



Geological Structure of The Grao Sakti Hot Spring Manifestation Based on Gravity Derivative Analysis

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Abstract:

Hot springs are among the most common geothermal surface manifestations, typically emerging through fractures formed by tectonic processes. The subsurface structures associated with the Grao Sakti hot spring manifestation in Jangkat, Merangin Regency, were identified using GGMplus gravity data by analyzing rock density contrasts through cross-sectional interpretations of the First Horizontal Derivative and Second Vertical Derivative of the gravity anomaly data. The Complete Bouguer Anomaly map reveals several gravity anomalies ranging from 73.8 to 174.6 mGal, which are interpreted as the Masurai, Hulunilu, and Sumbing volcanic complexes. Dikit Fault Segment has promoted the development of a fault-bend basin within the study area and the Barisan Mountain Range. Structural interpretation based on the FHD and SVD maps indicates the gravity derivative results indicate that the Grao Sakti manifestation is associated with a subsurface structure interpreted as a normal fault. This interpretation is consistent with regional geological evidence, and previous studies conducted along the Grao Sakti hot spring profile that normal fault is interpreted to have developed as a consequence of the formation under a transtensional tectonic regime movement of the Dikit Fault Segment, a major segment of the Sumatran Fault System, which trends in a northwest–southeast direction.

Keywords: GGMplus; first horizontal derivative (FHD); second vertical derivative (SVD); normal fault; hot springs

1. Introduction

Jambi Province is one of the regions in Indonesia with significant geothermal potential, primarily associated with volcanic activity and the Sumatran Fault System extending along the Barisan Mountain Range (Putri et al., 2024). One manifestation of this geothermal potential appears at the surface as hot springs that emerge through fractures or geological structures formed by tectonic or other geological processes, such as the Grao Sakti hot spring located in Jangkat District, Merangin Regency, Jambi Province. The Grao Sakti geothermal manifestation is situated at the contact between the Hulusimpang Formation (Tomh), which consists of andesitic lava and volcanic breccia, the Plio–Pleistocene volcanic products of the Old Masurai Caldera (Qhv), and the Langkup Granodiorite Formation (Tpgdl), within the Dikit Fault Segment (DFS) (Utama et al., 2021). Subsurface geological structures, particularly fault and fracture zones, play a fundamental role in controlling the migration of geothermal fluids toward the surface and can be effectively identified using geophysical methods, including the gravity method (Wijaya et al., 2026).

The gravity method is a geophysical technique capable of delineating subsurface geological structures based on variations in the physical properties of rocks, particularly density contrasts (Sarkowi, 2014). This study utilizes the Global Gravity Model Plus (GGMplus) 2013 dataset, which has a spatial resolution of 200 m, as preliminary gravity data to provide an initial regional interpretation prior to field investigations. Satellite gravity data provide an effective preliminary approach for geothermal exploration, particularly for delineating

potential reservoir zones and fault zones that may act as conduits for geothermal manifestations over extensive areas within a relatively short period, as demonstrated in southern Thailand (Phiranram et al., 2026). In geothermal exploration, prospective zones and subsurface geological structures can be delineated based on gravity-anomaly contrasts observed in the Complete Bouguer Anomaly (CBA) map. To further characterize the subsurface sources, the gravity anomalies can be separated into regional and residual components using the Moving Average method.

The presence of subsurface geological structures can be delineated from gravity-anomaly contrasts through the application of the *First Horizontal Derivative* (FHD) and *Second Vertical Derivative* (SVD) filters (Novianda et al., 2024). The FHD provides a qualitative assessment of horizontal gravity gradients by characterizing lateral variations in rock density, which can be indicative of subsurface structural discontinuities. In contrast, the SVD is highly sensitive to shallow-source anomalies, including high-frequency noise, as well as topographic effects. By calculating the second derivative of the gravity field in the vertical direction, the SVD enhances shallow structural features, facilitates the delineation of geological boundaries, and assists in characterizing the type of subsurface structure (Minarto & Saputri, 2025).

2. Method

Regional geology

Indonesia is located at the convergence of three major tectonic plates: the Eurasian Plate, the Pacific Plate, and the Indo-Australian Plate. This tectonic setting has resulted in the widespread development of geological structures and volcanic systems, particularly on the island of Sumatra. Sumatra is characterized by a major fault system and a chain of volcanoes extending from Aceh Province in the northwest to Lampung Province in the southeast. The principal tectonic structure is the Sumatran Fault System (Semangko Fault), which developed as a consequence of the oblique subduction of the Indo-Australian Plate beneath the Eurasian Plate (Fig 1). This subduction process has generated numerous fault segments, sustained magmatic activity, geothermal manifestations, and the formation of sedimentary basins throughout the island. The study area is located in the Jangkat District, Merangin Regency, Jambi Province, Indonesia, as indicated by the yellow box in Fig 1. The area is associated with the Sumatran Fault Zone, particularly the Dikit Fault Segment, which represents one of the major structural features controlling the regional geological framework.

