



SUBSURFACE CHARACTERIZATION OF THE MOUNT TALANG GEOTHERMAL SYSTEM USING GRAVITY AND THERMAL REMOTE SENSING

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ABSTRACT: Mount Talang is one of the active volcanic geothermal systems in West Sumatra, Indonesia, where reliable subsurface characterization is essential to reduce exploration uncertainty and improve resource assessment. This study integrates satellite gravity and thermal remote sensing to investigate the geothermal system. Complete Bouguer Anomaly (CBA) was calculated from gravity disturbance data derived from GGMplus and Full-Scale Topographic Gravity (FSTG) from SRTM2gravity, followed by regional-residual separation using a 2000 m upward continuation. Two-dimensional gravity modeling was integrated with a single Landsat-8 OLI/TIRS-derived Land Surface Temperature (LST) and Normalized Difference Vegetation Index (NDVI) analyses. The CBA (−38 to −10 mGal) and residual anomalies (−8 to 0 mGal) depict a low-density zone associated with hydrothermally altered and fractured volcanic rocks. The model indicates a shallow alteration zone (2.30 g/cm³) beneath the Bukik Gadang and Bukik Pincuran Tujuh hot springs and an intrusive body that may represent a potential heat source. The elevated LST (11–34°C) associated with low NDVI spatially coincides with known geothermal manifestations. The integrated results provide a useful reconnaissance approach for identifying potential geothermal structures and guiding further geophysical and geochemical investigations.

Keywords: *Subsurface characterization, Geothermal exploration, Gravity method, Mount Talang, Thermal Remote Sensing*

1. INTRODUCTION

Indonesia lies along the Pacific Ring of Fire, where the Indo-Australian Plate subducts beneath the Eurasian Plate, generating extensive Quaternary volcanism across Sumatra, Java, and eastern Indonesia [1]. This tectonic setting has endowed Indonesia with substantial geothermal resources; however, geothermal energy remains underutilized. In Central Sumatra, geothermal power contributes only 86 MW of the 1,730 MW installed generating capacity, compared with 542 MW from coal-fired and 631 MW from gas-fired power plants [2]. This imbalance highlights the need for more effective geothermal exploration to support Indonesia's transition toward renewable energy.

Geothermal systems in Sumatra are closely associated with the Great Sumatran Fault (GSF), which controls magma ascent, hydrothermal fluid circulation, and geothermal manifestations [3]. The Bukit Kili Geothermal Working Area (WKP), located within the Mount Talang volcanic complex, remains under exploration despite the presence of hot springs, fumaroles, altered rocks, and sulfur

deposits.

Gravity methods are widely used in geothermal exploration because subsurface density variations reflect hydrothermal alteration, fractured volcanic rocks, intrusive bodies, and geothermal reservoirs [4,5]. Previous studies at Mount Talang identified low gravity anomalies associated with altered volcanic rocks and high anomalies interpreted as dense intrusive bodies that may represent geothermal heat sources. More recently, GGMplus gravity data were used to identify northwest–southeast structural trends controlling geothermal manifestations [6]. Nevertheless, previous investigations relied mainly on gravity anomaly interpretation without quantitatively modeling the geometry of hydrothermal alteration zones, geothermal reservoirs, and magmatic heat sources. Furthermore, the relationship between subsurface structures and surface thermal manifestations remains insufficiently understood.

Thermal remote sensing provides complementary information for geothermal exploration by detecting surface responses to subsurface geothermal activity. Land Surface

Temperature derived from thermal infrared imagery identifies geothermal-related thermal anomalies, whereas the Normalized Difference Vegetation Index reflects vegetation stress associated with elevated temperatures and hydrothermal alteration [7-9]. Unlike previous Mount Talang studies that primarily interpreted gravity anomalies or structural trends, this study provides a site-specific integrated reconnaissance interpretation using GGMplus/SRTM2gravity-derived gravity anomalies, 2-D forward modeling, and Landsat-8 LST-NDVI analysis. The approach links subsurface density variations with surface thermal indicators to identify potential hydrothermal alteration zones, intrusive bodies, and structurally controlled geothermal features. The results provide preliminary constraints for Mount Talang geothermal exploration and a basis for subsequent field validation.

