



Subsurface density architecture of the Sibualbuali geothermal area, north Sumatra, inferred from GGMplus gravity data and 3D inversion

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ABSTRACT

Mount Sibualbuali in South Tapanuli, North Sumatra, is an active geothermal area characterized by volcanic structures and surface manifestations, including hot springs, warm ground, steaming ground, and fumaroles. However, the subsurface density architecture and its relationship to the geothermal system remain insufficiently constrained. This study investigates the gravity-derived subsurface structure of the Sibualbuali geothermal area using secondary Global Gravity Model Plus (GGMplus) data integrated with Complete Bouguer Anomaly analysis, spectral analysis, regional-residual separation, and three-dimensional gravity inversion. The Complete Bouguer Anomaly ranges approximately from -17 to 5 mGal and exhibits contrasting gravity patterns across the study area. Spectral analysis along eight profiles indicates mean characteristic depths of approximately 3.48 km for the deeper regional component and 0.70 km for the shallower residual component. Regional-residual separation further reveals localized gravity variations associated with shallow density contrasts. The 3D inversion resolves heterogeneous subsurface density domains that are interpreted in relation to the regional geological framework. Low-density material with an average density of approximately 2.35 g/cm³ is broadly consistent with sedimentary, altered, or highly fractured rocks, whereas intermediate-density material of approximately 2.56 g/cm³ is compatible with volcanic rocks. Higher-density domains averaging approximately 2.68 g/cm³ are consistent with denser intrusive or basement-related rocks. A relatively low-density body occurs within the modeled geothermal area and may represent a structurally controlled, altered, or reservoir-related zone; however, gravity data alone do not uniquely constrain permeability, fluid content, or thermal state. The results provide a regional framework for understanding the subsurface density architecture beneath Mount Sibualbuali and highlight zones that warrant further evaluation using independent geophysical, geological, and geochemical constraints.

1. Introduction

Geothermal systems are commonly associated with regions of active volcanism, where magmatic heat, permeable structures, hydrothermal alteration, and circulating groundwater interact to produce subsurface thermal anomalies and surface manifestations. In volcanic geothermal environments, understanding the geometry and physical properties of

subsurface rocks is important for identifying structural controls, potential fluid pathways, and zones that may be associated with hydrothermal alteration or reservoir development. Gravity methods are particularly useful for this purpose because lateral and vertical variations in rock density produce measurable changes in the gravitational field that can be used to infer subsurface density architecture [1, 2].

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Mount Sibualbuali is a Holocene stratovolcano located in Sipirok District, South Tapanuli Regency, North Sumatra. The volcano forms part of the Bukit Barisan volcanic belt and reaches an elevation of approximately 1819 m. Its morphology is strongly influenced by northwest–southeast-trending geological structures, and the volcanic edifice is composed mainly of andesitic to dacitic lava products [3–5]. Geothermal activity is expressed by several surface manifestations, including hot springs, warm ground, steaming ground, and fumaroles, particularly in the southern part of the volcanic complex [6, 7]. These manifestations indicate active subsurface heat and fluid circulation, although the geometry and density distribution of the deeper system remain incompletely constrained [8–10].

The geological framework of the Sibualbuali area is relatively complex (Fig. 1). The study area includes young alluvial deposits, the Sipupus and Kanan members, the Toru and Naribong volcanic formations, the Sihapas Formation, the Tapanuli Group, and volcanic products associated with the Lubukrata and Sibualbuali volcanic centers. The Tapanuli Group includes Permian volcanic rocks and intrusive bodies, whereas the Sibualbuali volcanic center is characterized by rhyodacitic ignimbrite, rhyolite domes, and subordinate andesite. Such lithological diversity is expected to produce significant contrasts in bulk density and therefore provides a suitable geological setting for gravity-based subsurface investigation [3, 11].

Previous studies in geothermal areas have demonstrated that gravity anomalies can provide useful constraints on subsurface structure where contrasting volcanic, sedimentary, intrusive, and altered rocks occur. In such environments, lower-density anomalies may be associated with sedimentary units, highly fractured rocks, hydrothermal alteration, or increased porosity, whereas higher-density anomalies may reflect denser volcanic, intrusive, or basement-related material. However, gravity data alone do not uniquely determine lithology, permeability, fluid content, or thermal state. Consequently, gravity-derived density models should be interpreted together with geological information and should be regarded as constraints on subsurface architecture rather than direct proof of geothermal reservoir conditions [12, 13].