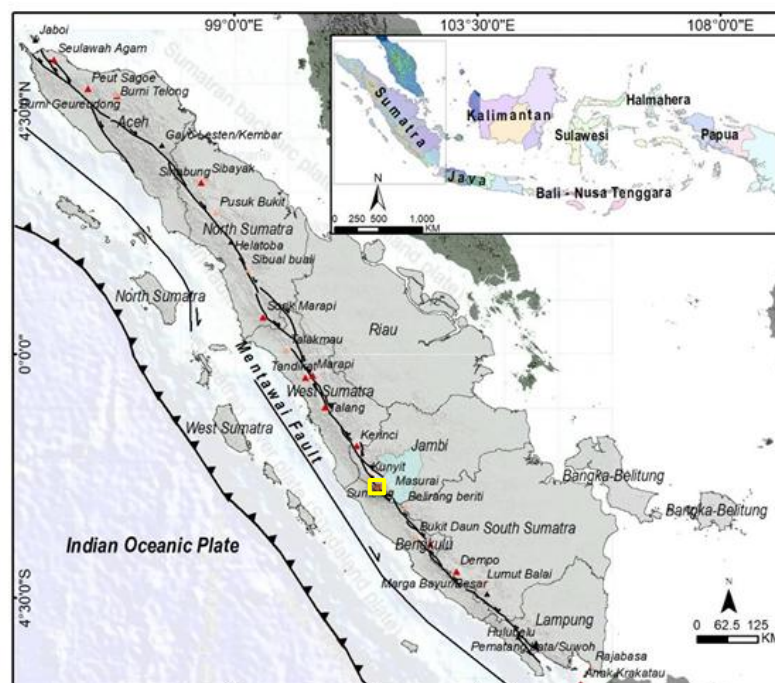


Figure 1. The tectonic evolution of the Grao Sakti area, Jangkat, Merangin, is associated with the Dikit Fault Segment of the Sumatran Fault Zone. ((Muraoka et al., 2010; Zahirovic et al., 2016) as cited in (Utama et al., 2021)).

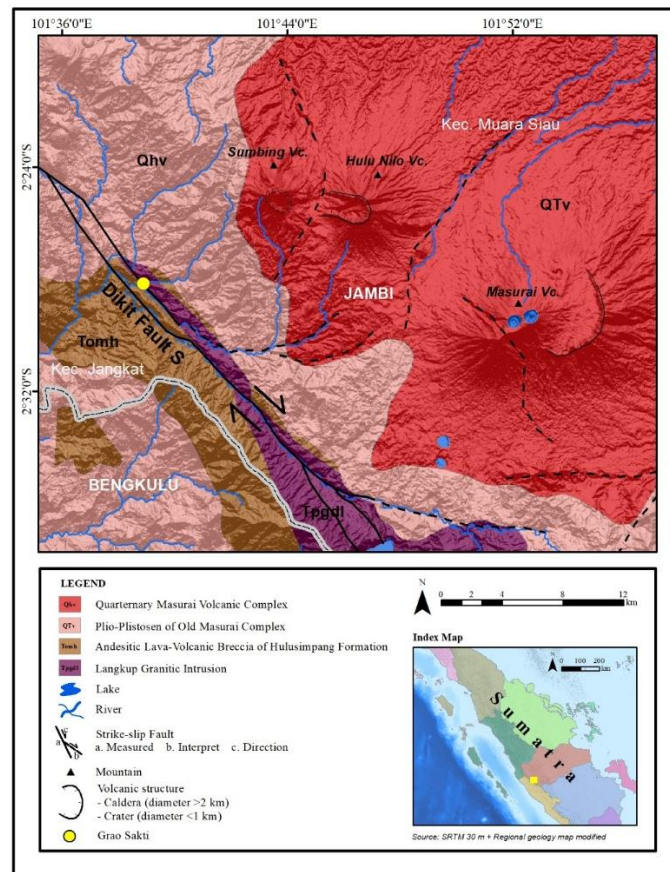


Figure 2. Regional geological map of the Grao Sakti area and its surroundings (Utama et al., 2021) .

Based on the regional geological setting (Fig 2), the study area is located within several geological formations, including the Plio–Pleistocene Old Masurai Caldera Formation (QTV), consisting of lava and pyroclastic deposits; the Hulupimpang Formation (Tomh), composed of lava and volcanic breccia; the Quaternary Masurai Volcanic Complex Formation (Qhv), consisting of pyroclastic materials and lava flows; and the Langkup Granodiorite Intrusive Formation (Tpgdl). The study area is also situated within the Dikit Fault Segment subsequently generates as normal fault structures, which exhibits a transtensional strike-slip deformation mechanism with a northwest–southeast orientation. This fault system plays an important role in the development of a fault-bend basin structure, also referred to as a graben structure or the Dikit Graben, which is marked by the occurrence of the Grao Sakti hot spring manifestation (Utama et al., 2021).

