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Magnetic data analysis using 2D inversion: A case study from Terak Radiogenic Geothermal area, Bangka Island, Indonesia

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Abstract

The presence of geothermal manifestation such as Terak hot spring near granite massive bodies on Bangka Island raises an importatnt question about the subsurface characteristics of a potential radiogenic system. As traditional geothermal system in Indonesia is well known, research must now focus on understanding the radiogenic system, especially on the subsurface information. This study addresses the local magnetic susceptibility of Terak subsurface hot spring by performing magnetic method. The integration of 2D to 3D magnetic data, field observations and geological information show high susceptibility data (>0.005 SI) which are indicated as granite intrusion which act as the heat source. A central zone of lower susceptibility (<0.005 SI) displays a distinct pattern, interpreted as a fracture zone as the hydrothermal fluid pathways. The identification of recharge area further supports the interpretation of an active hydrothermal system. The result of this study are in good agreement with the geological framework of the region and contribute to a better understanding of radiogenic geothermal systems in Indonesia.
Keywords: *Radiogenic geothermal, magnetic data, susceptibility, heat source, hydrothermal*

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1. INTRODUCTION

Indonesia is home to 40% of world geothermal prospect with total of 29 GWe potential and spread along quaternary volcanoes of Sumatera, Java to Sulawesi (Darma et al., 2021). Geologically, Indonesia is an intersection of three major plates (Eurasian plate, Australian plate and Pacific plate) which highly contribute to the presence of geothermal. Geothermal systems are generally classified into three classification according to their geological setting: volcanic, volcano-tectonic and non-volcanic. High to medium enthalpies are generally found in volcanic and volcanic-tectonic systems and low to medium enthalpies are generally found in non-volcanic system. Non-volcanic systems are predominantly distributed across the eastern part of the Sundaland as the extension of the continental shelf of Southeast Asia.

Among these non-volcanic systems, Bangka Island represents a significant example of a radiogenic geothermal system associated with granite intrusion. Hot spring manifestations can be found in Pelawan, Dendang, Pemali, Terak, Nyelanding, Permis, Sadap, Keretak and Celuak. The transition from volcanic to radiogenic heat source introduces new challenges and opportunities in geothermal exploration, particularly in characterizing the subsurface features of such systems. Several studies have been carried out to investigate the heat soure of Bangka geothermal systems. Siregar et al (2024) previously showed that the enormous concentration of U, Th and K within Bangka granite are responsible as the heat source for the geothermal system. Siregar et al (2022) reported the radiogenic heat production of Bangka granite range from 8.24-27.29, which can be classified as high heat production according to McCay and Younger (2017). Other studies (Ng et al., 2017; Ngadenin et al., 2014; Widana, 2013) previously confirmed that Bangka granite are highly correlated to the presence of U, Th and K. Thus, the question about the heat source of Bangka geothermal system has been answered.

At this point, an overreaching question must be considered: what are the characteristics of the subsurface beneath the Bangka hot spring?. In earlier research, Siregar and Kurniawan (2018) revealed the high resistivity zone in a shallow subsurface which interpreted as the continuity of granite bodies found in the surface of Nyelanding hot springs. In prior to that result, Siregar et al (2024) reported that Terak manifestation was found as the highest surface temperature (70.7 °C) and one of the highest radiogenic heat production. The intrusion of granite as a heat source in Terak hot spring is a catchy question to be investigated. Thus, this study endeavors to investigate the subsurface of Terak hot spring from the magnetic point of view. Magnetic method is particularly well suited for this purpose, as granite exhibit distinct magnetic susceptibility compared to surrounding lithologies. This approach allows for a more detailed imaging of subsurface features such as granite intrusions and potential fracture zones which act as transport path of hydrothermal fluids. Furthermore, this research will be the first to analyze the significance of magnetic anomalies in identifying granite intrusion enriched in radioactive elements which can alter the magnetic properties of surrounding rocks. This study can offers valuable insight into further exploration of Bangka geothermal system.

2. GEOLOGICAL SETTING

By the Late Triassic period, subduction of Sibumasu block and Indochina block derived two different magmatism along Malaysia Peninsular to Bangka Island, eastern range granite (I-type) and main range granite (S-type) (Ng et al., 2015). The magmatism episode of eastern granite was originated from the mixing of mantle and crust as a post-collisional product. Meanwhile the main range granite was formed from continental crust product which intruded Sibumasu block and interpreted as syn and post collisional product (Metcalfe, 2000). Schwartz et al (1995) interpreted that both of main range granite and eastern range granite are overlapped each other in Bangka Island. Ng et al (2017) reported that eastern range granite are found in northern part of tshe island, meanwhile the main range granite are dominantly found in southern part of the island.

