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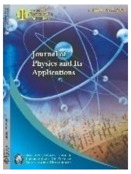

Detection of Altered Rock Zones by Applying the Essential Analyses of the Magnetic Method: A Case Study from the Lainea Geothermal Site, Southeast Sulawesi

La Hamimu[1]*, Al Rubayin[1], Suryawan Asfar[2], Laode Ihksan Juarzan[1], and Indrawati[1]

[1]*Department of Geophysical Engineering, Halu Oleo University, Sulawesi Tenggara, Indonesia*
[2]*Department of Geological Engineering, Halu Oleo University, Sulawesi Tenggara, Indonesia*

**Corresponding author:* *lahamimu@uho.ac.id*

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ABSTRACT

The essential analyses of the magnetic method represent a structured and integrative framework for resolving subsurface geometry and depth of magnetic anomaly sources in geothermal systems. This study demonstrates the methodological robustness of combining analytic signal processing, upward continuation, horizontal gradient magnitude (HGM), tilt angle derivative (TDR), and Euler deconvolution within a unified interpretation workflow. The approach is applied to reduced-to-pole (RTP) total magnetic intensity (TMI) anomalies ranging from −117 to +47 nT at the Lainea geothermal prospect, Southeast Sulawesi, Indonesia. Upward continuation to 1000 m objectively separates regional and residual components, isolating shallow low-magnetic anomalies associated with hydrothermal alteration. Derivative-based filters (HGM and TDR) consistently delineate structural boundaries and magnetic lineations trending N–S, NE–SW, and NW–SE, while TDR zero contours precisely define contact edges. Euler deconvolution (structural index = 0) constrains contact-type sources at depths of 1300–1500 m, with clustered solutions spatially coincident with derivative-defined edges. The convergence between edge detection and depth estimation quantitatively validates the internal consistency of the integrated workflow. Rather than relying on single-filter interpretation, this study highlights the advantage of systematically applying essential magnetic analyses to reduce ambiguity inherent in potential field data. The proposed integrative framework enhances reproducibility, improves structural resolution, and provides quantitative constraints on intrusive heat sources, thereby strengthening the reliability of magnetic methods in early-stage geothermal exploration and applied geophysics.

1. Introduction

Potential field methods are essential approaches in geophysical exploration and are widely employed to investigate natural resources based on the geological structures by mapping of several magnetic parameters such as a dip, boundary, area, etc. [1]. Magnetic data interpretation involves varying levels of complexity, ranging from simple one-dimensional models to three-dimensional representations aimed at fully characterizing anomaly sources ([2]). Within the framework of inverse modeling, optimization procedures are essential for estimating magnetic anomaly source models by fitting calculated responses to observed data, although the resulting solutions are inherently non-unique [3].

In the context of geothermal exploration, the ability to accurately delineate subsurface structures, fault systems, and altered rock zones is crucial, as these features are closely associated with heat sources and fluid pathways. Indonesia, located in a tectonically active region, possesses significant geothermal potential that can support sustainable energy development and long-term resource management. However, early-stage geothermal exploration requires reliable and cost-effective geophysical techniques to reduce uncertainty and exploration risk. Therefore, the application and improvement of magnetic interpretation methods are not only important from a scientific perspective but also have direct relevance to societal needs, including renewable energy development and resource utilization. In this regard, the interpretation of magnetic anomaly sources using advanced signal analysis techniques plays an important role in supporting geothermal exploration and decision-making processes.

Some techniques have been developed to characterize the anomaly sources. According to Saada [4], the analytic signal (AS), tilt angle derivative (TDR), Euler deconvolution (ED) are common techniques for characterizing the sources of anomaly. The application of these techniques can characterize the anomaly model both edge detection and the depth of anomaly sources ([4], [5], [6], [7], [1]). In this work, analytic signal, tilt angle derivative, and Euler deconvolution are implemented on the field data of magnetic anomaly measured at Lainea geothermal site with aim to represent the anomaly sources characterization. Lainea is one of the geothermal potential areas located in Southeast Sulawesi Province, eastern part of Indonesia. This site exhibits several hot spring manifestations at earth's surface as well as the altered rock [8].