Research procedures

The identification of geological structures associated with the Grao Sakti geothermal manifestation was conducted using gravity disturbance data derived from the 2013 satellite-based *Global Gravity Model Plus* (GGMplus). The dataset was obtained from the GGMplus database (<http://ddfe.curtin.edu.au/gravitymodels/GGMplus/>) and focused on the area surrounding the Grao Sakti hot spring in Jangkat District, Merangin Regency, Jambi Province, Indonesia, with a spatial sampling interval of 200 m, with the study area bounded by UTM coordinates X = 9,709,785–9,742,205 and Y = 121,641.4–159,801.5. The GGMplus dataset consists of gravity disturbance and elevation data, which were subsequently extracted, resulting in a total of 25,284 data points (Agustin & Wibawa, 2022). Subsequently, to obtain the Complete Bouguer Anomaly (CBA), the workflow of the gravity disturbance data from GGMplus were first converted into Free-Air Anomaly (FAA) using the corresponding elevation data from GGMplus. The resulting FAA was then subjected to Bouguer and terrain corrections to account for the gravitational effects of the rock mass and surrounding topography (Minarto & Saputri, 2025). Terrain correction was performed to account for the effects of topographic variations surrounding the study area. Spatial Digital Elevation Model (DEM) data

were processed using Global Mapper by extending the study area boundaries by 1,000 m for the local-scale analysis and 10,000 m for the regional-scale analysis in all directions. Therefore, an average density of 2.56 g/cm³ was obtained for the study area using the Parasnis density estimation method.

Data analysis

The Moving Average filter was subsequently applied using Oasis Montaj software to separate the regional and residual gravity anomalies by using window. Parameters used to determine the moving-average window width include radial power-spectrum analysis by plotting the wavenumber (k) against the natural logarithm of spectral power $\ln(A)$ (Minarto & Saputri, 2025). The characteristic anomaly wavelength (λ) was estimated from the spectral response and subsequently used to determine the appropriate window width (N) in relation to the grid spacing. Based on this analysis, a 9×9 moving-average window was selected for the study area. The selected window was applied to separate the long-wavelength regional component from the shorter-wavelength residual component while preserving the anomaly patterns associated with geological structures. This separation enhances the resolution of local gravity anomalies and provides a more reliable basis for geological interpretation. Mathematically, the Moving Average can be expressed as Eq 1:

$$g_r(x, y) = \frac{1}{N} \sum_{j=1}^N g(x_i, y_i) \quad (1)$$

where $g_r(x, y)$ is the regional gravity anomaly at position (x,y) that represents the gravity-anomaly values within the specified window and is the total number of data points included in the averaging window. The determination of lithological contact boundaries or subsurface geological structures can be conducted using derivative analysis from residual anomaly after the moving-average filtering process was applied, namely the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) were performed on regular 200 m x 200 m grid. The FHD analysis is applied to delineate lithological boundaries based on Eq 2 (Blakely, 1996), as follows:

$$\text{FHD} = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \quad (2)$$

The FHD Eq 2 represents the first derivative or first order of the gravity anomaly and provides a qualitative assessment of horizontal gravity-gradient variations within the study area. The x ($\partial g / \partial x$) and y ($\partial g / \partial y$) in the Eq 2 represent the Easting and Northing directions. Subsequently, the SVD method was employed to identify and characterize the types of geological structures present in the study area using the mathematical formulation given in Eq 3 as a second derivative or order from modification of the Laplace equation and is used to evaluate spatial variations in the gravity field (Minarto & Saputri, 2025). Based on the results of the synthetic model (Fitriana et al., 2020; Wahyudi et al., n.d.), structural characterization was performed by analyzing the absolute maximum and absolute minimum values of the SVD, as expressed in Eq 4, 5, and 6, with the zero value of SVD and maximum values of FHD used as a boundary condition for delineating geological characteristics. The corresponding Eq are given as follows:

$$\frac{\partial^2 g}{\partial z^2} = -\left(\frac{\partial^2 g}{\partial x^2} + \frac{\partial^2 g}{\partial y^2}\right) \quad (3)$$

$$\left(\frac{\partial^2 (\Delta g)}{\partial z^2}\right)_{\text{maks}} > \left|\left(\frac{\partial^2 (\Delta g)}{\partial z^2}\right)\right|_{\text{min}} \quad \text{Normal (Dip/Slip) Fault} \quad (4)$$

$$\left(\frac{\partial^2(\Delta g)}{\partial z^2}\right)_{\text{maks}} < \left|\left(\frac{\partial^2(\Delta g)}{\partial z^2}\right)\right|_{\text{min}} \quad \text{Reverse Fault} \quad (5)$$

$$\left(\frac{\partial^2(\Delta g)}{\partial z^2}\right)_{\text{maks}} = \left|\left(\frac{\partial^2(\Delta g)}{\partial z^2}\right)\right|_{\text{min}} \quad \text{Strike – Slip Fault} \quad (6)$$