1.1 Study Area and Geological Setting

Mount Talang is part of the Bukit Barisan volcanic arc formed by subduction of the Indo-Australian Plate beneath the Eurasian Plate along western Sumatra. The volcanic complex is structurally controlled by the Great Sumatran Fault (GSF), particularly the Sumani and Suliti fault segments, which produce a dominant northwest–southeast structural trend. These tectonic structures control magma ascent, fracture permeability, hydrothermal fluid circulation, and the distribution of geothermal manifestations.

Topographic features and distribution of geothermal area in the Mount Talang are shown on Fig. 1. The volcanic landscape is characterized by steep slopes, summit craters, radial drainage patterns, and elevations exceeding 2,500 m above sea level, whereas the surrounding areas consist of volcanic plains and tectono-volcanic depressions.

The geological framework of the study area is shown in Fig. 2. Mount Talang is predominantly composed of Quaternary volcanic rocks, including andesitic lava flows, volcanic breccias, pyroclastic deposits, welded tuffs, and hydrothermally altered volcanic rocks. These units overlie older metamorphic basement, granitic intrusions, and sedimentary formations of the Barisan and Tuhur Formations. Hydrothermal alteration is mainly developed along fault-controlled fracture zones, reflecting the strong influence of tectonic structures on geothermal fluid migration.

Geothermal manifestations are concentrated on the northern flank and around the summit crater, including the Bukik Gadang, Bukik Pincuran Tujuh, Garara, and Bukik Kili hot springs, together with fumaroles, steaming grounds, altered rocks, and

sulfur deposits. Their distribution indicates structurally controlled permeability associated with the GSF. The study area is located within the Bukit Kili Geothermal Working Area, which remains under exploration and is interpreted as a volcanic-hosted hydrothermal system sustained by magmatic intrusion beneath the Mount Talang volcanic complex [3].

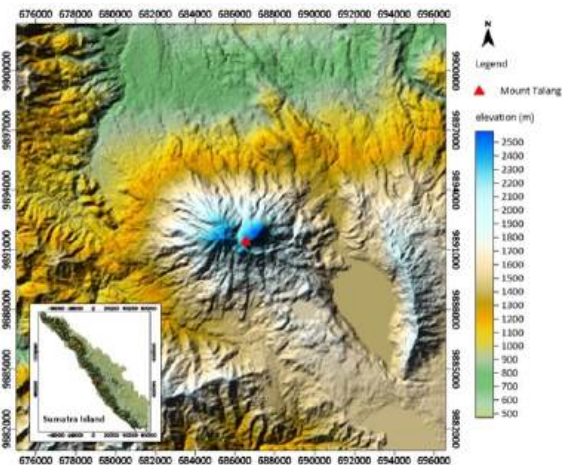


Fig. 1 Location and topographic setting of Mount Talang geothermal area, West Sumatra, Indonesia

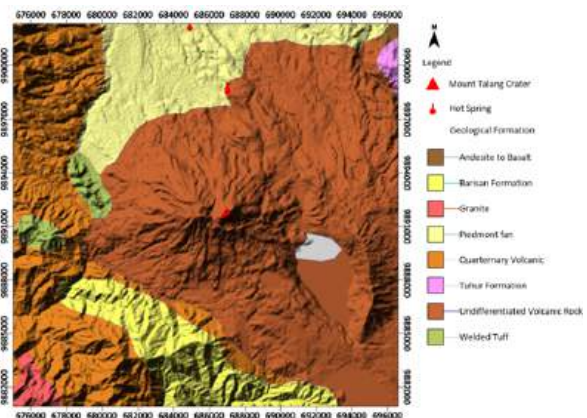


Fig. 2 Geological map of the Mount Talang

2. RESEARCH SIGNIFICANCE

This study highlights the value of integrating gravity and thermal remote sensing data to characterize geothermal systems in volcanic environments. By linking subsurface density variations with surface thermal responses, the approach reduces the uncertainty commonly associated with gravity interpretation alone. The spatial correspondence between low gravity anomalies, elevated LST, and reduced NDVI provides complementary evidence for identifying potential hydrothermal alteration zones. Combining 2-D

gravity modeling with surface thermal indicators reduces interpretational ambiguity and provides a reconnaissance framework for prioritizing areas for further geothermal investigation.

