3D MODELING AND DERIVATIVE ANALYSIS OF THE KETAHUN SEGMENT BASED ON GGMPLUS AND SRTM2 DATA FOR DISASTER MITIGATION

Clora Ulandari[1], Halauddin[1*], Refrizon[1], Hilmi Zakariya[2], Suhendra[1], Muchammad Farid[1], Alda Sulistiani[1], Hana Raihana[1], Nurul Apriyanti[1]

[1]The Departemen of Geophysics is Situated Withim the University Campus of Bengkulu University in Bengkulu, Bengkulu.

[2]The Address of the Kepahiang Geophysical Station is as follows Meteorology, Climatology and Geophysical Agency, Bengkulu

e-mail : halaukualasatu@gmail.com

Abstract. The island of Sumatra is one of the most tectonically active regions in Indonesia due to the interaction between the Sumatra subduction zone and the Sumatra Fault, resulting in high seismic activity. One of the important segments with the potential to cause earthquakes is the Ketahun Segment in Lebong Regency, Bengkulu Province. This study aims to map the three-dimensional (3D) fault structure and identify lithological density contrasts to support disaster mitigation efforts. The methods used include processing GGMPlus and SRTM2gravity satellite gravity data, complete Bouguer correction, regional-residual anomaly separation, first horizontal derivative (FHD) and second vertical derivative (SVD) analysis, and 3D inversion modeling using Grav3D software. The CBA analysis results show anomaly values of –8 to 50 mGal with sharp gradations indicating the presence of major fault structures. SVD and FHD analyses show the dominance of dip-slip faults with significant density contrasts. The 3D inversion modeling shows a density range of 1.02–3.52 g/cm³ with an average value of 2.27 g/cm³, where the low-density zone is at a shallow depth (0–1500 m) and the high-density zone is at a depth of 500–2000 m. The sharp boundary between the two zones indicates an active fault plane at a depth of 1000–2500 m. These findings provide a more representative picture of the fault geometry and can be used as a basis for developing earthquake mitigation strategies and spatial planning based on actual geological conditions in the Bengkulu region.

Keywords: 3D Inversion; GGMPlus Gravity; Ketahun Segment; Second Vertical Derivative; SRTM2gravity

INTRODUCTION

Geologically, this region is located at the meeting point of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. These three tectonic plates continue to move relative to each other and interact on a large geodynamic scale, forming an active and complex tectonic system in this region (Anver and J. Prasetyo, 2025). These interactions between tectonic plates make Indonesia one of the most seismically and volcanically active regions in the world, as reflected in the frequency of earthquakes and the distribution of active volcanoes throughout the archipelago (Álvarez et al., 2021; Qin et al., 2024). In particular, Sumatra Island is one of the most tectonically active regions in Indonesia. The island is dominated by two main elements of the tectonic system, namely the subduction zone in the west, where the Indo-Australian Plate subducts beneath the Eurasian Plate, and the Great Sumatran Fault (GSAF), which stretches from the northern to the southern tip of the island for more than 1.900 km (Chen et al., 2020; Syaputra et al., 2023). The interaction between these two major tectonic systems has resulted in complex deformation patterns, high seismic activity, and significant earthquake hazards along the western coast of Sumatra, including in Bengkulu Province. Lebong Regency is one of the areas in Bengkulu Province that is highly vulnerable to seismic activity. This is due to its geographical location.

The province of Bengkulu is tectonically located in an active zone with a relatively high level of earthquake vulnerability (Misliniyati et al., 2018). Specifically, the Lebong Regency, which lies within this province, is one of the areas most affected by seismic activity due to its position along the Ketahun Segment. Regionally, Bengkulu Province is affected by two primary earthquake sources, namely the Sumatra Subduction Zone, the Mentawai Fault, and the Sumatra Fault. These three seismic sources play an important role in triggering intense tectonic activity, especially in the coastal areas and mountains of western Sumatra (Farid

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

and Mase, 2020). One of the active fault segments that has significant seismic hazard potential in this region is the Ketahun Segment. This fault is identified as part of the Sumatra Fault system that extends parallel to the tectonic structure of Sumatra Island. This segment stretches through the Lebong Regency area, indicating that the region is directly traversed by the Ketahun Segment. Morphologically, this segment stretches for approximately ±85 km with a width of approximately ±20 km, oriented northwest-southeast, and crosses several important areas in Bengkulu Province (Oktarina et al.,2021). Tectonic activity in this segment has the potential to cause surface deformation, strong tremors, and secondary risks such as landslides and infrastructure damage. Therefore, a thorough understanding of the geometric characteristics and dynamics of the Ketahun Segment is crucial in mitigating the impact of earthquakes and in planning earthquake-resistant regional development.

Lebong Regency is traversed by the Ketahun segment, which is composed of highly varied lithology. In the western part of the fault, pre-Tertiary rocks such as granite are found, while in the eastern part, young sedimentary rocks such as sandstone, clay, and conglomerate are found (Hakim Al et al., 2022). In addition, the Hulusimpang Formation, consisting of lava, tuff, and volcanic breccia dating from the Oligocene to Miocene periods, dominates most of the study area (Al Ansory et al., 2023). These lithological differences cause significant rock density contrasts and play a major role in the development of active fault structures and deformation responses in the area. The existence of this active subduction zone causes high levels of seismicity in the surrounding area, including Lebong Regency. Many earthquakes have occurred in the study area, including one on March 15, 1952. According to BMKG (Meteorology, Climatology and Geophysics Agency) records, the earthquake had a magnitude of 6.8 SR with the epicenter located on land at coordinates 3.23° S-102.35° E. The earthquake was centered in the Ketahun Segment, causing severe damage to the villages of Tes and Muara Aman (Hasanah *et al.*, 2024; Ardiansyah, 2018).

This research is a development of a study conducted by Syaputra et al. (2023), which utilizes GGMPlus satellite gravity data to analyze fault patterns and successfully identifies three main types, namely thrust faults, normal faults, and strike-slip faults. However, this research still has limitations because the analysis is two-dimensional (2D) and only utilizes the first and second derivatives of gravity data (First Horizontal Derivative and Second Vertical Derivative), so it is not yet able to describe the geometry of the fault structure volumetrically and comprehensively. As an improvement on previous research, this study uses an integrative approach by combining GGMPlus satellite gravity data, SRTM2gravity topographic field corrections, FHD and SVD analysis, and three-dimensional (3D) inversion modeling. This approach provides advantages in visualizing fault structures in greater detail, including depth, orientation, and density contrast between lithologies, which play an important role in understanding tectonic deformation processes in the Ketahun Segment region (Hirt et al., 2019; Damayanti et al., 2025). The main objective of this research is to map the three-dimensional shape of the fault structure, determine the density contrast between lithologies that play a role in the tectonic deformation process, and provide supporting data for disaster mitigation efforts and spatial planning based on actual geological conditions. The results of this research are expected to produce a three-dimensional model of the Ketahun Segment, along with zones with high density contrasts that have the potential to become centers of deformation and seismic activity. This information is strategically valuable for disaster mitigation, as it can be used to anticipate potential earthquake hazards, determine zones prone to active faults, and serve as a scientific basis for spatial planning and sustainable development in the province of Bengkulu, which is located on an active tectonic zone.

METHODOLOGY

Geology Regional

Lebong Regency, located in Bengkulu Province, is situated in the main segment of a fault, an active fault system that stretches from north to south across the island of Sumatra. The Ketahun segment runs northwest-southeast and crosses the Rejang Lebong to the Lebong region. The study area consists of steep hills in the

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

west and alluvial valleys in the east, reflecting the strong influence of the active fault structure (Syaputra et al., 2023). The geological conditions of the Lebong Regency can be seen in Figure 1. Based on the Bengkulu geological map sheet (Al Ansory et al., 2023), several important geological structures have developed in this region, including faults, the Air Putih Strike-Slip Fault, and the Batang Ketahun Segment. These faults were formed in the Late Miocene epoch when major tectonic forces moved relative to each other in a north-south direction.