The availability of Global Gravity Model Plus (GGMplus) data provides an opportunity to examine regional and local gravity variations in areas where dense terrestrial gravity coverage is limited. In the present study, GGMplus data are used to construct the Complete Bouguer Anomaly, followed by spectral analysis, regional–residual anomaly separation, and three-dimensional inversion. The original dataset is reported to have a nominal spatial resolution of approximately 200 m, enabling detailed regional visualization of gravity-field variations across the Sibualbuali area. Nevertheless, the interpretation of such data must consider that nominal grid spacing does not necessarily correspond to equivalent geological resolving power, particularly when deep or localized subsurface structures are inferred [6, 14, 15].

A key unresolved issue at Mount Sibualbuali is the relationship between observed gravity anomalies and the subsurface distribution of volcanic, sedimentary, intrusive, and altered rocks beneath the geothermal manifestations. Previous geological observations establish the presence of volcanic centers, intrusive rocks, major structural trends, and geothermal manifestations, but the three-dimensional density architecture beneath the system has not been sufficiently characterized within an integrated gravity framework. This limits the ability to assess how shallow low-density zones, deeper high-density bodies, and structural boundaries may relate to the broader geothermal setting [4, 16].

Accordingly, this study aims to characterize the subsurface density architecture of the Sibualbuali geothermal area using GGMplus gravity data. Specifically, the study seeks to (1) map the

spatial distribution of Complete Bouguer Anomalies, (2) estimate characteristic depths of regional and residual gravity sources using spectral analysis, (3) separate regional and residual anomaly components, and (4) construct a three-dimensional density model to evaluate the distribution of major subsurface density domains. The resulting model is interpreted in conjunction with the regional geological framework to identify density structures that may be associated with sedimentary, volcanic, intrusive, altered, or potentially reservoir-related zones, while avoiding deterministic reservoir identification from gravity data alone.

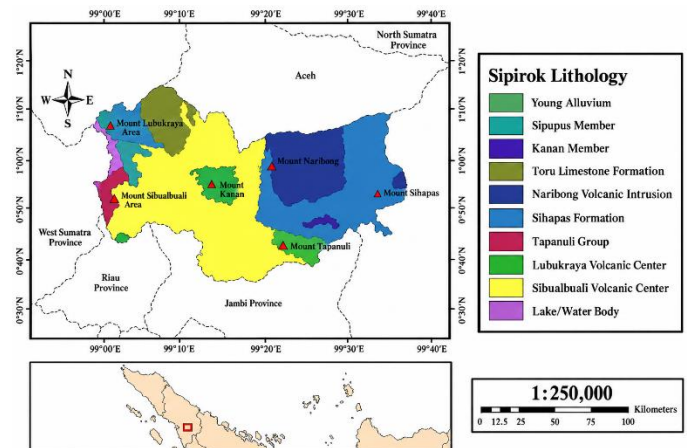


Fig. 1. Geological setting of the Mount Sibualbuali geothermal area, South Tapanuli, North Sumatra, Indonesia, showing the distribution of major lithological units, volcanic centers, and the regional location of the study area within Sumatra.

2. Method

2.1. Study area and gravity dataset

The study was conducted in the Mount Sibualbuali geothermal area, Sipirok District, South Tapanuli Regency, North Sumatra, Indonesia (Fig. 1). Mount Sibualbuali is located within the northern segment of the Bukit Barisan volcanic belt and is characterized by volcanic, sedimentary, and intrusive lithologies associated with an active geothermal environment.

The gravity analysis was based on secondary data obtained from the Global Gravity Model Plus (GGMplus) dataset. The original dataset used in this study has a nominal horizontal grid spacing of approximately 200 m and provides spatially continuous gravity-field information across the study area. The GGMplus data were used to characterize lateral gravity variations and to construct the gravity-anomaly dataset required for subsequent spectral analysis, regional–residual separation, and three-dimensional density modelling. Because the analysis used secondary gravity-model data rather than direct gravimeter observations collected during a field survey, the revised workflow focuses on the gravity-anomaly processing and modelling stages relevant to the available dataset.

2.2. Bouguer density estimation and complete bouguer anomaly

An estimate of the average near-surface rock density was obtained using the Parasnis method. This method evaluates the relationship between gravity and topographic terms to estimate an effective Bouguer density for the study area. The regression analysis produced an average density of approximately 2.17 g/cm³, which was subsequently adopted as the representative Bouguer density in the gravity-anomaly calculation.

