



Gravity-derived subsurface architecture and structural controls of the Terak and Keretak non-volcanic geothermal areas, central Bangka, Indonesia

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ABSTRACT

The Terak and Keretak geothermal areas in Central Bangka represent non-volcanic geothermal manifestations developed within a granitic and structurally deformed geological setting. This study investigates the subsurface density architecture and possible structural controls of these geothermal areas using satellite-derived gravity data. Free-air anomaly and elevation data were processed to obtain the Complete Bouguer Anomaly, followed by spectral analysis, regional-residual anomaly separation, two-dimensional forward modelling, and three-dimensional gravity inversion. The Complete Bouguer Anomaly ranges from approximately 23.7 to 40.9 mGal and shows distinct lateral gravity variations across the study area. Spectral analysis indicates two principal depth domains, with approximate boundaries at 2.7 and 6.8 km, interpreted as representing shallower residual and deeper regional gravity sources. The residual anomaly ranges from approximately -2.9 to 3.4 mGal, whereas the regional anomaly ranges from approximately 24.0 to 39.8 mGal. Two-dimensional and three-dimensional models indicate contrasting subsurface density domains that are consistent with Alluvium, the Tanjung Genting Formation, Klabat Granite, and the Pemali Complex. Higher-density domains are predominantly associated with granitic and basement-related materials, whereas lower-density zones correspond to shallower sedimentary units. The spatial correspondence between gravity gradients, interpreted structural boundaries, and the Terak and Keretak manifestations suggests that fault-related structures may influence subsurface fluid circulation. However, the gravity data primarily constrain density contrasts and structural geometry; therefore, the proposed radiogenic heat source and geothermal-fluid pathways should be regarded as a geological interpretation rather than direct evidence. These results provide a preliminary geophysical framework for understanding the subsurface architecture of the Terak and Keretak non-volcanic geothermal areas and for guiding future integrated geothermal investigations.

1. Introduction

Non-volcanic geothermal systems are increasingly recognized as important geothermal resources because they may occur outside active volcanic arcs and can be controlled by deep-seated structures, radiogenic heat production, and circulation of meteoric water through permeable crustal zones. In granitic terrains, long-lived radioactive isotopes such as U, Th, and K may contribute to crustal heat production, while fractures and faults provide pathways for groundwater circulation and heat transfer. In such settings, understanding the subsurface density architecture and structural framework is essential for evaluating

possible geothermal controls and identifying zones that may facilitate fluid migration [1, 2].

Bangka Island is part of the Sunda Shelf and is characterized by a complex geological history involving granitic intrusions, sedimentary and metamorphic units, and multiple fault and fracture systems [3–5]. The island contains widespread granitic rocks, including the Klabat Granite, which formed during the Triassic–Jurassic and is regionally associated with tin-bearing and radioactive minerals [6, 7]. Previous studies have reported the presence of monazite and elevated concentrations of Th and U in parts of the Bangka–Belitung region, providing a geological basis for considering radiogenic heat production as a possible contributor to local geothermal activity [8–10].

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The Terak and Keretak geothermal areas in Central Bangka are examples of non-volcanic geothermal manifestations occurring within this granitic setting. Previous observations indicate the presence of hot springs and structurally deformed rocks in both areas, while regional geological information suggests that normal and strike-slip faults are common and may influence subsurface permeability. The Terak manifestation, for example, has been reported to have a surface temperature of approximately 61.8 °C, with clear water, low discharge, and mildly acidic conditions [3, 11]. Previous magnetic investigations in the Keretak area also inferred shallow granitic bodies and subsurface structures beneath the geothermal manifestation.

Although previous studies have provided geological, magnetic, and geochemical information for parts of Bangka Island, the subsurface density distribution beneath the Terak and Keretak geothermal areas remains insufficiently constrained. In particular, the geometry of high- and low-density domains, the depth extent of possible granitic bodies, and their spatial relationship with mapped structures and geothermal manifestations require further investigation. This is important because gravity data can provide first-order constraints on subsurface density contrasts and can be used to evaluate regional and residual anomaly patterns, estimate source depths, and construct two-dimensional and three-dimensional density models. The original study therefore used satellite-derived gravity data as a preliminary geophysical approach to investigate the subsurface structure of both geothermal areas [12, 13].

