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Identification of the Manna Segment Sumatran Fault Using GGMplus Gravity Anomaly Data with the Second Vertical Derivative (SVD) Method

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ABSTRACT

This study uses the gravity method to assess the characteristics of the Manna segment fault, a part of the Sumatran fault. This research aims to contribute to the existing knowledge by providing additional insights into the fault's characteristics, which is essential for future disaster mitigation efforts. The Manna segment fault is geographically situated between coordinates 4.4ºS - 3.9º S and 102.7º E – 103.2º E, making this area prone to earthquake hazards. The gravity anomaly data, including free air and topography, were collected from 62,501 data points. The Simple Bouguer Anomaly (SBA) values obtained ranged from 25 mGal to 95 mGal. By utilizing the Second Vertical Derivative (SVD) method and dividing the study area into three regions with multiple sections, the analysis revealed that the minimum and maximum SVD values were relatively similar. This suggests that the Manna fault can be classified as a strike-slip fault, with SVD values ranging from Elkins-20 mGal to 6 mGal. The study identified branches of the main fault in regions 2 and 3 based on the SVD map. Overall, this study enhances our understanding of the Manna segment fault, providing valuable insights into its characteristics and contributing to future disaster mitigation efforts.

1. INTRODUCTION

One of the regions in Indonesia known for its high seismic activity is Sumatra. Sumatra has a distinct tectonic setting characterized by two significant features. Along the western coast of Sumatra, a subduction zone runs parallel to the coastline. The island is divided on land by the Sumatran fault, which extends from northern Andaman Bay to southern Semangko Bay, aligning with the subduction zone's lineament (Julius & Susanti, 2015). The Sumatran fault is crucial in accommodating a substantial portion of the dextral component of Sumatra's oblique convergence. This active shear fault zone spans 1900 km along the spine of Sumatra, posing seismic and fault hazards to the densely populated areas surrounding the fault zone. The Sumatran fault is highly segmented, consisting of 20 distinct main segments with lengths ranging from 60 to 200 km (Natawidjaja & Triyoso, 2007).

Bengkulu, located on the island of Sumatra, lies within the convergence zone of the Indo-Australian and Eurasian tectonic plates. The Sumatran fault line also intersects the region. In this area, the Indo-Australian plate moves northward, while the Eurasian plate moves southward (Hadi & Brotopuspito, 2016). One of the segments of the Sumatran fault in the Bengkulu region is known as the Manna fault. It is located between 4.4°S and 3.9°S latitude and 102.7°E and 103.2°E longitude (GGMplus, 2023). According to data from the BMKG

Earthquake database from 2002 to 2023, 36 earthquakes with magnitudes ranging from 1 to 6 have been detected in this segment. The largest earthquake recorded in this area occurred in 2008, with a magnitude of 5.6 and a shallow depth. The Manna segment of the Sumatran fault stretches from South Bengkulu Regency in Bengkulu Province to Pagar Alam in South Sumatra Province (BMKG, 2023). The 2022 Indonesia Earthquake Source and Hazard Map Book compiled by the National Center for Earthquake Studies identifies the Manna segment fault as a strike-slip fault (PuSGeN, 2022). Previous research by Sieh and Natawidjaja (2000) also classified the Sumatran fault as a strike-slip fault.

In this study, the authors aimed to identify the Sumatran fault of the Manna segment and analyze variations in gravity anomaly using the gravity anomaly/Gravity method. Previous studies on the Manna segment of the Sumatran fault have not extensively utilized this method, particularly the Second Vertical Derivative (SVD) gravity anomaly method. Therefore, the authors conducted this research to contribute to existing knowledge and support previous studies by examining the characteristics of the Manna fault segment, especially regarding future disaster mitigation. Sumatra, one of Indonesia's largest islands, possesses a significant potential for natural disasters, and each region exhibits distinct variations in gravity anomaly values (Munir, 2015).

The gravity method was chosen for this study because it enables the description of subsurface geological conditions based on variations in gravity values resulting from differences in rock density (Zakariya, 2021). The authors utilized Global Gravity Model Plus (GGMplus) data comprising satellite observations. GGMplus combines data from the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) and GRACE (Gravity Recovery and Climate Experiment) satellite gravity models and the Earth Gravitational Model 2008 gravity data. The data is available in grids with a resolution of approximately 220 meters (Hirt et al., 2013).

In this study, the authors employed the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) methods to determine the characteristics of the Manna Segment fault. The obtained fault characteristics will be validated using earthquake data from the BMKG database covering 2002 to 2023 (BMKG, 2023). This validation process aims to ensure the accuracy of the fault data obtained by comparing it with the recorded earthquake data.

Figure 1 Study Area Map.

2. METHOD

2.1 Data and Study Area

This study utilizes GGMplus Gravity Anomaly data. The research focuses on the Manna Segment fault area at coordinates 4.4º - 3.9º S and 102.7º - 103.2º E (Figure 1). The dataset consists of free air anomaly data and topography, comprising 62,501 data points and additional topographical data (GGMplus, 2023). The research procedure is outlined in Figure 2.