The Complete Bouguer Anomaly (CBA) was then constructed

to represent gravity variations associated primarily with lateral variations in subsurface mass density after accounting for the principal elevation and topographic contributions. Terrain correction was implemented using Oasis Montaj, following the processing procedure adopted in the original dataset.

The resulting CBA values were gridded to produce a spatial gravity-anomaly map. The CBA map was subsequently used as the principal input for spectral analysis and separation of the regional and residual gravity components [17, 18].

2.3. Spectral analysis

Spectral analysis was applied to estimate the characteristic depths of relatively shallow and deep gravity sources and to determine an appropriate filtering window for regional–residual anomaly separation. Eight profiles, designated A–A' through H–H', were extracted across the Complete Bouguer Anomaly map. The profiles were sampled at approximately 200 m spacing. Each profile was transformed from the spatial domain into the wavenumber domain, and the logarithm of spectral amplitude ($\ln A$) was evaluated as a function of wavenumber (k) see in Fig. 2.

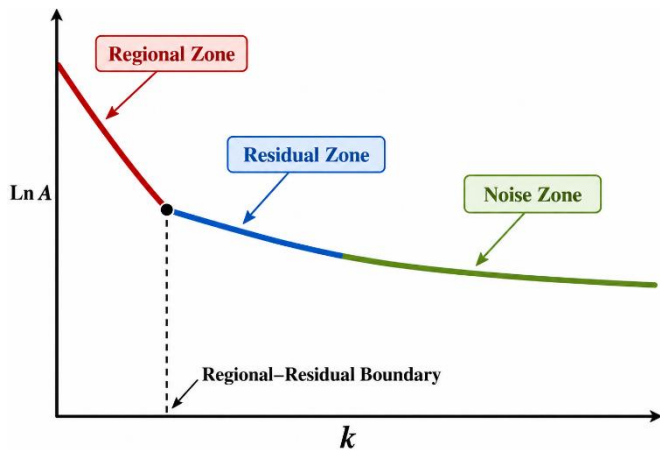


Fig. 2. Schematic spectral analysis showing the relationship between logarithmic spectral amplitude ($\ln A$) and wavenumber (k), with the regional, residual, and noise zones separated by characteristic changes in spectral slope. The regional–residual boundary is used to determine the cutoff wavenumber for subsequent anomaly separation.

For a gravity source ensemble, the slope of a linear segment in the logarithmic amplitude spectrum can be related to the average depth of the corresponding source population. Two dominant spectral gradients were identified:

- a low-wavenumber component representing relatively deeper gravity sources; and
- a higher-wavenumber component representing relatively shallower sources.

The spectral analysis yielded average characteristic depths of approximately 3482.6 m for the deeper component and 698.3 m for the shallower component. These values are interpreted in this study as characteristic depths of deeper and shallower gravity-source populations rather than as uniquely defined geological boundaries.

2.4. Regional–residual anomaly separation

The Complete Bouguer Anomaly contains the superimposed gravitational effects of relatively deep regional structures and shallower local density variations. These components were separated using a moving-average filter. The cutoff wavenumber derived from the eight spectral profiles was used to determine the

filtering window. The average cutoff wavenumber was approximately $k_c = 0.0007735$, which resulted in an estimated moving-average window width of approximately 41 grid cells.

The low-frequency component produced by the moving-average filter was interpreted as the regional gravity anomaly. The residual anomaly was calculated as Equation (1):

$$g_{res} = g_{CBA} - g_{reg} \quad \dots (1)$$

where g_{res} is the residual gravity anomaly, g_{CBA} is the Complete Bouguer Anomaly, and g_{reg} is the regional gravity anomaly. The equation (1) is used consistently in the revised manuscript because the residual field represents the remaining shorter-wavelength gravity component after removal of the regional background.

2.5. Interpretation of regional and residual gravity anomalies

The regional and residual gravity maps were evaluated based on anomaly amplitude, wavelength, lateral gradients, geometry, and spatial correspondence with the geological framework shown in Fig. 1. Regional gravity variations were primarily used to characterize relatively broad and deeper density variations, whereas residual anomalies were used to investigate more localized density contrasts potentially associated with volcanic units, structural boundaries, alteration, fractured zones, and shallow intrusive or sedimentary bodies.