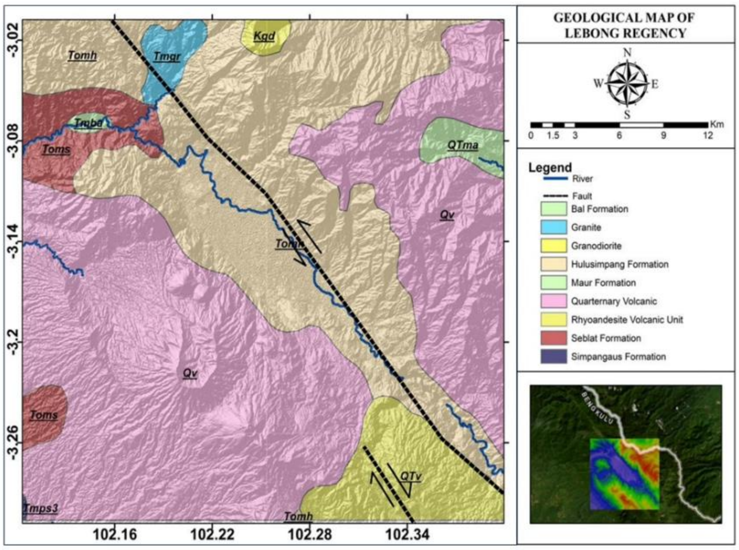


Figure 1. Geological Map of Lebong Regency, Bengkulu

The Lebong Regency area comprises several central rock units, namely the Simpangaur, Seblat, Hulusimpang, and Maur formations, as well as granite and granodiorite intrusions, and is accompanied by Quaternary volcanic and rhyolite-andesite units. The Simpangaur Formation is dominated by breccia and conglomerate; the Seblat Formation consists of sandstone and limestone. At the same time, the Hulusimpang Formation comprises lava, tuff, and volcanic breccia, dating from the Late Oligocene to the Early Miocene. The main structure in this region is the Ketahun Segment, which runs northwest-southeast and controls the morphology of the hills and narrow valleys. The combination of lithological variations and the presence of active faults gives the Lebong region a complex tectonic character and a high potential for earthquakes.

Research Location

The research location is in Lebong Regency, Bengkulu Province, at coordinates coordinates 3.3°–3.05°S and 102.1°–102.4°E, which tectonically lies on the active Ketahun Segment zone in a northwest–southeast direction. This area is dominated by hilly morphology and narrow valleys as a result of intense tectonic activity, posing a significant geological hazard. The topographic characteristics and geological conditions of the primary research data were obtained from the GGMPlus website http://ddfe.curtin.edu.au/gravitymodel/GGMplus/data and SRTM2Gravity http://ddfe.curtin.edu.au/models/SRTM2gravity2018. GGMPlus data was selected to reach 200 meters, enabling more detailed identification of rock density changes compared to conventional gravity data (Hirt et al., 2019). Meanwhile, the SRTM2gravity correction model, which has a spatial resolution of 7.2 arc-seconds (approximately 200 meters), was used to eliminate the significant influence of topographic relief in the mountainous region of Bengkulu, so that the gravity anomaly results better reflect the actual subsurface geological conditions (Khairunnisa and Pohan, 2025).

The gravity data obtained from field measurements do not directly reflect subsurface geological conditions because they are still influenced by non-geological factors. Therefore, several correction steps are required before the data can be further interpreted. The correction process includes free air correction, Bouguer correction, topographic correction, and theoretical gravity calculation. These steps produce the Complete Bouguer Anomaly (CBA) value, which represents variations in the distribution of mass below the surface after

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

the effects of elevation and topography have been taken into account (Khairunnisa and Pohan, 2025). CBA is obtained through the application of Free Air Anomaly (FAA) correction and topographic correction or Full Spherical Terrain Correction (FSTG). In this study, GGMPlus satellite gravity data is provided as gravity disturbances referring to the ellipsoid. Therefore, drift, tidal, and latitude corrections are not required. The corrections applied include Free Air Anomaly (FAA) correction, Bouguer correction to account for the influence of rock mass, and topographic correction. FAA correction aims to eliminate the effect of differences in observation point elevation relative to the reference plane, while FSTG is used to account for the contribution of topographic mass around the measurement location (Hardianza et al., 2025). Mathematically, the CBA value is determined by the equation (1):

$$CBA = FAA - FSTG \tag{1}$$

Separation of regional anomalies and residuals to distinguish between deep and shallow structural effects. Separation is performed using the moving average method, as this method is simple, stable, and effective in reducing regional trends. The window size is determined based on the area of the study so that regional trends can be reduced optimally (Zakariya et al., 2022). This separation is expressed in the equation (2):

$$\Delta g_{reg} = \frac{\Delta g(i-n) + \cdots + \Delta g(i) + \cdots + \Delta g(i-n)N}{N} \tag{2}$$

Where: *I* Station marker, *N* Window width, *n* The value obtained from (N – 1)/2, and Δg_{reg} Calculated regional anomaly

Residual anomalies are calculated by subtracting the complete Bouguer anomaly from the regional anomaly (Pratama et al., 2023). In the following equation (3):

$$\Delta g_{residual} = \Delta g_{CBA} - \Delta g_{regional} \tag{3}$$

The results of this separation show shallow anomaly patterns that are more sensitive to lithological changes and the presence of active faults.

The next stage of analysis is to detect lateral and vertical geological structure boundaries through gravity field derivatives. The first Horizontal Derivative (FHD) analysis is used to detect lateral fault and lithology boundaries. Maximum and minimum FHD values indicate locations where sharp density changes occur (Leni et al., 2023). The FHD value is calculated as follows:

$$FHD = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \tag{4}$$

In this context, $\frac{(\partial g)}{(\partial x)}$ it represents the first derivative of the Earth's gravitational field along the x-axis, whereas $\frac{(\partial g)}{(\partial y)}$ it denotes the derivative measured along the y-axis. In addition, Second Vertical Derivative (SVD) analysis was applied to detect vertical changes in rock density. This method is more sensitive to density contrasts, allowing fault boundaries to be identified more sharply (Sumintadireja et al., 2018). SVD is a second-order vertical derivative of gravity anomalies used to identify fault characteristics and shallow structural boundaries. The calculation of this second-order vertical derivative is based on Laplace's equation by Syaputra et al. (2023). The value is calculated through:

$$\nabla^2 \Delta g = 0 \tag{5}$$

For the vertical section, where a constant change in the Y-value can be defined as such:

$$\frac{\partial^2(\Delta g)}{(\partial z)^2} = -\frac{\partial^2(\Delta g)}{(\partial z)^2} \tag{6}$$

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

The application of vertical second derivatives allows the identification of fault movement properties when specific criteria are met (Reynolds,1997). That is:

1. Normal fault
   When it can be demonstrated that it can be deduced from the given data that the magnitude of the minimum negative anomaly does not exceed that of the maximum positive anomaly, this can be formulated as follows:

$$\left|\frac{\partial^2(\Delta g)}{(\partial z)^2}\right|\min < \frac{\partial^2(\Delta g)}{(\partial z)^2}\,max \tag{7}$$