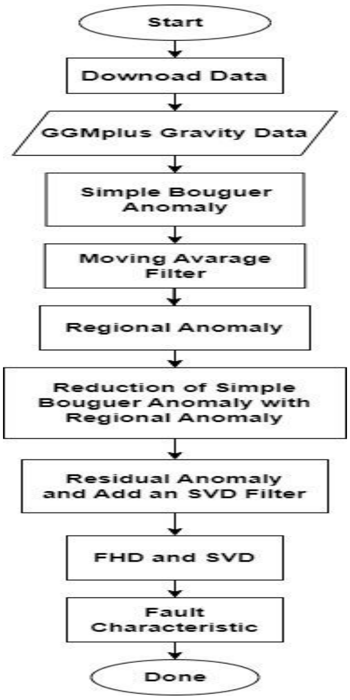


Figure 2 Research procedure flow chart.

2.2 Data Processing

2.2.1 Bouguer Correction and Simple Bouguer Anomaly

Data processing starts with Bouguer Correction (Figure 2). The Bouguer correction value is obtained using the Parasnis method, which estimates the average density. Equation 1 is used to calculate the Bouguer correction, where BC represents the Bouguer Correction (mGal), ρ represents the rock density (g/cm^3), and h represents the elevation (m) (Reynolds, 1997).

$$\mathrm{BC} = 0.04193\rho h \tag{1}$$

Then, the Simple Bouguer Anomaly (SBA) data is processed by applying the Bouguer Correction (BC) to the Free Air Anomaly (FAA) data.

$$\mathrm{SBA} = \mathrm{FAA} - \mathrm{BC} \tag{2}$$

2.2.2 Filter Moving Average and Regional Anomaly

The next step involves applying a moving average filter. The moving average method is used to distinguish between regional anomalies and residual anomalies. This is achieved by calculating the average value of the anomaly at each point over a specified interval. By applying the moving average, the regional anomalies can be determined. The residual anomalies are then obtained by subtracting the regional anomalies from the measured data. Mathematically, the one-dimensional moving average equation is as follows (Zakariya, 2021).

$$\Delta g_{reg} = \frac{\triangle g(i-n)+\cdots+\triangle g(i)+\cdots+\triangle g(i-n)}{N} \quad (3)$$

where :
i : station number
N : window width
n : the value of the number N reduced by 1 and divided by two
$\triangle g_{reg}$: magnitude of regional anomaly

2.2.3 Residual Anomaly

After the regional anomaly value is obtained, then to obtain the residual anomaly value you can use the following equation (Zakariya, 2021).

$$g_{res} = SBA - g_{reg} \quad (4)$$

2.3 Determination of Fault Characteristics

The next step is the derivative method which is used to determine the characteristics of the fault .

2.3.1 First Horizontal Derivative (FHD)

The First Horizontal Derivative method is used to identify the boundaries of subsurface geological structures by examining the changes in gravity anomaly horizontally between adjacent points at a given distance. The boundaries of geological structures can be determined by analyzing the maximum and minimum values of the horizontal first derivative. This method effectively identifies fault structures and reduces the impact of noise in the data. The First Horizontal Derivative method is applicable for describing both shallow and deep subsurface structures. The amplitude of the horizontal derivative can be expressed as follows (Cordell & Grauch, 1982).

$$\text{FHD}=\sqrt{\frac{(\partial g)2}{(\partial x)2}+\frac{(\partial g)2}{(\partial y)2}} \quad (5)$$

where $\frac{(\partial g)}{(\partial x)}$ is the first derivative of the earth's gravity field in the *x* direction and $\frac{(\partial g)}{(\partial y)}$ is the first derivative of the earth's gravity field in the *y* direction.

2.3.2 Second Vertical Derivative (SVD)

The Second Vertical Derivative method (SVD) is a second-order derivative of the gravity anomaly utilized to identify the fault characteristics or boundaries of shallow structures. The vertical second derivative can be calculated using the Laplace equation, as described by Zakariya (2021):

$$\nabla^2 \Delta g = 0 \quad (6)$$

for vertical sections where the change in the value of y is considered constant, it can be defined as:

$$\frac{\partial 2\ (\Delta g)}{(\partial z)2} = -\frac{\partial 2\ (\Delta g)}{(\partial z)2} \quad (7)$$

The vertical second derivative method can identify the characteristics of fault movement if it meets the criteria described by Reynolds (1997), as follows:

1. Normal fault

   If the absolute value of the minimum negative anomaly is smaller than the maximum positive anomaly value and can be stated:

$$\left| \frac{\partial 2\ (\Delta g)}{(\partial z)2} \right|_{min} < \frac{\partial 2\ (\Delta g)}{(\partial z)2}_{max} \quad (8)$$

2. Reverse fault

   If the absolute value of the maximum negative anomaly is greater than the maximum positive anomaly value and can be expressed in the form:

$$\left| \frac{\partial 2\ (\Delta g)}{(\partial z)2} \right|_{min} > \frac{\partial 2\ (\Delta g)}{(\partial z)2}_{max} \quad (9)$$

3. Transform fault

   If the absolute value of the minimum negative anomaly is almost the same as the maximum positive anomaly value and can be expressed in the form:

$$\left| \frac{\partial 2\ (\Delta g)}{(\partial z)2} \right|_{min} = \frac{\partial 2\ (\Delta g)}{(\partial z)2}_{max} \quad (10)$$

This study employs the Second Vertical Derivative (SVD) method, which separates shallow and deep structures using the second vertical derivative from Bouguer anomaly data (Felix et al., 2015). The SVD method was initially developed by Elkins in 1951 to determine gravity values on the Earth's surface, assuming that the horizontal plane of the ground is at a depth of $z = 0$ (Puspita, 2012). Derivatives derived from gravity data are highly valuable for structural interpretation (Firdaus et al., 2016). Moreover, this study utilizes the Elkins SVD Filter (Elkins, 1951) due to its ability to provide optimal results with clearer resolution and more representative boundaries of anomalous edges compared to other filters, thereby facilitating more accurate determination of fault characteristics and subsurface geological structures (Samodro, 2021).

