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Research Article

Fault Structure Analysis Using GGMPlus Satellite Gravity Data in Sumenep Regency, East Java for Disaster Mitigation

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Abstract

Sumenep Regency is an area that has experienced earthquakes with fatalities caused by the activity of the Rembang, Madura, Kangean, Sakala (RMKS) fault. This study aims to identify subsurface structures, particularly faults, in the Sumenep region using satellite gravity image data downloaded from GGMPlus. The gravity acceleration data obtained was processed into Complete Bouguer Anomalies (CBA) and separated into regional and residual anomalies using a Butterworth filter. Then, First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) analyses were performed to clarify the anomaly boundaries and subsurface structures. Next, 2D geological modeling was performed on the residual anomaly data to determine the types and boundaries between subsurface formation layers. The results of the study showed significant variations in gravity anomalies, with high contrasts in the southwest and southeast areas, indicating differences in the density of subsurface rocks. FHD and SVD analyses successfully delineated suspected faults, especially in areas with contact layers between low- and high-density rocks. The 2D modeling showed that the contact layer between the Ngrayong-Tawun Formation and the Ngrayong-Bulu Formation has a weak bond, making it more vulnerable to triggers such as earthquakes. These results emphasize the importance of further study and disaster mitigation related to active faults in the region. For future research, it is necessary to conduct field surveys and integrate them with other geophysical methods to improve the accuracy of the results.

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Introduction

Indonesia has a relatively high population growth rate. In 2020, Indonesia's population increased by 32.56 million people between 2010 and 2020 (BPS, 2021). Significant population growth needs to be balanced with improvements in the community's quality of life. One strategic step in enhancing quality of life is

conducting geological studies in areas planned for settlement, including sites for housing, schools, and other public facilities. Comprehensive geological studies enable both the government and the public to develop more effective disaster mitigation strategies, particularly in addressing the potential risks of earthquakes (Muslim & Endyana, 2015).

Earthquakes are natural disasters generally caused by tectonic activity, volcanic activity, or movement along active faults. Indonesia, which lies at the junction of three major tectonic plates, namely the Australian Plate, the Eurasian Plate, and the Pacific Plate, is a region with a high level of earthquake risk. These tectonic conditions cause earthquakes to occur relatively frequently and have the potential to significantly impact the livelihoods of communities, particularly for populations living near active fault zones (Murtianto, 2010).

Sumenep is one of the regencies on Madura Island that experienced an earthquake in 2018. This earthquake resulted in 46 people being injured and 4 fatalities. The earthquake was caused by an active fault, namely the Rembang, Madura, Kangean, Sakala (RMKS) fault (Wasito, 2024). One way to detect faults is to use geophysical methods.

One geophysical method for detecting faults is the gravity method. The gravity method is a geophysical technique that measures variations in the Earth's gravitational acceleration to identify subsurface structures. Its basic principle is to measure variations in gravitational acceleration values in a given area caused by differences in the density of subsurface rocks (Reynolds, 2011). The gravity values obtained from measurements are then corrected using several parameters, such as free-air, Bouguer, and terrain corrections, to produce a Complete Bouguer Anomaly map (Telford et al., 1990). The advantage of the gravity method is its ability to detect lateral density variations, which can help identify faults. However, its limitation is the relatively high level of ambiguity, which requires integration with other methods. The gravity data used in this study are satellite-derived images obtained from GGMPlus.

Satellite image data from the GGMPlus platform are commonly used, both for the early stages of mineral resource exploration (Muhlisin et al., 2025), geothermal area analysis (Karimah et al., 2021), and geological structure identification. In a similar previous study conducted by Pramadhana et al., (2024) Fault identification was also conducted using gravity satellite imagery data from GGMPlus. However, that study focused primarily on identifying the RMKS fault system, which resulted in a relatively large study area. In this study, the selected research area is limited to a portion of Sumenep Regency.

Therefore, it is important to conduct this research to identify subsurface structures in the Sumenep Regency, Madura, using the gravity method and GGMPlus satellite data. This study is expected to provide an overview of subsurface rock density variations that may indicate the presence of faults and to confirm the existence of faults that could act as sources of earthquakes and other disasters.

Research Method

Geology of the Study Area

The study area is located on Madura Island, specifically in Sumenep Regency. The study area is located on the Regional Geological Map of the Waru–Sumenep Sheet (Figure 1) (Situmorang et al., 1992). Sumenep Regency is situated within the Tertiary and Quaternary sedimentary zones, particularly the Rembang Zone, which is characterized by sandy sedimentary rocks and carbonate limestones. The Rembang Zone extends from the North Limestone Mountains in Rembang Regency to the eastern end of Madura Island (Sulistiyono, 2017).

