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GEOPHYSICS

Spectral Analysis in the Separation of Gravity Anomalies: Implications for Disaster Risk Reduction in the West Coast of Aceh

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ABSTRACT

This study assesses the effectiveness of satellite gravity methods in disaster risk mapping for the West Coast of Aceh, focusing on fault detection through variations in rock density. The collected data were processed to determine the complete Bouguer anomaly, with terrain corrections using an assumed density of 2.67 g/cm³. Local anomaly values ranged from -32.2 mGal to 27.2 mGal, with higher values in the northeast and lower values in the southwestern coastal areas. Spectral analysis was employed to separate regional and residual anomalies, enhancing the identification of local faults and deeper tectonic features. Gradient analysis was used to delineate geological boundaries, which were validated using geological maps. Horizontal derivatives revealed strong correlations with fault structures, while vertical derivatives highlighted major fault boundaries but were less effective at detecting smaller-scale features. The findings are expected to contribute to disaster risk reduction efforts and support sustainable development planning in West Coast of Aceh. Additionally, these results offer valuable insights for future research and decision-making in disaster mitigation.

Keywords: Satellite Gravity Data; Disaster Risk Reduction; Spectral Analysis

Análisis espectral en la separación de anomalías gravitatorias: implicaciones para la reducción del riesgo de desastres en la Costa Oeste de Aceh

RESUMEN

Este estudio evalúa la eficacia de los métodos de gravimetría satelital en la cartografía de riesgo de desastres para la Costa Oeste de Aceh, centrándose en la detección de fallas a través de variaciones en la densidad de las rocas. Los datos recopilados se procesaron para determinar la anomalía de Bouguer completa, con correcciones topográficas utilizando una densidad asumida de 2,67 g/cm³. Los valores de anomalía local variaron entre -32,2 mGal y 27,2 mGal, con valores más altos en el noreste y más bajos en las zonas costeras del suroeste. Se empleó el análisis espectral para separar las anomalías regionales y residuales, lo que permitió mejorar la identificación de fallas locales y características tectónicas más profundas. El análisis de gradientes se utilizó para delimitar los límites geológicos, los cuales se validaron mediante mapas geológicos. Las derivadas horizontales revelaron fuertes correlaciones con las estructuras de fallas, mientras que las derivadas verticales pusieron de manifiesto los límites de fallas principales, aunque fueron menos eficaces para detectar características de menor escala. Se espera que los resultados contribuyan a los esfuerzos de reducción del riesgo de desastres y respalden la planificación del desarrollo sostenible en la Costa Oeste de Aceh. Además, estos hallazgos ofrecen información valiosa para futuras investigaciones y la toma de decisiones en mitigación de desastres.

Palabras clave: datos de gravedad satelital; reducción del riesgo de desastres; análisis espectral

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1. Introduction

The West Coast of Aceh, particularly the regions of Aceh Barat and Nagan Raya, is located near the boundary of major tectonic plates, making it highly vulnerable to natural disasters such as earthquakes, landslides, and subsidence (Muhammad et al., 2021; Muksin et al., 2019). Although the region is characterized by complex geological settings and increasing economic development driven by natural resource exploitation—particularly coal excavation activities conducted by a mining company in the Meureubo District—its active tectonic framework generates region-specific geohazards that continuously threaten settlements, transportation networks, and critical infrastructure. However, many existing studies primarily focus on surface observations and regional-scale assessments, while the role of subsurface structural complexity in controlling hazard distribution remains insufficiently explored. Therefore, this study employs advanced geophysical methods to delineate fault zones and subsurface structures, aiming to improve disaster risk assessment in the West Coast of Aceh.

Advances in geophysical exploration, particularly satellite gravity methods, have enabled more precise subsurface mapping by detecting density variations in the Earth's crust. These techniques provide a non-invasive and efficient means of identifying fault zones and other tectonic features (Pohan et al., 2023). Gravity anomaly analysis, enhanced by spectral techniques, allows for the separation of regional and residual anomalies, improving the clarity of subsurface fault detection. Traditional methods for geological hazard assessment have been limited by their invasive nature or by the lack of resolution in mapping deep structures. The growing application of satellite gravity data offers a promising approach to overcoming these limitations, enabling more accurate and comprehensive disaster risk mapping.

This study aims to evaluate the effectiveness of satellite gravity data in identifying and mapping disaster-prone zones in Aceh Barat and Nagan Raya. Specifically, it aims to use gravity anomaly analysis to detect fault zones and understand their relationship to local tectonic activity. Through spectral analysis, the study will refine the separation of regional and residual anomalies to improve the identification of subsurface structures that contribute to seismic risks. The results of this analysis will be compared with geological maps to validate the identified fault zones, ultimately contributing to disaster risk mitigation strategies for the region.

To enhance the interpretation of gravity data, horizontal and vertical derivative methods will be applied (Maithya et al., 2020; Pocasangre et al., 2020). The horizontal derivative method is effective in highlighting lateral density variations, providing greater clarity in detecting near-surface fault intersections. In contrast, the vertical derivative method emphasizes deeper geological structures, offering insights into major fault boundaries that influence tectonic activity in Aceh Barat and Nagan Raya. The integration of these derivative filters will enable a more detailed interpretation of subsurface structures, contributing to a clearer understanding of the area's geological risks.

