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Subsurface Modeling Using Gravity Method for Geothermal Potential, Case Study: Mount Ciremai

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Abstract
Indonesia is located at three major tectonic plates which make Indonesia have mountain ranges, volcanic arcs, and fault zones, causing frequent seismic and volcanic activity. To understand how geological phenomena occur, subsurface analysis and modeling are required. This study aims to identify and map regional and residual gravity anomalies in the Mount Ciremai area using gravity survey methods. The analysis of these anomalies is utilized to interpret subsurface structures related to the geothermal system potential in the region. Gravity data used in this research were obtained from GGMplus satellite imagery, which were then processed to generate regional and residual anomaly maps. The gravity method was chosen for its ability to detect subsurface rock density variations, which are essential for revealing geological structures. This quantitative research uses an exploratory approach, aiming to identify major structural elements such as faults, magma chambers, and hydrothermal systems. Through gravity data processing and interpretation, the study also seeks to determine the main components of the geothermal system, including the heat source, reservoir, cap rock, and fluid pathways. The results are expected to contribute to a better understanding of subsurface geological characteristics and support geothermal energy exploration in the Mount Ciremai area.

Keywords: *Subsurface modeling; Gravity method; Geothermal potential; Geothermal energyMount Ciremai*

INTRODUCTION

Indonesia has a high potential for various geological disasters, such as volcanic activity, landslides, earthquakes, and tsunamis (Cummins, 2017; Hakim & Lee, 2020; Sukarman et al., 2020). Not only disasters, Indonesia is also rich in geological phenomena that can be utilized for exploration. One of the regions with significant geological potential is West Java which is home to several active volcanoes, including Mount Ciremai.

Mount Ciremai is a type A stratovolcano located at an elevation of 3,078 meters above sea level. It is situated at the coordinates 108°25' East Longitude and 6°55' South Latitude. Mount Ciremai is the highest mountain in West Java, located in three regencies: Kuningan, Cirebon, and Indramayu. This mountain is in an area bounded by the active fault of Cilacap-Kuningan, which extends from the northwest to the southeast and stands on a sedimentary rock formation from the Mio-Pliocen period (Binley et al., 2015; Corrado et al., 2014; Jayawickreme et al., 2014; Romero-Ruiz et al., 2018). Research about Mount Ciremai has been conducted since the early 1980s and has received more serious attention since the 2000s. There is a west-east oriented fault that aligns the old Ciremai caldera, which contributes to the presence of geothermal prospects in Sangkanhurip and Pejambon in the eastern part of the mountain (Dekkers et al., 2025; Hirt et al., 2013; Prabowo et al., 2023; Sehah, 2012).

Research to understand and subsurface structure of earth mapping can be carried out through various methods, including geophysical approaches. This method plays a crucial role in mitigating geological hazards, such as volcanic activity and earthquakes, and in conducting more in-depth geological research. One effective method is the gravity method. The gravity method is a geophysical method used to measure differences in various gravity fields of Earth. Gravity measurements are used to detect geological formations with different densities. Gravity anomaly is a gravity value that appears when there is a difference in density contrast of the subsurface of Earth (Lumbantoruan et al., 2023; Sarkowi, 2014; Wachidah & Minarto, 2018). Gravity field anomaly is defined as the difference between the measured gravity field value at topography or (x,y,z) position and the theoretical gravity field at the same location. Gravity anomaly refers to the difference between the measured gravity effect and the theoretical Earth's gravity model. The measured gravity itself represents the total vertical component of the gravitational potential caused by all mass density anomalies in the vicinity of the survey area, both in vertical and lateral directions (Allred et al., 2016; Gabàs et al., 2014; Van Dam, 2012).

The fundamental concept of gravity method is based on the Law of Gravitation of Newton, which asserts that the gravitational force between two particles with masses m_0 and m, separated by a distance ($r - r_0$) from their mass centers, is inversely related to the square of the distance and directly proportional to the product of their masses. This research uses GGMplus data, GGMplus provides the most comprehensive description of gravity of Earth with very high resolution and extensive coverage to date (Sucipto & Mulyati, 2020; Vel & Bedner, 2015). The satellite gravity data has great potential in identifying geothermal reservoirs.