Particular attention was given to: 1). spatial gradients separating high- and low-gravity domains; 2). correspondence between gravity patterns and major lithological units; 3). the relationship between low-density anomalies and geothermal manifestations; and 4). the distribution of higher-density domains that may be associated with volcanic, intrusive, or basement-related rocks. Gravity-anomaly amplitude was not used alone to assign a specific lithology or geothermal function.

2.6. Three-dimensional gravity inversion

Three-dimensional gravity inversion was applied to the residual gravity anomaly to estimate the spatial distribution of subsurface density contrasts. The modelling domain was discretized into a three-dimensional rectangular mesh. The original modelling configuration consisted of approximately $21 \times 24 \times 34$ cells, with a nominal cell dimension of approximately 450 m in the (x), (y), and (z) directions. The model extended to approximately 15 km below the surface, and approximately 8800 gravity data points were incorporated into the modelling procedure [19–21].

The inversion produced a three-dimensional distribution of density contrasts representing deviations from the reference/background density adopted during modelling. The resulting density-contrast volumes were then evaluated through horizontal and vertical sections to investigate the geometry and depth extent of the principal density domains. Because gravity inversion is inherently non-unique, the resulting model is interpreted as one density distribution compatible with the observed gravity field rather than as a unique representation of the subsurface [3, 6, 16].

2.7. Conversion and classification of density domains

The inversion results were interpreted in conjunction with representative rock-density values and the mapped geology of the Sibualbuali area [6, 14, 15]. Three principal density domains were recognized in the original model, with representative average densities of approximately:

- 2.35 g/cm³ for the lower-density domain;
- 2.56 g/cm³ for the intermediate-density domain; and
- 2.68 g/cm³ for the higher-density domain.

Rather than assigning these values uniquely to individual

lithologies, the revised interpretation treats them as density domains that are consistent with different geological materials. The low-density domain may be compatible with sedimentary rocks, highly fractured volcanic material, hydrothermal alteration, or relatively porous units. Intermediate densities are broadly compatible with volcanic rocks, whereas higher-density domains may correspond to denser volcanic, intrusive, or basement-related material.

2.8. Geothermal interpretation

The gravity-derived density model was integrated with the geological setting and known geothermal manifestations to assess possible relationships between subsurface density variations and the geothermal system. Low-density anomalies were evaluated as possible indicators of:

- Hydrothermally altered rocks;
- Enhanced fracture density;
- Porous or sedimentary material; and
- Potential reservoir-related zones.

However, low density was not treated as direct evidence of a geothermal reservoir because bulk density alone cannot uniquely constrain permeability, fluid saturation, or temperature. Similarly, higher-density bodies were interpreted principally as competent volcanic, intrusive, or basement-related material rather than being automatically classified as geothermal heat sources. The final interpretation therefore distinguishes between gravity-derived observations and their geological or geothermal implications [3, 6, 16].

Several limitations should be considered when interpreting the results. First, the study is based on secondary GGMplus gravity data rather than a dedicated dense ground-gravity survey. Consequently, nominal grid spacing should not be interpreted directly as equivalent subsurface geological resolution. Second, gravity inversion is non-unique, and different density distributions can produce similar gravity responses. The inferred lithological associations therefore depend on integration with existing geological information [19–21].

Third, the interpretation of low-density bodies as alteration- or reservoir-related features remains tentative without independent constraints from magnetotelluric, seismic, geochemical, borehole, or temperature data. Accordingly, the present analysis is intended primarily to characterize the three-dimensional subsurface density architecture and identify gravity anomalies that may warrant further geothermal investigation [14, 22, 23].

3. Results and discussion

3.1. Complete bouguer anomaly

The Complete Bouguer Anomaly (CBA) map reveals substantial lateral variation in the gravity field across the Mount Sibualbuali geothermal area. The anomaly values range approximately from -17 to 5 mGal, indicating significant subsurface density heterogeneity within the study area (Fig. 3). The southeastern part of the study area is dominated by relatively high Bouguer anomaly values, whereas lower anomaly values occur predominantly toward the western and central sectors. These variations are interpreted to reflect differences in the bulk density of subsurface geological units rather than simple topographic effects, because the CBA has already been corrected for the principal elevation and terrain contributions [24].

