Analysis of Rock Magnetic Susceptibility in a Local Fault Zone at Sangkrek, Kulon Progo Regency

Nadzif Muaffi[1], Thaqibul Fikri Niyartama[2*], Nugroho Budi Wibowo[3], Hana Rosyida[4]
[1,2,4] Department of Physics, Sunan Kalijaga State Islamic University. Yogyakarta 55281, Indonesia
[3] Class I Geophysics Station in Sleman. Yogyakarta, Indonesia
[*] thaqibul.niyartama@uin-suka.ac.id

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ABSTRACT

This study aims to analyze the pattern of magnetic anomaly distribution and determine the rock magnetic susceptibility values as a basis for identifying a local fault zone in the Dusun Sangkrek area, Kokap District, Kulon Progo Regency. The geomagnetic method was employed, with data acquisition conducted at 60 observation points using a Proton Precession Magnetometer (PPM) G-856 at 100-meter intervals. The total magnetic field data were corrected for daily variations and the International Geomagnetic Reference Field (IGRF) to obtain the total magnetic anomaly (ΔT). The magnetic anomaly values range from $-3{,}1 \times 10^2$ nT to $6{,}8 \times 10^2$ nT, where high anomalies are dominant in the northern part, composed mainly of andesitic rocks, while low anomalies are found in the western and southern parts, corresponding to the Sentolo and Alluvium Formations. Data processing stages include reduction to the pole (RTP), upward continuation, and two-dimensional (2D) modeling to characterize subsurface magnetic variations. The modeling results indicate that the magnetic susceptibility of rocks varies between $1{,}0 \times 10^{-4}$ and $1{,}1 \times 10^{-1}$ SI, with higher values associated with andesite and brecciated andesite, and lower values corresponding to siltstone, claystone, and sandstone. The contrasting distribution of susceptibility along several profiles reveals sharp lithological changes, interpreted as indications of a local fault zone that influences the subsurface magnetic distribution.

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1. INTRODUCTION

Indonesia is an archipelagic country located at the convergence of three major tectonic plates: the Eurasian Plate, the Indo-Australian Plate, and the Pacific Plate. The interaction among these plates has resulted in the formation of subduction zones, volcanic arcs, and highly complex geological structures in many regions [1]. Continuous tectonic and volcanic activity has significantly influenced the development of various rock formations and subsurface structures, including the occurrence of active faults and fracture zones that are widely distributed across Indonesia [2].

One of the regions characterized by complex geological conditions due to active tectonic and volcanic processes is the Special Region of Yogyakarta (DIY). The western part of this province, namely Kulon Progo Regency, comprises four principal lithostratigraphic units: the Andesite Formation, Kebobutak Formation, Sentolo Formation, and Alluvium Formation [3]. Variations in lithology within this region lead to differences in the physical and magnetic properties of rocks, which can be utilized to identify subsurface structures such as local fault zones. Previous studies have indicated that fault and fracture systems in the Kulon Progo area developed along Tertiary volcanic structures and were subsequently reactivated by younger tectonic events [4].

The magnetic characteristics of rocks are determined by the concentration of ferromagnetic minerals, including magnetite, ilmenite, and hematite, which contribute to the magnetic susceptibility of the rocks [5]. This parameter describes the ability of a rock to become magnetized under the influence of the Earth's magnetic field [6]. Variations in magnetic susceptibility serve as an important geophysical indicator for detecting lithological changes, formation boundaries, and subsurface geological structures such as faults or fractures, without the need for invasive methods such as drilling [7], [8].

The magnetic method is one of the most widely applied geophysical techniques for investigating subsurface structures based on variations in the intensity of the Earth's magnetic field [9]. Differences in magnetic susceptibility among rocks generate magnetic anomalies, which can be interpreted to delineate formation boundaries, fracture zones, or local fault structures [10]. By analyzing magnetic anomaly data and performing magnetic susceptibility modeling, it is possible to obtain the spatial distribution of rock magnetic properties, which reflects the local geological and structural conditions of the subsurface [11].