RESEARCH METHODS

The research area is located in Mount Ciremai (3,078 masl) as shown in Figure 1.

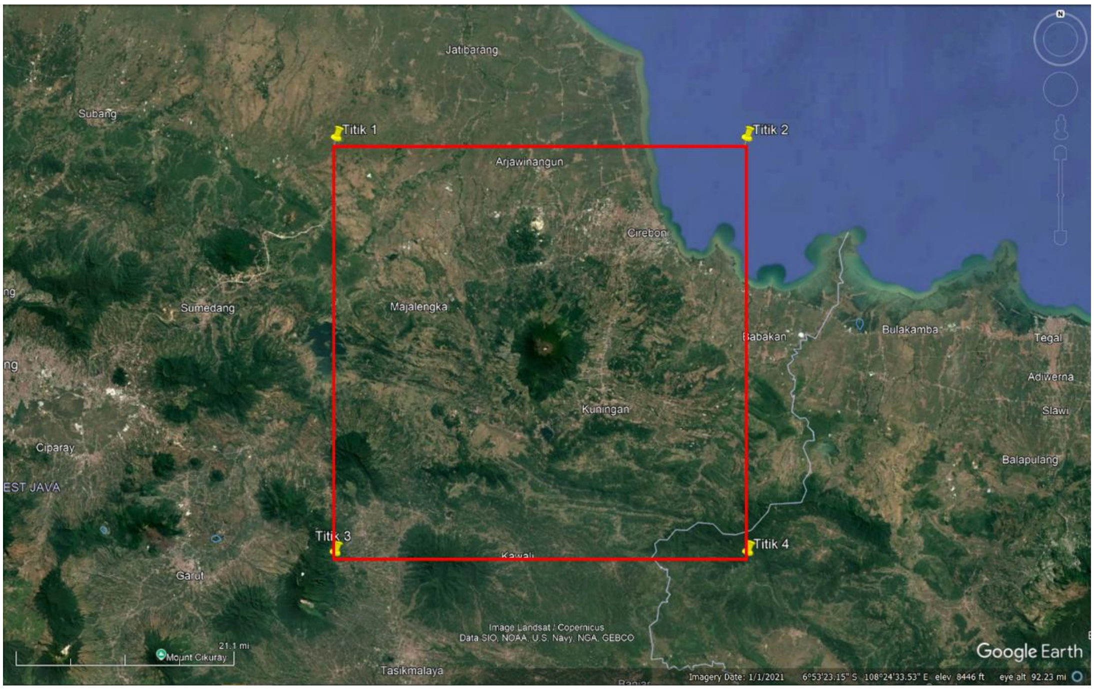

Figure 1 Complete Bourger Anomaly Map

Coordinate Points with Longitude and Latitude shown in Table 1

Table 1 Longitude and Latitude Points Coordinate

Point	Longitude	Latitude
1	108° 6'20.03"E	6°36'32.75"S
2	108°41'26.66"E	6°36'32.75"S
3	108° 6'20.03"E	7°11'38.61"S
4	108°41'26.66"E	7°11'38.61"S

This research used a geophysical method with an analytical approach to create a subsurface structure model in the Mt. Ciremai area. The data obtained from GGMplus satellite data can be accessed from (http://ddfe.curtin.edu.au/models/GGMplus/). Data in this study was carried out using secondary data, including satellite image gravity anomaly data.

In pre-processing data, Bouguer and terrain corrections were applied to improve gravity data accuracy by accounting for topographic effects. Regional and residual gravity anomaly maps were then created to help identify subsurface geological structures. After that, **Gravity Modeling** 2D inversion modeling were used to reveal detailed subsurface structures. The results were interpreted by comparing gravity anomalies with geological data and previous research around Mount Ciremai. Geological Interpretation was carried out, and the gravity anomaly patterns were analyzed concerning existing geological structures. Key features such as faults, magma chambers, and hydrothermal systems potentially linked to geothermal resources in the Mount Ciremai area were identified.