Siregar et al (2024) exposed the enormous intrusive granite bodies found along the island are strongly related to the presence of geothermal manifestation. Weinert et al (2021) classified >5 µW/m3 as High Heat Production (HHP) granite, meanwhile the radiogenic heat production in the central part of the island range from 20 µW/m3 to 182 µW/m3. Surprisingly, many geothermal manifestations are found in this region such as Terak, Keretak and Celuak hot springs as can be seen in Figure 1. Field observations show that the manifestations are closely located around granite outcorps and two major faults: Pemali and Payung Fault. These faults are strongly responsible as fluids ascend path along the manifestations.

The geological strutures of Bangka Island includes fractures, folds, lineament and faults. U (1986) identified two major faults with Northeast-Southwest which control Bangka Island: Pemali and Payung fault. Regionally, the morphology of Bangka relatively flat to low peneplain which was formed due to weathering, erosion and denudation processes over a period of millions of years (Ngadenin et al., 2014). The highest morphology in Bangka Island is granite Maras Hill (699 m), thus this phenomenon shows the absence relation of volcanic activities to Bangka geothermal systems.

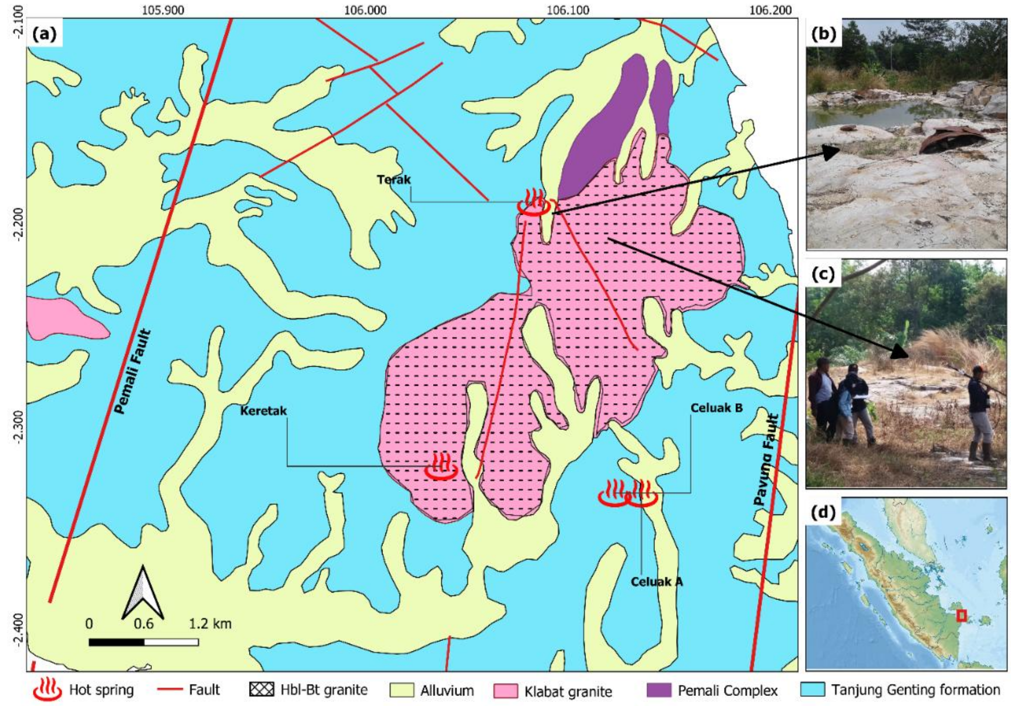

Figure 1. The distribution of geothermal manifestations around granite bodies in central part of Bangka Island: (a) Geological map of central part of Bangka Island, (b) granite intrusion around Terak hot spring, (c) Magnetic survey in identifying granite subsurface, (d) research area around Sumatera Island.

Geologically, Bangka Island was derived from the formation of Carbon-Permian Pemali Complex which can interpreted as the uplifting material of Paleo-tethys ocean as the subduction of Sibumasu and East Malaya block in progress (Barber et al., 2005). By the Early Triass, this formation was then covered by sedimentation of Ranggam Formation in the shallow marine environment. Ranggam formation consists of a mixture sandstone, metamorphic sandstone, clayey sandstone and mudstone with lenses of limestone and iron oxide. Late Triassic Granite intrude the older formation as a result of magma activities of the earth crust. Klabat Granite formation dominantly control the area geologically and strongly correlated to the high radiogenic heat production and geothermal presence. Some minerals which can be found in Bangka granite and are acted as host for radioactive elements are biotite, muscovite, monazite, and zircon (Widana & Priadi, 2015).