However, gravity interpretation is inherently non-unique, and density anomalies cannot independently determine lithology, heat production, or fluid circulation [6, 14, 15]. Therefore, gravity-derived structures should be interpreted together with regional geology and previous geophysical observations, while geothermal implications should be treated as conceptual rather than direct evidence. This distinction is particularly important for the Terak and Keretak areas, where the proposed radiogenic heat source and structurally controlled fluid pathways have not yet been directly validated by borehole, heat-flow, or subsurface geochemical data [4, 16].

Accordingly, this study aims to characterize the subsurface density architecture of the Terak and Keretak non-volcanic geothermal areas using satellite-derived gravity data. The analysis integrates Complete Bouguer Anomaly mapping, spectral analysis, regional–residual anomaly separation, two-dimensional forward modelling, and three-dimensional inversion. The objectives are to identify major subsurface density contrasts, estimate the depth distribution of gravity sources, evaluate possible structural boundaries associated with the geothermal manifestations, and assess how the gravity-derived architecture is consistent with the existing geological framework of Central Bangka. The results are intended to provide a preliminary geophysical basis for future integrated studies of the Terak and Keretak geothermal areas.

2. Method

2.1. Study area and gravity dataset

The study area covers the Terak and Keretak non-volcanic geothermal areas in Central Bangka Regency, Bangka Belitung Islands, Indonesia. The investigated region extends approximately from 2°00'48.78" to 2°30'27.01" S and 105°42'10.58" to 106°27'03.66" E. The locations of the geothermal manifestations and the spatial extent of the gravity analysis are shown in Fig. 1.

The study used secondary gravity and elevation data obtained from the TOPEX data portal. The original dataset consisted of elevation values and Free-Air Anomaly (FAA) values extracted for the study area. The original study refers to these data as “TOPEX

satellite gravity data.” However, for the revised manuscript, the exact gravity product, model version, spatial resolution, grid spacing, reference datum, and data uncertainty should be reported explicitly if this information can be recovered from the original download source. These parameters are important because they control the minimum spatial scale that can be reliably interpreted from satellite-derived gravity data [17, 18].

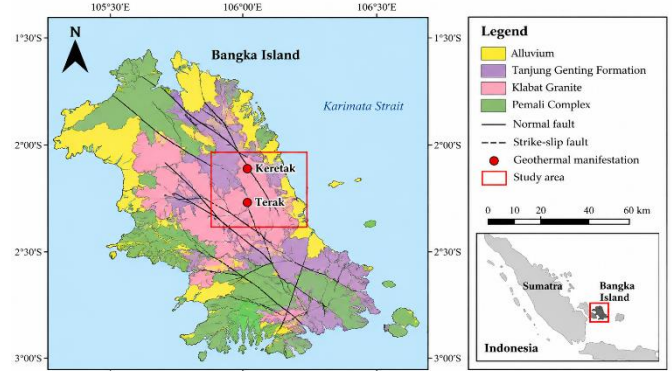


Fig. 1. Location of the Terak and Keretak geothermal areas and the spatial extent of the gravity dataset in Central Bangka, Indonesia.

The overall processing workflow consisted of gravity correction, Complete Bouguer Anomaly construction, spectral analysis, regional–residual separation, two-dimensional forward modelling, three-dimensional inversion, and geological interpretation. The main stages of the workflow are summarized in Fig. 2.

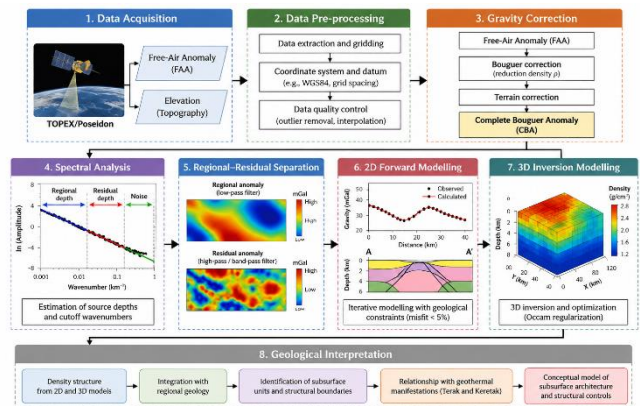


Fig. 2. Workflow of gravity-data processing and interpretation used in this study.