Gravity data processing, including filtering methods, can be carried out in either the spatial or frequency domain. To interpret specific subsurface features, the various frequency components contained within the gravity data are separated using mathematical filters that satisfy certain criteria—particularly, they must preserve the phase of the signal. In this study, gravity filtering is conducted using two methods: Moving Average and Polynomial.

1. Moving Average

The moving average method produces regional gravity anomaly data, and the residual anomaly is obtained **indirectly** by subtracting the smoothed (filtered) data from the original measured anomaly. This method serves as a **low-pass filter**, effectively suppressing high-frequency variations. It applies a **rectangular filtering** approach and maintains the original signal phase. The one-dimensional moving average with a single-window is defined by the following equation:

$$\Delta g_a(x_i) = \Delta g(x_i) - \frac{1}{N}\sum_{k=-a/2}^{k=a/2} \Delta g(x_i - k)$$

Two-dimensional separation using a single window is performed based on the following equation:

$$\Delta g_r(x,y) = \Delta g(x,y) - \frac{1}{N}\sum_{k=-a/2}^{k=a/2}\sum_{l=-a/2}^{l=a/2} \Delta g(x-k, y-l)$$

This demonstrates that the moving average functions as a low pass filter, with its frequency response described as follows:

$$K_{n(\alpha,\beta)} = \frac{Sin\frac{2\alpha+1}{2}W_nS}{(2\alpha+1)Sin\frac{W_nS}{2}} - \frac{Sin\frac{2\beta+1}{2}W_nS}{(2\beta+1)Sin\frac{W_nS}{2}}$$

K_n= frequency response

$W_nS = \frac{2\pi}{\lambda_n}S$, S refers to the distance between sampling points (sampling interval)

2. Polynomial

This method models the regional anomaly using a polynomial function, allowing the residual anomaly to be obtained indirectly. For 2D (map data), the second-order polynomial equation is expressed as follows:

$$\Delta g_i = c_1 + c_2 x_i + c_3 y_i + c_4 x_i^2 + c_4 x_i y_i + c_6 y_i^2$$

i=1,2,3,…….,n = observation station number
Δg_i= gravity anomaly
$c_1, c_2, \dots\dots\dots, c_3$= polynomial constants

The initial stage involves estimating the polynomial constants c_1 to c_6 based on the anomaly values Δg_i and the known coordinates of each observation station (x_i, y_i). Subsequently, the same second-order polynomial equation is used to calculate the regional anomaly Δg_i. This procedure is formally represented in matrix form as follows:

$$\begin{bmatrix} \Delta g_1 \\ \Delta g_2 \\ \cdot \\ \cdot \\ \Delta g_i \end{bmatrix} = \begin{bmatrix} 1 & x_1 & \cdot & \cdot & y_1 \\ 1 & x_i & \vdots & \vdots & y_2 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & x_i & \cdot & \cdot & y_i \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \cdot \\ \cdot \\ c_i \end{bmatrix}$$

To determine the polynomial constants ccc, when the number of observation stations exceeds the number of unknowns, the least squares method is employed. Once the constants are obtained, the regional anomaly can be computed using the following expression:

$$\begin{bmatrix} \Delta g_{1R} \\ \Delta g_{2R} \\ \cdot \\ \cdot \\ \Delta g_{iR} \end{bmatrix} = \begin{bmatrix} 1 & x_1 & \cdot & \cdot & y_1^2 \\ 1 & x_i & \vdots & \vdots & y_2^2 \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot \\ 1 & x_i & \cdot & \cdot & y_i^2 \end{bmatrix} \begin{bmatrix} c_1 \\ c_2 \\ \cdot \\ \cdot \\ c_i \end{bmatrix}$$

RESULT AND DISCUSSION

The Bouguer gravity anomaly reflects variations in the Earth's gravitational field caused by differences in subsurface mass density. These differences are typically the result of contrasting rock compositions and the distribution of materials beneath the surface, influenced by geological features such as faults, folds, magmatic intrusions, or sedimentary basins. These anomalies provide insights not only into surface geology but also into density changes extending down to the upper mantle. As a result, Bouguer anomaly interpretation plays a vital role in geophysical investigations, especially for understanding the Earth's subsurface structures and dynamics in greater detail. To better analyze these anomalies, filtering techniques are employed to distinguish between anomalies caused by deep sources and those from shallow ones. This differentiation helps isolate the regional component which represents large-scale deep structures and the residual component, which is more related to near-surface features. Despite advancements in filtering methods, this separation process remains somewhat uncertain, mainly due to challenges in clearly defining the depth boundaries of anomaly sources. In potential field analysis, data filtering can be performed either in the spatial or frequency domain, depending on the analysis strategy and data characteristics.

