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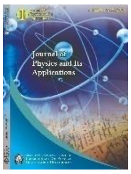

Investigation of the Geothermal Potential of Mount Seminung, West Lampung, Indonesia, Based on Magnetic Anomaly Data

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ABSTRACT

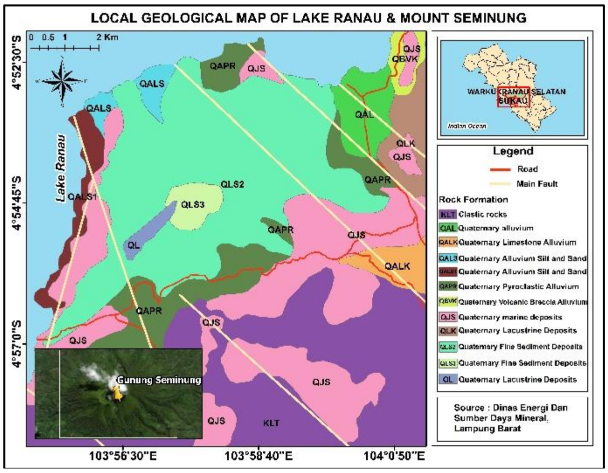
Indonesia has significant geothermal potential due to its location along the active tectonic Ring of Fire, characterized by intense volcanic activity and fault structures. One promising area is Mount Seminung in Sukau District, located in the southeastern part of the Ranau Caldera and influenced by the Sumatra Fault system. This study aims to analyze the distribution of magnetic anomalies as an initial indication of a geothermal system in the Mount Seminung area. The study employed the magnetic method by measuring total magnetic field intensity at several observation points across the study area using a proton precession magnetometer. The magnetic data were corrected for diurnal variations and the Earth's main magnetic field, then processed to produce a magnetic anomaly map. The results show low magnetic anomaly zones ranging from −374.2 nT to −9.0 nT, which are associated with hydrothermal alteration and geothermal manifestations, and high anomaly zones ranging from 181.5 nT to 871 nT related to relatively fresh volcanic rocks. The anomaly contrasts and elongated gradient patterns indicate the presence of faults or fractures that may act as pathways for geothermal fluids. Therefore, the low anomaly zones associated with these structures are recommended as targets for further investigation using geoelectric or magnetotelluric methods.

1. Introduction

Due to its geological conditions, shaped by strong tectonic and volcanic activity along the Ring of Fire, Indonesia has significant geothermal energy potential. With an estimated 29,038 MW of geothermal potential, Indonesia is among the nations with the most geothermal resources worldwide. Because geothermal energy can lessen reliance on fossil fuels and lessen the effects of global climate change, it is also regarded as an environmentally friendly renewable energy source. To support a sustainable energy supply and lower future carbon emissions, Indonesia's geothermal potential must be developed and utilized [1]. Geothermal energy is one of the most promising renewable energy sources in Indonesia, given its location in the Ring of Fire, marked by intense volcanic activity and geothermal manifestations on the surface [2]. The distribution of rock units is influenced by fault structures and fractures that run parallel to the Bukit Barisan Mountains, which control the location and orientation of lithology and geological zoning in the study area. The existence of these geological structures is very important in interpreting geophysical anomalies and the potential of geothermal systems, because fault zones can be pathways for hydrothermal fluid flow and are associated with geothermal manifestations on the surface. The application of geophysical methods, especially magnetic methods, which have proven to be effective in the early exploration stage to detect subsurface structures that may harbor geothermal systems [3, 4]. Variations in magnetic anomaly values can be used to identify zones that may be connected to geothermal systems and interpret lithological differences, according to a study conducted in the Sumani geothermal prospect area in West Sumatra [5]. According to Rajab et al. [6], another study conducted in Polewali Mandar demonstrates that the subsurface structure conditions that influence the geothermal system in the region can be described through the interpretation of magnetic anomaly models. Furthermore, a review of the literature by Astuti et al. [7] confirms that magnetic methods have been used extensively in different parts of Indonesia due to their ability to provide information about variations in the magnetic susceptibility of rocks, which are related to lithological changes, hydrothermal alteration zones, and the presence of geological structures like faults and fractures.

Magnetic methods are widely used in geophysical and geothermal surveys because they are sensitive to variations in rock magnetism associated with subsurface geological structures, lithological contrasts, and hydrothermal alteration zones. The Sumatra Fault's tectonic activity and Quaternary volcanic processes interacted to form the Ranau Lake and Mount Seminung region. According to research by Natawidjaja et al. [8], a significant eruption in the Late Quaternary period connected to the activity of the Sumatra Fault in the southern portion of Sumatra Island created the Ranau Caldera. On the caldera's edge, Mount Seminung formed as a post-caldera volcano. Magma mingling is also revealed by petrological analyses of Mount Seminung's youngest pyroclastic deposits, illustrating the intricate dynamics of the magmatic system [9].