This method offers a significant advantage because it allows the detection of magnetic variations caused by contrasts in subsurface lithology and can identify susceptibility contrasts commonly associated with fault zones [12]. Significant magnetic anomalies generally indicate abrupt lithological transitions or fractures produced by tectonic activity. Therefore, magnetic interpretation represents an effective approach for detecting local or concealed fault structures (blind faults) [13].

This study aims to analyze the distribution pattern of magnetic anomalies and determine the rock magnetic susceptibility values in the Dusun Sangkrek area, Kulon Progo Regency, which is thought to be influenced by a local fault zone. The magnetic method was chosen for its ability to detect subsurface variations in rock magnetization with high resolution and non-destructive measurement. The results of this research are expected to provide insights into the subsurface physical characteristics and enhance the understanding of the relationship between susceptibility variations and local fault structures in the study area. Furthermore, the findings may contribute to geological studies, resource exploration, and geohazard mitigation efforts in the future [14].

2. METHODS

2.1. Study Area

This research was conducted in Dusun Sangkrek, Kokap District, Kulon Progo Regency, Special Region of Yogyakarta, which is geographically located between coordinates 7° 50′ 52″ S – 7° 52′ 33″ S and 110° 05′ 25″ E – 110° 06′ 31″ E. The study area is part of the Kulon Progo Mountains Zone, which is composed of the Andesite Formation, Kebobutak Formation, Sentolo Formation, and Alluvial deposits [3], as shown in Figure 1.

Geomorphologically, the region exhibits undulating to steep hilly terrain with elevations ranging from 100 to 500 meters above sea level. The topography is primarily influenced by ancient volcanic activity from Mount Ijo and subsequent tectonic processes that have produced several local fault structures across the area [13].

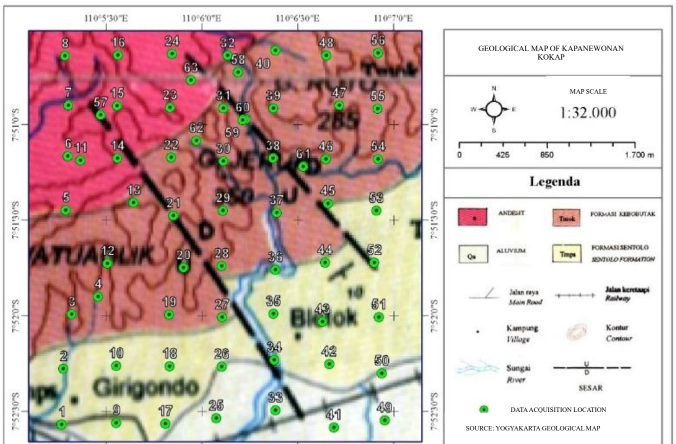

Figure 1. Geological Map of Area

Magnetic data acquisition was carried out using a Proton Precession Magnetometer (PPM) Geometrics G-856, which measures the total magnetic field intensity in nanotesla (nT) units. The survey was conducted at 63 observation points with measurement intervals ranging from 200 to 600 meters, depending on topographic conditions and field accessibility. Measurements were performed using the looping method, in which repeated readings were taken at a magnetic base station at the beginning and end of each survey session to correct for diurnal magnetic variations [15].

The survey design was established based on the assumed orientation of the local fault, which trends northwest–southeast (NW–SE). Therefore, the measurement lines were aligned parallel to the expected fault direction to better represent local geological structures. Each observation point was recorded with its geographic coordinates and elevation using a Global Positioning System (GPS) and the National Digital Elevation Model (DEMNAS) data. As one of the potential field methods in geophysics, the magnetic method is widely used because of its ability to detect magnetic anomalies without direct contact with rock outcrops [4]. This technique is particularly effective in volcanic and tectonic regions, where it can be applied to identify formation boundaries and magnetic contrast zones associated with fault activity [16].

