

# Subsurface Structure of Palu-Koro Fault Zone Using TOPEX Satellite Gravity Data and Regional-Residual Anomaly Separation

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## ABSTRACT

The Palu-Koro Fault in Central Sulawesi represents a highly active tectonic feature with significant seismic hazard potential, yet detailed subsurface mapping remains challenging due to the difficult terrain in the region. This study analyzed the subsurface structure of the fault zone by utilizing TOPEX satellite gravity data to overcome accessibility issues. The primary objective was to delineate the fault geometry and characterize subsurface lithological boundaries through density contrasts. The data processing stage initially determined the average surface rock density using the Parasnis method, which yielded a precise value of 2.45 grams per cubic centimeter. This density was subsequently applied to generate the Simple Bouguer Anomaly map. To distinguish between deep-seated regional trends and shallow local structures, the study employed two filtering approaches: the second-order polynomial method and the Moving Average method. The results demonstrated that both filtering techniques yielded consistent residual anomaly patterns. The main trace of the Palu-Koro Fault was clearly identified as a continuous low-anomaly zone, interpreted as a fracture system filled with low-density sedimentary deposits. Conversely, significant high-amplitude positive anomalies were detected adjacent to the fault trace, suggesting the existence of shallow high-density bodies such as igneous intrusions or uplifted basement blocks. This research concluded that the integration of satellite gravity data with regional-residual anomaly separation successfully mapped the structural complexity of the area, providing critical baseline data for updating seismic hazard models and enhancing disaster mitigation strategies in Sulawesi.

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## 1. INTRODUCTION

Indonesia is located at the convergence of three major tectonic plates of the world, namely the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate, which makes it one of the regions with the most complex geological settings and highest disaster susceptibility globally [1]. The dynamic interactions among these plates generate very high seismic and volcanic activity, causing frequent earthquakes and volcanic eruptions that have significant socio-economic impacts on society [2]. One of the most prominent tectonic features that plays a major role in seismic activity in eastern Indonesia is the Palu-Koro Fault on Sulawesi Island [3]. This fault is known to be highly active and has triggered numerous destructive earthquakes, with historical records indicating 19 significant seismic events between 1910 and 2013, most of which were associated with the Palu Valley and the movement of the Palu-Koro Fault [4]. The complexity of the geological structure in this region necessitates continuous monitoring and the application of appropriate geophysical methods to mitigate future disaster risks. Studies on crustal deformation and the identification of subsurface structures in this zone are therefore crucial, given the high seismic hazard potential and the tectonic complexity evidenced by a series of large earthquakes in the past [5].

In the field of geophysical exploration, the gravity method is one of the most fundamental and effective techniques for mapping subsurface structures, both for energy resource exploration and disaster mitigation purposes. Since the early twentieth century, this method has been widely applied in oil and gas exploration and has continued to advance rapidly in terms of instrumentation, data acquisition, processing, and interpretation [6]. The basic principle of this method relies on variations in the density of subsurface rock materials, which cause anomalies in the Earth's gravitational field. Significant lateral density contrasts are often strong indicators of geological structures such as faults, igneous intrusions, or sedimentary basins, which can be identified through gravity anomaly maps [7]. This method has thus become a reliable tool for detecting and characterizing rock formations and geological structures that are not directly observable at the surface.

The application of the gravity method for active fault analysis involves separating regional and residual anomalies to better highlight targets at specific depths. Analyses of Bouguer anomalies and Free Air Anomalies (FAA) are routinely used to provide detailed images of subsurface structures, where discontinuities in anomaly values are often associated with the presence of fault planes [8]. The effectiveness of this method has been demonstrated in various case studies in Indonesia, such as research on the Lembang Fault in Bandung, which revealed Bouguer anomalies ranging from  $-2$  mGal to  $52$  mGal and identified normal fault characteristics through Second Vertical Gradient (SVG) analysis [9]. In addition, studies in Nabire Regency, Papua, successfully utilized secondary data to identify potential faults, with the analysis results showing linear patterns indicative of two main fault zones [10]. The use of satellite-based gravity data has become increasingly popular because it can cover wide and inaccessible regional areas, offering greater time and cost efficiency compared to conventional terrestrial measurements [11].

