

Research Paper

Integrated gravity, GNSS, and seismic analysis for fault mapping in Sulawesi island: Insights into the Palu-Koro Fault

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ABSTRACT

The Palu-Koro Fault is one of the most active left-lateral strike-slip faults in Indonesia. This study integrates gravity data (GGMPlus), GNSS measurements, and seismic analysis to better understand the fault structure and tectonic behavior. The results show that the high First Horizontal Derivative (FHD) value along the fault corresponds to a sharp density gradient related to high tectonic activities. The secondary fault branches and lineaments can also be identified from Tilt Derivative (TDR), emphasizing the fault system's complexity. GNSS data from the INA-CORS network reveals patterns with notable extensional dilatation rates exceeding 100 nanostrain/year in pull-apart basins and compressional zones displaying significant uplift potential. Shear strain measurements highlight regions with deformation rates exceeding 250 nanostrain/year, particularly in the central Palu-Koro Fault segment. Seismicity clustering analysis indicates shallow to intermediate-depth earthquakes along the fault, majority at depths 20–30 km, reflecting lateral tectonic forces align with strike-slip Palu-Koro Fault activities. The integration of gravity, GNSS, and seismicity results critical insights into the fault's heterogeneity, deformation processes, and potential for large seismic events, contributing to enhanced hazard risk assessment and mitigation strategies in this geologically dynamic region.

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1. Introduction

Sulawesi lies at the dynamic triple junction of the Eurasian, Pacific, and Australian plates, where complex tectonic processes, including subduction, collision, and extension, have resulted in a highly active and geologically intricate region [1–3]. The Palu-Koro Fault, a prominent left-lateral strike-slip fault, plays a critical role in shaping the tectonic framework of Central Sulawesi [4]. With a documented history of significant seismic activity, including the devastating $M_W 7.5$ earthquake in 2018, this fault remains a focal

point for understanding seismic hazards and crustal deformation in the region [5].

Previous studies have investigated the Palu-Koro Fault using geophysical and geodetic approaches, such as seismic analysis, GNSS measurements, optical imagery, and InSAR [5–9]. While these methods have provided valuable insights into fault kinematics and deformation, they face inherent limitations. GNSS and seismic data alone often lack the spatial resolution needed to map fault structures across complex terrains comprehensively. Similarly, seismic data primarily capture episodic events and do not provide a continuous representation of subsurface mass distribution or deformation [10].

GNSS data, obtained through continuous monitoring stations, provide critical information about surface deformation by tracking crustal motion with high precision over time. These measurements are essential for understanding tectonic strain patterns,

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including compressional and extensional deformation zones around active faults [11]. In the Palu-Koro Fault region, GNSS data have been used to identify pull-apart basins and localized uplift zones associated with left-lateral strike-slip motion [12]. By quantifying strain accumulation rates, GNSS analysis offers insights into stress build-up along the fault, which is crucial for assessing earthquake potential. However, GNSS data alone are limited by the spatial distribution of monitoring stations, which may not fully capture variations in deformation across complex fault systems [13].

Seismicity analysis complements GNSS data by providing information on earthquake frequency, magnitude, and depth, which reflect the fault's dynamic behavior. In the Palu-Koro Fault region, seismicity is characterized by shallow to intermediate-depth earthquakes clustered along the fault trace [7]. These events reveal patterns of strain release and highlight zones of heightened tectonic activity [4]. Furthermore, studies of the 2018 M_w 7.5 Palu earthquake demonstrated that super shear rupture events along the Palu-Koro Fault are critical for understanding fault mechanics and seismic hazards in the region [5]. However, seismicity analysis primarily focuses on episodic events and may not capture gradual deformation processes or subtle strain accumulation in quiescent periods.

This study addresses these gaps by integrating ultrahigh-resolution satellite-derived gravity data (GGMPlus) with GNSS and seismic data to achieve a comprehensive analysis of the Palu-Koro Fault. The GGMPlus model, offering detailed information on Earth's gravity field with a resolution of 7.2 arcsec, is uniquely suited for delineating subsurface density contrasts and fault structures over broad areas [14]. By combining GGMPlus data with GNSS-based surface deformation models and seismicity clustering, this study provides an unprecedented view of the Palu-Koro Fault's geometry, tectonic activity, and its implications for regional hazard assessment. This novel integration enhances the spatial and structural resolution of fault detection, overcoming the limitations of individual methods. The findings contribute to a more robust understanding of deformation processes, strain accumulation, and seismic potential along the Palu-Koro Fault, offering critical insights for disaster risk mitigation in one of Indonesia's most tectonically active regions.

2. Study area and its geological setting

Sulawesi Island, situated at the tectonic convergence of the Eurasian, Pacific, and Australian plates, is characterized by a unique and highly complex geological environment [1,2]. The island comprises four prominent arms, each featuring a series of active volcanic mountain ranges that reach elevations exceeding 3000 m above sea level. This rugged and dynamic topography is underpinned by active tectonic processes, making Sulawesi one of the most geologically active regions in Indonesia [3].

The focus of this study is the Palu-Koro Fault, a major left-lateral strike-slip fault extending from northwest to southeast across Central Sulawesi. This fault is a critical feature of the region's tectonic framework, facilitating the lateral motion and collision of the Sula block with the surrounding plates [4,15]. The research area includes the city of Palu and its surrounding regions, where the fault passes through a diverse geological setting, including young Holocene sedimentary rocks, metamorphic rocks, and volcanic formations. The fault's central segment, which traverses Palu, is particularly interesting due to its high seismicity and role in shaping the region's tectonic deformation [6].

There are many historical records of earthquakes in the Sulawesi area. In 1907, 1909, 1937, 1968, and 2018, the massive

earthquakes struck along the Palu-Koro Fault, with the 1909 event being the most devastating [17]. An earthquake with a magnitude of 7.2 occurred along and near the Palu-Koro Fault in 1968, causing the tsunami [18,19].

The Palu-Koro Fault, which extends from northwest to southeast of Sulawesi Island, is a large active strike-slip fault in Southeast Asia that slices through a suite of quickly excavated metamorphic rocks of low to high grade, with the Sula block in the center of the triple junction [20–22]. The Palu-Koro and Matano faults, respectively, facilitate the Sula block's collision with the Eurasian plate at its western and southwestern ends, while the North Sulawesi trench accompanies it at its northern end [17]. From 1992 to 1999, GPS plate convergence data revealed that the Palu-Koro Fault has a left-lateral slip rate of 34–38 mm/year [23].

Fig. 1 shows a Miocene-Pliocene magmatic arc in West Sulawesi, which is characterized by exceptionally young granitoid intrusions that have intruded into a sequence of Cenozoic volcanoclastic and Precambrian-Mesozoic metamorphic rocks, where the basement originated in Gondwana [24]. During the Middle Cretaceous period, these continental components were deposited along the Southeast Sunda land edge. The Palu-Koro Fault, a massive strike-slip fault that may traverse the whole lithosphere, cuts through all of these rocks [17]. Limited existing fission-track data indicate that the Neogene intrusives and their metamorphic hosts along the Palu Fault were rapidly uplifted during the Pliocene, and geomorphic studies indicate that uplift continues to the present day. Because of Neogene magmatism, almost all of the basement rocks have been exposed to regional metamorphism, and some have a heat transfer overprint [1]. Indications of non-coaxial ductile deformation could be found in several areas between these metamorphic phases [17].

This location is well-suited for integrating satellite gravity data (GGMPlus), GNSS-based surface deformation models, and seismicity analysis. The geological and tectonic diversity provides a rich setting for examining the fault's structural characteristics, strain accumulation, and seismic behavior. By focusing on this region, the study aims to improve the understanding of the Palu-Koro Fault's dynamics and its implications for seismic hazard assessment.

3. Data

This study utilized three primary datasets: satellite-derived gravity data (GGMPlus), GNSS observations, and seismic records to comprehensively analyze the Palu-Koro Fault in Sulawesi. Each dataset provides critical insights into the fault's structure, deformation processes, and seismic activity.

3.1. GGMPlus data

The GGMPlus dataset represents an ultrahigh-resolution model of Earth's gravity field, integrating satellite, airborne, and terrestrial gravity data with topographic information. This model achieves a spatial resolution of 7.2 arcsec (approximately 200 m) and provides critical information on gravity anomalies, such as gravity disturbances, accelerations, and geoid undulations [14]. The data were obtained from the Curtin University portal and are particularly suited for delineating subsurface density contrasts and identifying fault structures in tectonically active regions. For this study, the GGMPlus dataset was processed to extract Simple Bouguer Anomaly (SBA) and enhanced with filtering techniques, including First Horizontal Derivative (FHD), Second Vertical Derivative (SVD), and Tilt Derivative (TDR), to highlight fault boundaries and subsurface density contrasts.