3. Results and Discussion

The processing results of the Complete Bouguer Anomaly (CBA) data shown in Fig 3 reveal a gravity anomaly range from the lowest value of 73.8 mGal, represented by blue colors, to the highest value of 174.6 mGal, represented by pinkish-red colors distributed throughout the study area. The CBA map indicates several high-gravity anomalies between 134.9 mGal – 174.6 mGal interpreted as the presence of the Masurai Volcano, Hulunilu Volcano, and Sumbing Volcano, which are included within the Quaternary Masurai Volcanic Complex Formation (Qhv), dominated by pyroclastic deposits and lava flows. Furthermore, a high-gravity anomaly extending from the northwest to the southeast is identified as the Barisan Mountain Range, which is consistent with the regional geological setting characterized by the Hulusimpang Formation (Tomh), consisting predominantly of lava and volcanic breccia. The Dikit Fault Segment is associated with a low-gravity anomaly ranging from 73.8 to 93.1 mGal, corresponding to the Langkup Granodiorite Intrusion Formation (Tpgdl). The geothermal manifestation, indicated by the yellow point within the low-anomaly zone, is interpreted to be associated with a *fault-bend basin* formed as a result of displacement along the Dikit Fault Segment and the associated geometric change caused by fault bending (Utama et al., 2021).

The Complete Bouguer Anomaly represents the combined effects of regional (deep-seated) and residual (shallow) anomalies using the Moving Average method with radially averaged power spectrum in Fig 4, the gravity data were smoothed, resulting in a more continuous and less noisy gravity field. The regional anomaly map (Fig 5a) shows gravity anomaly values ranging from 73.5 mGal (blue colors) to 173.6 mGal (pinkish-red colors). The anomaly distribution pattern remains similar to that observed on the CBA map, indicating that the gravity anomalies extend to considerable depths. These deep-seated anomalies are associated with the presence of the Masurai Volcano, Hulunilu Volcano, and Sumbing Volcano. In addition, moderate to high gravity anomalies, ranging from 102 mGal to 141.3 mGal, extend from the northwest to the southeast and are interpreted as the expression of the Barisan Mountain Range and the low-gravity anomaly, represented by the blue color and ranging from 73.5 to 91.3 mGal, is interpreted as being associated with the Dikit Fault Segment.

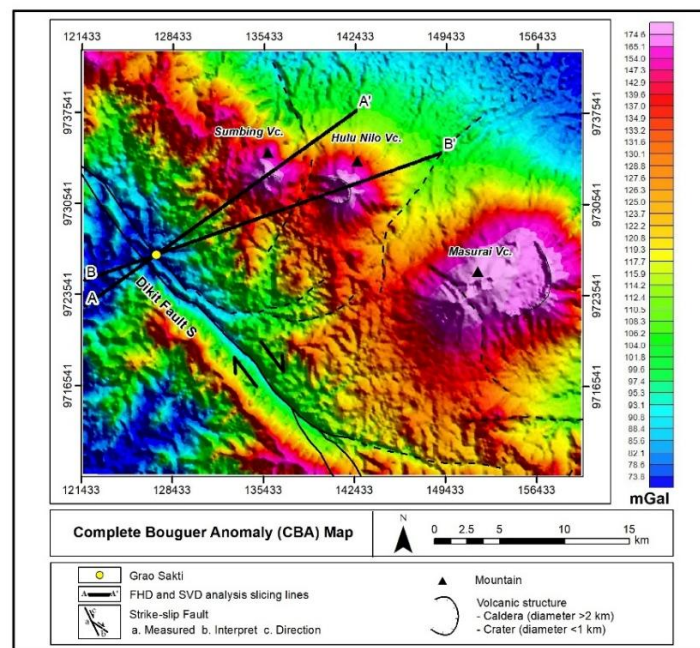


Figure 3. Complete Bouguer Anomaly (CBA) map of the Grao Sakti geothermal manifestation area.

