



Subsurface architecture of the Enggano forearc revealed by satellite gravity and integrated 2D–3D modeling

Dea Elfira Primasiwi^a, Ikah Ning Prasetyowati Permanasari^a, Rahmat Nawi Siregar^{a,*}

^a Department of Physics, Institut Teknologi Sumatera, Way Huwi, Jati Agung, South Lampung, Lampung 35365, Indonesia

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ABSTRACT

Enggano Island is located within the forearc of the Sunda subduction system, where the Indo-Australian Plate converges obliquely beneath the Sunda Plate and generates high tectonic and seismic activity. This study investigates the subsurface architecture beneath Enggano Island using satellite-derived gravity data integrated with spectral analysis and two- and three-dimensional gravity modeling. Free-air anomaly and topographic data obtained from the TOPEX dataset were processed to derive the complete Bouguer anomaly, followed by separation of regional and residual gravity components. Spectral analysis was applied to estimate the characteristic depths of gravity sources, while 2D forward modeling and 3D inversion were used to constrain the geometry and density distribution of subsurface structures. The complete Bouguer anomaly ranges from 73.8 to 1350.8 mGal, with relatively high anomalies concentrated in the southwestern part of the study area and lower anomalies toward the eastern and southeastern sectors. Spectral analysis indicates characteristic source depths of approximately 10.35 km for the regional component and 5.98 km for the residual component. The 2D gravity model identifies a high-density oceanic crustal body of approximately 3.43 g/cm³ descending beneath a continental crustal domain with a density of approximately 2.67 g/cm³. The model also resolves the Kemiki, Kuwau, and Malakoni formations together with Quaternary alluvium beneath Enggano Island. Three-dimensional inversion further indicates that the high-density subducting structure becomes recognizable from approximately 4.05 km depth. These results demonstrate that satellite gravity data, combined with integrated 2D–3D modeling, can provide first-order constraints on the subsurface geometry of the Enggano forearc and its relation to the Sunda subduction system.

1. Introduction

The western margin of Sumatra is one of the most tectonically active regions in Southeast Asia, where the Indo-Australian Plate converges obliquely beneath the Sunda Plate along the Sunda subduction zone. This convergence has produced a complex tectonic system consisting of the deep-sea trench, accretionary prism, forearc basin, volcanic arc, and major strike-slip structures across Sumatra. The oblique nature of convergence also contributes to distributed deformation within the overriding plate and the development of major tectonic structures parallel to the western margin of the island. Within this regional framework, the forearc islands west of Sumatra represent important surface expressions of the accretionary system and provide valuable constraints on the geometry and evolution of the plate boundary [1, 2].

Enggano Island occupies the southern part of this forearc system and is situated close to the active Sunda subduction zone. Its tectonic position makes the region particularly important for understanding the relationship between crustal structure, density contrasts, and subduction-related deformation. The original geological interpretation of the study area indicates that Enggano is associated with the accretionary prism and is influenced by regional fault systems generated by oblique plate convergence. The island itself is composed of several sedimentary and volcanic-sedimentary units, including the Kuwau, Kemiki, and Malakoni formations as well as younger alluvial deposits [3–5].

The combination of active convergence, complex lithology, and structural deformation makes the subsurface architecture beneath Enggano difficult to characterize using surface geological observations alone. The tectonic significance of the Enggano region is further emphasized by its high seismic activity.

* Corresponding author.

E-mail address: rahmat.siregar@fi.itera.ac.id (R. N. Siregar).

Historical seismicity around western Sumatra indicates repeated large earthquakes associated with the subduction system, including events attributed to the Enggano segment. The thesis dataset also documents a high concentration of earthquakes around the study region and relates this seismicity to the interaction between the oceanic and overriding plates [6, 7].

Previous regional investigations have additionally suggested the presence of spatially variable gravity anomalies and possible locking behavior along the forearc and subduction system west of Sumatra. In particular, gravity and bathymetric observations have been interpreted to reflect substantial lateral variations in crustal density and tectonic structure within the forearc [8–10]. These characteristics highlight the need for improved constraints on the geometry and density distribution of subsurface structures beneath Enggano.

Gravity methods provide an effective means of investigating such structures because variations in the measured gravity field are directly related to lateral and vertical contrasts in subsurface density. In tectonically complex regions, gravity anomalies can therefore be used to infer changes in crustal composition, sedimentary thickness, fault-related structures, and high-density lithospheric bodies. Satellite-derived gravity datasets are particularly useful for offshore and island settings such as Enggano, where dense terrestrial gravity observations are difficult to obtain. The use of satellite gravity allows continuous regional coverage and provides a practical basis for identifying first-order crustal structures before more detailed geophysical surveys are conducted. In the present study, gravity and elevation data derived from the TOPEX dataset are used to investigate the spatial variation of the gravity field around Enggano Island [3, 11].