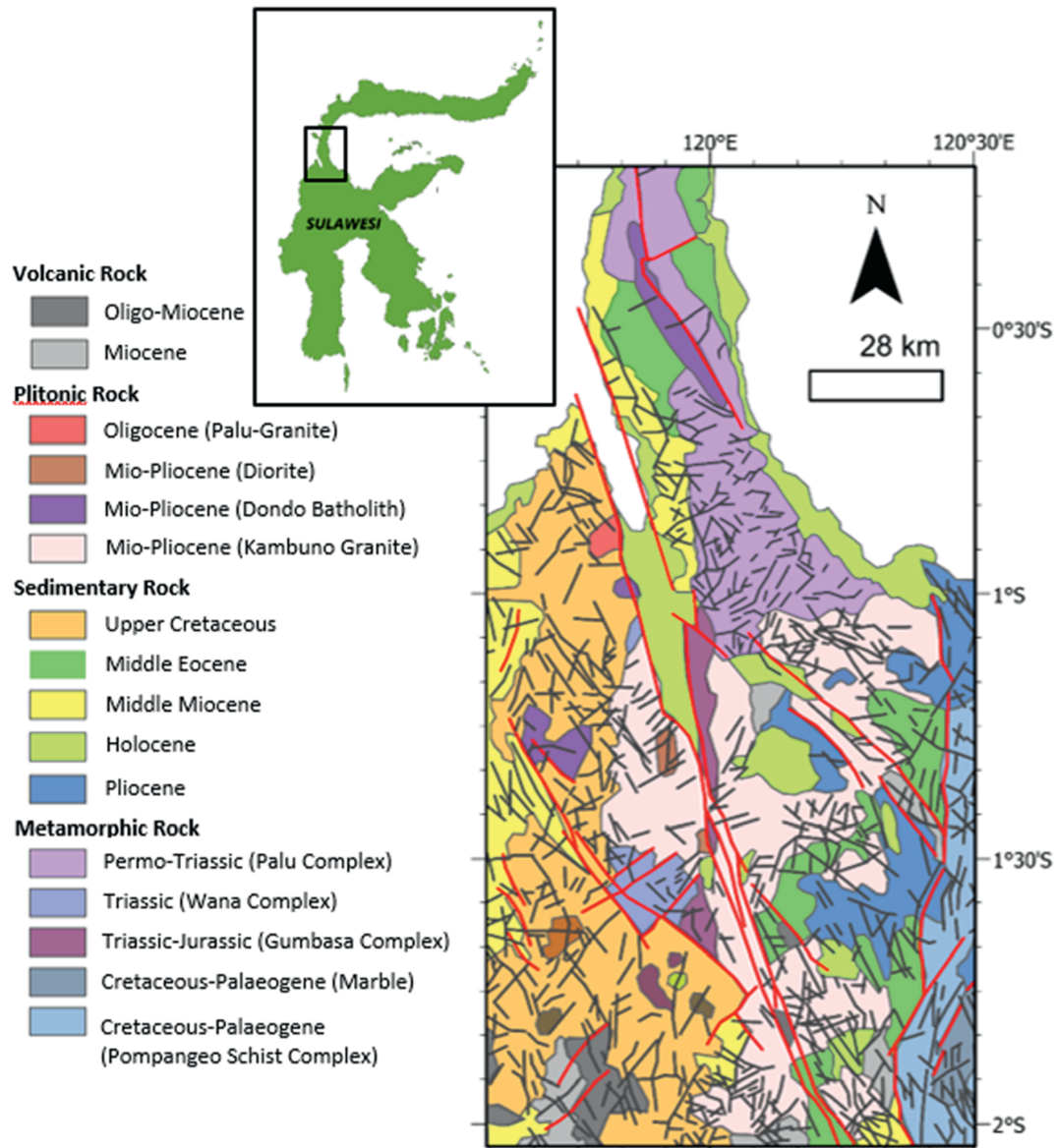


Fig. 1. Geological map of the Palu area. Modified from Watkinson, I. M., 2011 [16].

3.2. GNSS data

We used GNSS observation data from the GEODYSSSEA network between 1994 and 2004 for the entire Sulawesi island [25]. The detailed observation and its estimated velocities are summarized in Table 1. In Sulawesi, those 58 GNSS stations have been installed primarily to observe the deformation behavior along the Palu-Koro Fault. The GNSS data were processed using GIPSY software to derive precise coordinates and velocities for the whole of Sulawesi Island. The detailed strategy was described in the previous study [25]. This enabled the generation of deformation models, including principal shear strain, maximum shear strain, and dilatation rates, which reveal patterns of crustal deformation and strain accumulation along the focus area, studying the Palu-Koro Fault and its surroundings. The GNSS data provided key insights into surface deformation, including extensional zones on the fault's eastern and western sides and compressional zones along the main fault trace.

3.3. Seismic data

Seismicity data were obtained from prior studies [7] and reanalyzed for this research to investigate earthquake distributions and focal mechanisms along the Palu-Koro Fault. This dataset was instrumental in identifying zones of strain release and characterizing fault behavior during major seismic events, such as the $M_W 7.5$ earthquake in 2018.

These three complementary datasets provide a robust foundation for analyzing the Palu-Koro Fault's structure, deformation, and seismicity, allowing for a detailed investigation of its tectonic behavior and associated hazards.

4. Methods

This study employs an integrated approach combining gravity data analysis, GNSS-based surface deformation modelling, and

Table 1

Detailed GNSS site velocities corresponding to ITRF2000 with two-sigma uncertainty and their correlation.

Site	Lon (°)	Lat (°)	EW	σ_{EW}	NS	σ_{NS}	Corr
batu	114.791	-3.867	26.40	1.05	-10.81	0.69	-0.027
blkp	116.815	-1.272	25.81	0.74	-13.16	0.45	-0.017
tnjb	117.641	0.558	24.10	1.36	-12.64	0.87	-0.022
tawa	117.979	4.251	24.27	0.62	-16.51	0.39	-0.019
sand	118.121	5.842	27.88	0.22	-16.93	0.15	0.012
koep	123.663	-10.177	47.70	1.29	41.79	0.93	-0.046
kapa	124.280	-9.776	39.02	0.42	36.90	0.29	-0.006
ende	121.766	-8.707	31.12	0.40	23.28	0.31	-0.026
lira	125.739	-8.059	39.45	0.51	39.17	0.34	-0.015
sana	125.991	-2.048	-13.53	1.75	17.27	1.04	-0.008
tern	127.342	0.860	-54.00	1.41	14.90	0.85	-0.020
ambo	128.117	-3.775	13.78	1.83	19.75	0.89	0.005
baub	122.795	-5.471	25.70	4.07	6.43	4.05	-0.042
ujpd	119.581	-5.154	27.74	0.73	-5.86	0.51	-0.024
toar	121.489	-4.582	26.78	0.52	-0.09	0.36	0.001
kend	122.736	-4.227	24.12	5.09	8.29	2.78	0.054
pare	119.650	-3.978	25.39	0.25	-7.81	0.16	-0.030
redo	120.367	-3.539	23.83	0.93	-4.31	0.67	0.005
Mali	120.905	-2.595	19.95	1.11	-0.58	0.62	-0.058
lara	119.382	-1.855	12.13	3.98	-0.54	3.33	-0.042
sung	120.010	-1.512	15.47	1.84	-1.50	1.48	0.105
bara	119.460	-1.427	22.27	0.82	-8.66	0.58	-0.031
wata	119.587	-0.874	21.57	0.47	-4.57	0.36	0.001
pl02	119.635	-0.795	22.06	1.09	-4.61	0.57	-0.019
pl03	119.681	-0.727	21.15	1.07	-3.32	0.56	-0.018
pl04	119.720	-0.708	20.27	1.09	-2.39	0.56	-0.017
loli	119.788	-0.770	20.16	1.19	1.84	0.59	-0.017
p14p	119.837	-0.906	22.13	1.47	1.84	0.70	-0.021
pl09	119.866	-0.758	17.95	1.07	6.52	0.56	-0.018
pl18	119.867	-0.908	18.35	1.20	4.64	0.60	-0.022
pl08	119.880	-0.867	22.59	1.05	7.00	0.55	-0.022
pl10	119.880	-0.735	17.98	1.06	8.87	0.55	-0.018
pl11	119.896	-0.742	19.27	1.21	10.38	0.60	-0.019
palp	119.906	-0.916	21.62	1.06	7.78	0.56	-0.022
pl12	119.948	-0.716	18.05	1.00	14.93	0.53	-0.019
pl19	119.971	-0.718	19.80	3.44	16.03	1.32	-0.019
pl17	119.994	-0.722	18.16	1.42	31.19	0.67	-0.018
slby	120.016	-0.723	19.82	1.76	15.89	0.79	-0.016
pl16	120.044	-0.719	17.04	1.60	22.14	0.73	-0.025
tobp	120.095	-0.709	17.27	0.80	21.88	0.46	-0.017
kamb	120.904	-1.908	2.88	2.18	8.93	1.46	-0.020
wuas	120.316	-1.424	12.46	0.51	8.48	0.38	-0.007
luwu	122.772	-1.040	-2.62	2.71	15.94	1.52	0.006
ampa	121.436	-1.010	-5.03	1.98	13.96	1.22	0.073
suli	120.428	-1.007	17.07	1.86	25.73	1.59	-0.011
dong	120.005	-0.248	15.07	2.07	23.15	1.46	-0.045
sgti	120.122	0.127	12.59	4.54	27.93	3.59	0.021
tomi	120.850	0.453	17.92	0.69	28.80	0.47	-0.031
pala	120.434	0.482	18.98	2.40	28.26	1.67	-0.013
toli	120.794	1.121	22.83	0.30	31.10	0.17	-0.020
gt03	122.617	0.625	21.28	0.61	17.53	0.40	-0.006
gt01	122.852	0.639	17.22	0.49	15.56	0.39	0.001
gt04	122.964	0.559	18.96	0.54	11.94	0.34	-0.055
goro	123.029	0.605	17.37	0.36	10.35	0.29	-0.122
gt06	123.102	0.541	18.04	0.48	8.93	0.34	-0.041
gt08	123.189	0.528	18.92	0.74	5.67	0.45	0.017
gt10	123.248	0.510	21.32	0.74	5.94	0.42	-0.009
mana	125.064	1.331	20.97	2.56	-6.37	1.43	0.036

seismicity clustering to investigate the structural and tectonic dynamics of the Palu-Koro Fault in Sulawesi.

