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# Study on the Significance of Reduction to the Equator (RTE), Reduction to the Pole (RTP), and Pseudogravity in Magnetic Data Interpretation

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**Abstract:** Interpretation of geomagnetic anomaly data is challenging, due to the influence of the Earth's dipole magnetic field. In this study, we investigate the significance of employing methods to transform dipole anomalies into monopoles, aiming to enhance the interpretability of the data. Four methods were examined: Reduce to Pole (RTP), Reduce to Equator (RTE), and Pseudo-Gravity. The RTP method was implemented using general equations for RTP, Pseudo-inclination (PI), and Nonlinear thresholding (NTRTP). The computation programs for RTP and RTE were developed using the Matlab programming language. Synthetic models were constructed to investigate the effects of inclination values, object dimensions, and positions on the resulting magnetic anomaly response. The result shows that NTRTP methods give the best result with coefficient correlation >0.9. It can be used in every condition (low or high inclination). The implementation was conducted utilizing magnetic data in the Gunung Pandan geothermal area. The application of the reduced to the pole (RTP) technique on the field data successfully remove the dipole effects, and make interpretation process easier. Based on RTP map, the range of anomaly values spanning from -800 nT to 1000 nT. High anomalies were observed at the Gunung Pandan site, indicative of a probable intrusion of andesitic igneous rock.

**Keywords**: Magnetic anomaly; Pseudogravity; Reduce to equator; Reduce to pole

## Introduction

The magnetic method is one of the geophysical methods that utilizes the Earth's magnetic field. This magnetic method has been widely applied in various fields such as structural mapping, identification of mineralization zones, and others. The interpretation process of geomagnetic data tends to be more challenging compared to the gravity method, partly due to the dipolar nature of the Earth's magnetic field. Therefore, prior to interpretation, further data processing is required to remove the dipolar effects of the Earth's magnetic field, enabling qualitative interpretation of magnetic data.

Methods that can be used to address this issue are Reduce to Pole (RTP) and Reduce to Equator (RTE). Essentially, RTP and RTE attempt to assume that the magnetic anomalies in the measurement area appear as if they are located at the pole or at the equator, respectively. The results of these reductions will display magnetic anomalies that exhibit monopole characteristics, facilitating easier interpretation. In addition to RTP and RTE, another method that can be used to improve the quality of magnetic data is the pseudogravity method. In this study, the analysis of synthetic magnetic data and field magnetic data is conducted using the Reduce to Pole, Reduce to Equator, and Pseudogravity methods to determine the advantages and limitations of each method in enhancing the quality of magnetic anomaly data.

Baranov (1957) first introduced the concept of RTP and stated that RTP is a convolution operation in the spatial domain. Bhattacharyya (1965) employed Fast Fourier Transform (FFT) to perform RTP in the

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frequency domain. The use of Fast Fourier Transform makes RTP easier to implement, but in equatorial regions (low latitude), RTP in the frequency domain may yield unstable results. RTP becomes unstable when the inclination approaches zero or is less than $5^0$ and may estimate the magnetization direction less accurately (Gerovska et al., 2009). Blakely (1995) proposed the use of RTE; however, this method is challenging to process horizontal magnetic data. RTP in the frequency domain has the advantage of being simple and easy to perform, making it applicable for interpreting magnetic anomalies in low latitude regions using RTP. Several studies have been conducted to address the Reduce to Pole issue in equatorial regions (Shuey, 1972; Silva, 1986; Mendonça & Silva, 1993; Shi et al., 2012; Guo et al., 2013; Hao et al., 2018, Zuo et al., 2021). Macleod et al. (1993) suggested a pseudo-inclination approach.

Hansen et al. (1989) proposed an approach using Wiener Filtering as a denoising filter. The results of this method tend to produce overly smooth RTP and also remove signals at short wavelengths (Li, 2008). Keating et al. (1996) further developed the Wiener Filtering method using an energy balance technique to estimate the noise-to-signal power ratio, employing a deterministic noise model. In this method, iterations are performed to minimize the differences between the observed data and the RTP results. Zhang (2014) proposed the NTRTP method, he divides the general RTP operator equation into real and imaginary parts, which are then convolved with a special filter called Nonlinear thresholding. The pseudogravity method converts magnetic anomaly data into gravity anomaly data based on the Poisson relation law (Blakely, 1995). Barka (2020) utilized pseudogravity in interpreting magnetic anomaly data because it can accurately depict the magnetic distribution at the location of anomaly sources.