These factors suggest that the Ranau–Seminung region is a significant volcanotectonic system for geothermal potential and regional geological research. The geological map in Figure 1 of the Mount Seminung and Lake Ranau area illustrates the distribution of rock units and geological structures that developed in the volcanotectonic zone in the southern part of Sumatra Island. Based on the map and lithological mapping, this region is dominated by volcanic rocks, pyroclastic deposits, and Quaternary sedimentary rocks, which reveal the evolution of the Ranau volcano and the post-caldera Seminung. The volcanic rock deposits around Lake Ranau are the result of ancient volcanic eruptions that formed the Ranau volcanic complex, which was followed by the formation of the Seminung volcano in the southeastern part of the main caldera [10]. Geothermal manifestations in this area take the form of hot springs controlled by geological structures, such as faults and lithological contacts, indicating an active hydrothermal system beneath the surface. To estimate the reservoir temperature, Zainal et al. [11] used the silica (SiO_2) geothermometer method, which is based on silica solubility as a function of temperature, and produced reservoir temperature estimates ranging from 150 to 184°C, which is classified as a medium-temperature geothermal system. These results indicate that the Ranau Lake area has significant geothermal energy development potential, although comprehensive characterization of the subsurface system still requires an integrated geoscience approach.



Source : Dinas Energi Dan Sumber Daya Mineral, Lampung Barat

Fig. 1: Geological map of Lake Ranau-Mount Seminung

Previous research in the Ranau Lake and Mount Seminung areas has identified a prospective geothermal system based on geological and geochemical studies. A study by Zainal et al. [11] in Lake Ranau shows that reservoir temperature estimates using the silica (SiO_2) geothermometer method point to the existence of a medium-temperature geothermal system, thereby strengthening the potential for geothermal energy development in the region. Geologically, the Ranau Lake-Mount Seminung area is composed of Quaternary volcanic deposits whose distribution is controlled by caldera morphology and structural fractures [10], and shows complex magmatic dynamics due to magma mingling processes in the youngest pyroclastic deposits of Mount Seminung [9]. In the context of geophysics, several studies in Indonesia have demonstrated the effectiveness of magnetic methods for identifying geothermal prospect zones. In Mandailing Natal, a digital-based mapping approach successfully described the spatial distribution of geothermal potential [12], while in Polewali Mandar, the interpretation of magnetic anomaly models delineated indications of subsurface heat sources [6]. A study on the Karangrejo geothermal manifestation in Pacitan also confirmed that low magnetic anomalies correlate with hydrothermal alteration zones [4]. Similar findings were reported in Kasinan–Songgoriti, East Java, where magnetic methods were used to identify geothermal reservoirs through low anomaly responses [3], as well as in non-volcanic systems in Terak Village, Central Bangka, which showed that changes in magnetic susceptibility are related to hydrothermal fluid activity [13, 14].

Previous studies have shown that magnetic data processing using derivative techniques, such as the Horizontal Gradient Derivative (HGD) and the Second Vertical Derivative (SVD), is effective for clarifying structural boundaries and fault zones that may serve as geothermal fluid pathways [15]. Although these studies demonstrate the effectiveness of magnetic methods, most research still focuses on qualitative interpretations of anomalies or is limited to specific manifestation areas, without comprehensive integration of the regional volcanotectonic context and magnetic field derivative analysis to clarify the boundaries of subsurface structures. Although geological and geochemical studies have confirmed the geothermal potential of the Ranau–Seminung area, the spatial characterization of subsurface magnetic anomaly patterns associated with post-caldera structural controls and possible geothermal fluid pathways remains insufficiently documented.

This study contributes to the preliminary interpretation of geothermal potential in the Mount Seminung-Lake Ranau area through the integration of magnetic anomaly analysis, topographic characteristics, and regional geological interpretation. The study also demonstrates the effectiveness of magnetic anomaly analysis in identifying hydrothermal alteration zones associated with geothermal systems. It provides a preliminary subsurface geothermal anomaly map to support further geothermal exploration in volcanic areas. The application of geophysical methods, especially magnetic methods, has been proven effective in the initial exploration stage for detecting subsurface structures that may host geothermal systems [3, 4]. Magnetic methods measure fluctuations in the total magnetic field intensity at Earth's surface, which arise from differences in rock magnetic properties [5].

These variations reflect mineralogical changes induced by hydrothermal alteration, which oxidize ferromagnetic minerals like magnetite to hematite and cause them to lose magnetization [7]. Because of this, regions with low magnetic anomalies are often thought to exhibit high hydrothermal activity and may be associated with geothermal reservoirs [6]. Under these conditions, the results of this study are magnetic anomaly distribution patterns that can identify low-anomaly zones as indicators of hydrothermal alteration processes and reveal the spatial relationship between fault structures and underground geothermal systems. The combination of stratigraphic, geophysical, and petrological data places Seminung-Ranau as an important volcanic-tectonic system and a moderate geothermal prospect in the South Sumatra-Lampung region. Magnetic anomalies are a crucial indicator for determining geothermal potential in both volcanic and non-volcanic systems, according to these diverse studies.