4.1. Fault detection based on gravity data

The GGMPlus dataset was utilized to derive the Simple Bouguer Anomaly (SBA), which provides initial insights into the subsurface mass distribution. The Simple Bouguer Anomaly calculation follows the equation [26].

$$\Delta g_{\text{abs}} = g - A_B + F - \gamma \quad (1)$$

where g is the gravity measurement, F is the free air correction, A_B is Bouguer correction and γ is the normal gravity. The Simple Bouguer Anomalies reflect mass anomalies with a mean crustal density above or below 2.67 g/cm^3 in most geological situations. Simple Bouguer anomalies ignore topographic features, such as mountains or valleys. Simple Bouguer correction tends to compensate for measurements taken near topographic features.

The theoretical model of the gravity response to the fault structure becomes a basis for fault analysis. Fig. 2(a) shows the theoretical model of the gravity response from a single fault, characterized by a combination of low gravity gradient on one side and high gravity gradient on the other side. Fig. 1(b) shows the theoretical model of the gravity response from a double fault, characterized by a combination of low gravity gradient in the center and high gravity gradient on both sides [27].

In order to accurately identify fault positions, this study applied several gravity data filtering methods, including the First Horizontal Derivative (FHD), Second Vertical Derivative (SVD), and Tilt Derivative (TDR).

4.2. First Horizontal Derivative (FHD)

The FHD is a method employed in gravity data analysis to emphasize horizontal variations in subsurface density. This approach aids in identifying the boundaries or edges of geological structures, such as faults, basins, or rock intrusions, by computing the horizontal gradient of the Bouguer Anomaly [28]. Mathematically, FHD can be expressed as:

$$\text{FHD} = \sqrt{\left(\frac{\partial \Delta g}{\partial x}\right)^2 + \left(\frac{\partial \Delta g}{\partial y}\right)^2} \quad (2)$$

where Δg is the Bouguer Anomaly, x and y are the horizontal directions (east-west and north-south).

4.3. Second Vertical Derivative (SVD)

The SVD analysis is used to highlight near-surface or shallow anomalies [28]. SVD is a measure of curvature, as shallow gravity anomalies decrease with height more rapidly than deeper anomalies, resulting in greater curvature. The calculation of the SVD map for the vertical gravity component (g_z) is easier to perform in the spatial domain from the horizontal gradient using Laplace's equation [29].

$$\frac{\partial^2 g_z}{\partial z^2} = - \left(\frac{\partial^2 g_z}{\partial x^2} + \frac{\partial^2 g_z}{\partial y^2} \right) \quad (3)$$

4.4. Tilt Derivative (TDR)

In order to obtain a clearer geological structure based on gravity data, TDR filtering was applied [10,30,31]. TDR represents the local phase, which is defined as follows:

$$\text{TDR} = \tan^{-1} \left(\frac{\frac{\partial g}{\partial z}}{\frac{\partial g}{\partial h}} \right) \quad (4)$$

where $\frac{\partial g}{\partial h} = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}$ dan $\frac{\partial g}{\partial x}, \frac{\partial g}{\partial y}, \frac{\partial g}{\partial z}$, are first order derivatives of the gravity field in x, y and z directions. The tilt angle

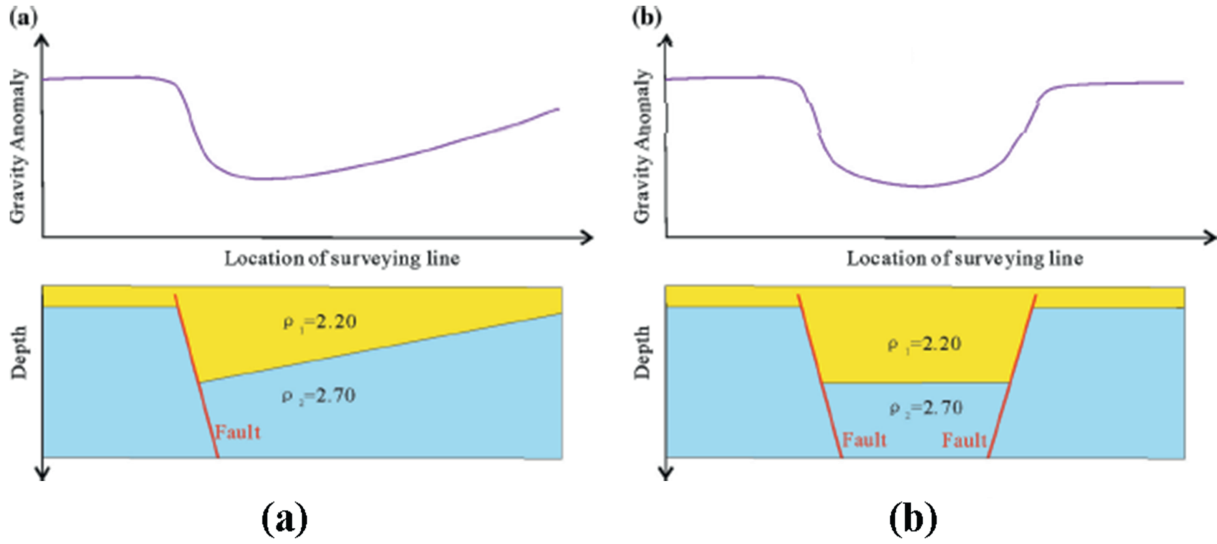


Fig. 2. The theoretical model of structural forces and gravity response. (a) structural force of a single fault and gravity response; (b) structural force of a double fault and gravity response [27].

θ is measured in either radians or degrees [10]. In this study, TDR was calculated using Geosoft/Oasis Montaj [32].

4.5. Surface deformation based on GNSS data

The GNSS data was processed to obtain coordinate and velocity [25] based on a time series decomposition method (e.g. Ref. [33]) followed by strain rate calculation. The strain rate modelling is based on linking displacement rate data (**d**) with deformation parameters (**A**) through a linear relationship expressed as [34,35]:

$$\mathbf{d} = \mathbf{A}\mathbf{m} + \boldsymbol{\epsilon} \quad (5)$$

where **d** is the observed velocity data ($V_{x1}, V_{y1}, \dots, V_{xn}, V_{yn}$) in the horizontal components, **A** is the design matrix containing geometric terms (distances $\Delta x, \Delta y$), **m** is deformation parameters, including translation components ($U_x, \dots, U_y$), rotation (ω), normal strain rates ($\epsilon_{xx}, \epsilon_{yy}$), and shear strain rate (ϵ_{xy}), and $\boldsymbol{\epsilon}$ is the residual error vector.

For horizontal deformation, the deformation parameters **m** are defined as:

$$\mathbf{m} = [U_x \ U_y \ \omega \ \epsilon_{xx} \ \epsilon_{yy} \ \epsilon_{xy}]^T \quad (6)$$

The design matrix (**A**) relates velocity data to deformation parameters and is defined for each point as:

$$\begin{bmatrix} 1 & 0 & \Delta y_1 & \Delta x_1 & 0 & \Delta y_1 \\ 0 & 1 & -\Delta x_1 & 0 & \Delta x_1 & \Delta y_1 \\ 1 & 0 & \Delta y_2 & \Delta x_2 & 0 & \Delta y_2 \\ 0 & 1 & -\Delta x_2 & 0 & \Delta x_2 & \Delta y_2 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \Delta y_n & \Delta x_n & 0 & \Delta y_n \\ 0 & 1 & -\Delta x_n & 0 & \Delta x_n & \Delta y_n \end{bmatrix} \quad (7)$$

To solve for **m**, a linear least-squares inversion is applied:

$$\mathbf{m} = (\mathbf{A}^T \mathbf{C}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{C}^{-1} \mathbf{d} \quad (8)$$

where **C** is the covariance matrix of the observed velocities.