Previous gravity studies along the western Sumatra forearc have demonstrated the potential of satellite gravity for investigating the subduction system. Regional studies have identified pronounced gravity contrasts associated with the oceanic plate, forearc structures, and accretionary domains. A previous investigation in the Pagai–Sipora sector, for example, used TOPEX gravity data and 2D–3D modeling to interpret a high-density oceanic plate descending beneath a lower-density continental domain [12, 13]. However, comparable integrated analyses specifically focused on Enggano Island remain limited in the source material used in this study. In particular, the combined use of complete Bouguer anomalies, spectral analysis, regional–residual separation, 2D forward modeling, and 3D inversion offers an opportunity to obtain a more coherent representation of the subsurface density architecture beneath this southern forearc sector [6, 14, 15].

Accordingly, this study aims to characterize the gravity anomaly distribution and reconstruct the subsurface structure beneath Enggano Island using satellite-derived gravity data. The analysis integrates complete Bouguer anomaly mapping, spectral analysis, separation of regional and residual components, 2D forward modeling, and 3D gravity inversion. The specific objectives are to identify the spatial distribution of gravity anomalies, estimate the characteristic depths of regional and residual gravity sources, constrain the density distribution and geometry of major subsurface units, and evaluate their possible relationship with the subduction-related structure beneath the Enggano forearc. By integrating these approaches, the study provides a first-order geophysical model of the subsurface architecture of Enggano Island and contributes to a better understanding of density variations within the Sunda forearc.

2. Method

2.1. Study area and geological setting

Enggano Island is located offshore of southwestern Sumatra within the Bengkulu Province, Indonesia, and forms part of the forearc system of the Sunda subduction zone. The study area extends approximately from 4°52′08.94″ to 5°33′27.33″ S and from 100°51′27.42″ to 102°44′19.97″ E. This region lies between the Indian Ocean to the southwest and the western margin of Sumatra to the northeast and encompasses Enggano Island and the surrounding offshore area (Fig. 1).

Geologically, Enggano Island consists of several stratigraphic units, including the Kuwau, Kemiki, and Malakoni formations, together with younger alluvial deposits. These units are associated with the accretionary-prism environment of the Sunda forearc and are affected by regional tectonic structures related to oblique convergence along the western Sumatra margin. The geological information was used as an independent constraint for interpretation of the gravity-derived subsurface models [6, 14, 15].

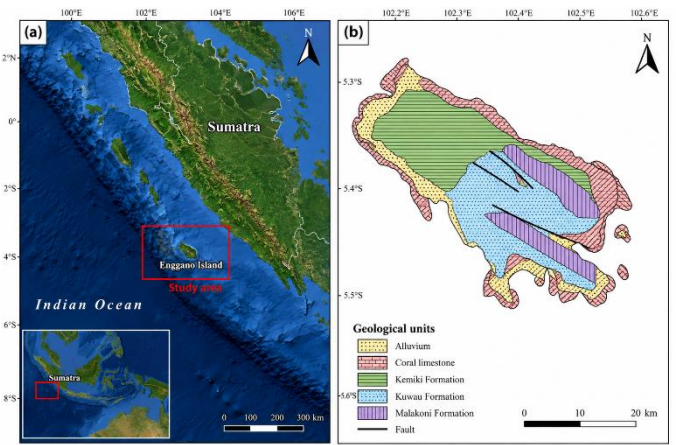


Fig. 1. Location and geological setting of Enggano Island, western Sumatra, Indonesia.

2.2. Gravity and ancillary datasets

The gravity analysis was based on secondary satellite-derived data obtained from the TOPEX database. The dataset was accessed on 5 June 2022 and contains geographic coordinates, elevation, and free-air anomaly (FAA) values for the study region. The gravity observations were provided on a regularly distributed spatial grid and were subsequently processed to derive the Bouguer anomaly used for subsurface interpretation [4, 16].

Topographic information required for terrain correction was obtained from Shuttle Radar Topography Mission (SRTM) data provided by the United States Geological Survey. Geological information and earthquake hypocenter data were additionally incorporated to constrain and evaluate the geophysical interpretation [17, 18]. According to the original workflow (Fig. 2), the gravity processing and modeling were conducted using Microsoft Excel, Oasis Montaj 8.4, Surfer, Grablox 1.6e, and Bloxer 1.6e.