In our previous study, we have quantitatively investigated the geological structure employing the application of the geomorphic method. This method integrates the analysis of morphotectonics by joining data of digital elevation model (DEM) and lithology type. Here, the activity of tectonic is manifestly classified by using index of activity called relative tectonic activity index (RTAI). This index is generally derived from the geological and geomorphological structures [9].

Based on the results obtained from the analysis of the RTAI, it was found that tectonic activity in the study area can be classified into three categories in the area of study that is high tectonic activity, medium tectonic activity, and low tectonic activity. According to a quantitative analysis of RTAI of geothermal areas of Lainea [9], the high activity of tectonic at the Lainea geothermal site covering two watersheds with total area of ± 20.5 km^2. The medium tectonic and low tectonic activities are respectively covering five watersheds with total area of ± 40.9 km^2 and two watersheds with total area of ± 12.8 km^2. Basically, Areas classified as having high tectonic activity may have a higher potential of seismic hazards due to the propagation of the geological structures.

2. Brief Review of the Geology of Research Area

The research area in this study is part of the southeastern arm of Sulawesi composed of several types of rock. The distribution of rocks in this study area is shown in Fig. 1.

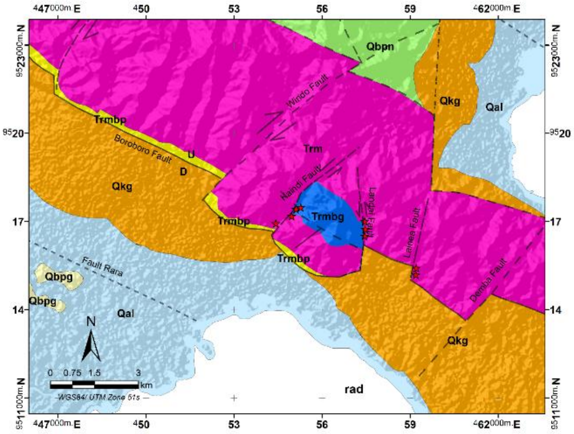

Fig. 1 Regional geological map consisting of Metamorphic Rock Unit (Trm), Meta-Limestone Unit (Trmbg), Meta-Sandstone Unit (Trmbp), Non-carbonate Sandstone Unit (Tbpn), Limestone Sandstone Units (Tbpg), Conglomerate Rock Unit (Qkg)) and Alluvium deposits (Qal). ([10]).

As can be seen in this figure, there are several rock units found in this region ([10]), that is

1. Rock unit of metamorphic (Trm) consist of several types of lithology that is quartzite, slate, schist and phyllite.
2. Rock unit of meta-limestone (Trmbg) located around the sloping area. The rock unit at this sloping is typically classified as the metamorphic limestone.
3. Rock unit of meta-sandstone (Trmbp) distributed in the southern part of the metamorphic unit, well-layered with the quartzite type insertion.
4. Rock unit of non-carbonate sandstone (Tbpn) with a lithological type of the sandstones. This type is characterized by the inserted black claystone.
5. Rock unit of the limestone-sandstones (Tbpg) consists of interchanging of the coarse sandstone with fine sandstone and contains the Mollusca fossils.
6. Rock unit of the conglomerate (Qkg) composed of conglomerate and sandstone. In particular, the grain size of the composition is in form the boulder-crust.
7. Rock units of Alluvium are composed of the clay, gravel, blocks, and sand.

At the Lainea research area, Geothermal potential trending southeast can also be found around the structure zone. In term of the geological structure, the research area has three groups of faults. According to the brief review of previous study [9], based on their direction, the main groups of faults presented in this area namely:

1. The faults of Boro-boro, Aonope, Andinete, Putemata, and Sibingguru which are grouped into the northwest–southeast (NW–SE) fault trend.
2. The faults of the Windo, Wolasi, Hariri, Demba, Kaindi, and Anggowila that is classified in the faults trend of southwest-northeast (SW-NE).
3. The faults of Lainea, Rara, and Landai that is classed in the north-south (N-S) fault direction.