High Bouguer anomaly values are generally consistent with the presence of relatively dense volcanic, intrusive, or basement-related material. Conversely, lower anomalies may indicate less dense sedimentary units, fractured volcanic rocks, hydrothermally altered material, or zones with comparatively higher porosity. However, gravity-anomaly magnitude alone cannot uniquely identify lithology, and interpretation therefore requires comparison with the geological framework presented in Fig. 1.

The spatial contrast between high- and low-anomaly domains is particularly important because sharp lateral gravity gradients may indicate boundaries between geological units or subsurface

structural zones. These transitions may also coincide with faults or lithological contacts that influence geothermal-fluid circulation.

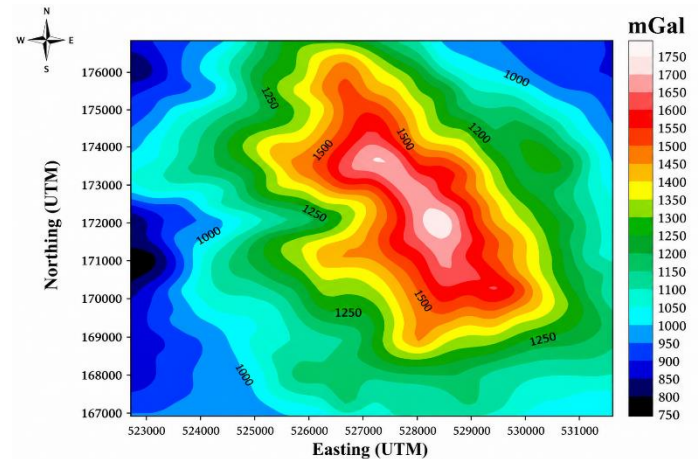


Fig 3. Complete Bouguer Anomaly map of the Mount Sibualbuali geothermal area showing the spatial distribution of gravity anomalies ranging approximately from -17 to 5 mGal.

3.2. Spectral depth estimation

Spectral analysis was conducted along eight profiles, A–A' through H–H', extracted from the Complete Bouguer Anomaly map (Fig. 4). The resulting spectra show two principal linear-gradient segments that represent relatively deep and shallow source populations [20, 21, 25]. The estimated depths of the deeper component range from approximately 2968.5 to 4158.4 m, with an average characteristic depth of approximately 3482.6 m. In contrast, the shallower component generally ranges from several hundred metres to approximately 1 km, with an average depth of approximately 698.3 m.

The deeper spectral component is interpreted as reflecting broad density contrasts associated with relatively deep geological structures, such as basement-related or major volcanic–intrusive architecture. The shallower component likely reflects local density heterogeneities related to volcanic units, sedimentary layers, structural zones, weathering, or hydrothermal alteration. These depths should be regarded as characteristic source depths rather than exact geological interfaces. In particular, the deeper depth of approximately 3.5 km should not be interpreted directly as an upper–lower crustal boundary without independent seismic or geological constraints.

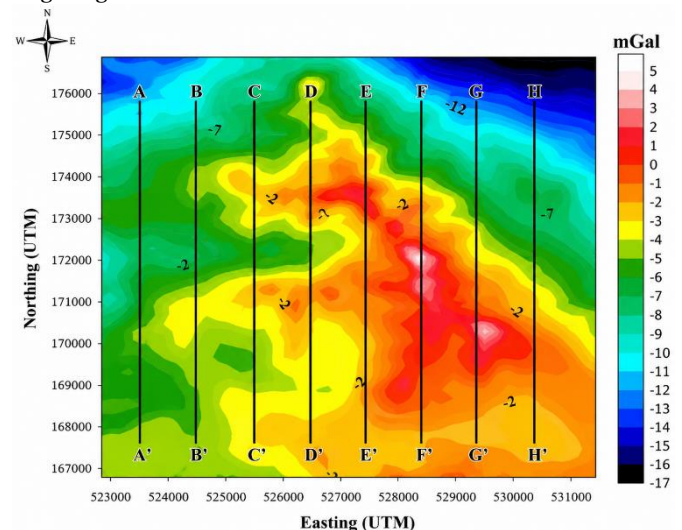


Fig. 4. Complete Bouguer Anomaly map showing eight analysis profiles (A–A' to H–H') used for spectral analysis to estimate the characteristic depths of shallow and deep gravity sources.