3. RESULTS AND DISCUSSION

3.1 Gravity Anomaly in the Research Area

3.1.1 Simple Bouguer Anomaly (SBA)

Based on the study data obtained, a SBA is obtained from the results of data processing of FAA and BC. As for getting the BC value, an average density estimation value is needed which can be obtained from the Parasnis method, namely by connecting the graphic plot between the density values obtained with the FAA value, then a treadline is carried out on the graph, which is done in Microsoft Excel . Based on Figure 3, the estimated average density for the distribution area of the Manna segment fault obtained from the Parasnis method is 2.1644 g/cm^3.

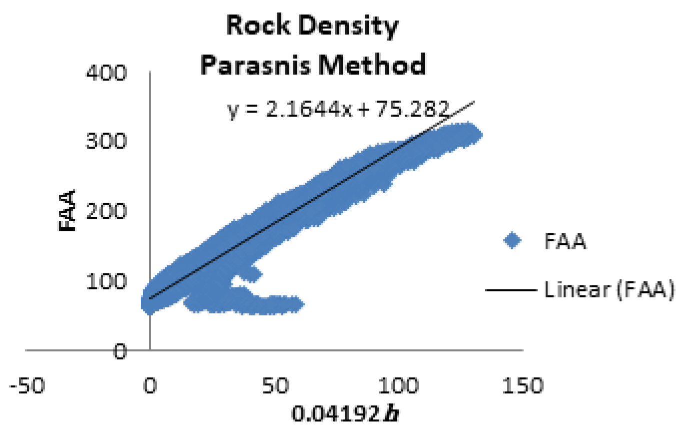


Figure 3 Estimated average density by Parasnis method.

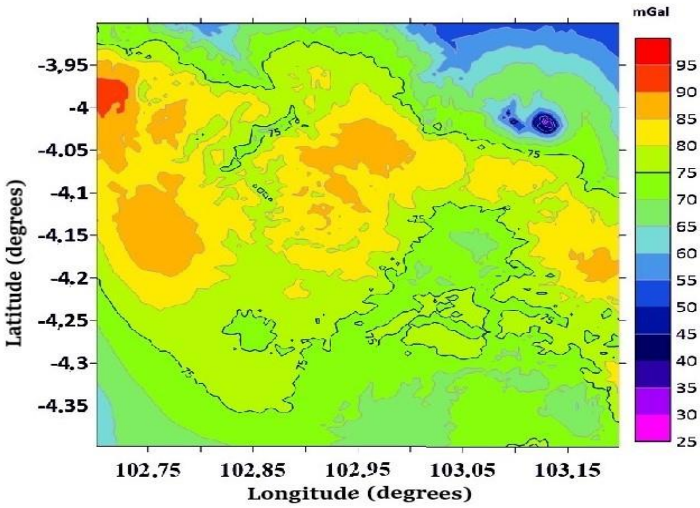


Figure 4 Simple Bouguer Anomaly (SBA) map of the Manna segment fault area.

Based on the average rock density table provided by W.M. Telford et al. (1990) and Reynolds (2011), using the FAA (y variable) and 0.04192h (x variable), the estimated average density value for the fault distribution area obtained from the Parasnis method is 2.1644 g/cm3. Since the Manna segment consists of sedimentary rock formations, as indicated by Indarto et al. (2009), the estimated average density value from the Parasnis method is appropriate for describing the geological conditions in the distribution area of the Manna segment fault in South Bengkulu.

After obtaining the estimated average density value, it is used to calculate the Bouguer Correction (BC) and determine the Simple Bouguer Anomaly (SBA). The distribution of SBA values for the Manna segment fault area is depicted in Figure 4, with a range of SBA values between 25 mGal and 95 mGal. High SBA values are represented by orange to red colors, while low Bouguer anomaly values are depicted in blue to purple. Higher SBA values indicate the presence of denser rocks beneath the surface, influenced by variations in rock density.

The obtained SBA values align with the geological characteristics of the surrounding rocks in the research area. It is necessary to separate regional and residual anomalies to analyze anomalies affected by shallow surface structures.

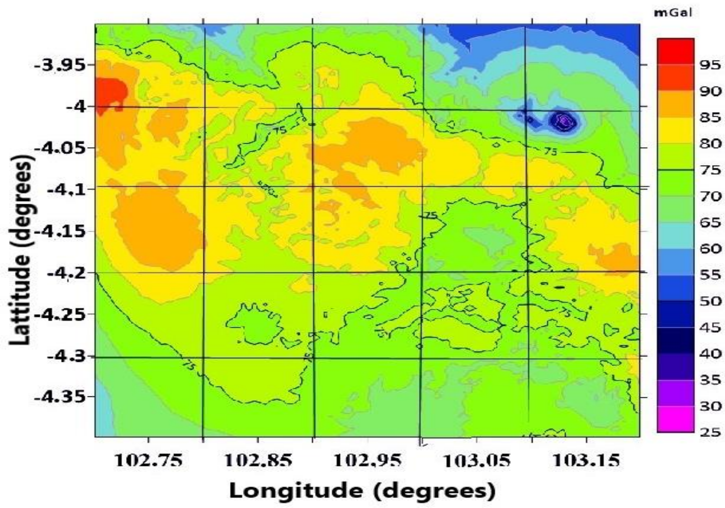


Figure 5 Slice paths for spectrum analysis.