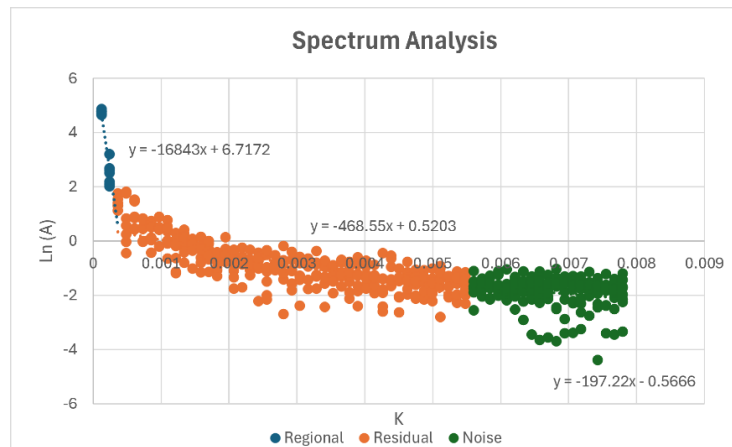


Figure 4. Radially averaged power spectrum of the Bouguer gravity anomaly

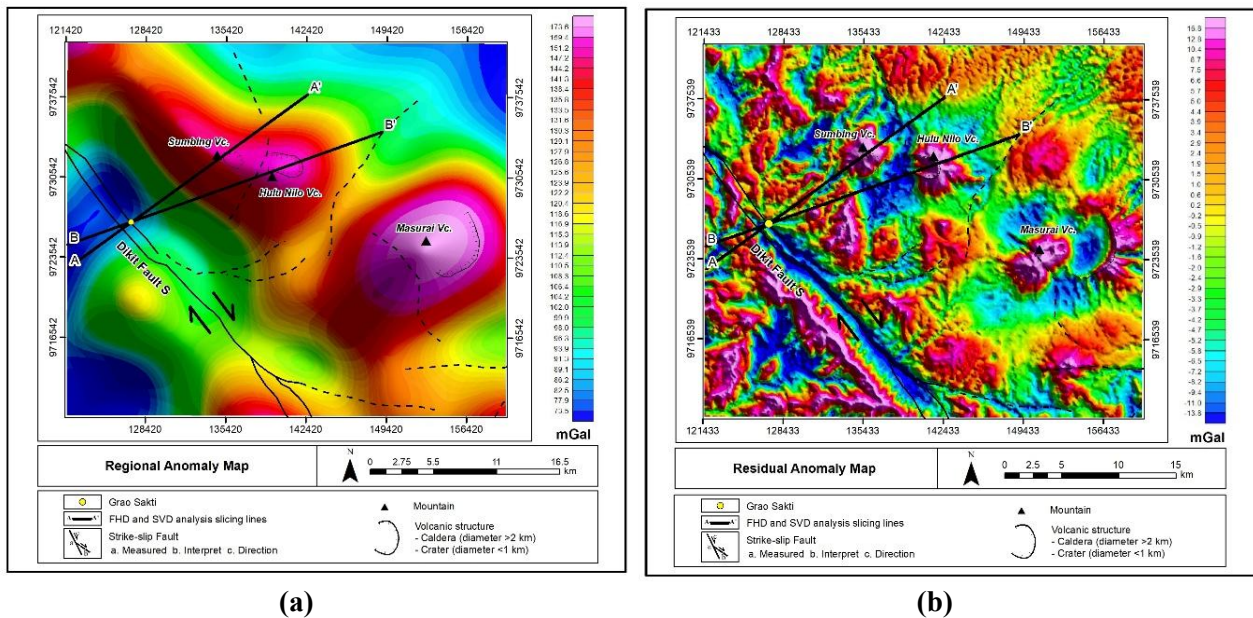


Figure 5. (a) Regional anomaly map; (b) Residual anomaly map.

The residual anomaly map (Fig 5b) shows clearer anomaly closures, with gravity values ranging from -13.8 mGal, represented by blue colors, to 16.8 mGal, represented by pinkish-red colors. High-gravity anomalies exhibit a similar distribution pattern to the CBA map with values of 3.4 mGal to 16.8 mGal, particularly associated with the presence of the Masurai Volcano. However, the residual anomaly map reveals a more distinct horseshoe-shaped fault pattern that forms a caldera structure on the eastern side of the Masurai Volcano. High-gravity anomalies are also observed around the Hulunilu Volcano and Sumbing Volcano, which are separated by fault structures consistent with the regional geological map. A similar high-anomaly pattern extends from the northwest to the southeast and is interpreted as the expression of the Barisan Mountain Range. Meanwhile, the Grao Sakti hot spring manifestation, indicated by yellow points, is located within a low-gravity anomaly zone with range -13.8 mGal to -6.5 mGal represented by blue colors. This low anomaly is interpreted to be associated with the Fault-Bend Basin as deformation and displacement activity of the Dikit Fault Segment.

After obtaining the regional and residual gravity anomalies, derivative analyses using the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) methods were conducted. The FHD and SVD maps (Figs 6a and 6b) show gravity anomaly distributions that correlate with the regional geological setting, revealing several subsurface structures, including fault zones and the Masurai Volcano caldera

structure. The Grao Sakti hot spring manifestation, indicated by yellow points, is located along the Dikit Fault Segment zone, which extends in a northwest–southeast direction. To investigate the structural control responsible for the emergence of the Grao Sakti hot spring manifestation, two cross-sectional analyses were performed: profile A–A', extending toward the Masurai Volcano, and profile B–B', extending across the Hulunilu Volcano area.