Spectral analysis will be employed to distinguish between regional and residual gravity anomalies, enhancing the accuracy of subsurface fault mapping (Wu et al., 2022). By separating anomalies across different wavelengths, spectral techniques allow for the identification of geological structures, offering a comprehensive view of the tectonic dynamics in the region. This method enhances the clarity of fault zone detection and contributes to a better understanding of seismic risks in Aceh Barat and Nagan Raya. The integrated application of derivative filters and spectral analysis will provide a more refined mapping of the region's geological hazards, contributing to more effective disaster preparedness strategies.

The application of satellite gravity data, derivative methods, and spectral analysis in this study is expected to significantly improve disaster risk assessment in the West Coast of Aceh. By providing a detailed understanding of subsurface fault zones, the findings will strengthen the region's capacity to mitigate the impact of natural disasters. This research will serve as a valuable reference for future studies on geohazard management in other tectonically active regions. Additionally, the results will aid policymakers in making informed decisions related to infrastructure planning and disaster preparedness in Aceh. This will help ensure safer and more sustainable development.

Geological Setting

The study area is located southwest of the Barisan Mountains, bordered by the Anu Batee strike-slip fault, which forms a scarp running in a northwest-southeast direction. This coastal plain, with an average elevation of 100 meters above sea level, is known as the Meulaboh Embayment and comprises Plio-Pleistocene deposits. The area lies within a Neogene sedimentary basin in North Sumatra, featuring depositional environments ranging from fluvial to sub-littoral, with rock formations that include sandstone, siltstone, mudstone, minor conglomerate, and limestone (Cameron et al., 2007; Dipatunggoro, 2007; Natawidjaja, 2018).

The stratigraphic sequence of the West Aceh Basin unconformably overlies Tertiary rocks from the Hulumasen Group and older pre-Tertiary rocks of the Woyla Group, which were deposited during the Tertiary period in the West Aceh Basin (Cameron et al., 2007). The stratigraphic sequence in the region, from youngest to oldest, consists of Alluvium, the Meulaboh Formation, the Tutut Formation, Tertiary rock units, and pre-Tertiary rock units. Further information on the lithological characteristics of each unit is presented in Table 1.

The administrative boundaries of Aceh Barat and Nagan Raya Regencies are delineated by the red line in Figure 1, which also displays the geological layout of the study area, including satellite gravity measurement points marked as dots. The map, scaled at 1:550,000, demonstrates the alignment of administrative boundaries with the geological map, supporting accurate correlation between gravity data processing and the region's geological features.

Table 1. Stratigraphic Table Based on Age (Youngest to Oldest) (Cameron et al., 2007):

No	Stratigraphic Unit	Lithology	Age	Depositional Environment
1	Alluvium	Loose particles ranging from clay to gravel	Recent	Coastal plains, major rivers
2	Meulaboh Formation	Sandstone, clay, gravel/pebble	Pleistocene	Fluvial to swamp
3	Tutut Formation	Sandstone, mudstone, conglomerate, thin lignite layers (coal-bearing)	Plio-Pleistocene	Fluvial to paralic
4	Tertiary Rock Unit	Siltstone, sandstone, mudstone, tuff, porphyritic basalt, breccia, agglomerate	Oligocene-Miocene	Paralic to fluvial
5	Pre-Tertiary Rock Unit	Limestone, metavolcanic rocks, breccia, basalt, greenschist, phyllite	Pre-Tertiary	Deep marine to shallow marine