2.2. Gravity data processing and complete bouguer anomaly

The gravity dataset was first organized according to longitude, latitude, elevation, and Free-Air Anomaly values. The original processing included Bouguer correction and terrain correction to obtain the Complete Bouguer Anomaly (CBA) [19–21]. The Bouguer correction accounts for the gravitational effect of rock material between the observation point and the reference datum. In the original workflow, the simple Bouguer anomaly was calculated using Equation (1):

$$\Delta g_B = FAA - 0.04193\rho h \quad \dots (1)$$

where FAA is the Free-Air Anomaly, ρ is the Bouguer reduction density in g/cm³, and h is elevation in metres. Terrain correction was subsequently applied to account for the gravitational influence of surrounding topography. The resulting corrected gravity field was then used to construct the Complete Bouguer Anomaly map [1].

2.3. Spectral analysis and depth estimation

Spectral analysis was performed on the Complete Bouguer Anomaly to estimate the characteristic depths of regional and residual gravity sources. The anomaly data were transformed from the spatial domain into the wavenumber domain using the Fourier transform in Equation (2):

$$F(k) = \int_{-\infty}^{\infty} f(x)e^{-ikx} dx \quad \dots (2)$$

where $F(k)$ represents the gravity signal in the wavenumber domain, $f(x)$ is the spatial gravity signal, and k is the wavenumber.

The logarithm of spectral amplitude ($\ln A$) was plotted against wavenumber to distinguish spectral segments associated with regional, residual, and noise components. Linear regression was applied to each spectral segment, and the changes in spectral slope were used to identify characteristic wavenumber boundaries [3, 6, 16].

The original analysis identified approximate cutoff wavenumbers of 0.03 and 0.17, corresponding to interpreted depth domains of approximately 6.8 and 2.7 km, respectively. However, these depths should be reported as approximate spectral estimates rather than exact geological boundaries. The final manuscript should also state the wavenumber units and the equation used to convert spectral slope into depth.

2.4. Regional–residual anomaly separation

The Complete Bouguer Anomaly contains gravity responses from both deeper and shallower density sources. To separate these components, frequency-domain filtering was applied based on the spectral cutoff values. The regional component was obtained by retaining the low-wavenumber, long-wavelength part of the gravity field, whereas the residual component was obtained from the higher-wavenumber, shorter-wavelength signal. The residual anomaly emphasizes relatively shallow density variations, while the regional anomaly reflects deeper and broader crustal-scale density variations. The original study applied low-pass and band-pass filtering to perform this separation [6, 14, 15].

This description corrects an inconsistency in the original thesis, where one methodological paragraph incorrectly stated that the low-pass filter removes low-wavenumber components. For the revised manuscript, the correct interpretation should be retained:

- Low-pass filter → preserves low wavenumbers → regional anomaly.
- Band-pass/high-frequency component → emphasizes shallower residual anomaly.

The resulting regional and residual anomaly maps were subsequently used to identify major gravity gradients and possible structural boundaries.

2.5. Two-dimensional gravity forward modelling

Two two-dimensional gravity profiles were constructed across the study area to investigate subsurface density variations beneath and around the Terak and Keretak geothermal manifestations. The profiles were positioned to intersect the geothermal manifestations, mapped structural features, and contrasting gravity-anomaly domains. The original study used a horizontal profile B–B' across the Terak area and a diagonal profile A–A' across the Keretak area. Forward modelling was performed iteratively by adjusting subsurface body geometry and density until the calculated gravity response approximated the observed anomaly. Geological information and published density values were used as constraints on the initial model. The original modelling procedure used a trial-and-error approach and considered model misfits below 5% acceptable [3, 6, 16].

The final interpretation should treat these 2D models as non-unique solutions. Therefore, the modelled bodies are interpreted as density domains consistent with known geological units, rather than as unique determinations of lithology [19–21]. The original thesis reports model misfits of approximately 4.849% for profile B–B' and 3.285% for profile A–A'.

2.6. Three-dimensional gravity inversion

Three-dimensional modelling was conducted to evaluate the lateral and vertical distribution of subsurface density contrasts across the broader study area. The original 3D model covers approximately 105.697 km in the x direction and 55.321 km in the y direction. The horizontal model was subdivided into 20×20 cells, producing 400 cells per layer. The vertical model extends to approximately 9.1 km depth and consists of nine layers, resulting in a total of 3600 model cells [19–21].

The modelling consisted of an initial forward model followed by inversion and sequential optimization. The original workflow used Grablox 1.6e for three-dimensional modelling and Bloxer 1.6e for subsequent visualization and interpretation. The inversion procedure included optimization of:

- Base level,
- Density,
- Occam density regularization,
- Block elevation or thickness,
- and Occam height regularization.