The regional geological map of the Sumenep area used in this study shows the presence of several rock formations, namely the Tawun Formation (Tmt), Ngrayong Formation (Tmtn), Bulu Formation (Tmb), Pasean Formation (Tmp), Madura Formation (Tpm), Pamekasan Formation (Qpp), and alluvium (Qa) (Situmorang et al., 1992). The formations in the study area are generally of Tertiary age, with only the Pamekasan Formation and alluvium being of Quaternary age. The oldest formation is the Tawun Formation, which dates from the Early to Middle Miocene. It consists of claystone, marl, and clayey limestone with interbeds of orbitoidal limestone. The Ngrayong Formation is the second oldest, of Middle Miocene age, and is composed of interbedded quartz sandstone, orbitoidal limestone, and claystone. The Bulu Formation was formed during the same geological period as the Ngrayong Formation, namely the Middle Miocene. However, it is relatively young. It consists of bedded limestone interbedded with sandy marl. The Pasean Formation is of Late Miocene age and consists of an interbedding of sandy marl with clayey limestone, sandy limestone, and oolitic limestone. The Madura Formation is the youngest Tertiary formation, dating from the Pliocene, and is composed of reef limestone and dolomitic limestone. The

Pamekasan Formation is a Pleistocene Quaternary formation and consists of conglomerate, sandstone, claystone, and limestone. The youngest unit is Holocene alluvium, composed of quartz sand, clay, mud, gravel, and pebbles. The regional geological map also indicates the presence of several anticlines, including the Batuputih, Tempajung, and Sumberwaru anticlines, as well as one syncline, the Eden syncline. In addition to folds, faults are present, although most are interpreted as such.

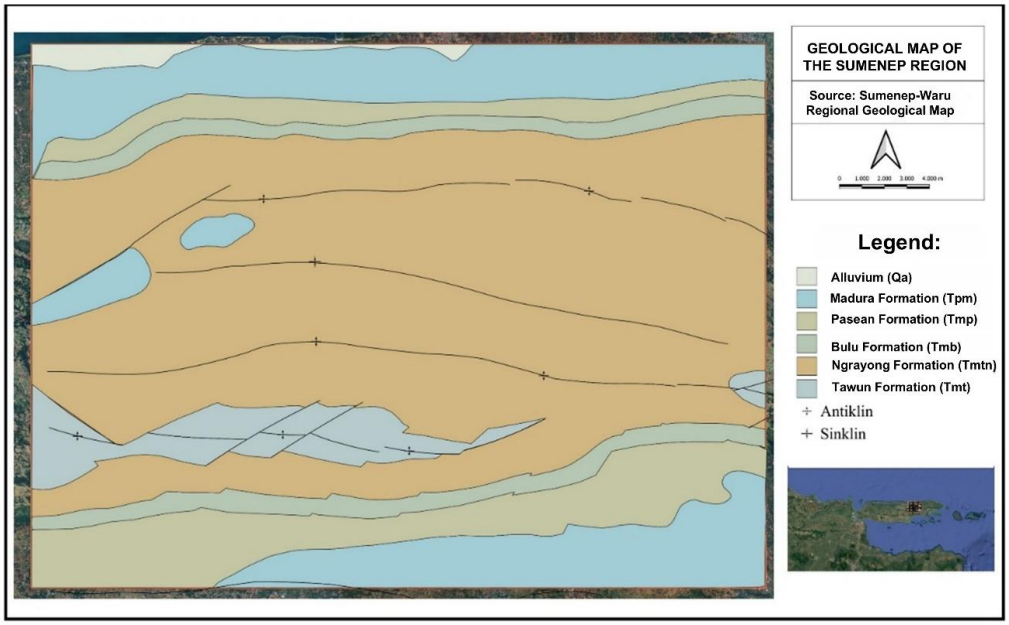


Figure 1. Geological Map of Sumenep (Situmorang et al., 1992)

Study Area Location

Data acquisition for this study was conducted in October 2025 using satellite imagery to obtain gravity acceleration data in the Sumenep area, specifically within the coordinates 6°53'59.99" – 7°03'35.86" S and 113°32'33.63" – 113°45'17.00" E. The study area covers approximately 23 × 17 km, with a spacing of 220 m between data points and a total of 8,008 observation points (Figure 2).