4.5.1. Dilatation rate

The dilatation rate (Δ) represents the volumetric change in the Earth's crust due to deformation. It is computed as the trace of the strain rate tensor:

$$\Delta = \epsilon_{xx} + \epsilon_{yy} \quad (9)$$

where ϵ_{xx} is the normal strain rate in the x-direction, and ϵ_{yy} is the normal strain rate in the y-direction. A positive dilatation rate indicates crustal expansion, while a negative rate indicates compression.

4.5.2. Maximum shear strain

The maximum shear strain $\epsilon_{\max}$ quantifies the maximum deformation due to shear forces. It is calculated as:

$$\epsilon_{\max} = \frac{1}{2} \sqrt{(\epsilon_{xx} - \epsilon_{yy})^2 + 4\epsilon_{xy}^2} \quad (10)$$

where ϵ_{xx} is the shear strain rate component.

4.5.3. Principal shear strain

The principal shear strain directions $\gamma_{\max}$ are derived from the eigenvalues of the strain rate tensor:

$$\gamma_{\max} = \sqrt{\left(\frac{\epsilon_{xx} - \epsilon_{yy}}{2}\right)^2 + \epsilon_{xy}^2} \quad (11)$$

The principal strains correspond to the directions of maximum and minimum strain rates in the horizontal plane.

4.6. Seismicity analysis

Seismicity analysis is a critical approach for understanding fault dynamics and assessing seismic hazards. By evaluating earthquake parameters such as frequency, magnitude, depth, and spatial distribution, seismicity analysis provides valuable insights into the mechanical behavior of faults and associated crustal deformation processes. This methodology integrates concepts from earthquake physics and geodynamics to characterize fault activity and tectonic stress accumulation.

4.6.1. Earthquake magnitude and depth distribution

Earthquake magnitude (M_w) and depth (d) provide fundamental indicators of fault behavior. Shallow earthquakes (<30 km) are typically associated with brittle deformation in the upper crust, while intermediate-depth events (30–70 km) often reflect deeper crustal deformation or subduction-related processes. The relationship between magnitude and frequency is expressed using the Gutenberg-Richter law [36].

$$\log N(M) = a - bM \quad (12)$$

where $N(M)$ denotes the number of earthquakes with a magnitude of M or greater, a is the seismic activity level, b is the slope of the magnitude-frequency distribution, indicative of stress conditions. The depth distribution of earthquakes along a fault reveals the depth extent of brittle deformation and the interaction between fault segments.

4.6.2. Spatial clustering

Seismic events often cluster along active fault segments, reflecting regions of high tectonic strain or stress release. Spatial clustering can be analyzed using earthquake density [37].

$$E_d = \frac{\text{Number of Events}}{\text{Area of region}} \quad (13)$$

where E_d is the earthquake density.

4.6.3. Temporal patterns

Temporal variations in seismicity, including aftershock sequences and seismic swarms, reflect the stress evolution along faults. Omori's Law describes the decay of aftershock rates over time [38].

$$n(t) = \frac{K}{(t + c)^p} \quad (14)$$

where $n(t)$ is the number of aftershocks at time t , while K , c , and p are Empirical constants dependent on the fault's stress conditions.

4.7. Integration of gravity data, GNSS deformation models, and seismicity clustering

The integration of gravity data, GNSS-based deformation models, and seismicity clustering provides a comprehensive framework for understanding fault dynamics, crustal deformation, and seismic hazard assessment. Each dataset complements the others, enabling cross-validation and enhancing spatial and temporal resolution.

4.7.1. Validation of subsurface density contrasts and fault geometries

Gravity data, particularly from the Simple Bouguer Anomaly (SBA) and filtered derivatives (FHD, SVD, TDR), were used to identify subsurface density contrasts associated with fault zones. GNSS deformation models provided surface displacement data to correlate these contrasts with active tectonic processes. Seismicity clustering further highlighted areas of active faulting, allowing validation of subsurface fault geometries identified from gravity anomalies [37,39,40].

4.7.2. Correlation of surface deformation patterns with fault activity

Surface deformation patterns derived from GNSS data, such as strain rates and dilatation, were directly linked to fault activity [41]. In this case, regions with high shear strain rates correlated

with strike-slip fault segments [40], dilatation patterns (expansion and compression zones) matched tectonic features identified in gravity maps, such as pull-apart basins and uplift zones. Seismicity clusters provided temporal validation, with active fault segments showing higher rates of earthquake occurrence, confirming ongoing deformation.

4.7.3. Identification of potential seismic hazard zones

Strain accumulation and seismicity clustering results were used to identify potential seismic hazard zones. The high seismicity density combined with high strain rates marks zones of potential rupture and gravity-derived subsurface anomalies associated with stress accumulation, such as crustal loading in compressional zones. Temporal patterns of seismicity (e.g., aftershock decay rates) highlight stress redistribution along faults [42].

5. Results

5.1. Seismicity analysis

The seismicity along the Palu-Koro Fault is characterized by a high frequency of seismic events, with epicenters primarily clustered along the fault trace. Fig. 3(a) illustrates the distribution of strong earthquakes ($M > 6$) that occurred along the Palu-Koro Fault from 2010 to 2018, including the $M_{7.5}$ September 28, 2018 tsunami event. These earthquakes exhibit significant variation in focal mechanism, magnitude, depth, and spatial distribution, providing insights into the fault's complex tectonic behavior. Fig. 3(b) shows relocated shallow seismicity from 2009 to 2018, with magnitudes ranging from M_3 to $M_{7.5}$. The horizontal and vertical location uncertainties are approximately 4.6 km and 6.1 km, respectively [7]. Epicenters are predominantly located along or near the fault, with distinct clusters in the Palu region and surrounding zones. A greater concentration of earthquakes is observed in the eastern segment of the fault compared to the western portion. Notably, epicenters are densely clustered near the cities of Palu and Donggala, which experience frequent shallow seismicity, mostly at depths of 10–20 km (Fig. 3(c)). This depth pattern is consistent with the behavior of left-lateral strike-slip systems, which generally generate shallow to intermediate earthquakes due to horizontal shear. The central segment of the fault, passing through the Palu region, shows a particularly high density of seismic events at both shallow and intermediate depths, indicating ongoing strain accumulation and release, as exemplified by the $M_{7.5}$ earthquake in 2018. While the Palu-Koro Fault is predominantly a shallow strike-slip fault with most events occurring within the upper 30 km of the crust, the presence of intermediate and deeper earthquakes suggests deeper crustal deformation processes and possible interactions with underlying structures.

5.2. Deformation based on the gravity data

5.2.1. Bouguer Anomaly

The Simple Bouguer Anomaly provides information about the distribution of subsurface masses, which is very useful for identifying geological structures such as faults and active tectonic zones. The Palu-Koro main fault lies in a transition zone between high anomaly values (red to yellow zones) and low anomaly values (blue to green zones) [43]. Significant gravity gradient changes along this fault path indicate differences in subsurface density, reflecting the presence of active fault structures (Fig. 4). The Simple Bouguer Anomaly map shows a very good correlation with the existence of the Palu-Koro Fault and its surrounding fault structures. The anomaly value transitions, gravity gradients, and the high-low anomaly distribution pattern align with the

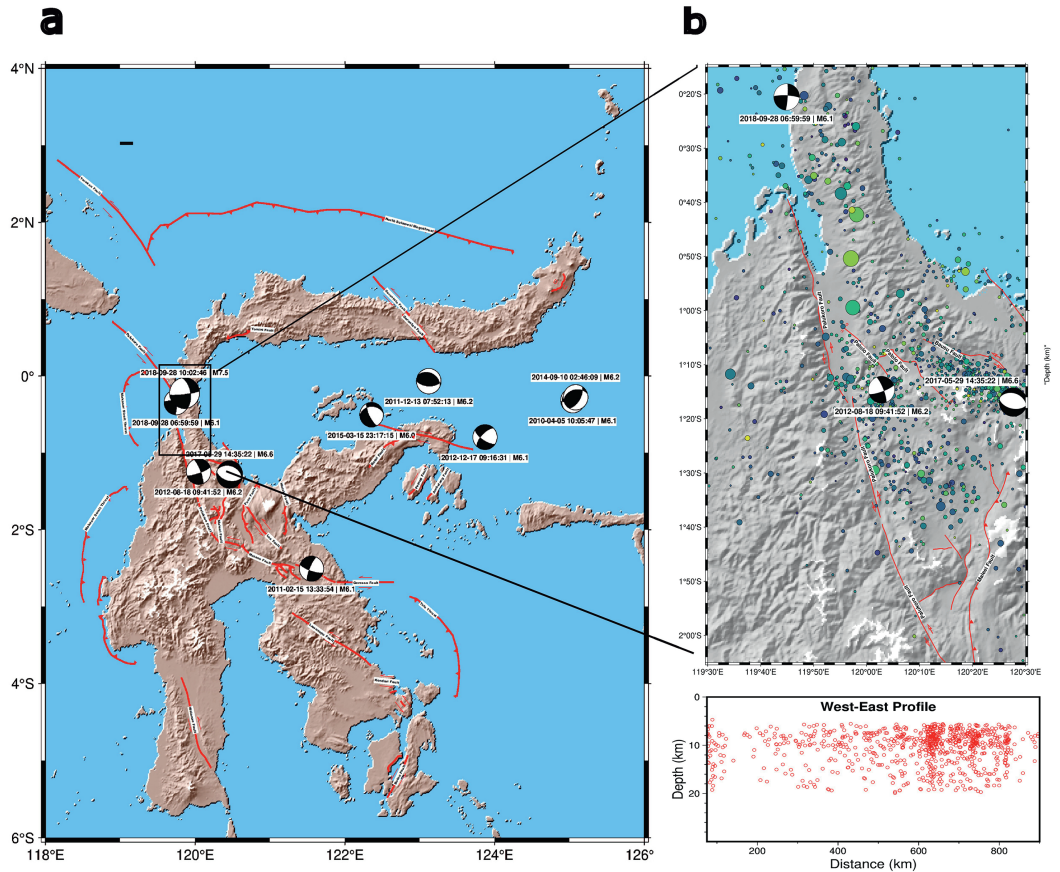


Fig. 3. (a) Epicenters and focal mechanisms of $M > 6$ earthquakes that occurred on Palu-Koro and other prominent faults from 2010 to 2018. (b) Epicentral map of shallow seismicity along Palu-Koro Fault from 2010 to 2018 and its W-E cross-section.