3. METHOD

Magnetic data were performed over a 500×500 m^2 area surrounding Terak hot springs in August 2019, with 100 meter spacing stations. This spacing was applied to balance spatial resolution feasibility in mapping shallow subsurface features, consistent with similar geothermal magnetic surveys (Feng et al., 2024) which have demonstrated its effectiveness in detecting granite intrusion and fracture zones (Verkoyan et al., 2021). The data acquisition process involved three main steps: (1) instrument calibration, (2) field measurements and (3) data processing. The calibration was conducted by tuning the Proton Precisiona Magnetometer (PPM) G-856 sensor to match the inspected ambient magnetic field strength in the region. For Indonesia region, the magnetic field value is around 45,000 nT. The measurement in this method was performed by base and rover method. This method use two sensors: a sensor placed at the base (T base) to record daily variations and a sensor to measure the magnetic field as can be seen in Figure 2.

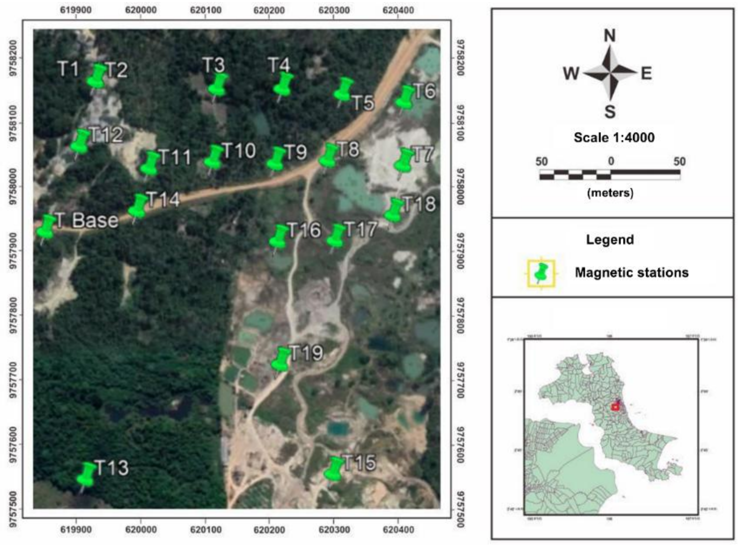

Figure 2. Magnetic measurement in identifying the subsurface of Terak Hot Spring

The magnetic field data collection was prepared by setting a series of PPM instruments. The N (North) indicator of sensor was directed to north of earth. Thus, the magnetic field value can be shown on the instrument console. Measurements at each points were carried out 5 times with a time difference of about 15 seconds for each reading, as 34 protons in the sensor re-precess. The result of the magnetic field readings and environmental conditions around the measurement point were then recorded in the magnetic measurement log which has been prepared.

The data was processed by organizing the field-acquired magnetic data including station ID, elevation, UTM coordinates, acquisition time, and magnetic field of both rover-base sensors. Base station were recorded every 30 seconds to track diurnal variation. A scaling factor was computed to interpolate magnetic field strength at the base station and was later applied to control the rover data. Daily variation (diurnal correction) was calculated to minimize temporal magnetic fluctuation during acquisition.

The International Geomagnetic Reference Field (IGRF) corrections were applied to isolate total magnetic anomalies. The corrected data were then used to produce elevation and magnetic anomaly with Oasis Montaj Software. The total magnetic values were distinguished from local (residual) features from regional trends. Reduction to the Pole (RTP) was applied to correct for inclination and declination, improving anomaly symmetry. Finally, 2D forward modelling was conducted using GYM-SYS to interpret structures and identify features associated with geothermal activity.

4. RESULT

Total magnetic field anomaly refers to the magnetic field intensity at a specific point resulting from subsurface target. The total magnetic field anomaly is obtained after applying several corrections to the raw field data such as diurnal correction and International Geomagnetic Reference Field (IGRF) correction. The contour pattern of the total magnetic field anomaly (Figure 3) over topography typically consists of numerous pairs of low to high magnetic anomaly closures which represent magnetic dipole anomalies. A large number of dipole pairs in the anomaly map show consistent pattern which typically reflects the presence of board, deep-seated sources-indicating that the total magnetic field is influenced by regional magnetic anomalies rather than shallow or local structures.