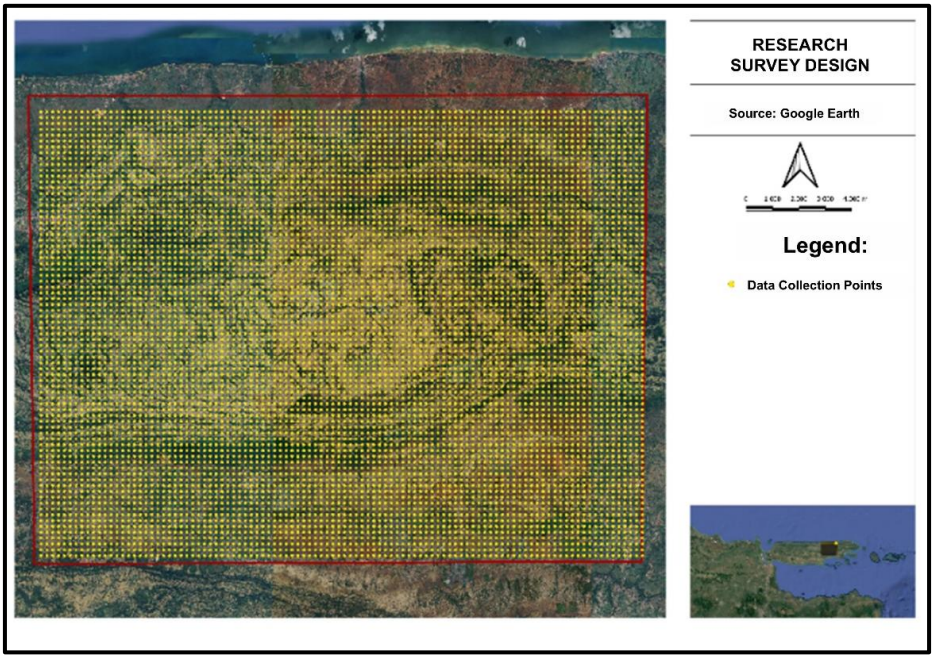


Figure 2. Research survey design map

The gravity data were obtained from the Global Gravity Model Plus (GGMPlus), a platform that provides gravity data derived from global gravity field models based on information from GRACE and GOCE satellites, the EGM2008 model, and gravity topography from RTM forward modeling (Suprianto et al., 2021). The available data include geographic coordinates, elevation, and gravity disturbance, which represents the difference between the Earth's observed gravity and the normal gravity at the same location.

Gravity Method

The gravity method is based on Newton's Law, which states that the force between two particles with masses (m_1 and m_2) is directly proportional to the product of the two masses and inversely proportional to the square of the distance between them. Mathematically, this law can be expressed as follows (Telford et al., 1990).

$$\vec{F} = \gamma \left(\frac{m_1 m_2}{r^2}\right) \hat{r} \quad (1)$$

Which $\vec{F}$ is the force (N), γ is the gravitational constant (γ = 6,67 × 10^{-11} N m^2 kg^{-2}), $m_1$and m_2 are the masses of the objects, and r is the distance between them. After obtaining the gravitational acceleration, the data are processed to produce the Complete Bouguer Anomaly (CBA). The CBA is obtained by subtracting the theoretical gravity from the observed gravity values and correcting for the effects of celestial bodies, surrounding terrain, and other local influences at the measurement points. This reduction is expressed as follows (Telford et al., 1990).

$$g_B = g_{obs} - g_t + (\Delta g_L + \Delta g_{FA} + \Delta g_B + \Delta g_T) \quad (2)$$

Where g_{obs} is the observed gravity value, g_t is the theoretical gravity value, Δg_L is the latitude correction, Δg_{FA} is the free-air correction, Δg_B is the Bouguer correction, and Δg_T is the terrain correction.

For more accurate interpretation, the Bouguer anomaly is separated into residual and regional anomalies. The residual anomaly represents shallower sources compared to the regional anomaly (Jacob et al., 2018). This is particularly advantageous for structural identification, especially when the objective is to analyze more local structures. In this study, the anomaly separation is performed using a Butterworth filter.

Further analysis is then carried out using the First Horizontal Derivative (FHD) and the Second Horizontal Derivative (SVD). Derivative analysis is highly sensitive to even the smallest variations in gravity values. The First Horizontal Derivative helps delineate anomaly boundaries, while the Second Horizontal Derivative enhances resolution, allowing subsurface structures to be identified more clearly (Hinze et al., 2013). Subsequently, the residual anomaly is sliced to model the subsurface geology or to generate a 2D cross-sectional representation.

Results and Discussion

Complete Bouguer Anomaly (CBA)

The Complete Bouguer Anomaly (CBA) map ranges from 60.4 mGal to 136 mGal (Figure 3). The CBA values are divided into two categories, namely low anomalies and high anomalies. These variations are represented by colors, with pink indicating high anomaly values and dark blue indicating low anomaly values. The anomaly values show a linear relationship with rock density. High anomalies indicate the presence of high-density rocks, while low anomalies indicate the presence of lower-density rocks in the study area (Sutasoma et al., 2025).