This study uses Bouguer gravity anomaly data to help interpret the geothermal system in the research area. The analysis includes two primary approaches: spectral analysis in the frequency domain, and three spatial filtering methods namely, the moving average and polynomial fitting. These techniques aim to extract regional and residual anomalies to better reveal the characteristics of the subsurface. The purpose of this separation is to identify key components of the geothermal system, such as the heat source, reservoir, cap rock, and structural pathways or traps for geothermal fluids. The initial step in the data processing involved digitizing the Bouguer anomaly map of the study area. Contour values were digitized and transformed into a gridded dataset with a spatial resolution of 1 km. Using this grid, a Bouguer anomaly contour map was generated with a 5 mGal contour interval as a foundation for further analysis. The density value used in the Bouguer correction was based on an average of 3.3 g/cm³.

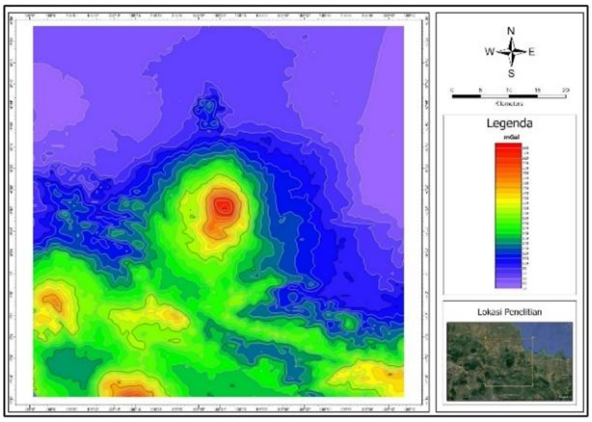

Figure 2 Bouguer gravity anomaly map of the Mt. Ciremai area

Interpretation of Gravity Spectrum Data about the Geodynamics of the Mount Ciremai Area

Spectral analysis is employed to evaluate the frequency content within gravity data, aiming to understand the relative depth of anomaly sources. This is achieved through Fourier transformation, which converts the data from the spatial domain (distance or location) into the frequency domain. This transformation allows for the identification of signal characteristics based on their wavelengths: short-wavelength signals are generally associated with shallow sources, while longer wavelengths indicate deeper sources.

Understanding the distribution of these wavelengths is crucial for identifying discontinuity surfaces, which are linked to variations in lithology and subsurface structures. This information serves as the foundation for interpreting the geological conditions and geothermal systems within the study area. As part of this process, Bouguer anomaly cross-sections are generated along a profile crossing Mount Ciremai, providing a more comprehensive vertical view of the subsurface structure.

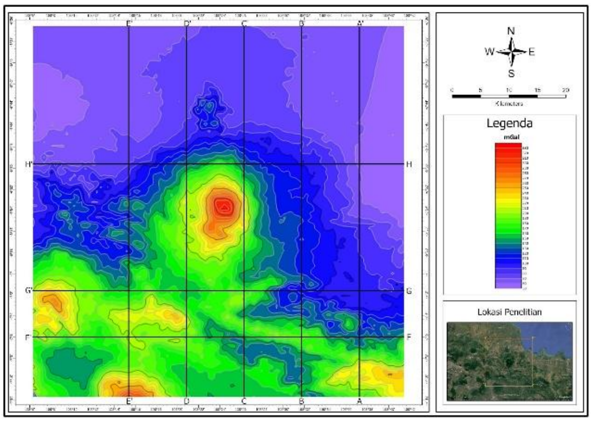

Figure 3 The orientation of the spectral analysis profiles on the Bouguer gravity anomaly map

Depth Estimation

One of the primary advantages of spectral analysis in geophysical studies is its ability to estimate the depth of subsurface anomaly sources. This depth estimation is derived by analyzing the gradient of the power spectrum curve specifically, the logarithm of amplitude plotted against the wavenumber which reflects the frequency contributions from various depths.

