Delineation of Fractured Aquifer Zones Using TDR and HDTDR Analysis of Magnetic Anomaly Data in Sumbang, Banyumas, Indonesia

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Abstract

Groundwater occurrence in volcanic environments is strongly controlled by fractures and structural discontinuities that act as secondary pathways for groundwater flow. This study applies Tilt Derivative (TDR) and Horizontal Derivative of Tilt Derivative (HDTDR) filters to Reduction to the Equator (RTE)-transformed magnetic anomaly data to identify structural lineaments and delineate prospective fractured aquifer zones in Sumbang Village, Banyumas Regency, Indonesia. The TDR filter successfully enhanced magnetic anomaly boundaries, while HDTDR provided sharper and more localized edge responses, enabling clearer identification of lineament patterns and structural intersections. The results reveal dominant northwest–southeast (NW–SE) lineaments with secondary northeast–southwest (NE–SW) trends. Lineament density analysis (0–0.12108 m/m^2) classified the area into low, moderate, and high-density zones, where moderate to high-density zones with intersecting lineaments were interpreted as favorable locations for fractured aquifer development. Integration with geological and hydrogeological information indicates that these structural features may facilitate groundwater infiltration and subsurface flow within Quaternary volcanic formations of Slamet Volcano. This study demonstrates that the integrated application of RTE, TDR, HDTDR, and lineament density analysis is effective for identifying structurally controlled fractured aquifer prospects and supporting groundwater exploration in volcanic terrains.

Keywords: fractured aquifer; HDTDR; magnetic anomaly; Sumbang; TDR

I. INTRODUCTION

Groundwater represents one of the most critical freshwater resources for sustaining domestic, agricultural, farm, and industrial demands, particularly within regions dominated by volcanic landscapes. In volcanic environments, groundwater occurrence is heavily governed by lithological characteristics and secondary porosity, which typically develops as fractures, faults, joints, and cooling cracks within lava flows. The southern slope of Slamet Volcano, situated in the Banyumas Regency of Central Java, serves as a vital recharge area for the Purwokerto–Purbalingga Groundwater Basin. Geologically, this region comprises diverse Quaternary volcanic products, including lava flows, volcanic breccias, tuffs, and lahar deposits originating from the historical activity of Slamet Volcano (Djuri et al., 1996). Although pristine volcanic rocks generally exhibit relatively low primary porosity, well-interconnected fracture networks substantially enhance subsurface storage capacity and hydraulic conductivity, thereby forming highly productive fractured aquifers (Singhal & Gupta, 2010; Fernandes et al., 2023). Previous hydrogeological investigations have demonstrated that spring discharges on the southern slopes of Slamet Volcano are intimately linked to groundwater circulation pathways controlled by these rock fracture systems (Iswahyudi et al., 2018; An Nisaa & Putra, 2024). Consequently, characterizing the spatial

distribution and geometric configuration of fracture networks is imperative for effective groundwater exploration and the sustainable management of water resources in this volcanic terrain.

Despite their hydrogeological significance, fractured aquifers remain among the most challenging systems to characterize due to the discontinuous, highly heterogeneous nature of fracture zones and their profound structural complexity. Conventional groundwater exploration in volcanic terrains has traditionally relied on electrical resistivity (geoelectric) methods, owing to their capacity to differentiate water-bearing strata from surrounding lithologies based on resistivity contrasts (Eugene-Okorie et al., 2020; Wahab et al., 2021). However, executing geoelectric surveys in volcanic settings often encounters major technical hurdles, particularly within hard, highly resistive lava formations that impede optimal electric current injection. Furthermore, the resulting data are typically restricted to localized 2D profiles, rendering them less effective for mapping regional, structurally controlled groundwater conduits. In reality, the productivity of a fractured aquifer is primarily governed by fracture density, connectivity, and spatial orientation rather than lithological attributes alone (Chandra et al., 2019; Ringel et al., 2024). Hence, a more comprehensive geophysical approach is required to map and delineate these subsurface structural controls across broader volcanic frameworks.

The magnetic method is widely utilized in hydrogeological investigations within volcanic terrains because magnetic anomalies are highly sensitive to lithological contacts, faults, fractures, and alteration zones that dictate groundwater circulation (Oni et al., 2020; Dumont et al., 2021). Various studies have confirmed that derivative filters, such as the Horizontal Derivative (HD) and First Vertical Derivative (FVD), are highly effective at enhancing structural boundaries in magnetic anomaly data (Blakely, 1995; Daud et al., 2019). Even so, both filters are constrained by their sensitivity to source depth: strong anomalies from shallow bodies commonly overprint the residual maps and mask deeper structural signatures. To address these shortcomings, edge-enhancement approaches such as the Tilt Derivative (TDR) and the Horizontal Derivative of the Tilt Derivative (HDTDR) have been introduced. By normalizing the ratio between vertical and horizontal gradients, the TDR responds equally to shallow and deep sources and therefore accentuates structural boundaries across a range of depths. The HDTDR, in contrast, produces markedly crisper definition of structural edges, which allows geological contacts, faults, and lineament patterns to be recognized more distinctly (Salem et al., 2008; Arısoy & Dikmen, 2013). Although these methods are well-established in structural geology and mineral exploration, their application to fractured aquifer mapping in volcanic environments, particularly in Indonesia, remains sparse, thereby presenting a substantial research gap.

This study applies TDR and HDTDR filters to magnetic anomaly data transformed via Reduction to the Equator (RTE) to identify structural lineaments in Sumbang Village, Sumbang District, Banyumas Regency. The resulting structural framework is utilized to estimate the distribution of prospective fractured aquifer zones suitable for groundwater resource development (Demirel et al., 2018). The lineaments extracted from the data are interpreted as preferential conduits for subsurface groundwater flow within the study area, while zones characterized by dense fracture intersections are regarded as promising targets for high-yield groundwater production. The principal novelty of this study resides in the combined use of RTE, TDR, and HDTDR filtering to delineate structurally controlled fractured aquifers within the geologically complex volcanic terrain on the southern flanks of Slamet Volcano. Ultimately, the results are anticipated to furnish a robust and highly reliable foundation for optimizing borehole siting, strengthening regional groundwater exploration, and supporting the long-term sustainable management of the Purwokerto–Purbalingga Groundwater Basin.