Based on the success of previous studies, this research aims to apply gravity analysis in Central Sulawesi to map the characteristics of the Palu–Koro Fault in a more comprehensive manner. Considering the challenging terrain along several segments of the fault, this study will utilize satellite gravity data from TOPEX to analyze anomalies around the fault zone. The use of satellite data allows for the identification of regional structural patterns that may be missed by local surveys, while also enabling the separation of anomalies originating from the main fault and other secondary anomaly sources. By integrating Bouguer anomaly analysis and regional-residual anomaly separation methods, it is expected that the boundaries, orientation, and continuity of the Palu–Koro Fault can be mapped more accurately. The results of this study are expected to provide an important contribution to the updating of seismic hazard maps in the Sulawesi region.

## 2. RESEARCH METHOD

This research was conducted in the active tectonic region surrounding the Palu–Koro Fault, Central Sulawesi, which is geographically bounded by coordinates  $119.7417^\circ$  E to  $120.0083^\circ$  E and  $0.9249^\circ$  S to  $1.4581^\circ$  S. The primary data used in this study were obtained from the TOPEX satellite, which provides essential geophysical parameters including positional data (longitude and latitude), surface elevation, and Free-Air Anomaly (FAA) values. The TOPEX satellite gravity data utilized in this study has a spatial resolution of 1 arc-minute (approximately 1.8 km grid spacing). To generate the continuous maps, the data was interpolated using the Kriging gridding method. While satellite gravity data has grid resolution limits for pinpointing very narrow, near-surface fault ruptures, it is highly effective and reliable for delineating the broader, deep-seated regional fault zone dynamics and major lithological boundaries. The use of satellite data in preliminary studies is considered highly efficient for identifying regional geological structures over wide areas that are difficult to access through terrestrial surveys [12]. All stages of the research, from data acquisition and processing to final interpretation, are systematically summarized in a flowchart presented in Figure 1.

The data processing stage began with the determination of the average surface rock density using the Parasnis graphical method, which aims to minimize the correlation between topography and Bouguer anomalies. In this method, the average density value ( $\rho$ ) is obtained from the slope of a linear regression resulting from a plot of FAA values versus elevation, as represented by Equations (1) to (4). Accurate density determination is crucial because errors in density estimation can lead to the appearance of spurious anomalies correlated with topography [13]. The density value derived from the Parasnis method was subsequently used as input to calculate the Simple Bouguer Anomaly (SBA) at each measurement point in order to reduce the effect of rock mass above the reference datum.

$$y = a + xb \quad (1)$$

$$FAA = a + 0.04194hb \quad (2)$$

$$SBA = FAA - 0.04192h\rho \quad (3)$$

$$Residual = SBA - Regional \quad (4)$$

After obtaining the Simple Bouguer Anomaly (SBA) map, the analysis was continued using anomaly separation techniques to distinguish the responses of shallow and deep geological structures with the aid of Surfer software. In this study, the separation of regional and residual anomalies was carried out by comparing two mathematical filtering methods, namely the second-order polynomial method and the Moving Average

method with a  $21 \times 21$  window size. This separation is based on the principle that regional anomalies with long wavelengths represent deep sources, whereas residual anomalies with short wavelengths represent shallow sources [14], [15]. The residual anomaly was then calculated mathematically by subtracting the regional anomaly values from the total SBA values at each grid point.

The final result of the filtering process produced two variants of residual anomaly maps (polynomial-based and moving-average-based) that were ready for interpretation. The interpretation focused on the residual anomaly maps by applying slicing techniques to areas exhibiting high anomaly gradients around the Palu–Koro Fault zone. These profile slices were analyzed to identify the continuity of fault structures and subsurface lithological boundaries based on the measured density contrasts. The interpretation results were subsequently validated against local geological conditions to explain the deformation mechanisms occurring in the study area [16].