The figure presented illustrates examples of Bouguer gravity anomaly spectrum curves obtained through Fourier transformation for four cross-sectional profiles: A, B, C, and D. These curves are used to calculate the gradient values for each profile, which are then interpreted as indicators of the relative depth of the anomaly sources within the study area.

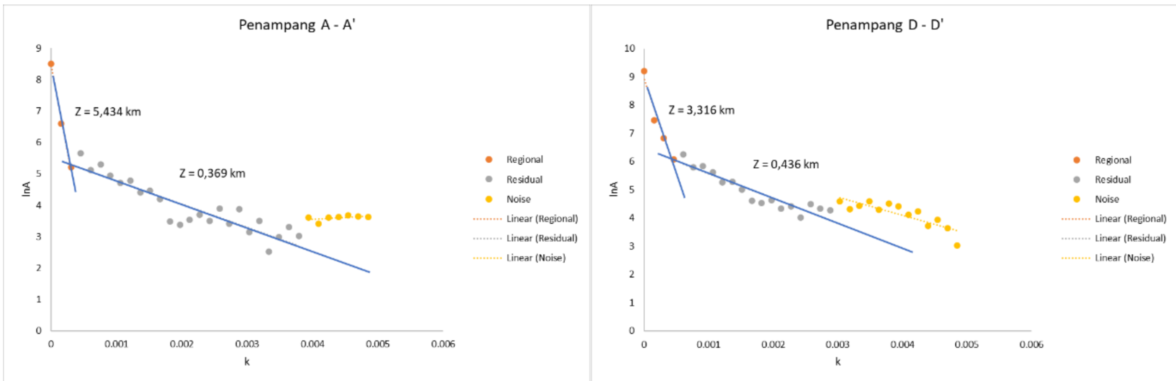

Figure 4 Example of a k curve against Ln A on a Bouguer gravity anomaly section.

The depth estimation of the discontinuity surface was performed using Microsoft Excel. The procedure involved inputting the natural logarithm of amplitude (LnA) and wavenumber (k) data into a spreadsheet, then plotting a graph to show the relationship between wavenumber and LnA. This graph, known as the power spectrum curve, is analyzed by applying linear regression to the linear segment of the curve. The resulting slope (gradient) is used to estimate the depth of the discontinuity surface.

This gradient correlates with the depth of the anomaly source, following the principle that higher frequencies are linked to shallow sources, whereas lower frequencies correspond to deeper ones. Microsoft Excel's statistical features, including trendline and regression tools, are utilized to derive the regression equation and calculate the standard deviation for each profile.

Moving Average

The moving average technique is applied to distinguish anomalies based on their wavelengths. To perform this effectively, it is essential to define an appropriate window width for the filtering process. Before separating the regional and residual anomalies using this method, the Bouguer anomaly data is organized into a regular grid with a spacing of 1 km, and the filtering window width is established.

The following equations are used to calculate the window width:

$$\mathbf{k = 2\pi / \lambda,}$$
$$\mathbf{\lambda = N \times x}$$

The parameters are defined as:

- **N**: window width (number of data points)
- **k**: wavenumber
- **x**: sampling interval (1 km)
- **λ**: wavelength

The wavenumber (k) is derived by performing a Fourier transform on the Bouguer anomaly data, which produces a graph depicting the relationship between the wavenumber and spectral amplitude. A cutoff wavenumber is then chosen from this graph to separate the regional and residual components.

The selected window size was then applied in the moving average process on the Bouguer anomaly data to extract the regional anomaly component. Subsequently, the residual anomaly was obtained by subtracting the regional anomaly from the Bouguer anomaly. The final results are presented in the form of a regional anomaly map in Figure 5, while the residual anomaly map is shown in Figure 6.