3.3. Regional gravity anomaly

The moving-average filter derived from the spectral analysis was used to isolate the regional gravity component. The regional anomaly ranges approximately from -5.6 to -0.4 mGal and displays a smoother spatial pattern than the Complete Bouguer Anomaly, consistent with the expected contribution of relatively deep and broad density sources (Fig. 5). The regional anomaly is characterized by relatively higher values toward the southeastern part of the area and lower values toward the central to northern sectors. The smoother geometry suggests that these variations may reflect broad-scale changes in deeper crustal or basement-related density rather than shallow localized structures [16, 26, 27].

The southeastern high may therefore indicate a relatively dense subsurface domain, possibly associated with competent volcanic or intrusive material. In contrast, the regional low may represent a deeper low-density zone or a thick accumulation of less dense volcanic and sedimentary material. The regional anomaly provides the background gravity field required to distinguish deeper regional trends from shallower local density variations.

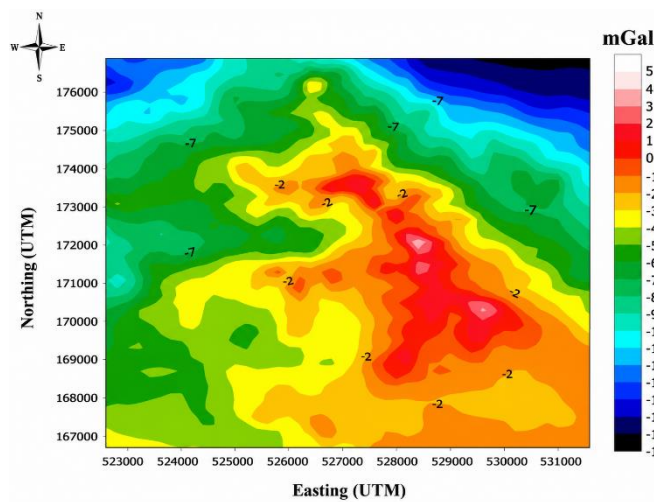


Fig. 5. Complete Bouguer Anomaly map of the Mount Sibualbuali geothermal area, showing the regional anomaly variations ranging approximately from -5.6 to -0.4 mGal across the study area.

3.4. Residual gravity anomaly

The residual gravity anomaly was obtained by subtracting the regional component from the Complete Bouguer Anomaly (Fig. 6). The resulting values range approximately from -14 to 8 mGal, representing shorter-wavelength density variations associated with more localized subsurface structures. The residual map exhibits a more irregular anomaly pattern than the regional field. High residual anomalies, approximately 3 to 8 mGal, indicate local zones of relatively high density contrast, whereas low anomalies, approximately -14 to -5 mGal, indicate relatively low-density material. Intermediate values approximately between -4 and 2 mGal form transition zones between the major density domains. [20, 21, 25].

The low residual anomalies are particularly relevant to geothermal interpretation because reduced bulk density may be associated with hydrothermal alteration, intense fracturing, increased porosity, or low-density sedimentary and volcanic units. Nevertheless, these features cannot be uniquely identified as geothermal reservoirs from gravity data alone. The spatial relationship between residual anomalies and mapped geological units indicates that local density contrasts are likely controlled by a combination of lithology, volcanic history, and structural processes.

3.5. Three-dimensional density distribution

Three-dimensional inversion of the residual gravity anomaly was

used to investigate the geometry and depth distribution of subsurface density contrasts (Fig. 7). The original inversion model consisted of approximately $21 \times 24 \times 34$ cells, with a nominal cell dimension of approximately 450 m, and extended to a maximum depth of approximately 15 km. Approximately 8800 gravity data points were incorporated into the modelling procedure [16, 26, 27]. The resulting 3D model reveals substantial density heterogeneity beneath the study area.

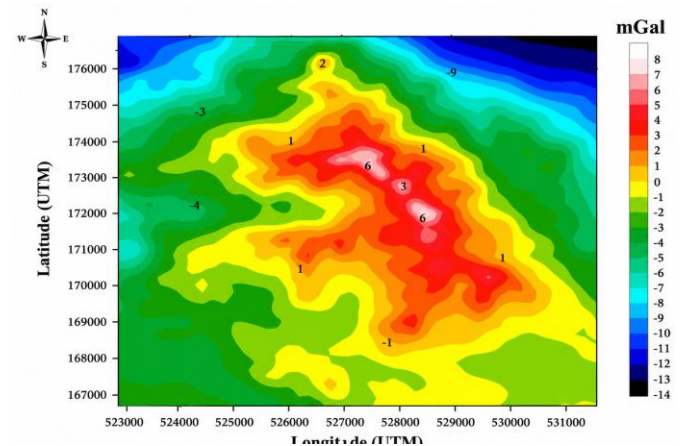


Fig. 6. Residual gravity anomaly map of the Mount Sibualbuali geothermal area obtained by subtracting the regional component from the Complete Bouguer Anomaly. The residual anomaly ranges approximately from -14 to 8 mGal and highlights localized, relatively shallow subsurface density variations potentially associated with lithological, structural, and hydrothermal features.