3. MATERIALS AND METHODS

3.1 Gravity and Remote Sensing Data

This study integrated satellite gravity and thermal remote sensing data to characterize the Mount Talang geothermal system. Gravity disturbance data equivalent to the Free-Air Anomaly (FAA) were obtained from the Global Gravity Model Plus (GGMplus), which integrates GRACE, GOCE, EGM2008, and topographic gravity information with a spatial resolution of approximately 200 m [10]. Topographic correction was derived from the SRTM2gravity model (90 m resolution), and its Full-Scale Topographic Gravity product was used to calculate the Complete Bouguer Anomaly [11]. Thermal remote sensing employed Landsat-8 OLI/TIRS Collection 2 Level 1 imagery acquired on 1 November 2025 (6.36% cloud cover), with 30 m multispectral and 100 m thermal spatial resolution (resampled to 30 m) [9]. These datasets were integrated to characterize subsurface structures and surface thermal anomalies associated with geothermal activity.

3.2 Complete Bouguer Anomaly and Anomaly Separation

In this study, the CBA was derived by subtracting the Full-Scale Topographic Gravity (FSTG) effect from the GGMplus gravity disturbance. Because FSTG incorporates the gravitational contribution of terrain over the full topographic spectrum, the resulting anomaly represents a topographically corrected gravity field used here for subsurface interpretation [11]. In this study, the CBA was calculated using the Full-Scale Topographic Gravity derived from the SRTM2gravity model [11]:

$$CBA = FAA - FSTG \quad (1)$$

where CBA is the Complete Bouguer Anomaly (mGal), FAA is the Free-Air Anomaly obtained from GGMplus, and FSTG is the Full-Scale Topographic Gravity from SRTM2gravity. To separate deep regional structures from shallow volcanic and geothermal features, the CBA was processed using upward continuation at heights of 1000, 1500, 2000, and 2500 m.

Among the tested continuation heights (1000–2500 m), 2000 m was selected as a practical separation level because the regional NW–SE anomaly trend remained stable while short-wavelength anomalies associated with shallow volcanic sources were substantially attenuated. Residual anomalies were subsequently obtained by subtracting the regional anomaly from the CBA.

3.3 2-D Gravity Modeling

Two-dimensional gravity modeling was performed using the GM-SYS module in Oasis Montaj through an iterative forward-modeling approach, in which subsurface polygonal bodies were assigned density values and adjusted until the calculated gravity response matched the observed anomaly [12].

$$g(x, z) = 2G\Delta\rho \int \frac{zdx - xdz}{x^2 + z^2} \quad (2)$$

where $g(x, z)$ is the gravitational response, G is the gravitational constant, and $\Delta\rho$ is the density contrast between subsurface bodies and surrounding materials.

Modeling was carried out along profile Z–B (Fig. 5) crossing the volcanic summit and geothermal manifestation zones. Residual gravity anomaly data were used as input, while density values were constrained using regional geological information and previous geothermal gravity studies [13]. Subsurface geometry and density values were adjusted iteratively until the calculated anomaly matched the observed anomaly with minimum RMS error.

3.4 Thermal Remote Sensing Analysis

Thermal remote sensing analysis was performed using Landsat-8 OLI/TIRS Collection 2 Level 1 imagery obtained from the USGS Earth Explorer platform. Radiometric calibration and atmospheric correction were applied before retrieving Land Surface Temperature (LST). Digital Number (DN) values were first converted to Top of Atmosphere (TOA) spectral radiance using [8-9,14-15]:

$$L_\lambda = M_L \times Q_{CAL} + A_L \quad (3)$$

L_λ represents TOA spectral radiance ($W/m^2sr\mu m$), M_L is the radiance multiplicative scaling factor, A_L is the radiance additive scaling factor, Q_{CAL} is the quantized calibrated pixel value. Brightness Temperature (BT) was then calculated as:

$$BT = \frac{K_2}{\ln\left(\frac{K_1}{L_\lambda} + 1\right)} - 273.15 \quad (4)$$

where K_1 and K_2 are thermal calibration constants. To estimate land surface emissivity, NDVI was first calculated using Landsat-8 OLI Bands 5 and 4:

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (5)$$

NIR and RED represent near-infrared and red reflectance values, respectively. The NDVI values were then used to determine the proportion of vegetation P_v :

$$P_v = \left(\frac{NDVI - NDVI_{MIN}}{NDVI_{MAX} - NDVI_{MIN}} \right)^2 \quad (6)$$