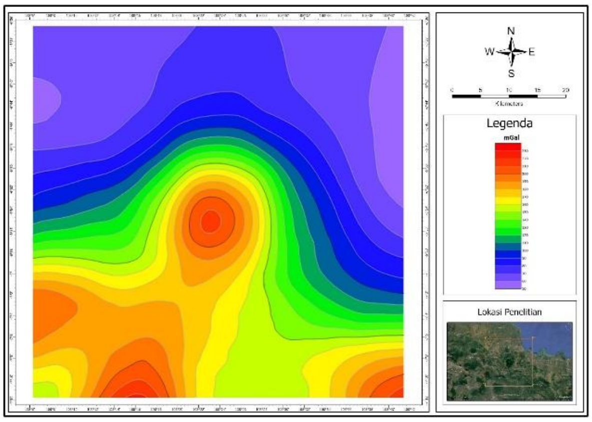

Figure 5 The regional gravity anomaly map of the Mount Ciremai area was generated using the moving average method, with a window size of 23 x 23 km.

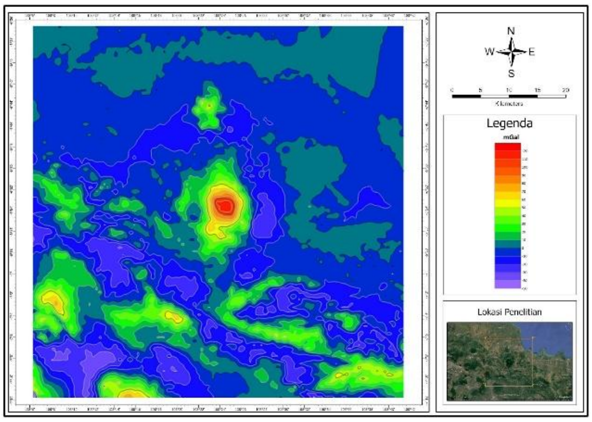

Figure 6 Residual Bouguer gravity anomaly map of the Mount Ciremai area generated using the moving average method, with a window size of 23 x 23 km.

Polynomial Method

To separate regional and residual anomalies, a polynomial approach was adopted by testing multiple orders to determine the most representative outcome. From the evaluations, a first-order polynomial with a second-degree power function was found to be the most effective and was used as a reference for comparison with other methods. The polynomial model generated through this process represents the regional anomaly, while the residual anomaly is derived by subtracting the regional component from the Bouguer anomaly. The visual results of this modeling are presented in Figure 7 for the regional anomaly map and in Figure 8 for the residual anomaly map.

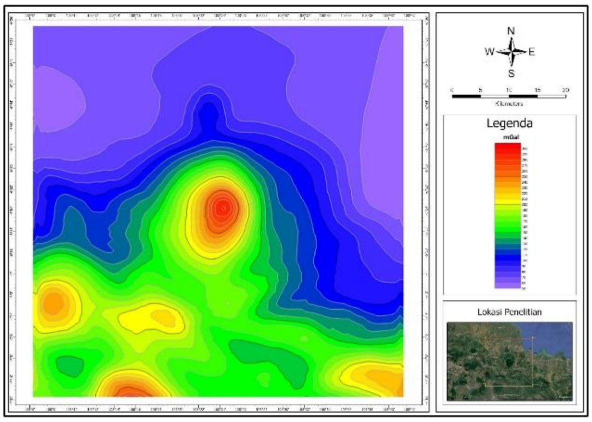

Figure 7 Regional gravity anomaly map of Mount Ciremai using the polynomial filtering method.

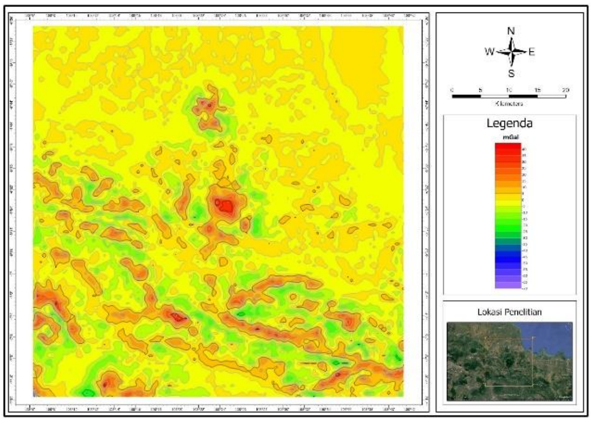

Figure 8 Residual gravity anomaly map of Mount Ciremai using the polynomial filtering method.