The magnetic field data obtained from field measurements were subsequently processed to derive the total magnetic anomaly (ΔT). The resulting anomaly data were then interpreted to analyze the spatial distribution of magnetic anomalies and estimate the rock magnetic susceptibility values within the study area.

2.2. Data Processing

The acquired magnetic data were processed using Oasis Montaj 8.4, Surfer 13, and ArcGIS 10.4. The data processing workflow consisted of a series of correction and filtering steps designed to remove external magnetic influences, separate shallow and deep anomaly components, and generate a subsurface magnetic susceptibility model.

The first stage involved diurnal correction, which was performed using repeated measurements at the magnetic base station. This correction aimed to eliminate the influence of daily fluctuations in the Earth's magnetic field caused by ionospheric activity and magnetic storms. The correction values were calculated based on the difference between the base readings at the beginning and end of each survey session, and then applied to all observation points to ensure that the data represented the true magnetic conditions.

The next step was the main field correction using the International Geomagnetic Reference Field (IGRF) model, in order to remove the global magnetic field component and isolate the total magnetic anomaly (ΔT) that reflects local variations due to differences in rock magnetic properties. The IGRF-corrected data were then presented as a total magnetic anomaly map, showing the spatial distribution of magnetic intensity across the study area.

A topographic correction was subsequently applied to minimize the effect of elevation differences on the magnetic field intensity. In areas with rugged topography, the measured magnetic field may vary due to surface undulation; therefore, this correction ensured more accurate interpretations. After all corrections were applied, spectral filtering was conducted to separate regional and residual anomaly components using a power spectrum-based band-pass filter. This separation distinguishes anomalies associated with deep-seated regional sources from those produced by shallow or local magnetic bodies (noise).

To better define the position of the magnetic sources, Reduction to the Pole (RTP) processing was applied. This transformation shifts magnetic anomalies directly above their causative sources by removing the effects of the Earth's magnetic declination and inclination [17]. The RTP process is particularly important in low-latitude regions such as Indonesia, where magnetic anomalies tend to be displaced from their true source positions. Following RTP, upward continuation was applied to emphasize deep anomaly components and suppress the influence of shallow sources [18].

The final stage of processing involved two-dimensional (2D) forward modeling using the GM-SYS module in Oasis Montaj. Modeling was performed along profiles that intersected the major anomaly zones to estimate the vertical distribution of rock magnetic susceptibility (χ). The inversion process was conducted by iteratively comparing the theoretical model response with observed anomaly data until the best-fitting model was achieved. The resulting susceptibility values were then compared with reference values from Telford et al. (2012) [4] to infer the corresponding lithological composition.

3. RESULTS AND DISCUSSION

3.1. Total Magnetic Field

The total magnetic field intensity in the study area ranges from 44747,7 nT to 45733,8 nT. The distribution pattern (Figure 2) shows a distinct gradient between the eastern and western parts of the study area. High magnetic field values (45023 – 45733 nT) are predominantly observed within the Andesite Formation, whereas lower values (44747.7 – 44858.4 nT) occur in the southwestern part of the formation. In the Kebobutak Formation, the total magnetic field ranges between 44750 nT and 45733 nT, with localized low values near Mount Jeruk, which are attributed to surface limestone deposits overlying sedimentary layers.

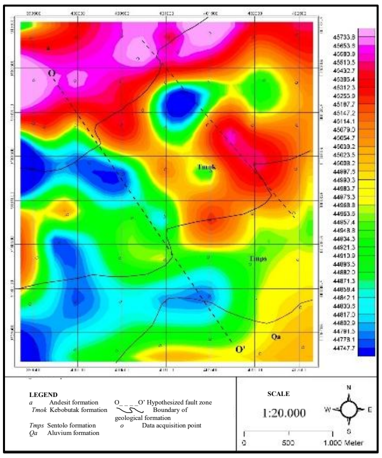

Figure 2. Distribution of total magnetic field intensity in the study area

The Sentolo Formation exhibits total magnetic field values ranging from 44747,7 nT to 45255,9 nT, dominated by low anomalies that indicate the presence of non-magnetic sedimentary lithology. Meanwhile, the Alluvium Formation shows values between 44778,1 nT and 45008,2 nT, reflecting the low magnetic susceptibility of silt, clay, and sand layers [3], [13].