## Method

*Reduce to Pole*

Reduce to Pole is one of the steps to simplify the interpretation of magnetic data, where this method attempts to assume that the magnetic anomalies in the measurement area appear as if they are located at the pole, resulting in magnetic anomalies that exhibit monopole characteristics.

$$R(\theta) = \frac{1}{[\sin(I) + i\cos(D-\theta)]^2} \tag{1}$$

From the equation, it can be seen that if the inclination is low (approaching 0), and D-θ = ± $90^0$ (Red dashed line in Figure II.3), instability occurs. RTP becomes unstable when the inclination approaches zero or is less than $5^0$ and may estimate the magnetization direction less accurately (Gerovska et al., 2009).

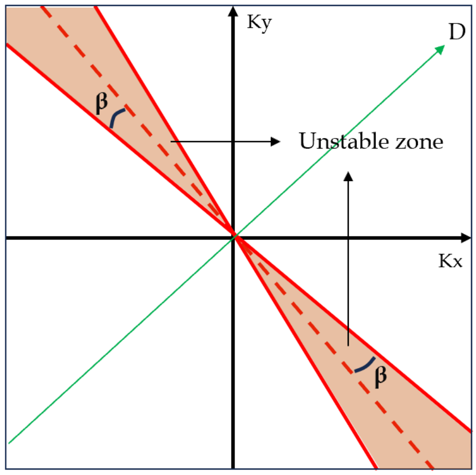


**Figure 1.** Characteristics of the RTP Operator in the wavenumber domain. The unstable zone is indicated by the red-colored region

Macleod et al. (1993) developed the RTP method by proposing the concept of pseudo-inclination to address the RTP issue in equatorial regions (low inclination). In this study, pseudo-inclination is used as a control for the RTP filter in equatorial regions.

$$R_{PI}(\theta) = \frac{[\sin(I) - i\cos(I)\cos(D-\theta)]^2}{[sin^2(I') + cos^2(I')cos^2(D-\theta)].[sin^2(I) + cos^2(I)cos^2(D-\theta)]}, \tag{2}$$

Where I' is the pseudo-inclination, which has a value greater than the inclination. If |I'| < |I|, |I'| = |I|. The value of I' is usually set between 200-300 (Macleod et al., 1993). Zhang (2014) proposed the Nonlinear thresholding (NTRTP) method. In his research, Zhang divided the general RTP operator equation into real and imaginary parts, which were then convolved with a special filter called Nonlinear thresholding.

$$Xnew = \begin{cases} x & , abs(x) \le 0.9.A \\ sign\,(x).\left(0.9.A + 0.1.A.\sin\left(\frac{\theta-\theta_1}{\theta_2-\theta_1}\right).\pi\right) & , abs(x) > 0.9.A \end{cases} \tag{3}$$

Where x is the real and imaginary value, A is the threshold value, $\theta_2$ and $\theta_1$ represent the limits when the amplitude is greater than 0.9A.

*Reduce to Equator*

In contrast to Reduce to Pole, the Reduce to Equator method transforms the magnetic field to the equator. Simply put, this method assumes that the measurements are conducted in the equatorial region (0° inclination). The general equation for Reduce to Equator is shown as follows:

$$L(\theta) = \frac{[\sin(I) - i\cos(I)\cos(D-\theta)]^2 \times (-\cos^2(D-\theta))}{[\sin^2(I') + \cos^2(I')\cos^2(D-\theta)] \times [\sin^2(I) + \cos^2(I)\cos^2(D-\theta)]} \quad (4)$$

*Pseudogravity*

This method converts magnetic anomaly data into gravity anomaly data based on the Poisson relation law (Blakely, 1995). The Pseudogravity transformation is based on the Poisson relation between magnetic potential and gravity field. Based on Panepinto (2014), accurate estimates of the geometric parameters of the unknown source can be more easily and rapidly calculated by the transformed pseudo-anomalies. The general equation for this method is shown as follows:

$$F(\theta) = \frac{G.\rho/M}{[\sin(I_a) + i\cos(I).\cos(D-\theta)]^2.r} \quad (5)$$

Where G is the gravitational constant (6.6738), ρ is the density contrast (g/cm$^3$), M is the magnetization in Gauss, I_a is the inclination for amplitude correction (>I), I is the inclination, D is the declination, and r is the wavenumber (radians/ground-unit).

Pseudogravity exhibits interesting characteristics, as it can reduce the presence of signals from shallow anomaly sources and enhance the amplitude of magnetic anomalies originating from deeper sources (Pratt & Shi, 2004). This method can accurately and rapidly estimate the geometric parameters of the sources (Nabighian, 1972; Fedi, 1989).

## Result and Discussion

*Syntetic Data*

Synthetic magnetic data were used to observe the effects of the RTP, RTE, and pseudogravity methods on magnetic data. Figure 1 shows the synthetic model used in this study. The model parameters are presented in Table 1.