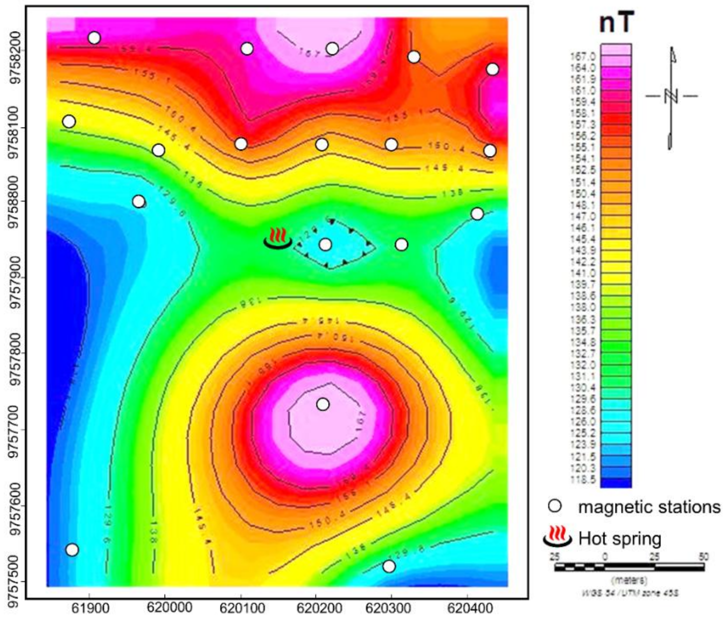

Figure 3. Magnetic dipole on total magnetic anomaly around Terak hot spring

Furthermore, in separating local anomaly from regional anomaly, the upward continuation was applied to the total magnetic anomaly. Upward continuation transforms the data by projecting the measurement to a higher elevation which helps isolate the local (residual) anomaly. This process was determined through various height approach and by analyzing the contour patterns. In this study, the observed magnetic data were smoothed by removing regional effect using upward continuation. The upward continuation was performed at several elevations as shown in Figure 4 in order to assess the variability in the local anomaly values.

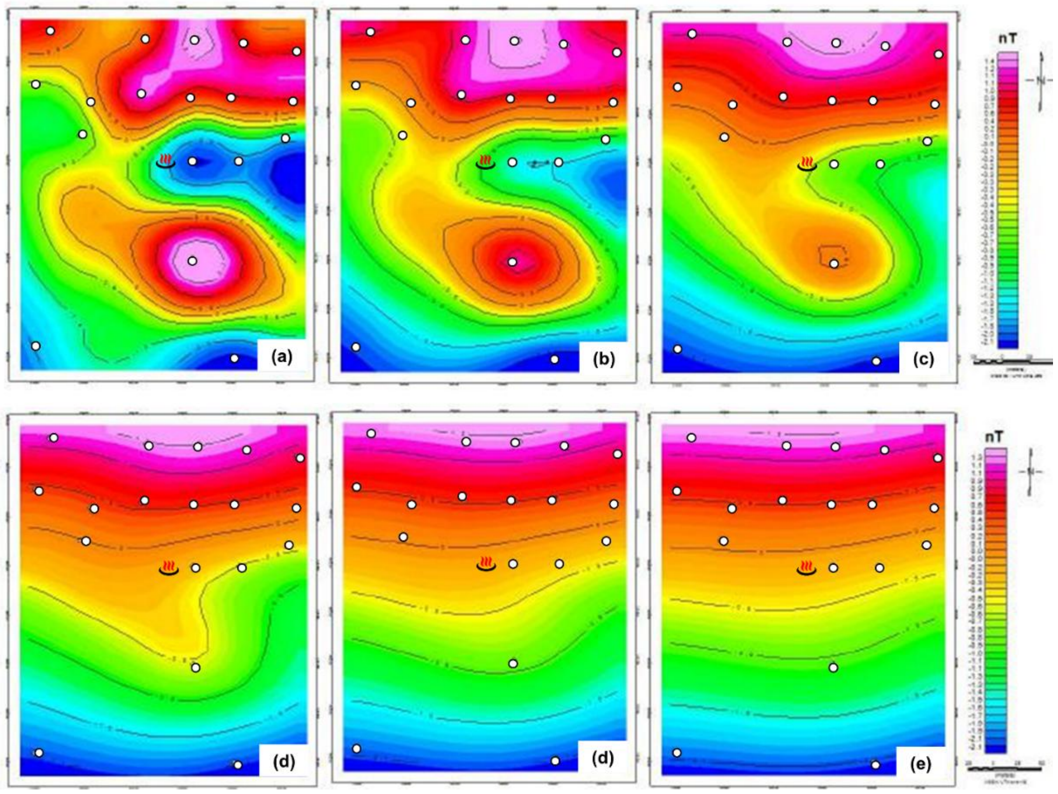

Figure 4. Local anomaly produced from upward continuation at various heights: (a) 50 m, (b) 100 m, (c) 150 m, (d) 200 m, (e) 250 m, and (f) 300 m.

