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Subsurface Structural Identification and Seismicity Correlation in West Java Using EMAG2 Geomagnetic Data

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A B S T R A C T

West Java represents one of Indonesia's most seismically active regions, characterized by complex interactions between the Indo-Australian subduction zone and active onshore fault systems. This study investigated subsurface geological configurations and their relationship to earthquake occurrences using Earth Magnetic Anomaly Grid (EMAG2) data with a 2-arc-minute resolution. The research methodology utilized Reduction to the Pole (RTP) to eliminate dipolar effects caused by the equatorial location, followed by spectral analysis to separate regional and residual anomalies. To precisely map structural lineaments, First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) techniques were applied to the residual data. The processed maps revealed distinct anomaly contrasts, with high magnetic intensities (up to 300 nT) associated with volcanic intrusions and low anomalies (approximately −100 nT) indicating sedimentary basins or hydrothermally altered zones. A critical analysis of the December 15, 2017, Tasikmalaya earthquake (Mw 6.5) identified a strong correlation between the epicenter and a significant low magnetic anomaly zone of −150 nT. This specific signature was interpreted as a fracture zone characterized by rock demagnetization resulting from tectonic stress accumulation. These findings confirm that integrating EMAG2 data with derivative filtering is a robust approach for delineating active tectonic structures, thereby contributing essential data for regional seismic hazard mitigation.

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1. INTRODUCTION

Indonesia is an archipelagic country with highly complex geographical conditions and tectonic settings because it is located in the Pacific Ring of Fire. This region represents a convergence zone of three major tectonic plates of the world, namely the Indo-Australian Plate moving northward, the relatively stable Eurasian Plate, and the Pacific Plate moving westward. The convergent interaction among these plates generates an active subduction zone extending from Sumatra, Java, to Nusa Tenggara, which serves as the main source of seismic activity in the Indonesian region [1]. The three tectonic plates in the Indonesian region are among the most active in the world, resulting in a higher frequency of earthquakes in Indonesia compared to other countries. This fact places Indonesia at the top rank among the ten countries with the highest frequency of earthquakes worldwide [2].

One of the regions with a very high level of seismic vulnerability is the western part of Java Island. This area is prone to earthquakes due to the presence of the subduction zone south of Java as well as the existence of active onshore faults that contribute to the complexity of the geological structure. Seismic activity in this region is highly intensive because of continuous energy accumulation along plate convergence zones and fault systems [3]. Within this geological framework, various folds and faults are formed, acting as pathways for the release of seismic energy. In West Java, six major regional faults have been identified, namely the Cimandiri, Cipeles, Baribis, Lembang, Palabuhanratu, and Citanduy faults [4].

An earthquake is defined as a sudden release of energy in the form of vibrational waves that propagate throughout the Earth's surface due to disturbances or fractures within the Earth's crust. Such seismic events are very difficult to predict accurately in terms of their specific time and location, and therefore often result in destructive disasters, including the potential generation of tsunamis that can cause severe damage and loss of life when they occur in coastal areas. The identification of earthquake hazard potential is therefore crucial, considering the continuous growth of infrastructure and population density in earthquake-prone regions [5]. Consequently, earthquakes are among the most feared natural phenomena due to their impacts, which can result in loss of life, significant material damage, and destruction of vital infrastructure [6].

The movement of tectonic plates and subsurface rock deformation have been shown to exert a significant influence on the Earth's magnetic field [7]. When tectonic plates shift or experience stress, the distribution of ferromagnetic minerals in the Earth's crust may undergo changes in orientation or magnetic properties due to piezomagnetic effects or thermal processes. For example, magnetite minerals may lose their magnetization when exposed to temperatures exceeding the Curie temperature and regain their magnetic properties when the temperature decreases again, thereby recording traces of past tectonic processes. This phenomenon leads to variations in magnetization patterns within igneous rocks as well as geologically altered rocks. Variations in rock susceptibility values beneath the surface are subsequently measured as magnetic anomalies that differ from the Earth's main magnetic field [8].