Land Surface Emissivity E was subsequently estimated using:

$$E = 0.004 \times P_v + 0.986 \quad (7)$$

Finally, Land Surface Temperature (LST) was calculated using the emissivity-corrected brightness temperature equation:

$$LST = \frac{BT}{1 + \left(\frac{\lambda BT}{C_2} \right) \ln(E)} \quad (8)$$

λ is the wavelength of emitted thermal radiation for Landsat-8 Band 10 (10.895), and C_2 is the second radiation constant. The resulting LST distribution was subsequently analyzed together with NDVI patterns to identify thermal anomaly zones associated with geothermal manifestations and hydrothermal alteration within the Mount Talang geothermal system.

3.5 Geothermal System Mapping

Geothermal system mapping was performed by integrating gravity-derived subsurface structures with Land Surface Temperature, NDVI, and geothermal manifestation data to establish the relationship between geothermal heat sources, reservoirs, permeability structures, and surface geothermal expressions. Areas with elevated LST, typically 4–10 K higher than the surrounding background [7,8,16], were considered potential geothermal anomaly zones. The interpretation was refined by correlating high LST, low residual gravity anomalies, low NDVI values, geothermal manifestations, and structural trends derived from gravity analysis. This integrated approach was used to delineate potential hydrothermal alteration zones, geothermal zones, possible intrusive bodies

associated with heat sources, and structurally controlled fluid pathways beneath the Mount Talang geothermal system.

4. RESULTS AND DISCUSSION

4.1 Complete Bouguer Anomaly of Mount Talang

The Complete Bouguer Anomaly map of the Mount Talang geothermal area is shown in Fig. 3. The CBA, calculated from GGMplus disturbance gravity and SRTM2gravity topographic correction data, ranges from approximately –38 to –10 mGal and reflects subsurface density variations after removing the effects of topographic masses. Low gravity anomalies dominate the central volcanic edifice and extend toward the northeastern and southeastern parts of the study area. These anomalies are interpreted as low-density volcanic rocks affected by hydrothermal alteration, intense fracturing, and pyroclastic deposits, where mineral alteration and increased porosity reduce the bulk rock density.

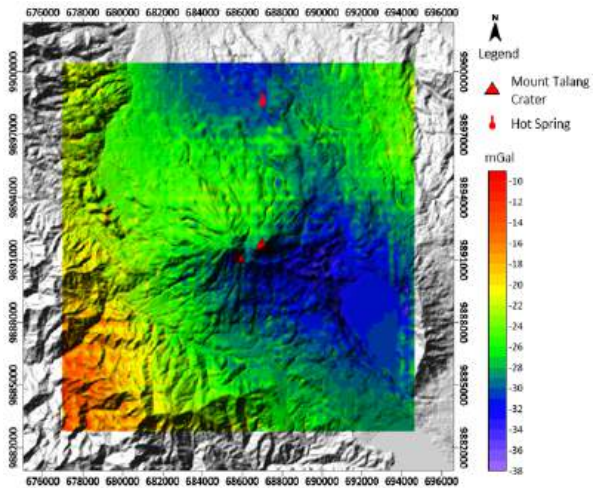


Fig. 3 Complete Bouguer Anomaly map of the Mount Talang

In contrast, relatively high gravity anomalies occur mainly in the western and southwestern sectors and are interpreted as denser volcanic rocks or shallow intrusive bodies beneath the volcanic complex. The anomaly pattern exhibits a dominant northwest–southeast orientation, consistent with the regional structural trend of the Great Sumatran Fault, indicating strong tectonic control on the geothermal system. Geothermal manifestations, including Bukik Gadang and Bukik Pincuran Tujuh hot springs, are predominantly located along the transition between low and moderate gravity anomalies, suggesting that hydrothermal fluid

circulation is controlled by fracture permeability developed within altered volcanic rocks.