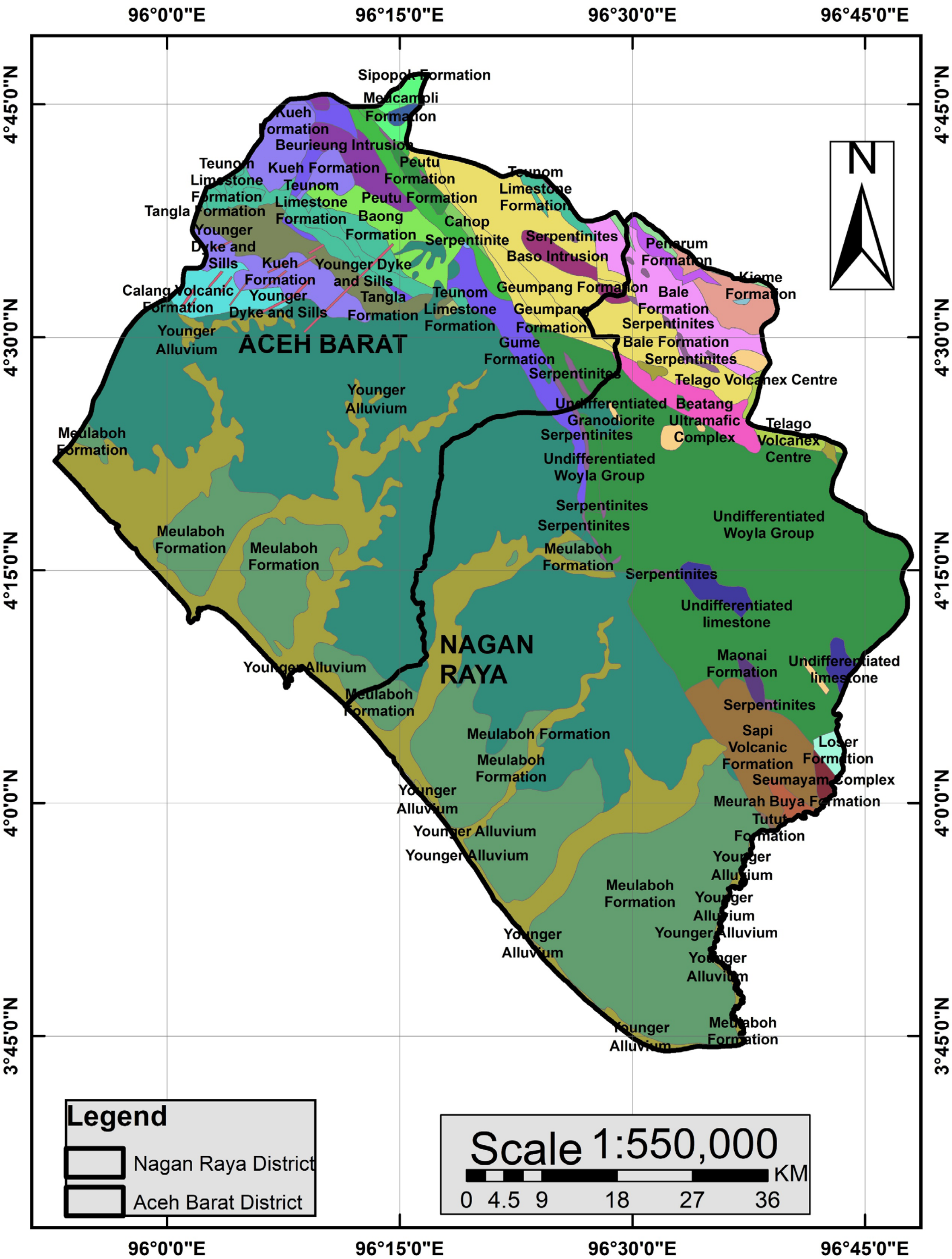

Figure 1. Administrative map of Aceh Barat and Nagan Raya overlaid with a geological map, including measurement points (Cameron et al., 2007).

Methodology

Satellite gravity data, including geographic coordinates and elevation, are available in ASCII-XYZ format from the website http://topex.ucsd.edu/cgi-bin/get_data.cgi (Sandwell et al., 2014; Sandwell & Smith, 2009; Yanis et al., 2019). The spatial resolution is 1 arc-minute per grid for both latitude and longitude, with estimated accuracy of approximately 0.1 mGal for gravity data and 1 meter for elevation measurements. This research focuses on the area between longitudes 95.30°E - 97.00°E and latitudes 3.45°N - 4.50°N, covering a total of 3,648 data points within Aceh Barat and Nagan Raya Districts.

Initially presented as the Free Air Anomaly (FAA), the gravity data for this study undergoes a series of corrections to produce the Complete Bouguer Anomaly, which guarantees a precise subsurface interpretation. Assuming an average rock density of 2.67 g/cm³ for the study area, the process begins with the application of a latitude correction, which accounts for the variations in gravity caused by the Earth's rotation and ellipsoidal shape (Ismail et al., 2020; Putri et al., 2021). To ensure that the data aligns correctly for subsequent analysis, it is imperative to eliminate latitude-dependent gravitational variations based on the International Gravity Formula (Eq.1).

$$g_{\phi} = \left(g_0 \ \ 1 + \beta sin^2(\phi) - \gamma sin^2(2\phi)\right) \quad \text{(Eq. 1)}$$

$$g_{\phi} = 9.780327\left(1 + 0.0053024 sin^2(\phi) - 0.0000058 sin^2(2\phi)\right) \quad \text{(Eq. 2)}$$

where: g_{ϕ}= gravity at latitude ϕ (in mGal); g_0 = standard gravitational acceleration at the equator; ϕ= latitude in degrees.

This is followed by the application of a Bouguer correction to compensate for the gravitational effect of the rock mass between the measurement point and the reference level. The Bouguer correction incorporates this mass effect, which refines the gravity data to enable more accurate detection of subsurface anomalies. In addition, terrain correction is applied to reduce the impact of irregular topography on the measurements, particularly in regions where substantial variations in surface elevation might distort the results in milligal (mGal).

$$BA = g - \gamma + \beta h - 2\pi G\rho h + \rho T \quad \text{(Eq.3)}$$

Where BA is Bouguer Anomaly, g(*mGal*) is the value of absolute gravity, γ (*mGal*) is the value of the normal gravity correction (latitude), $\beta h \left(\frac{mGal}{m}\right)$ is the free air anomaly, and T is terrain corrections. The Complete Bouguer Anomaly (CBA) data obtained is further processed by performing regional-residual separation using first-order trend surface analysis (Mulugeta et al., 2021; Pocasangre et al., 2020).