This study aims to analyze the sources of magnetic field anomalies in order to identify subsurface geological structures in the study area. The spatial distribution map of magnetic field anomalies in West Java is shown in Figure 1, which indicates variations in high and low magnetic intensity values associated with regional geological structures. Closely spaced anomaly contours on the map often indicate lithological boundaries or fault zones that separate rocks with different magnetic susceptibilities [9]. By analyzing these anomaly patterns, it is expected that potential geological structures relevant to future geohazard mitigation can be mapped.

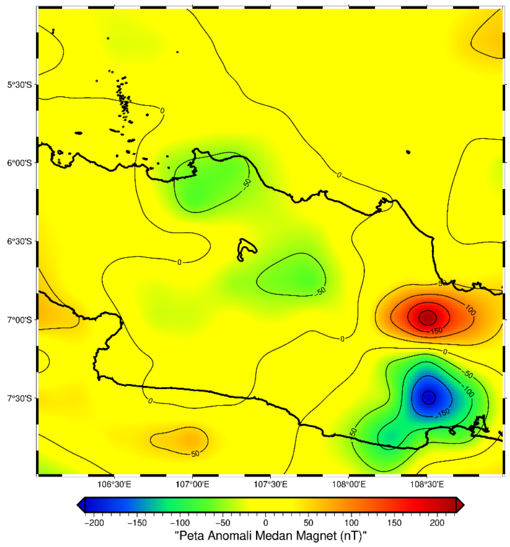

Fig. 1. Map of Magnetic Field Anomalies in West Java

2. RESEARCH METHOD

The primary data used in this study were obtained from the Earth Magnetic Anomaly Grid (EMAG2) with a spatial resolution of 2 arc-minutes. The study area is focused on West Java, bounded by geographic coordinates of 5° S – 8° S and 106° E – 109° E, based on data from 2017. The use of EMAG2 data is highly effective for regional-scale analysis because this compilation integrates satellite, marine, and aeromagnetic measurements capable of representing global lithospheric magnetic anomalies [10]. The initial stage of the study began with the collection and extraction of the grid data, which were then processed to produce a Total Magnetic Field Anomaly map as the basis for preliminary interpretation prior to further geophysical corrections.

After the raw data were obtained, a crucial processing step was the application of Reduction to the Pole (RTP) correction. This mathematical process aims to transform the inclination angle of the data as if the measurements were conducted at the Earth's magnetic pole (inclination of 90 degrees), thereby eliminating dipole effects caused by the low-latitude (equatorial) location of the study area. At polar inclination, the anomaly response takes the form of a monopole, in which the anomaly peak is positioned directly above the causative body, thus minimizing errors in target location determination [11]. This transformation is particularly important because magnetic anomalies in equatorial regions such as Indonesia often exhibit complex patterns due to interactions with the predominantly horizontal main geomagnetic field vector. After the calculations were completed, the RTP magnetic anomaly map was used as the fundamental dataset for anomaly separation processes. To mitigate instability and edge-effect artifacts common at low/equatorial latitudes, a spatial grid padding technique was applied (xrft.pad) prior to the RTP transformation. The grid was padded by one-third of its size in both easting and northing directions. The transformation was computed using the harmonica Python library, which effectively stabilizes the anomaly response without requiring a separate Pseudo-gravity transform. The grid was subsequently unpadded for further spatial analysis.

The next stage involved the separation of regional and residual anomalies to distinguish responses from deep sources (regional) and shallow sources (residual). In this study, the regional-residual separation was performed purely through spatial mathematical modeling. After reprojecting the RTP data into a Cartesian coordinate system, a third-order polynomial trend surface was fitted to the grid using the verde Python library (verde.Trend(degree=3)). This third-order polynomial approach acts as an effective low-pass filter, which suppresses high-frequency local information while enhancing and clarifying regional patterns [12]. The regional component was then mathematically subtracted from the original RTP data to obtain the residual anomaly. Theoretically, this separation leverages the principle that deeper sources are characterized by longer wavelengths compared to shallow sources [13]. Because this method relies on direct spatial polynomial fitting rather than spectral frequency cut-offs, Radially Averaged Power Spectrum (RAPS) depth estimations were not utilized in this workflow.