**Table 1.** Parameters of Synthetic Magnetic Data

| Parameter | P1 | P2 | P3 |
|---|---|---|---|
| Susceptibility | 0.03 | 0.03 | 0.03 |
| Width (m) | 1,000 | 1,000 | 1,000 |
| Length (m) | 750 | 750 | 750 |
| Thickness (m) | 800 | 800 | 1,000 |
| X coordinate | 2,250 | 3,750 | 3,000 |
| Y coordinate | 3,000 | 3,000 | 3,000 |
| Depth (m) | 500 | 500 | 2,800 |

The results of calculating the Magnetic Anomaly response, RTP, RTE, RTP Pseudo Inclination, NTRTP, and pseudogravity at an inclination of 50 can be seen in Figure 3. The calculated magnetic anomaly and RTE results can indicate the location of anomalies. At low inclinations, both the RTP method using the general equation and pseudo-inclination failed to identify the presence of anomaly sources. This is due to the low inclination values, which cause instability as explained in the previous section. However, the NTRTP and pseudogravity method successfully mapped the anomalies, but both of these methods are unable to distinguish the presence of closely spaced anomalies, causing the three anomalies to appear as if they are a single anomaly.

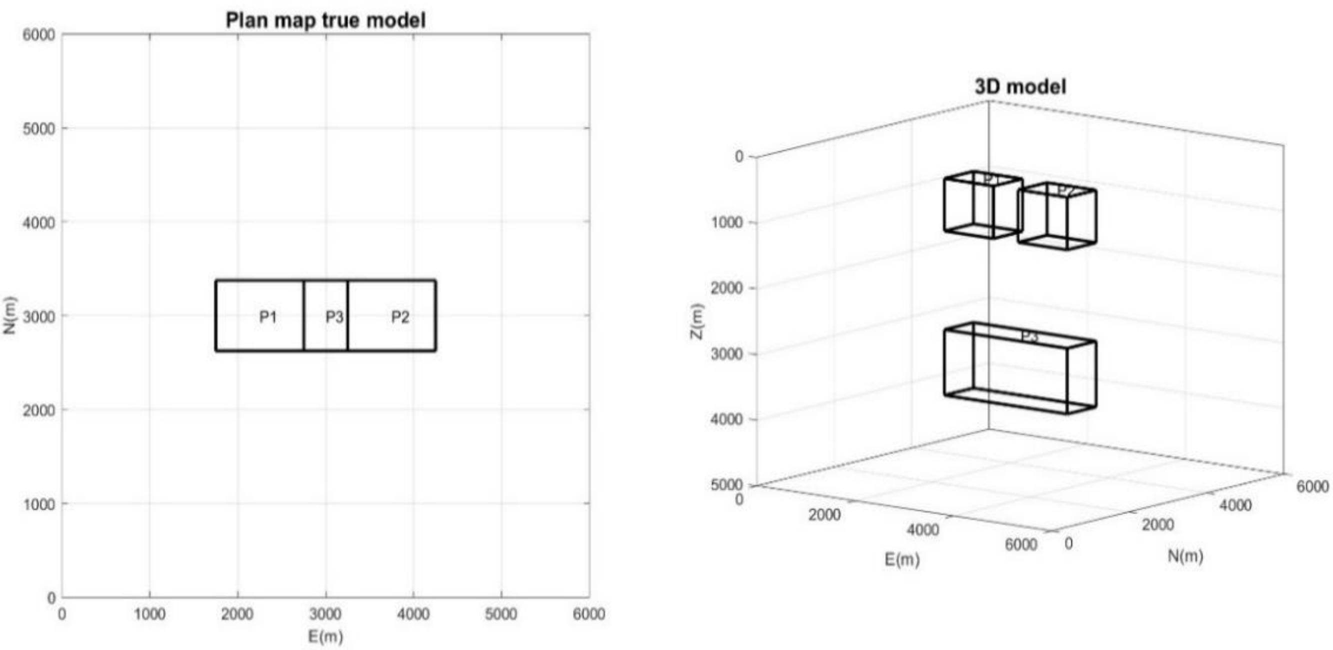


**Figure 2.** Synthetic magnetic data model

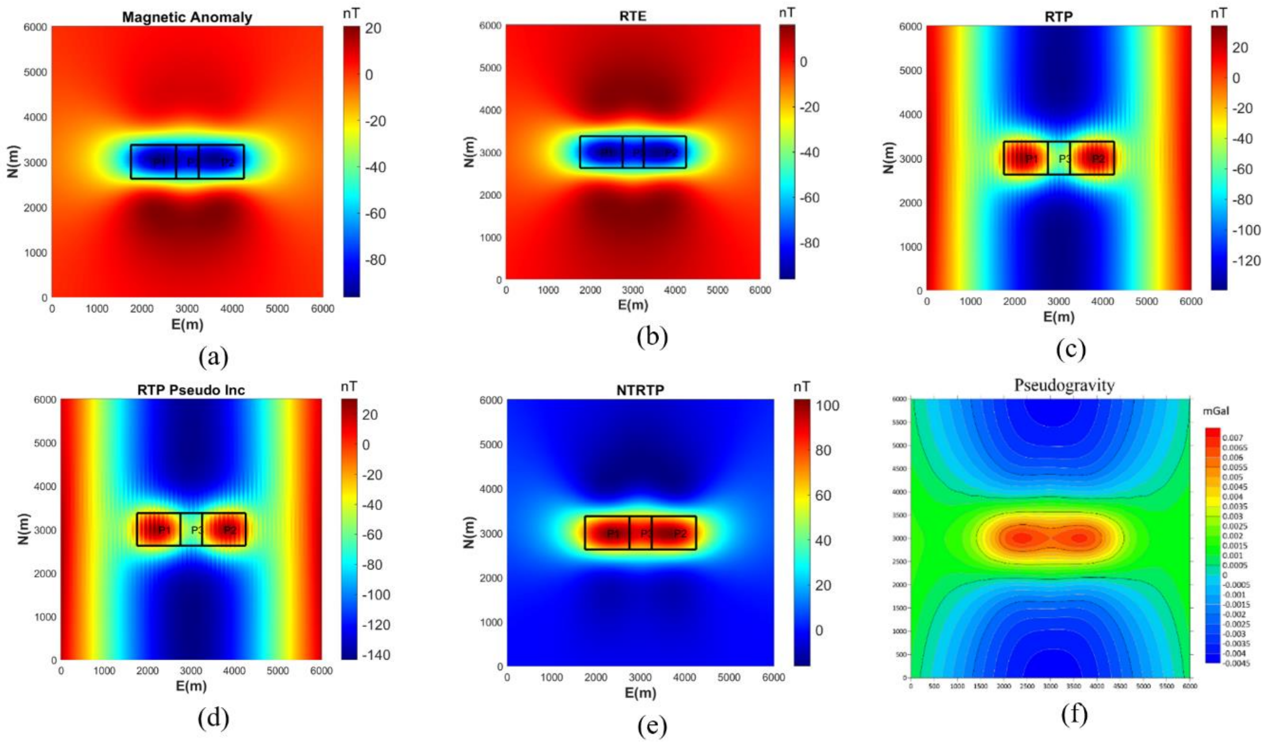


**Figure 3.** Results of synthetic model calculations at an inclination of 50. Synthetic magnetic anomalies (a) RTE (b) RTP-Pseudo Inclination (c) RTP General Equation (d) Nonlinear Thresholding RTP (e) Pseudogravity (f)

The results of calculating the Magnetic Anomaly response, RTP, RTE, RTP Pseudo Inclination, NTRTP, and pseudogravity at an inclination of $30^0$ can be seen in Figure 4. The calculated magnetic anomaly and RTE results successfully indicate the location of anomalies but still exhibit some noise. The RTP method, using the general equation, pseudo-inclination, and NTRTP successfully identified all anomaly sources (P1, P2, P3). However, upon closer examination, the RTP-PU and RTP-PI methods seem to struggle in depicting the presence of P3 due to its relatively deeper depth compared to other anomaly sources, whereas the NTRTP and Pseudogravity methods successfully identify the existence of P3.