2.3. Bouguer anomaly processing

The free-air anomaly data were corrected for the gravitational contribution of material between the observation point and the reference datum. An average surface density was first estimated by evaluating the relationship between Bouguer anomaly and elevation over a range of assumed densities. The density adopted for the Bouguer correction was 2.55 g cm⁻³, as determined from the minimum correlation between the gravity anomaly and topography in the original processing workflow [19–21]. The simple Bouguer anomaly (SBA) was calculated as Equation (1).

$$SBA = FAA - g_B \quad \dots (1)$$

where FAA is the free-air anomaly and g_B is the Bouguer correction. The Bouguer correction was calculated as Equation (2).

$$g_B = 0.04193\rho h \quad \dots (2)$$

where ρ is the assumed Bouguer density in g cm^{-3} and h is the elevation in meters. Because topographic relief around the observation points can modify the measured gravity field, terrain correction was subsequently applied using SRTM topographic data [14, 22, 23]. The complete Bouguer anomaly (CBA) was then calculated as Equation (3).

$$CBA = SBA - TC \quad \dots (3)$$

where TC denotes the terrain correction. The resulting complete Bouguer anomaly dataset was transformed into Universal Transverse Mercator coordinates and gridded for subsequent spectral analysis, regional–residual separation, and gravity modeling.

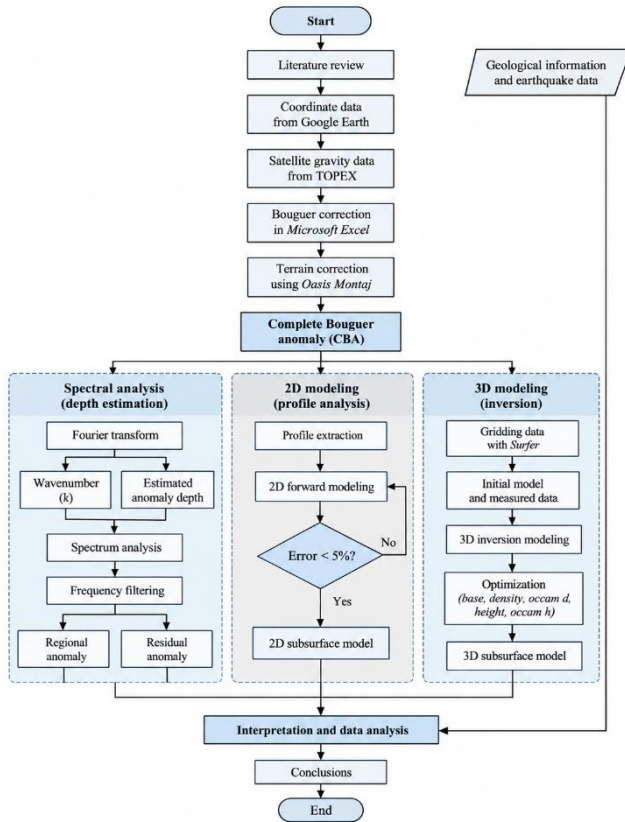


Fig. 2. Simplified research workflow.

2.4. Spectral analysis and regional–residual separation

Spectral analysis was applied to the complete Bouguer anomaly to estimate the characteristic depths of gravity sources and determine the wavelength threshold used for anomaly separation. The gravity data were transformed from the spatial domain into the wavenumber domain using the Fourier transform [14, 22, 23].

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

where $f(x)$ represents the gravity anomaly along the analyzed profile and (k) is the wavenumber.

The logarithm of the amplitude spectrum was evaluated as a function of wavenumber. Linear segments of the spectrum were interpreted as representing gravity sources at different characteristic depths, with the slope of each segment providing an estimate of source depth. The resulting spectral characteristics were subsequently used to define the cutoff wavelengths for separating deeper regional and shallower residual components.

Regional and residual gravity anomalies were separated in Oasis Montaj. According to the original processing workflow, low-

pass filtering was used to isolate the long-wavelength regional component, whereas a band-pass filtering procedure was employed to resolve the shorter-wavelength residual component [6, 14, 15].

2.5. Two-dimensional gravity forward modeling

Two-dimensional forward modeling was performed along a southwest–northeast profile crossing Enggano Island. The profile was selected from the complete Bouguer anomaly map to intersect the principal gravity gradient and the major geological domains interpreted across the study area. The original profile extended for approximately 175 km, from the Indian Ocean southwest of Enggano toward the eastern part of the study region, with a maximum model depth of approximately 21.54 km. The initial geometry and density values were constrained using the regional geological information and representative rock densities [8].

Forward modeling was conducted by iteratively modifying the geometry and density of subsurface bodies until the calculated gravity response reproduced the observed anomaly. The original modeling procedure applied a trial-and-error adjustment and considered a model acceptable when the discrepancy between the observed and calculated responses was less than 5% [6, 14, 15].

2.6. Three-dimensional gravity inversion

Three-dimensional gravity modeling was performed using Grablox 1.6e and subsequently visualized and interpreted using Bloxer 1.6e. The inversion domain covered approximately 209.415 km in the x direction and 76.421 km in the y direction, with a vertical extent of 21.54 km. The model domain was discretized into 20×20 horizontal cells for each layer, corresponding to 400 cells per layer. Ten vertical layers were used, yielding a total of 4,000 model blocks. The initial density range extended from approximately 1.0 to 3.43 g cm^{-3} , with the density constraints derived from the preceding 2D gravity interpretation.