II. METHOD

A. Location and Time

Magnetic data were acquired across Sumbang Village and its vicinity, administratively situated within the Sumbang District, Banyumas Regency, Central Java Province (Figure 1). Subsequent data processing, modeling, and comprehensive interpretation were conducted at the Geophysics Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University, Purwokerto. The entire research framework spanned a 16-month period, from March 2025 to June 2026

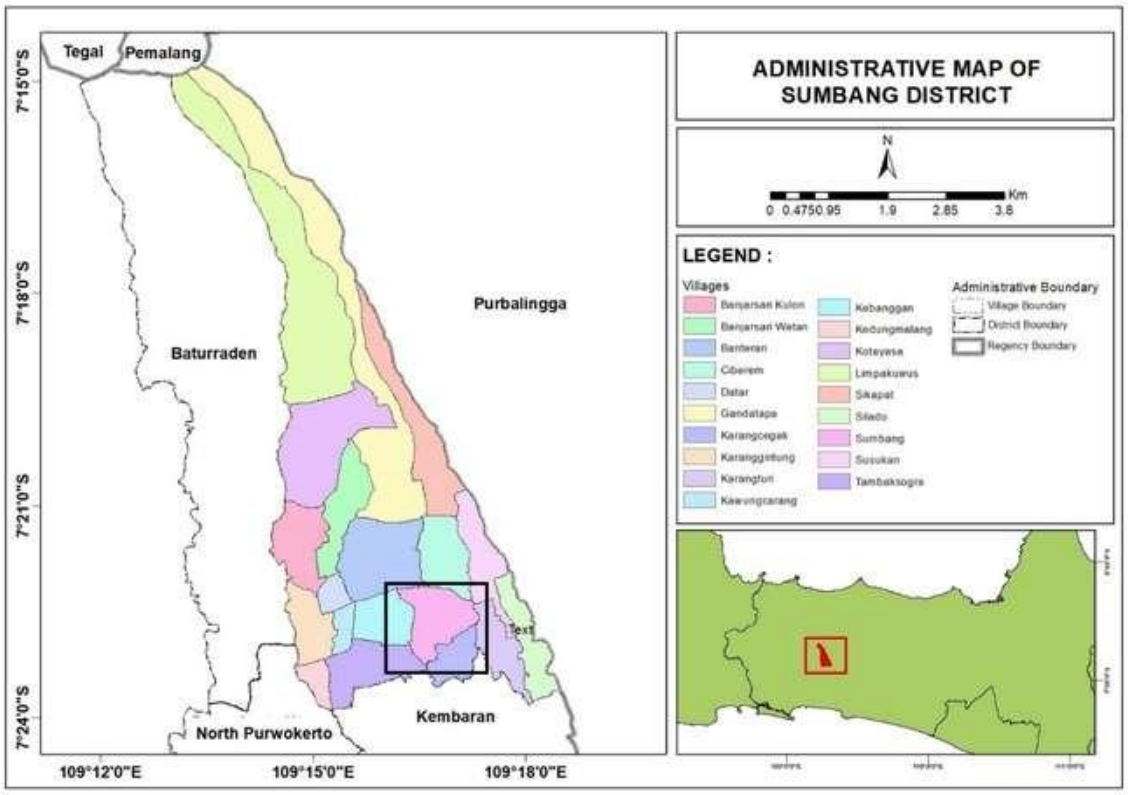

Figure 1. Administrative map of the research area; Sumbang District, Banyumas Regency.

B. Research Equipment

The main equipment used to measure in situ total magnetic field intensity in this study was a GSM-19T Proton Precession Magnetometer (PPM) with an absolute accuracy of 0.05 nT. Ancillary equipment comprised a Global Positioning System (GPS) receiver for the precise spatial positioning of survey stations, a magnetic compass to align the PPM sensor with magnetic north during data acquisition, and a portable computer for field data processing. Google Earth was used to support pre-survey planning and the design of the survey grid. Furthermore, specialized software platforms were employed for subsequent data processing and analysis: QGIS and Oasis Montaj were utilized to construct the study area and magnetic anomaly contour maps, while ZondGM2D was used for 2D modeling of subsurface anomalous sources. These datasets were integrated with digital geological maps to constrain and guide the data interpretation and analysis process.

C. Research Procedure

Field operations began with magnetic measurements at 256 pre-selected survey stations, whose positions were defined in advance using Google Earth. The stations were arranged on a fairly regular grid, with an interstation spacing of roughly 100 m, so as to provide even

spatial coverage of the study area. The raw total magnetic intensity data were subsequently subjected to diurnal and International Geomagnetic Reference Field (IGRF) corrections. The diurnal correction was applied to mitigate the influence of time-varying external magnetic field variations induced by solar activity during the survey period, whereas the IGRF correction eliminated the Earth's core-derived main magnetic field component. The fully corrected dataset is hereinafter referred to as the total magnetic anomaly data (Sehah et al., 2020).

Because these total magnetic anomaly data were initially distributed across an uneven surface (topographical surface), mathematically expressed as $\underline{U}(x,y,z)$, they required reduction to a horizontal surface (mean topographic elevation) to facilitate subsequent processing stages. This reduction process yields a transformed total magnetic anomaly dataset projected onto to a level at a constant elevation of z_0, denoted mathematically as $U(x,y,z_0)$. The reduction to a horizontal surface was executed utilizing a Taylor series expansion approach, as formulated in Equation (1) (Blakely, 1995).

$$U(x,y,z_0)^{[i+1]} = U(x,y,z) - \sum_{n=0}^{\infty} \frac{(z-z_0)^n}{n!} \frac{\partial^n}{\partial z^n} U(x,y,z_0)^{[i]} \quad (1)$$

Equation (1) has been developed in the form of an iteration, where the desired value of $U(x,y,z_0)$ can be estimated through a good approach, i.e. the value of $U(x,y,z_0)$ obtained from the i-th iteration is reused to obtain the value of $U(x,y,z_0)$ at the $(i+1)$ iteration. The iteration process is done adequately, so that the obtained $U(x,y,z_0)$ values show convergence (Blakely, 1995).

In practice, measured magnetic anomalies are commonly overprinted by broad, long-wavelength contributions from deep-seated subsurface sources, which are conventionally referred to as regional anomalies and must be accounted for before interpreting shallower features. Consequently, isolating this regional trend is imperative to extract the local (residual) anomaly data that directly correlate with the shallow targets of investigation. Upward continuation is a widely adopted potential field transformation technique that projects magnetic field data from an initial horizontal surface to another surface with a higher elevation (Blakely, 1995). The optimal continuation height is determined iteratively until the long-wavelength anomalous contour patterns become stable and exhibit minimal high-frequency variations. This attenuation process effectively captures the regional component, which is subsequently subtracted from the total field data to isolate the localized anomalous features. The upward elevation is carried out using Equation (2).

$$U(x,y,z_0-\Delta z) = \frac{\Delta z}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{U(x',y',z_0)}{\sqrt{[(x-x')^2+(y-y')^2+\Delta z^2]^3}} dx'dy' \quad (2)$$

The regional magnetic anomaly data obtained is then used to correct the total magnetic anomaly data that has been distributed on a horizontal surface. This process generates local magnetic anomaly data that is also distributed in the horizontal surface. The local magnetic anomaly is assumed to be clean of the influence of regional anomalies and other magnetic components that are not the target of the study, making them more representative for use in the modeling and interpretation of subsurface structures (Sehah et al., 2020).