This study aims to identify potential geothermal zones in the Mount Seminung area, West Lampung, Indonesia, by analyzing magnetic anomaly data. This area was chosen because it shows signs of geothermal activity, as indicated by its geological conditions and surface manifestations. The results are expected to contribute to the initial mapping of geothermal prospect areas through a magnetic approach used to observe the distribution of geothermal potential in the study area, determine priority zones for further exploration, and serve as the basis for recommendations for the integration of geophysical and geochemical surveys to obtain a more comprehensive geothermal system model.

2. Methods

2.1. Data Acquisition and Data Collection

The research location (Figure 2) is in the Mount Seminung area and its surroundings, West Lampung Regency, Lampung Province, which is regionally included in the Ranau post-caldera volcanic zone. Geographically, the research area is located at coordinates 4.90°-4.93° South Latitude and 103.95°-103.98° East Longitude. The magnetic survey was conducted over an area of approximately 2 km × 2 km using a Proton Precession Magnetometer (PPM) G-857 with 95 observation points and an average station spacing of 200 m. Observation points were distributed systematically across the study area and positioned using GPS. Two PPM units were employed, one mobile unit for field mapping and one base-station unit for monitoring diurnal variations. Each station was measured repeatedly at five points arranged in a square pattern with 2–3 m spacing, yielding a minimum of 25 measurements per station. Diurnal variations were monitored using a base station located near the center of the survey area and recorded every 2 minutes during acquisition. Data consistency was evaluated through repeated measurements, with accepted variations of less than 20 nT.

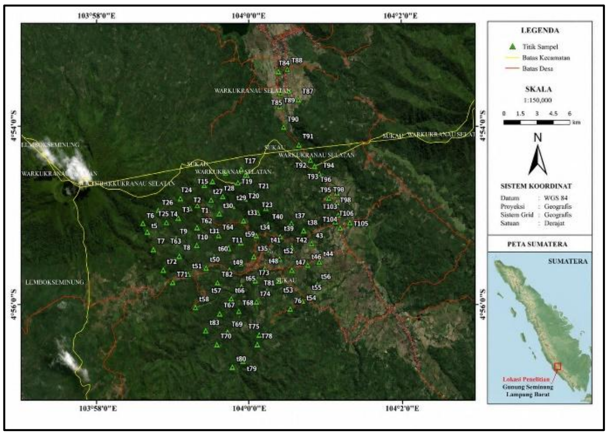


Fig. 2: Research point map

To minimize cultural magnetic noise during data acquisition, observation points were carefully selected and mapped, accounting for the presence of artificial magnetic sources, such as power lines, roads, buildings, vehicles, and metallic objects. Measurements were conducted in relatively open areas with minimal human activity to reduce external magnetic interference that could affect the magnetic field measurements. In addition, because the survey focused on the geothermal prospect area of Mount Seminung, West Lampung, most measurement locations were situated in volcanic and relatively remote areas, which naturally minimized anthropogenic magnetic noise during the survey. By measuring changes in the Earth's magnetic field intensity, which are influenced by variations in each lithology's magnetic susceptibility, magnetic methods and geophysical techniques identify variations in the magnetic properties of subsurface rocks.

The accuracy and effectiveness of magnetic field data collection have improved thanks to advances in measurement technology. Using an ATMEGA 328P microcontroller, Ghozali and Nugroho [16] developed a microcontroller-based Proton Precession Magnetometer (PPM) that can accurately and affordably record changes in the overall magnetic field. The PPM operates via proton precession in a magnetic field, with the Earth's magnetic field determining the signal frequency [17]. Magnetic methods are widely used in geophysical surveys because they are sensitive to variations in rock magnetism associated with subsurface geological structures. Magnetic methods are widely used in geothermal exploration because they can detect variations in rock magnetism associated with subsurface geological structures.

2.2. Data Processing

Magnetic anomaly analysis is commonly used to analyze the spatial distribution of magnetic anomaly sources in greater detail [18, 19]. PPM data processing begins with checking data consistency by observing differences across iterations. The received data shows a variation of less than 20 nT. In this calculation, geomagnetic anomaly values were obtained by correcting the average data received for daily variations and by using the International Geomagnetic Reference Field (IGRF) downloaded from the 2020 World Geomagnetic Model IGRF Calculator. The reduction process was then carried out on a flat plane in the middle of the topography because the study area had undulations that could not be ignored. The Reduction to a flat plane was performed using a MATLAB-based numerical correction to minimize the influence of topographic variations on the magnetic anomaly distribution. The correction process employed several parameters, including equivalent dipole depth, average elevation reference, magnetic inclination and declination, regional field inclination and declination, damping factor (λ), grid interval in the x-direction, and data length. The flat-plane Reduction reference elevation was determined as the average of the highest and lowest elevations in the study area, resulting in approximately 880 m above sea level.

The input dataset consisted of longitude, latitude, elevation, and magnetic anomaly values obtained from field measurements. The magnetic anomaly data were subsequently interpolated onto a regular grid and transformed to a reference flat plane before reduction-to-pole processing and further interpretation. Therefore, it was necessary to facilitate the model by reducing it to the North Pole using the Oasis Montaj software. Data from previous surveys and field survey results were thoroughly analyzed to construct a model of the regional geological and hydrological conditions in the area. The total magnetic anomaly is a variation in the Earth's magnetic field measured at the surface, caused by differences in the magnetic properties of subsurface rocks relative to the Earth's reference magnetic field [20].