The initial forward model was subsequently refined through inversion. According to the workflow implemented in the original study, model optimization involved sequential adjustments of the model base, density, height, and Occam-type density and height parameters. The inversion was used to minimize the discrepancy between the observed and calculated gravity fields and to reconstruct the three-dimensional density distribution beneath Enggano Island.

2.7. Integrated geological and seismotectonic interpretation

The gravity-derived models were interpreted by integrating the density distribution with available geological information and earthquake hypocenter data. Lithological assignments in the 2D model were constrained using the mapped geological formations of Enggano Island, whereas the spatial distribution of high- and low-density domains in the 3D model was evaluated with respect to the regional tectonic configuration.

Earthquake hypocenter data were additionally compared with the complete Bouguer anomaly and interpreted subsurface structure to assess the spatial correspondence between seismicity and the inferred subduction-related density architecture [16]. This integrated interpretation was used to evaluate the relationship between the gravity anomalies, crustal density contrasts, forearc structure, and the subduction system beneath Enggano Island.

3. Results and discussion

3.1. Spectral characteristics and depth of gravity sources

Spectral analysis of the complete Bouguer anomaly reveals three distinguishable wavelength domains that can be associated with regional, residual, and high-frequency components of the gravity field (Fig. 3a). The logarithmic amplitude spectrum shows clear changes in gradient with increasing wavenumber, indicating that the observed gravity field is generated by sources occurring at different characteristic depths. The transition between the regional and residual components occurs at a cutoff wavenumber of approximately 0.02588, whereas the transition toward the higher-frequency component occurs at approximately 0.094883. These spectral boundaries provide the basis for separating long-

wavelength gravity variations from shallower, shorter-wavelength anomalies.

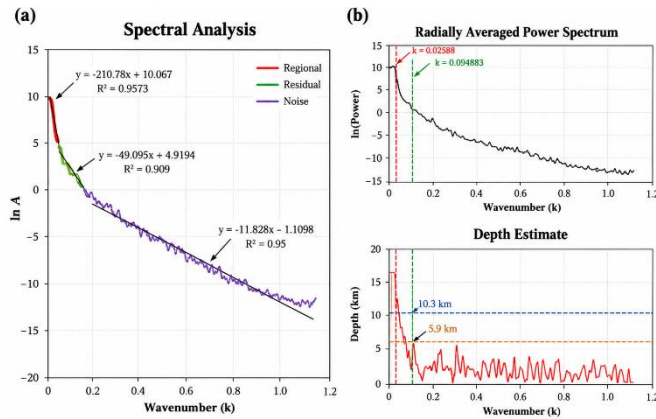


Fig. 3. Spectral analysis and depth estimation of the complete Bouguer anomaly. (a) Logarithmic amplitude spectrum showing regional, residual, and noise components. (b) Radially averaged power spectrum and estimated source depths, with characteristic depths of approximately 10.3 and 5.9 km.

The depth estimates derived from the spectrum indicate a characteristic regional source depth of approximately 10.35 km and a residual source depth of approximately 5.98 km (Fig. 3b). These values are consistent with the values of 10.3472 and 5.97787 km obtained from the original spectral analysis. The distinction between the two source levels suggests that the gravity field around Enggano Island contains contributions from both deeper crustal-scale structures and shallower density heterogeneities associated with the forearc and island geology.

Fig. 3 therefore provides an important depth constraint for the subsequent interpretation. The long-wavelength regional component is interpreted as representing deeper and more laterally extensive density variations, whereas the residual field emphasizes shallower geological structures. Rather than assigning individual spectral depths directly to a specific lithological boundary, these values are more appropriately regarded as characteristic depths of ensembles of gravity sources. Such an interpretation is particularly important in a tectonically complex forearc setting, where several bodies with contrasting densities may contribute simultaneously to the observed gravity field [24–25].

The separated regional anomaly ranges from approximately 50.6 to 344.8 mGal, whereas the residual anomaly varies from approximately –85.2 to 66.8 mGal. The relatively broad residual range indicates substantial short-wavelength density contrasts beneath and around Enggano Island. These shallower contrasts are subsequently investigated using the 2D and 3D gravity models.

3.2. Complete Bouguer anomaly distribution

The complete Bouguer anomaly across the Enggano region ranges from approximately 73.8 to 1350.8 mGal (Fig. 4). According to the original gravity interpretation, the highest anomaly values, approximately 765.4–1350.8 mGal, occur toward the southwestern part of the study region, whereas lower values of approximately 73.8–280.4 mGal characterize the eastern to southeastern sectors. This large spatial variation indicates pronounced lateral contrasts in subsurface mass distribution across the forearc system.

