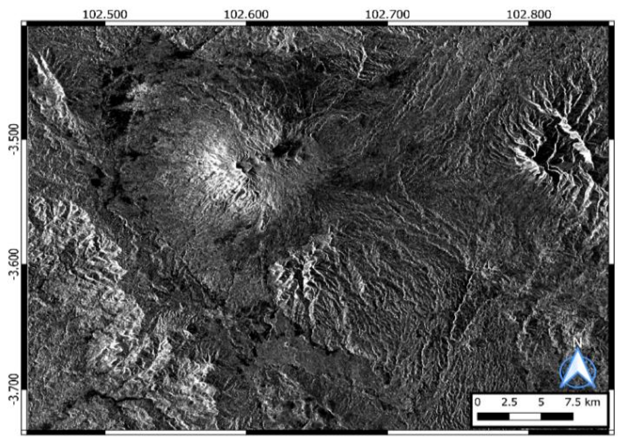

Figure 2. Image map of ALOS PALSAR in the Kepahiang Bengkulu area

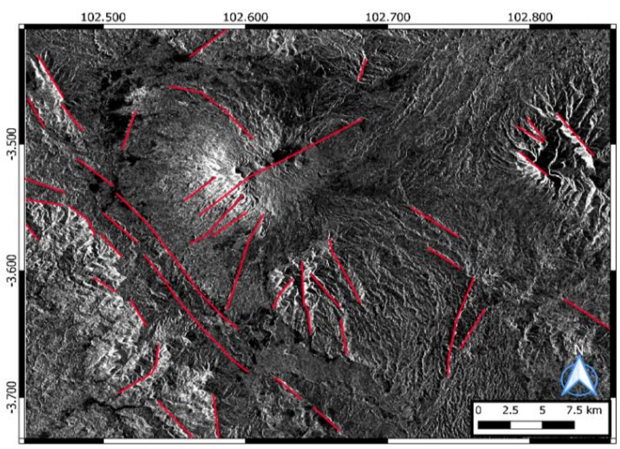

Figure 3. Map of ALOS PALSAR image alignment results using QGIS software in the Kepahiang Bengkulu area

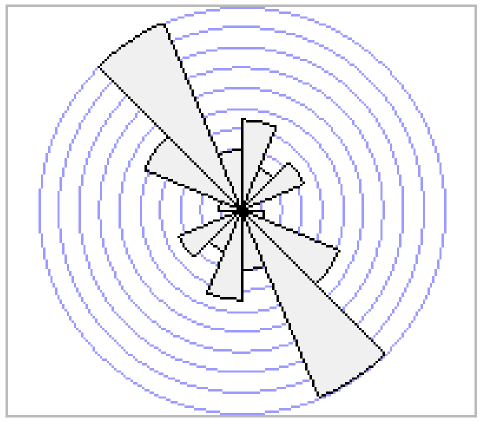

Figure 4. Rose diagram of the ALOS PALSAR image alignment in the Kepahiang Bengkulu area

Figure 4 shows the dominant lineament pattern trending northwest-southeast with an orientation of 320° NW or 140° SE. Some of them are trending northeast-southwest and almost north-south. After knowing the direction of the geological alignment in the study area, a geophysical survey was carried out, namely a magnetotelluric and gravity survey. Based on the straightness trending northwest-southeast, two profiles are made perpendicular to the straightness direction. By making a straight line profile, it is hoped that several Kepahiang geothermal structures will be obtained.

Magnetotelluric

From the 15 measurement points, each apparent and phase resistivity curve was obtained. Figure 1 shows the apparent and phase resistivity curves of several MT measurement points in the study area. The curve of each measuring point is smooth and has high data quality. Apparent resistivity curves from all stations show clear consistency, and apparent resistivity values with short periods (8×10^{-2} to $\pm 10^{1}$ seconds). The observed apparent resistivity value decreases with increasing period, indicating that there is a shallow low resistivity layer. Low to moderate resistivity indicates the presence of caprock and geothermal reservoirs. To analyze further, a 2D inversion stage is carried out.