The total magnetic field at a given point is the sum of the regional magnetic field (main Earth and regional fields), daily magnetic field variations (diurnal), and contributions from local magnetic sources below the surface. The total magnetic anomaly value is obtained after correcting for temporal fluctuations in the magnetic field and regional components, so that the remaining anomaly reflects subsurface physical variations directly related to the properties of the rocks concerned. Mathematically, the total magnetic anomaly (ΔH) is calculated from the difference between the magnetic field measured in the field (H_P) and several correction components, mainly reference magnetic field corrections such as the International Geomagnetic Reference Field (IGRF) and daily (diurnal) variations [20]. The basic formula is written as follows:

$$\Delta H = H_p - H_{IGRF} - H_d \qquad (1)$$

Where ΔH is the total magnetic anomaly (nT), H_P = total magnetic field measured in the field (nT), H_{IGRF} = theoretical magnetic field based on the IGRF model (nT), H_d = correction for diurnal magnetic field variation (nT). The corrected total magnetic anomaly is then displayed in the form of a total magnetic anomaly contour map, which illustrates the variation in magnetic field values in the study area. Total magnetic anomaly values are usually interpreted qualitatively and quantitatively: high anomaly values may indicate the presence of rocks with relatively high magnetism, such as basaltic lava or fresh andesite, while low or negative anomaly values are often associated with hydrothermal alteration zones or rocks with low magnetic susceptibility, including sedimentary rocks or rocks that have undergone demagnetization due to geothermal heat [20]. The total magnetic anomaly data then forms the basis for further processing stages, such as Reduction to poles (RTP), Reduction to a flat plane, separation of regional and residual anomalies, and the application of magnetic field derivative techniques (derivative analysis) to clarify the boundaries of lithology and subsurface structures that play a role in controlling the geothermal system.

The corrected magnetic anomaly data were then analyzed qualitatively and quantitatively by creating contour maps and magnetic anomaly distribution maps. The analysis was carried out by observing the distributions of anomaly values, magnetic contrast, and the spatial relationships between anomalies and surface morphology and geological conditions. To find potential variations in lithology, weathering levels, and the impact of hydrothermal processes, high and low anomaly values were compared. Additionally, signs of geological features, such as faults and fractures that serve as fluid-migration pathways, were identified using gradient analysis and anomaly alignment patterns. The integration of previous survey data and field-measurement results was also carried out to strengthen understanding of the regional geological and hydrological framework.

2.3. Data Interpretation

The interpretation stage involves correlating magnetic anomaly results with regional geological information, topographical conditions, and geothermal system characteristics. These techniques help map subsurface heterogeneity in greater detail and prepare data for further geological interpretation or three-dimensional modeling. Zones with high magnetic anomalies are interpreted as fresh volcanic rocks with relatively high ferromagnetic mineral content. In contrast, zones with low anomalies are interpreted as rocks that have undergone hydrothermal alteration or demagnetization, or as composed of non-magnetic sedimentary material. Anomalies associated with certain alignments are interpreted as geological structures that may serve as geothermal fluid circulation pathways. As a result, the final interpretation provides a conceptual summary of subsurface conditions and early indications of geothermal prospect zones, which can serve as a foundation for additional research employing more thorough modeling and integrated geophysical techniques.

3. Results and Discussion

3.1. Topography of Mount Seminung

The shape of the earth's surface reflects the effects of tectonic and volcanic activity, as well as long-term erosion, making topographic analysis a crucial first step in geological research and geothermal exploration. An overview of ridges, valleys, and transition areas, which are frequently governed by geological structures like faults and fractures, can be obtained from variations in elevation, slope, and contour patterns. In volcanic areas, morphological variations are generally related to eruption centers, lava flows, and collapse zones orbasins, so that topographic analysis not only explains surface conditions but also helps identify possible hydrothermal fluid flow paths. Therefore, topographic interpretation serves as the basis for understanding the relationship between morphology, structural control, and the potential of geothermal systems in the study area.

The complex morphology of the Mount Seminung area in West Lampung Regency is reflected in the topographic map of the study area (Figure 3), which displays variations in surface shape. The map scale and contour grid show the distribution of surface elevations between 552 meters and 1,236.4 meters above sea level. The Universal Transverse Mercator (UTM) coordinate system was used because it provides spatial measurements in meters, making it more suitable for topographic, geological, and magnetic anomaly analysis than geographic coordinates. The map's gradient colors show changes in elevation across the map. Blue and dark blue show low elevation areas, green to yellow show medium elevation, and orange to red and purple show high elevation. This color distribution is not just a visual representation; it also shows how the relief in the study area differs due to geological and geodynamic processes.