2. Reverse fault
   When it is evident that it is evident that the absolute value of the maximum negative anomaly is more pronounced than that of the maximum positive anomaly, it is formulated as follows:

$$\left|\frac{\partial^2(\Delta g)}{(\partial z)^2}\right|\min > \frac{\partial^2(\Delta g)}{(\partial z)^2}\,max \tag{8}$$

3. Transform fault
   When the absolute value is evident that there is a proportionate relationship between the minimum negative anomaly and the maximum positive anomaly, the relationship can be written as:

$$\left|\frac{\partial^2(\Delta g)}{(\partial)^2}\right| = \frac{\partial^2(\Delta g)}{(\partial z)^2}\,max \tag{9}$$

Although Equations (7)–(9) provide mathematical criteria for failure classification based on SVD amplitude relationships (Reynolds, 1997). The formulation is based on numerical simulation and gravity modeling. Therefore, its application in field geological interpretation needs to be supported by independent geological evidence. In this study, the classification of fault movements does not only refer to the SVD amplitude, but also combined with the FHD limit, regional geological map correlation, and the density contrast of 3D inversion results, thus increasing the reliability of structural interpretation. Three-dimensional (3D) inversion modeling was performed using Grav3D, applying zero-order Tikhonov regularization with an L2-norm (Occam-type) smooth inversion scheme and depth weighting to stabilize the solution. A uniform mesh of 200 m × 200 m × 200 m was adopted following the GGMPlus resolution, and the regularization parameter (β) was selected based on the trade-off curve. The reference density was set to 2.27 g/cm³. The final model achieved an RMS misfit of <5%, indicating good agreement between observed and calculated gravity data, with a maximum density contrast (Δρ) of ±2.50 g/cm³ associated with the active fault zone (Muttaqien and Nurjaman, 2021). 3D processing using Grav3D software with cba data as the primary input. Gravity inversion software that enables modeling of subsurface density distribution based on gravity field data. The inversion process is carried out using a regularization approach and control of physical parameters to produce a stable and realistic model (Adhi et al., 2018). The 3D inversion results display a subsurface volumetric model that illustrates the distribution of rock density in the study area. Zones with high density contrast are interpreted as lithological boundaries or active faults. With this approach, the geometry of the Ketahun Segment can be more clearly and accurately determined, while also supporting earthquake hazard mitigation efforts in the Bengkulu region (Damayanti et al., 2025). Rock density interpretation was performed based on the results of 3D inversion modeling generated from Grav3D processing. The density contrast values that appeared were used to distinguish lithological types and identify fault zones. The reference rock density range is shown in Table 2, where low density values are interpreted as loose sediment layers, and medium density reflects compacted sedimentary rocks. In contrast, high density indicates the presence of bedrock. Sharp density change zones in the model indicate the possible presence of active fault planes.

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

RESULTS AND DISCUSSION

The results of research using the gravity method in Lebong Regency analyzed data consisting of free air anomaly (FAA) data and full-scale topographic gravity (FSTG) data to obtain complete bouguer anomaly map values, regional anomalies, residual anomalies, SVD analysis, and 3D modeling. Interpretation of gravity data used density value tables by Telford (1990), and adjusted to the geological conditions of the research location. The area around Ketahun Segment is one of the tectonic zones in Bengkulu Province that has high potential for geological activity, such as earthquakes and surface deformation. The Ketahun Segment was formed as a result of the Indo-Australian plate subducting beneath the Eurasian plate along the western Samudra. This process creates enormous convergent forces in the earth's crust, because not all of the pressure is channeled through the subduction zone; some of the energy is released on land in the form of horizontal and inclined faults, one of which is the Ketahun Segment.

The Complete Bouguer Anomaly (CBA) structure weakens the Earth's crust because it is composed of loose sedimentary rocks and tectonic fractures. This causes the fault to be more active because pressure is easily transmitted through the fragile rocks in the basin. The results of this study produced a CBA map with a range of values between –8 and 50 mGal, with a very contrasting gradation pattern from the southwest to the northeast of the study area. The southwest zone is dominated by high (positive) anomalies associated with the presence of high-density igneous and metamorphic rocks. At the same time, the northeast shows low (negative) anomalies reflecting the presence of low-density loose sediment deposits. The sharp gradation pattern at the boundary of these two zones is a strong indicator of the existence of significant geological structures such as active faults and striking lithological differences this gravity contrast corresponds to regional geological conditions in Lebong, where older granitic basement rocks dominate the southwest, while younger unconsolidated sediments occupy the northeast. The anomaly transition therefore reflects lithological juxtaposition across the Ketahun Segment. In general, a positive CBA indicates a denser and more compact subsurface mass. In comparison, a negative CBA indicates a lighter and more porous rock mass, especially in the Quaternary sediment zone that developed in the northeast of the Ketahun Segment.

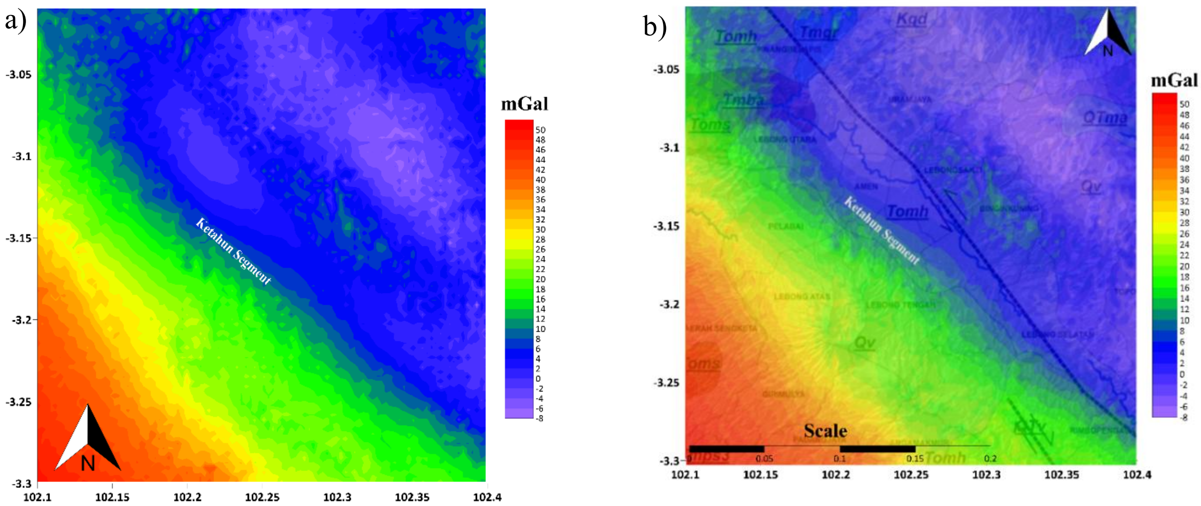


Figure 2. (a) Complete Bouguer Anomaly (CBA) research area map, (b) Complete Bouguer Anomaly (CBA) Overlay Map Geology

Separation of regional anomalies and residuals using the moving average method with a smoothing window adjusted to the scale of the regional tectonic structure of the Ketahun segment to separate the effects of shallow and deep masses. The separation results show that regional anomalies exhibit a dominant pattern with a range of values from –6 mGal to 46 mGal. The linear gradation pattern from southwest to northeast indicates the influence of a central tectonic structure (deep-seated structure), possibly related to the extensive Sumatra fault system. This area indicates the presence of a central fault structure that separates the solid rock

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106
Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

block in the southwest and the sedimentary block in the northeast (Figure 3a). Meanwhile, residual anomalies obtained from the difference between CBA and regional anomalies have a value range of –9 to 11 mGal. These residual anomalies show a more complex and higher resolution pattern, making them more sensitive to shallow structures such as active faults, fault branches, and surface lithological variations. High residual zones indicate relatively shallow hard igneous rocks, while low residual zones reflect the presence of loose sedimentary deposits. The residual contour pattern also shows a southwest–northeast lineament consistent with the direction of the Ketahun Segment, reinforcing indications of ongoing tectonic activity (Figure 3b). The anomaly alignment follows the regional NW–SE structural trend of the Sumatra Fault system. This pattern indicates that shallow density variations are structurally controlled by the Ketahun Segment and associated lithological boundaries.