After the residual anomaly was successfully separated from its regional component, the analysis was continued using anomaly image enhancement techniques through derivative methods. The first transformation applied was the First Horizontal Derivative (FHD), which functions to detect edges or lateral boundaries of the anomalous source bodies. The FHD method is highly sensitive to horizontal changes in magnetic susceptibility, and therefore peaks in the FHD curve are often associated with the locations of geological contact boundaries or fault zones [14]. Subsequently, the Second Vertical Derivative (SVD) method was applied to delineate more detailed structures and to separate overlapping anomalies. SVD has the capability to enhance high-frequency anomalies related to shallow geological features, allowing structural boundaries in the study area to be mapped more distinctly.

Computationally, both FHD and SVD were processed using the harmonica library after the residual grid was converted to Cartesian coordinates. It is important to note that no prior smoothing was applied to the residual grid before derivation, as the robust third-order polynomial separation naturally provided a stable, low-noise baseline. The FHD was derived directly from the first-order easting (x) and northing (y) derivatives, formulated as:

$$FHD = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2} \quad (1)$$

Following Laplace's equation, the SVD was calculated mathematically as the negative sum of the second-order horizontal derivatives:

$$SVD = -\left(\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2\right) \quad (2)$$

The entire sequence of data processing stages in this study, from EMAG2 data acquisition to derivative analysis, is systematically summarized in a flowchart. This diagram illustrates the logical sequence of data processing steps to ensure the validity of the final interpretation results. The technical procedures, along with the inputs and outputs of each process, are presented in detail in figure 2. This workflow was designed to ensure that the interpretation of subsurface structures is based on data that have been properly corrected and methodologically verified.

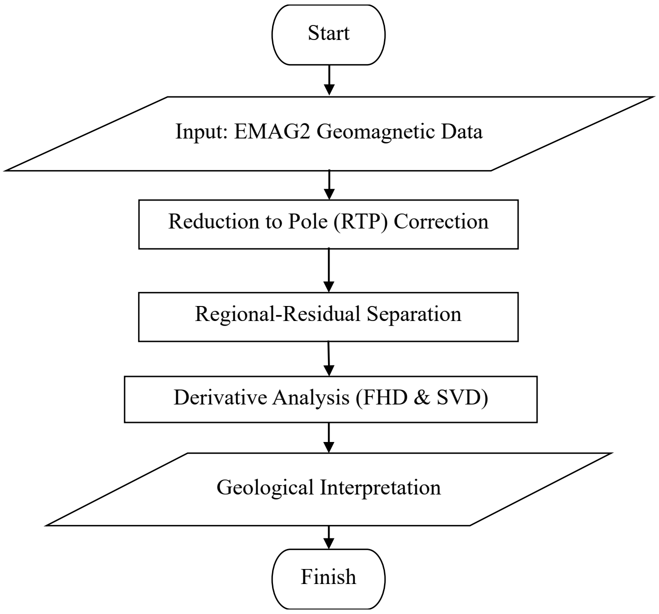

Fig. 2. Flowchart of the research methodology

3. RESULTS AND DISCUSSION

3.1. Magnetic Anomaly Data Processing

The initial stage of data interpretation began with the analysis of the Reduction to the Pole (RTP) magnetic anomaly map. This process is crucial for magnetic data in equatorial regions such as Indonesia to eliminate the asymmetry of anomaly shapes caused by the low inclination of the Earth's magnetic field. Figure 3 shows the distribution of corrected magnetic anomaly intensities, with color gradations from dark blue to red representing variations in subsurface rock susceptibility values. Red and yellow areas indicate high (positive) anomaly intensities reaching up to 300 nT, which are generally associated with intrusive igneous rocks or volcanic rocks rich in ferromagnetic minerals. In contrast, dark blue colors represent low (negative) anomalies of approximately −100 nT, which can be interpreted as thick sedimentary rocks or demagnetized zones caused by hydrothermal alteration [11]. With the RTP correction, the anomaly centers are now positioned directly above their causative bodies, thereby minimizing distortion due to dipolar effects and enabling more accurate source location interpretation.