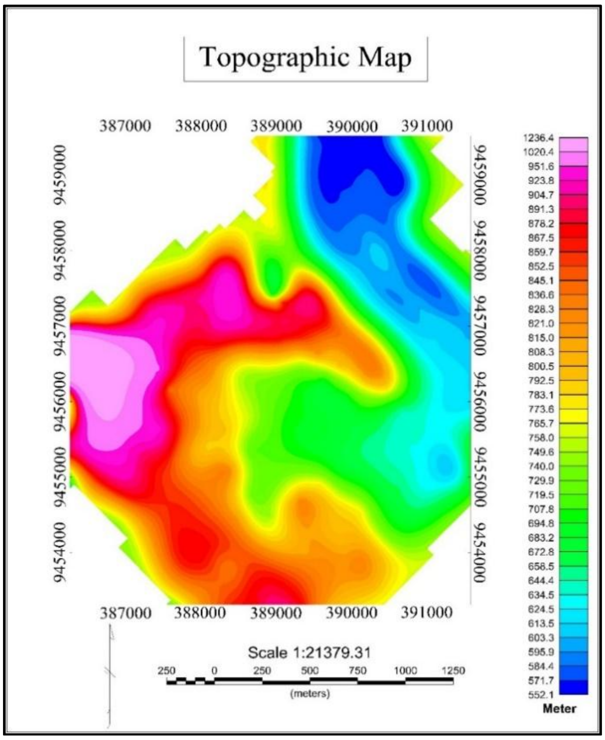


Fig. 3: Topographic map

High elevations, marked by shades of red to purple, generally develop in the western and northwestern sectors of the map. This zone corresponds to the ridges and steep slopes of Mount Seminung, which were formed by the accumulation of volcanic products, including lava and pyroclastic deposits, as well as by magmatic accretion. The contour lines in this zone are relatively dense, indicating steep slopes. In contrast, low elevations marked by blue to dark blue colors are scattered across the east to northeast. This zone is interpreted as a gentler valley or basin, most likely associated with Lake Ranau and surface basin areas that have undergone erosion and deposition of fine material. This morphology has less-defined edges, indicating that the slope is less steep than in the volcanic ridge.

The middle of the map features a transition zone with medium elevations, mostly green to yellow. This zone connects the volcanic hills in the west with the lowlands in the east. This pattern is consistent with findings from geomorphological studies showing that topographic transition areas often reflect changes in the dominance of geological processes, from volcanic to erosion- and sedimentation-dominated conditions [21]. The western part has a higher contour density, indicating that elevation changes quickly over short distances and revealing steep volcanic slopes. The eastern part has a wider contour spacing, indicating that the land slopes down more gently toward the waters and the basin of Lake Ranau.

3.2. Magnetic Field

The total magnetic field map in regional magnetic surveys is an initial representation that shows the combined response from the Earth's main magnetic field and subsurface anomaly sources. Although it still contains regional components, this map provides important information about the general distribution pattern of rock magnetism and its spatial relationship with surface morphology and geological features. Variations in the overall magnetic field frequently indicate interactions between volcanic bodies, sedimentary deposits, and active geological structures in volcanic environments that form around tectonic lakes and caldera systems. Therefore, analysis of the total magnetic field map is a crucial preliminary step before further transformation or separation of anomalies.

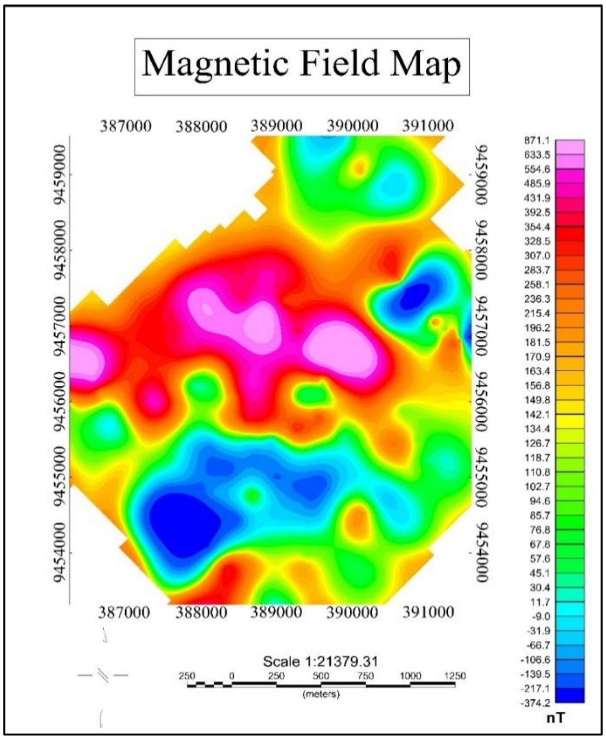


Fig. 4: Magnetic Field Map

The total magnetic field map (Figure 4) of the Mount Seminung area and its surroundings, which borders Lake Ranau, shows quite contrasting variations in magnetic field values. The map's color scale indicates that the total magnetic field intensity ranges from roughly 0.2 nT to 871.1 nT, reflecting variations in the magnetic properties of subsurface rocks. The degree of hydrothermal alteration, the presence of geological structures, and variations in lithology are typically linked to these variations. Zones with relatively high magnetic field values of around 181.5 nT to 871 nT are indicated by red to purple colors and are predominantly found in the body of Mount Seminung. This zone is interpreted as being associated with relatively fresh volcanic rocks, such as lava and volcanic breccia, which generally have higher magnetic mineral content, for example magnetite.