3.1.2 Regional anomaly

Regional anomaly refers to anomalies originating from deeper layers of the Earth's crust and gravitational field. To determine the distribution of regional anomalies, a spectrum analysis process is conducted to separate them from residual anomalies. This study created eight incision paths to analyze the SBA profile and perform spectrum analysis.

Figure 5 illustrates the incision used for spectrum analysis, where the Fourier series is transformed from the distance/space domain to the wavenumber domain. This analysis helps determine the estimated depths of the regional and residual anomalies and the window width values. Table 1 presents the results, showing an average regional depth of 4415.84 meters and a residual depth of 289.874 meters.

For the moving average process, it is necessary to use an odd window width value. This study obtained a window width of 25, which meets the requirement for the moving average analysis.

Then After the moving average value is obtained, the value obtained is filtered between the moving average value obtained and the SBA obtained so that regional anomaly values are obtained.

Table 1 Calculation of window width

Regional Zone (m)	Residual Zone (m)	C_1	C_2	Λ	K	N
-3064.7	-436.98	13.175	9.7565	0.001301	4829.736	19.31894
-4554.2	-206.76	13.644	9.1054	0.001044	6018.546	24.07418
-5356.2	-258.46	14.18	9.0232	0.001012	6211.225	24.8449
-4649.2	-262.12	14.219	9.2084	0.001142	5501.305	22.00522
-4925.8	-25.858	14.385	10.166	0.000861	7297.285	29.18914
-7188.8	-475.01	14.459	9.8528	0.000686	9158.088	36.63235
-3078.9	-324.43	13.201	10.295	0.001055	5955.556	23.82222
-2508.9	-329.37	12.527	10.052	0.001136	5533.087	22.13235
-4415.84	-289.874		Window Width			25.25241

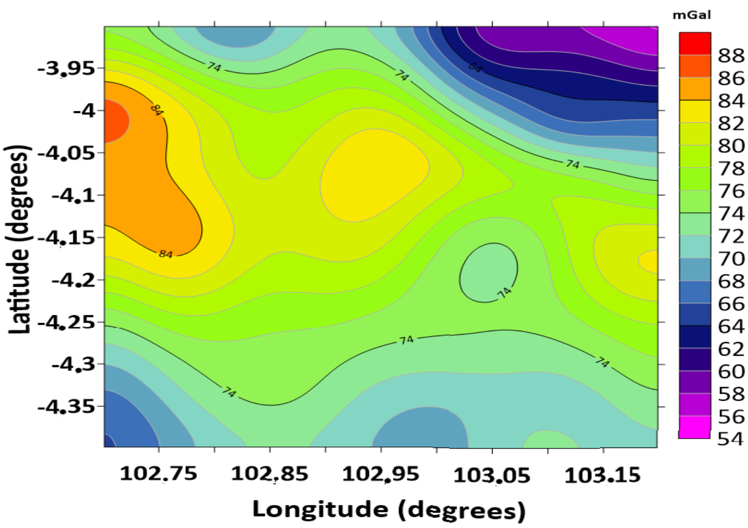


Figure 6 Regional anomaly map of study area.

Based on the data analysis, Figure 6 illustrates the distribution of regional anomaly values in the study area. The regional anomaly values range from 54 mGal to 88 mGal. In the western part of the research area, the orange-to-red color indicates high regional anomaly values ranging from 84 mGal to 88 mGal. Meanwhile, the purple to yellowish green represents regional anomaly values ranging from 54 mGal to 80 mGal.

Notably, there is a distinctive pattern of numerous contour lines in green within the range of 74 mGal to 80 mGal. This pattern suggests the presence of the Manna fault anomaly. However, the SVD method with an Elkins filter will be employed in the subsequent processing steps to further analyze and visualize the anomaly more effectively.

3.1.3 Residual anomaly

Residual anomaly refers to a local anomaly originating at a shallower depth compared to the regional anomaly. It provides insights into the characteristics of shallow subsurface structures, including faults, basins, and exposed rock formations. The residual anomalies are obtained by subtracting the regional anomalies from the Simple Bouguer Anomaly (SBA) values.