The anomaly pattern shown in Figure 4 (a) at 50 m exhibits a distinctly clear and highly contrast pattern from low to high anomaly. The high anomaly can be found in the center and northern part of the area, suggesting the presence of numerous geological anomaly near the surface. The features indicate a high degree of spatial variability, which is a typical of shallow subsurface structures with varying magnetic properties. In contrast, the anomaly patterns gradually changes from 100 m to 300m (Figure 4 b-f). A 100 m continuation show a noticeable transformation which the local anomaly are still noticeable, the intensity begins to attenuate and some contour shows signs of dispersion which interpreted as the influence of near-surface magnetic source. At 150 m, the anomaly in the center region of the area show more attenuation compared to 50 m height. This attenuation pattern can be investigated to 300 m height which reflect a predominantly regional magnetic field, where most local effect have been effectively attenuated.

The local anomaly at 50 m presents a clear and complex pattern of local anomaly which are no longer significantly influenced by regional anomalies. Such low-elevation anomaly maps are crucial for understanding subsurface features in both two-dimensional (2D) and three-dimensional (3D) interpretations. All data processing and analysis in this study were then conducted in 50 m height as shown in Figure 5.

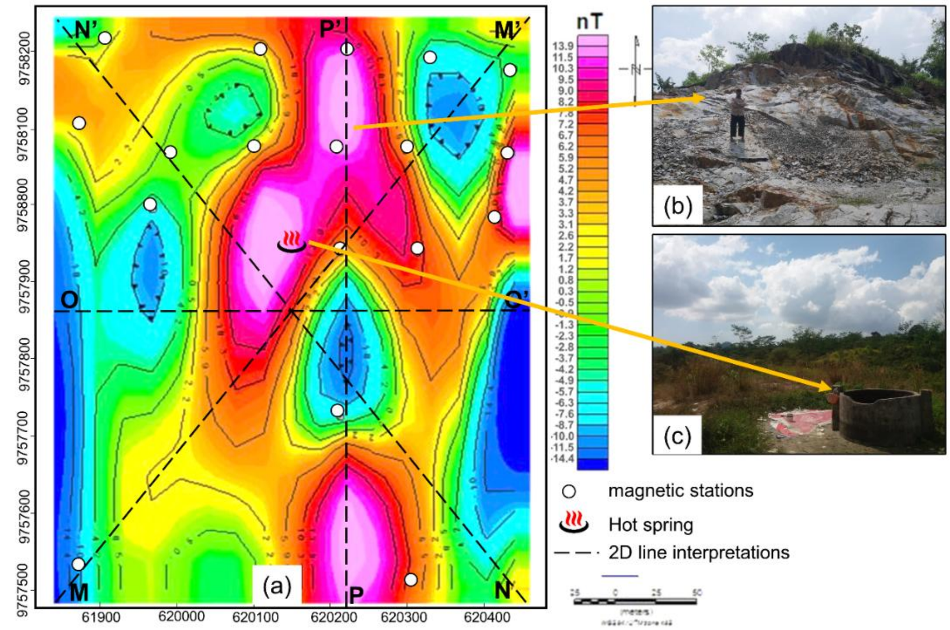

Figure 5. The observed local magnetic field after (a) reduce to pole correction with (b) granite intrusive bodies around (c) Terak hot spring

5. DISCUSSION

The locally separated magnetic anomaly date were then reduce to the pole to remove the effects of the magnetic inclination angle. This correction is essential due to the inherent dipole nature of magnetic anomalies often results in asymmetrical anomaly patterns, which can complicate the interpretation of field data. By applying this filter, the magnetic anomaly is transformed into a pattern as if it were measured at the magnetic pole where inducing field is vertical. This processing step simplifies the anomaly pattern, typically centering the magnetic anomaly directly over its source, thus more straightforward geological interpretation can be applied. The result of this correction shows that the local magnetic source is likely located directly beneath the anomaly as shown in Figure 5.

In supporting the quantitative interpretation, 2D models were constructed from 4 lines in Figure 5. The 2D models along selected profiles extracted from the local magnetic anomaly which previously subjected to reduction to the pole. Those specific profiles were selected as they slice both high and low anomalies which are expected to reveal the subsurface cross-sections with high magnetic susceptibility values. This approach is aimed to estimate the potential location of granite intrusion as heat source for Terak hot spring.