These optimization stages were applied to reduce the mismatch between observed and calculated gravity responses. The original model used a density range of approximately $1.0\text{--}2.8\text{ g/cm}^3$. For the revised manuscript, the lower density bound should be re-evaluated because 1.0 g/cm^3 is unusually low for consolidated rocks at kilometre-scale depths. Ideally, density bounds should be constrained by realistic petrophysical values for Alluvium, Tanjung Genting Formation, Klabat Granite, and Pemali Complex.

2.7. Geological interpretation of gravity models

Interpretation was conducted by integrating the gravity anomaly patterns, 2D and 3D density models, regional geology, and previously mapped structural information. The original study interpreted the principal subsurface units as Alluvium, Tanjung Genting Formation, Klabat Granite, and Pemali Complex based on modelled density ranges and regional geological information. In the revised interpretation, gravity-derived density domains should not be treated as unique lithological identifications. Instead, the following terminology should be used:

- “consistent with Alluvium,”
- “interpreted as Tanjung Genting Formation,”
- “compatible with Klabat Granite,”
- “possibly representing Pemali basement.”

Similarly, mapped faults and strong gravity gradients should be interpreted as possible structural boundaries rather than direct proof of active geothermal-fluid pathways.

2.8. Methodological limitations

Gravity modelling is inherently non-unique because different combinations of density, geometry, and depth can generate similar gravity responses. Therefore, the 2D and 3D models presented in this study represent geologically constrained interpretations rather than unique subsurface solutions [14, 22, 23].

Additional uncertainty arises from the spatial resolution of the satellite-derived gravity dataset, assumptions regarding reduction density, spectral-depth estimation, and density bounds used during modelling. Consequently, the gravity results are used primarily to characterize subsurface density architecture and possible structural controls, while interpretations regarding radiogenic heat production and geothermal-fluid circulation are considered conceptual and require independent validation using geochemical, thermal, magnetic, or borehole data.

3. Results and discussion

3.1. Complete bouguer anomaly pattern

The Complete Bouguer Anomaly (CBA) map reveals a heterogeneous gravity field across the Terak and Keretak

geothermal areas. The anomaly values range from approximately 23.7 to 40.9 mGal, indicating marked lateral variations in subsurface density distribution. Higher gravity values are concentrated mainly in the eastern, southeastern, southern, and locally western parts of the study area, whereas lower anomalies are more prominent toward the northern and northeastern sectors. The original CBA map can be retained as Fig. 3 in the revised manuscript.

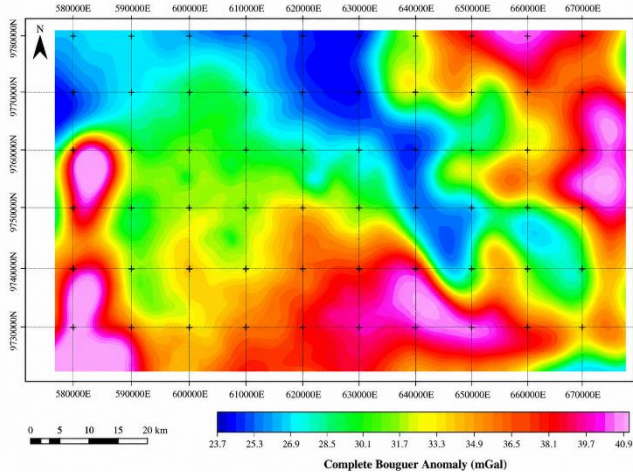


Fig 3. Complete Bouguer Anomaly map of the Terak and Keretak geothermal areas.

The high-anomaly zones are interpreted as density domains consistent with relatively dense subsurface rocks, including the Klabat Granite and deeper basement-related units. In contrast, low-anomaly zones are associated with lower-density near-surface materials such as alluvial and sedimentary deposits. The original manuscript assigns relatively low-density materials to Alluvium and higher-density responses to granitic bodies [24].

However, gravity data constrain density contrasts rather than lithology uniquely. Therefore, the high anomalies should be interpreted as being consistent with granitic or basement rocks, rather than as definitive proof of granite occurrence. The spatial coincidence between these anomalies and the known regional geology nevertheless supports this interpretation.

3.2. Spectral analysis and estimated source depths

The spectral analysis of the CBA data shows three principal wavenumber domains interpreted as regional, residual, and noise components. The original analysis identifies two cutoff wavenumbers at approximately 0.03 and 0.17, which separate the regional, residual, and high-frequency noise components. The corresponding estimated characteristic depths are approximately 6.8 km for the boundary between regional and residual sources and approximately 2.7 km for the boundary between residual sources and noise [20, 21, 25]. The original spectral plot can be retained as Fig. 4, although it should be redrawn more clearly.