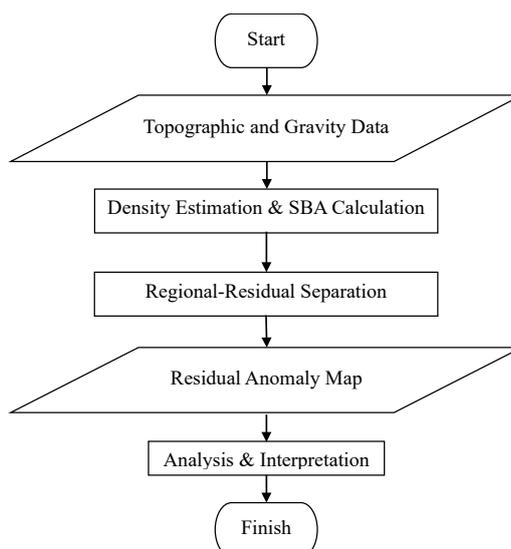


Fig. 1. Flowchart

### 3. RESULTS AND DISCUSSION

#### 3.1. Topography and Geological Setting of the Study Area

The surface physical conditions of the study area are visualized through a topographic map presented in Figure 2. This map shows significant elevation variations around the Palu–Koro Fault zone, where the main fault trace is marked by a bold black line cutting across the study area. The presence of the fault is indicated by linear morphological features (lineaments) expressed as contrasting valleys and mountain ranges, which are characteristic of active left-lateral (sinistral) strike-slip fault zones in Sulawesi [17]. In addition, the map is complemented by a red box inset that clarifies the data acquisition boundaries within a regional context. This topographic observation represents a crucial initial step for correlating surface features with subsurface anomaly responses discussed in subsequent sections.

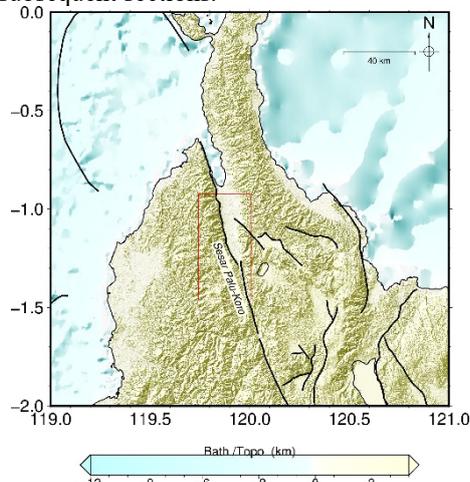


Fig. 2. Topographic map of the Palu–Koro Fault

### 3.2. Rock Density Estimation (Parasnis Method)

The determination of the average surface rock density was conducted using the Parasnis method to ensure accurate gravity data reduction. Based on the regression graph shown in Figure 3, a strong linear relationship is observed between elevation values (X-axis) and Free Air Anomaly values (Y-axis). The slope of the linear regression derived from this plot yields an average density value of  $2.45 \text{ g/cm}^3$  (converted from 2.4498 for standard unit simplification). This density value represents upper crustal rocks in the study area and falls within the typical range for sedimentary to altered igneous rocks [13]. The use of this precise density value is essential to minimize spurious correlations between topography and the resulting Bouguer anomalies. The linear regression yielded a high correlation coefficient of  $R^2 = 0.8734$ . This high statistical confidence demonstrates that the estimated density of  $2.45 \text{ g/cm}^3$  is exceptionally robust for topographic reduction in this specific area. Consequently, minor density variations (e.g.,  $\pm 0.05 \text{ g/cm}^3$ ) are statistically constrained and will not significantly alter the overarching structural patterns of the resulting Bouguer and residual anomalies.