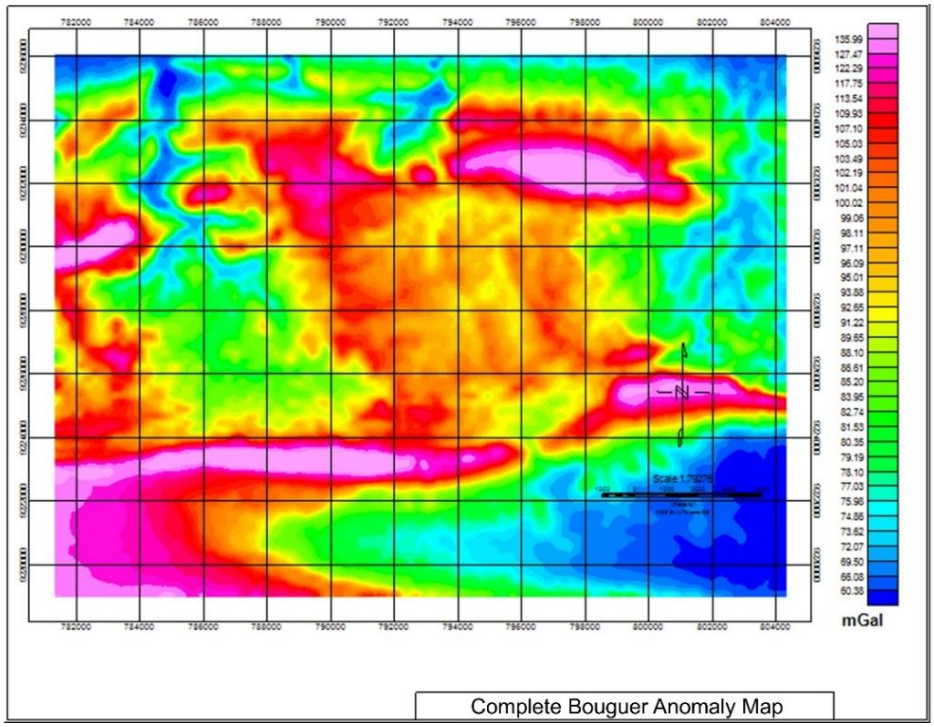


Figure 3. Complete Bouguer Anomaly Map

Regional and Residual Anomalies

The regional anomaly (Figure 4a) shows very little difference compared to the Complete Bouguer Anomaly map, considering that the satellite data coverage provided by GGMPlus is global in nature (Hirt et al., 2013). The regional anomaly represents deeper subsurface structures. As depth increases, subsurface structures tend to become more uniform. This results in a relatively uniform color pattern in the regional anomaly map (Sutasoma et al., 2025).

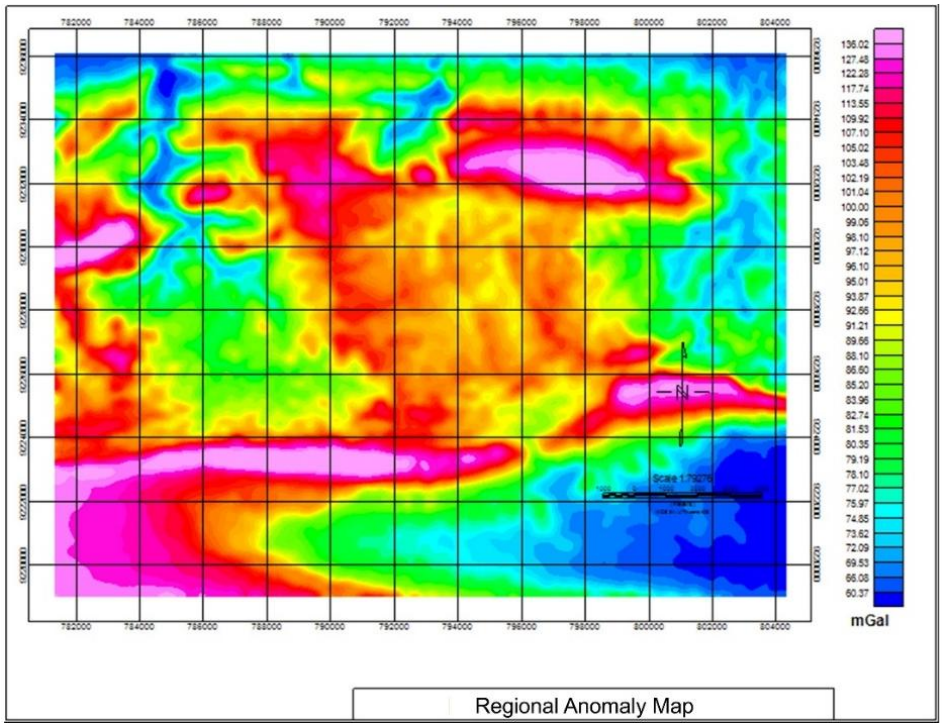
The resulting residual anomaly map shows a different distribution of values than the regional anomaly map. The value range shown in the residual anomaly map is −8.24 to 9.0 mGal (Figure 4b). This is because residual anomalies represent shallower subsurface structures. The shallower the subsurface layer, the more heterogeneous the structures become, leading to more varied anomaly values. In the residual anomaly, the anomaly contrast is highly variable, particularly in the northwestern and southern parts of the study area. Anomalies with large value differences that are closely spaced may indicate either lithological boundaries or subsurface structures. Based on the geological map, the anomaly contrast extending from west to east suggests lithological boundaries among the Tawun Formation, Ngrayong Formation, and Bulu Formation. These strong contrasts may also be interpreted as resulting from structural features in the area, particularly within the Tawun Formation, including the Sumberwaru anticline and associated faults. In the northwestern part of the map, anomaly contrasts are also observed, likely caused by lithological boundaries between the Ngrayong Formation and the Madura Formation, as well as between the Bulu Formation, the Pamekasan Formation, and the Madura Formation.