3. Method

3.1. Magnetic Data

A ground magnetic survey was carried out at the site of Lainea geothermal in November 2020. The measurement of field data used two instruments of Proton Precession Magnetometer 19-T with a resolution of 0.1 nT. The first instrument is operated to measure the magnetic field at base station that could be used to calculate the temporal variation of the magnetic field. The second instrument is used to measure the magnetic field at the observation point. Furthermore, the data obtained from field measurements are corrected from temporal variation or diurnal correction with aim of calculating total magnetic intensity (TMI).

The TMI anomaly is then obtained by applying the reduction of theoretical magnetic field. This reduction is generally based on the international geomagnetic reference field or IGRF ([11]). In addition, the implementation of the reduced to pole (RTP) technique is carried out by using the Oasis Montaj's software ([12]). This final process corrects the position of the TMI anomaly of TMI anomaly so that it is accurately above the anomaly ([1]).

3.2. Separation of the Residual-Regional Using Upward continuation

Upward continuation technique is applied on the TMI anomaly RTP to filter the shallow source that is produced from deeply source or regional source. This technique is frequently used in magnetic anomaly analysis ([2]). Procedure of the Upward continuation is accomplished up to altitude of 1000 m. In this altitude, the trend of anomaly map is relatively not modified. Here, the The Geosoft program ([12]) is used for visualizing the map of upward continuation. Thereafter, this map is straightforward employed to extract the residual map from the TMI anomaly map.

3.3. Horizontal Gradient Magnitude (HGM)

Horizontal Gradient Magnitude (HGM) is one of computational approach that is very useful for mapping a fault location ([5]). Principally, HGM defines the strong interaction of two types of rock having the different magnetizations ([13]). This method generates the highly anomaly and reflects the location from anomaly source. HGM(x,y) from a magnetic field M(x,y) is empirically formulated as follow ([14])

$$\mathrm{HGM}(x,y)=\sqrt{\left(\frac{\partial M}{\partial x}\right)^2+\left(\frac{\partial M}{\partial y}\right)^2} \qquad (1)$$

where $\frac{\partial M}{\partial x}$ and $\frac{\partial M}{\partial y}$ are the first derivative of magnetic field toward variable of x and y axes, respectively. The asymptotic function of HGM peaks on magnetic contact with three assumptions ([15]) that is

1. The magnetic field and the source of magnetization are in vertical direction
2. The magnetic contact is a vertical contact
3. The source has a thick extent.

To prevent the multiple phenomena from thin body, this method should be applied on the RTP magnetic field ([5]). Moreover, Geosoft program ([12]) is used to calculate the first derivative using equation (1) produced from the map of RTP total magnetic intensity RTP.

3.4. Tilt Angle Derivative (TDR)

Improvement of signal analysis methods to determine the location and vertical magnetic contact without a priori information can be effectively carried out by using the first horizontal amplitude gradient from the angle of inclination ([16], [17]). This method is very interesting to use because it is fundamental and practical to be implemented ([2]). The tilt angle derivative (TDR) or tilt angle of a magnetic field M(x,y) is formulated as follows [(17]):

$$\theta=\tan^{-1}\left[\frac{\partial M}{\partial z}\Big/\frac{\partial M}{\partial h}\right] \qquad (2)$$

where $\frac{\partial M}{\partial z}$ is the first derivative of magnetic field toward variable of z axes and $\frac{\partial M}{\partial h}$ is the HGM(x,y).

The average distance between contour angles of 0° and angles of +45° or -45° is the depth of the anomaly ([7]). The results of the TDR technique can point out the location of the source of TMI anomaly as well as make equal the contrast for high and low anomalies ([17]). The tilt angle derivative yielding a zero value (it means close or exactly to the anomaly source) can be used to detect the edge of the source ([16]). Process of the tilt derivative is carried out using the Geosoft program ([12]).