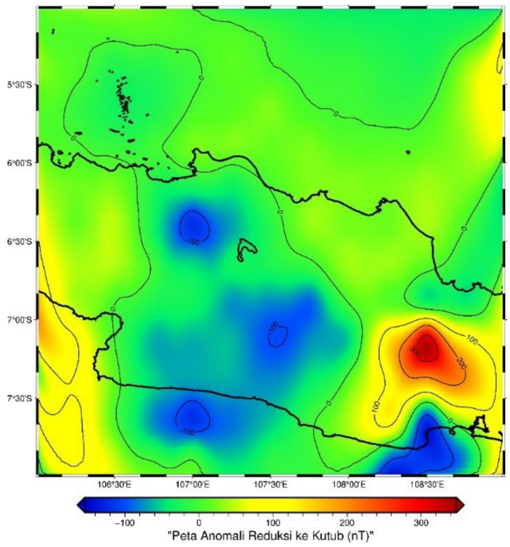

Fig. 3. Reduction to the Pole (RTP) Magnetic Anomaly Map

After obtaining the RTP data, spectral separation was performed to generate the Regional Magnetic Anomaly Map. This map represents magnetic responses originating from very deep and extensive sources, such as basement rocks or large-scale crustal structures. Figure 4 displays the regional anomaly pattern produced using a third-order polynomial method, which was selected because it effectively models long-wavelength regional geological trends without removing important features. The polynomial function models the regional trend of the total magnetic field data, which is then subtracted from the original data to obtain the local component [15]. The contour patterns on the regional map appear smoother and dominated by long-wavelength variations, reflecting regional geological structures located at significant depths beneath West Java.

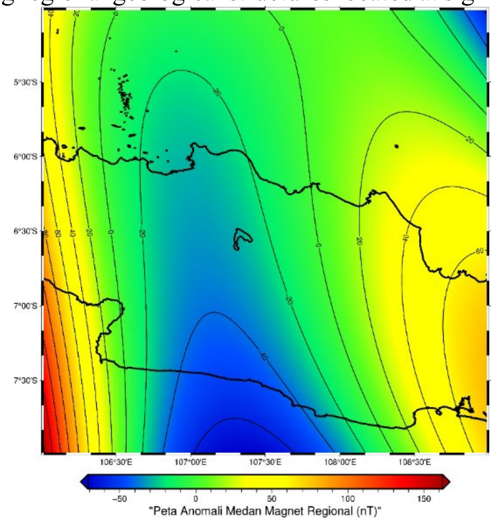

Fig. 4. Regional Magnetic Anomaly Map

The next step was the extraction of the Residual Magnetic Anomaly Map, obtained by subtracting the regional anomaly from the RTP data. Figure 5 presents the residual anomaly map, which visualizes local magnetic field variations related to shallow exploration targets, such as shallow intrusions or near-surface fault zones. In this map, the focus of interpretation becomes sharper, allowing local geological structures to be identified more clearly than in the total magnetic data. Concentrations of high anomalies reaching up to 300 nT are observed in relatively narrow and localized areas, indicating strong contrasts in rock susceptibility within the shallow crust. These residual anomalies provide the most relevant information regarding subsurface geological configurations directly associated with potential earthquake sources or other active tectonic features [16].