This condition is consistent with the general characteristics of volcanic areas, where unaltered igneous rocks produce a high magnetic response. Conversely, zones with low to very low magnetic fields, ranging from approximately -374.2 nT to -9.0 nT, are marked by dark blue to light blue colors and are scattered mainly to the east and southeast of the study area, approaching the Ranau Lake region. This zone is thought to consist of hydrothermally altered sedimentary and/or volcanic rocks. Low magnetic anomalies result from the alteration process that converts magnetite into non-magnetic minerals, thereby reducing the magnetic mineral content. In geothermal prospect areas, where alteration zones frequently form around hot fluid pathways, this pattern is frequently observed [5]. The presence of geological features like faults or fracture zones is indicated by the comparatively abrupt change in magnetic field values between the high zone at Mount Seminung and the low zone towards Lake Ranau. The movement of geothermal fluids from depth to the surface may be regulated by these structures, which act as weak zones. The existence of structural zones associated with low magnetic anomalies is a common feature of geothermal systems, both in volcanic and non-volcanic environments [13].

This interpretation is consistent with previous studies indicating that geothermal manifestations in the Ranau–Seminung area comprise eight hot springs and two altered rock occurrences spatially associated with volcanotectonic structures within the Danau Ranau geothermal system [22, 23]. The correspondence between mapped fault structures, geothermal manifestations, and low-magnetic-anomaly zones indicates that these structural features likely act as permeability pathways controlling subsurface hydrothermal fluid circulation in the study area. The distribution pattern of magnetic anomalies in the Mount Seminung area not only reflects zones of hydrothermal alteration characterized by low magnetic anomaly values, but also indicates the influence of volcanotectonic structures and morphological boundaries on the geothermal system.

The spatial association between low magnetic anomaly zones, topographic transitions, and inferred structural trends suggests that geological structures may play an important role in controlling subsurface geothermal fluid circulation. These findings provide a preliminary geological and geothermal interpretation of the structural controls associated with the geothermal system in the study area. Based on this interpretation, the distribution of the total magnetic field in the Mount Seminung and Lake Ranau areas shows a close relationship between rock magnetism variations, geological conditions, and geothermal system potential. Therefore, the total magnetic field map can serve as a basis for initial exploration to identify geothermal prospect zones that warrant further study using other geophysical and geological methods.

The interpretation of low magnetic anomaly zones as preliminary geothermal prospect areas is also consistent with previous magnetotelluric (MT) investigations conducted in the Ranau geothermal area, which identified subsurface structures associated with geothermal systems [22]. However, comprehensive geothermal reservoir characterization requires integration with additional geophysical, geochemical, and subsurface datasets.

3.3. Reduction to a Flat Surface

The correction stage for topographic effects in geomagnetic studies is an important procedure for improving the reliability of data interpretation. Differences in elevation between measurement points can cause variations in the distance between the sensor and the source of anomalies below the surface, so that the measured magnetic field amplitude does not fully represent the contrast in the magnetic properties of the rocks. This condition becomes even more significant in areas with steep topography, such as volcanic regions, where elevation changes over relatively short distances. Therefore, Reduction to a flat plane is performed to standardize the observation position at a single reference elevation, so that the resulting anomaly distribution better reflects variations in subsurface lithology and geological structure rather than the influence of surface relief.

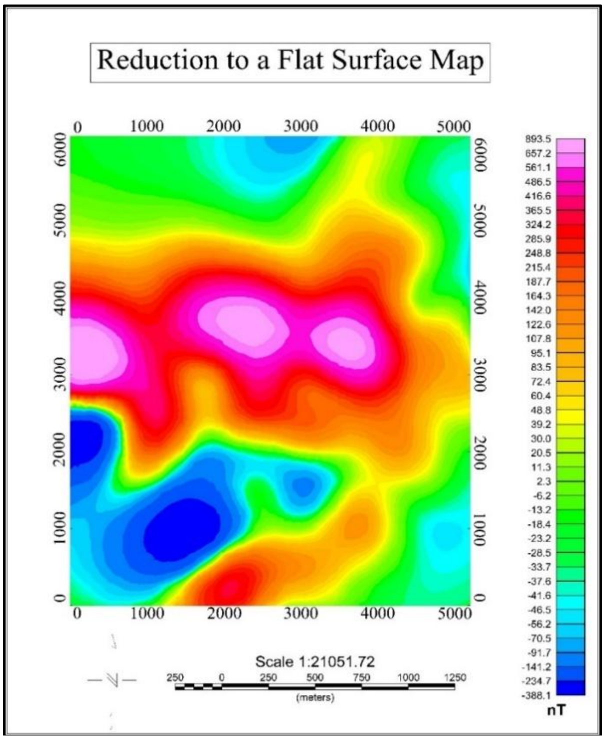


Fig. 5: Reduction to a flat surface map

The flat-field reduction map (Figure 5) shows the distribution of total magnetic field anomalies, corrected to minimize the influence of surface topography and better reflect subsurface variations. In magnetic data processing, the data are flattened so that each point is measured as if it were at a common reference height. This way, the magnetic anomalies are not affected by differences in surface measurement height. This method is especially important in volcanic areas like Mount Seminung, where the surface relief is uneven and could lead to a false magnetic field reading if the elevation is not corrected first. The magnetic anomaly values from the flat-plane reduction range from about -388.1 nT to 893 nT, as indicated by the color scale on the map. Warm hues like red, orange, and light purple indicate high magnetic anomalies, typically exceeding 215 nT, with some zones reaching maximum values near 893 nT.