Three principal density domains were identified, with representative average absolute densities of approximately: 1). 2.35 g/cm³ for the lower-density domain; 2). 2.56 g/cm³ for the intermediate-density domain; and 3). 2.68 g/cm³ for the higher-density domain. Rather than assigning each density value uniquely to a specific lithology, the density domains are interpreted in relation to the known geological framework. The low-density domain, averaging approximately 2.35 g/cm³, is compatible with relatively porous sedimentary rocks, strongly fractured volcanic material, hydrothermally altered rocks, or other low-density geological units. The original study associates these values with parts of the Sihapas Formation, Naribong volcanic units, Sipupus Member, and young alluvial deposits.

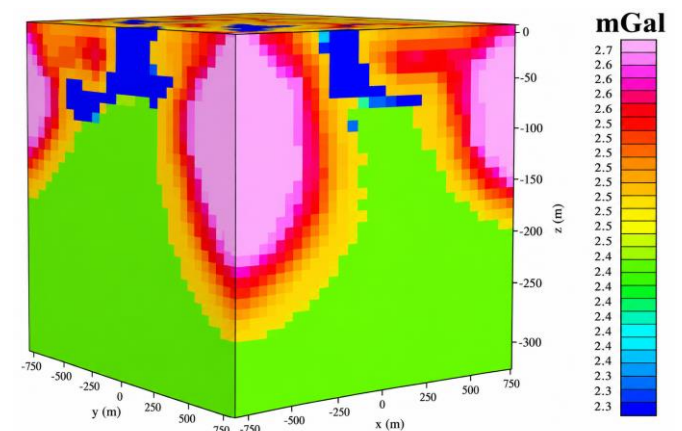


Fig. 7. Three-dimensional subsurface density model of the Mount Sibualbuali geothermal area obtained from gravity inversion, showing the spatial distribution of low-, intermediate-, and high-density domains with depth.

The intermediate-density domain, averaging approximately 2.56 g/cm³, is broadly consistent with volcanic rocks, including andesitic and rhyodacitic material associated with the Toru volcanic formation and

the Lubukrata volcanic center. The higher-density domain, averaging approximately 2.68 g/cm³, is compatible with denser intrusive or basement-related material. The original geological correlation links these density values with granite, Toba-related intrusive rocks, and rhyolitic intrusive units beneath the Sibualbuali volcanic complex.

3.6. Geological significance of the density domains

The density distribution reflects the complex volcanic and structural history of Mount Sibualbuali. The contrast between lower-density shallow to intermediate domains and denser deep-seated bodies suggests that the subsurface is composed of heterogeneous volcanic, sedimentary, intrusive, and altered materials. Low-density zones may represent locations where fracturing, hydrothermal alteration, or sedimentary accumulation has reduced bulk density. Such zones are potentially important for geothermal circulation because increased fracture density and porosity may enhance fluid storage and permeability [16, 26, 27].

By contrast, higher-density bodies may indicate relatively competent intrusive or volcanic units. These units may influence the geometry of the hydrothermal system by acting as structural boundaries or controlling fluid pathways along their margins. Importantly, density variations should not be interpreted only in terms of rock type. Hydrothermal alteration can significantly modify primary rock density, while fracture networks can reduce bulk density even in otherwise dense volcanic or intrusive rocks.

3.7. Possible geothermal-related low-density zone

The original inversion identifies a relatively low-density volume with an average density of approximately 2.48 g/cm³, previously interpreted as a geothermal reservoir at a depth of approximately 5 km. In the revised interpretation, this feature is regarded more cautiously as a possible geothermal-related low-density zone rather than a confirmed reservoir. The selected density interval may reflect: 1). fractured volcanic rocks; 2). hydrothermal alteration; 3). increased porosity; 4). sedimentary material; 5). or a combination of these factors.