These results suggest that the observed gravity field contains contributions from both relatively deep and shallow density sources. The deeper regional component likely reflects broad crustal-scale density variations, whereas the shallower residual component is more sensitive to local structural and lithological contrasts. The estimated depths should be considered approximate rather than exact geological boundaries because spectral-depth estimation is sensitive to window selection, data resolution, and the definition of the linear segments.

3.3. Regional and residual gravity anomalies

The residual anomaly map ranges from approximately -2.9 to 3.4 mGal. Low residual anomalies occur mainly in several localized zones, whereas high residual anomalies appear as isolated positive features

distributed across the study area [16, 26, 27]. The original residual map can be used as Figure 5a, while the regional map can be used as Fig. 5b.

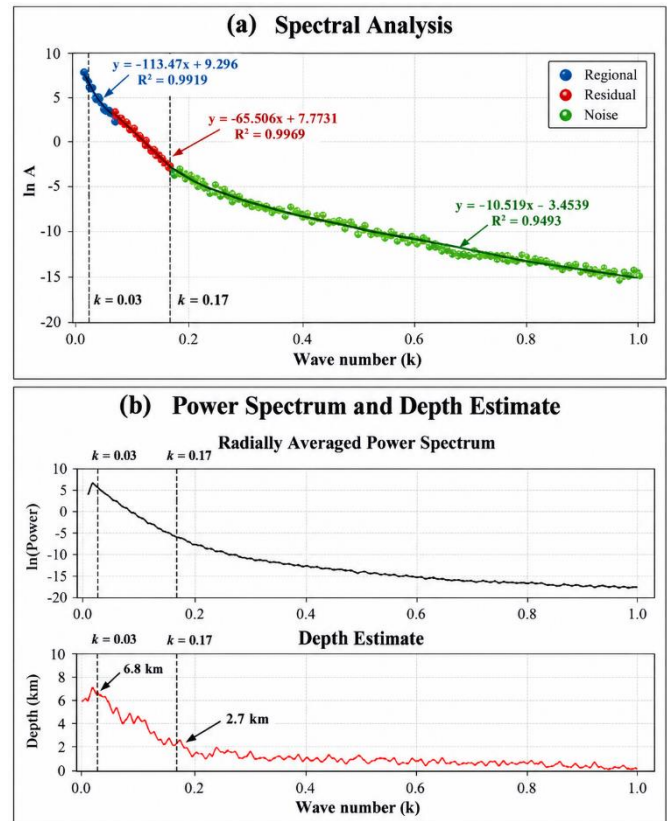


Fig. 4. Radially averaged gravity spectrum and interpreted regional, residual, and noise domains.

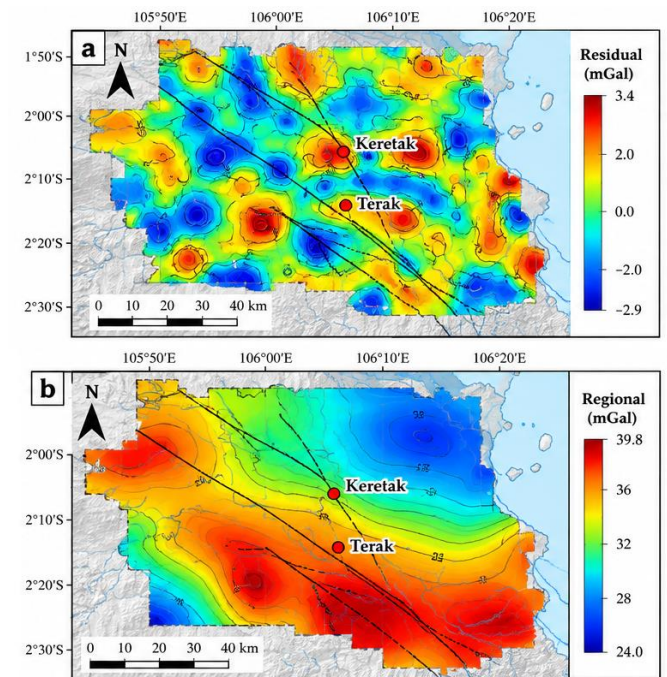


Fig. 5. (a) Residual gravity anomaly map and (b) regional gravity anomaly map of the Terak and Keretak areas.