3.5. Euler Deconvolution

The Euler deconvolution is one of techniques that can be used to interpret magnetic data automatically and fast ([4]). This technique is applied to calculate the depth of anomaly object ([2]). These calculations were performed using the GM-SYS 3D program ([12]). The technique of Euler deconvolution is based on the equation of the Euler homogeneity.

This homogeneity equation relates the magnetic field and its gradient components for the source location, with the degree of homogeneity N being considered as a structural index ([18]). The structural index is a rating measure of the change in the field with distance. The magnetic field which is the interface and contact has a structural index N = 0 ([2], [4]). In this study the Euler deconvolution technique was applied to calculate the depth of anomaly objects with windows size 10. The depth solution is estimated in the range of 750-1500m with a depth tolerance of 15%.

4. Result and Discussion

The RTP map of the total magnetic intensity anomaly shows negative and positive magnetic magnitudes ranging from -117 nT to 47 nT (**Fig. 2**). The part of the positive anomaly is observed in the lower area trending in the NW - SE direction and in the upper right area trending in the N-S direction. These areas correspond to the distribution of Quaternary rock unit, namely Conglomerate Rock Units (Qkg) and Alluvium Deposits (Qal).

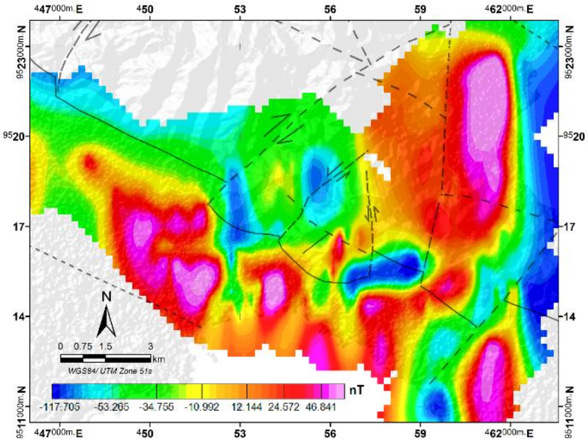

Fig. 2. The RTP map from the total magnetic intensity anomaly of the Lainea. The color gradation shows the magnitude of TMI (nT) and the black line shows faults.

In contrast, the negative or low anomaly area shows the distribution of Metamorphic rock unit (Trm). This area shows correspondingly the boundary lineation of high and low anomalies which are consistent with the Boro-boro fault, the Lainea fault and the Demba fault. Around this lineation, there are three areas having low anomaly closure. The first area is located in the center part with hot springs enclosing the appearance point of the hot spring. In this area, the emergence of hot spring manifestations (Kaendi, Awomolo, Rampant and Lainea) is a geothermal reservoir zone ([8]). This could indicate that the two low anomaly closure areas located in the slightly center part to the north direction are interpreted as altered rock zones. Further analysis of this anomaly is investigated using continuation technique and the magnetic derivative analysis.

The results of the upward continuation at an altitude of 1000m indicate a regional anomaly map (Fig. 3) which is a source of deep anomalies. The lifting height of 1000m is correspondingly expected as regional depth. The altered rock zone is no longer visible at this depth. The trend of positive and negative anomalies corresponds to the direction of the main fault in the study area. The map in the Fig. 3 is then subtracted from the map of RTP to produce a map of shallow source as illustrated in Fig. 4. The residual map shows more evidently three altered rock zones close to the main fault in the research area.