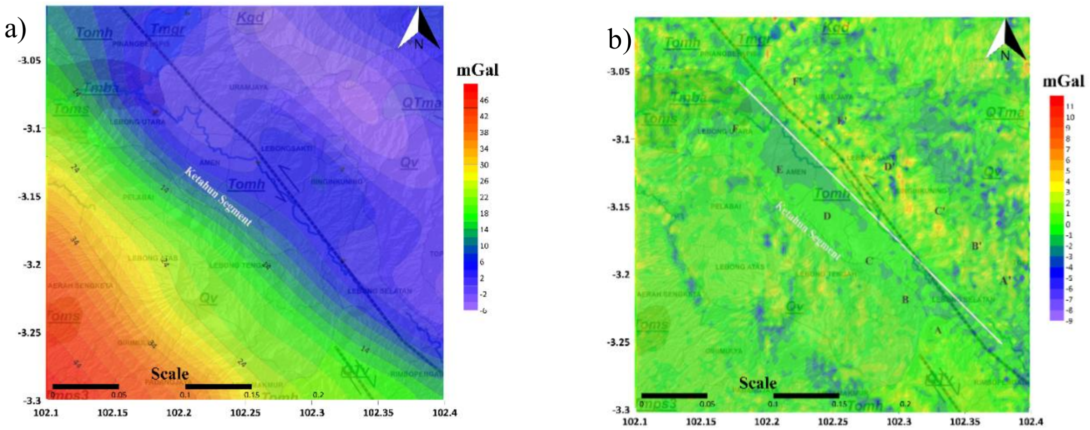


Figure 3 (a) Regional Anomaly Overlay Geology Map ; (b) Residual Anomaly Overlay Geology Map

The characteristics of the fault can be further analyzed by making cuts on six main paths along the fault zone (Figure 4). The results of the Second Vertical Derivative (SVD) analysis show that the minimum SVD values on the six lines are lower than the maximum SVD values (Table 1). This condition indicates the dominance of a down-dip fault character in the Ketahun segment. The maximum and minimum SVD values clearly indicate the boundaries of the fault structure. At the same time, the FHD analysis results reinforce the existence of significant lateral density contrasts along the fault zone. The combination of FHD and SVD analyses shows a geophysical response consistent with active fault characteristics, where tectonic activity is reflected in high anomalies around the fault zone (Figure 5).

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106
Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

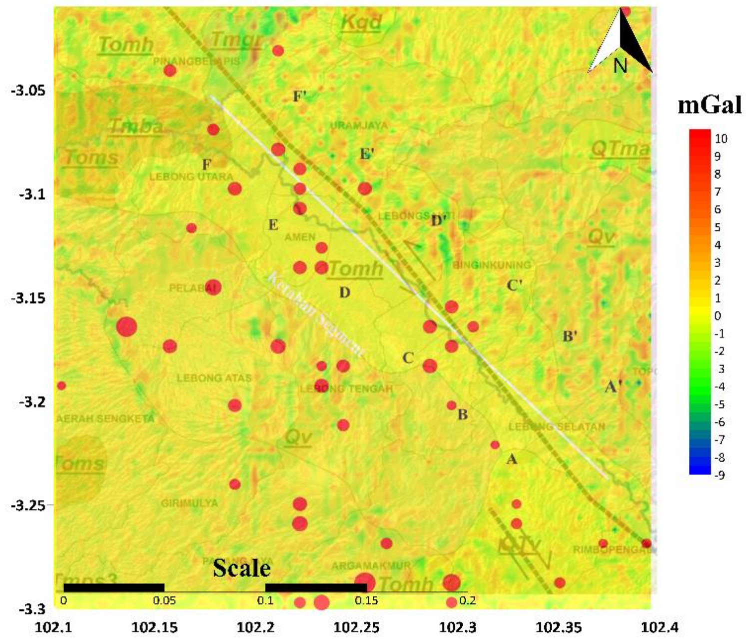
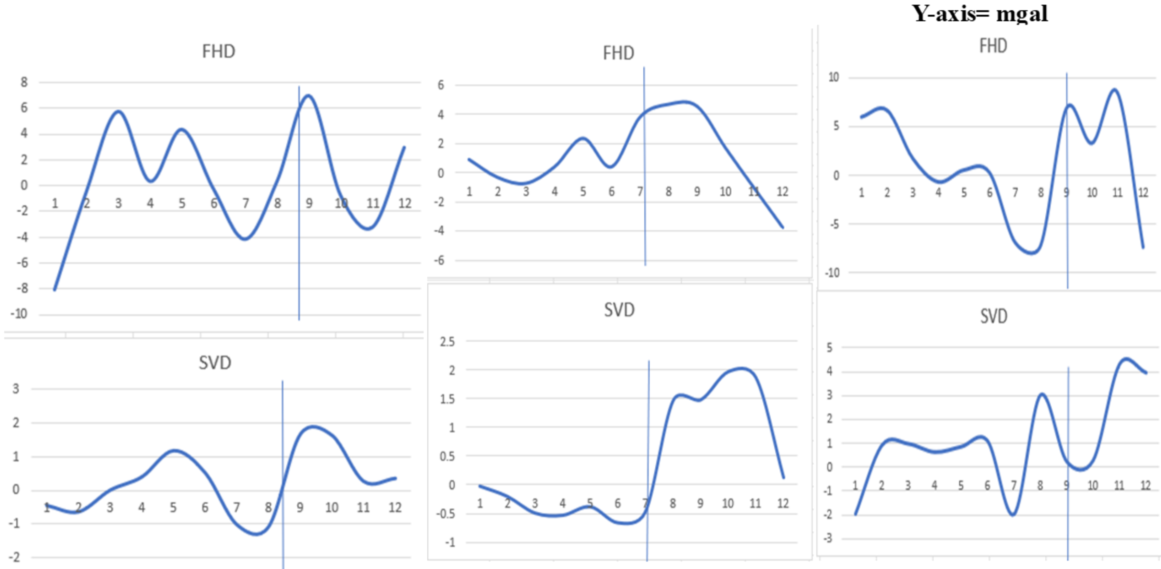