The inherent dipolar nature of local magnetic anomalies frequently yields highly complex and asymmetrical contour patterns, thereby complicating structural and geological interpretations, particularly in low-latitude magnetic environments. To suppress these dipolar distortions and enhance the spatial resolution of anomalous features, advanced data transformation techniques are required. Among these, Reduction to the Equator (RTE) is a widely adopted potential-field transformation method that shifts the magnetic field response

to simulate conditions under a completely horizontal ambient magnetic field at the magnetic equator (Aina, 1986). The differential relationship on the RTE filter can be expressed as Equation (3).

$$\partial^2 \Delta T_e / \partial_\lambda \, \partial_v = \partial^2 \Delta T_{\lambda v} / \partial x^2 \quad (3)$$

with ΔTe is an RTE magnetic anomaly.

Although the local magnetic anomaly contour maps generated via Reduction to the Equator (RTE) offer an improved spatial correlation with subsurface anomalous sources, structural boundaries and discontinuity zones must be further enhanced through advanced boundary-detection techniques. To achieve this, gradient analysis was executed utilizing the Horizontal Derivative (HDR) and Vertical Derivative (VDR) operators, which are highly effective at amplifying anomalous responses associated with lateral and vertical susceptibility contrasts. This derivative-based approach serves to delineate lithological contacts, faults, fractures, and other structural lineaments that potentially govern subsurface groundwater circulation systems.

Subsequently, Tilt Derivative (TDR) and Horizontal Derivative of Tilt Derivative (HDTDR) filters were applied to the RTE-transformed local magnetic anomaly dataset. The TDR filter normalizes the ratio of the vertical gradient to the total horizontal gradient, thereby mitigating depth-dependent amplitude decay and allowing structural boundaries from both shallow and relatively deep-seated sources to be identified with equal clarity. Concurrently, the HDTDR filter represents a higher-order derivative expansion that significantly enhances edge-response sharpness, effectively resolving localized geological structures characterized by high magnetic contrasts. The integration of TDR and HDTDR filtering, facilitates the delineation of subsurface structural frameworks with a higher degree of spatial precision than that afforded by conventional, isolated derivative operators. The mathematical formulation of the TDR function for magnetic anomaly data is expressed in Equation (4) (Blakely, 1995).

$$TDR = Arctan \frac{VD}{HD} \quad (4)$$

Meanwhile, the HDTDR value can be calculated using Equation (5) (Blakely, 1995).

$$HDTDR = \sqrt{\left(\frac{\partial TDR}{\partial x}\right)^2 + \left(\frac{\partial TDR}{\partial y}\right)^2} \quad (5)$$

III. RESULTS AND DISCUSSIONS

A. Research Result

Field data acquisition yielded total magnetic intensity (TMI) data integrated with spatial coordinates and elevation profiles across 256 measurement stations, featuring a nominal spatial resolution of approximately 100 m. Following the application of diurnal and International Geomagnetic Reference Field (IGRF) corrections, the total magnetic anomaly values were found to range from -2271.95 – 2337.87 nT, while the topographic elevation of the study area varied between 129.05 – 188.26 m. Because the initial anomaly data were distributed across an uneven topographical surface, they were mathematically reduced to a horizontal datum corresponding to the mean topographic elevation of 104.54 m using Equation (1) (Blakely, 1995). Subsequently, regional-residual anomaly data separation was executed using the upward continuation method projected to an altitude of 850 m, isolating a regional anomaly component ranging from 800.52–836.52 nT. Subtraction of this regional trend yielded the local (residual) magnetic anomaly dataset, which ranged from -3089.49 – 1502.98 nT. This local anomaly dataset serves as the foundational framework for subsequent subsurface structural analysis and interpretation. Furthermore, the resulting local magnetic anomaly contour map of Sumbang Village, Sumbang District is illustrated in Figure 2.

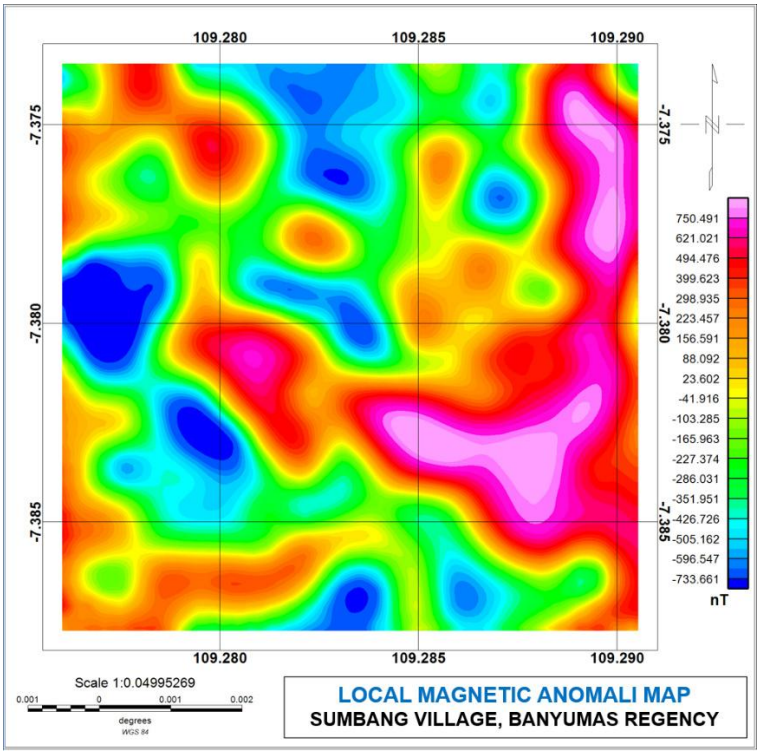

Figure 2. Local magnetic anomaly map of Sumbang Village, Sumbang District, Banyumas Regency, Indonesia, after regional–residual separation. Anomaly values range from approximately −3089.49 to 1502.98 nT; the color scale does not display the extreme minimum and maximum values.

The local magnetic anomaly map initially displayed complex patterns due to the dipolar characteristics of the Earth's magnetic field. This dipolar effect obscured the boundaries of subsurface anomalous sources, making it difficult to identify potential water-bearing fracture zones within the volcanic rock complex. To mitigate the asymmetric effects induced by the local magnetic inclination and declination, thereby sharpening the horizontal positioning of the anomalous sources, a Reduction to The Equator (RTE) transformation was applied (Nnaemeka et al., 2023). The RTE transformation generated a modified magnetic anomaly ranging from -2056.54 – 2264.55 nT as mapped in Figure 3. This transformed configuration displays significantly more pronounced and well-defined anomalous trends compared to the untransformed dataset. Specifically, the RTE anomaly contour map shows clear lithological variations, a dominant northwest–southeast (NW–SE) geological structural lineament trend, and distinct low-magnetic anomaly zones that are interpreted to be associated with the development of fractured aquifer systems in the study area.