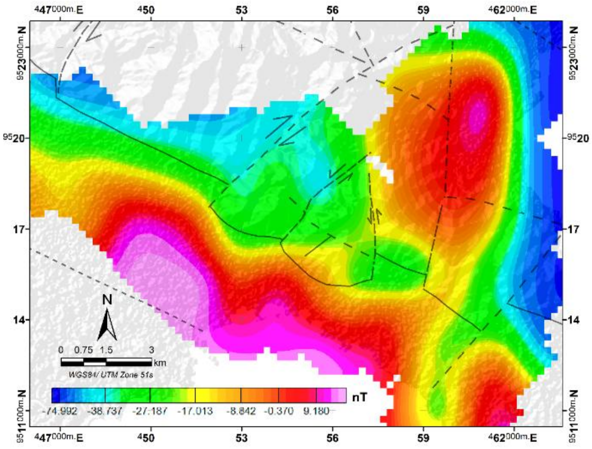

Fig. 3. Map of the upward continuation of the total magnetic intensity at altitude of 1000m. The color gradation shows the magnitude of TMI (nT) and the white polygon shows the altered zone.

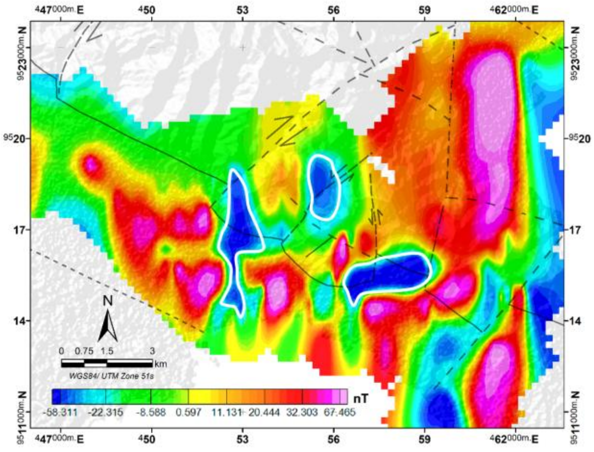

Fig. 4. The map of total magnetic intensity residual. The color gradation shows the magnitude of TMI (nT) and the white polygon shows the altered zone.

The edges of the altered rock zone shown on the HGM map (Fig. 5) are more obvious than those on the RTP map of total magnetic intensity. Here, the peak magnitude shows several anomalies indicating altered rock and fault zones. In the middle part of the map, the closure peak magnitude indicates an altered rock contact edge. This indication is only observed on the eastern part and is not visible on the two altered rock zones as shown on the residual RTP map (Fig. 4). Another anomaly is a number of magnitude lineation indicating faults. The lineation is trending in the NE - SW direction (correlating to the Demba fault), the N-S trend, as well as the NW-SE trend.

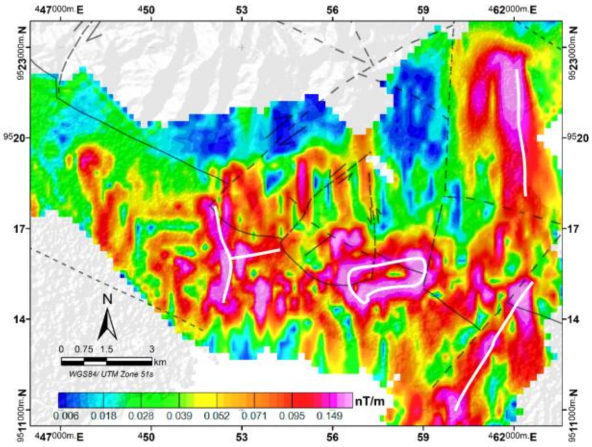

Fig. 5. The map of Horizontal Gradient Magnitude (HGM). The white lines show the peak magnitude of the HGM and the black lines show the fault.

Further analysis is carried out by joining the results of the Euler deconvolution and the tilt derivative filter solutions (**Fig. 6**). The TDR analysis shows the availability of faults, which appear in the form of magnetic lineation, as well as the boundary edges of the anomaly sources denoted by the zero TDR contour. The zero contour is shown with a red line separating the magnetic susceptibility with a positive value marked a red-pink gradient and a negative value marked a green-blue gradient.