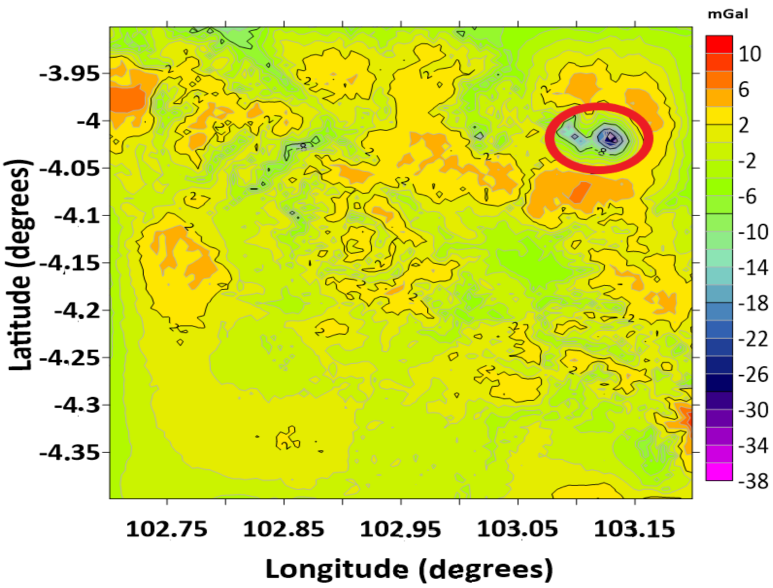
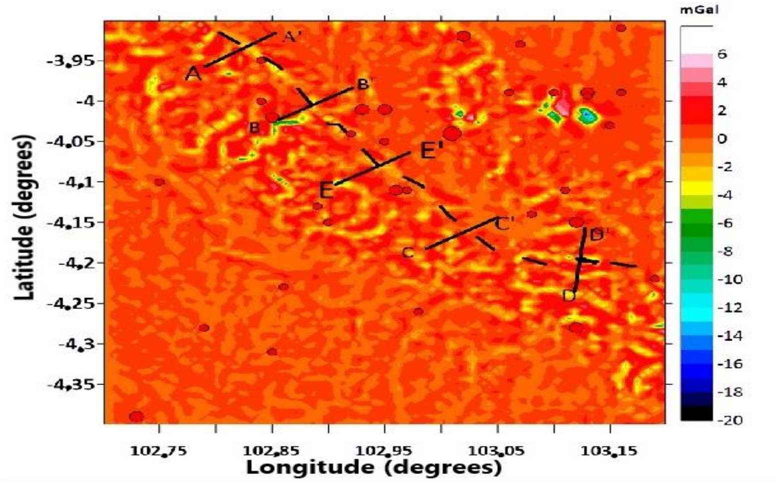


Figure 7 Residual anomaly map of study area.

Based on the data processing results, Figure 7 illustrates a more intricate pattern of residual anomalies compared to the SBA pattern and regional anomalies. The range of residual anomaly values in the study area varies from -38 mGal to 10 mGal. High values of residual anomalies are depicted in orange to red colors, while blue-purple colors represent low values. A specific area, Mount Dempo, highlighted in red in Figure 7, displays low residual anomaly values. The contour lines of the residuals demonstrate a diverse range of values, indicating the influence of the study area's topography. These residual anomalies are primarily shallow.

3.2 Determination of Fault Characteristics

To analyze the characteristics of the Sumatran fault, specifically the Manna segment, the area is divided into three regions to facilitate the observation of fault patterns. This division is based on the primary fault and the branching of the fault. The FHD and SVD methods are employed to determine the fault characteristics. The FHD analysis enables examining changes in anomaly values horizontally from one point to another. At the boundary of a geological structure, the FHD value tends to reach its maximum or minimum value within the dataset. On the other hand, the SVD analysis allows for identifying anomalies caused by geological structures, with absolute maximum and minimum values limited by a zero value as the boundary of the geological structure. By analyzing the minimum and maximum values of the SVD, the characteristics and types of the Sumatran fault in the Manna segment can be determined. To aid in locating the faults, earthquake data with magnitudes of M ≥ 3 and depths ≤ 30 km are plotted on the SVD map of each region.



>=Minimum	<Maximum	%	Count	Symbol...	Size...
1.2	3	69.4	25	●	0.1 in
3	5	27.8	10	●	0.15 in
5	7	2.8	1	●	0.2 in

Figure 8 Map of SVD Elkins region 1.