The results of 2D resistivity modeling based on MT data reveal that there is a low resistivity spread between the Bogor Babakan hot springs and the Air Sempiang hot springs, starting from near the surface to a depth of about 1,800 meters. This low resistivity value is interpreted as caprock. Below this layer, there is a moderate resistivity zone which is interpreted as a reservoir zone. In addition, in the northeastern region, low resistivity near the surface and moderate to high resistivity are also seen at. This low resistivity value is also interpreted as a rock that is undergoing change (alteration rock). Alteration rock is the interaction between the hot fluid and the surrounding rock causing changes in chemical and physical properties, which turn the rock into new minerals (Sugianto et al., 2012).

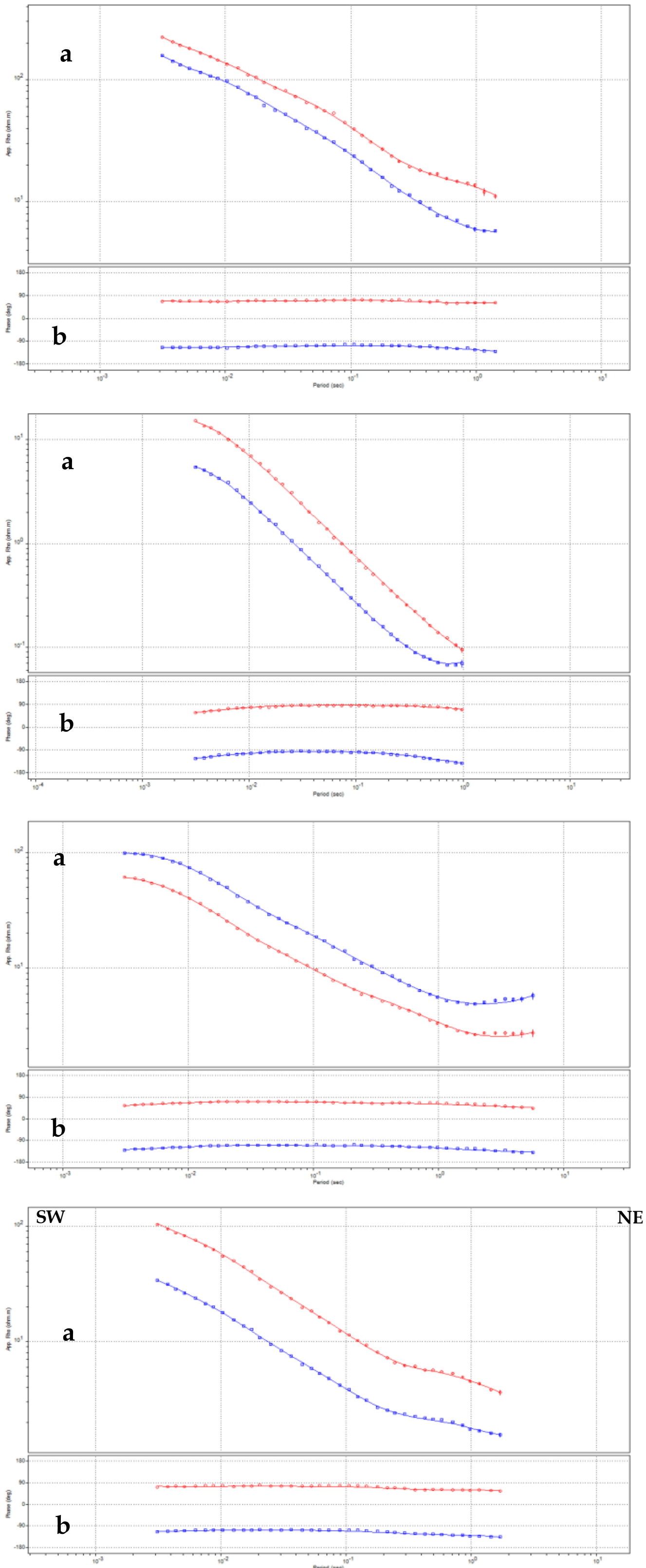

Figure 5. MT response curve: (a) resistivity vs period, (b) phase vs period

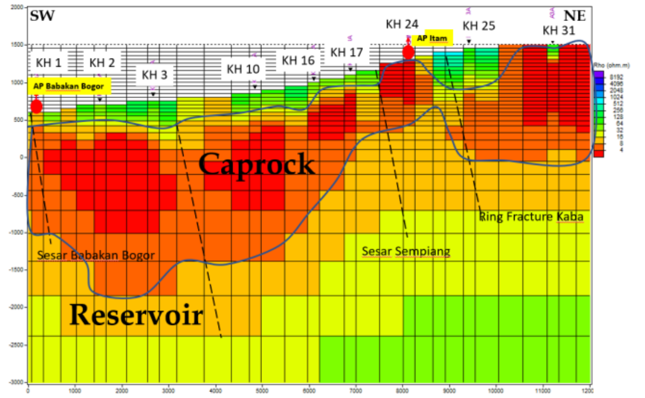

Figure 6. Cross-section of the resistivity model

It is suspected that the geothermal reservoir is located at the bottom of the caprock, characterized by a distribution of low to medium resistivity values (32 – 256 Ohm-m). At deeper depths this low resistivity forms a closed anomaly pattern, with moderate resistivity values in the central region.

Table 1. Classification of Rock Formations Based on Rock Resistivity Values

	Resistivity (Ohm-m)	Rock Formation
Layer 1	256 – 512	Kaba Pyroclastic Flow
Layer 2	4 – 32	Old Kaba Pyroclastic Flow
Layer 3	32 - 256	Old Kaba Lava 3

Gravity