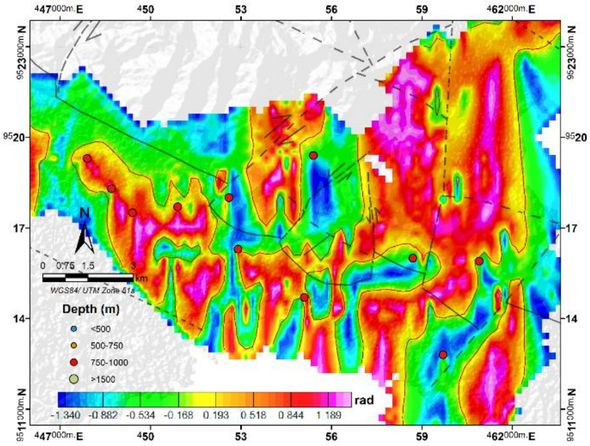

Fig. 6. The map of tilt derivative of the total magnetic field of RTP and the solution of index 0 structural 3D-Euler. Color gradations show angle magnitude (rad), black lines indicate faults.

The distribution of positive values is exactly over the source corresponding to unaltered rock. The overlap of TDR with the Euler deconvolution solution indicates that the edge of the body anomaly between the two filters are consistent with each other. In addition, the TDR map shows correspondingly a distribution of negative values indicating the distribution of the altered rock zones from a more extensive residual map (**Fig. 4**). These zones can be specifically found at around the faults of Boro-boro, Windo, Kaindi, Laindi as well as the Lainea fault. In general, the correlation with the Euler deconvolution solution for the structure index 0 shows that there is a contact anomaly indicating the rock intrusion. This intrusion can prospectively produce the altered rock zone at a depth of 1300-1500m. The results of magnetic anomaly data analysis obtained from this study can consistently confirm the manifestation of the geothermal system at Lainea. The hot spring source at the Lainea's geothermal system has an intrusive or plutonic rock characteristics with the depth estimation of 1250-1500 meters ([8]).

Finally, the magnetic interpretations derived from the HGM and TDR analyses (Fig. 5) and the depth solutions obtained from Euler deconvolution (Fig. 6) provide a detailed characterization of subsurface structures and altered rock zones in the study area. This characterization shows a strong correspondence with the geomorphotectonic framework previous study in the Lainea geothermal area ([9]). The magnetic lineations identified from the HGM and TDR analyses, which trend predominantly in the N–S, NE–SW, and NW–SE directions, are consistent with the main fault systems and tectonic lineaments inferred from relative tectonic activity indices. This agreement indicates that the surface expressions of tectonic activity recognized through geomorphic analysis are directly linked to subsurface structural features detected by magnetic methods. While our previous work focused on classifying tectonic activity based on surface morphology and drainage characteristics ([9]), the present study provides complementary subsurface constraints by quantitatively delineating the geometry, boundaries, and depth of magnetic anomaly sources. In particular, the Euler deconvolution results indicate contact-type anomalies at depths of approximately 1300–1500 m, which are interpreted as intrusive bodies associated with geothermal alteration zones. These depth estimates extend the geomorphotectonic interpretation into the subsurface and support the conceptual model of a structurally controlled geothermal system at Lainea. The integration of geomorphotectonic and magnetic analyses therefore offers a more comprehensive understanding of the geothermal system, demonstrating the value of combining surface-based tectonic indicators with subsurface geophysical evidence for geothermal exploration and resource assessment.

5. Conclusion

Application of the signal analysis method and Euler deconvolution was effective and efficient in analyzing the magnetic anomaly data. The main fault and the distribution of formation is properly confirmed through analysis of positive anomaly trends obtained from TMI map. The HGM implementation can completely verify the edge detection of the body anomaly in the form of the altered rock and there are several magnetic lineation paths trending in the N-S, NE-SW, and NW-SE directions. The combined results of TDR and Euler deconvolution can show the detection of edge and depth of the anomaly. In particular, the altered rock zones can be specifically found at Boro-boro fault, Windo fault, Kaindi fault, Laindi fault, and also Lainea fault. A contact anomaly indicating the rock intrusion may generate the altered rock zone at a depth of 1300-1500m.

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