The anomaly pattern is unlikely to be controlled by a single geological body. Rather, it reflects the combined gravitational response of the oceanic domain, sedimentary sequences, the forearc architecture, Enggano Island, and the crust toward mainland Sumatra. High gravity values are generally consistent with domains containing relatively dense material, whereas lower

anomalies may reflect thicker accumulations of lower-density sedimentary material or other low-density crustal domains. Consequently, the Bouguer anomaly map should be interpreted primarily as a representation of integrated subsurface density variation rather than as a direct map of individual geological boundaries.

The location of profile A–A' is also shown in Fig. 4. The profile extends for approximately 175 km from the southwestern offshore domain toward the east–northeast and intersects Enggano Island before approaching the continental side of the study area. The profile was selected to cross the principal gravity gradient and thereby sample the transition among the major density domains identified from the Bouguer anomaly field.

The strong gravity gradient encountered along A–A' is particularly important because it implies a significant lateral variation in the density architecture of the subsurface. The 2D forward model was therefore used to test whether this variation could be represented by a configuration consisting of relatively dense oceanic material, sedimentary cover, and a lower-density overriding crustal domain.

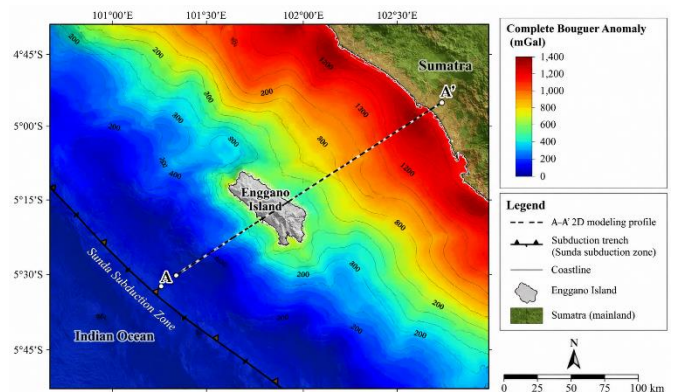


Fig. 4. Complete Bouguer anomaly map of the Enggano Island study area, showing the spatial distribution of gravity anomalies and the location of the A–A' profile used for two-dimensional gravity modeling. Higher anomaly values are concentrated toward the northeastern part of the study area, whereas lower values occur toward the southwestern offshore region. The Sunda subduction zone is shown for tectonic context.

3.3. Two-dimensional subsurface structure

The 2D forward model along profile A–A' provides a satisfactory reproduction of the observed gravity response (Fig. 5a). The calculated gravity curve follows the overall variation in the observed complete Bouguer anomaly, with a reported modeling error of 4.912%. The original profile spans gravity values of approximately 100–1580 mGal and extends to a model depth of approximately 21.54 km. The relatively small mismatch between the calculated and observed responses indicates that the adopted density configuration represents a plausible first-order model of the subsurface, although the inherent non-uniqueness of gravity modeling should be recognized.

A prominent feature of the model is a high-density body interpreted as oceanic crust, assigned a density of approximately 3.43 g/cm³, that extends beneath a lower-density crustal domain with a density of approximately 2.67 g/cm³ (Fig. 5b). The geometry of this density contrast is consistent with the regional expectation of an oceanic plate descending beneath the overriding forearc–continental system. In the original model, this geometry becomes apparent near the offshore sector at a depth of approximately 5.96 km, where the model also incorporates the deep marine environment. The overlying marine sedimentary material was represented by a density of approximately 1.82 g/cm³.

Toward Enggano Island, the model contains several shallower bodies that were correlated with mapped geological units. The

Kuwau Formation (Tmk), composed principally of interbedded sandstone, siltstone, and claystone, was represented by a density of approximately 2.35 g/cm^3 . The Kemiki Formation (Tmkp), which includes tuff, sandy tuff, and tuffaceous siltstone, was modeled at approximately 1.80 g/cm^3 . The Malakoni Formation (QTm), characterized by reef limestone, calcirudite, calcarenite, and related carbonate material, was represented by a density of approximately 2.55 g/cm^3 , whereas younger alluvial deposits were assigned a lower density of approximately 1.70 g/cm^3 .