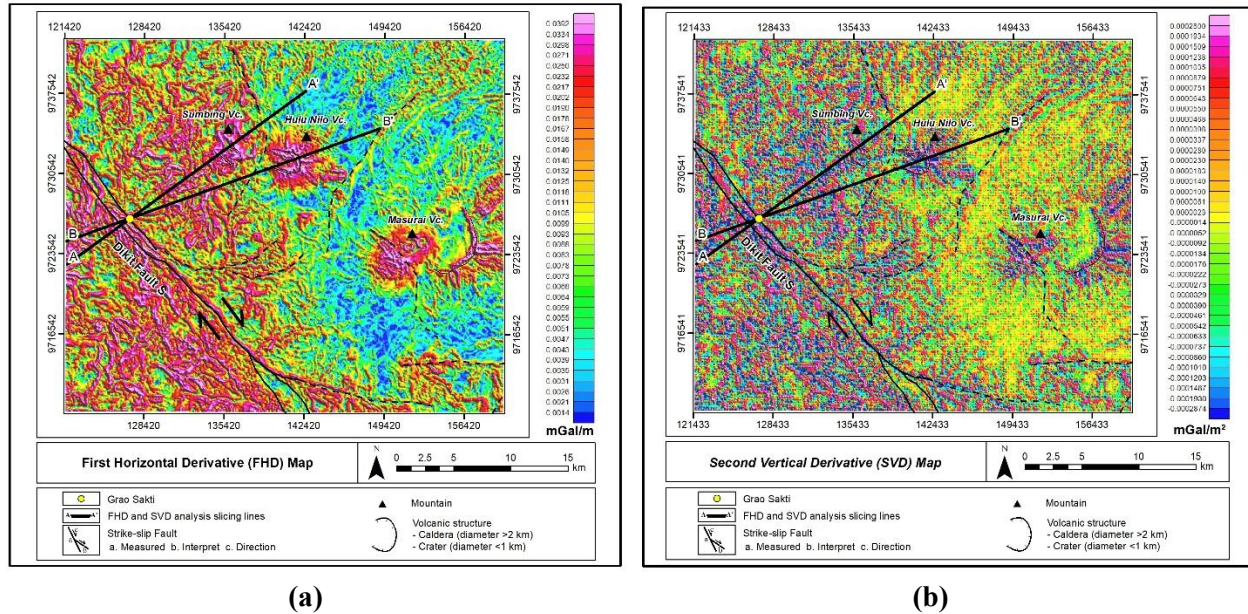


Figure 6. (a) First Horizontal Derivative (FHD) anomaly map; (b) Second Vertical Derivative (SVD) anomaly map.

Based on the cross-sectional analysis, profile A–A' (Fig 7), 10 anomalies were identified and interpreted as structural features which correlates the residual anomaly, FHD, and SVD results. Based on the SVD curve interpretation, the Grao Sakti geothermal manifestation area, indicated by the purple line at point P4, is identified as a normal fault. This interpretation is supported by the SVD values, with a maximum value of 0.00057 and a minimum value of 0.00016 (Fitriana et al., 2020; Wahyudi et al., n.d.). The development of this structure is interpreted to be associated with the movement of the Dikit Fault Segment, which exhibits a strike-slip deformation pattern with a northwest–southeast orientation, resulting in the formation of a fault-bend basin (Utama et al., 2021). This extensional setting subsequently generated normal fault structures. Several fault structures are also identified around the Sumbing Volcano area, including a normal fault at P8 with an SVD maximum value of 0.00116 and a minimum value of 0.00010, a reverse fault at P9 with an SVD maximum value of 0.00019 and a minimum value of 0.00022, and a normal fault at P10 with an SVD maximum value of 0.00065 and a minimum value of 0.00009, as indicated by the colored boxes.

In profile B–B' (Fig 8), 8 anomalies were identified and interpreted as structural features which also correlates the residual anomaly, FHD, and SVD results. Based on the SVD curve interpretation, the Grao Sakti geothermal manifestation area, indicated by the purple line at P14, is interpreted as a normal fault with an SVD maximum value of 0.00031 and a minimum value of 0.00028. This structure is associated with the presence of the Dikit Fault Segment in the regional geological setting, which represents a strike-slip fault system oriented northwest–southeast. The movement of this fault segment generated a fault-bend basin structure, resulting in the development of normal faults controlling the geothermal fluid pathway (Utama et al., 2021). Furthermore, a reverse fault structure is identified in the Hulunilu Volcano area. At P17, the SVD maximum value is 0.00013, which is lower than the minimum value of 0.00039 (Fitriana et al., 2020; Wahyudi et al., n.d.), while at P18, the SVD maximum and minimum values are 0.00023 and 0.00026, respectively. Based on the correlation between the residual anomaly, FHD, and SVD curves, the subsurface structural characteristics within the study area can be identified and summarized (Table 1).

Following the overlay (Fig 9) of the interpreted structural features with the regional geological map at points P4 and P1 as white line, the FHD and SVD results show a strong spatial correlation with the Dikit Fault

Segment mapped in the regional geology. The structure is interpreted as a normal fault associated with the NW–SE orientation of the Sumatran Fault Zone. This structural configuration is interpreted to have promoted the development of a *fault-bend basin*, which subsequently acted as a pathway for the upward migration of geothermal fluids and the emergence of the Grao Sakti hot-spring manifestation, indicated by the yellow point.