Positive anomaly zones are thought to be composed of rocks with high magnetic susceptibility, such as fresh andesite, basaltic lava, or shallow igneous intrusions that still contain ferromagnetic minerals. These high-amplitude positive anomalies are indicative of relatively dense, compact volcanic rock bodies that have not experienced significant hydrothermal alteration. Conversely, zones of low to negative magnetic anomalies are indicated by shades of blue to green, with anomaly values ranging from -388.1 nT to -6.2 nT. Rocks that have undergone hydrothermal alteration, severe weathering, or demagnetization due to the oxidation of primary magnetic minerals are typically associated with these low anomalies. Zones with low magnetic anomaly values in geothermal systems are frequently associated with areas of alteration induced by geothermal fluid circulation, which lowers magnetic response and magnetic mineral content. Low-anomaly zones are potential sites for geothermal reservoirs or cap rocks due to these circumstances [20].

The lateral distribution of magnetic anomalies on the map shows quite sharp variations in values between high- and low-anomaly zones. These contrasting changes in anomaly gradients may indicate the presence of subsurface geological structures, such as faults or fractures, which act as lithological boundaries or hydrothermal fluid migration pathways. Such structures generally develop in active volcanotectonic systems and play an important role in controlling the distribution of heat and fluids in geothermal systems. Thus, this flat-field reduction map provides a strong preliminary overview of variation in subsurface magnetic properties, which is very useful for guiding further interpretation, such as residual anomaly mapping, field derivatives, or inversion modeling. This information can then be combined with surface geological data to determine the location of geothermal control structures, fluid circulation pathways, and reservoir potential, especially in volcanic systems such as Mount Seminung.

3.4. Reduction To Pole

Direct interpretation of total magnetic field anomalies in magnetic data analysis often fails to accurately reflect the positions of subsurface sources, especially in areas affected by the Earth's magnetic field inclination. The effects of inclination and declination can cause the anomaly shape to become asymmetrical and shift from the actual source location. Therefore, a mathematical transformation is needed to normalize the direction of magnetization so that the anomaly response can be more easily interpreted geologically. One commonly used approach is the Reduction to the Pole (RTP) transformation, which conceptually assumes vertical magnetic field conditions at the magnetic pole, thereby shifting the anomaly distribution toward a more centered position above the source.

The magnetic anomaly map resulting from the Reduction to the Pole (RTP) transformation in Figure 6 shows the distribution of magnetic anomalies that have been corrected for the effects of the Earth's magnetic field inclination and declination. The Reduction to Pole transformation aims to shift the magnetic anomaly response so that the anomaly peak is directly above its source, resulting in a more symmetrical and representative anomaly pattern of the subsurface geological conditions. The application of Reduction to Pole is very important in low to mid-latitude regions, such as Indonesia, because the inclination of the Earth's magnetic field can cause lateral shifts in anomalies in raw magnetic data [24]. Based on the Reduction to Pole results, the magnetic anomaly values in the study area ranged from approximately −588.4 nT to 1225.5 nT. The high magnetic anomaly zone, indicated by red to purple colors with values ranging from 449.9 nT to 1225.5 nT, was predominantly located in the central to southern parts of the study area.

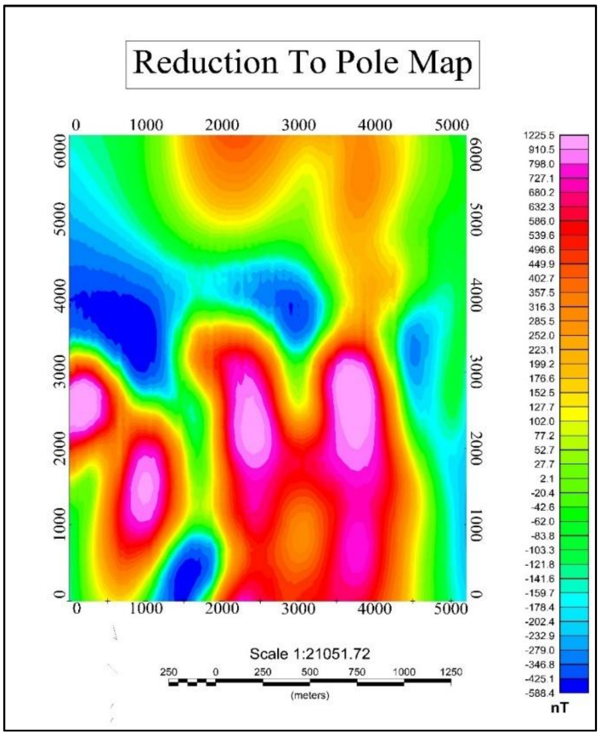


Fig. 6: Reduction to pole map

The existence of a subsurface magnetic source with high magnetic susceptibility is indicated by this comparatively closed and symmetrical high anomaly pattern. This condition is typically associated with the presence of ferromagnetic minerals in igneous or volcanic rocks, which produce a stronger magnetic response than the surrounding rocks [25]. On the other hand, the low magnetic anomaly zone, represented by blue to green hues, is primarily located in the northwest and northeast regions of the study area and ranges from roughly -588.4 nT to -20.4 nT. This area is interpreted as sedimentary rock, altered rock, or areas of severe weathering that have low magnetic susceptibility.