The variation in total magnetic field intensity reflects the heterogeneity of subsurface lithology, where volcanic rocks containing ferromagnetic minerals such as magnetite and hematite generate higher magnetic field values, while non-magnetic sedimentary rocks produce lower values [4], [15]. In addition to lithological differences, topographic variations and local geological conditions also influence the observed total magnetic field pattern [10]. The total magnetic field map serves as the foundation for diurnal and IGRF corrections, which are subsequently used to generate the magnetic anomaly map (ΔT) representing the local magnetic characteristics of the subsurface rocks [9].

3.2. Magnetic Anomaly

Magnetic anomaly values were obtained from the IGRF correction and diurnal variation correction applied to the total magnetic field data. Based on the data processing results, the magnetic anomaly map (Figure 3) shows anomaly values ranging from –310 nT to 680,5 nT. The distribution pattern of magnetic anomalies closely resembles that of the total magnetic field, where high anomaly values dominate the northern part of the study area composed mainly of andesitic rocks, while low anomalies are observed in the Sentolo and Alluvium Formations.

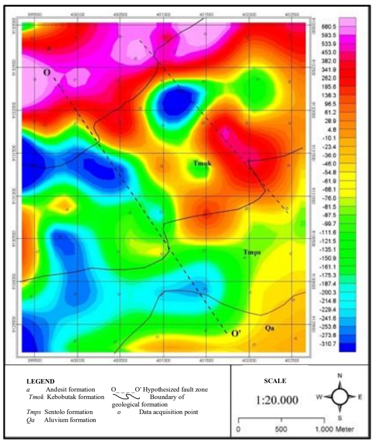

Figure 3. Magnetic anomaly distribution in the study area

High anomaly values between 4,8 nT and 680,5 nT are concentrated in the northern sector, where dark, hard andesite rocks are prevalent. These rocks were formed from magma solidification, are frequently found around fractures and steep outcrops, and typically exhibit high magnetic susceptibility. In contrast, the southwestern part of this formation shows lower anomaly values ranging from –310,7 nT to –187,4 nT, suggesting the presence of rocks with weaker magnetic properties.

In the Kebobutak Formation, magnetic anomalies vary between –310,0 nT and 533,9 nT, reflecting differences in the lithological composition, which includes andesite breccia, tuff, lapilli tuff, agglomerate, and andesitic lava intercalations. Relatively high anomaly values (96,5–533,9 nT) are typically found in areas dominated by andesite breccia and basalt, whereas low anomalies (–310,7 to –54,8 nT) occur near Mount Jeruk, which is composed predominantly of limestone and andesite breccia.

The Sentolo Formation exhibits anomaly values ranging from –310,0 nT to –61,9 nT, primarily associated with non-magnetic sedimentary rocks such as limestone and sandstone. However, a relatively high anomaly zone (96,5–380,5 nT) is observed along the boundary with the Kebobutak Formation, which may be attributed to variations in rock depth or lithological contrast.

Within the Alluvium Formation, anomaly values range from –241,6 nT to –61,9 nT, representing a low magnetic response due to the predominance of gravel, silt, clay, and sand, which have weak magnetic properties. However, some areas show slightly higher anomaly values than those in the Sentolo Formation, likely due to the presence of underlying hard volcanic rocks, such as andesite breccia or lava andesite, at relatively shallow depths [4], [15].

Overall, the magnetic anomaly pattern strongly correlates with lithological variations. Igneous rocks containing a high concentration of magnetic minerals (e.g., magnetite and hematite) produce high magnetic anomalies, while sedimentary formations exhibit lower values. These variations indicate that the physical properties and depth of rock layers are the main factors influencing the observed magnetic anomalies in the Sangkrek area.