The highest positive magnetic anomalies are spatially concentrated in the northeastern corner and within an elongated NW–SE-trending zone across the central-southern sector, potentially indicating the occurrence of volcanic rocks with relatively high magnetic susceptibility. Conversely, prominent negative anomalies are distributed along the western margin, central-northern sector, and southwestern part of the study area, accompanied by several isolated magnetic lows in the south-central region. These negative anomalies frequently occur near steep magnetic gradients separating adjacent positive and negative zones, potentially indicating subsurface structural discontinuities. Such features may reflect fractured and weathered rock formations characterized by reduced magnetic susceptibility, which could facilitate groundwater circulation through secondary permeability networks. Nevertheless, magnetic anomaly patterns alone cannot unequivocally establish the presence of groundwater-bearing fractures. Therefore, the initial geological interpretations are further

investigated using the Tilt Derivative (TDR) and Hyperbolic Tilt Derivative (HDTDR) filters to improve the objective identification and delineation of subsurface structural lineaments.

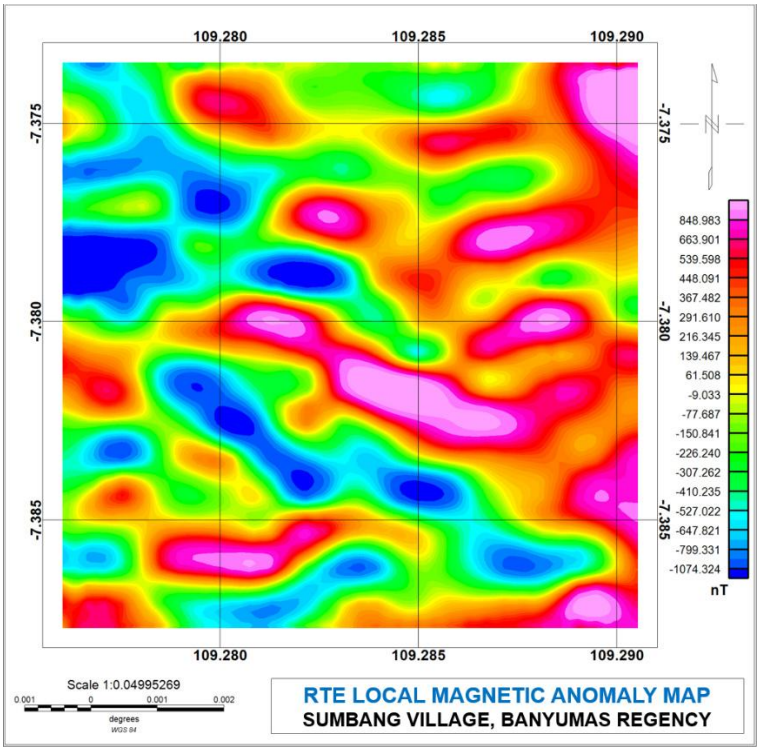

Figure 3. Local magnetic anomaly map of Sumbang Village, Sumbang District, Banyumas Regency, after Reduction to the Equator (RTE). Anomaly values range from −2056.54 to 2264.55 nT; the color scale does not display the extreme minimum and maximum values.

Following the Reduction to the Equator (RTE) transformation, the application of Horizontal Derivative (HDR) and Vertical Derivative (VDR) filters to the local magnetic anomaly data significantly enhanced the structural resolution of subsurface geological features within the study area (Akin et al., 2011; Núñez-Demarco et al., 2023). The HDR filter yielded values ranging from 0.0276 – 27.3818 nT/m, effectively delineating lithological contact boundaries characterized by maximum horizontal gradient zones. Prominent ridge patterns observed on the HDR map are interpreted as fracture networks, localized faults, and lithological boundaries that govern the local hydrogeological system. Concurrently, the VDR analysis produced values spanning from -37.677 – 35.180 nT/m, displaying closely juxtaposed positive and negative anomalies that form steep vertical gradients. These diagnostic anomalous signatures indicate robust magnetic susceptibility contrasts induced by intact lithological contacts, fault planes, and highly fractured zones.

Both HDR and VDR maps consistently reveal a predominance of structural lineaments which are oriented northwest–southeast (NW–SE), accompanied by secondary trends in a northeast–southwest (NE–SW) direction. This spatial pattern indicates that regional geological structures strongly influence the distribution of local magnetic anomalies. Furthermore, the maximum gradient zones identified on both derivative maps are interpreted as potential fracture networks and faults. These structural discontinuities may act as preferential pathways for subsurface groundwater flow and potentially support groundwater accumulation within the study area. Consequently, the derived structural framework provides crucial baseline information to support targeted hydrogeological mapping and groundwater exploration within the study area. The corresponding HDR and VDR contour maps are presented in Figures 3 and 4, respectively.

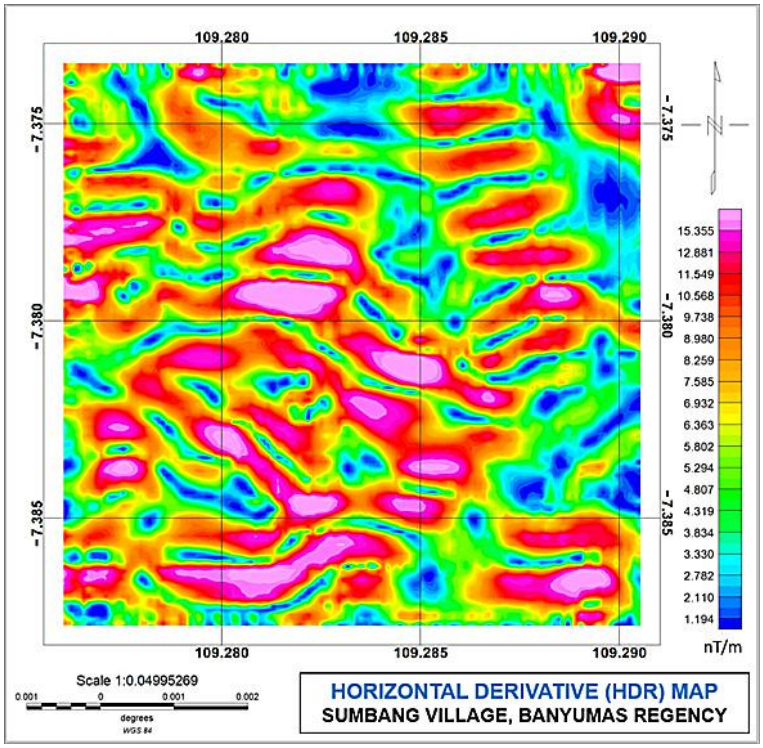

Figure 3. Horizontal derivative (HDR) map of the RTE-transformed local magnetic anomaly of Sumbang Village, Sumbang District, Banyumas Regency. High HDR values (in nT/m) delineate the edges of magnetic sources.