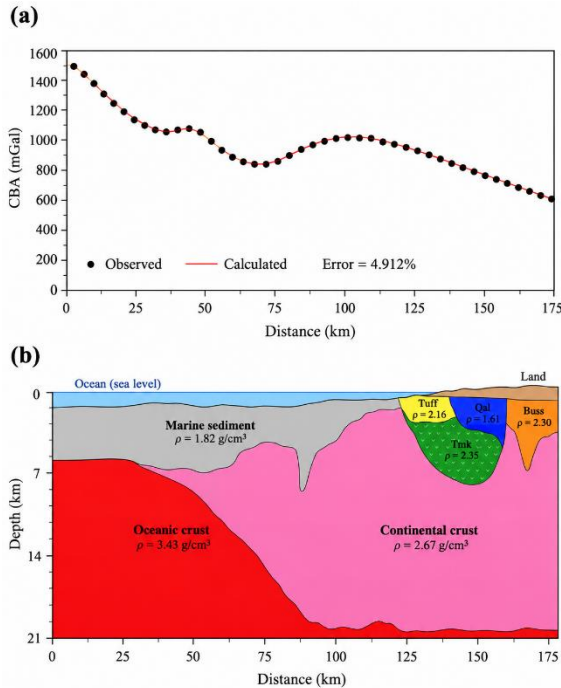


Fig. 5. Two-dimensional gravity forward modeling along profile A–A' across the Enggano Island region. (a) Comparison between observed and calculated complete Bouguer anomaly values, showing a modeling error of 4.912%. (b) Interpreted subsurface density model indicating the oceanic crust (3.43 g/cm^3) descending beneath the continental crust (2.67 g/cm^3), together with marine sediment and the principal geological units of Enggano Island.

These density variations demonstrate that the gravity response across Enggano cannot be explained solely by the deeper crustal contrast. Shallow sedimentary and carbonate units also modify the shorter-wavelength component of the anomaly. This interpretation is consistent with the spectral analysis in Fig. 3, which identifies both deep and shallow source populations. Thus, the spectral results and the 2D model provide mutually complementary constraints: the former estimates characteristic source depths, whereas the latter translates the anomaly variations into a geologically interpretable density configuration.

Nevertheless, the 2D model represents only one cross-section through a three-dimensional geological system. Bodies outside the profile plane can contribute to the observed gravity response, and different combinations of geometry and density may generate similar anomalies. For this reason, the interpretation was extended using 3D inversion [24].

3.4. Three-dimensional density distribution

The 3D inversion resolves substantial lateral and vertical heterogeneity in density beneath the Enggano region (Fig. 6). The inversion model spans densities from approximately 1.00 to 3.43 g/cm^3 , with an average density of 2.23496 g/cm^3 across the model blocks. The modeled volume extends to approximately 21.54 km depth and was discretized into 400 blocks per layer and 10 vertical layers, resulting in a total of 4000 inversion blocks.

Fig. 6 highlights the heterogeneous character of the subsurface in three dimensions. Higher-density domains are interspersed with intermediate- and lower-density material rather than forming a simple planar boundary. This is expected in a forearc environment consisting of oceanic crust, sedimentary packages, accretionary materials, and overriding crustal units. The occurrence of high-density material toward the oceanic side and at depth is consistent with the high-density body inferred independently from the 2D profile.

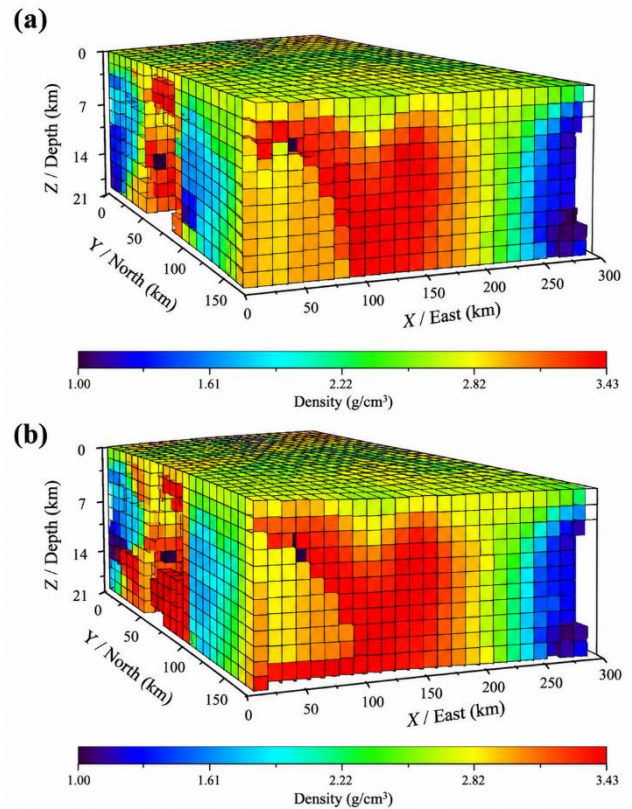


Fig. 6. Three-dimensional density distribution beneath the Enggano Island region derived from gravity inversion. (a–b) Alternative views of the final 3D voxel model showing lateral and vertical variations in subsurface density over the modeled volume. The color scale represents density values ranging from approximately 1.00 to 3.43 g/cm^3 , highlighting contrasting low- and high-density domains within the forearc subsurface structure.