Derivative Analysis

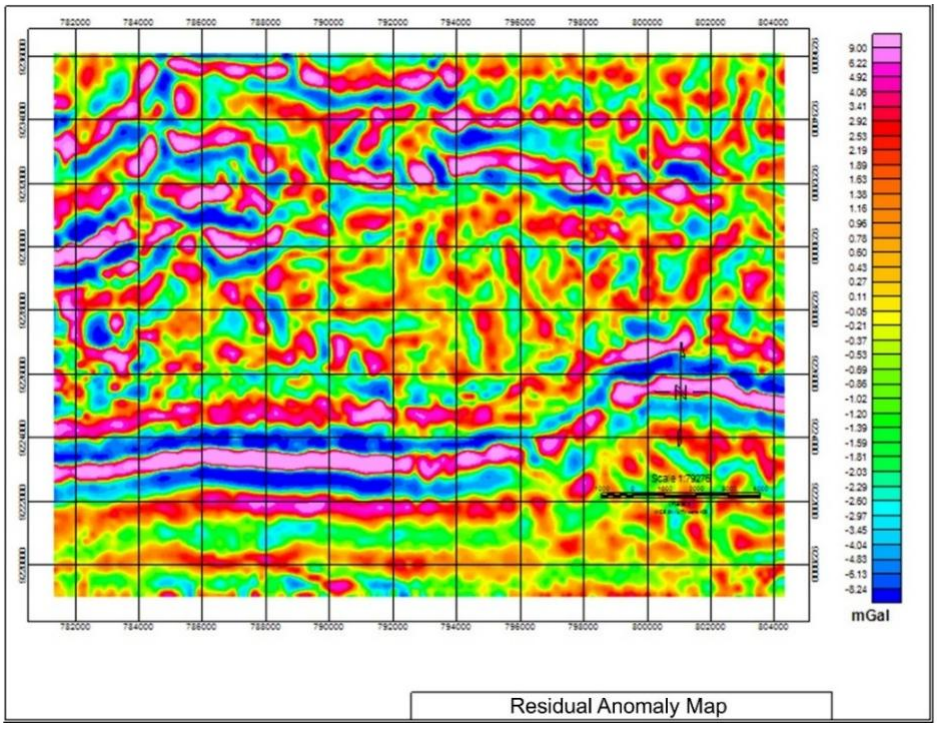
The residual anomaly map is then used as the basis for derivative analysis, namely the First Horizontal Derivative (FHD) and the Second Vertical Derivative (SVD). This is done because the residual anomaly represents shallow subsurface structures, which are the main target of this study.

The FHD map is obtained from the horizontal derivative of the residual anomaly. By applying FHD analysis, interpretation becomes easier and more accurate, as the FHD map can clearly delineate the boundaries of anomaly sources (Hinze et al., 2013). The values displayed on the FHD map (Figure 5a) range from 0.002 to 0.058 mGal. High FHD values are observed in two areas that correspond to those identified in the residual anomaly map. This supports the previous interpretation that lithological boundaries are present in these areas. The SVD map is used to identify subsurface structures, particularly

faults, especially in areas with maximum FHD values (indicated by pink) and SVD values approaching zero.

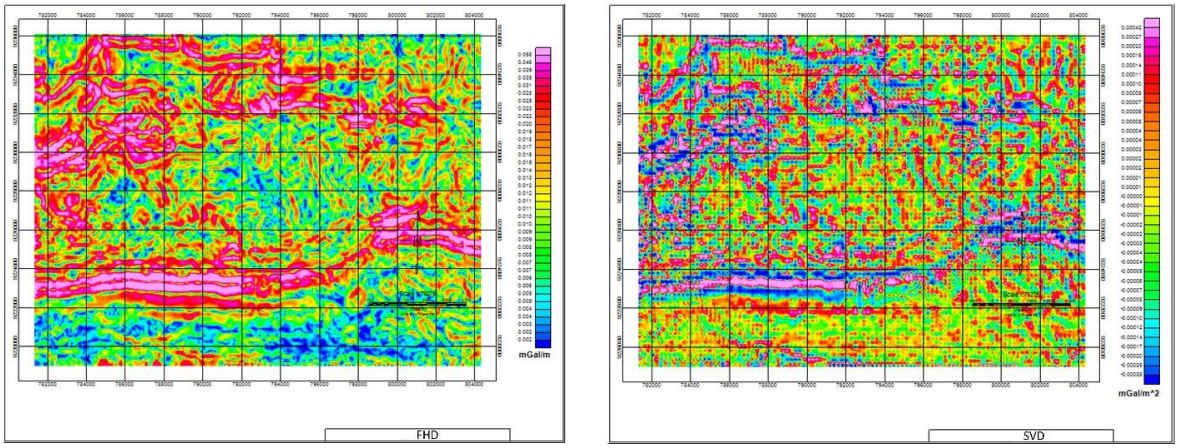


(a)



(b)