To further separate the anomaly sources, a spectral filtering process was applied to distinguish regional and local anomaly components using the radial average power spectrum method. The resulting regional magnetic anomaly map (Figure 4) shows values ranging from –310,7 nT to 677,1 nT, with a slightly narrower range compared to the initial anomaly map due to the removal of short-wavelength local anomalies.

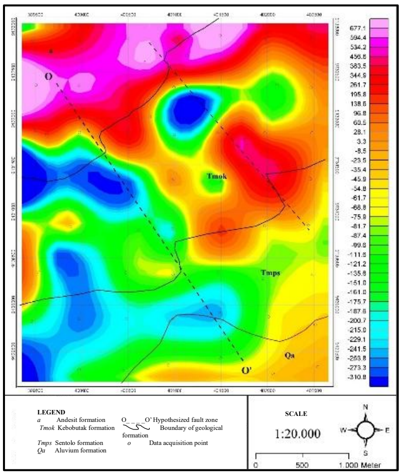

Figure 4. Regional magnetic anomaly map

3.3. Reduce To Pole

The regional magnetic anomaly data were used as the primary input for the Reduction to the Pole (RTP) process, as this component represents the magnetic response of large-scale and deeper geological structures. Using regional anomalies ensures that the RTP output reflects a more stable and geologically meaningful distribution of magnetic sources [10].

The RTP transformation aims to relocate the magnetic anomaly peaks directly above their causative bodies by eliminating the effects of the Earth's magnetic inclination and declination. In Indonesia, the magnetic inclination typically ranges from –30° to –40°, with a declination of a few degrees to the west. Consequently, natural magnetic anomalies often appear asymmetric relative to their sources. Applying RTP corrects these directional effects, resulting in more symmetrical anomaly patterns that are easier to interpret [4].

The RTP results derived from the regional anomaly data (Figure 5) show that the magnetic anomaly pattern in the study area becomes clearer and more focused compared to the uncorrected data. The anomaly values after RTP range from –280,0 nT to 650,0 nT, which is slightly narrower than the initial range due to the removal of directional and local field effects. High anomaly zones remain dominant in the northern and northeastern sectors, composed mainly of andesite and volcanic breccia, while low anomaly zones are found in the western and southern parts, dominated by the Sentolo and Alluvium Formations.

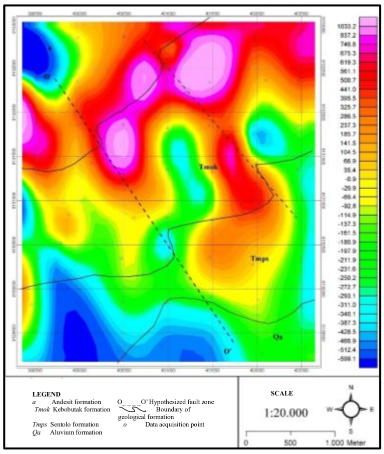

Figure 5. Reduction to the Pole (RTP) anomaly map

The RTP transformation enhances the boundaries between lithological formations and clarifies subsurface lithological transitions. The resulting anomaly pattern shows a dominant northeast–southwest (NE–SW) orientation, consistent with the regional lithological and geomorphological trends of the Kulon Progo region [3], [9]. This RTP stage serves as a critical foundation for subsequent processing steps such as upward continuation and 2D modeling, ensuring that the interpretation is based on directionally corrected anomalies free from local disturbances. This improves the accuracy and reliability of the resulting rock susceptibility models [15].

3.4. Upward Continuation

The results of the upward continuation process at the highest level, 1 000 m above the surface, are shown in Figure 6. Increasing the continuation height leads to a reduction in the amplitude of local anomalies, producing a progressively smoother magnetic anomaly map. As the continuation height increases, the anomaly closures become broader and gentler, indicating the dominance of regional anomalies generated by deep-seated magnetic sources.