The structures detected in the study area cover the northwest-southeast direction which is in line with the active Sumatran fault. Residual anomaly results indicate the presence of estimated structures, especially in the northeast–southwest. Based on the results of forward modeling, it was found that the profile includes hot water manifestations in Babakan Bogor (southwest) and hot water manifestations in Itam (northeast) which have a geothermal system formed due to the existence of the Kaba volcano.

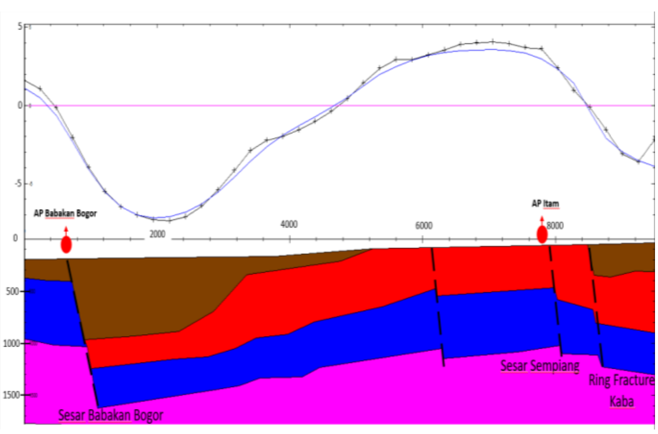

Figure 7. Density model cross-section

It is suspected that the structure contained in the manifestation of hot water in Itam is caused by the presence of a new caldera formed by the eruption of Mount Kaba, which then forms local faults in the study area. The density range observed in both models is between 2 g/cc to 3 g/cc.

In this forward modeling, the identified components in the geothermal system are cap rock and reservoir rock. The cap rock was found at a depth of about 1 kilometer, which is located in the layer of the Kaba Tua Pyroclastic Flow. The existence of this cap rock is due to its impermeable nature and the high content of clay minerals around the manifestation of the Sempiang hot springs. Meanwhile, reservoir rocks were found at a depth of about 1.5 kilometers, which includes the Kaba Tua III Lava layer. In this layer, the rock has undergone deformation and is located in a zone of destruction due to faults in the study area, which causes the formation of intensive fractures and higher permeability properties.