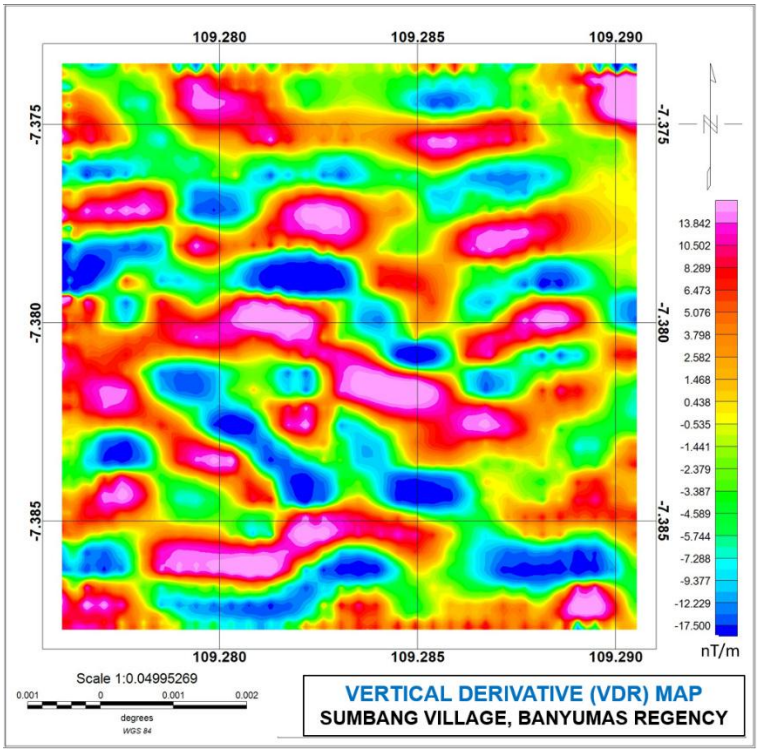

Figure 4. Vertical derivative (VDR) map of the RTE-transformed local magnetic anomaly of Sumbang Village, Sumbang District, Banyumas Regency. Positive and negative VDR values (in nT/m) highlight the shallow magnetic source boundaries.

To further delineate geological structural boundaries within the RTE local magnetic anomaly dataset, the Tilt Derivative (TDR) and the Horizontal Derivative of the Tilt Derivative (HDTDR) filters were applied. As defined in Equation (4), the TDR is computed as the arctangent of the ratio between the VDR and the total HDR grids. Because this ratio is amplitude-independent, the filter effectively balances the responses of shallow and deep sources and of weakly and strongly magnetized bodies, thereby enhancing subtle features that are commonly masked in the original anomaly map (Salem et al., 2008). The TDR is inherently bounded between $-\pi/2$ and $\pi/2$ rad, irrespective of the amplitude of the input anomaly. Positive values are typically observed over magnetic sources, negative values over the adjacent non-magnetic background, and the zero contour approximates the horizontal location of source edges, particularly for near-vertical contacts. Structural boundaries such as faults, fractures, and lithological contacts are therefore identified along transition zones of near-zero TDR values. In this study, TDR values range from −1.5626 to 1.5698 rad, approaching the theoretical limits of the filter and indicating effective amplitude balancing across the dataset. The resulting map reveals prominent structural lineaments that reflect tectonic control on the spatial distribution of the volcanic rocks, thereby providing a structural framework for the subsequent HDTDR analysis.

Subsequently, the HDTDR filter yielded a markedly sharper and more spatially localized response along structural boundaries, with values ranging from −0.0000387 to 0.0891472 rad/m. Because HDTDR maxima are centered over source edges and are largely insensitive to differences in source depth and magnetization amplitude, the filter enables lineament patterns and fracture intersections to be resolved with superior spatial precision (Arısoy & Dikmen, 2013). The dominant, intersecting lineaments on the HDTDR map indicate a structurally complex framework, attributed mainly to localized tectonic deformation and the volcanic history of Slamet Volcano, which together control fracture development and, hence, the potential occurrence of fractured aquifers. The TDR and HDTDR maps derived from the RTE local magnetic anomalies are shown in Figures 5 and 6, respectively, with the HDTDR contour map delineating structural trends more distinctly. Zones of high lineament density or multiple intersections generally exhibit enhanced secondary permeability, as interconnected fractures and joints facilitate groundwater storage and circulation, making them promising targets for fractured aquifer development (Fernandes et al., 2023). Nevertheless, such zones should be regarded as prospective rather than proven productive aquifers.

Fractured aquifers are characterized by groundwater occurrence and flow that are strongly influenced by the geometry, density, aperture, orientation, and connectivity of fractures rather than by the primary porosity of the intact rock matrix. In volcanic terrains, fractures, joints, and other structural discontinuities can create secondary porosity and preferential flow pathways, thereby increasing the capacity of otherwise compact volcanic rocks to transmit groundwater (Singhal & Gupta, 2010; Fernandes et al., 2023). Fracture intersections are important because connected structural discontinuities can create continuous hydraulic pathways that facilitate groundwater flow through the rock mass. However, high fracture or lineament density does not always correspond to a productive aquifer, as groundwater flow is also influenced by fracture aperture, connectivity, fracture infilling, weathering conditions, and the overall hydrogeological setting (Fernandes et al., 2023). Therefore, the dense and intersecting lineament patterns identified through the TDR and HDTDR analyses can be considered important structural indicators of prospective fractured aquifer zones. The geological structural features may enhance fracture connectivity and provide potential pathways for groundwater circulation; however, they should not be regarded as direct evidence of groundwater occurrence or aquifer productivity without further hydrogeological validation.

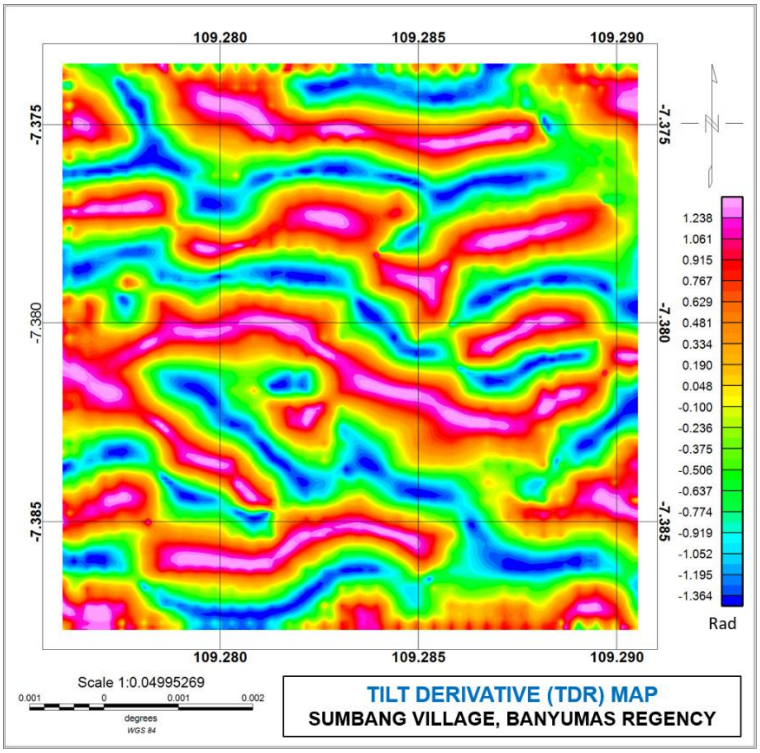

Figure 5. Tilt derivative (TDR) map derived from the RTE-transformed local magnetic anomaly of Sumbang Village, Sumbang District, Banyumas Regency. TDR values range from −1.5626 to 1.5698 rad; the color bar shows the principal contour intervals only.