Spectral Analysis

Radial spectral analysis is a widely adopted technique in potential field interpretation to investigate the depth characteristics of gravity sources by analyzing the distribution of spectral energy with respect to wavenumber. In gravity studies, this method is particularly effective for estimating sedimentary thickness and basement depth through examination of the radially averaged spectrum derived from Bouguer anomaly data (Telford et al., 1990). Previous studies have demonstrated that radial spectrum analysis provides reliable depth estimates for subsurface structures, especially in regions with complex tectonic settings (Pohan et al., 2023).

In this study, sedimentary thickness and basement depth were estimated at selected locations using the spectral peak approach applied to gravity anomaly data (Blakely, 1996). The analysis is based on a two-dimensional Fourier transform, whereby spatial gravity anomalies are converted into the frequency domain (Pohan et al., 2023; Telford et al., 1990). To minimize directional effects and emphasize wavelength-dependent features, the resulting two-dimensional spectrum was averaged radially along concentric circles centered at the origin of the frequency domain. The spectral results are presented on a logarithmic scale as a function of the radial wavenumber k, which is defined as the square root of the sum of the squared horizontal wavenumber components.

$$F(k) = \int_{-\infty}^{\infty} f(x)e^{ikx}dx \quad \text{(Eq.4)}$$

where $k = \frac{2\pi}{\lambda}$, is a wavenumber. The equation can write as follows:

$$F(k) = \left|F\left(k\right)\right|e^{i\theta k} \quad \text{(Eq.5)}$$

The radial amplitude spectrum was calculated by averaging the Fourier amplitudes over each concentric ring and is expressed:

$$|F(k)| = \left[ReF(k)^2 + ImF\left(k\right)^2\right]^{\frac{1}{2}} \quad \text{(Eq.6)}$$

$$\theta = \text{Arctan}\ \frac{Im\ F(k)}{Re\ F(k)} \quad \text{(Eq.7)}$$

The function $|F(K)|$represents the amplitude and $\theta(K)$is a phase of the spectrum. The Fourier transform of the gravitational potential of a point mass can be represented as follows (Blakely, 1996).

$$F(g) = 2\pi GM\frac{e^{|k|(z_0 - z')}}{|k|} \quad \text{(Eq.8)}$$

When observing the gravitational potential on a horizontal flat plane, the corresponding Fourier transform equation can be expressed as follows:

$$A = Ce^{|k|(z_0 - z')} \quad \text{(Eq.10)}$$

Where A is an amplitude and C is a constant. By applying logarithms to the results of the Fourier transform, a correlation can be revealed between the amplitude of the spectrum (A) and the wavenumber (k), as well as the difference in anomalous depth (z_0 - z'). Therefore, this relationship can be described by the following equation (Telford et al., 1990):

$$Ln\ A = \left(z_0 - z^{'}\right)|k| + Ln\ C \quad \text{(Eq.11)}$$

Using this equation, the boundary of an anomalous source field can be delineated by plotting a logarithmic graph of the wavenumber (k) against the amplitude (ln A). The slope of this graph directly corresponds to the depth of the boundary plane of the anomalous source.

Furthermore, the Bouguer anomaly's horizontal and vertical derivatives are calculated to enhance the visibility of linear structures and fault zones in the study area. Detecting hidden subsurface variations is facilitated by these derivatives sharpen gravity signals. Following processing, the results are compared to existing geological maps and other geophysical datasets. This comparison serves to verify the interpretation and ensures that the identified gravity anomalies are consistent with recognized geological structures, thereby establishing a robust framework for comprehending the subsurface geology of the region (Hinze et al., 2013; Telford et al., 1990).

$$HD = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \quad \text{(Eq. 12)}$$

$$SVD = \frac{\partial^2\ \Delta\ g(x'y)}{\partial z^2} = -\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\ \Delta\ g\left(x^{'}y\right)\right) \quad \text{(Eq. 13)}$$

where (∂g/∂x) and (∂g/∂y) denote the directional derivatives of the gravitational anomaly (g) in the x and y axes, respectively.

Results and Discussion

The Complete Bouguer Anomaly (CBA) values in the study area range from -36.2 mGal to 42.4 mGal (Figure 2.), reflecting the region's fundamental geological structures and lithological variations. The higher positive anomaly values, mostly observed in the northeastern region, indicate the presence of denser rock formations, which are likely associated with older consolidated sedimentary layers or intrusive igneous bodies. These areas may consist of sandstone and limestone, which are characterized by high densities. On the other hand, the southwestern coastal region, characterized by negative anomaly values, is associated with younger, less dense sedimentary layers such as shale or unconsolidated deposits. This contrast in the Complete Bouguer Anomaly values provides critical insights into the subsurface geology of the region.

The northeastern part of the study area exhibits Complete Bouguer Anomaly values ranging from 11.1 to 42.4 mGal, indicating denser rock formations beneath the elevated terrain near the Barisan Mountains. The high gravity values in this region are likely attributed to tectonic uplift, which has exposed older and more consolidated rock units. This area forms part of the Bukit Barisan Mountain range, where uplift and faulting have influenced the distribution of lithological units. As we move southwest toward the coastal plain, lower gravity values are observed, reflecting the presence of less dense sediments such as coastal alluvium and Pleistocene deposits in the Meulaboh Embayment.