Figure 4. SVD Geology Overlay Map

X-axis= Distance (Km)
Y-axis= mgal



(a) *(b)* *(c)*

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

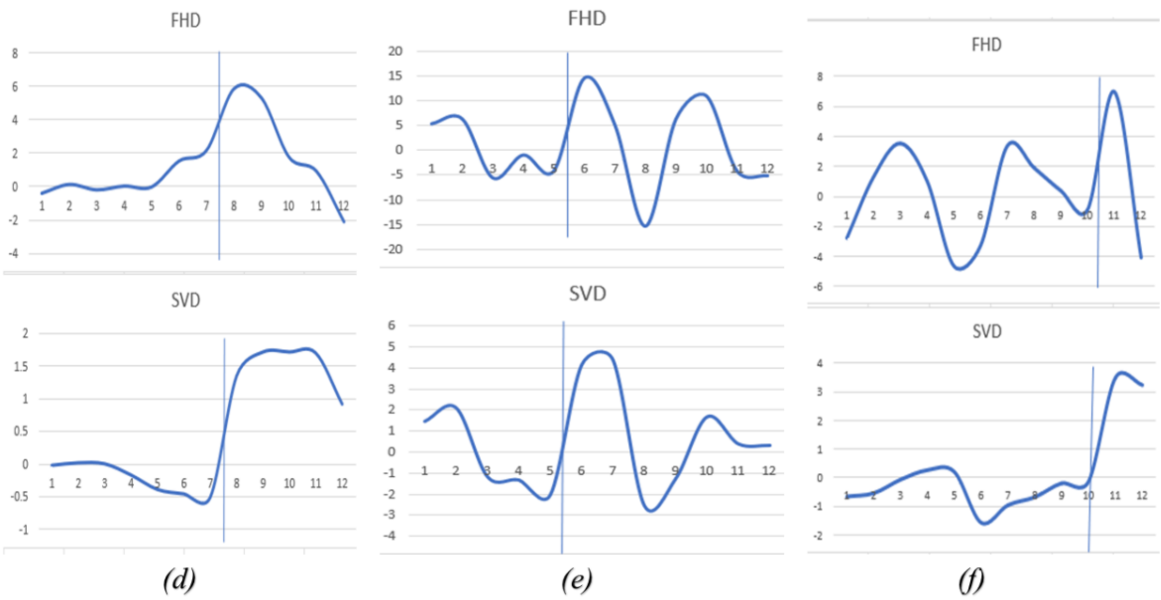


Figure 5. Graph of maximum and minimum SVD and FHD

Table 1. Result Values

Slice	Longitude	Latitude	|SVD Min|	|SVD Max|	Fault Characteristics
A-A’	102.3635142	-3.22102	1.090035118	1.641126341	Downward Fault
B-B’	102.3297446	-3.184625535	0.474755358	1.466052689	Downward Fault
C-C’	102.2942502	-3.1394927	3.001625559	4.299192576	Downward Fault
D-D’	102.250587	-3.120433338	0.510088445	1.722627363	Downward Fault
E-E’	102.232774	-3.077042912	2.030764207	4.382554153	Downward Fault
F-F’	102.2001543	-3.045513825	0.148074857	3.229923673	Downward Fault

The results of 3D inversion modeling using Grav3D software provide a volumetric picture of the subsurface density distribution in the Ketahun Segment zone (Figure 7). In general, the density range is between 1.02 and 3.52 g/cm³. The modeled density values range from 1.02 to 3.52 g/cm³, with an average density of approximately 2.27 g/cm³. The maximum density contrast (Δρ) 2.50 g/cm³ occurs between the low-density sedimentary zone (1.02–1.85 g/cm³) and the high-density igneous basement (3.10–3.52 g/cm³). A pronounced density gradient is observed at depths of 1000–2500 m, exceeding 0.8 g/cm³ per 500 m interval. This sharp contrast represents a structural discontinuity interpreted as the active fault plane. The spatial continuity of this boundary along the SW–NE direction confirms its consistency with regional tectonic trends.

To quantitatively evaluate the reliability of the inversion result, the model misfit between observed and calculated gravity responses was assessed using the Root Mean Square (RMS) error criterion. The RMS value was computed from the difference between observed gravity anomalies and forward-calculated responses derived from the final density model. The inversion converged to an RMS misfit of less than 5% relative to the total anomaly range, indicating good agreement between measured and modeled data. The convergence behavior during iterative optimization was stable, and no significant oscillatory artifacts were observed in the recovered density distribution. Furthermore, forward modeling verification reproduced the principal southwest–northeast anomaly gradient and high-contrast boundaries, confirming that the interpreted density discontinuity reflects a genuine geological structure rather than a numerical inversion artifact.

The sharp density contrast in the eastern part of the model shows the presence of a significant lithological boundary, which is interpreted as the presence of an active fault plane. These findings are in line with previous research results by Syaputra et al. (2023), which identify the presence of a strike-slip fault in the Ketahun

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

segment through FHD and SVD analysis. However, this study makes a new contribution through the integration of GGMPlus and SRTM2gravity with 3D inversion modeling, which produces a more representative fault geometry model. Lithological differences and high density contrasts indicate that the Ketahun Segment developed at a firm lithological boundary. This has important implications for mapping earthquake-prone zones and planning disaster mitigation in the Bengkulu region. Based on data from the National Earthquake Study Center (PuSGeN, 2017), the Ketahun Segment is classified as part of the Sumatra strike-slip fault system. However, the SVD analysis in this study indicates the presence of a dip-slip component in the central fault zone. Therefore, the fault movement in the study area is interpreted as oblique-slip rather than purely strike-slip. This interpretation is consistent with the NW–SE structural trend observed in regional geological maps and surface morphology. Regional geological mapping shows lithological juxtaposition between pre-Tertiary granitic rocks in the southwest and Quaternary sedimentary deposits in the northeast, supporting the presence of a major structural discontinuity. Furthermore, microtremor-based seismic microzonation studies in Lebong Regency (Hasanah et al., 2024), reveal high amplification factors aligned with the interpreted fault trace, providing additional geophysical validation. Therefore, the interpreted structure is classified as an oblique-slip fault with a dominant dip-slip component rather than a purely normal fault.