The residual high anomalies are interpreted as shallow to intermediate-depth high-density bodies that may be associated with granitic or other dense intrusive materials. In contrast, low residual anomalies are consistent with lower-density sedimentary or unconsolidated materials [16, 26, 27]. The regional anomaly varies from

approximately 24.0 to 39.8 mGal. Low regional anomalies dominate the northern to northeastern part of the study area, whereas high regional anomalies are concentrated in the eastern, southeastern, southern, western, and northwestern sectors. The regional high-anomaly domains are interpreted as deeper high-density crustal bodies that are compatible with the widespread Klabat Granite and basement-related rocks. The regional low-anomaly zones may reflect relatively lower-density sedimentary or altered basement materials. Taken together, the regional and residual maps indicate that both deep and shallow density contrasts contribute to the gravity signature of the Terak and Keretak areas.

3.4. Two-dimensional gravity modelling

Two 2D gravity profiles were constructed across the study area. Profile B–B' crosses the Terak geothermal manifestation and nearby mapped structural features, whereas profile A–A' intersects the Keretak manifestation and associated structural trends [20, 21, 25]. The original profile-location map can be retained as Fig. 6, while the 2D models can be combined as Fig. 7–8.

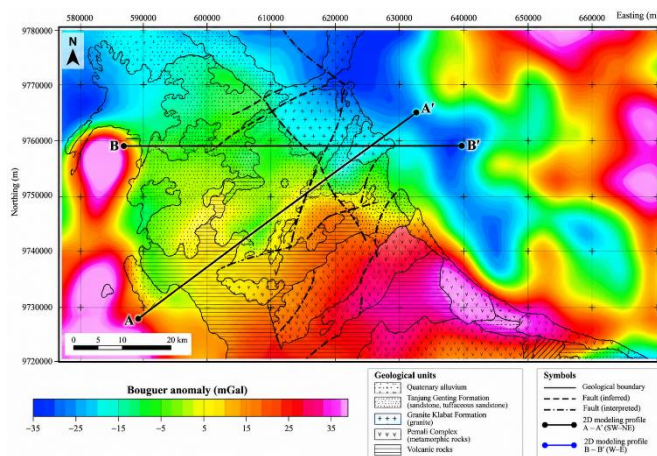


Fig 6. Location of the A–A' and B–B' gravity-model profiles across the Terak and Keretak geothermal areas.

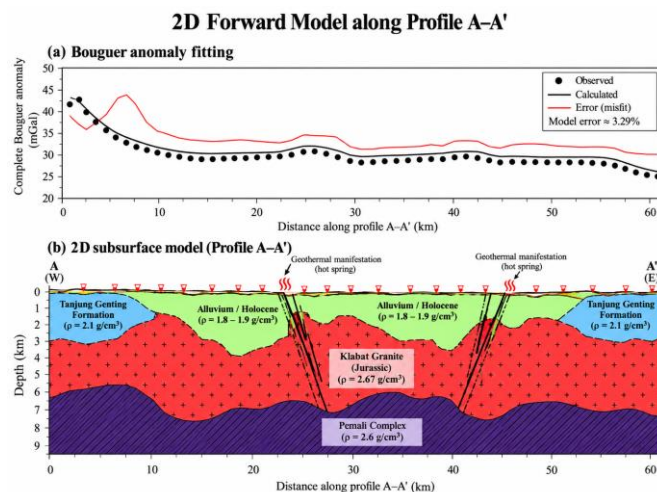


Fig 7. Two-dimensional gravity models along A–A'.

The B–B' model yields a reported misfit of approximately 4.849%, while the A–A' model gives a misfit of approximately 3.285%. The models indicate a layered subsurface composed of relatively low-density near-surface units and denser rocks at depth. The original interpretation assigns these density domains to Alluvium, the Tanjung Genting Formation, Klabat Granite, and the Pemali Complex. In particular, the denser bodies are interpreted as being consistent with granitic and basement-related rocks, while the overlying lower-density layers are associated with sedimentary and unconsolidated units. The

model geometry also shows abrupt lateral changes in density that coincide spatially with mapped structural features. These boundaries may represent fault-related contacts or zones of structural discontinuity [16, 26, 27].