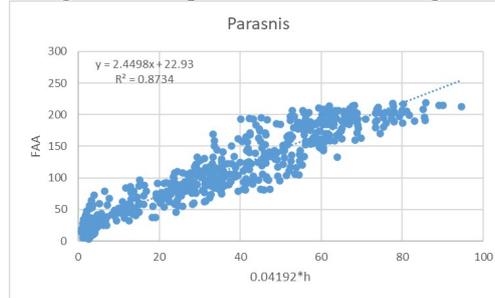


Fig. 3. Density estimation using the Parasnis method

### 3.3. Simple Bouguer Anomaly (SBA) Map

The distribution of gravity anomalies corrected for topographic effects is presented in the Simple Bouguer Anomaly (SBA) map shown in Figure 4. This map displays highly variable contour patterns, including zones with very low gravity anomaly values, approaching zero, that coincide with the interpreted Palu–Koro Fault trace. Such low anomaly values along the fault zone are commonly associated with fracture zones or graben structures filled with low-density sediments [16]. Conversely, on the western side of the fault trace, a pronounced high anomaly response is observed, reaching values of up to 2300 mGal. The sharp contrast between low anomalies along the fault zone and high anomalies in surrounding areas indicates the presence of strong structural discontinuities or distinct subsurface lithological boundaries.

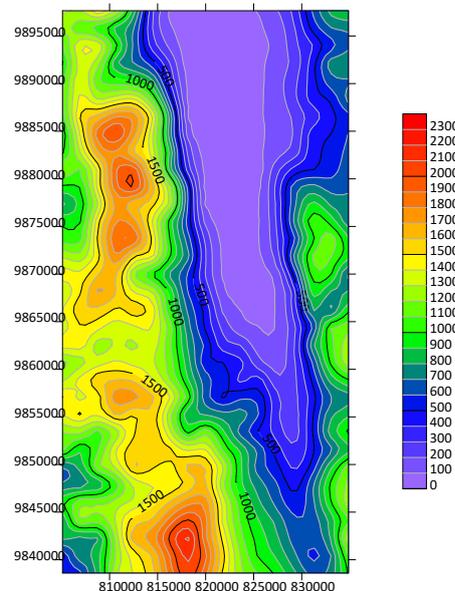


Fig. 4. Simple Bouguer Anomaly (SBA) map of the Palu–Koro Fault

### 3.4. Regional Anomaly Analysis

The separation of regional anomalies from the SBA data was performed using two comparative approaches: the second-order polynomial method and the  $21 \times 21$  Moving Average method, as shown in Figure 5 and Figure 6, respectively. The second-order polynomial method was selected due to its capability to model

regional geological trends characterized by long-wavelength curvature, which often represent basement rocks or deep-seated structures [7]. Meanwhile, the Moving Average method with a  $21 \times 21$  window smooths anomaly values by averaging surrounding data points, effectively reducing high-frequency noise and producing a smoother regional trend. The application of both methods aims to ensure that the resulting residual anomalies genuinely represent shallow geological targets rather than mathematical artifacts. Both regional anomaly maps exhibit consistent regional gravity trends, with gradual increases and decreases from east to west across the study area.

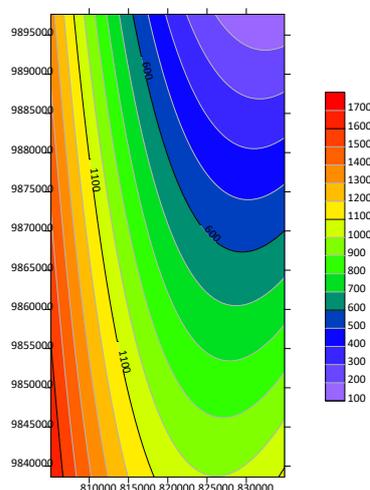


Fig. 5. Regional anomaly map derived from second-order polynomial filtering of the Palu-Koro Fault

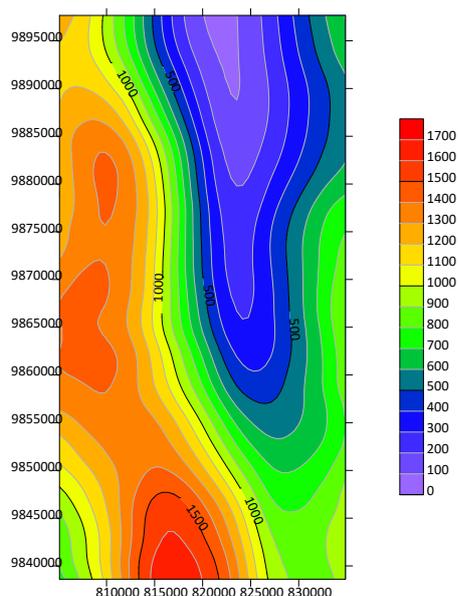


Fig. 6. Regional anomaly map derived from  $21 \times 21$  Moving Average filtering of the Palu-Koro Fault