The occurrence of geothermal manifestations at the surface supports the presence of active fluid circulation within the volcanic system, but gravity density alone cannot demonstrate reservoir permeability, temperature, or fluid saturation. The approximate 5 km depth should therefore be considered a model-dependent depth estimate rather than a uniquely resolved reservoir boundary. This interpretation is particularly important because the spectral analysis indicates a characteristic deeper gravity-source depth of approximately 3.48 km, which is shallower than the deepest portion of the interpreted low-density volume.

This difference likely reflects the distinct nature of the two approaches: spectral analysis estimates average source depths from wavelength characteristics, whereas 3D inversion distributes density contrast throughout the model volume. Consequently, the two depth estimates should not be expected to correspond exactly.

3.8. Implications for the Sibualbuali geothermal system

The integrated gravity interpretation indicates that the Sibualbuali geothermal area is characterized by a heterogeneous density architecture consisting of relatively low-, intermediate-, and high-density domains. The low-density domains may be associated with fractured, altered, sedimentary, or porous volcanic rocks that could facilitate geothermal-fluid circulation. Intermediate-density volcanic rocks may represent the main volcanic framework of the system, while higher-density deep bodies may correspond to intrusive or basement-related rocks.

The spatial association between geothermal manifestations, volcanic structures, and density contrasts suggests that structural boundaries may play an important role in controlling fluid pathways. In particular, transitions between contrasting density domains may correspond to fault-controlled or fracture-dominated zones where permeability is enhanced. However, the gravity results do not independently demonstrate the presence of a commercial geothermal reservoir. Confirmation would require integration with other datasets, such as

magnetotelluric resistivity, seismic velocity, geothermal geochemistry, temperature-gradient measurements, and borehole information.

Accordingly, the principal contribution of this study is the characterization of the subsurface density architecture and the identification of density anomalies that may be relevant to the geothermal system [28, 29].

4. Conclusion

This study characterized the subsurface density architecture of the Mount Sibualbuali geothermal area using GGMplus gravity data, Complete Bouguer Anomaly analysis, spectral analysis, regional-residual separation, and three-dimensional gravity inversion. The Complete Bouguer Anomaly ranges approximately from −17 to 5 mGal, indicating substantial lateral variations in subsurface density across the study area. Spectral analysis along eight profiles yielded average characteristic depths of approximately 3.48 km for the deeper gravity-source component and 0.70 km for the shallower component. The residual gravity field ranges approximately from −14 to 8 mGal and highlights localized density variations that are interpreted to reflect differences in lithology, fracturing, alteration, and subsurface structure. Three principal density domains were identified from the inversion results, with representative average densities of approximately 2.35, 2.56, and 2.68 g/cm³. These values are broadly consistent with lower-density sedimentary or altered/fractured material, intermediate-density volcanic rocks, and denser intrusive or basement-related units, respectively. A relatively low-density volume with an average density of approximately 2.48 g/cm³ occurs within the modeled geothermal area. Rather than being interpreted as a confirmed geothermal reservoir, this feature is considered a possible geothermal-related low-density zone that may reflect fractured, altered, porous, or reservoir-related rocks. The previously reported depth of approximately 5 km should therefore be regarded as a model-dependent estimate rather than a uniquely resolved reservoir boundary. Overall, the gravity results indicate that the Mount Sibualbuali geothermal area is characterized by a heterogeneous subsurface density structure controlled by the distribution of sedimentary, volcanic, intrusive, and possibly hydrothermally altered rocks. The study provides a regional framework for identifying density anomalies that may be relevant to geothermal fluid circulation and subsurface structural controls. However, because gravity inversion is inherently non-unique and the analysis is based on secondary GGMplus data, the interpreted geothermal significance of the low-density domains should be validated using independent geophysical, and other information.

CRedit authorship contribution statement

Singih Hidayat: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Visualization. **Yosi Setiawan:** Methodology, Resources, Data curation, Writing – review & editing. **Ratni Sirait:** Supervision, Methodology, Writing – review & editing. **Nadiyah Az Zuhriyyah:** Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Lailatul Husna Lubis:** Conceptualization, Supervision, Methodology, Project administration, Writing – review & editing. **Nivedita Chaubal-Durve:** Validation, Formal analysis, Visualization, Writing – review & editing. **Arti Hadap:** Validation, Methodology, Formal analysis, 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.

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