geological interpretation of this area, where the Palu-Koro Fault serves as a major element influencing crustal deformation. Low anomalies in basin zones and high anomalies in mountainous regions or uplifted tectonic blocks support the tectonic characteristics and fault activity in this region.

Three perpendicular slices from the fault were taken to observe anomaly variations in the fault area based on GGMPlus data (Fig. 4). The slicing result for SBA AA' indicates that the Palu-Koro Fault area is characterized by lower anomalies compared to its surroundings. The slicing results for BB' and CC' show changes in anomalies within the fault area. The SBA GGMPlus map is still able to represent subsurface structures, although it is still influenced by terrain effects.

The interpretation of faults based on the SBA map provides only preliminary assumptions. This is because the Bouguer map still combines regional anomalies (deep subsurface) and residual anomalies (near the surface), which can cause interpretation ambiguities. Reducing these ambiguities can be achieved using filters such as the First Horizontal Derivative (FHD), Second Vertical Derivative (SVD), and Tilt Derivative.

5.2.2. First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD)

FHD is used to determine the horizontal boundary location of density contrast (rock edges) from gravity data [28]. The FHD GGMPlus map from SBA GGMPlus shown in Fig. 5 has values ranging from 0 to 130 mGal. High FHD values along the Palu-Koro Fault mark significant density boundaries, indicating the location of major fault zones. These values reflect left-lateral strike-slip

movement, causing density contrasts on either side of the fault, with high stress areas that have the potential to be earthquake energy release centers. Low FHD values in the surrounding areas indicate subsidence, which results from extensional forces along the fault.

Second Vertical Derivative (SVD) is a gravity data processing method useful for enhancing near-surface anomaly effects by eliminating deeper anomalies, particularly for detecting density contrast boundaries, such as faults [44]. SVD High values, represented by orange to red colors, indicate areas with high density or positive boundaries between dense rock masses, such as crustal uplift zones or dense rock intrusions. In the segments of the Palu-Koro Fault, this suggests the possibility of basement rock zones being uplifted due to tectonic forces. Meanwhile, low SVD values indicate zones with low density or negative boundaries, often representing basins or subsidence zones, such as sedimentary basins [45]. In addition to the main fault, several fault branches indicated by anomaly contrast changes near the main fault highlight the structural complexity of the region. It is shown that visually, the SVD is clearer than the FHD.

The FHD and SVD of GGMPlus were subjected to three perpendicular slices cutting through the fault to observe anomaly changes more clearly, as shown in Fig. 6.

The graphs of slicing AA', BB', and CC' for FHD and SVD from GGMPlus in the fault area all show a downward trend compared to the surrounding regions. The anomaly response from the slicing of the FHD and SVD maps in the study area (Fig. 6) aligns with the theoretical gravity anomaly response model for double faults (Fig. 2) and the geological map of the study area (Fig. 1). The

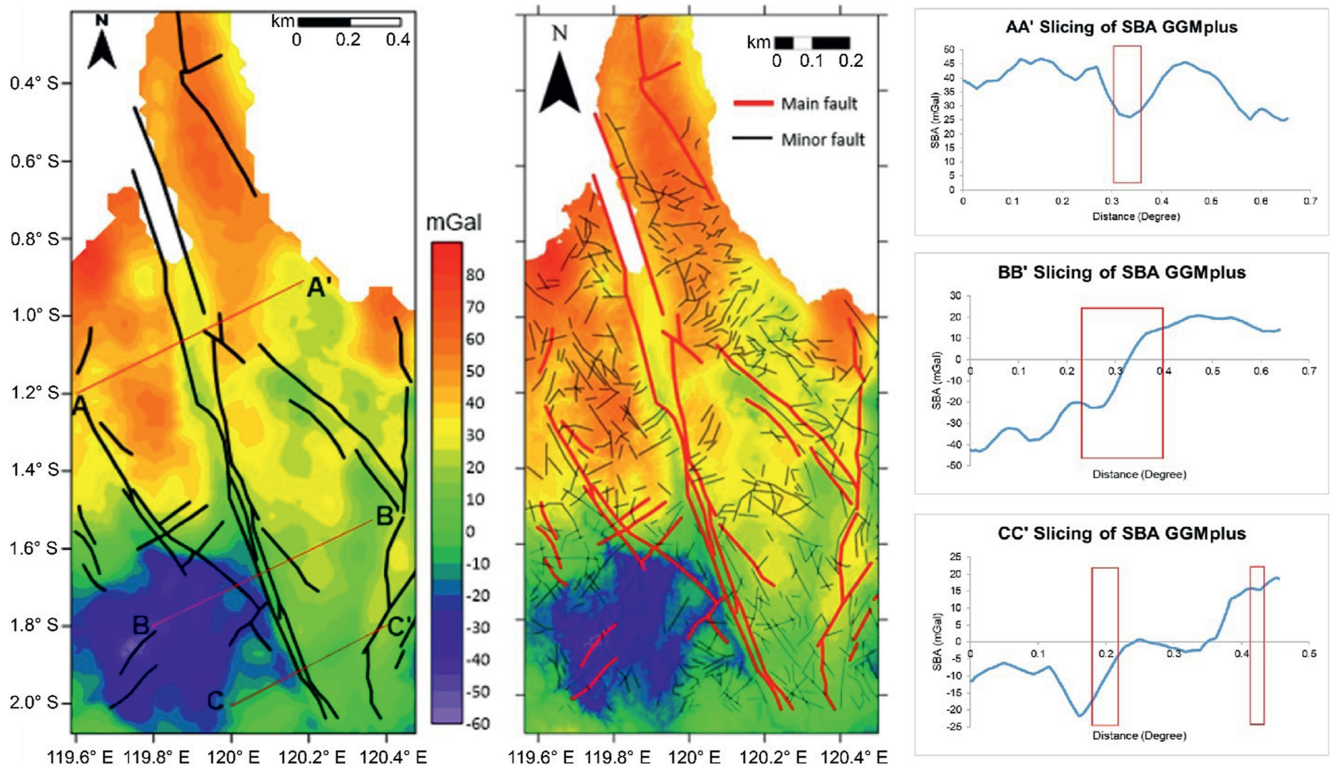


Fig. 4. Simple Bouguer Anomaly maps, fault structure, and perpendicular slices of the major fault, combined with the anomaly response from slicing the SBA GGMplus (the red box is symbolized as the fault area).

gradient increase in slicing AA' at a distance of $0.2\text{--}0.3^\circ$ marks a high-density contrast zone associated with intense tectonic activity, creating boundary zones along the Palu-Koro Fault. The central area between the two faults in slicing AA' is dominated by young Holocene sedimentary rocks, resulting in low anomalies in that region.

In the slicing BB', high gradients appear in two segments, around $0.15\text{--}0.3^\circ$, indicating two density boundary zones likely representing the main fault and a fault branch. Based on the geological map of the second red box fault area, the region is dominated by Middle Eocene sedimentary rocks and includes some volcanic rocks from the Oligo-Miocene. Consequently, the FHD airborne gravity graph in that area shows high values because volcanic rocks have a higher density contrast than sedimentary rocks. Additionally, the maximum values in that region are due to the lithological boundaries between sedimentary and volcanic rocks. Meanwhile, the slicing CC', which represents a minor fault segment, shows smaller gradients than slicing AA' and BB'. However, a high gradient is still observed between 0.05 and 0.2° , indicating the presence of a small fault branch or secondary deformation zone near the main fault. Since the slicing CC' intersects with a less dominant fault, the density contrast across the fault is weaker, leading to lower gravity gradient responses, and the FHD and SVD anomalies are subtler [27]. Moreover, the area around CC' likely consists of more homogeneous lithology (rocks with similar density and composition), resulting in minimal lateral density contrasts. Gravity methods like GGMplus respond to mass/density contrasts, so where such contrasts are small, the gravity signature becomes unclear or diffuse [28].