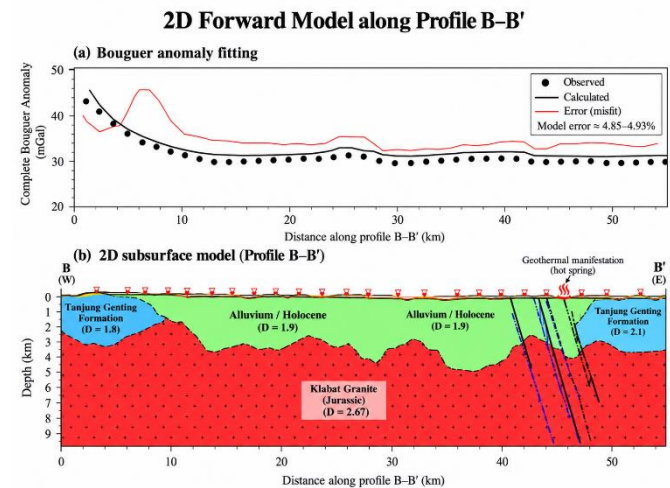


Fig 8. Two-dimensional gravity models along B–B'.

3.5. Three-dimensional density structure

The 3D model extends over approximately 105.697 km × 55.321 km and to a depth of approximately 9.1 km. The model is divided into 20 × 20 horizontal cells and nine vertical layers, resulting in 3600 model cells. The inversion produces density variations from approximately 1.0 to 2.8 g/cm³ in the original model. The lower bound of this range should be re-evaluated in the revised analysis because it is very low for consolidated rocks at depth. The original 3D views can be simplified and retained as Fig. 9, preferably showing only the most informative perspectives.

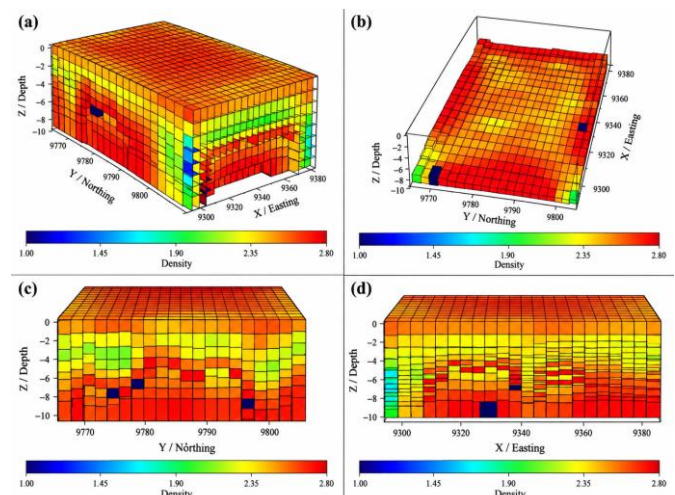


Fig. 9. Three-dimensional density block model of the study area displayed in multiple perspectives: (a) oblique 3D view of the overall density distribution, (b) top view, (c) north–south vertical section, and (d) east–west vertical section. The color scale represents density values ranging from 1.00 to 2.80 g/cm³, illustrating the spatial variation of subsurface density and the distribution of low- and high-density zones within the modeled geothermal system.

The original manuscript highlights two depth intervals: approximately 3.36–4.42 km and 7.93–9.1 km. At the shallower of these two levels, the model shows both high- and low-density domains, whereas the deepest layer is dominated by high-density material. The high-density domains are interpreted as being compatible with Klabat Granite and deeper basement rocks. The increasing dominance of dense

material at greater depth is consistent with the interpretation that granitic and metamorphic basement rocks underlie much of the study area. Nevertheless, the 3D model should not be interpreted as directly proving intrusive geometry or lithological contacts. Rather, it provides a volumetric representation of density contrasts that can be compared with the regional geological framework.

3.6. Structural controls and geothermal implications

One of the most important features of the gravity interpretation is the spatial association between geothermal manifestations, density gradients, and mapped faults. The original study notes that both Terak and Keretak are located close to structural features interpreted as faults, and these faults are proposed to act as pathways connecting deeper thermal sources with the surface.

This interpretation is geologically plausible because major density gradients commonly coincide with structural boundaries. In the present study, abrupt lateral changes in gravity response and modelled density appear spatially compatible with the mapped fault framework. However, the gravity data alone do not demonstrate active fluid flow along these faults. Therefore, the structural interpretation should be expressed more cautiously: the faults are interpreted as possible permeability pathways or structural controls rather than proven active conduits.