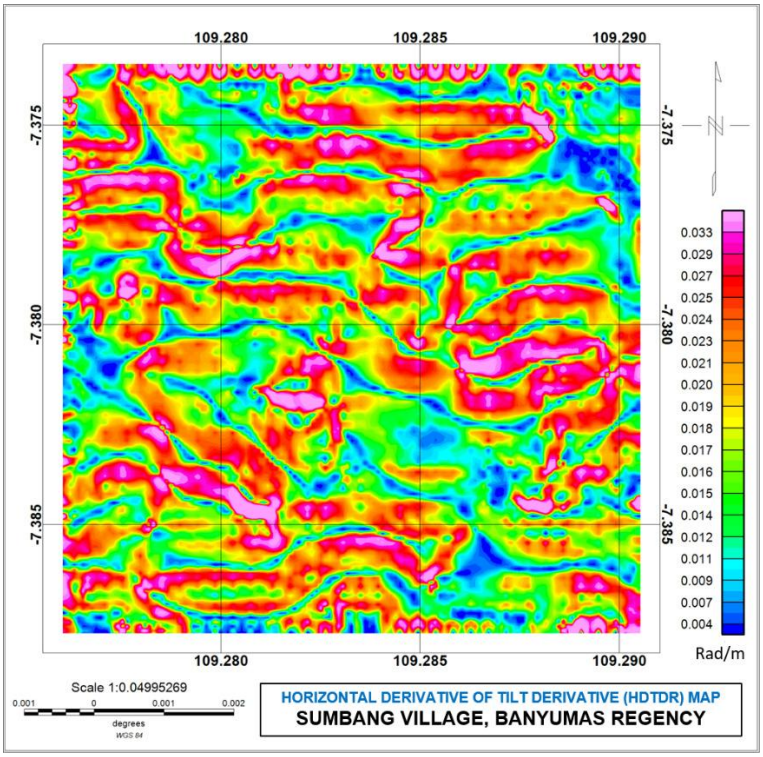

Figure 6. Horizontal derivative of tilt derivative (HDTDR) map derived from the RTE-transformed local magnetic anomaly of Sumbang Village, Sumbang District, Banyumas Regency. HDTDR values range from −0.0000387 to 0.0891472 rad/m; the color bar shows the principal contour intervals only.

B. Discussion

The lineament density map, generated from the structural lineaments interpreted from the Tilt Derivative (TDR) and Horizontal Derivative of Tilt Derivative (HDTDR) maps of the RTE-transformed local magnetic anomaly, is presented in Figure 5. The extracted lineaments display a complex and spatially variable structural pattern across the study area. On the basis of the calculated density values, the area was classified into low (0–0.02706 m/m^2), moderate (0.02706–0.05745 m/m^2), and high (0.05745–0.12108 m/m^2) lineament density zones. High-density zones occur locally in several parts of the area, particularly where lineaments are closely spaced or intersect, whereas low-density zones are characterized by sparse structural features. This spatial variation reflects the heterogeneous distribution and intensity of fractures and other structural discontinuities within the subsurface volcanic formations, with higher densities generally indicating more intensively fractured rock masses. Such a pattern is consistent with the geological setting of Sumbang Village, which is underlain by Quaternary volcanic products of Slamet Volcano, including lava flows, volcanic breccias, tuffs, and lahar deposits. These materials may be fractured by tectonic stresses, volcanic activity, and the cooling and contraction of lava bodies, producing fractures and cooling joints that generate secondary porosity and enhance structural connectivity in otherwise relatively compact rocks. Variations in lineament density may therefore serve as an important indicator of the spatial distribution of fracture-controlled pathways that potentially influence groundwater occurrence and circulation within the volcanic aquifer system (Djuri et al., 1996; An Nisaa & Putra, 2024).

From a hydrogeological perspective, the variation in lineament density offers further insight into the potential distribution of fractured aquifer zones. Areas of moderate to high lineament density are regarded as more favorable for fractured aquifer development because closely spaced and interconnected fractures can increase secondary porosity and permeability, thereby promoting groundwater infiltration, storage, and flow within volcanic rocks (An Nisaa & Putra, 2024). Where fractures intersect, the resulting network commonly provides multiple flow paths and improves hydraulic connectivity, whereas isolated or sparsely distributed fractures tend to restrict groundwater movement. Consequently, areas where lineament sets of different orientations converge, such as the NW–SE and NE–SW sets identified in this study, are more likely to host interconnected fracture networks. In particular, the localized high-density zones shown in red in Figure 5 may indicate greater structural complexity and potentially higher fracture connectivity, and they are therefore considered priority targets for further fractured aquifer investigation. This interpretation is supported by the occurrence of springs in Sumbang District and along the southern slopes of Slamet Volcano, which suggests that groundwater circulation in the area is partly controlled by fractures and other structural discontinuities within the volcanic deposits. Springs commonly emerge where permeable fracture zones intersect the topographic surface or where permeability contrasts impede downward flow, so their distribution can reflect the underlying structural framework.

Lineament density alone, however, is insufficient to establish groundwater occurrence, fracture connectivity, or aquifer productivity. Magnetic lineaments reflect contrasts in magnetization, and not all of them necessarily correspond to open, hydraulically conductive fractures, since fracture aperture, infilling by secondary minerals, weathering, and recharge conditions also govern groundwater flow. In volcanic settings, lithological heterogeneity and variable weathering profiles can further complicate the relationship between structural density and hydraulic conductivity. Therefore, the identified moderate- to high-density zones should be regarded as prospective fractured aquifer targets that require further validation using hydrogeological observations and complementary subsurface data, such as well inventories, spring discharge measurements, and electrical resistivity surveys. Integrating

these datasets would allow the structural interpretation to be calibrated against actual hydraulic behavior and would reduce the uncertainty associated with indirect geophysical inference. This integrated approach is particularly important for groundwater exploration, where drilling decisions based solely on indirect structural indicators carry a considerable risk of unproductive wells. Accordingly, the lineament density map provides a useful spatial framework for prioritizing subsequent geophysical investigations and for identifying potential groundwater exploration targets within the volcanic rock complex of the study area (Kassa, 2024).