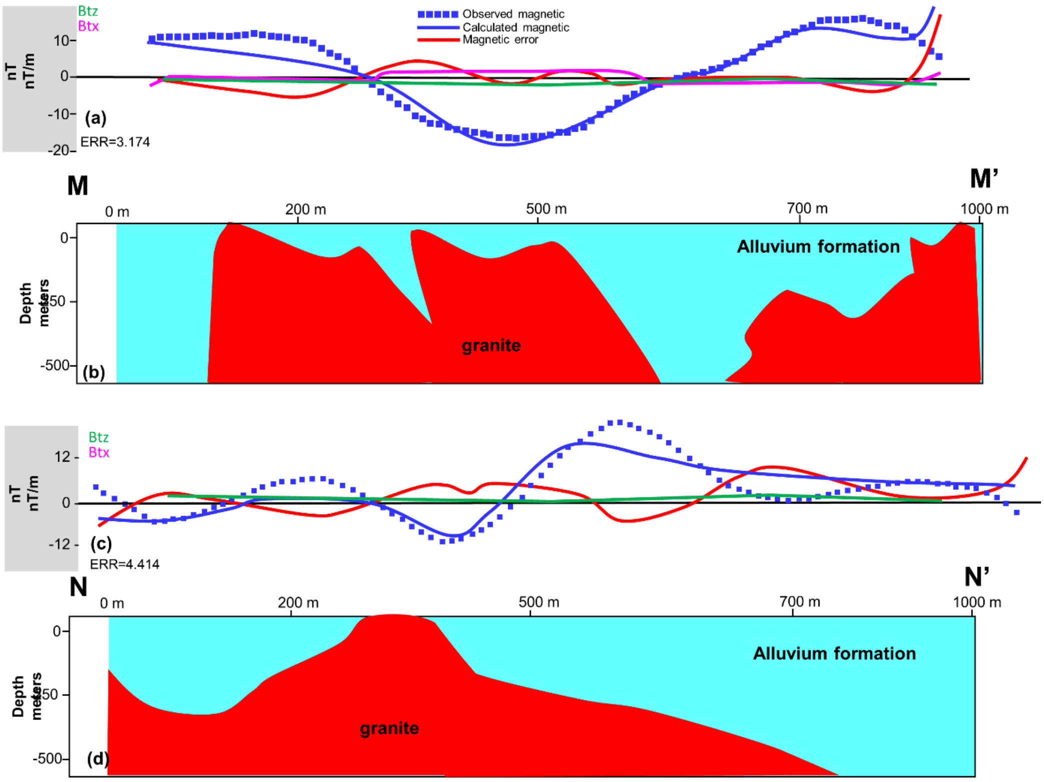

Figure 6. The 2D modelling of line M-M’ with (a) data reference curve, (b) subsurface cross section and N-N’ line with (c) data reference curve, (d) subsurface profile.

Along each profile line, 2 D magnetic modelling was conducted to represent subsurface geological structures down to a depth of approximately 500 m. The 2D models are presented in two main components for each profile: the measured magnetic anomaly data as reference curves (Figure 6 a, c and Figure 7a, c) and illustrate the modeled-cross sections of the subsurface (Figure 6 b, d and Figure 7 b,d). The dashed blue line represents the observed magnetic field as the reference for comparison in modelling. The solid blue line indicates the calculated magnetic response generated by the model. The closer this line matches to the dashed reference, the smaller the modeling error margin. A red line represents the error curve, calculated as the difference between the observed and calculated magnetic fields. Additionally, a light green line (Btx) represents the horizontal gradient of the total magnetic field, while the purple line (Btz) denotes the vertical gradient which help enhance the visibility of subtle anomaly.