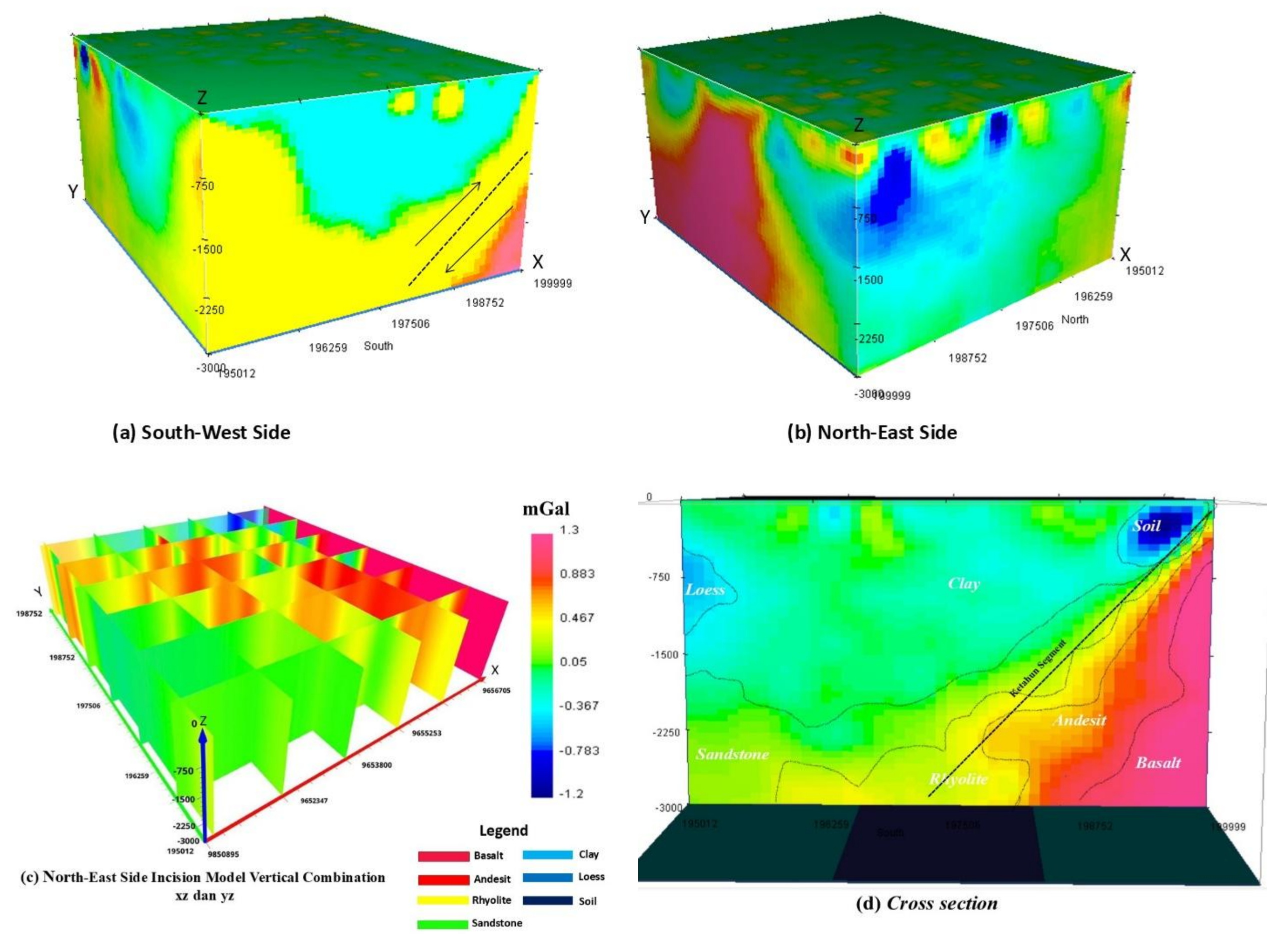


Figure 6. 3D model of subsurface structures in the study area

Based on 3D inversion modeling (Figure 6), subsurface density contrast shows an evident pattern both vertically and laterally. The low-density zone with values of 1.02–1.85 g/cm³ is located at a depth of 0–1500 m and is associated with young sedimentary lithology in the form of soil, clay, and loess. This zone is weak because it is loose, unconsolidated, and has low mechanical support for tectonic activity. This weak zone

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

develops mainly in the northeast part of the Ketahun Segment and follows the direction of the main fault. In contrast, the high-density zone with a value of 3.10–3.52 g/cm³ is located at a depth of about 500–2000 m and reflects the presence of hard igneous rocks such as andesite and basalt. The dominant formation around the high-density zone is the Hulusimpang Formation, which consists of lava, tuff, and volcanic breccia composed of andesite–basalt (Oligocene–Miocene age). Meanwhile, Quaternary sedimentary deposits in the form of sand, silt, and clay are found in the weak zone. This lithological difference results in a sharp density contrast, so that the boundary between the two acts as an active fault plane. The cross-section shows that the density contrast begins to form at a depth of about 500 m and becomes more pronounced at a depth of 1000–2500 m below the surface. At this depth, the weak zone above the sedimentary unit is not yet fully connected to the high-density zone below it. However, at depths greater than 2000 m, the weak zone begins to merge with the bedrock unit, forming a more geometrically distinct fault plane. Structurally, the Ketahun Segment has a southwest–northeast (SW–NE) orientation, parallel to the regional direction of the Sumatra Fault. This direction also shows a pattern of horizontal displacement that indicates shear movement, with a dip component around the central fault zone. The depth of the active fault plane is estimated to be at 1000–2500 m, marked by a significant change in density gradient and a sharp lithological transition zone. The existence of an active fault at this depth indicates that the Ketahun Segment still has the potential to transfer tectonic energy to shallower sedimentary layers. The geotectonic implication of this condition is increased seismic vulnerability around the fault zone. When an earthquake occurs, weak zones in shallow sedimentary layers can amplify seismic waves, resulting in greater shaking. This finding is consistent with the seismic microzonation results by Hasanah et al.(2024), which show high amplification values along active fault lines in the Lebong region.

Based on the results of 3D inversion modeling (Table 3), the subsurface zone around the Ketahun segment shows a density range of 1.02 to 3.52 g/cm³. Low-density values (1.02–1.85 g/cm³) are found at relatively shallow depths (0–1500 m) and are associated with sedimentary lithologies such as soil, clay, and loess. Medium density values (2.27–2.68 g/cm³) at a depth of 1500–3000 m represent sandstone and rhyolite, while high density values (3.10–3.52 g/cm³) at a depth of 500–2000 m indicate the presence of andesite and basalt igneous rocks. These density changes indicate a lithological transition zone and confirm the existence of active faults that cut through sedimentary and igneous rock units.

Table 2. Rock Density Values (Telford, 1990), (Reynolds, 1997)

Type of Rock	Density value (g/cm³)	Depth (m)
Sedimentary rock		
Soil	1.02	0 – ±100 m
Clay	1.85	±0 - 1500 m
Loess	1.43	±0 - 750 m
Sandstone	2.27	±1500 - 3000 m
Igneous rock		
Rhyolite	2.68	±1500 - 2500 m
Andesite	3.10	±750 - 2000 m
Basalt	3.52	±500 - 1500 m

Figure 7(d) shows a cross-section of the 3D inversion modeling results. This cross-section pattern shows a clear density contrast between the shallow zone and the deeper zone. The low-density zone (1.02–1.85 g/cm³) dominates the upper part of the cross section and is associated with unconsolidated loose sediment layers. Meanwhile, the high-density zone (3.10–3.52 g/cm³) is located at depths of (500–2000) m and indicates the presence of hard igneous rocks, such as andesite and basalt. The contact plane between the two zones is interpreted as an active fault, formed at depths of approximately (1000–2500) m. This apparent fault geometry pattern supports the results of SVD and FHD analyses, which indicate the presence of a down-dip fault in the Ketahun segment. Based on the results of subsurface density modeling, a low-density zone with values ranging from 1.02 to 1.85 g/cm³ was identified, spread across a depth of 0–1500 meters. This zone is associated with young sedimentary lithology such as soil, loess, and clay, which are loose, unconsolidated, and have low mechanical resistance to tectonic forces. Geotectonically, this low-density zone is categorized as a weak zone

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

because it is susceptible to deformation, displacement, and seismic wave amplification. The distribution of weak zones tends to develop in the northeast part of the Ketahun Segment, which follows the direction of the main fault movement. In contrast, at a depth of about 500–2000 meters, a high-density zone with a range of 3.00–3.52 g/cm³ was identified. This zone indicates the presence of hard igneous rocks such as andesite and basalt, which have high compactness and excellent mechanical resistance to deformation. Based on lithological interpretation, this zone represents basement rock that acts as a strong foundation beneath the sedimentary layer. The contrast in density between the low and high zones indicates a sharp change in physical properties at the boundary between the two, which is geologically interpreted as an active fault plane. Based on its orientation and direction of propagation, the Ketahun Segment has a dominant southwest-northeast (SW-NE) pattern. It is parallel to the Sumatra Fault system, which is the main tectonic structure in the western part of Sumatra Island.

The rock formation that dominates the high-density zone is the Hulusimpang Formation, which consists of lava, tuff, and volcanic breccia composed of Oligocene–Miocene andesite-basalt. On the other hand, in the low-density zone, Quaternary sedimentary deposits consisting of clay, sand, and silt are found, resulting from young fluvial and alluvial deposition processes. The contrast in density and differences in lithological characteristics between these two formations reinforce the interpretation of an active fault zone that forms the main structural boundary in the study area. The results of 3D subsurface density modeling show that the Ketahun Segment plane is likely to be at a depth of around 1000–2500 meters. This plane is marked by a lithological transition zone and a very contrasting density change, reflecting the existence of a fault plane that is still tectonically active. The existence of active faults at this depth indicates that deformation energy from tectonic activity can still be transferred to shallow layers, thereby increasing the potential for local seismic vulnerability. Tectonically, the interaction between active fault zones and weak sediment zones plays an important role in amplifying seismic waves during earthquakes. When seismic waves pass through loose sediment layers with low density, the vibration energy tends to increase due to the local resonance effect. This condition explains why the area around the Ketahun Segment has the potential to experience greater surface shaking than areas with more compact bedrock. This finding is in line with the microtremor results by Syah et al. (2024), which show high amplification values along the active fault line in the Lebong region. Thus, the relationship between density contrast, fault activity, and subsurface lithological properties provides a comprehensive picture of the seismotectonic characteristics of the Ketahun Segment and serves as an important basis for earthquake risk mitigation efforts in this region.