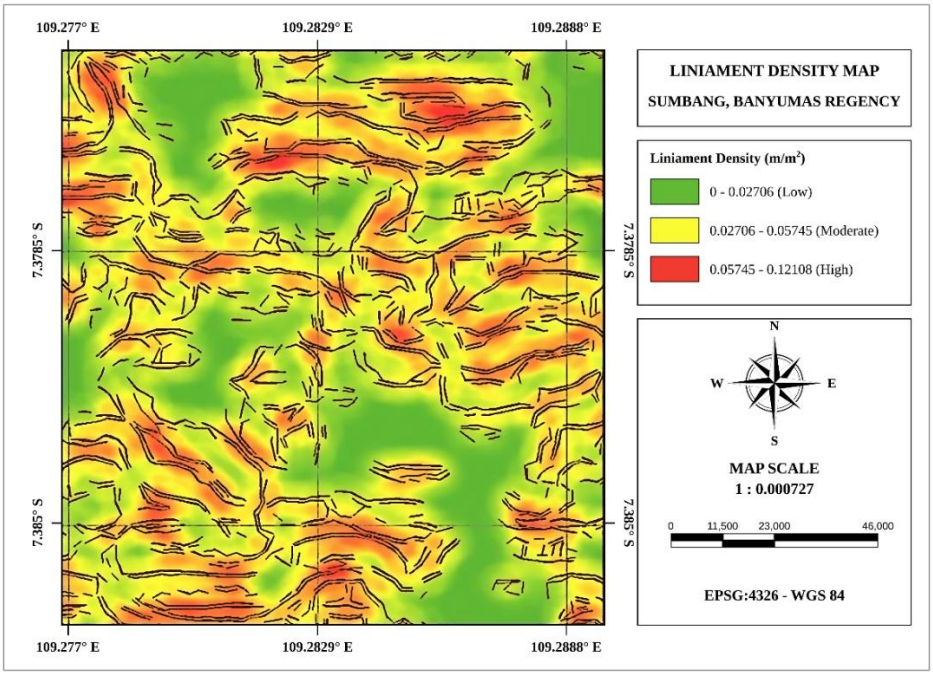

Figure 7. Lineament density map of Sumbang Village, Sumbang District, Banyumas Regency, derived from structural lineaments interpreted from the TDR and HDTDR maps of the RTE-transformed local magnetic anomaly. Black lines represent the interpreted lineaments; density is classified as low, moderate, and high.

The structural pattern inferred from the TDR and HDTDR analyses can be further evaluated against the regional geological setting shown in Figure 8. The extracted lineaments display a dominant northwest–southeast (NW–SE) orientation with a secondary northeast–southwest (NE–SW) set, producing several zones of structural intersection. According to the regional geological map, the study area is underlain by lahar deposits of Slamet Volcano (Qls), lava flows of Slamet Volcano (Qvls), and undifferentiated volcanic rocks (Qvs). The spatial correspondence between these lineaments and the distribution of Quaternary volcanic units provides an important geological context for interpreting the prospective fractured aquifer zones identified from the lineament density analysis. Within these formations, fractures, joints, and localized weathering may enhance secondary porosity and permeability, particularly in compact volcanic rocks of low primary porosity (Djuri et al., 1996; An Nisaa & Putra, 2024). In addition, the contrasting lithological characteristics of lava flows and lahar deposits may influence the continuity of fracture networks and, consequently, the pathways of groundwater flow. Lava flows commonly develop cooling joints and tectonic fractures, whereas lahar deposits, being heterogeneous mixtures of poorly sorted volcanic fragments, may exhibit variable permeability (Fisher & Schmincke, 1984). Interpreting the lineaments within this lithological framework therefore helps to constrain where structurally controlled groundwater circulation is most likely to occur.

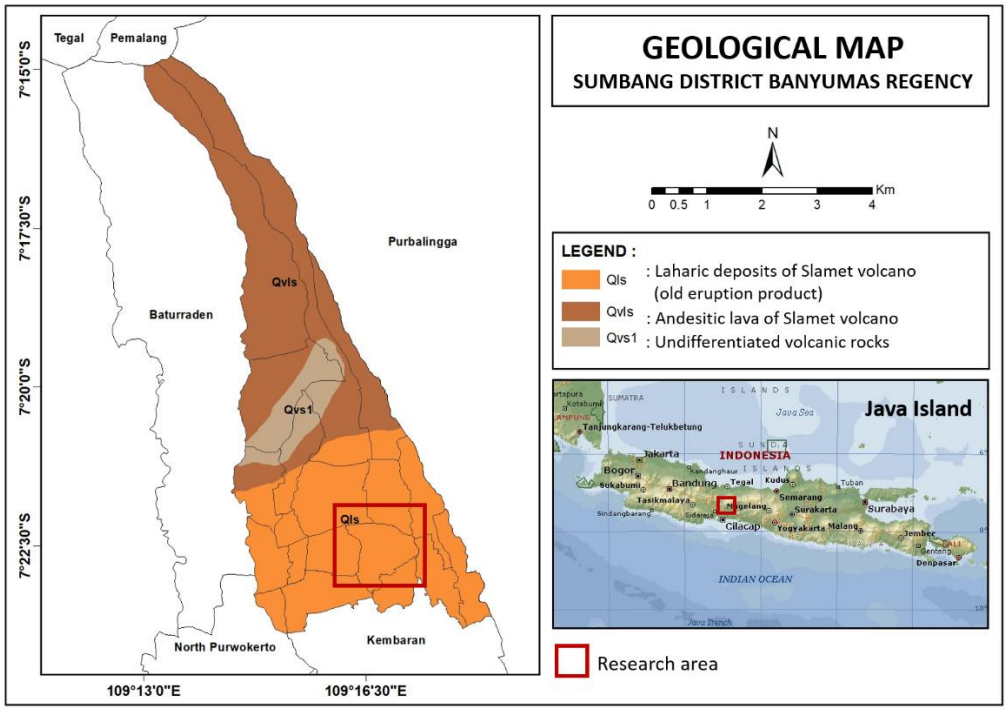

Figure 8. Geological map of Sumbang District, Banyumas Regency, showing the distribution of laharic deposits (Qls), andesitic lava (Qvls), and undifferentiated volcanic rocks (Qvs1) of Slamet Volcano. The red box indicates the research area and the inset shows its location in Central Java (modified from the Geological Map of the Purwokerto and Tegal Sheet, Djuri et al., 1996).

Synthesizing magnetic lineament analysis with regional geological and hydrogeological information yields an integrated view of the factors governing groundwater occurrence in the study area. The results suggest that groundwater distribution reflects the combined influence of the lithological properties of the volcanic deposits, which control primary porosity and permeability, and the presence of structural discontinuities that enhance secondary permeability and facilitate flow along fractured zones (Olaka et al., 2022). This interpretation is consistent with hydrogeological observations in Sumbang District, where groundwater occurs within an unconfined aquifer system associated with lahar deposits overlying volcanic breccias (An Nisaa & Putra, 2024). In this volcanic setting, fractures and their intersections may enhance secondary porosity and hydraulic connectivity, providing preferential pathways for groundwater infiltration and subsurface flow through the Quaternary volcanic sequence. Accordingly, moderate- to high-density lineament zones identified from the magnetic data may indicate favorable areas for fractured aquifer occurrence, particularly where they are associated with geological units that facilitate groundwater circulation. However, these zones should be considered potential targets rather than direct indicators of productive aquifers, since groundwater occurrence is also controlled by fracture connectivity, lithology, weathering, and recharge conditions. Therefore, integrating magnetic lineament density with geological and hydrogeological information provides a reliable basis for prioritizing potential fractured aquifer zones for further hydrogeophysical investigation and groundwater exploration.