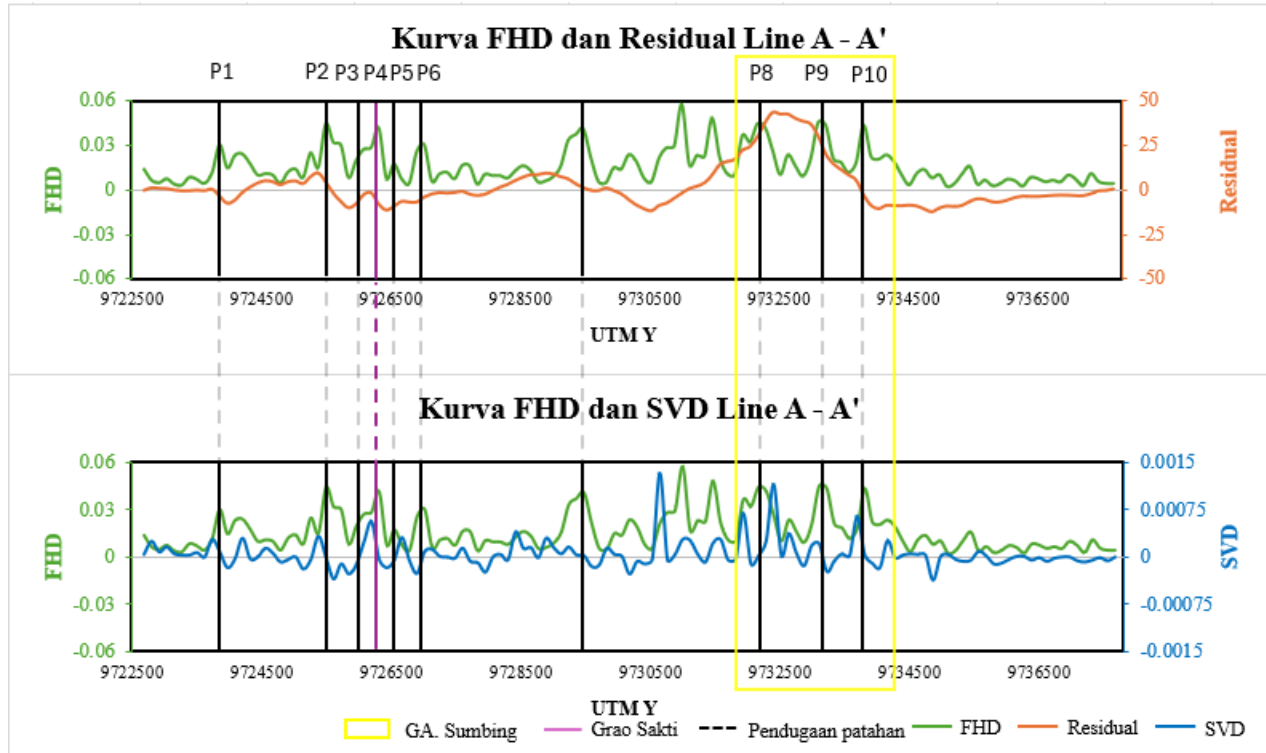


Figure 7. Correlation of FHD, SVD, and residual anomaly along profile A–A'.