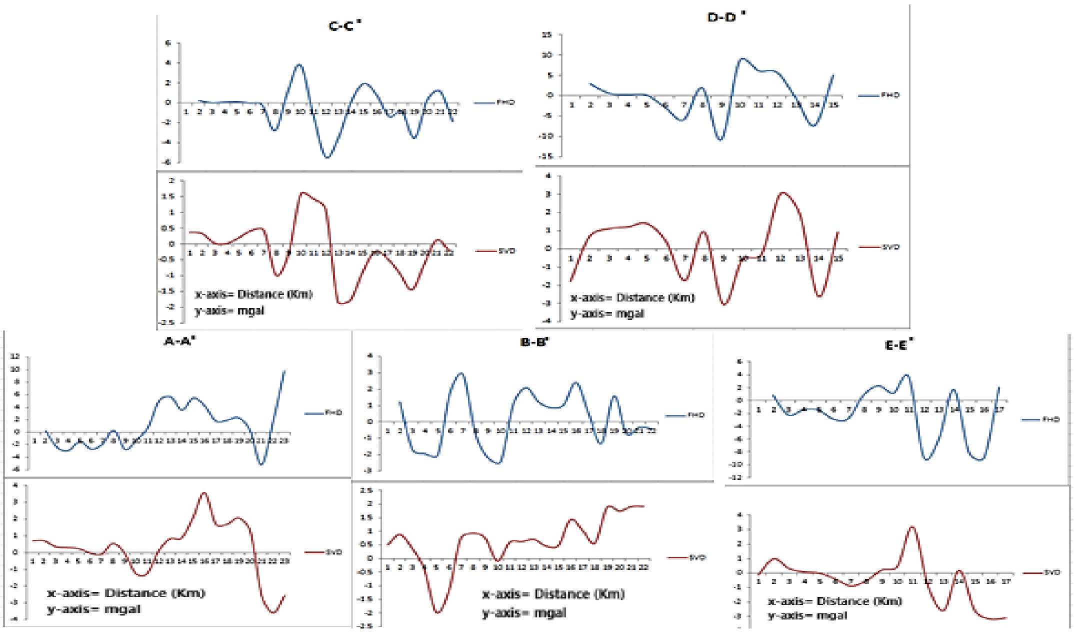


Figure 9 Graph of maximum and minimum SVD Region 1.

3.2.1 Region 1

Region 1 is the main fault of the Manna segment, this fault is in an area with a range of 102.7º - 103.19º East longitude and 3.9º - 4.2º Southern latitude. On the SVD region 1 map, 5 large slice were made to identify the location and characteristics of the fault (Figure 8). This incision is made based on the main line of the fault which is marked with a dotted line on the contour map obtained. The number of incisions made must be adjusted to the area of the study area and the length of the main fault line pattern obtained. The pattern of determining the main line of the Manna segment fault can be seen on the contour map. There are different contour patterns that form elongated and branching lines which are marked in yellow according to the Elkins filter method (Elkins, 1951). For region 1, the pattern of the main fault of the Manna segment is in accordance with the Sumatran fault data (PuSGeN, 2022).

The study of the FHD and SVD graphic analysis of each incision are shown in Table 2 and Figure 9. The incision in section (A-E) is the suspected location of the Manna segment fault. Based on Table 2 and Figure 8 on the Manna fault segment for the A-A', B-B', C-C', D-D', and E-E' incisions obtained from the value |SVD Min|and |SVD Max| which is correlated with the FHD value shows that |SVD Min| and |SVD Max| which are not much different or almost the same/equivalent. So for the Manna fault segment in the incision which includes A-A', B-B', C-C', D-D', and E-E', it can be interpreted as a characteristic of a type of transform fault.

Table 2 Analysis of minimum and maximum SVD Region 1

Slice	Minimun SVD	Maximum SVD	Fault Characteristics
A-A’	1.37	1.39	Transform Fult
B-B’	1.97	1.92	Transform Fault
C-C’	1.58	1.82	Transform Fault
D-D’	3.05	3.04	Transform Fault
E-E’	3.17	3.18	Transform Fault

3.2.2 Region 2

After completing the research in Region 1, the investigation proceeds to Region 2, a branching fault originating from the main fault in Region 1. Region 2 encompasses an area with a longitude ranging from 103.02º to 103.19º E and a latitude ranging from 3.90º to 4.18º S.

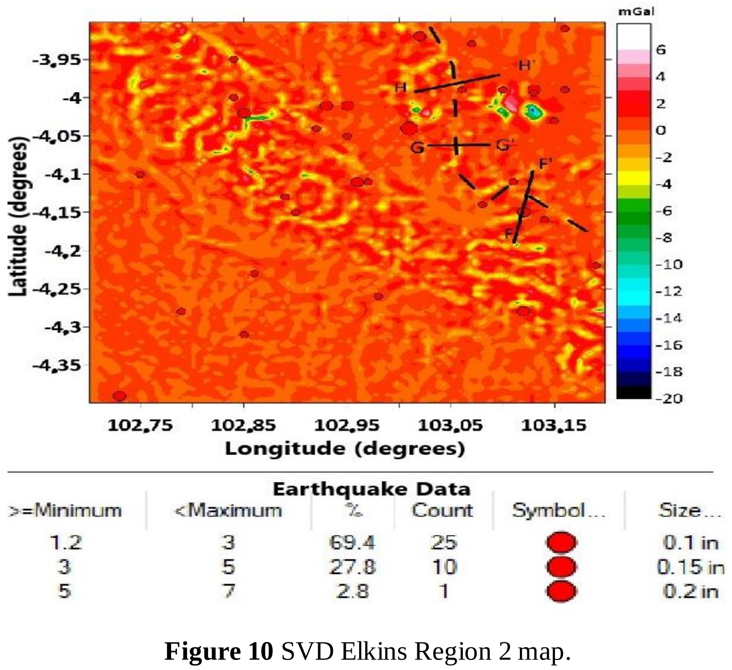


Figure 10 SVD Elkins Region 2 map.