To enhance the accuracy of geological interpretations, the regional and residual gravity anomalies were separated using spectral analysis. This method allows for the distinction between deeper structures, represented by regional anomalies, and shallower subsurface features, indicated by residual anomalies. Spectral analysis involves applying a Fourier transform to the gravity data, converting it into the frequency domain (Blakely, 1996; Telford et al., 1990). This process helps identify different wavelengths associated with various geological layers, enabling more accurate differentiation between shallow and deep formations.

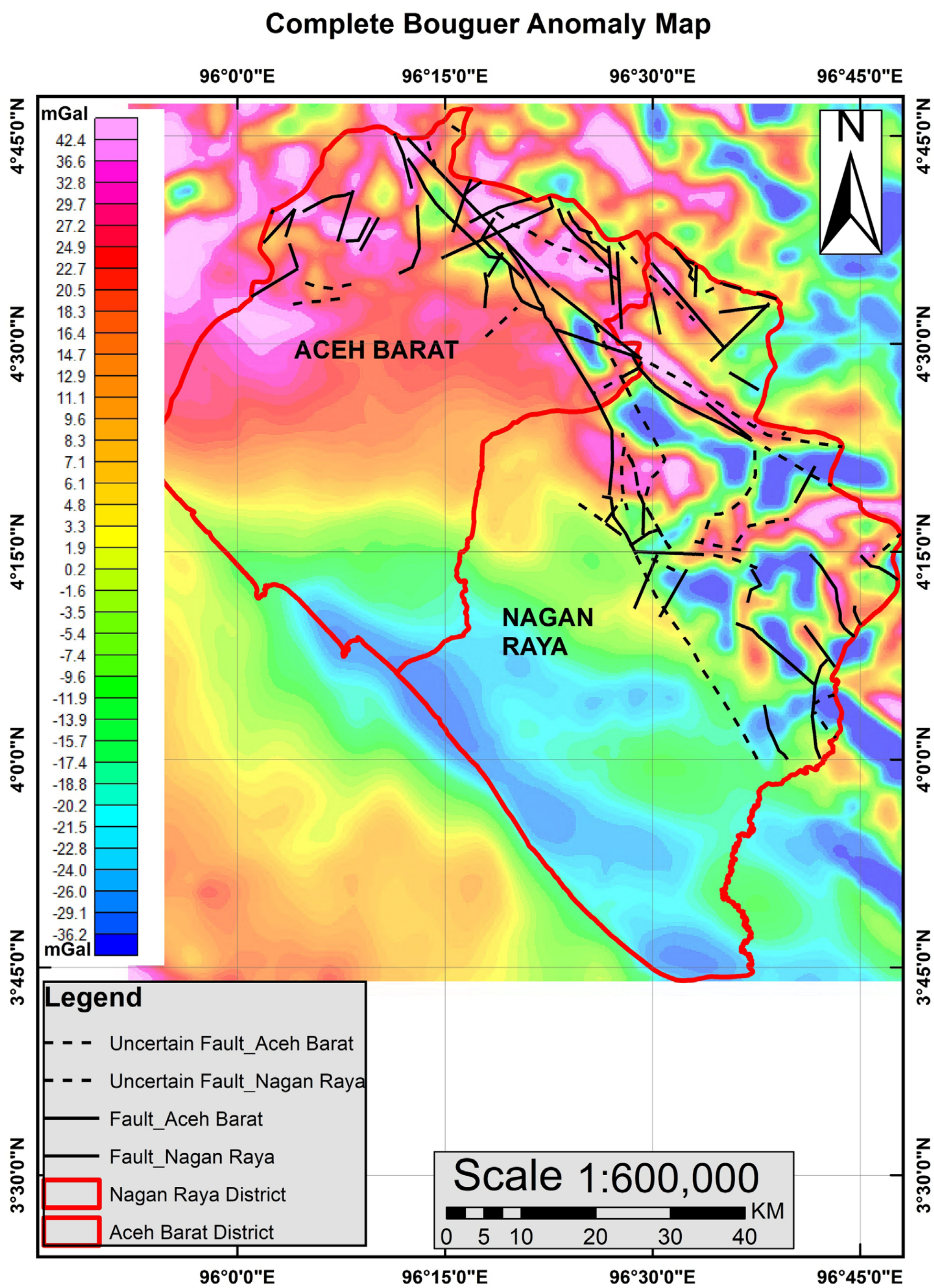

Figure 2. Result of gravity data processing, showing the Complete Bouguer Anomaly (CBA) based on an assumed average density.

The spectral analysis in this study proved particularly effective in refining the interpretation of the Bouguer anomaly data. By using a moving average filter, anomalies associated with shallower structures were isolated, while the regional anomalies were attributed to deeper tectonic features. This technique improves the clarity of geological boundaries and improves the understanding of fault zones and other subsurface structures. The window width used in the filter was determined based on the power spectrum of the Bouguer anomaly, which helps in estimation of depth ranges for both regional and residual anomalies.

The residual anomaly values, after applying the spectral analysis, ranged from -32.2 mGal to 27.2 mGal (Figure 3.), revealing more intricate subsurface details. These residual anomalies highlight smaller-scale geological structures, such as local faults and fractures, that are often difficult to detect using conventional gravity methods. The ability to separate regional and residual components enables a more nuanced understanding of the geological features in the study area, particularly in relation to faulting and tectonic activity along in the West Coast of Aceh (Pohan et al., 2023).