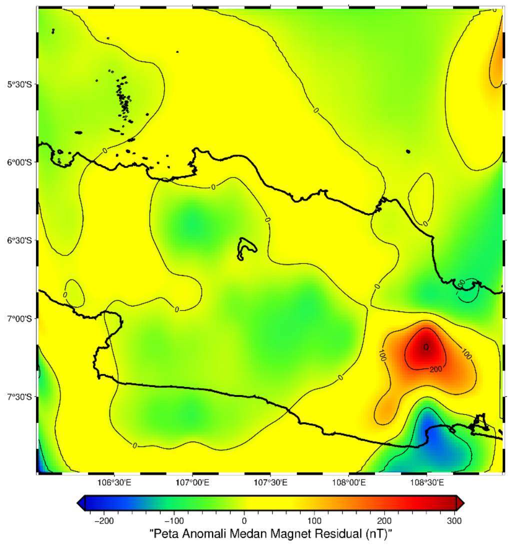

Fig. 5. Residual Magnetic Anomaly Map

3.2. Derivative Analysis and Structural Boundaries

To further delineate the geological structural boundaries indicated on the residual anomaly map, a First Horizontal Derivative (FHD) analysis was performed. Figure 6 shows the FHD filtering results, which function to detect edges or lateral boundaries of the anomalous source bodies (edge detection). This method is highly sensitive to horizontal changes in magnetic intensity values, where peak (maximum) values in the FHD curve generally coincide with lithological contact boundaries or fault zones [14]. In the map, two dominant regions with anomaly gradient values of approximately 0.01 nT/m are identified. The lineament patterns formed by these FHD peak values can be interpreted as fault pathways or intrusion boundaries separating rock blocks with different magnetic properties.

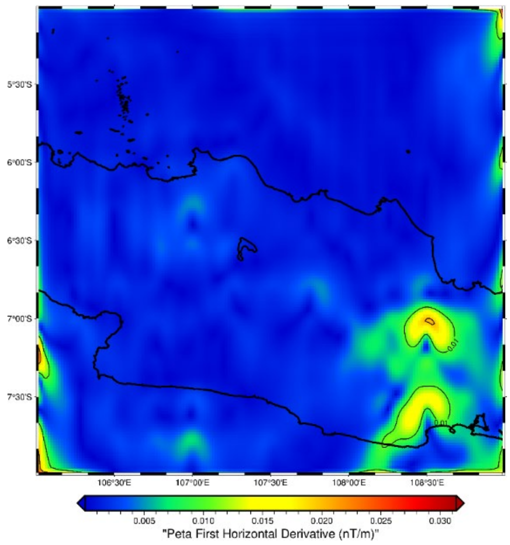

Fig. 6. First Horizontal Derivative (FHD) Map

The analysis was continued using the Second Vertical Derivative (SVD) method to separate overlapping local anomalies and enhance the effects of shallow sources. Figure 7 presents the SVD map, where anomalies appear more isolated and focused on more specific areas. Zero (0) derivative values on the SVD map are often used to delineate the exact boundaries of subsurface anomaly sources. In southeastern West Java, a relatively strong anomaly response is observed with values ranging from -4×10^{-6} nT/m² to 4×10^{-6} nT/m². These high-frequency anomaly patterns confirm the presence of complex shallow geological structures, which are most likely related to active fault systems in the region [17].