Table 2. Classification of Rock Formations Based on Rock Density Values

	Density (g/cc)	Rock Formation
Layer 1	2	Kaba Pyroclastic Flow
Layer 2	2.53	Old Kaba Pyroclastic Flow
Layer 3	2.4	Old Kaba Lava 3
Layer 4	3	Old Kaba Lava 2

Corresponding results were obtained for the magnetotelluric and gravity methods, namely the geothermal reservoir is located at the bottom of the caprock with moderate resistivity (32 – 256 Ohm-m) and a density of 2.4 g/cc with the Lava Kaba Tua III rock formation and the caprock is at low resistivity (4 – 32 Ohm-m) and a density of 2.53 g/cc with the Kaba Tua Pyroclastic Flow rock formation.

Conclusion

Based on the results of the research described above, it can be concluded that, among other things, the geological lineament is obtained in the dominant study area northwest-southeast with an orientation of 320° NW or 140° SE. Some of them are trending northeast-southwest and almost north-south. In addition, two perpendicular profiles were made to see the response of the magnetotelluric and gravity methods. Based on the results of 2D inversion on MT and forward gravity modeling, the results are consistent with the magnetotelluric and gravity methods, namely the geothermal reservoir is located at the bottom of the caprock with moderate resistivity (32 – 256 Ohm-m) and a density of 2.4 g/cc with the Kaba Lava rock formation. Tua III and caprock are at low resistivity (4 – 32 Ohm-m) and a density of 2.53 g/cc with the Kaba Tua Pyroclastic Flow rock formation. The manifestation of hot water in Babakan Bogor (southwest) and the manifestation of hot water in Itam (northeast) have a geothermal system formed due to the existence of the Kaba volcano. It is suspected that the structure contained in the manifestation of hot water in Itam is caused by the presence of a new caldera formed by the eruption of Mount Kaba, which then forms local faults in the study area.

Acknowledgments

Thank you to Drs. Ir. Agus Laesanpura, M.S., and Asep Sugianto., S.T., M.T for their valuable guidance, advice, and support throughout the research process of this thesis. Additionally, thank you for family and friends for their unwavering support.

Author Contributions

Conceptualization, Nindia E. Larasati, Agus Laesanpura; methodology, Nindia E. Larasati, Agus Laesanpura; investigation, Asep Sugianto; software, Asep Sugianto, Agus Laesanpura; writing-original draft, Nindia E. Larasati, Agus Laesanpura; writing-review and editing, Nindia E. Larasati, Agus Laesanpura.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflict of interest.

References

Abdel, Z. M., Saibi, H., Mansour, K., Khalil, A., & Soliman, M. (2018). Geothermal Exploration Using Airborne Gravity and Magnetic Data at Siwa Oasis, Western Desert, Egypt. *Renewable and Sustainable Energy Reviews*, *82*, 3824–3832. https://doi.org/10.1016/j.rser.2017.10.088

Arsadipura, S., Djukardi, D., & Kholid, M. (2011). Penyelidikan Geofisika Terpadu Gaya Berat, Geomagnet dan Geolistrik Daerah Panas Bumi Kepahiang, Kecamatan Kaba Wetan, Kabupaten Kepahiang, Provinsi Bengkulu. *Prosiding Hasil Kegiatan Pusat Sumber Daya Geologi, 1*, 653–663.

Bayer, P., Attard, G., Blum, P., & Menberg, K. (2019) The Geothermal Potential of Cities. *Renewable and Sustainable Energy Reviews, 106*, 17–30. https://doi.org/10.1016/j.rser.2019.02.019

Budiraharjo, S., Utama, W., Warnana, D. D., & Darmawan, A. (2017). Analisis Inversi 2D Metode Occam untuk Memodelkan Resistivitas Bawah Permukaan Data Magnetotellurik. *Jurnal Geosaintek,* *3*(1), 1-12. https://doi.org/10.12962/j25023659.v3i1.2950

Cagniard, L. (1953). Basic Theory of the Magneto-Telluric Method of Geophysical Prospecting.