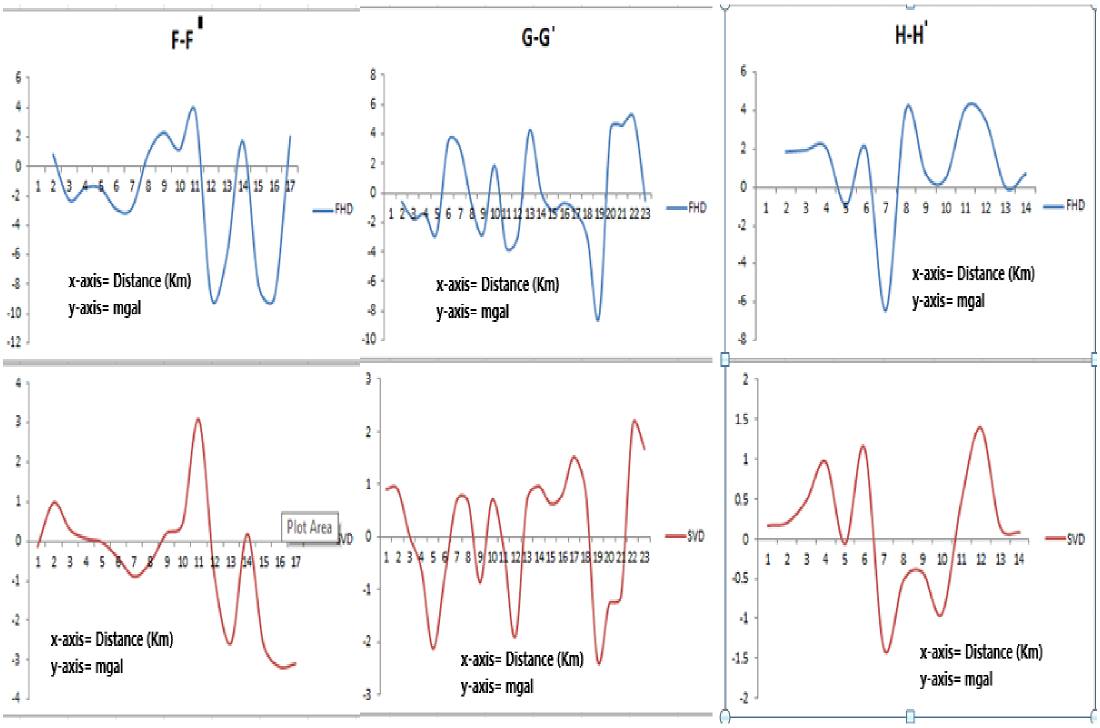


Figure 11 Graph of maximum and minimum SVD Region 2.

To identify the location and characteristics of the fault in Region 2, three distinct cross-sections are created on the SVD map, as depicted in Figure 10. These cross-sections are positioned carefully to align with the fault line pattern, which is relatively narrower due to being a branch of the main fault in the Manna segment. After analyzing the FHD and SVD graphs in Region 2 and compiling earthquake data from 2002 to 2022 from each slice, the findings are presented in Table 3 and Figure 11. Section (F-H) among the slices indicates the suspected location of the Manna segment fault. Upon examining Table 3 and Figure 10 for the Manna fault segment in slices F-F', G-G', and H-H', it is observed that the |SVD Min| and |SVD Max| values do not differ significantly. Therefore, based on the analysis of these slices, it can be inferred that the Manna fault segment exhibits characteristics of a transform fault or strike-slip fault. Additionally, it is worth noting that Region 2 is located close to Dempo Mountain, indicating the proximity of the fault position to this geological feature.

Table 3 Minimum and maximum SVD analysis in Region 2

Slice	Minimun SVD	Maximum SVD	Fault Characteristics
F-F’	3.17	3.08	Transform Fault
G-G’	2.35	2.14	Transform Fault
H-H’	1.37	1.39	Transform Fault

3.2.3 Region 3

Region 3 is part of the Manna segment fault which is part of the main fault branch of this Manna segment. Region 3 is in an area with coordinates ranging from 103.06º - 103.19º East longitude and 4.19º - 4.27º Southern latitude. On the SVD map in Figure 12, region 3 is made as many as 2 broad incisions to identify the location and characteristics of the fault and is accumulated with the same earthquake data as regions 1 and 2. From the analysis of the FHD and SVD region 3 graphs which are divided into 2 incisions. The incisions on sections (I and J) are the suspected locations of the Manna segment faults. Based on Table 4 and Figure 13 on the Manna fault segment for I-I' and J-J' incisions have |SVD Min| and |SVD Max| which correlates with the FHD value shows a value that is not much different. So for the Manna Fault segment in the incision which includes I-I' and J-J' it is interpreted as a characteristic of a type of transform fault. This is based on the graph. The results of this analysis show that in region 3 which is only divided into 2 incisions, it can be used to determine the characteristics of faults in this segment of the Manna fault.

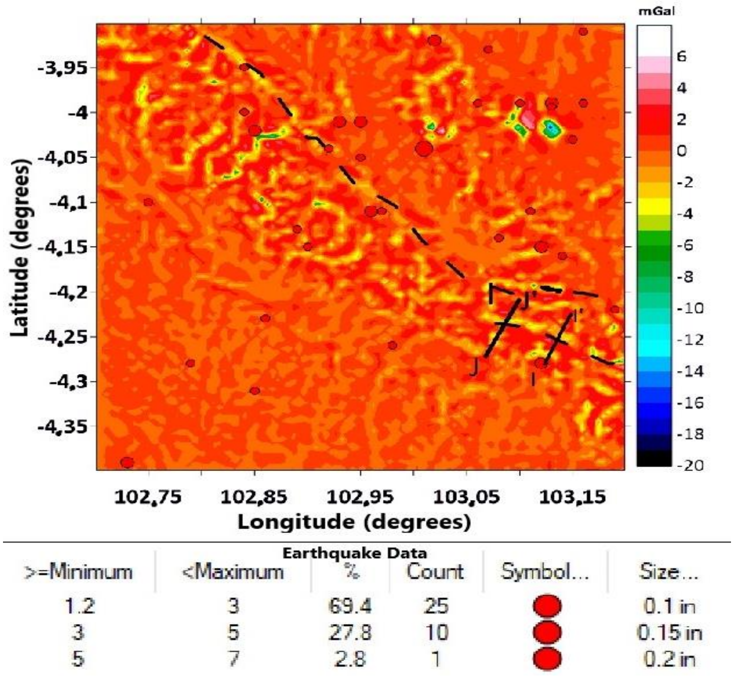


Figure 12 Map of SVD Elkins Region 3.