5.2.3. Tilt Derivative (TDR) GGMplus

The TDR map from SBA GGMplus is shown in Fig. 7 with values ranging from -1.4 to 1.4 mGal. TDR maps generally represent short

wavelengths that extract information about potential lineaments [10]. Along the main path of the Palu-Koro Fault, high gradients are observed, corresponding to the boundaries of subsurface density contrasts and marking the location of the main active fault [45]. High TDR values reflect intense tectonic activity, such as left-lateral strike-slip movement, creating crustal deformation along the fault. Low TDR values occur on the western and eastern sides of the fault, indicating subsidence areas or basins formed due to fault activity [46]. The TDR pattern also highlights several fault branches associated with the main fault. These branches are essential as they reflect the distribution of secondary deformation around the Palu-Koro Fault. The TDR GGMplus map clearly identifies the Palu-Koro Fault region with a pattern of anomaly linearity.

5.3. Surface deformation based on GNSS data

We utilized GNSS-derived strain rate to study the surface deformation along the Palu-Koro Fault. Surface deformation modelling of the Palu-Koro Fault region and its surroundings was conducted using Velocity Interpolation for Strain Rate (VISR), as mentioned above in the method section [34]. The strategy is an optimally horizontal strain rate field based on spatial weighting of the minimum, maximum, and incremental spatial smoothing constants to be 1 km, 160 km, and 20 km, respectively, to accommodate the GNSS stations' coverage. We used $0.1^\circ \times 0.1^\circ$ gridded spatial extent with the Voronoi spatial weighting scheme. We also performed the Gaussian weighting scheme to estimate the eigenvalues of the horizontal strain rate tensor. Based on the strain rate tensor, we can model the principal shear strain, the maximum dilatation rate, and the maximum shear strain rate as has been demonstrated in the previous studies [47–51].

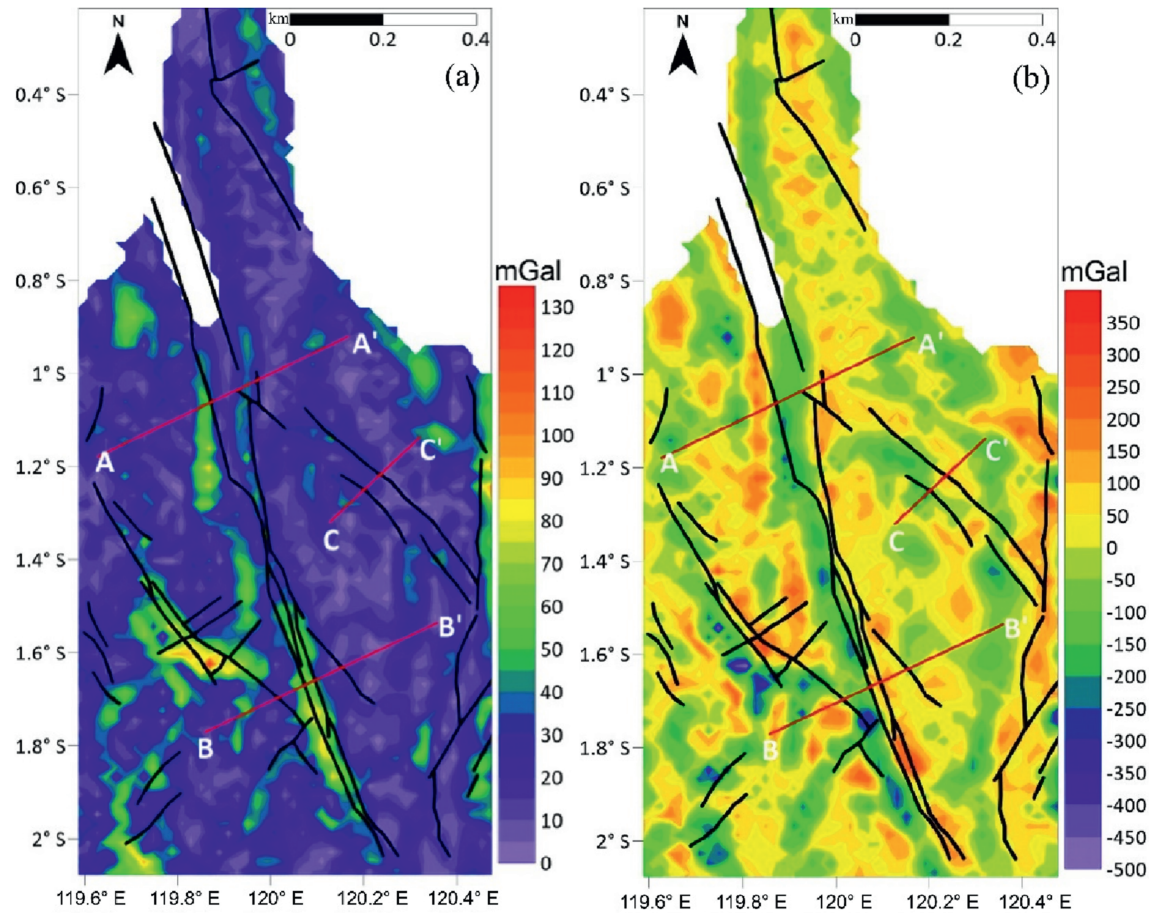


Fig. 5. (a) FHD and (b) SVD from GGMPlus. The black line indicates the major and minor fault structures. The red line denotes the slicing profiles to observe the anomaly change related to the fault structure.

5.3.1. Principal strain

The principal strain rate map (Fig. 8(a)) illustrates the crustal deformation pattern around the fault, which is a combination of extensional and compressional strain. In the Palu-Koro Fault region, extensional strain zones dominate on either side of the fault, reflecting basin-opening processes due to left-lateral strike-slip motion. The compressional strain zones along the main fault indicate potential crustal uplift and accumulation of tectonic energy. Extensional strain is clearly visible on the eastern and western sides of the fault, demonstrating that the left-lateral motion of the Palu-Koro Fault generates tensile forces around the tectonic basins, commonly referred to as pull-apart basins, where the crust stretches and subsides due to lateral tension. The combination of extensional and compressional strain in this region highlights the tectonic complexity of the Palu-Koro Fault. The left-lateral strike-slip activity produces heterogeneous deformation around the fault. Therefore, the GNSS shear strain concentrations along the fault match the known kinematics of left-lateral strike-slip movement resulting from the regional tectonic convergence at the Sulawesi triple junction [16].

5.3.2. Dilatation rate

The dilatation rate map illustrates volume changes within the Earth's crust, showing either expansion (positive) or compression (negative) with its uncertainties reflected on the contour of the black lines for each 40 nanostrain/yr per line. The strain rate uncertainty shows that most of the Palu-Koro region along the fault

lines is below 40 nanostrain/year, which is relatively small considering the estimated strain rate (Fig. 8). Fig. 8(b) indicates that positive dilatation rates occur in the eastern region of the Palu-Koro Fault, with high positive dilatation values (>100 nanostrain/yr). This reflects significant deformation in this area, potentially associated with sedimentary basin formation or other tectonic processes. This is indicative of crustal extension or spreading, often linked to pull-apart basins caused by the left-lateral strike-slip motion of the Palu-Koro Fault [4]. On the other hand, negative dilatation rates are observed in the western region of the Palu-Koro Fault, indicating compression or crustal narrowing. This zone suggests localized uplift or stress accumulation due to compressional tectonic forces along specific fault segments. Based on this, the area along the main fault shows a transition between compression (red) and expansion (blue), reflecting the strike-slip activity of the Palu-Koro Fault. This pattern underscores the fault's role as a dominant deformation zone separating areas with distinct strain patterns.

5.3.3. Maximum strain rate

The maximum strain rate map (Fig. 8(c)) shows very high maximum strain values exceeding 250 nanostrain/year along the main path of the Palu-Koro Fault, particularly in the central and northern sections. This reflects intense deformation due to the left-lateral strike-slip activity of the fault and highlights regions with concentrated tectonic energy, which have the potential to be primary locations for large earthquake releases. Intermediate