The contrasting anomaly values between high- and low-magnetic zones indicate significant changes in rock physical properties and suggest the possible presence of lithological boundaries or subsurface geological structures. The Reduction to Pole transformation also clarifies the boundaries and gradients of magnetic anomalies, allowing the pattern of magnetic field changes to be more clearly observed. The presence of geological features, such as faults or fracture zones, that regulate the distribution of subsurface magnetic sources may be indicated by a sharp, extended transition zone between high- and low-anomaly areas. This is consistent with earlier research: Reduction to Pole analysis is useful for determining subsurface structural patterns and lithological variations based on the distribution of magnetic anomalies [25, 24]. The distribution of subsurface magnetic sources in the study area is generally better depicted by the Reduction to Pole map. Differences in lithology and the impact of locally developed geological structures are reflected in variations in magnetic anomaly values. To gain a more thorough grasp of subsurface conditions, these findings can serve as a solid foundation for additional geological interpretation and integration with other geophysical data.

4. Conclusions

The Mount Seminung area and its environs exhibit complex morphological and subsurface magnetic characteristics that are heavily influenced by volcanotectonic processes, as indicated by topographic analysis and magnetic data. With elevations ranging from 552 to 1,236.4 meters above sea level, the topographic map demonstrates notable elevation variations. While low to medium elevations extend towards Lake Ranau with more sparse contours indicating gentle to concave morphology, high elevations are mostly found on the body of Mount Seminung with dense contours reflecting steep volcanic slopes. These elevation variations indicate the influence of regional geological structures on landscape formation. The results of magnetic data measurement and processing show a fairly contrasting variation in total magnetic field values, with arange of values between approximately -374.2 nT and 871.1 nT. Zones with high magnetic field values of around 181.5 nT to871.1 nT generally develop in the area of Mount Seminung and are interpreted as being associated with relatively fresh volcanic rocks rich in magnetic minerals. Conversely, zones with low to negative magnetic fields ranging from approximately -374.2 nT to -9.0 nT predominantly develop towards Lake Ranau and are interpreted as hydrothermally altered rocks or sedimentary materials with low magnetic mineral content. The flat-field reduction transformation produces magnetic anomaly values ranging from approximately −388.1 nT to 893 nT, clarifying the distribution of anomalies by eliminating the influence of topographic variations. Furthermore, the Reduction to pole results show a more contrasting range of magnetic anomalies, namely from approximately -588.4 nT to 1,225.5 nT.

The anomaly pattern after Reduction to the pole becomes more symmetrical and centered above the magnetic source, allowing lithological boundaries and indications of subsurface geological structures to be identified more clearly. Low magnetic anomaly zones with values below approximately -20 nT to -588.4 nT are interpreted as alteration zones or weak zones that have the potential to become geothermal fluid circulation pathways. Overall, the results of this study show that the combination of topographic analysis, total magnetic field, plane reduction, and Reduction to the pole can provide a strong preliminary picture of variations in subsurface magnetic properties and indications of structures controlling the geothermal system in the Mount Seminung area. Low-magnetic-anomaly zones associated with sharp elevation changes and morphological boundaries are interpreted as geothermal prospect areas. This study suggests that magnetic methods are effective as an initial stage of geothermal exploration in volcanic areas with complex relief, particularly for identifying alteration zones and geological structures that control fluid flow. Information on magnetic anomaly values and their distribution patterns can serve as a basis for determining the locations of additional surveys.

Future geoelectric or magnetotelluric (MT) investigations should be prioritized in the low-magnetic-anomaly zones around the structural transition between Mount Seminung and the Lake Ranau area, particularly in areas associated with mapped fault structures and geothermal manifestations, as these zones are interpreted to represent potential hydrothermal fluid circulation pathways. However, the interpretations obtained remain indicative because this study used only one geophysical method and had a limited number and distribution of measurement points. Hence, the details of subsurface heterogeneity were not optimally described. For future studies, integrating other geophysical methods, such as resistivity, magnetotellurics, and gravity surveys, is recommended to provide a more comprehensive interpretation of reservoir depth, structural characteristics, and potential geothermal reservoir volume. In addition, quantitative magnetic modeling and a more detailed geological structure study are needed to improve the accuracy of interpretation geothermal potential in the Mount Seminung area. Conclusions describe the answers to the hypotheses and research objectives or scientific findings obtained. The conclusion does not repeat the results and discussion, but rather summarizes the findings, as expected, in relation to the objectives or hypotheses, and outlines the actions to be taken for the next phase of the research.

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