### 3.5. Residual Anomaly Interpretation Along the Palu-Koro Fault

A detailed analysis of residual anomalies was conducted to delineate the geometry of the Palu-Koro Fault using results from the second-order polynomial filter (Figure 7 and Figure 8) and the Moving Average filter (Figure 9 and Figure 10). In both filtering results, the fault trace is consistently marked by a low-anomaly pattern, visualized by white dashed lines on the maps. This interpretation is supported by cross-sectional slicing analysis along three different profiles, which reveals significant gravity value decreases at distances between 10 km and 20 km along each profile. These gravity deficits indicate the presence of weak zones or fractured rocks along the fault plane, characterized by lower densities compared to the surrounding wall rocks. The consistent “valley-shaped” anomaly pattern observed across all three slices provides strong geophysical evidence for the continuity of the Palu-Koro Fault beneath the surface.

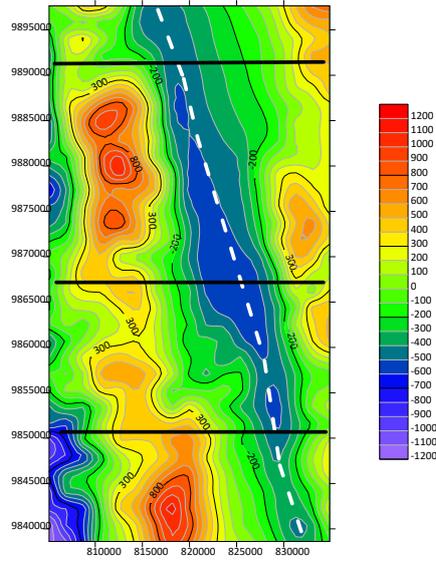


Fig. 7. Residual anomaly map from second-order polynomial regional-residual separation of the Palu–Koro Fault with three slices

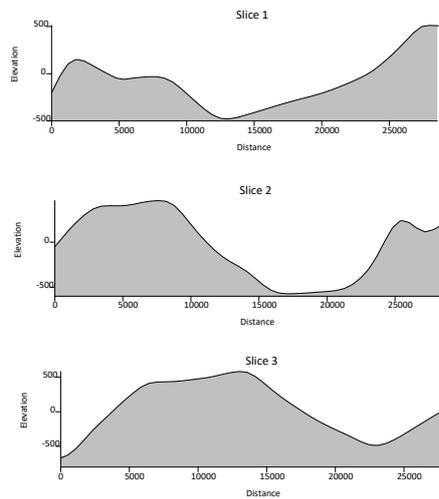


Fig. 8. Two-dimensional slice visualization of the residual anomaly map from second-order polynomial regional-residual separation with three slices

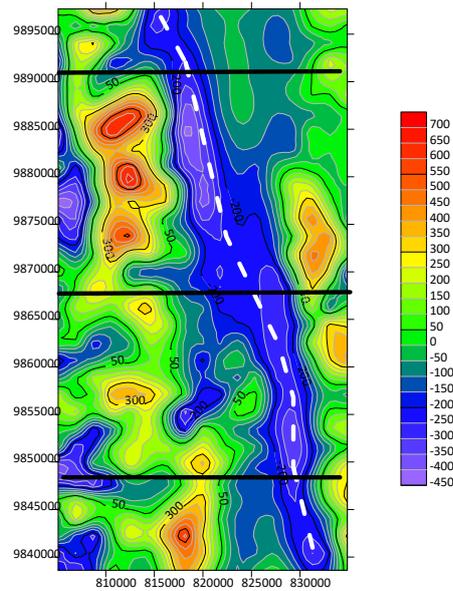


Fig. 9. Residual anomaly map from  $21 \times 21$  Moving Average regional-residual separation of the Palu–Koro Fault with three slices