Interpretation of Regional and Residual Gravity Anomalies Related to Geothermal System Potential

A geothermal system refers to a local geological setup in which a portion of the Earth's thermal energy can be harnessed through the extraction of circulating hydrothermal fluids that are transported to the surface or point of use. This system comprises key components namely a heat source, a reservoir, a cap rock, and fluid circulation, each playing a crucial role in the sustainability of the geothermal system.

1. Heat Source

   Based on the separation of regional components from gravity anomaly data using the Moving Average and Polynomial methods, and concerning previous geological studies, the potential heat source in the Mount Ciremai area is suspected to be located within the Cantayan Formation. This formation consists of andesitic breccia, sandstone, and limestone from the Late Miocene, as confirmed by the presence of microforaminifera. This composition suggests the possibility of andesitic magmatic activity, a common characteristic of thermal intrusions that act as the energy source in geothermal systems. Mount Galunggung showed that high-density andesitic rocks, such as those in the Cantayan Formation, are associated with magmatic intrusions that serve as heat sources. In the context of the regional anomaly map. On the regional gravity anomaly maps (figure 9), zones with high gravity acceleration values (180–230 mGal for the Moving Average and 230–300 mGal for the Polynomial method) are indicated as areas containing high-density rock masses, which can be associated with the presence of thermal intrusions or magma chambers. Andesitic volcanic rocks are generally the main heat source in hydrothermal-type geothermal systems.

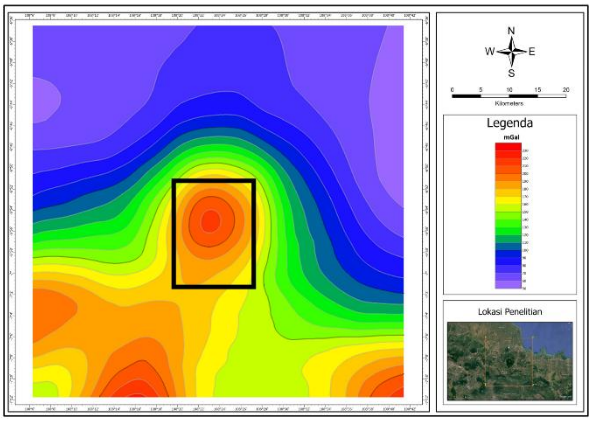

Figure 9 The regional gravity anomaly map of Mount Ciremai was generated using the Moving Average filtering method, with a window size of 23 × 23 km. (The black box indicates the area with potential as a heat source).

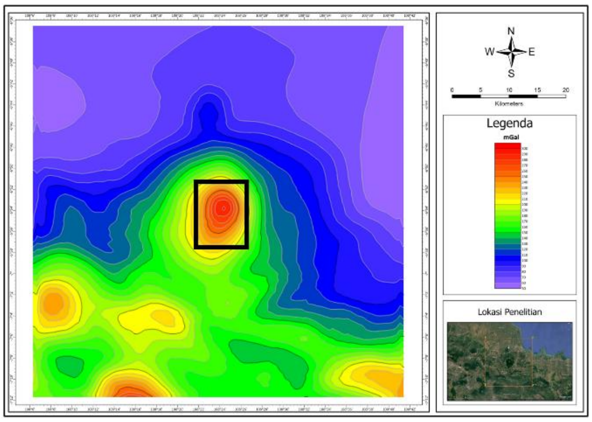

Figure 10 The regional gravity anomaly map of Mount Ciremai was generated using the Polynomial filtering method. (The black box indicates the area with potential as a heat source).