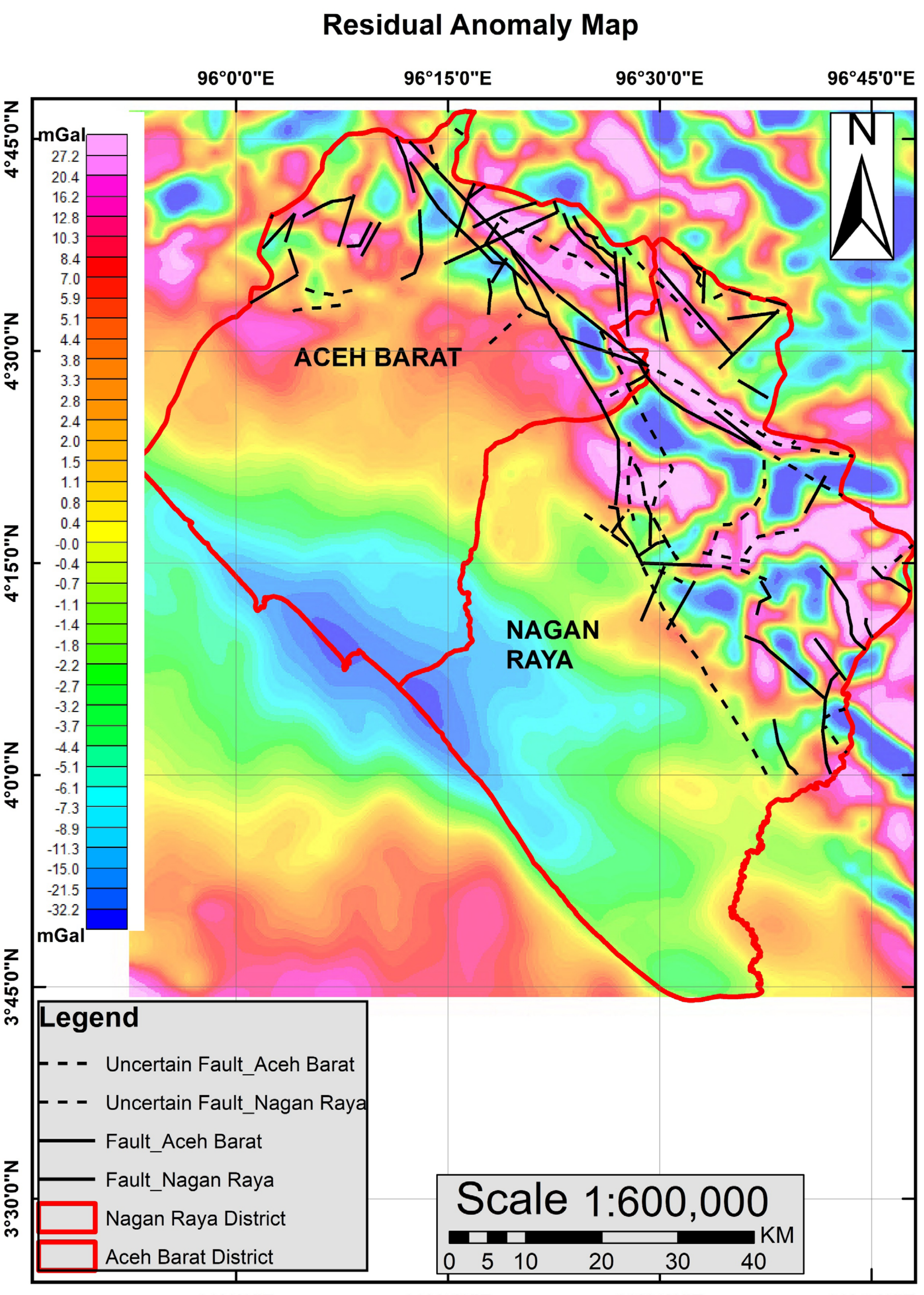

Figure 3. Result of residual anomaly derived from spectral analysis

Enhancement using Derivative Analysis

The horizontal derivative values of the gravity data range from 30.4 to 2,490.0 mGal/km (Figure 4.). These elevated values correspond with prominent geological structures, particularly fault zones and lithological boundaries. The northeastern part of the study area exhibits significant peaks in the horizontal derivative, indicating active tectonic processes and faulting in the highland areas. This pattern provides valuable insights into the subsurface stress regime and fault orientations, which are essential for understanding the tectonic behavior of the region. When overlaid on the geological map, the horizontal derivative data closely aligns with known fault lines, such as the Anu Batee shear zone. This correlation supports the conclusion that abrupt shifts in subsurface density, highlighted by the horizontal derivative, are strongly associated with fault zones. The dashed black lines on the geological map represent pre-identified faults, further validating the gravity derivative analysis.