Geophysics, *18*(3), 605–635. https://doi.org/10.1190/1.1437915

Chave, A., & Jones, A. (2012). *The Magnetotelluric Method: Theory and Practice*. Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139020138

Kusnadi, D., Nurhadi, M., & Suparman, S. (2014). Penyelidikan Terpadu Geologi dan Geokimia Daerah Panas Bumi Kabupaten Kepahiang, Bengkulu. *Prosiding Hasil Kegiatan Pusat Sumber Daya Geologi*, Bandung, Indonesia, 435-445. Retrieved from https://123dok.com/document/yd2rwr1q

Gamble, T., Goubau, W. M., & Clarke, J. (1979). Magnetotellurics with a Remote Magnetic Reference. *Geophysics, 44*, 53–68. https://doi.org/10.1190/1.1440923

Gasperikova, E., Rosenkjaer, G. K., Arnason, K., Newman, G. A., & Lindsey, N. J. (2015). Resistivity Characterization of the Krafla and Hengill Geothermal Fields through 3D MT Inverse Modeling. *Geothermics*, *57*, 246–257. https://doi.org/10.1016/j.geothermics.2015.06.015

Herlambang, R. F., & Novranza, K. (2016). Pemetaan Kelurusan Menggunakan Remote Sensing dan Korelasinya terhadap Distribusi Manifestasi Permukaan di Daerah Potensi Geothermal Kepahiang, Bengkulu. *Prosiding Seminar Nasional Fisika (E-Journal), 5*, SNF2016-EPA. https://doi.org/10.21009/0305020412

Hochstein, M. P., & Sudarman, S. (1993). Geothermal Resources of Sumatra. *Geothermics, 22*(3), 181-200. https://doi.org/10.1016/0375-6505(93)90042-L

Iqbal, M., & Juliarka, B. R. (2019). Analisis Kerapatan Kelurusan (Liniament Density) di Lapangan Panas Bumi Suoh-Sekincau, Lampung. *Journal of Science and Applicative Technology, (S.I.), 3*(2), 61-67. https://doi.org/10.35472/jsat.v3i2.212

Isa, M., Cesarian, D. P., Abir, I. A., Yusibani, E., Surbakti, M. S., & Umar, M. (2020). Remote Sensing Satellite Imagery and In-Situ Data for Identifying Geothermal Potential Sites: Jaboi, Indonesia. *International Journal of Renewable Energy Development, 9*(2), 237-245. https://doi.org/10.14710/ijred.9.2.237-245

Kasbani, K. (2009). Tipe Sistem Panas Bumi di Indonesia dan Estimasi Potensi Energinya. *Buletin Sumber Daya Geologi, 4*(3), 23-30. https://doi.org/10.47599/bsdg.v4i3.184

Lillesand, T. M., Kiefer, R. W., & Chipman, J.W. (2004). *Remote Sensing and Image Interpretation* (5th Edition). New York: John Wiley & Sons Inc.

Maithya, J., Fujimitsu, Y., & Nishijima, J. (2020). Geothermics Analysis of Gravity Data to Delineate Structural Features Controlling the Eburru Geothermal System in Kenya. *Geothermics, 85*, 101795. https://doi.org/10.1016/j.geothermics.2019.101795

Novranza, K., & Cahyaningrum, D. (2018). Remote Sensing Technology for Mapping Area of Interest (AoI) in Electro Magnetic Survey Design in KMS Geothermal Field. *Prosiding-Seminar Nasional*, 15–16. Retrieved from http://senter.ee.uinsgd.ac.id/repositori/index.php/prosiding/article/view/senter2017p2

Pellerin, L., Johnston, J. M., & Hohmann, G. W. (1996). A Numerical Evaluation of Electromagnetic Methods in Geothermal Exploration. *Geophysics, 61*(1), 121–130. https://doi.org/10.1190/1.1443931