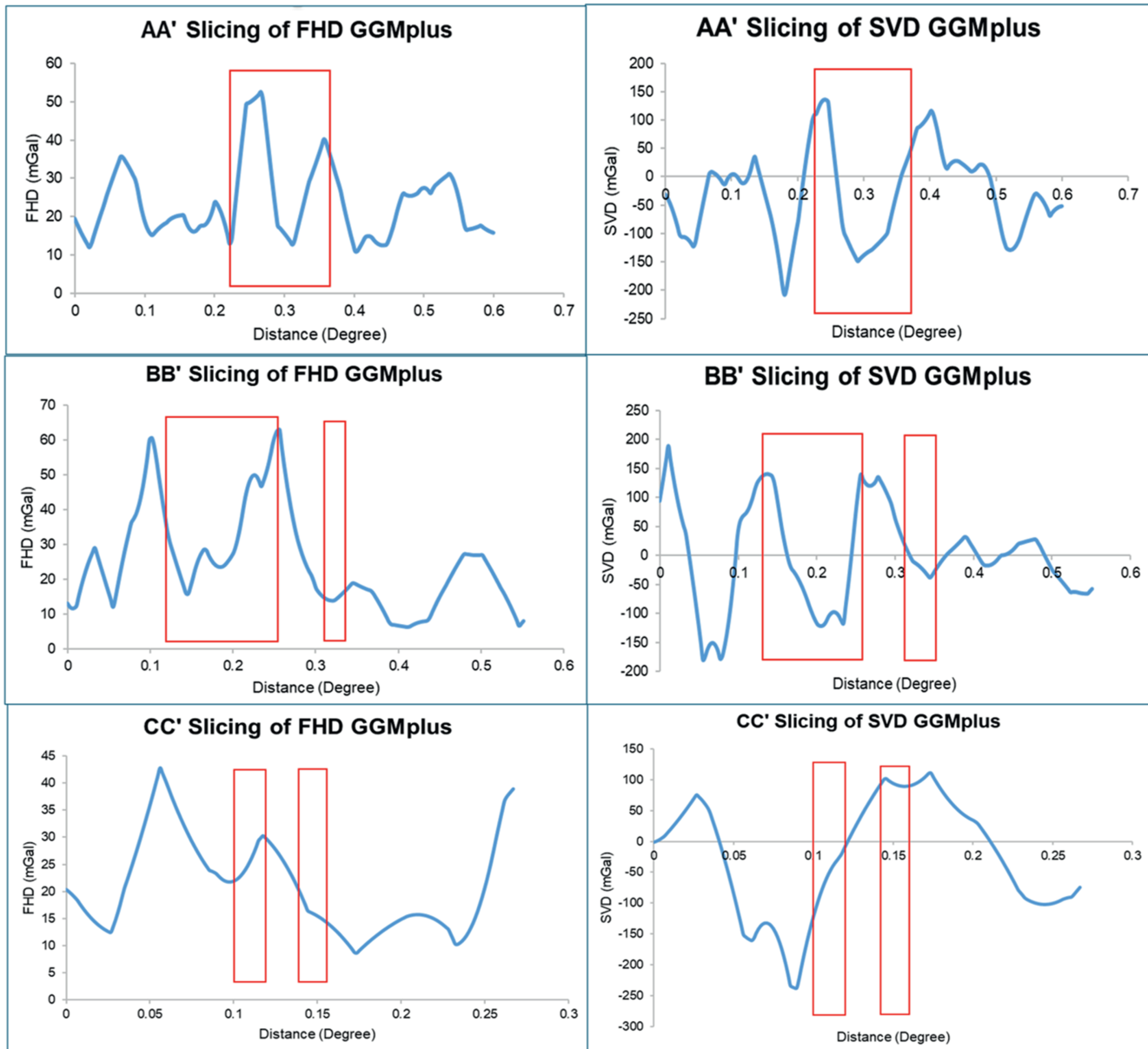


Fig. 6. Respond FHD and SVD of GGMplus Anomaly, red box as fault zone.

strain zones, ranging between 50 and 150 nanostrain/year, are observed in areas farther from the fault. These indicate weaker deformation, likely resulting from strain propagation from the activity along the main fault. These structures accommodate distributed deformation and suggest a multi-segmented, complex fault system [12].

5.4. Integration of gravity, GNSS, and seismicity

The integration of gravity, GNSS, and seismicity aims to provide a comprehensive understanding of fault geometries, surface deformation patterns, and seismic hazard zones [4,12]. Therefore, the discussion focuses on the validation of fault geometries, the relationship between surface deformation patterns and fault activity, and the identification of potential seismic hazard zones.

5.4.1. Validation of fault geometries

Validating fault geometries requires a detailed analysis of subsurface, surface deformation patterns, and fault activity in order to confirm the location, extent, and activity of fault geometries along the Palu-Koro Fault. The SBA provides insights into subsurface density contrasts that are indicative of fault zones. The high FHD values along the Palu-Koro Fault correspond to sharp density gradients caused by fault activity [27]. The SVD enhanced near-surface features, revealing shallow fault zones and crustal uplift areas, particularly in the fault's central and southern segments [28]. The TDR is also able to identify secondary faults and lineaments branching from the main fault, showcasing the structural complexity of the Palu-Koro Fault system [10]. Meanwhile, GNSS-derived shear strain rates highlight zones of lateral motion along the strike-slip Palu-Koro Fault. High shear strain along the fault trace correlates with FHD-identified density contrasts, confirming active fault segments.

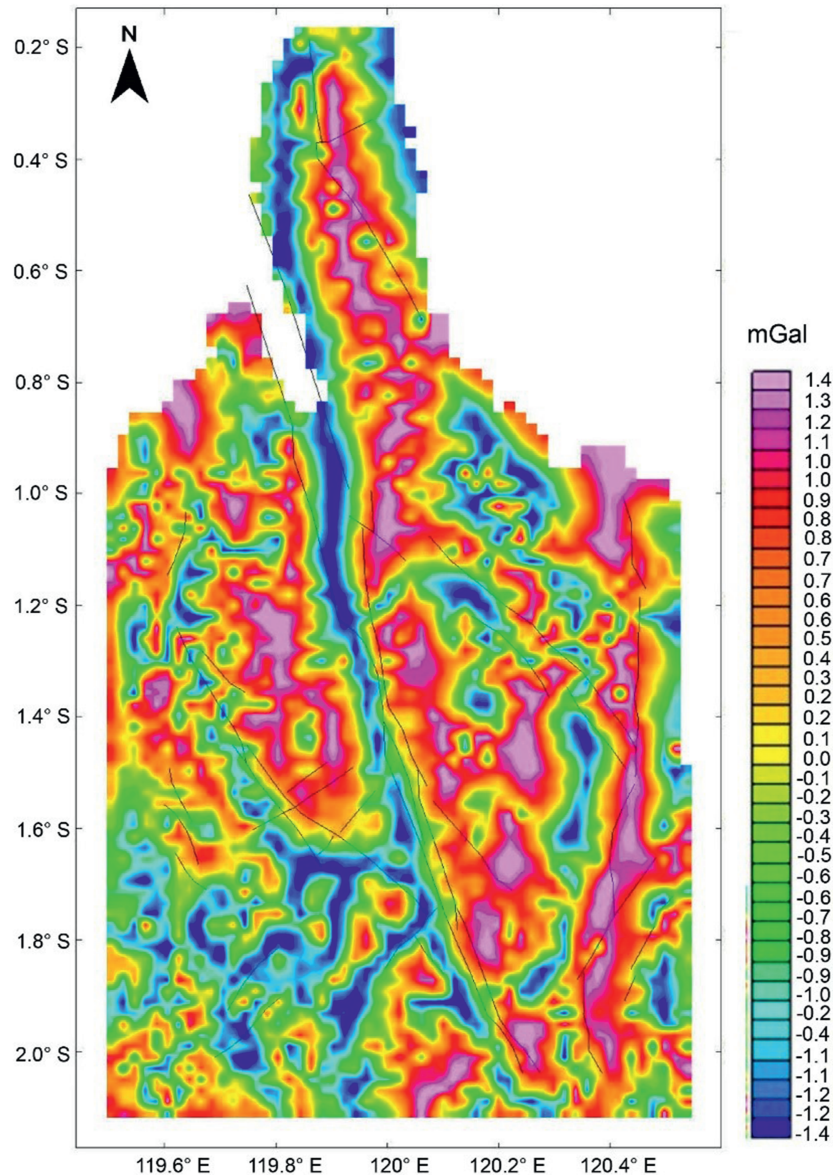


Fig. 7. Tilt derivative map derived from GGMplus, highlighting horizontal and vertical gradients of subsurface density contrasts.

Zones of extension and compression observed in the GNSS-derived dilatation model align with gravity anomalies. Extensional areas, such as pull-apart basins, correlate with low-density regions, while compressional zones near restraining bends align with high-density anomalies. Shallow seismicity is shown by earthquake clusters near the surface that align with GNSS-detected deformation zones and gravity-derived density contrasts, confirming fault activity in the upper crust. Nevertheless, deeper seismic events (30–70 km) also occur, validating subsurface fault structures inferred from gravity data and showing a possibility of interactions between the Palu-Koro Fault and deeper crustal processes [13]. Moreover, Seismic clusters along secondary fault branches identified in TDR maps confirm the activity of these smaller structures, enhancing the understanding of fault system complexity [7].

The integration of gravity, GNSS, and seismicity datasets provides a comprehensive validation of the Palu-Koro Fault geometries:

- (1) Alignment of subsurface and surface features shows that the gravity anomalies reveal subsurface density contrasts, GNSS

deformation models capture surface displacement patterns, and seismicity clusters validate active deformation along these structures.

- (2) Structural complexity shows secondary fault branches identified in TDR maps are supported by GNSS shear strain patterns and seismic clusters, emphasizing the multi-segmented nature of the Palu-Koro Fault.
- (3) Active deformation zones shown by high FHD values, GNSS strain rates, and seismicity density clusters consistently highlight the central segment of the Palu-Koro Fault near Palu as a zone of intense tectonic activity.