The vertical derivative analysis reveals values ranging from -254,778.2 to 236,073.0 mGal/km² (Figure 5.). These extreme values may indicate pronounced density contrasts in the subsurface, which are commonly associated with folded or faulted geological structures. The presence of distinct positive and negative peaks in the northeastern part of the study area suggests zones of intensified structural complexity, where tectonic uplift and deformation may be more developed. Zero-crossing points between adjacent positive and negative anomalies are likely to represent boundaries between contrasting geological blocks or transitions in lithology. The vertical derivative data is particularly useful for understanding the type and nature of faulting within the study area. Abrupt transitions between positive and negative peaks suggest the presence of both normal and reverse faults (Sarkowi & Wibowo, 2021). These features are consistent with the broader tectonic framework of the region, where the Anu Batee fault system plays a significant role in shaping the subsurface geology. The fault boundaries derived from the vertical derivative analysis also correlate well with the scarp features observed on the geological map.

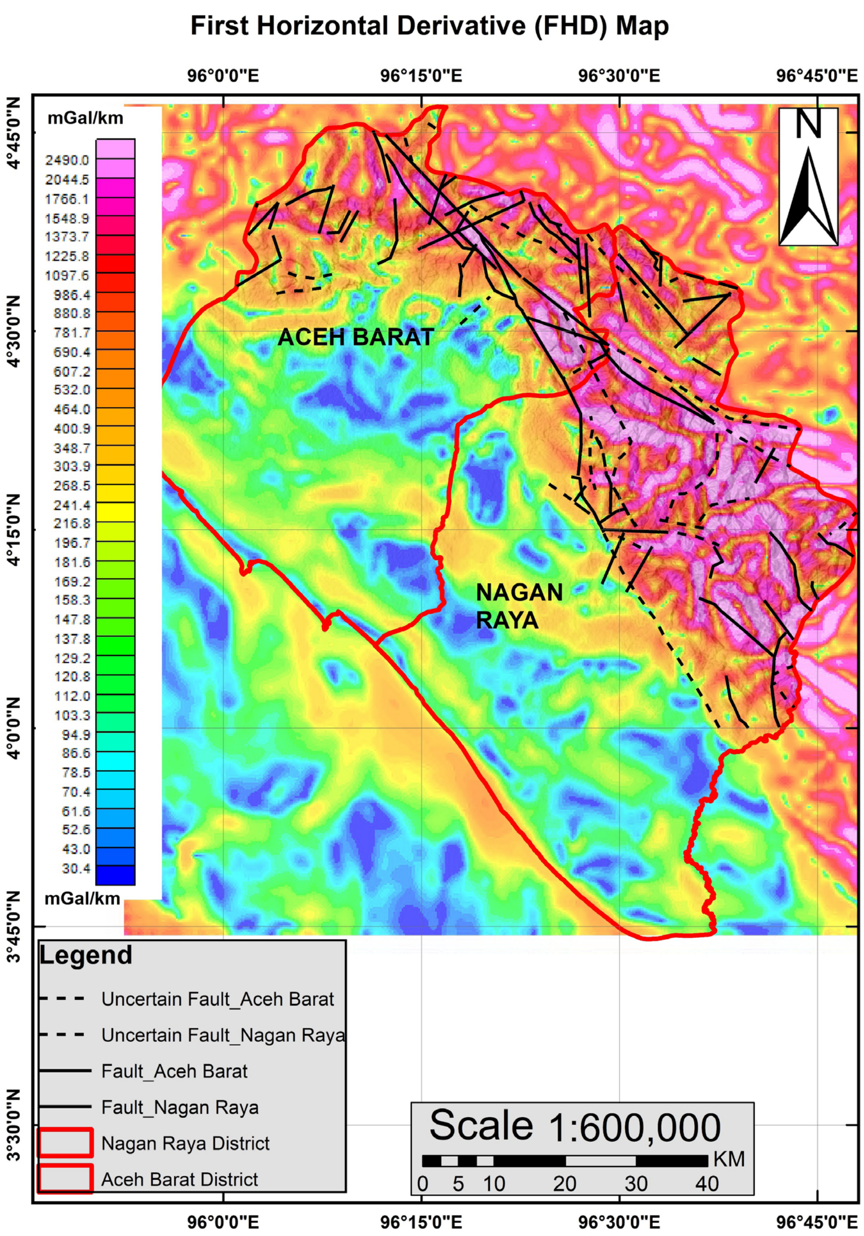

Figure 4. Result of First Horizontal Derivative (FHD) filter analysis based on residual anomaly.