**Table 2.** Correlation Coefficients of the Synthetic Model with the Synthetic Model at the Pole ($90^0$)

| Method | Inclination | |
|---|---|---|
| | 5 | 30 |
| RTE | 0.8933 | 0.8968 |
| RTP-PU | 0.2199 | 0.9988 |
| RTP-PI | 0.2199 | 0.9988 |
| NTRTP | 0.9095 | 0.9529 |

Quantitative analysis was conducted by calculating the correlation coefficient between the calculated results and the synthetic model at an inclination of $90^0$ (pole). The correlation coefficient values range from 0 to 1, with values closer to 1 indicating a stronger relationship between the variables. The calculation results are shown in Table 2. Based on Table 2, it is evident that the NTRTP method consistently provided the best results at both low and high inclinations, with correlation coefficient values ranging from 0.78 to 0.82.

*Real Data*

The data used in this study is the magnetic anomaly data of the Gunung Pandan area, East Java. The data was collected in 2020, covering an area of 4 km x 4 km. The measurements were conducted using a proton precision magnetometer GSM-19T. A total of 245 stations were established with distances between stations ranging from 50m to 150m. The processing of the acquired magnetic anomaly data begins with diurnal correction and IGRF correction to obtain the total magnetic intensity (TMI) map. Subsequently, the RTP, RTE, and Pseudogravity methods will be applied to the TMI map to obtain interpretable magnetic anomaly maps. Then, the residual-regional anomaly separation will be performed using the moving average method. The final map results will be interpreted using additional data such as geological maps or other geophysical data. This integration of data will provide a comprehensive understanding of the magnetic anomalies in the Gunung Pandan area and aid in the interpretation of geological structures and features.