The third model layer, corresponding to approximately 4.05 – 6.11 km depth, has density values between approximately 1.00 and 3.43 g/cm^3 and an average density of approximately 2.9 g/cm^3 . Low-density zones within this layer were interpreted in the original study as sedimentary material, whereas the highest densities were associated with mafic lithologies such as gabbroic material typical of oceanic crust. The appearance of the high-density domain from approximately 4.05 km depth is one of the principal observations of the inversion and provides an independent three-dimensional constraint on the geometry identified in the 2D model [26].

To emphasize these spatial relationships, selected horizontal and vertical representations of the inversion are presented in Fig. 7. These views show that the density architecture varies both laterally and with depth, with the high-density domain becoming increasingly prominent beneath the forearc. The density contrast is not interpreted as a perfectly sharp petrological interface; rather, the gravity inversion depicts a smoothed representation of subsurface mass distribution. Consequently, boundaries inferred from the 3D model should be considered approximate zones of transition [27].

The deeper model is also informative. The original interpretation selected the tenth layer, beginning at approximately 18.53 km, as a representative deeper section. At this depth, relatively high densities were interpreted as reflecting predominantly mafic lithologies, including basaltic and diabasic material. The persistence of relatively dense material to this depth supports the interpretation that the gravity field is influenced by a substantial high-density crustal component rather than only by shallow lithological variations.

Taken together, Figs. 6 and 7 demonstrate that the 3D inversion broadly supports the main structural configuration inferred from the 2D forward model. The principal contribution of the 3D model is therefore not to provide a unique lithological solution, but to show that the high-density structure has appreciable lateral extent and can be traced through multiple depth levels.

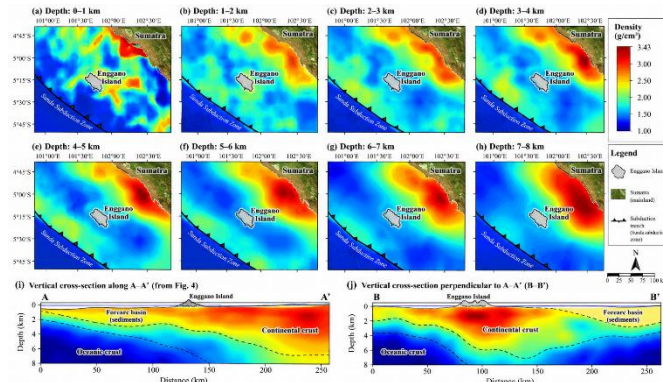


Fig. 7. Horizontal and vertical representations of the three-dimensional density model beneath the Enggano Island region. (a) Horizontal density slices at selected depths from approximately 1 to 5 km, illustrating the lateral variation of subsurface density. (b) Vertical cross-sections along profiles A-A' and B-B' showing the interpreted transition from oceanic crust beneath the Indian Ocean toward the forearc and continental crust beneath Enggano Island and mainland Sumatra. (c) Three-dimensional perspective view of the density model, highlighting the spatial relationship between Enggano Island, the Sunda subduction zone, and the main subsurface density domains. Density values range from approximately 1.00 to 3.43 g/cm³.

3.5. Integrated tectonic interpretation of the Enggano forearc

The combined gravity results support a first-order tectonic interpretation in which a relatively high-density oceanic domain extends beneath a lower-density forearc–continental system beneath Enggano Island. This relationship is summarized in Fig. 8, which integrates the 2D forward model, 3D inversion, and regional tectonic setting into a single conceptual interpretation.

The most important evidence is the consistency among several independent components of the gravity analysis. First, the complete Bouguer anomaly exhibits a strong regional gradient (Fig. 4). Second, spectral analysis identifies both deep and shallow characteristic source levels (Fig. 3). Third, the 2D model requires a high-density body of approximately 3.43 g/cm³ beneath a lower-density domain of approximately 2.67 g/cm³ to reproduce the observed gravity response (Fig. 5). Finally, the 3D inversion identifies high-density material beginning at approximately 4.05 km depth and continuing into deeper model layers (Figs. 6 and 7).

On this basis, the high-density body is interpreted as representing the oceanic plate or oceanic crustal domain associated with the Sunda subduction system, whereas the overlying and landward lower-density material represents forearc sedimentary and crustal units. Fig. 8a–b illustrates the principal vertical density relationships along two orientations,

while Fig. 8c summarizes their three-dimensional geometry. Fig. 8d presents the resulting tectonic concept, in which the oceanic plate descends beneath the Enggano forearc and toward the continental margin.