Qin, Q., Zhang, N., Nan, P., & Chai, L. (2011) Geothermal Area Detection Using Landsat ETM+Thermal Infrared Data and Its Mechanistic Analysis, A Case Study in Tengchong, China. *Intern. J. Appl. Earth Observ. Geoinform, 13*(4), 552-559. http://10.1016/j.jag.2011.02.005

Risdianto, D., & Kusnadi, D. (2010). The Application of a Probability Graph in Geothermal Exploration. *Proceedings World Geothermal Congress 2010*, Bali, Indonesia, 1-6. Retrieved from https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2010/1188.pdf

Rodi, W., & Mackie, R. L. (2001). Nonlinear Conjugate Gradients Algorithm for 2-D Magnetotelluric Inversion. *Geophysics, 66*(1), 174–187. https://doi.org/10.1190/1.1444893

Iswahyudi, S., Saepuloh, A., & Widagdo, A. (2014). Delineating Outflow Zones Using Linear Features Density (LFD) Derived from Landsat Imagery at Paguyangan, Brebes, Central Java. *Proceedings, 3rd International ITB Geothermal Workshop*. Retrieved from https://www.researchgate.net/publication/355444540

Saibi, H., Khosravi, S., Cherkose, B. A., Smirnov, M., Kebede, Y., & Fowler, A. R. (2021). Magnetotelluric Data Analysis Using 2D Inversion: A Case Study from Al-Mubazzarah Geothermal Area (AMGA), Al-Ain, United Arab Emirates. *Heliyon, 7*(6), e07440. https://doi.org/10.1016/j.heliyon.2021.e07440

Saptadji, N. M. (2001). *Teknik Panas Bumi, Diktat Kuliah Prodi Teknik Perminyakan*. Bandung: ITB.

Sarjani, F., Yohandri, Y., & Sumantyo, J. T. S. (2017). Pengolahan Citra Satelit ALOS PALSAR Menggunakan Metode Polarimetri untuk

Klasifikasi Lahan Wilayah Kota Padang. *EKSAKTA, 18*(1), 69-77. https://doi.org/10.24036/eksakta/vol18-iss01/21

Sihombing, R. B., & Rustadi. (2018). Metode Gaya Berat. *Jurnal Geofisika Eksplorasi, 4*(2), 159-172. https://doi.org/10.23960/jge.v4i2.14

Silva-Fragoso, A., Ferrari, L., Norini, G., Orozco-Esquivel, T., Corbo-Camargo, F., Bernal, J. P., Castro, C., & Arrubarrena-Moreno, M. (2021). Geology and Conceptual Model of the Domuyo Geothermal Area, Northern Patagonia, Argentina. *Journal of Volcanology and Geothermal Research, 420*, 107396. https://doi.org/10.1016/j.jvolgeores.2021.107396

Sugianto, A., & A.W, A. K. (2012). Survei Magnetotellurik Daerah Pana Bumi Kepahiang Kabupaten Kepahiang, Bengkulu. *Pusat Sumber Daya Geologi, 19*. Retrieved from http://psdg.bgl.esdm.go.id/prosiding_2012/Buku1Energi/17.SURVEIMAGNETOTELLURIKDAERAHPANASBUMIKEPAHIANG.pdf

Taqiuddin, Z., Nordiana, M., & Rosli, S. (2016). Utilizing of Geophysical Method for Geothermal Exploration in Aceh Besar (Indonesia). *Intern. Res. J. Eng. Technol, 03*(04), 2234-2238. Retrieved from https://www.researchgate.net/publication/307174069

Yamamoto, A. (1999). Estimating the Optimum Reduction Density for Gravity Anomaly: A Theoretical Overview. Journal of the Faculty of Science, Hokkaido University. Series 7, Geophysics, 11(3), 577–599. Retrieved from http://hdl.handle.net/2115/8850