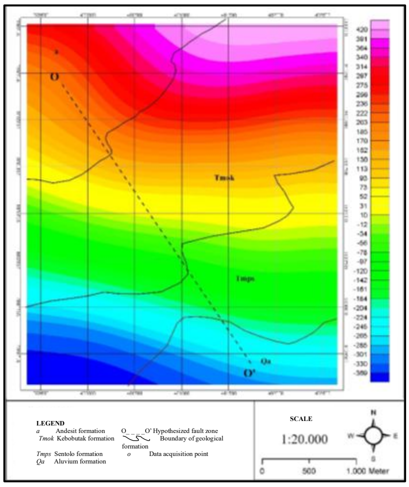

Figure 6. Upward continuation result at 1000 m elevation

High anomaly closures ranging from 256,0 nT to 420,0 nT are predominantly observed within the Andesite Formation and parts of the Kebobutak Formation, which are composed of hard volcanic rocks such as andesite, basalt, and volcanic breccia with high magnetic susceptibility. In contrast, low anomaly closures ranging from –369,0 nT to 56,0 nT are distributed across the western Kebobutak Formation, the Sentolo Formation, and the Alluvium Formation, which generally consist of limestone, sandstone, and silt exhibiting low magnetic susceptibility [15], [9].

The upward continuation results clearly demonstrate that shallow magnetic effects have been effectively reduced, leaving patterns that primarily reflect the response of deeper magnetic rock sources. The continuation maps thus serve as the foundation for subsequent two-dimensional (2D) modeling, aimed at determining the distribution of magnetic susceptibility values and interpreting subsurface geological structures within the study area [13].

3.5. 2D Model

The final stage of magnetic data processing involved two-dimensional (2D) modeling, which aimed to determine the distribution of rock magnetic susceptibility values and the subsurface lithological configuration within the study area. Modeling was performed using the Mag2DC software, based on the regional magnetic anomaly data that had been previously reduced to the pole (RTP) and upward continued.

The 2D models were constructed along several profiles (AA'–FF') representing north–south and east–west orientations across the study area (Figure 7). Each profile was selected according to the magnetic anomaly pattern and surface geological conditions, allowing for a representative depiction of the main lithological variations. The modeling process employed a trial-and-error approach, where susceptibility, depth, and layer thickness parameters were iteratively adjusted until the calculated anomaly curve closely matched the observed magnetic anomaly [4].

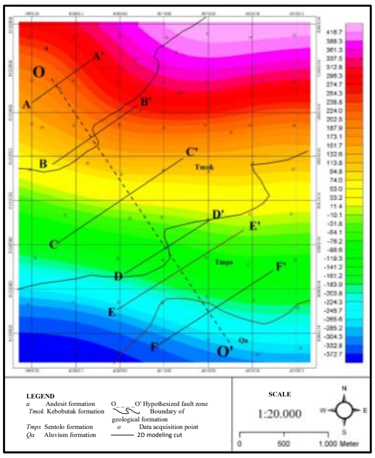

Figure 7. 2D modeling section locations (AA'–FF')

The modeling results (Figure 8, 9, 10, 11, 12, and 13) indicate several subsurface layers with distinct magnetic susceptibility values corresponding to different lithological units. The rock susceptibility values in the study area range from $1,00 \times 10^{-5}$ SI to $1,08 \times 10^{-1}$ SI. The Alluvium Formation shows susceptibility values between $1,0 \times 10^{-5}$ and $3,0 \times 10^{-4}$ SI, indicating non-magnetic sediments such as silt, clay, and sand at shallow depths of approximately 0–50 m. The Sentolo Formation exhibits values between $1,0 \times 10^{-4}$ and $4,0 \times 10^{-3}$ SI, consistent with weakly paramagnetic rocks such as limestone and sandstone, typically found at depths of 50–150 m. The Kebobutak Formation presents susceptibility values ranging from $1,3 \times 10^{-3}$ to $4,2 \times 10^{-2}$ SI, consisting of moderately to highly magnetic volcanic rocks such as andesite breccia, tuff, and agglomerate, located at depths of 150–250 m. The Andesite Formation has the highest susceptibility values, between $7,3 \times 10^{-2}$ and $1,08 \times 10^{-1}$ SI, representing igneous basement rocks composed of andesite and basalt that are rich in ferromagnetic minerals such as magnetite and hematite, occurring at depths greater than 250 m.