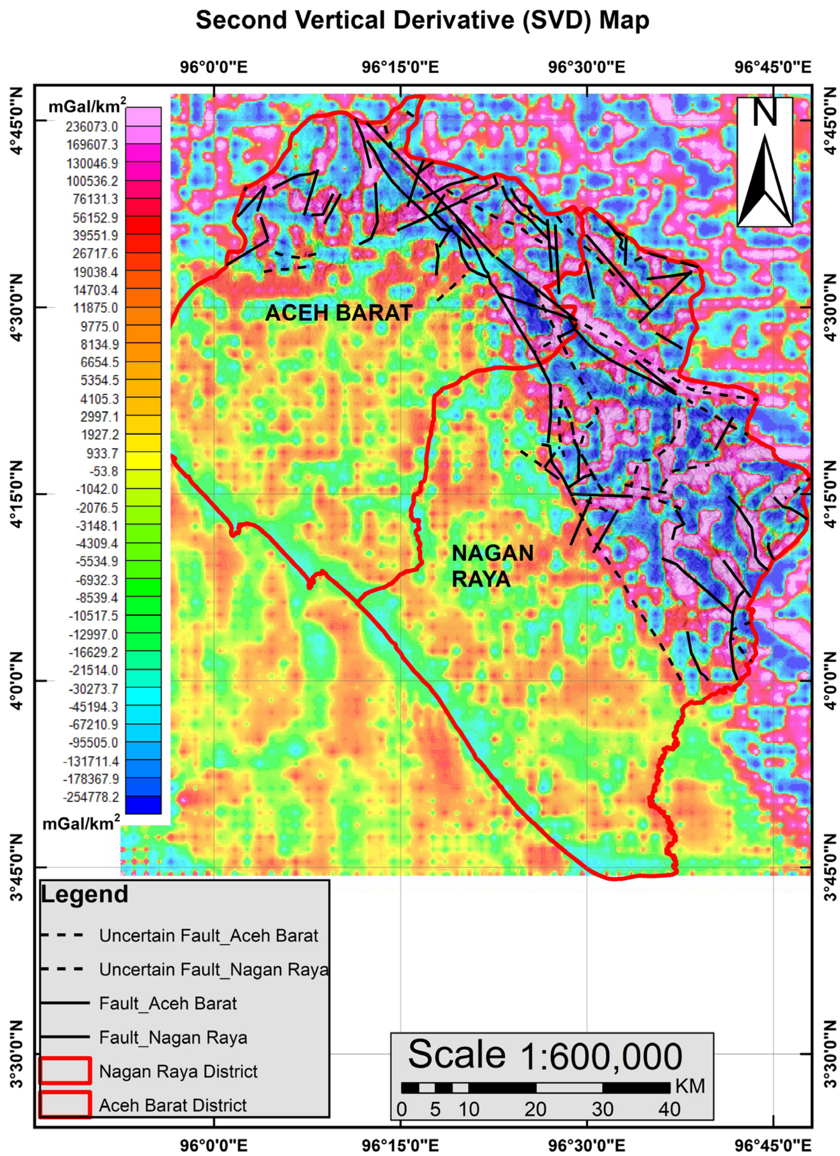

Figure 5. Result of Second Vertical Derivative (SVD) filter analysis based on residual anomaly.

Structural Influence on Gravity Anomalies

The tectonic activity associated with the Anu Batee shear zone significantly influences the gravity anomalies observed in the study area. Elevated fault blocks in the northeastern region contrast with the subsiding coastal plains in the southwest, indicating ongoing tectonic movement. The combination of regional-residual anomaly differentiation, along with horizontal and vertical derivative analysis, confirms that these tectonic structures have a profound impact on subsurface density distributions. Faults identified in the northeastern region are particularly significant for seismic risk assessments, as their proximity to densely populated areas increases the potential for earthquake hazards (Pohan et al., 2023; Yanis et al., 2022). Especially through derivative methods, the comprehensive analysis of gravity data provides a detailed understanding of fault networks, which is essential for assessing earthquake hazards in the West Coast of Aceh. In addition to earthquake hazards, the gravity anomalies and their derivatives indicate areas potentially prone to landslides, particularly along the northeastern mountain slopes. Elevated gravity values correspond to denser, more compact rock formations that may become unstable if fractured along fault lines, leading to slope instability. Tectonic activity further exacerbated the risk, underscoring the importance of monitoring. Understanding the relationship between gravity anomalies and landslide susceptibility is crucial for disaster risk mitigation in the region, particularly in areas where steep terrain and fault zones intersect.

The southwestern coastal area of West Aceh, characterized by lower gravity anomalies, hosts the majority of coal mining activity. The relatively low gravity values suggest that coal seams lie within more recent, less dense sedimentary formations, such as those associated with the Meulaboh Embayment. The residual gravity anomalies in this area provide additional evidence for the distribution of coal-bearing strata, which is vital for planning resource extraction activities. These findings are particularly relevant for optimizing coal mining operations while ensuring that resource extraction does not intensify geological hazards such as landslides or ground subsidence.

The interpretations derived from gravity and derivative analyses were cross-validated with updated geological maps of the area. The close alignment of interpreted fault structures with mapped faults supports the reliability of the satellite gravity data in revealing subsurface geological characteristics. However, the limited resolution of satellite gravity data may reduce interpretive precision of interpreted fault structures. Future studies could benefit from further validation using seismic data or ground-based gravity data to improve result accuracy. Nevertheless, integrating gravity data with geological mapping provides a robust framework for disaster risk assessment, particularly in the tectonically active regions of West Aceh.

Conclusion

This study demonstrates that the integration of satellite gravity data including spectral, horizontal and vertical derivative analyses with geological mapping proves to be an effective approach for assessing disaster risks in the West Coast of Aceh. The identified fault lines and areas of tectonic activity provide useful insights into earthquake and landslide hazards and supporting safer resource extraction planning. This approach can be extended to other regions facing similar tectonic challenges, serving as a model for ongoing monitoring and hazard mitigation.

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