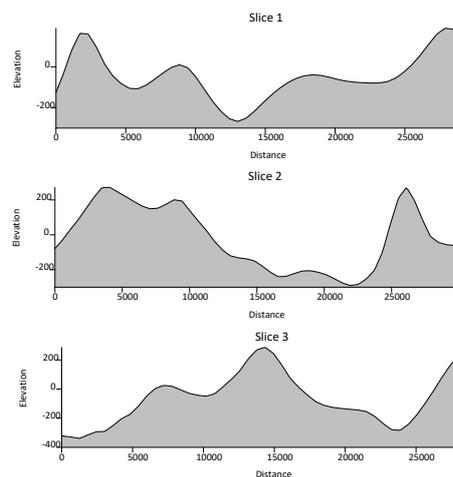


Fig. 10. Two-dimensional slice visualization of the residual anomaly map from  $21 \times 21$  Moving Average regional-residual separation with three slices

### 3.6. Identification of Local High Anomalies Near the Fault Zone

In addition to the low anomalies associated with the fault zone, high positive residual anomalies were also identified around the Palu–Koro Fault, as shown in Figure 11 through Figure 14. Analysis using four slice profiles on both polynomial and Moving Average residual maps reveals sharp anomaly peaks with amplitudes reaching 800–1000 mGal at distances of approximately 0.5 km to 2 km. These narrow yet high-amplitude anomalies indicate the presence of shallow, high-density geological bodies, such as igneous intrusions or uplifted basement blocks. The irregular anomaly pattern observed in the fourth slice suggests that the geometry of the causative body may be non-uniform or affected by complex structural deformation. The coexistence of high-density anomalies adjacent to low-density fault-related anomalies further emphasizes the structural complexity of the Palu–Koro Fault zone.

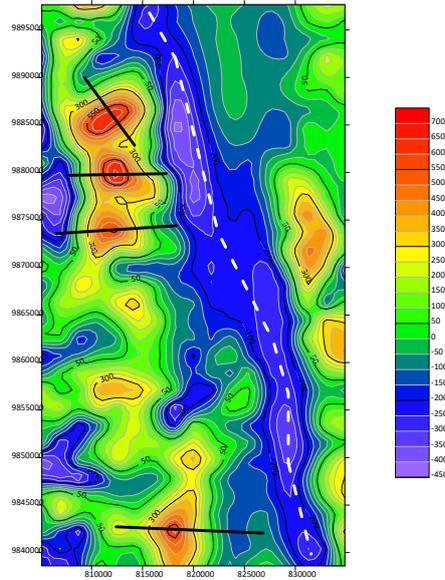


Fig. 11. Residual anomaly map from second-order polynomial regional-residual separation of the Palu–Koro Fault with four slices

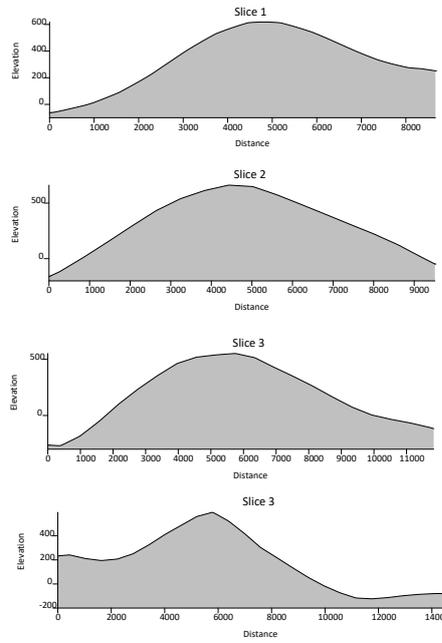


Fig. 12. Two-dimensional slice visualization of the residual anomaly map from second-order polynomial regional residual separation with four slices