The delineation of low-density zones at shallow depths (0–1500 m) above the identified fault plane indicates mechanically weak areas that are highly susceptible to seismic wave amplification. These weak zones are dominated by unconsolidated sediments, which are prone to deformation when tectonic stress is released along the Ketahun segment. Reactivation or displacement of the fault may generate moderate to small-magnitude earthquakes; however, due to shallow, weak zones, ground shaking intensity at the surface can be significantly amplified, increasing the potential for structural damage to residential buildings and local infrastructure. In such conditions, non-engineered or poorly reinforced houses are particularly vulnerable to cracking, tilting, or partial collapse. Furthermore, fault-induced ground deformation may modify local drainage patterns and surface morphology, potentially triggering secondary hazards, such as localized flooding or landslides, especially in areas with alluvial deposits and gentle slopes. Therefore, these low-density zones should be designated as high-risk areas in seismic microzonation and spatial planning. Furthermore, the identification of the active fault geometry at depths of approximately (1000–2500 m) provides essential input for defining active fault corridors, regulating land use, and guiding the implementation of earthquake-resistant building design. The integration of subsurface density contrasts and fault geometry thus establishes a scientific basis for disaster mitigation strategies in Lebong Regency, particularly in reducing seismic risk associated with the active Ketahun segment. (PuSGeN, 2017; Hasanah et al., 2024).

These findings not only provide an overview of the geotectonic conditions of the study area but also have direct implications for the potential impact of future earthquakes. Therefore, the interpretation of the 3D

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

modeling results is not limited to mapping subsurface structures, but also serves as an important basis for disaster mitigation planning and strategies. The interpretation of the 3D model shows that weak zones dominated by loose sediments at a depth of 0–1500 m play an important role in seismic wave amplification. These zones are distributed along the main fault line and are associated with low density values, thus potentially increasing seismic vulnerability in the surrounding area. Conversely, high-density zones composed of hard igneous rocks have more stable mechanical characteristics and can be the main controllers of deformation patterns. The significant differences between these two zones confirm that active fault planes develop at contrasting lithological boundaries. Based on these conditions, areas located above weak zones are projected to have higher levels of shock hazard when seismic activity occurs. These geotectonic implications are an important basis for developing disaster mitigation strategies based on actual geological conditions.

From a mitigation perspective, information on fault geometry and subsurface density distribution can be used to strengthen spatial planning, determine safe construction zones, and prioritize disaster management. Areas located above or near weak zones should be considered high-risk areas and require structural reinforcement of buildings and adequate early warning systems. Furthermore, this research not only contributes to the scientific aspect of fault structure mapping but also has strategic value in supporting disaster mitigation policies and seismic-resistant regional planning in Bengkulu Province. The results of 3D inversion modeling, which reveal the presence of low-density zones and active fault planes, have strategic implications for earthquake mitigation in the Lebong Regency area. Low-density zones at shallow depths that are loose and unconsolidated have a high potential for seismic wave amplification during earthquakes. Therefore, areas located above or near these zones need to be designated as high-risk zones in regional spatial plans. Structural mitigation strategies can be implemented through the application of earthquake-resistant building standards (Badan Standardisasi Nasional, 2019), foundation reinforcement, and restrictions on the construction of vital infrastructure in vulnerable zones.

On the other hand, non-structural mitigation can include the preparation of seismic microzonation maps, the implementation of sensor-based early warning systems, and community education programs on preparedness and evacuation routes. The integration of geophysical data from 3D modeling with disaster management planning will strengthen the seismic resilience of the region. These findings support the development of evidence-based disaster management policies that local governments can adopt to strengthen spatial planning and reduce the risk of damage caused by tectonic activity along the Ketahun Segment. Consequently, the integration of subsurface density contrasts and fault geometry obtained from this study offers a practical framework for disaster mitigation planning in Lebong Regency and its surrounding areas.

CONCLUSION AND SUGGESTIONS

The Complete Bouguer Anomaly (CBA) values range from (–8 to 50 mGal) with a southwest–northeast gradient along the Ketahun segment. Regional anomalies range from (–6 to 46 mGal), while residual anomalies range from (–9 to 11 mGal) and clearly delineate shallow fault-related structures. The FHD analysis highlights sharp lateral density contrasts, and the SVD results indicate a dominant down-dip fault mechanism. The results of integrating GGMPlus and SRTM2gravity data through FHD, SVD, and 3D inversion modeling analysis show that the active fault zone has a southwest–northeast (SW–NE) orientation with an active fault plane depth in the range of 1000–2500 m. The density contrast between shallow sediments (1.02–1.85 g/cm³) and hard igneous rocks (3.10–3.52 g/cm³) confirms the existence of active fault planes and weak zones that have the potential to amplify seismic waves. This finding is an essential update in understanding the tectonic character of the Ketahun region, which shows a combination of quantitative inversion parameters, derivative amplitude relationships, and geological validation confirms that the structure is best interpreted as an oblique-slip fault with a dip-slip component.

The implications of this finding are very significant for disaster mitigation. Weak zones around faults need to be designated as active fault zones in spatial planning, with the strengthening of earthquake-resistant

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106
Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

buildings, the determination of evacuation routes, and the implementation of early warning systems. The results of 3D modeling can be used as a basis for compiling seismic microzonation maps to support disaster risk reduction strategies. Local governments and related agencies are advised to conduct regular seismic monitoring, public education, and further research with the integration of other geophysical data to improve the accuracy and resilience of the region to earthquakes.

ACKNOWLEDGMENTS

This research was supported by the Indonesian Agency for Meteorology, Climatology, and Geophysics, which is responsible for monitoring geophysical across Bengkulu Province, including the Kepahiang region. The author also extends appreciation to Curtin University for offering an open-access platform that facilitated the use of GGMPlus and SRTM2gravity data in this research.

REFERENCE

Adhi, A., Wahyudi, Suryanto, W., & Sarkowi, M. (2018). GRAV3D Validation using Generalized Cross Validation (GCV) Algorithm by Lower Bounds Approach for 3D Gravity Data Inversion. *Scientific Journal of Informatics*, *Vol. 5*, *No*.

Al Ansory, A. R., Hana Raihana, Pritama, V. L., Saputri, W., Maghribi, F. B., Muchammad Farid, Arif Ismul Hadi, Halauddin, Harlianto, B., & Sugianto, N. (2023). Delineasi Nilai Resistivitas Di Lapangan Panas Bumi Tambang Sawah Menggunakan Metode Magnetotellurik. *Buletin Sumber Daya Geologi*, *18*(3), 145–154. https://doi.org/10.47599/bsdg.v18i3.386

Álvarez, O., Pechuan Canet, S., Gimenez, M., & Folguera, A. (2021). Megathrust Slip Behavior for Great Earthquakes Along the Sumatra-Andaman Subduction Zone Mapped From Satellite GOCE Gravity Field Derivatives. *Frontiers in Earth Science*, *8*(February), 1–22. https://doi.org/10.3389/feart.2020.581396

Anver, G. K., & J. Prasetyo, S. Y. (2025). Analysis of Earthquake Intensity on Java Island Using K-Means Clustering and GeoMap. *Jurnal Indonesia Sosial Teknologi*, *6*(1), 469–479. https://doi.org/10.59141/jist.v6i1.1359

Ardiansyah, S. (2018). Analisis Gempabumi Merusak Kabupaten Lebong- Bengkulu 6 Desember 2017. *Stasuin Geofisika Kepahiang-Bengkulu*, *4*(156).