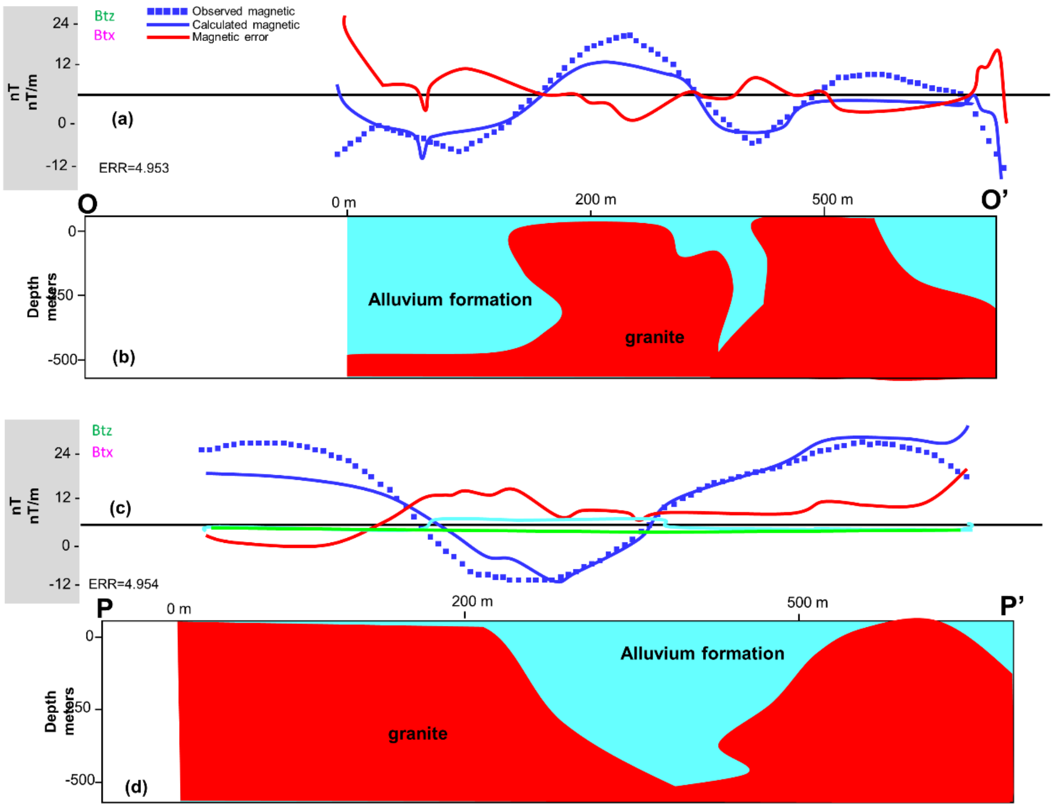

Figure 7. The 2D modelling of line O-O' with (a) data reference curve, (b) subsurface cross-section andP-P' line with (c) data reference curve, (d) subsurface profile.

The 2D modelling indicate the presence of granite intrusions domination along all the profiles. In each cross section, the forward models reveals subsurface bodies characterized by relatively high magnetic susceptibility values which are typical of granite due to outcrops found at the research area. The intrusion geometry varies slightly across each profile, but all models show vertically extensive features with broad lateral continuity, suggesting that the bodies likely form part of larger plutonic complex which form Granite Klabat formation. The 2D models provide strong geophysical evidence for granite emplacement at depth, supporting the hypothesis of subsurface granite intrusion beneath Terak hot spring.

Moreover, we further investigate Terak hot spring subsurface with 3D modelling from local anomaly map as can be seen from Figure 8 (a). The high susceptibility values (>0.005 SI in most blocks) and modeled depth support the presence of granite intrusive bodies, referring as heat source for Terak geothermal systems. The consistency of granite intrusion anomaly in both horizontal and vertical direction suggest a huge granite beneath Terak hot spring. This is confirmed by field observations (Figure 8 (e)) where extensive granite outcrops are mined by traditional mining.