Figure 4. (a) Regional Anomaly Map and (b) Residual Anomaly Map



(a) **(b)**

Figure 5. (a) FHD Map, and (b) SVD Map

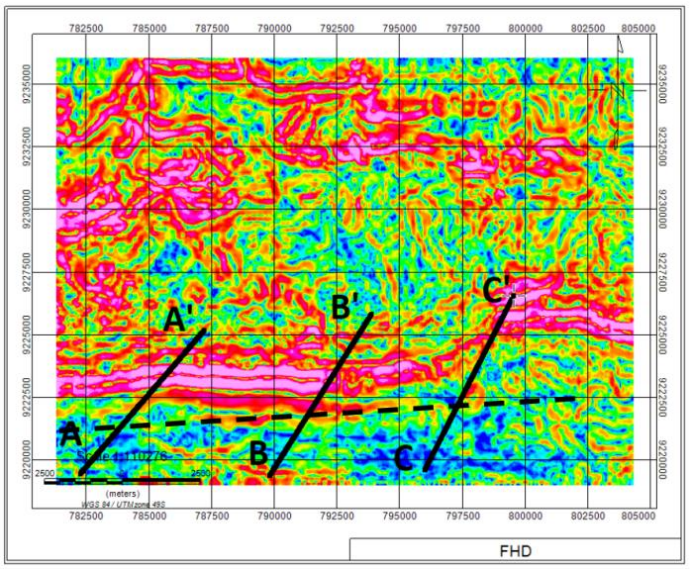


Figure 6. Cross-Section Lines on the FHD Map

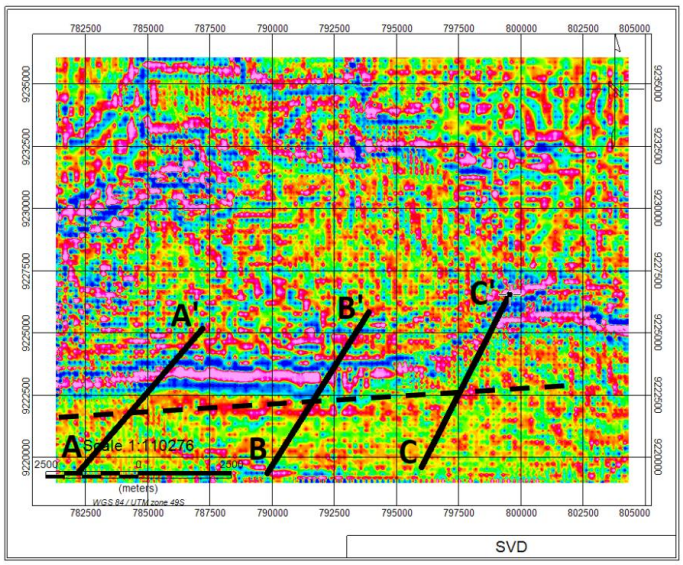


Figure 7. Cross-Section Lines on the SVD Map

To support the analysis, fault delineation was carried out by drawing three cross-section lines perpendicular to the interpreted structures, namely A–A', B–B', and C–C'. These cross-sections were then analyzed to delineate faults on the FHD and SVD maps.

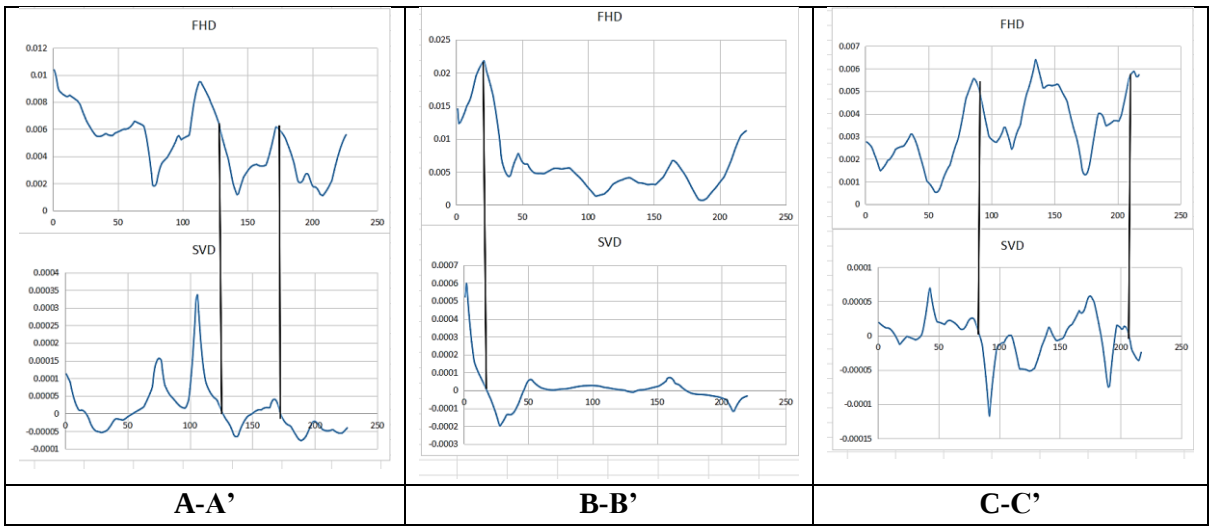


Figure 8. Cross-Section Graphs of the FHD and SVD Maps along A–A', B–B', and C–C'

From the resulting cross-section graphs, contrasts in density values were identified, characterized by maximum FHD values and SVD values that decrease significantly toward zero. Linear trends observed in the curves indicate a relationship between these two parameters, which may suggest the presence of faults (Hofi et al., 2024). All three graphs show density contrasts that further support the interpretation of faults in the area. However, this interpretation cannot yet be fully confirmed, as there is no direct evidence other than the presence of regional lithological boundaries. To validate the results, 2D geological modeling was performed using cross-section lines X1–X1', Y–Y', and Z–Z' on the residual anomaly map (Figure 9).