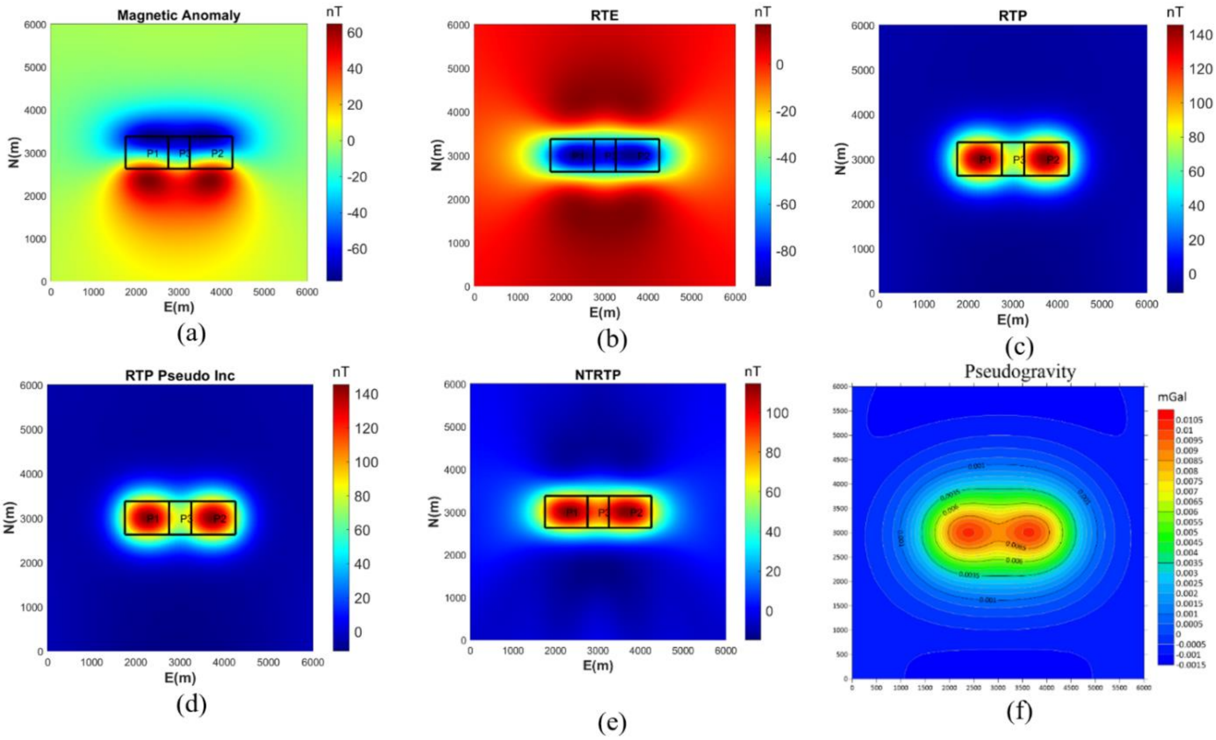


**Figure 4.** Results of synthetic model calculations at an inclination of 300. Synthetic magnetic anomalies (a) RTE (b) RTP-Pseudo Inclination (c) RTP General Equation (d) Nonlinear Thresholding RTP (e) Pseudogravity (f)

*Geology of study area*

Gunung Pandan is a non-active volcano located in Bojonegoro Regency, East Java Province, with an elevation of 897 meters. Gunung Pandan is a dormant volcano (Santoso et al., 2018) and identified as one of eleven geothermal prospects in East Java (Setijadji, 2010). According to van Bemmelen (1949), the physiography of the North East Java Basin consists of several zones, namely the Southern Mountain Zone, Solo Zone, Kendeng Zone, Randublatung Zone, Rembang Zone, Quaternary Volcano Zone, and North Java Alluvial Plain. Based on this physiographic classification, the study area falls within the Kendeng Anticlinorium or Kendeng Zone. The predominant lithology in the Kendeng Zone is clay-marl-sandstone with low compaction (Pringgoprawiro & Sukido, 1983). This area a depositional area containing volcanogenic material and sediments with a thickness of up to 8000 m (Smyth et al., 2008). The geological map of the study area is shown in Figure 5.

According to Setijadji (2010), Gunung Pandan is one of the geothermal prospects in East Java. Based on seismic information, an earthquake with a magnitude of 4.2 occurred around the Gunung Pandan area in 2015 (Aji et al., 2018), indicating ongoing tectonic activity in Gunung Pandan. The geothermal manifestations in the Gunung Pandan area consist of three hot springs: Banyukuning, Jari Kasinan, and Tadahan. The Banyukuning hot spring is located along the river on volcanic breccia outcrops within the Gunung Pandan volcanic rock unit. The Jari Kasinan hot spring is located in the Jari village. The lithology in this area consists of andesite lava with argillic alteration. The Banyukuning manifestation is controlled by the Banjar fault, while the Jari Kasinan manifestation is controlled by the Jati fault (Thoha et al., 2014).