Badan Standardisasi Nasional. (2019). *SNI 1726-2019: Indonesia Seismic Resistance Design Guideline for Buildings and Other Structures (in Indonesian)*. www.bsn.go.id

Chen, L., Wang, X., Liang, X., Wan, B., & Liu, L. (2020). Subduction tectonics vs. Plume tectonics—Discussion on driving forces for plate motion. *Science China Earth Sciences*, *63*(3), 315–328. https://doi.org/10.1007/s11430-019-9538-2

Damayanti, C., Sismanto, S., Setiawan, A., & Handayani, L. (2025). Identifying the Basement Structure of the Sula Fault Zone in the Banggai-Sula Microcontinent Region, Molucca Sea, based on 2D Gravity Inversion Modelling using Particle Swarm Optimisation and 3D Modelling using Grablox. *Rudarsko Geolosko Naftni Zbornik*, *40*(2), 137–154. https://doi.org/10.17794/rgn.2025.2.10

Farid, M., & Mase, L. Z. (2020). Implementation of seismic hazard mitigation on the basis of ground shear strain indicator for spatial plan of Bengkulu city, Indonesia. *International Journal of GEOMATE*, *18*(69), 199–207. https://doi.org/10.21660/2020.69.24759

Hakim Al, M. M., Idrus, A., & Suryanto, W. (2022). Geology and Ore Characteristics of Low Sulfidation Epithermal Gold Mineralization At Tambang Sawah, Lebong, Bengkulu Province. *Kurvatek*, *7*(2), 81–92. https://doi.org/10.33579/krvtk.v7i2.3185

Hardianza, M., Hadi, A. I., & Hilmi Zakarya. (2025). Identifikasi Batuan Reservoir Panas Bumi di Daerah Tambang Sawah, Lebong Provinsi Bengkulu Menggunakan Data Gravitasi Satelit GGMPlus dengan Inversi 2D. *Jurnal Fisika Unand*, *14*(2), 177–183. https://doi.org/10.25077/jfu.14.2.177-183.2025

Hasanah, P., Misliniyati, R., Amri, K., Zalbuin, L., Hadi, A. I., Fadli, D. I., & Unib, U. B. (2024). *Mikrozonasi kerentanan seismik di kawasan Kabupaten Lebong Provinsi Bengkulu berdasarkan data uji mikrotremor Microzoning of seismic vulnerability in Lebong Regency , Bengkulu Province based on microtremor test data*. *13*(3), 1–8. https://doi.org/10.24815/jacps.v13i3.39485

Hirt, C., Yang, M., Kuhn, M., Bucha, B., Kurzmann, A., & Pail, R. (2019). SRTM2gravity: An Ultrahigh Resolution Global Model of Gravimetric Terrain Corrections. *Geophysical Research Letters*, *46*(9), 4618–4627.

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026

https://doi.org/10.1029/2019GL082521

Khairunnisa, W. I., & Pohan, A. F. (2025). Identifikasi Segmen Talamau Menggunakan Kombinasi Data Satelit GGMPlus dan Koreksi SRTM2gravity Berdasarkan Analisis Second Vertical Derivative (SVD). *Jurnal Fisika Unand*, *14*(2), 198–204. https://doi.org/10.25077/jfu.14.2.198-204.2025

Leni, A. F. F. P. F., Arif Ismul Hadi, Hilmi Zakariya, & Refrizon, R. (2023). Identification of the Manna Segment Sumatran Fault Using GGMplus Gravity Anomaly Data with the Second Vertical Derivative (SVD) Method. *Jurnal Ilmu Fisika | Universitas Andalas*, *15*(2), 123–136. https://doi.org/10.25077/jif.15.2.123-136.2023

Misliniyati, R., Mase, L. Z., Syahbana, A. J., & Soebowo, E. (2018). Seismic hazard mitigation for Bengkulu Coastal area based on site class analysis. *IOP Conference Series: Earth and Environmental Science*, *212*(1). https://doi.org/10.1088/1755-1315/212/1/012004

Muttaqien, I., & Nurjaman, J. (2021). Two-dimensional inversion modeling of magnetotelluric (MT) synthetic data of a graben structure using SimPEG. *Riset Geologi Dan Pertambangan*, *31*(1), 1–12. https://doi.org/10.14203/risetgeotam2021.v31.1121

Oktarina, M., Tanjung, M, R., & Devatama, N. (2021). Penentuan Daerah Terdampak Longsor Di. *Teknik Geologi: Ilmu Pengetahuan Dan Teknologi*, *4*(2), 1–6.

Pratama, I. P. D., Osawa, T., & As-Syakur, A. R. (2023). Identification of Fault Zone in Bali Using GGMPlus Gravity and Alos-2 Palsar-2 Data. *Jurnal Geografi*, *15*(1), 46–63. https://doi.org/10.24114/jg.v15i1.40772

PuSGeN, 2017. (2017). *Pusat Studi Gempa Nasional (Indonesia)Pusat Penelitian dan Pengembangan Perumahan dan Permukiman (Indonesia)*.

Qin, Y., Chen, J., Singh, S. C., Hananto, N., Carton, H., & Tapponnier, P. (2024). Assessing the Risk of Potential Tsunamigenic Earthquakes in the Mentawai Region by Seismic Imaging, Central Sumatra. *Geochemistry, Geophysics, Geosystems*, *25*(5). https://doi.org/10.1029/2023GC011149

Reynolds, J. M. (1997). *An introduction to applied and environmental geophysics* (1st ed.). British Library in Publication Data.

Sumintadireja, P., Dahrin, D., & Grandis, H. (2018). A note on the use of the second vertical derivative (SVD) of gravity data with reference to Indonesian cases. *Journal of Engineering and Technological Sciences*, *50*(1), 127–139. https://doi.org/10.5614/j.eng.technol.sci.2018.50.1.9

Syah, M. T., Al-Ansory, A. R., Hardiansa, D., Panjaitan, A., Saragih, R., Sugianto, N., Halauddin, H., & Harlianto, B. (2024). Identification of Rock Characteristics Using the Microtremor Inversion Method at Air Putih Geothermal Field, Lebong Regency. *Journal of Technomaterial Physics*, *6*(1), 47–55. https://doi.org/10.32734/jotp.v6i1.16047

Syaputra, E. W., Refrizon, R., & Zakariya, H. (2023). Identifikasi Sesar Segmen Ketahun Berdasarkan Metode First Horizontal Derivative (FHD) dan Second Vertical Derivative (SVD) Data Anomali Gaya Berat GGMplus. *Jurnal Fisika Unand*, *12*(4), 598–607. https://doi.org/10.25077/jfu.12.4.598-607.2023

Telford, W. M., Geldart, L. P. and Sheriff, R. E. (1990). *Applied Geophysics : Second Edition*.

Zakariya, H., Margiono, R., Novitri, A., & Pevriadi, A. (2022). Identifikasi Anomali Gravitasi di Wilayah Sulawesi Tenggara Berdasarkan Data Gravitasi GGMplus. *PROGRESS : Jurnal Geofisika*, *1*(1), 62–69. https://jurnal.stmkg.ac.id/index.php/pjg

DOI : http://dx.doi.org/10.12962/j25023659.v12i2.9106

Received: 26-01-2026 Reviewed: 08-02-2026 Accepted: 07-04-2026 Available Online: 30-04-2026