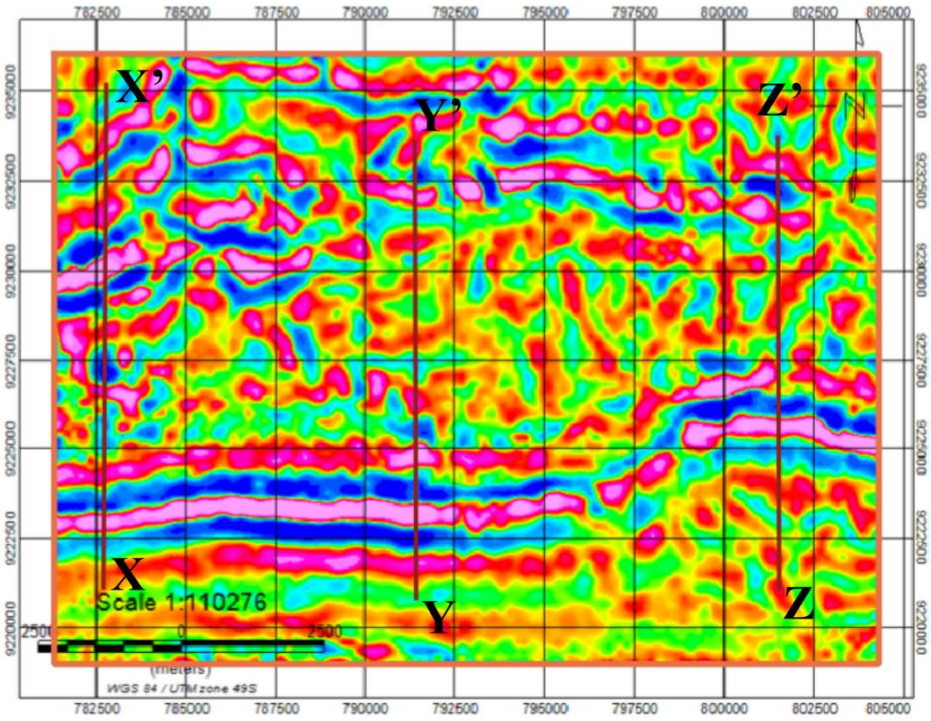


Figure 9. Cross-Section lines X1–X1', Y–Y', and Z–Z' on the residual anomaly map

The results of the 2D geological modeling based on the residual anomaly (Figure 10) indicate variations in lithological boundaries. The study area comprises several lithological units derived from different formations, as indicated by variations in rock density. The Tawun Formation is assumed to have a relatively low density, approximately 1.9 g/cm³, as it is dominated by claystone despite being older. Meanwhile, the Ngrayong Formation is interpreted to have variable densities ranging from 2.2 to 2.3 g/cm³. These density variations are interpreted as indications of differences in the lithological composition within the formation.

The interpretation results of the 2D cross-sections along lines X–X' and Y–Y' indicate the presence of several formations, namely the Madura Formation, Pasean Formation, Bulu Formation, Ngrayong Formation, and Tawun Formation. These results are consistent with the regional geology of the study area. The vulnerable zones in these cross-sections occur at the contact between the Tawun Formation and the Ngrayong Formation. These two formations differ in both lithology and age. The Tawun Formation was formed during the Early Miocene and consists of claystone, marl, and clayey limestone with intercalations of orbitoidal limestone. In contrast, the Ngrayong Formation was deposited during the Middle Miocene and consists of interbedded quartz sandstone, orbitoidal limestone, and claystone.

The interpretation results of the 2D cross-section along line Z–Z' indicate the presence of several formations, namely the Madura Formation, Pasean Formation, Bulu Formation, and Ngrayong Formation. These results are also consistent with the regional geology of the study area. The vulnerable zone in this cross-section is located at the contact layer between the Bulu Formation and the Ngrayong Formation. These two formations differ in lithology and age. The Bulu Formation was formed during the Middle to Late Miocene and consists of bedded limestone with intercalations of sandy marl, whereas the Ngrayong Formation, formed during the Middle Miocene, consists of interbedded quartz sandstone, orbitoidal limestone, and claystone.