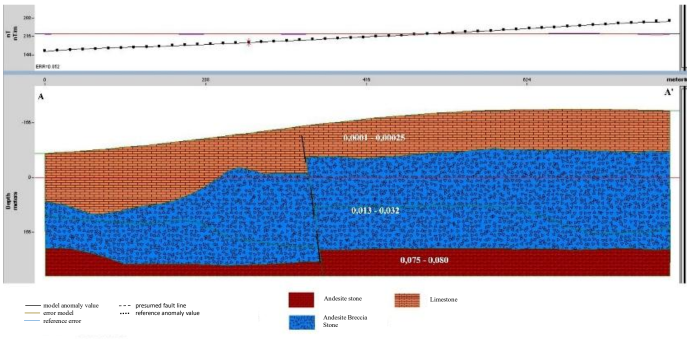

Figure 8. Profile Section AA’

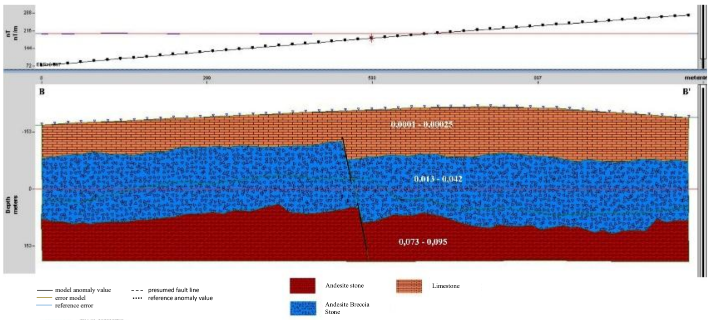

Figure 9. Profile Section BB’

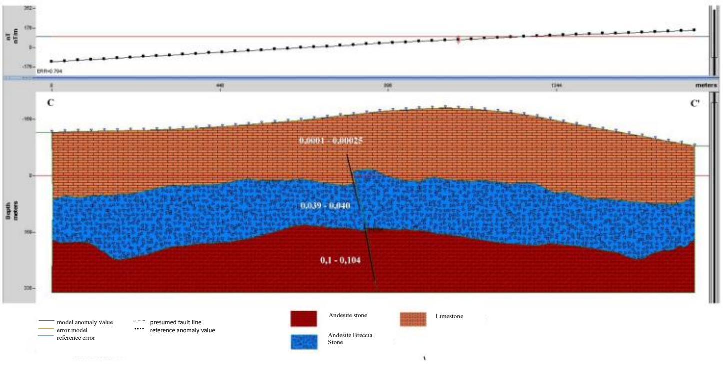

Figure 10. Profile Section CC’

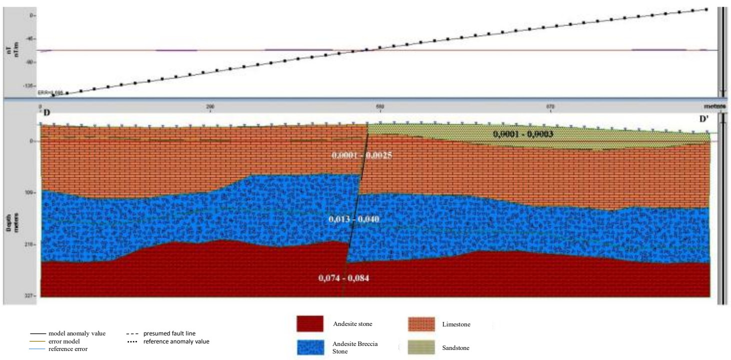

Figure 11. Profile Section DD’