4.2 Regional and Residual Anomalies of Mount Talang

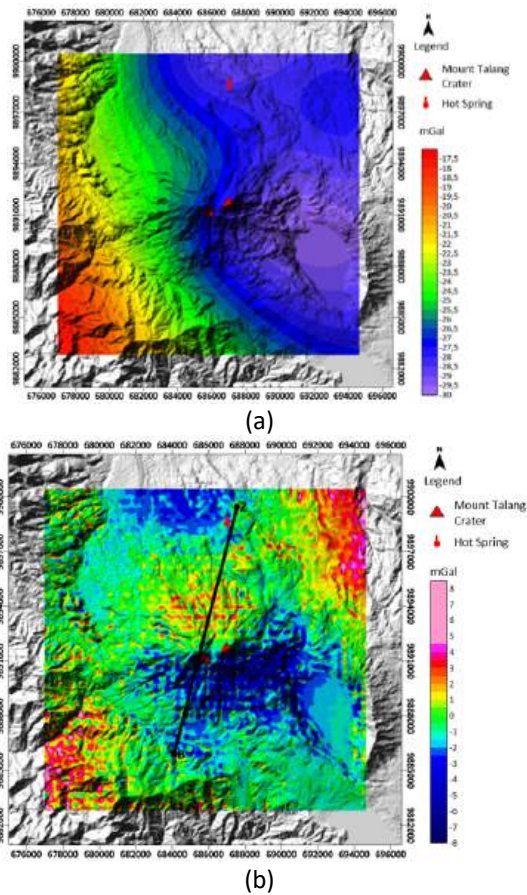


Fig. 4 (a) Regional gravity anomaly derived from 2000 m upward continuation and (b) residual gravity anomaly of the Mount Talang geothermal area.

The regional anomaly was obtained by upward continuation of the Complete Bouguer Anomaly data. Although continuation heights of 1000, 1500, 2000, and 2500 m were evaluated, the 2000 m level was selected because it best preserved the regional geological pattern while effectively suppressing short-wavelength anomalies related to shallow volcanic sources. The resulting regional anomaly (Fig. 4a) exhibits a dominant northwest-southeast trend, consistent with the Great Sumatran Fault, indicating that deep tectonic structures exert a primary control on the Mount Talang geothermal system.

The residual anomaly was obtained by subtracting the 2000 m regional anomaly from the CBA (Fig. 4b). Negative residual anomalies (approximately -8 to 0 mGal) are concentrated around the volcanic summit and coincide with the

Bukik Gadang, Bukik Pincuran Tujuh, Garara, and Bukik Kili geothermal manifestations. These low-density anomalies are interpreted as hydrothermally altered and fractured volcanic rocks that may represent potential geothermal zones. In contrast, positive residual anomalies represent denser volcanic rocks and shallow intrusive bodies, whereas their northwest-southeast alignment indicates fracture-controlled permeability pathways that facilitate geothermal fluid migration.

4.3 2-D Subsurface Modeling

The 2-D gravity model was constructed along profile Z-B, extending from 687545.321466 mE, 9899466.429881 mN to 684096.125 mE, 9885912.55 mN, crossing the Mount Talang summit and the Bukik Gadang and Bukik Pincuran Tujuh geothermal manifestations. The profile was selected because it intersects the main residual gravity anomaly interpreted as the principal geothermal structural corridor. The interpreted lithological units and density values are summarized in Table 1, while the final model is shown in Fig. 5.

Table 1. Interpreted lithological units and density values of the 2D gravity model [4,13]

Lithological Interpretation (Color)	Density (g/cm^3)	Geological Interpretation
Pyroclastic deposits (yellow)	2.10	Tuff, volcanic ash, pyroclastic materials
Hydrothermal alteration zone (Green)	2.30	Altered and fractured volcanic rocks
Andesitic volcanic body (Orange)	2.55	Andesitic lava and compact volcanic rocks
Old volcanic basement (Purple)	2.67	Consolidated volcanic basement rocks
Regional basement (Dark blue)	2.85	Dense regional crustal basement
High-density intrusive body (red)	2.9	Possible laccolithic intrusion

The model identifies six subsurface units with densities ranging from 2.10 to 2.90 g/cm^3 . Pyroclastic deposits (2.10 g/cm^3) form the shallow volcanic cover, whereas a low-density zone (2.30 g/cm^3) beneath the geothermal manifestations is interpreted as hydrothermally altered and fractured volcanic rocks that function as a shallow geothermal reservoir. The main volcanic edifice consists of andesitic rocks with a density of 2.55 g/cm^3 ,

underlain by an older volcanic basement (2.67 g/cm^3) and a dense regional basement (2.85 g/cm^3).