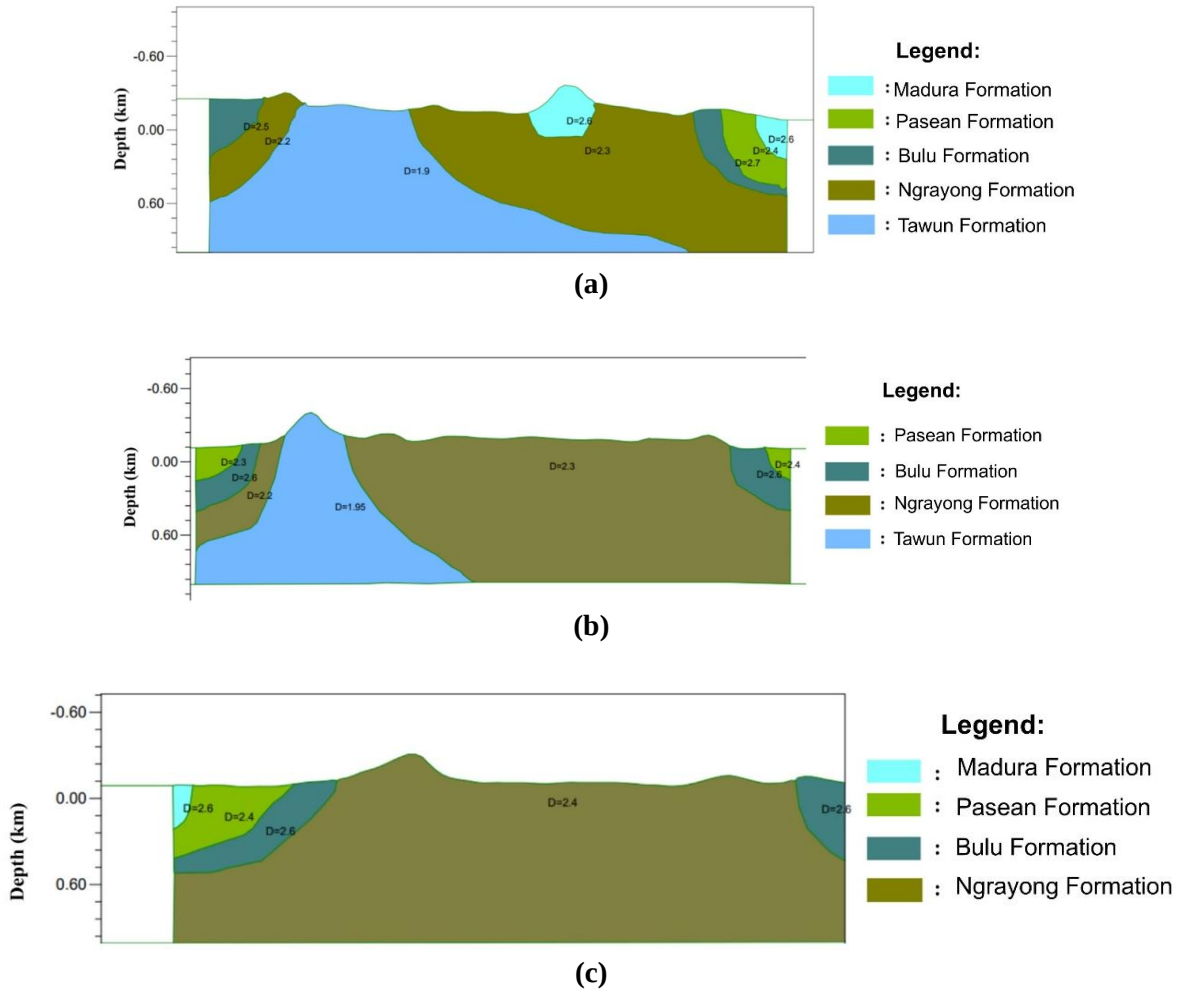


Figure 9. Geological modeling results (a) X–X', (b) Y–Y', and (c) Z–Z'

Discussion

The study area comprises various geological formations, namely the Tawun Formation (Tmt), Ngrayong Formation (Tmtn), Bulu Formation (Tmb), Pasean Formation (Tmp), Madura Formation (Tpm), Pamekasan Formation (Qpp), and alluvial deposits (Qa). Variations in lithology and geological age among these formations directly influence rock density, which in turn affects the observed gravity anomaly responses. These density variations are not only controlled by lithological composition but also by tectonic activity around fault zones, which modifies the physical properties of rocks through deformation and fracturing processes (Ryanto et al., 2019).

Differences in density due to variations in lithology and geological age result in less cohesive contact zones between formations, producing clear density contrasts in gravity data (Sutasoma et al., 2021). In the study area, the contacts between the Tawun Formation and the Ngrayong Formation, as well as between the Bulu Formation and the Ngrayong Formation, exhibit significant density contrasts, reflected as changes in gravity anomaly gradients. The differences in age and lithology between these formations lead to weaker bonding at the contact interfaces, making them less consolidated (Sutasoma et al., 2022). This condition makes the rock layers more susceptible to external disturbances, particularly seismic activity associated with the Rembang, Madura, Kangean, and Sakala (RMKS) fault system located to the north of Madura Island.

In addition, the presence of fold structures, such as the Batuputih Anticline, Tempajung Anticline, Sumberwaru Anticline, and Eden Syncline, indicates tectonic deformation that also influences the distribution of rock density. This deformation causes subsurface mass redistribution, which contributes to the variations in gravity anomalies identified in the anomaly maps and subsurface modeling results.
This study provides more detailed information on local-scale fault structures than previous studies that focused on regional-scale faults, such as the RMKS system. The results of this study can be utilized by the government as supporting information in formulating disaster mitigation policies in the study area.

Conclusion

The geological characteristics of the study area are marked by complex variability of rock formations, ranging from the Tawun Formation (Tmt) to alluvial deposits (Qa), which significantly influence the distribution of rock density and subsurface gravity anomaly responses. Sharp density contrasts, particularly at the contact zones between formations such as the Tawun, Ngrayong, and Bulu Formations, indicate low rock cohesiveness due to differences in geological age and lithological composition. This condition is further supported by tectonic deformation, as evidenced by fold structures such as the Batuputih Anticline and the Eden Syncline, as well as by the activity of the regional Rembang–Madura–Kangean–Sakala (RMKS) fault system. These tectonic dynamics lead to subsurface mass redistribution and weakening of interlayer bonding, thereby increasing the area's vulnerability to seismic disturbances. Overall, these findings provide valuable information for the government in formulating disaster mitigation policies and spatial planning strategies based on integrated geophysical and geological data. Based on the results of this study, one possible mitigation measure is to implement preventive actions before granting permits for residential or infrastructure development in areas intersected by faults. For future research, further studies involving direct field surveys and integration with other geophysical methods are recommended to obtain more accurate results.

Conflicts of Interest

The authors declare no conflict of interest.

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