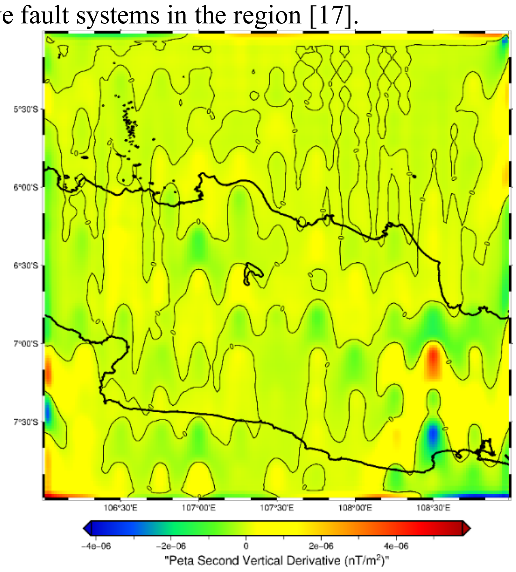

Fig. 7. Second Vertical Derivative (SVD) Map

While the FHD and SVD zero-contours highlight regions of high structural contrast, it is essential to acknowledge the inherent limitations of the 2-arc-minute (~4 km) spatial resolution of EMAG2v3. However, these magnetic lineaments are interpreted as the deep-seated basement architecture that controls the formation of active faults at the surface. A qualitative comparison shows that the major NW-SE and W-E magnetic lineaments identified in this study align with the orientation of regional fault systems mapped in the National Source and Fault Map (PusGen), such as the Cimandiri and Baribis zones. These magnetic anomalies likely delineate the boundaries of crustal blocks or 'zones of weakness' that act as the structural framework for the active fault segments reported by PusGen. Thus, while the resolution prevents a 1:1 mapping of individual fault segments, the results successfully capture the regional tectonic grain that governs the seismicity of West Java.

3.3. Correlation between Magnetic Anomalies and Seismicity

The final interpretation was conducted by correlating magnetic anomaly patterns with historical earthquake data to identify earthquake-generating structures. Figure 8 presents the map of a significant earthquake that occurred on 15 December 2017 with a magnitude of Mw 6.5. This earthquake was centered at coordinates −7.4921° S and 108.1743° E with a depth of 90 km, which is administratively located in Tasikmalaya Regency, West Java. While the ~90 km depth indicates an intermediate-depth intraslab mechanism, its spatial alignment with a prominent onshore -150 nT magnetic anomaly suggests a physical coupling. Intermediate-depth intraslab earthquakes often project their tectonic stress upward, exploiting and reactivating long-lived zones of crustal weakness, such as ancient fractures or the boundaries of deep sedimentary basins in the overlying lithosphere. Consequently, the low magnetic signature is computationally interpreted as a pre-existing structural boundary characterized by rock demagnetization—potentially facilitated by hydrothermal fluid alteration or stress accumulation along these projected crustal pathways [3]. Therefore, the magnetic anomaly maps the crustal vulnerability zone that responds to the deeper tectonic regime, rather than representing the direct seismogenic source of the 90 km event.

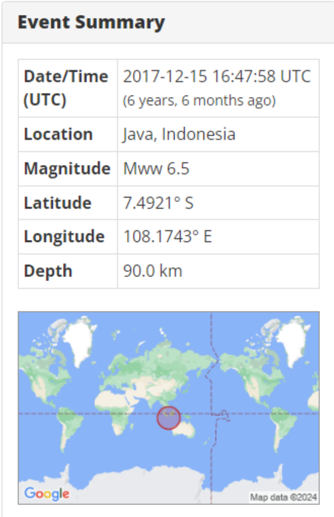

Fig. 8. Earthquake Map of 15 December 2017

4. CONCLUSION

This study successfully identified subsurface structures and tectonic settings in the West Java region through the analysis of EMAG2 geomagnetic data. The application of the Reduction to the Pole (RTP) correction method and the separation of regional–residual anomalies proved to be effective in isolating magnetic responses originating from the shallow Earth's crust. Further analysis using derivative methods, namely the First Horizontal Derivative (FHD) and the Second Vertical Derivative (SVD), was able to enhance lithological boundaries and delineate lineament zones associated with geological fault structures [14]. The resulting anomaly patterns provide a clear depiction of the complexity of geological structures that cannot be observed solely from total magnetic anomaly data.

The integrated interpretation indicates a strong spatial correlation between residual magnetic anomalies and seismic activity, particularly for the Tasikmalaya earthquake event on 15 December 2017. At the earthquake epicenter location (latitude −7.5° and longitude 108.5°), a low magnetic anomaly value of approximately −150 nT was identified, supported by contrasting patterns on the SVD map, which indicate the presence of a fracture zone or rock demagnetization due to tectonic energy release. This finding confirms that active fault zones are often characterized by a decrease in magnetic intensity resulting from rock alteration along fault planes [3]. Nevertheless, the anomalies detected around latitude −7° and longitude 108.5° have not yet shown a direct relationship with the available earthquake data; therefore, further complementary geological or geophysical investigations are required to determine the sources of these anomalies.

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