The identified structural lineaments suggest that meteoric water infiltrating the recharge zones on the slopes of Slamet Volcano may flow toward lower-elevation areas through fractures, joints, and weathered zones within lahar deposits, lava flows, and other volcanic formations. The orientation, density, and connectivity of these structural features may form secondary permeability pathways that influence groundwater circulation. In particular, lineament intersection zones may enhance groundwater movement through interconnected

fracture networks, potentially directing subsurface flow toward discharge areas such as natural springs and downgradient unconfined aquifers, as conceptually shown in Figure 9 (Ringel et al., 2024). The spatial association between the inferred groundwater pathways and moderate- to high-density lineament zones suggests that areas characterized by closely spaced and intersecting lineaments may have greater potential for secondary porosity, permeability, and hydraulic connectivity. Consequently, these structurally favorable zones can be prioritized for further hydrogeophysical investigation and field validation to evaluate their groundwater potential and support sustainable groundwater resource development for domestic and agricultural needs in the study area.

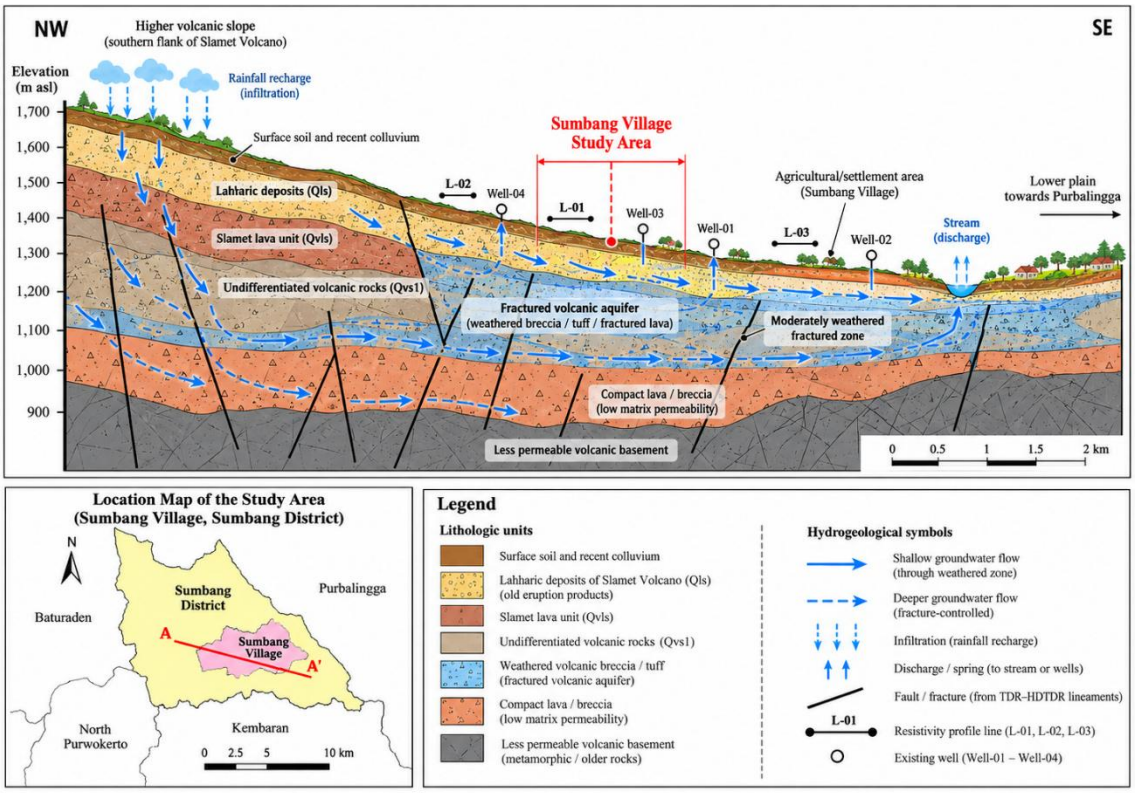

Figure 9. Conceptual NW-SE cross-section (A-A') of the Sumbang Village study area, illustrating inferred groundwater recharge on the southern slope of Slamet Volcano and subsurface flow through weathered and fractured volcanic units toward possible discharge zones. Faults and fracture zones are inferred from magnetic lineaments.

The conceptual model in Figure 9 integrates these inferences into a schematic hydrogeological framework along a NW-SE cross-section across the study area. Rainfall infiltrating the higher volcanic slope is shown percolating through the surface soil and colluvium into the underlying lahar deposits (Qls), lava flows (Qvls), and undifferentiated volcanic rocks (Qvs1), where weathering and fracturing create a laterally continuous, fractured volcanic aquifer. Within this zone, groundwater is inferred to move along two complementary pathways: a shallow flow through the weathered mantle and a deeper, fracture-controlled flow guided by faults and fracture zones interpreted from the magnetic lineaments. The underlying compact lava and breccia, characterized by low matrix permeability, probably act as a semi-confining boundary that restricts downward leakage and promotes lateral flow, a configuration commonly recognized in conceptual models of volcanic aquifers (Join et al., 2005). Because permeability in such rocks is largely governed by the geometry and connectivity of discontinuities (Singhal & Gupta, 2010), lineament intersection zones are likely to concentrate flow toward the lower plain, where groundwater

may emerge as discharge to streams or be tapped by wells. Nevertheless, as the section is schematic and based on inferred structures, it should be treated as a working hypothesis to be tested through hydrogeophysical surveys and borehole data.

IV. CONCLUSION

This study demonstrates that applying the Tilt Derivative (TDR) and Horizontal Derivative of Tilt Derivative (HDTDR) filters to RTE-transformed local magnetic anomaly data is effective for delineating subsurface geological structures and identifying prospective fractured aquifer zones in Sumbang Village, Sumbang District, Banyumas Regency, Central Java, Indonesia. Both filters enhanced the boundaries of magnetic anomaly sources, with TDR values ranging from −1.5626 to 1.5698 rad and HDTDR values from −0.0000387 to 0.0891472 rad/m; HDTDR produced sharper and more localized responses along structural boundaries, thereby resolving lineament patterns and structural intersection zones more clearly. The study area is dominated by northwest–southeast (NW–SE) lineaments, with secondary northeast–southwest (NE–SW) trends, forming a dense, intersecting structural network within the Quaternary volcanic formations of Slamet Volcano, with lineament density ranging from 0 to 0.12108 m/m². Zones of moderate to high lineament density, particularly where structures are closely spaced and intersecting, are interpreted as structurally favorable for fractured aquifer development, with groundwater inferred to migrate from recharge areas on the slopes of Slamet Volcano toward lower elevations through fractures, joints, and weathered volcanic rocks. The delineated zones merit prioritization in further hydrogeophysical and groundwater exploration efforts. However, they denote prospective fractured aquifer settings only and should not be taken as direct evidence of aquifer productivity; confirmation through hydrogeological observations and integration with complementary subsurface datasets is required.

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