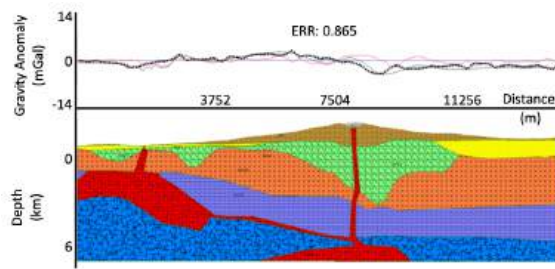


Fig. 5 Two-dimensional gravity model along profile Z-B. The black dashed line represents the observed anomaly, the solid black line the calculated anomaly, and the red line the residual error.

A shallow high-density body (2.90 g/cm^3) is interpreted as a possible laccolithic intrusion that may represent a local heat source, whereas a deeper high-density body ($>6 \text{ km}$) is interpreted as a possible batholithic intrusion associated with the deeper magmatic system [4,5]. The NW–SE structural pattern may provide permeable pathways for hydrothermal fluid migration toward surface manifestations. The calculated gravity response closely matches the observed anomaly with an RMS error of 0.865 mGal . Nevertheless, gravity modeling is inherently non-unique because different density distributions and subsurface geometries can produce similar gravity responses. To reduce this ambiguity, density values were constrained using regional geology, previous gravity studies, and the distribution of geothermal manifestations. Gravity-based methods have also been applied to monitor mass and fluid changes in geothermal reservoirs, demonstrating the broader applicability of gravity observations in geothermal assessment [17]. Consequently, the proposed model should be regarded as a geologically constrained interpretation rather than a unique subsurface solution. Integrating gravity, geological information, and thermal remote sensing provides complementary constraints on the interpreted structures.

4.4 Thermal Remote Sensing Analysis

Thermal remote sensing analysis was performed using Landsat-8 OLI/TIRS imagery to evaluate surface thermal conditions associated with the Mount Talang geothermal system. The LST map (Fig. 6a) shows temperatures ranging from approximately $11\text{--}34^\circ\text{C}$, with the highest values concentrated around the summit crater, Bukik Gadang, Bukik Pincuran Tujuh, and the Bukik Kili geothermal

prospect. These thermal anomalies are interpreted as surface expressions of hydrothermal activity associated with enhanced subsurface heat flow (7,8).

Additional high-temperature anomalies were identified over settlement areas; however, these were excluded from geothermal interpretation because they are associated with built-up surfaces rather than volcanic structures or known geothermal manifestations. Consequently, geothermal anomalies were identified only where elevated LST coincided with low residual gravity anomalies and mapped geothermal manifestations, thereby minimizing the influence of anthropogenic heat.

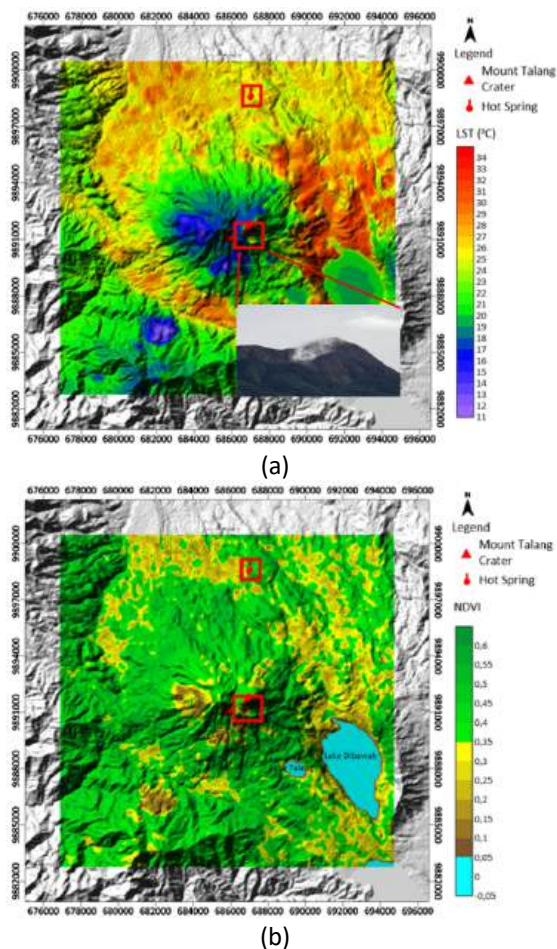


Fig. 6 (a) Land Surface Temperature map and (b) Normalized Difference Vegetation Index map of the Mount Talang geothermal area.