5.4.2. Correlation of surface deformation patterns with fault activity

Correlation of surface deformation patterns with fault activity is clearly shown, where the high FHD SBA values correspond to shear strain zones identified in GNSS models, validating the fault's location and activity (1). And the TDR enhances the identification

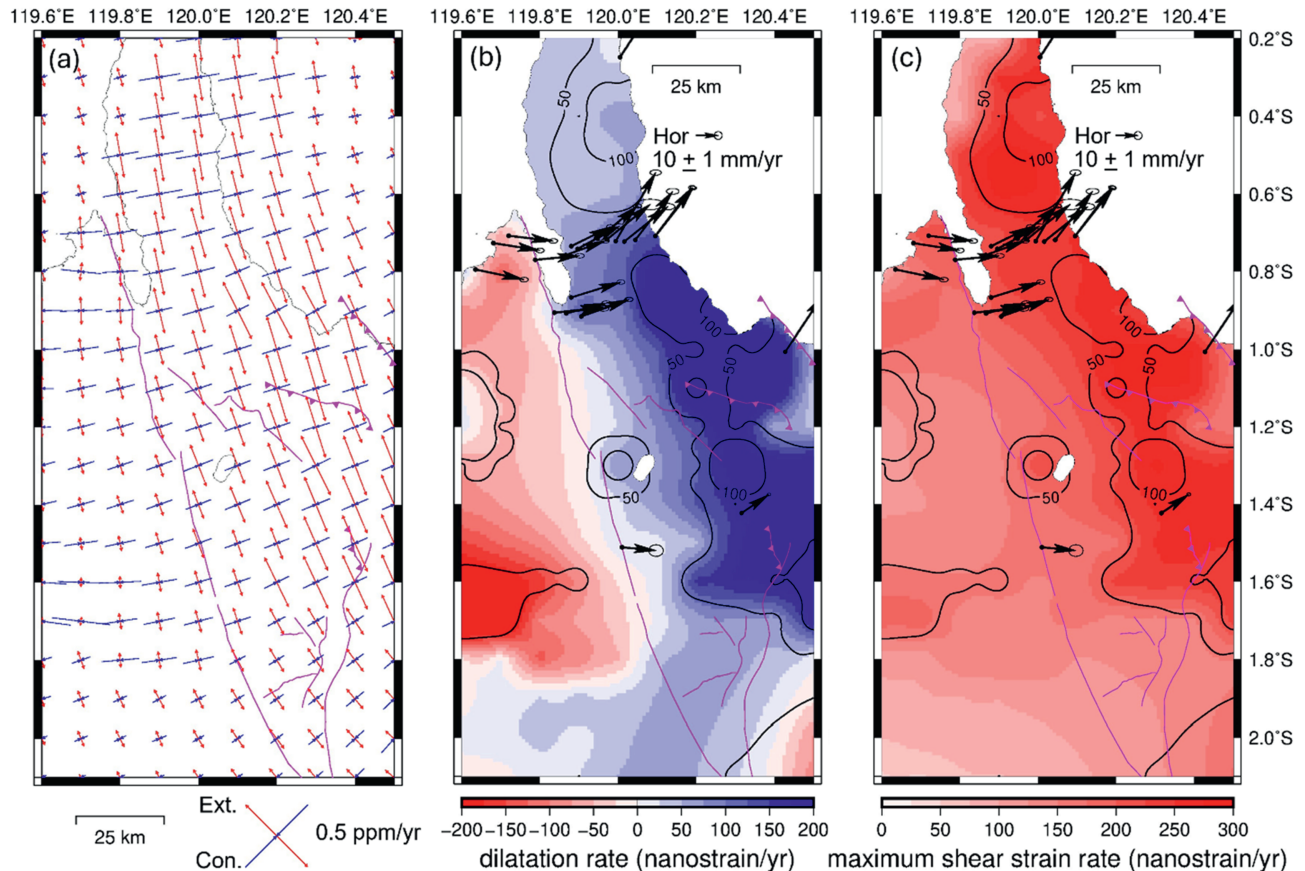


Fig. 8. Distribution map of the principal strain rate, the dilatation rate, and the maximum shear strain rate. The black line contour denotes the dilatation and uncertainty of the maximum shear strain rate. The black arrows indicate GNSS velocity based on ITRF2000 with two-sigma uncertainty.

of secondary faults and tectonic lineaments, revealing structural complexities that influence surface deformation patterns [30]. Moreover, the high shear strain rates derived from GNSS measurements are concentrated along the Palu-Koro Fault. These zones align with strike-slip fault activity, confirming lateral tectonic motion. Also, the GNSS-dilatation patterns reveal extensional zones in pull-apart basins and compressional zones near fault bends or restraining segments. These deformation patterns align with fault geometry, highlighting zones of active faulting. Based on the seismic clusters and strain zones, it was found that the clusters of shallow earthquakes align with high GNSS shear strain and dilatation zones, confirming active deformation in these regions. Meanwhile, the seismicity near secondary fault branches identified in TDR maps validates the presence of smaller, active fault structures.

The integration of gravity, GNSS, and seismicity datasets shows a clear correlation of surface deformation patterns with fault activity:

- (1) GNSS-derived shear strain and dilatation patterns align with gravity-inferred density contrasts and seismicity clusters.
- (2) Active fault segments, identified through FHD and seismicity, correlate with GNSS deformation, confirming the role in accommodating tectonic forces Supendi et al. [7].

5.4.3. Identification of potential seismic hazard zones

The integration of gravity data, GNSS deformation models, and seismicity clustering enables a comprehensive assessment of

tectonically active regions and highlights areas at risk of future seismic events [42]. High FHD values indicate sharp density contrasts along the Palu-Koro Fault zones, suggesting regions of significant stress concentration and build-up of tectonic forces [5]. The TDR maps enhance the detection of secondary faults and lineaments that contribute to the structural complexity and increase seismic risk in adjacent zones, which can also host seismic events.

Meanwhile, the GNSS-high shear strain zones align with strike-slip Palu-Koro Fault activity, which causes the regions to be prone to seismic events due to the build-up and release of lateral tectonic forces. The GNSS-dilatation shows that the extensional zones, such as pull-apart basins, are associated with fault activity, while compressional zones indicate areas of tectonic loading. Moreover, earthquake clustering shows that high-density seismic clusters align with GNSS strain zones and gravity-derived fault geometries, confirming areas of active deformation. Based on the seismic depth distribution, it shows that the shallow earthquakes (<30 km) correspond to surface deformation zones identified by GNSS data, while intermediate-depth events (30–70 km) validate subsurface fault activity highlighted in gravity data. On the other hand, the areas with low seismicity (seismic gap) but high GNSS strain rates and gravity anomalies indicate potential seismic hazard zones where stress is accumulating without immediate release [10].

The integration of these gravity, GNSS, and seismic analysis enables a comprehensive assessment of seismic hazard zones:

- (1) Subsurface to surface correlation, where gravity anomalies reveal stress accumulation at depth, while GNSS data

confirm strain accumulation at the surface. Seismicity clustering validates fault activity in these regions.

- (2) Active fault segments, where High FHD values, GNSS-derived shear strain rates, and seismic clusters consistently identify active fault segments as potential seismic hazard zones.
- (3) Secondary hazards, where secondary fault branches and lineaments identified in TDR maps align with localized GNSS deformation and seismic clusters, highlight smaller but significant hazard zones.

6. Conclusion

This study integrates gravity data, GNSS deformation models, and seismicity clustering to provide a comprehensive analysis of the Palu-Koro Fault. The results reveal significant insights into Palu-Koro Fault geometries, surface deformation patterns, and seismic hazard zones.

- (1) The validation of Palu-Koro Fault geometries shows that subsurface density contrasts identified through gravity anomalies, particularly high FHD and TDR values, align with GNSS-derived shear strain patterns and seismicity clusters, confirming active fault segments. The secondary fault branches and lineaments can also be identified from gravity and seismic data, emphasizing the complexity of the fault system.
- (2) The correlation of surface deformation with Palu-Koro fault activities, as shown by the GNSS data, can reveal high shear strain and dilatation patterns that align with gravity-inferred density contrasts and seismicity clustering, highlighting zones of active tectonic motion. The temporal validation from seismic clustering confirms the ongoing deformation processes along the Palu-Koro Fault system.
- (3) The identification of seismic hazard zones results in zones with overlapping high-density gravity anomalies, GNSS strain accumulation, and seismic clustering, which represent areas of significant seismic hazard potential. The secondary faults and tectonic lineaments identified in TDR maps align with localized deformation and seismic activity, marking additional risk zones.

The integration of these datasets provides a robust framework for analyzing Palu-Koro and surrounding fault systems, advancing our understanding of tectonic processes, and enhancing seismic hazard assessments in the Sulawesi region.

CRedit authorship contribution statement

Leni Sophia Heliani: Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Cecep Pratama:** Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ade Anggraini:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bondan Galih Dewanto:** Validation, Software, Data curation. **Al Shida Natul:** Visualization, Formal analysis, Data curation. **Dwi Lestari:** Validation, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that there is no conflicts of interest.

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