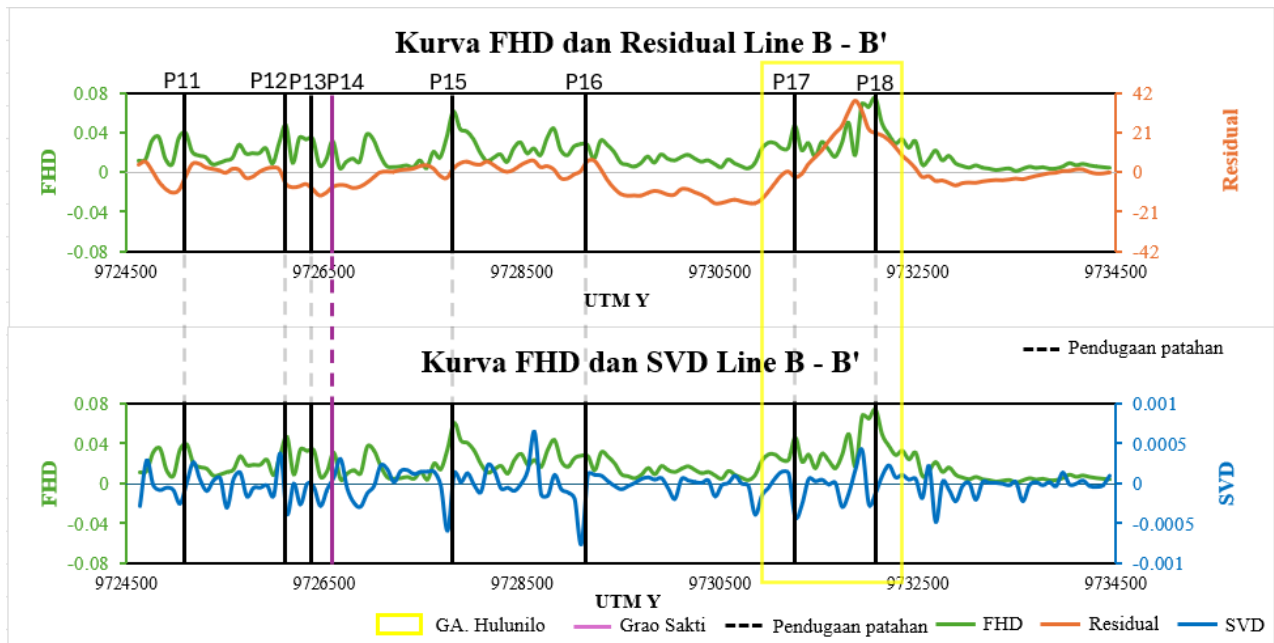


Figure 8. Correlation of FHD, SVD, and residual anomaly along profile B–B'.

Table 1. Fault type analysis.

Sayatan	Plot	SVD Maks	SVD Min	Fault type
Line A-A'	P1	0.00029	0.00016	Normal
	P2	0.00034	0.00034	Strike-slip
	P3	0.00057	0.00026	Normal
	P4	0.00057	0.00016	Normal
	P5	0.00032	0.00016	Normal
	P6	0.0001	0.00025	Reverse
	P7	0.00004	0.00016	Reverse
	P8	0.00116	0.0001	Normal
	P9	0.00019	0.00022	Reverse
	P10	0.00065	0.00009	Normal
Line B-B'	P11	0.00027	0.00027	Strike-slip
	P12	0.00038	0.00038	Strike-slip
	P13	0.00004	0.00028	Reverse
	P14	0.00031	0.00028	Normal
	P15	0.00013	0.00059	Reverse
	P16	0.00011	0.00076	Reverse
	P17	0.00013	0.00039	Reverse
	P18	0.00023	0.00026	Reverse

Note : Dikit Fault Grao Sakti

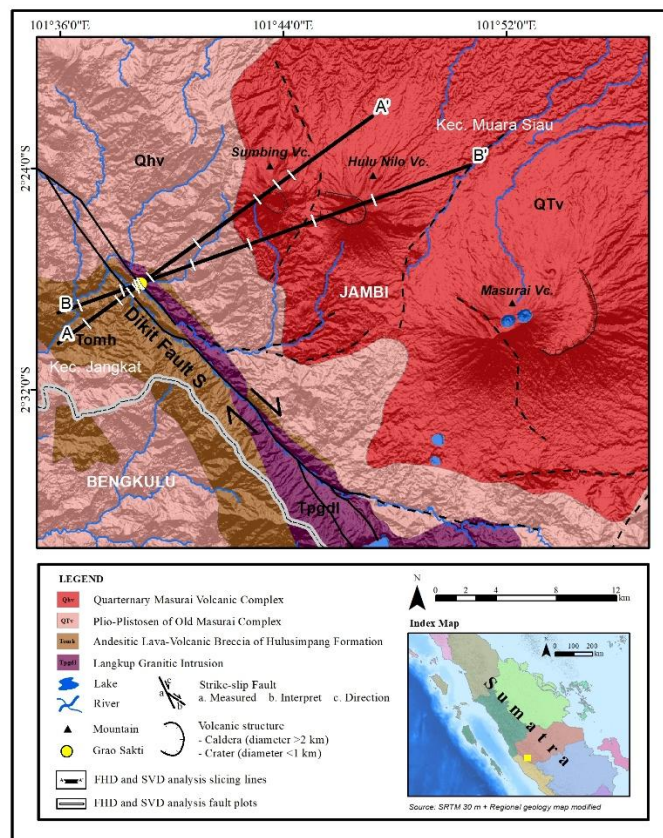


Figure 9. Overlay structural result between geological regional and anomaly along A-A' profile and B-B' profile

4. Conclusion

The Complete Bouguer Anomaly (CBA) map of the study area shows gravity values ranging from 73.8 mGal to 174.6 mGal. Based on residual map, the high-gravity anomalies with value 3.4 mGal to 16.8 mGal are interpreted as being associated with the presence of the Masurai Volcano and its surrounding caldera structure, as well as the Hulunilu Volcano and Sumbing Volcano. The Dikit Fault Segment zone is identified as extending in a northwest–southeast direction, which is consistent with the regional geological setting and is characterized by low-gravity anomalies associated with the Grao Sakti hot spring manifestation, with a value of -13.8 mGal to -6.5 mGal. Based on derivative analysis using the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) methods, the occurrence of the Grao Sakti geothermal manifestation is interpreted to be controlled by normal fault activity. In profile A–A', the identified normal fault is characterized by an SVD maximum value of 0.00057 and a minimum value of 0.00016, while in profile B–B', it shows an SVD maximum value of 0.00031 and a minimum value of 0.00028. The development of this normal fault is interpreted to be related to the formation of a fault-bend basin generated by the displacement of the Dikit Fault Segment, which represents a strike-slip fault system.

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