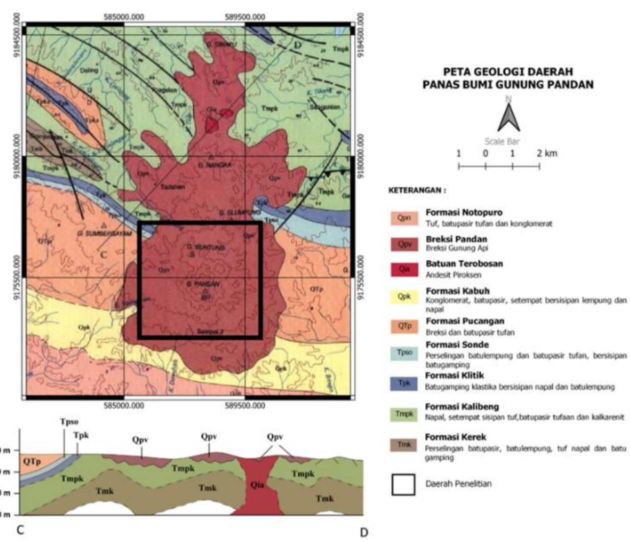


**Figure 5.** Geological Map of the Study Area (Modified from Pringgoprawiro & Sukido, 1983)

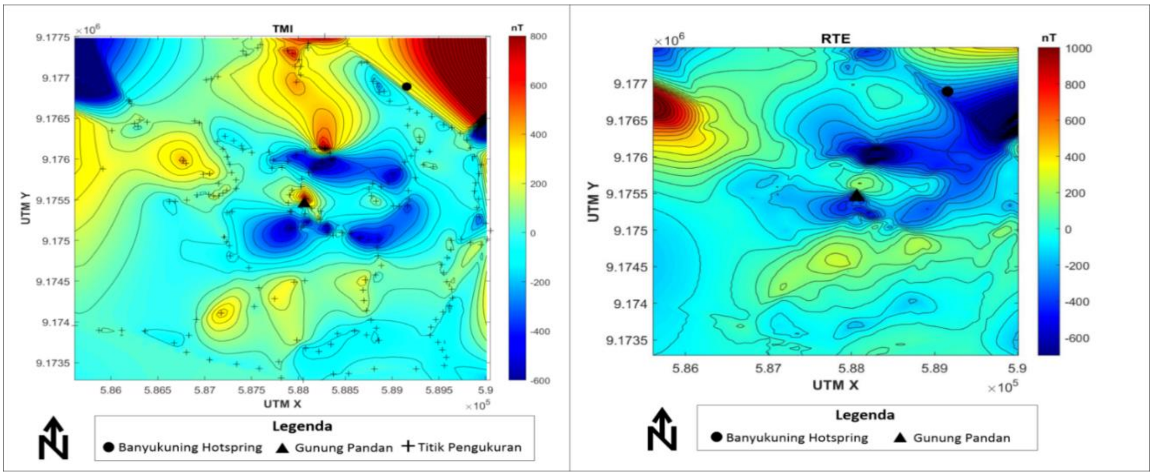


**Figure 6.** Total Magnetic Intensity (TMI) (a) and Reduce to Equator (RTE) (b) Map of the Study Area

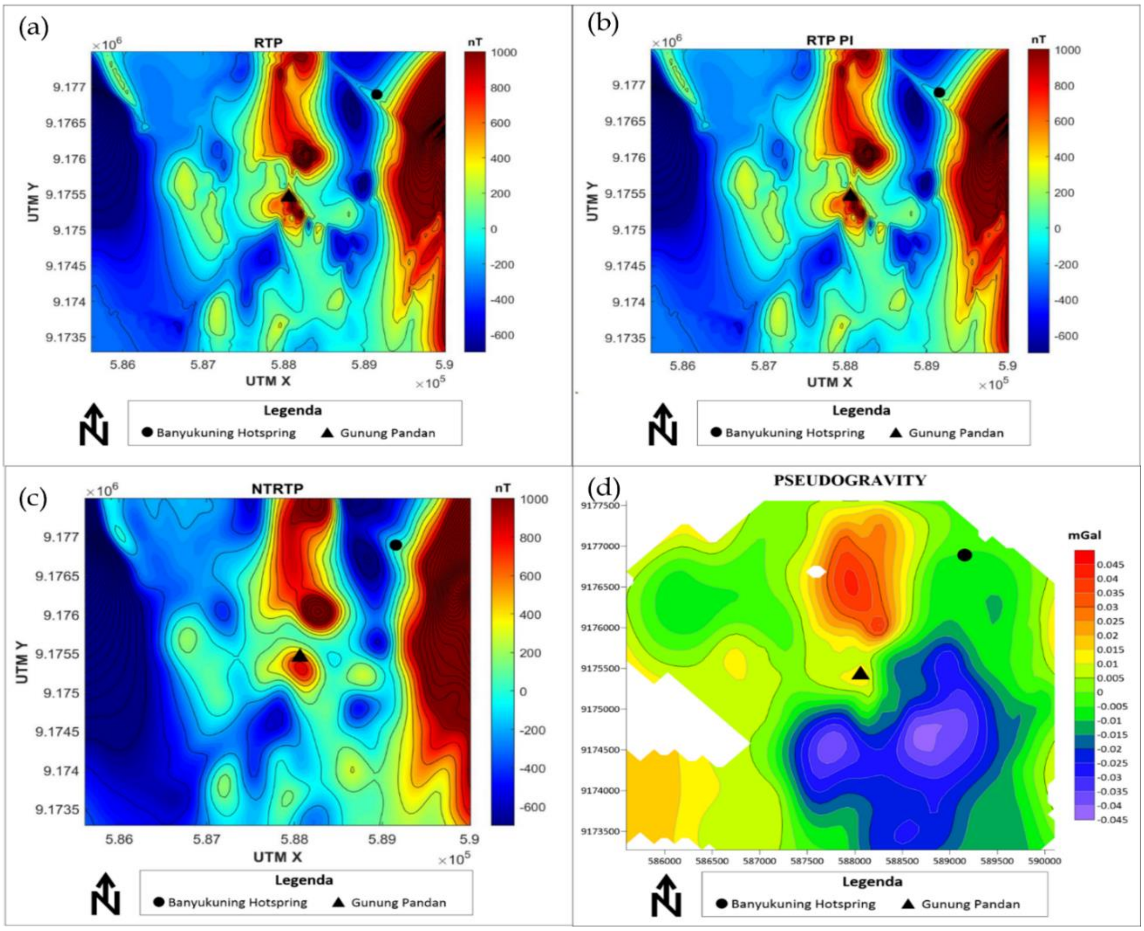


**Figure 7.** Reduce to pole classic equation (a), RTP-Pseudo Inclination (b), NTRTP (c), and Pseudogravity (d) Map of the study area

*Field Data Analysis*

*Total Magnetic Intensity (TMI) Map*

The gridding method used to create the total magnetic intensity (TMI) map is the minimum curvature method. The gridded data is then visualized using the software developed in this research. The resulting map can be seen in Figure 6(a). Based on the map, the study area exhibits magnetic anomaly ranges from -600 nT to 800 nT. From the TMI map, the interpretation process is still challenging due to the dipole nature of the anomalies.

*Reduce To Equator Map*

In principle, the Reduce to Equator method has the same objective as the Reduce to Pole method, but the reduction process is performed towards the equator. The results of the reduce to equator calculation are shown in Figure 6(b). Based on Figure 6(b), it can be observed that the calculated results have an anomaly value range from -600 nT to 1000 nT. The pattern produced by the RTE method tends to be similar to the TMI map pattern, which is likely due to the study area being located near the equator (inclination = -31.319, declination = 0.8), resulting in insignificant changes during the reduction process. In this RTE map, the interpretation process tends to be challenging due to the paired anomalies (dipoles) present.

*Reduce to Pole Map*

Reduce to Pole is performed to obtain monopole magnetic anomalies, making the interpretation process easier. The Reduce to Pole calculations are performed using three methods/equations: the general equation, pseudo-inclination equation, and nonlinear thresholding equation. The results of the Reduce to Pole calculation for each method are shown in Figure 7(a-c). Based on Figure 7(a-c), it can be observed that each method has an anomaly value range from -800 nT to 1000 nT. The RTP map for each method tends to produce very similar patterns, but the NTRTP map appears to be smoother compared to the other RTP methods. In the RTP map, there is an elongated pattern from south to north.