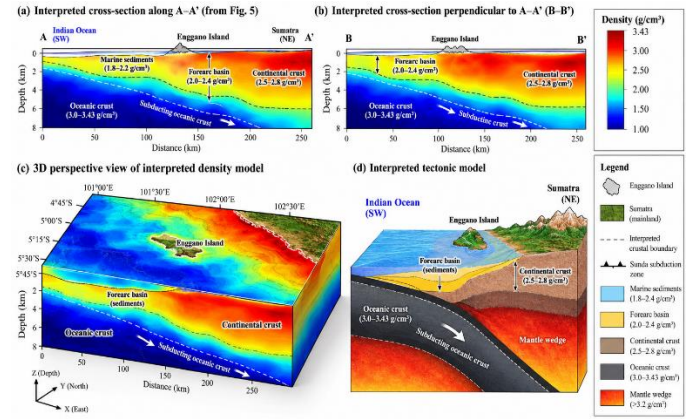


Fig. 8. Integrated interpretation of the subsurface structure beneath Enggano Island derived from the gravity inversion results. (a) Vertical density section along profile A-A', (b) vertical section perpendicular to A-A' (B-B'), (c) three-dimensional perspective view of the interpreted density model, and (d) conceptual tectonic model showing the subducting oceanic crust, forearc basin, continental crust, and mantle wedge beneath the Enggano forearc region.

This interpretation is also compatible with the seismicity distribution reported in the original study. Earthquake hypocenters from the USGS catalog for 1921–2021 are concentrated around the Enggano region, with the dataset dominated by events shallower than approximately 60 km. The occurrence of shallow seismicity near the forearc and trench is consistent with an actively deforming plate-boundary environment. However, the hypocenter distribution should be regarded as complementary tectonic evidence rather than direct validation of the gravity-derived density boundaries because earthquake locations and gravity anomalies respond to different physical properties.

The integrated model in Fig. 8 therefore represents a plausible structural interpretation rather than a uniquely resolved geological geometry. Gravity inversion is intrinsically non-unique, and the results depend on the assumed density range, model parameterization, and available geological constraints. In addition, the gravity dataset used here is satellite-derived rather than based on a dense network of terrestrial or marine gravimetric observations. These limitations mean that absolute boundary depths should be treated cautiously.

Nevertheless, the agreement between the spectral depths, 2D forward model, 3D inversion, mapped geology, and regional tectonic context provides a coherent first-order picture of the Enggano forearc. The results indicate that the gravity field records both shallow lithological heterogeneity associated with the geological formations of Enggano Island and a deeper high-density structure related to the oceanic plate. The combination of these components explains why the gravity signature is spatially complex and why a single-layer interpretation would be insufficient [28–29].

Most importantly, the integration shown in Figs. 3–8 demonstrates the value of combining spectral analysis, regional–residual separation, 2D forward modeling, and 3D inversion rather than relying on a single gravity product. Spectral analysis constrains characteristic source depths, the Bouguer anomaly defines the regional density gradient, the 2D model provides a detailed cross-sectional interpretation, and the 3D inversion evaluates the lateral continuity of the inferred density structure. Together, these approaches provide a more robust framework for interpreting the subsurface architecture of Enggano Island within the Sunda forearc.

4. Conclusion

This study demonstrates that satellite-derived gravity data, when integrated with spectral analysis, 2D forward modeling, and 3D inversion, can provide a coherent first-order representation of the subsurface structure beneath Enggano Island and the surrounding Sunda forearc. The complete Bouguer anomaly exhibits a broad range of approximately 73.8–1350.8 mGal, indicating strong lateral density contrasts across the study area. Spectral analysis further distinguishes deeper and shallower gravity-source components, with characteristic depths of approximately 10.35 km for the regional component and 5.98 km for the residual component.

The 2D gravity model along profile A–A' indicates a high-density oceanic crustal domain of approximately 3.43 g/cm³ descending beneath a lower-density crustal domain of approximately 2.67 g/cm³. The model also resolves shallower units associated with the Kuwau, Kemiki, and Malakoni formations and alluvial deposits, showing that both deep crustal structure and local lithological variations contribute to the observed gravity field.

The 3D inversion supports the 2D interpretation by revealing a heterogeneous density distribution between approximately 1.00 and 3.43 g/cm³. A prominent high-density structure becomes apparent from about 4.05 km depth and persists into deeper model levels, providing additional support for the interpretation of a subduction-related oceanic crustal body beneath the Enggano forearc.

Overall, the combined interpretation of Figs. 3–8 indicates that the gravity field around Enggano Island reflects the interaction of shallow sedimentary and volcanic-sedimentary units with a deeper high-density crustal structure associated with the Sunda subduction system. Although the gravity solution is non-unique and should be constrained further using terrestrial or marine gravity, seismic, or other geophysical observations, the present results provide a useful regional framework for understanding the density architecture and tectonic configuration of the Enggano forearc.

CRedit authorship contribution statement

Dea Elfira Primasiwi: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ikah Ning Prasetyowati Permanasari:** Writing – review & editing, Investigation. **Rahmat Nawi Siregar:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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