The NDVI map (Fig. 6b) ranges from approximately -0.05 to 0.60 . High NDVI values characterize densely vegetated volcanic slopes, whereas lower values occur around the summit crater, geothermal manifestation zones, hydrothermally altered rocks, and exposed pyroclastic deposits, indicating vegetation stress related to elevated surface temperatures. A strong

negative relationship between LST and NDVI was observed ($R^2 = 0.787$, $n = 6400$, $p < 0.001$) (Fig. 7), indicating that higher surface temperatures generally correspond to lower vegetation density. However, because this relationship is also influenced by land cover, geothermal interpretation was restricted to anomalies coinciding with known manifestations, low residual gravity, and volcanic structures.

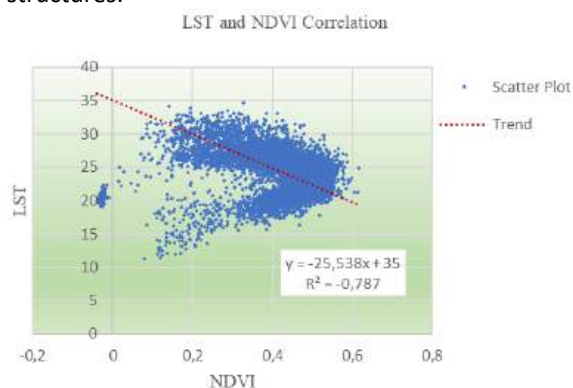


Fig. 7 LST–NDVI relationship showing a significant negative correlation.

4.5 Integrated Geothermal System Interpretation

The integrated interpretation delineates a low-density hydrothermally altered zone (2.30 g/cm^3) beneath the Bukik Gadang and Bukik Pincuran Tujuh hot springs, interpreted as a potential shallow geothermal zone. Shallow and deeper high-density bodies are interpreted as possible intrusive bodies associated with the geothermal heat system. These interpretations remain preliminary because gravity data alone cannot uniquely determine reservoir properties or confirm active magmatic heat sources.

Thermal remote sensing complements the gravity interpretation by showing that elevated LST and reduced NDVI values coincide with geothermal manifestations and low residual gravity anomalies, indicating active hydrothermal processes. Although high-temperature anomalies are also present over settlement areas, only anomalies spatially associated with volcanic structures, geothermal manifestations, and gravity-derived alteration zones were interpreted as geothermal features. Accordingly, areas where known geothermal manifestations coincide with elevated LST, low NDVI, and low residual gravity are qualitatively classified as high-confidence geothermal anomalies. Areas supported by two or three indicators are considered moderate-confidence, whereas isolated thermal or gravity anomalies are treated as low-confidence features requiring further validation. The northwest–southeast structural trend identified in this study is consistent with the structural control reported for

the Ungaran geothermal system, where fracture density strongly governs geothermal fluid circulation and the distribution of surface manifestations [5]. The interpreted alteration zone and northwest–southeast structural trend are consistent with previous gravity and geological studies [3, 6]. However, unlike previous studies that mainly interpreted gravity anomalies, this study constrains the geometry of the alteration zone and identifies possible shallow and deep intrusive bodies through 2-D gravity modeling. Integrating gravity with thermal remote sensing provides complementary constraints that reduce interpretation ambiguity and strengthen the reconnaissance interpretation of the Mount Talang geothermal system.

5. CONCLUSION

The integration of satellite-derived gravity, one 2-D forward model, and Landsat-8 thermal remote sensing provides a reconnaissance interpretation of the Mount Talang geothermal system. CBA values range from -38 to -10 mGal , while residual anomalies of -8 to 0 mGal delineate low-density zones associated with hydrothermally altered and fractured volcanic rocks. The model identifies a potential alteration zone (2.30 g/cm^3) and possible shallow and deep intrusive bodies, with an RMS misfit of 0.865 mGal . LST ranges from 11 – 34°C and shows a strong inverse relationship with NDVI ($R^2 = 0.787$), with geothermal manifestations occurring within coincident thermal and gravity anomalies. The integrated approach reduces interpretational ambiguity and provides a useful reconnaissance framework for geothermal exploration; however, further geophysical and geochemical investigations are required to validate reservoir properties, fluid pathways, and interpreted heat sources.

6. ACKNOWLEDGMENTS

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