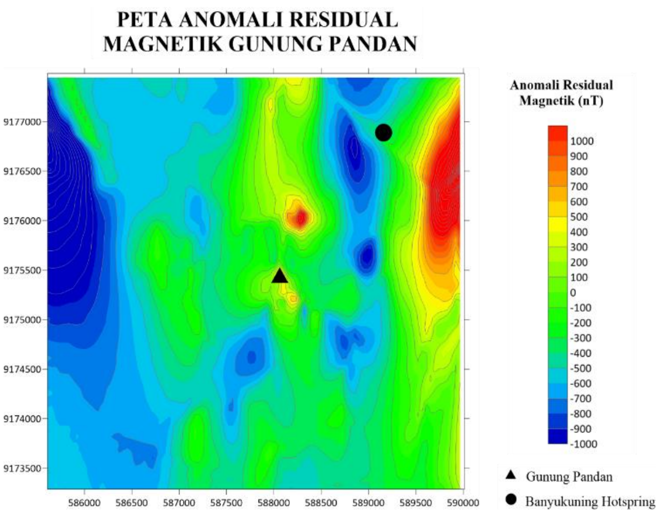


**Figure 8.** Residual anomaly map of the study area

*Pseudogravity Map*

The pseudogravity method is applied to simplify the interpretation process by converting magnetic anomaly data into gravity anomaly data. Additionally, the pseudogravity method can effectively identify subsurface anomaly sources (Mashhadi & Safari, 2020). The results of the pseudogravity calculation show an anomaly value range from -0.045 mGal to 0.045 mGal, as shown in Figure 7(d). Based on the pseudogravity map, it can be observed that low-density areas are located in the southern part of the study area, while high-density areas are situated in the northern part, around Gunung Pandan.

*Residual Anomaly Map*

The residual anomaly map is obtained using the moving average method with a window size of 7x11. The results of the residual anomaly map are shown in Figure 8. The residual map exhibits anomaly values ranging from -800 nT to 1200 nT. High anomaly values are distributed around Gunung Pandan, while low anomaly values are observed around the Banyukuning hot spring and the western part of the study area.

*Interpretation*

In the RTP map, it can be observed that high anomalies are found at the location of Gunung Pandan, extending northward. Based on geological information, these high anomaly values indicate the presence of rocks with high magnetic properties. Considering their location, this is likely attributed to the intrusion of andesitic igneous rocks. Additionally, low anomalies are found around the Banyukuning hot spring manifestation, suggesting a pathway of hot water flow. Furthermore, the low magnetic anomaly values in other areas are indicative of thick sediment deposits with lower magnetic properties compared to the surrounding areas.

To further strengthen the interpretation, pseudogravity calculations were performed. The pseudogravity transformation helps reduce the dominance of shallow magnetic sources and enhances the amplitude of magnetic anomalies from deeper sources (Pratt & Shi, 2004). The pseudogravity calculation results reveal the presence of a low anomaly in the southern part of Gunung Pandan. This aligns with the findings of Alawiyah et al. (2022) and Aji et al. (2018), who identified negative anomalies in the southern part of Gunung Pandan based on gravity and magnetic data. The presence of these negative anomalies is likely due to hot rock conditions or can be interpreted as a heat source.

Combining the information from the RTP and pseudogravity maps, it can be inferred that Gunung Pandan exhibits magnetic anomalies associated with the presence of andesitic intrusions, while the Banyukuning hot spring area represents a pathway of hot water flow. The low magnetic and gravity anomaly values in the southern side of Gunung Pandan interpreted as heat source. Based on Alawiyah et al. (2022), this heat source probably originated from the same souce as Gunung Wilis.

## Conclusion

Based on the results obtained from the synthetic data, the NTRTP method proves to be the most effective compared to other RTP and RTE methods, both at low and high inclinations, with correlation coefficients ranging from 0.78 - 0.82. The pseudogravity method demonstrates good results when applied to areas with high inclinations (≥15$^0$). The implementation of the methods on field data shows that all three RTP methods (RTP-PU, RTP-PI, and NTRTP) successfully remove the dipole effects from the research data. The RTP maps reveal high anomalies located at Gunung Pandan, extending northward, with values ranging from 400 nT to 1000 nT. These anomalies are believed to be associated with andesitic intrusive rocks. Additionally, low anomalies (-400 nT to -600 nT) are observed around the Banyukuning hot spring manifestation, indicating a pathway of hot water flow. The pseudogravity map and residual anomaly map indicate the presence of low anomalies in the southern part of Gunung Pandan. These negative anomalies are likely caused by hot rock conditions or can be interpreted as a heat source. Overall, the research findings highlight the effectiveness of the NTRTP method in enhancing the quality of magnetic anomaly data interpretation. The combined analysis of RTP, pseudogravity, and residual anomaly maps provides valuable insights into the geological characteristics, potential heat sources, and hydrothermal systems in the study area.

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**Author Contributions**

Conceptualization, Mira Nailufar Rusman, Susanti Alawiyah, Indra Gunawan; methodology, Mira Nailufar Rusman, Susanti Alawiyah, Indra Gunawan; inverstigation,; Susanti Alawiyah, Wawan Gunawan A. Kadir, Djoko Santoso, Eko Januari Wahyudi, Waskito Aji, Indra Gunawan; writing-original draft, Mira Nailufar Rusman; writing-review and editing, Mira Nailufar Rusman, Susanti Alawiyah, Indra Gunawan.

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**Conflicts of Interest**

All authors declare no conflicts of interest.

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