2. Reservoir

A geothermal reservoir is a volume of permeable rock capable of storing and transmitting hot fluids. Interpretation of the residual anomaly maps generated. Reveals significant gravity anomalies around the central part of Mount Ciremai, with values exceeding >70 mGal (Moving Average) and >5 mGal (Polynomial) These values indicate the presence of high-density, permeable rocks, likely resulting from hydrothermal alteration or fractured structures. The Ciherang Formation, dated to the Pliocene and composed of volcaniclastic breccia, has been identified as a permeable rock unit with the potential to serve as the main reservoir in the Ciremai geothermal system. Furthermore, the estimation of reservoir temperatures in this area ranges between 210–230°C, with fluid flow modulated by magmatic intrusions and the pore or fracture system within the volcaniclastic unit.

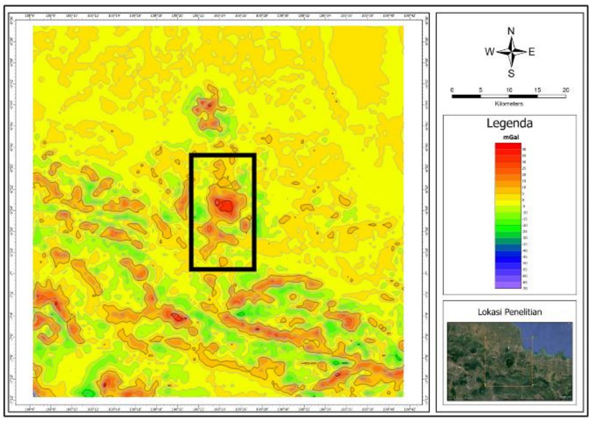

Figure 11 Residual gravity anomaly map based on the Polynomial filtering method. (The black box indicates the area with potential as a reservoir).

3. Cap Rock

Caprock is a critical element in a geothermal system, functioning as a seal that prevents hot fluids from escaping to the surface. Its key characteristics include low porosity and permeability, making it impermeable to fluid flow. Based on the distribution patterns of gravity anomalies in the residual maps (Polynomial), zones of low to moderate rock density (indicated by blue and green colors) surrounding the high anomaly zones suggest the presence of a cap rock layer enclosing the heat source and reservoir. The Subang Formation, composed of calcareous claystone interbedded with sandstone and containing *Pulleniatina primalis* fossils, has been identified as a rock unit with high impermeability, strong compaction, and relatively young geological age. These characteristics make it a strong candidate for the cap rock in the Mount Ciremai geothermal system.

4. Fluida Circulation

Hot fluid circulation is a dynamic process governed by the presence of temperature gradients and rock permeability. Hot fluid moves from the heat source area through reservoir rocks and eventually reaches the surface, where it is recharged by cold fluids from the recharge zone. The analysis of all three residual anomaly maps reveals a consistent pattern in which high anomaly zones (interpreted as heat source or reservoir areas) are surrounded by moderate to low anomaly zones. This pattern suggests the presence of fault or fracture systems (secondary permeability) that act as main pathways for upward hot fluid circulation.

This pattern reinforces the hypothesis that fracture systems, resulting from active faults or other geological structures, play a crucial role in fluid transport mechanisms within the hydrothermal system of Mount Ciremai. Identifying these zones is essential, as they directly affect the efficiency and productivity of the geothermal system.

CONCLUSION

Gravity anomaly analysis using Moving Average and Polynomial methods can indeed subsurface density distribution patterns in the Mount Ciremai area. The regional anomalies indicate a high-density mass zone at the mountain's center, while the residual anomalies reveal local details related to prospective geothermal potential. From the analysis of horizontal gradient and residual anomaly maps, 54 geological structures were mapped, including anticlines, synclines, thrust faults, strike-slip faults, and lithological boundaries. These structures serve as the main controls of the geothermal system, particularly the Cilacap–Kuningan fault zone and the anticline in the eastern area. The geothermal heat source is likely derived from the high-density Cantayan Formation, potentially containing magmatic intrusions. The reservoir is located within the Ciherang Formation, characterized by permeable rocks and associated with high residual anomalies. The Subang Formation is identified as the cap rock due to its low density and impermeability. Fluid movement is facilitated through fault and fracture networks, supporting circulation and surface recharge.

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