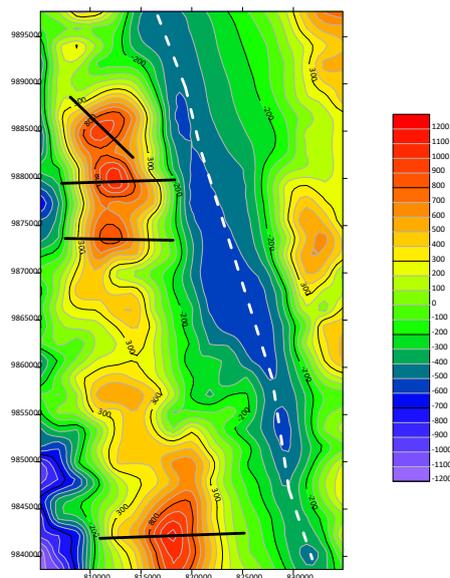


Fig. 13. Residual anomaly map from  $21 \times 21$  Moving Average regional-residual separation of the Palu–Koro Fault with four slices

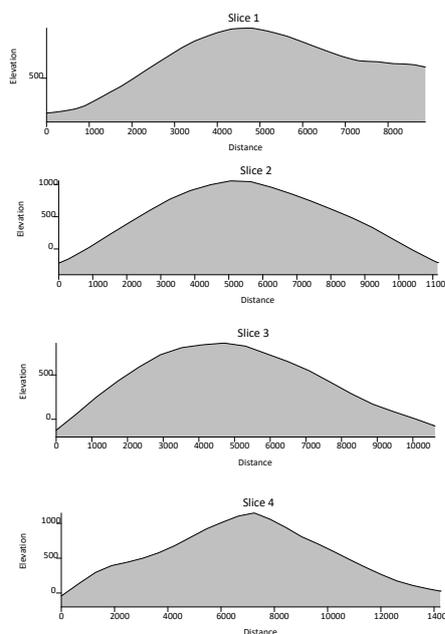


Fig. 14. Two-dimensional slice visualization of the residual anomaly map from  $21 \times 21$  Moving Average regional-residual separation with four slices

### 3.7. Validation with Previous Geological Studies

The continuous low-anomaly zone delineated from the residual maps strongly correlates with the established geological trace of the Palu-Koro Fault. By comparing our interpreted fault trace (dashed lines in the residual maps) with the surface rupture and seismicity distribution mapped by Natawidjaja et al. [3], a high degree of spatial agreement is observed. The pronounced gravity deficit precisely coincides with the highly deformed, multi-segment fault geometry associated with the 2018 Mw7.5 Palu earthquake. Furthermore, the structural lineaments derived from the gravity data align with the high slip-rate fault segments previously identified by Bellier et al. [17]. This corroborates that the low-density anomaly accurately represents the heavily fractured zone and sedimentary fill within the active fault structure, validating the effectiveness of the chosen separation methods without the strict necessity of secondary derivative filtering.

## 4. CONCLUSION

This study successfully mapped the subsurface structural characteristics of the Palu–Koro Fault zone using TOPEX satellite gravity data. The gravity data reduction process was based on an average surface rock

density of 2.45 g/cm<sup>3</sup>, obtained through the Parasnis method. The application of this density value resulted in a Simple Bouguer Anomaly (SBA) map that accurately reflects geological variations within the study area. The resulting anomaly contour patterns indicate significant density contrasts between the fault deformation zone and the surrounding regional rocks.

Further analysis through regional and residual anomaly separation demonstrates a high degree of consistency between the second-order polynomial and Moving Average methods. The main trace of the Palu–Koro Fault is clearly identified as a low-anomaly zone, representing a fractured zone or low-density sedimentary rocks. In contrast, cross-sectional slicing analysis also reveals the presence of very high local anomalies adjacent to the fault trace. These positive anomalies are interpreted as responses from intrusive rock bodies or uplifted basement blocks associated with the complexity of tectonic activity in the region.

Overall, the gravity method is proven to be an effective geophysical approach for delineating geological structures in seismically active regions such as Central Sulawesi. The combination of applied anomaly separation techniques successfully separates shallow and deep anomaly responses, thereby enhancing geological interpretation. The mapping of subsurface density variations provides an important contribution to understanding fault geometry and earthquake-generating structures. These findings are expected to serve as a fundamental reference for disaster mitigation efforts and for the development of more detailed geophysical surveys in the future.

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