3.7. Radiogenic heat interpretation

The original conceptual model attributes the geothermal system to radiogenic heat generated within granitic rocks and subsequent heating of meteoric water. Previous studies cited in the manuscript report radioactive elements and minerals in Bangka granites, including K, Th, and U-bearing phases. Additional XRF data from Terak granite samples indicate measurable potassium concentrations, although the original study does not provide sufficient quantitative U and Th data to calculate volumetric radiogenic heat production directly [16].

Therefore, the gravity results are consistent with the presence of extensive dense granitic bodies at depth, but the interpretation of these bodies as significant radiogenic heat sources remains indirect. The original conceptual geothermal model can still be retained as Fig. 10, but it should be clearly labelled as a conceptual interpretation.

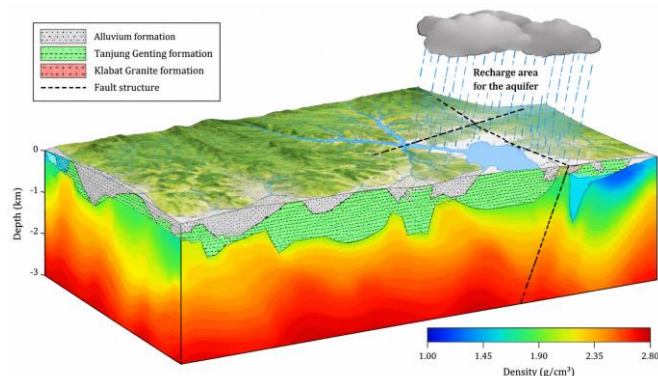


Fig. 10. Conceptual three-dimensional hydrogeological model of the Terak–Keretak geothermal area showing the spatial relationship between surface recharge, geological units, fault structures, and subsurface density distribution. The upper part illustrates meteoric recharge and infiltration into the aquifer system, whereas the subsurface section shows the Alluvium Formation, Tanjung Genting Formation, and Klabat Granite. Dashed lines indicate interpreted fault structures that may act as pathways for fluid circulation. The density distribution is shown using a color gradient from 1.00 to 2.80 g/cm³, consistent with the 3D gravity model.

The gravity results indicate that the Terak and Keretak geothermal areas are underlain by a heterogeneous subsurface characterized by shallow low-density materials and deeper high-density domains. The latter are interpreted as being consistent with granitic and basement

rocks, while strong lateral density gradients coincide with regional structural trends. The combination of CBA mapping, spectral analysis, residual and regional anomaly separation, 2D forward modelling, and 3D inversion suggests that the subsurface architecture is structurally complex and potentially favorable for fluid circulation [28, 29].

4. Conclusion

The gravity analysis indicates that the Terak and Keretak geothermal areas are characterized by a heterogeneous subsurface density structure composed of shallow low-density materials and deeper higher-density domains. The Complete Bouguer Anomaly ranges from approximately 23.7 to 40.9 mGal, while spectral analysis suggests two principal source-depth domains at approximately 2.7 and 6.8 km. Regional–residual separation further shows that shallow and deep density contrasts contribute differently to the observed gravity field. Two-dimensional forward modelling and three-dimensional inversion indicate density distributions that are consistent with the Alluvium, Tanjung Genting Formation, Klabat Granite, and deeper basement-related units. The high-density domains are predominantly interpreted as granitic and basement rocks, whereas lower-density zones are associated with shallower sedimentary and unconsolidated materials. The 2D models along profiles B–B' and A–A' reproduce the observed gravity response with reported misfits of approximately 4.849% and 3.285%, respectively. The spatial correspondence between gravity gradients, interpreted structural boundaries, and the Terak and Keretak geothermal manifestations suggests that fault-related structures may influence subsurface fluid circulation. However, the gravity data primarily constrain density contrasts and subsurface geometry; they do not independently prove lithology, active fluid flow, or the magnitude of radiogenic heat production. Therefore, the interpretation of Klabat Granite as a radiogenic heat source and faults as geothermal-fluid pathways should be regarded as a geologically plausible conceptual model supported by regional geological information rather than direct evidence from gravity data alone. Overall, this study provides a preliminary geophysical framework for understanding the subsurface architecture and possible structural controls of the Terak and Keretak non-volcanic geothermal areas. Further integration with heat-flow measurements, geochemical and isotopic data, petrophysical constraints, magnetic or electrical-resistivity surveys, and borehole information is required to better constrain the heat source, reservoir conditions, and hydrological connectivity of the geothermal system.

CRedit authorship contribution statement

Dwi Anggraeni: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation. **Ganesha Antarnusa:** Writing – review & editing.

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.

Acknowledgment

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