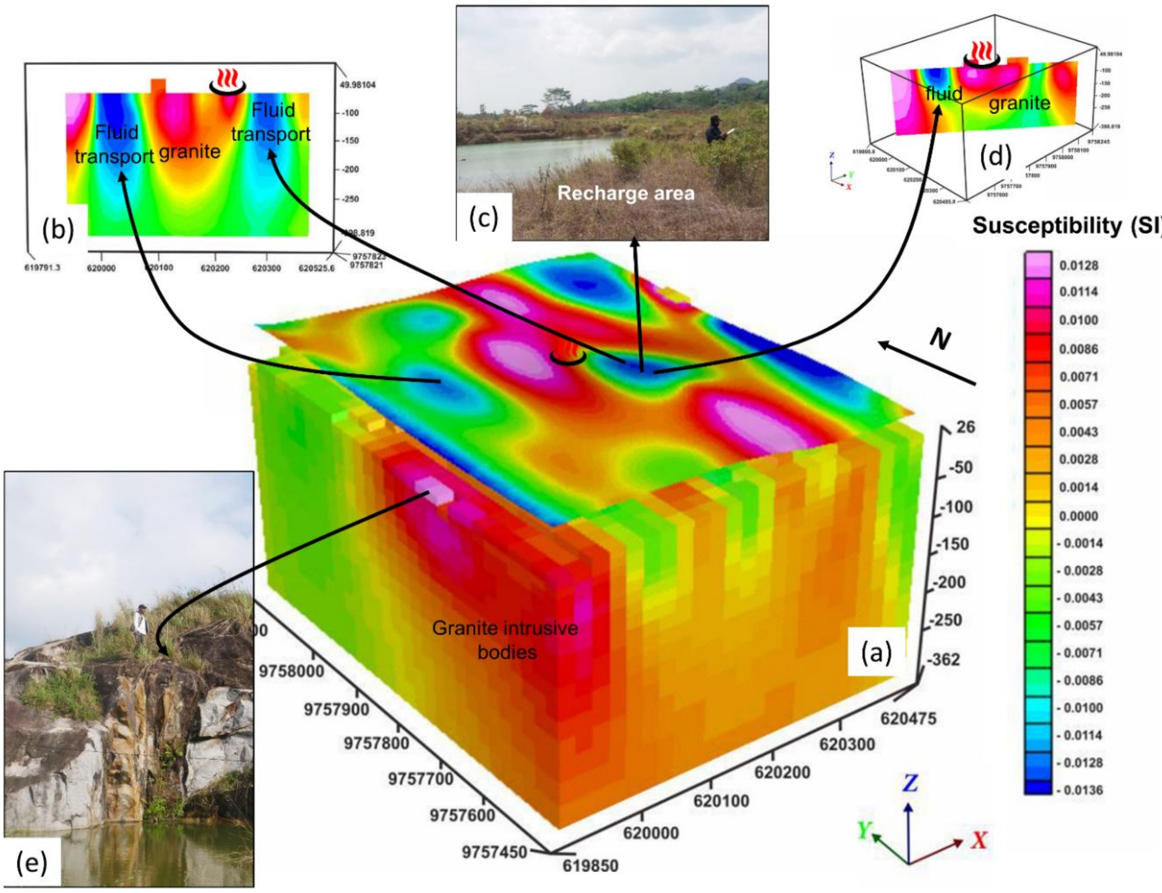

Figure 8. The intrusion granite bodies based on (a) 3D modelling of Terak hot spring. The low susceptibility of the area show (b) the fluid pathways, (c) recharge area, (c) granite bodies beneath the hot spring and (e) huge granite outcrops.

Unfortunately, due to limited magnetic area, the 3D model only show the information of 300 m depth, thus no reservoir information can be described. This shallow depth constraints the deeper information of geothermal features, particularly the reservoir zone which typically lies at greater depths in non-volcanic geothermal systems. As a result, direct characterization of the reservoir is not possible from this dataset. However, despite this limitation, a high detailed crack between granite and alluvium formation can be seen clearly which shows as the path for fluid transportation as ascend and descend. The two vertical cross sections extracted from 3D model (Figure 8 b and d) show the vertical fluid transport pathways aligned with the granite intrusion. These are interpreted from the gradient in susceptibility, where high contrasts reflect the fractured zones or fault that enable fluid pathway.

The structural discontinuities serve as conduits for ascending geothermal fluids and descending meteoric water. A huge abandoned tin mining pool (Figure 8 c) near to Terak hot spring is interpreted as recharge area for meteoric water to penetrate to the reservoir. This area is located near regions of relatively low susceptibility which corresponding to fractured or weathered granite. The recharge area serve as the entry point for meteoric water which migrates downward and interacts with granite bodies. Although the model does not extend to the reservoir depth, the spatial correlation between magnetic anomalies and known geological features supports the interpretation of fluid pathways controlled by fractures.

6. CONCLUSION

The magnetic data clearly delineates the prensence of granite intrusive bodies around Terak hotspring which characterized by high susceptibility values. These intrusions are associated with magnetic anomalies and are confirmed by granite outcrops which indicate the strong relation between geophysical and geological data. Vertical gradients and susceptibility based on 3D model shows the fluid migration pathways, suggesting the presence of local fault activities in facilitating the hydrothermal fluid circulation. The combination of granite intrusion as heat source, the fractures around the area which act as the fluid pathways, and a surface recharge zone suggest that the area could be geologically favorable for hydrothermal systems. This study supports previous research which revealed that the radiogenic geothermal system in Bangka Island was influenced by the presence of granite as one of the key factor in addressing the heat source.

Further work is urged to enhance the comprehensiveness of Terak geothermal system. Magnetoteluric (MT) method is essential for describing the structures of radiogenic geothermal system in answering the location of reservoir, cap rocks and the continuation of granite as heat source. Gravity method can be an alternative solution in analyzing the presence of local fault which control Terak geothermal systems. Geochemistry of the hot spring is the most crucial aspect for investigating how the hot spring and all associated minerals take place in the formation of radiogenic geothermal systems.

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