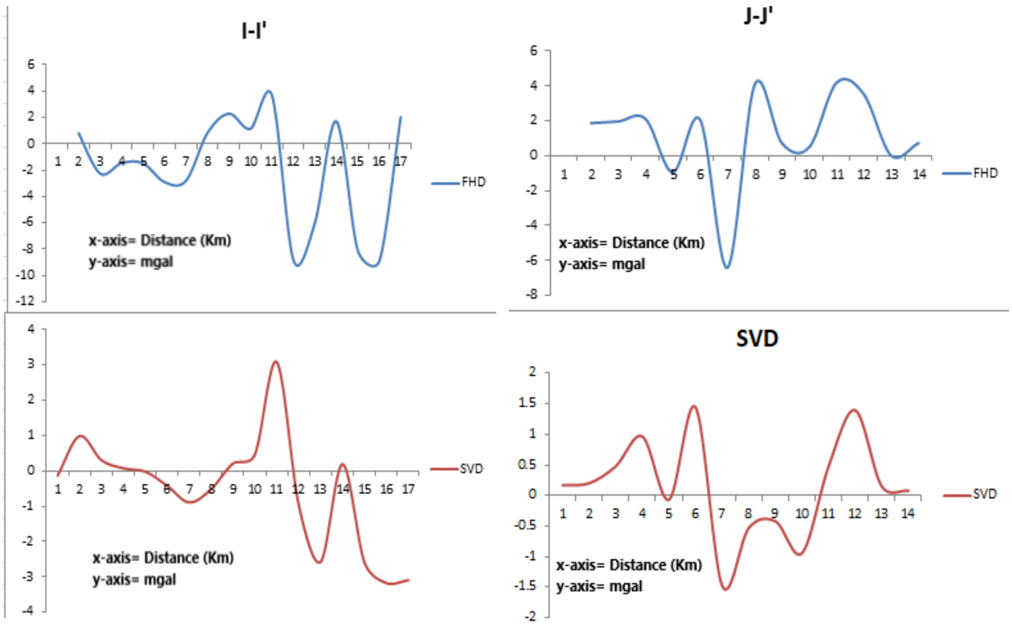


Figure 13 Graph of maximum and minimum SVD Region 3.

Table 4 Minimum and maximum SVD analysis Region 3

Slice	Minimun SVD	Maximum SVD	Fault Characteristics
I-I'	1.71	1.75	Transform Fault
J-J'	1.44	1.47	Transform Fault

In the three regions analyzed using the Second Vertical Derivative (SVD) method, the |SVD Min| and |SVD Max| values obtained are relatively similar or equivalent. These values also correlate with the FHD values. According to the guidelines of the SVD method outlined in Reynolds (1997), this indicates that the Manna segment fault is characterized as a Strike-Slip Fault. This interpretation is consistent with the 2012 Indonesian Earthquake Source and Hazard Map Book compiled by the National Center for Earthquake Studies, which identifies the Manna segment fault as a type of Strike-Slip Fault. Therefore, the results obtained through the SVD method align with data from the National Center for Earthquake Studies in 2022 and previous studies conducted using different methods.

The position of the fault identified in this study using the SVD method corresponds to the Sumatran fault in the Manna segment, as indicated by Pusgen's 2022 data. Additionally, the SVD maps reveal branching faults in Region 2 and Region 3.

In the specific research conducted on the Manna segment of the Sumatran fault area, the gravity anomaly value in this region is heavily influenced by the underlying rock density. The shallow depth information from the residual anomaly is crucial for interpreting and identifying more specific subsurface structures. The residual anomaly map provides a distribution pattern of contours, including high, moderate, and low anomalies. Both the residual and regional anomaly maps are essential for fault interpretation.

When applying the Elkins filter, a decrease in anomaly values is observed, indicating a fault distribution pattern ranging from -2 mGal to -4 mGal. The Elkins map reveals numerous branches of the Manna fault in the South Bengkulu area, characterized by consistent anomaly values.

4. CONCLUSION

Based on the research findings, it can be concluded that the Simple Bouguer Anomaly (SBA) values in the distribution area of the Manna segment fault range from 25 mGal to 90 mGal. The regional anomaly ranges from 54 mGal to 88 mGal, while the residual anomaly ranges from -38 mGal to 10 mGal. The derivative analysis shows that the minimum and maximum values on the First Horizontal Derivative (FHD) curve correspond to zero values on the Second Vertical Derivative (SVD) curve. This indicates that the maximum and minimum SVD values are relatively similar, suggesting that the fault type at the research site is a strike-slip fault. Furthermore, the study results reveal that this fault has branches in Region 2 and Region 3 of the SVD map.

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