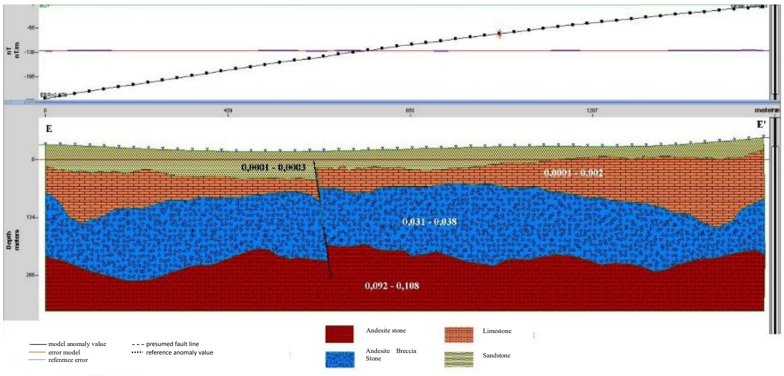

Figure 12. Profile Section EE’

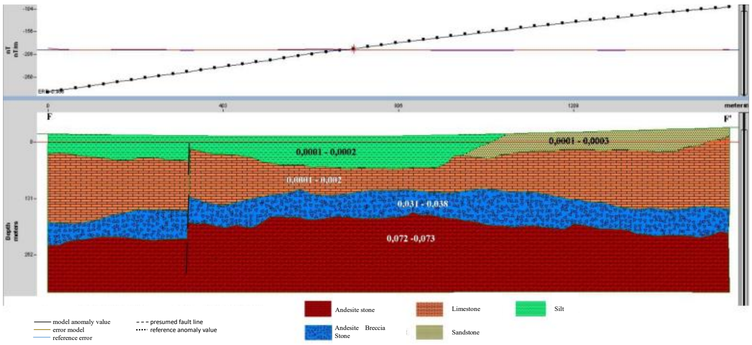

Figure 13. Profile Section FF’

The distribution pattern of magnetic susceptibility across all profiles shows a consistent relationship between high-susceptibility zones and high-anomaly regions on the RTP map, particularly in the northern and northeastern sectors. Conversely, low anomalies in the western and southern areas are associated with non-magnetic sedimentary rocks of the Sentolo and Alluvium Formations. The 2D modeling results reveal that magnetic anomaly variations in the Sangkrek area are primarily controlled by lithological contrasts rather than by major fault structures. Therefore, the interpreted magnetic susceptibility values provide a reliable basis for identifying formation boundaries and estimating the depth of the basement rocks within the study area [15], [9].

4. CONCLUSION

Based on the geomagnetic analysis conducted in Dusun Sangkrek, Kapanewon Kokap, Kulon Progo Regency, the magnetic anomaly values range from $-3,1 \times 10^2$ nT to $6,8 \times 10^2$ nT. High anomalies are dominant in the northern part, composed mainly of andesitic rocks, while low anomalies occur in the Sentolo and Alluvium Formations, which are non-magnetic. This pattern reflects the differences in the magnetic properties of subsurface rocks, which serve as the primary control on the magnetic field variations in the study area. The results of the two-dimensional (2D) modeling show that the rock magnetic susceptibility values vary between $1,0 \times 10^{-4}$ and $1,1 \times 10^{-1}$ SI, with higher values observed in andesite and breccia rocks, and lower values in sedimentary rocks such as limestone, sandstone, and clay. The distribution of these values indicates a clear correlation between high magnetic anomalies and ferromagnetic volcanic lithology, as well as low anomalies associated with non-magnetic sedimentary formations. It can therefore be concluded that lithological differences and rock layer depth are the main factors controlling the magnetic characteristics in the study area, where volcanic rocks exhibit strong magnetic responses, while sedimentary rocks show weak responses to the Earth's magnetic field.

DECLARATION

Author Contribution

N. Muaffi and H. Rosyida, processed the experimental data, performed the analysis, drafted the manuscript and designed the figure. T.A Niyartama and N.B Wibowo was involved in planning and supervised the work. All authors discussed the results and commented on the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

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