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Subsurface Modeling of High Sulfidation Epithermal Deposit Systems Based on Geomagnetic Data in the Tulungagung Area, East Java

Pemodelan Bawah Permukaan Sistem Endapan Epitermal Sulfidasi Tinggi Berdasarkan Data Geomagnetik di Wilayah Tulungagung, Jawa Timur

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Abstract- The presence of metallic minerals in vuggy silica in Tulungagung, East Java, is characteristic of the high sulfidation epithermal (HSE) deposit system. This research quantitatively analyzes the distribution and geometry of metal mineral deposits in the research area using geomagnetic methods. The research analyzes the alteration and mineralization zones of the HSE deposits and builds a subsurface model. The geomagnetic method aims to determine subsurface conditions based on the magnetic properties of rocks. This research was conducted as many as 417 points with a distance between points of 50 - 700 meters, randomly from a lot area of 95 km^2. The results of the reduce-to-pole (RTP) map analysis show that the alteration and mineralization zones of the HSE are seen in low magnetic anomaly values due to dominant alteration and the presence of complex faults, so that destructive magnetite occurs. The results of wave spectrum analysis obtained an estimated regional depth of ± 539 meters, which was used for subsurface modeling. The model shows the environment and geometry of the HSE deposits. The presence of alteration and mineralization in the study area is at low susceptibility values < 2 x 10-3 SI, controlled by faults and permeable lithologies. Dacite intrusions with high susceptibility values > 15 x 10-3 SI are interpreted as host rocks carrying mineralization in the study area.

Keywords: High Sulfidation Epithermal, Geomagnetic, Susceptibility, Alteration and Mineralization Zones, Subsurface Model

Abstrak- *Kehadiran mineral logam dalam silika vuggy di Tulungagung, Jawa Timur, merupakan karakteristik dari sistem endapan epitermal sulfidasi tinggi (HSE). Penelitian ini menganalisis secara kuantitatif distribusi dan geometri endapan mineral logam di area penelitian dengan menggunakan metode geomagnetik. Penelitian ini juga mencakup analisis zona alterasi dan mineralisasi pada endapan HSE serta pembangunan model bawah permukaan. Metode geomagnetik bertujuan untuk menentukan kondisi bawah permukaan berdasarkan sifat kemagnetan batuan. Penelitian dilakukan pada 417 titik pengukuran dengan jarak antartitik 50-700 meter secara acak pada area seluas 95 km^2. Hasil analisis peta reduce-to-pole (RTP) menunjukkan bahwa zona alterasi dan mineralisasi pada sistem HSE terlihat pada nilai anomali magnetik rendah, yang disebabkan oleh dominasi proses alterasi dan keberadaan sesar kompleks sehingga terjadi penghancuran magnetit (destructive magnetite). Hasil analisis spektrum gelombang menghasilkan estimasi kedalaman regional ± 539 meter, yang digunakan untuk pemodelan bawah permukaan. Model tersebut menunjukkan lingkungan dan geometri dari endapan HSE. Keberadaan zona alterasi dan mineralisasi di area penelitian berada pada nilai suseptibilitas rendah < 2 x 10^{-3} SI, yang dikontrol oleh sesar dan litologi yang permeabel. Intrusi dasit dengan nilai suseptibilitas tinggi > 15 x 10^{-3} SI diinterpretasikan sebagai batuan induk (host rock) yang membawa mineralisasi di area penelitian.*

Kata Kunci: *Epitermal Sulfidasi Tinggi, Geomagnetik, Suseptibilitas, Zona Alterasi dan Mineralisasi, Model Bawah Permukaan*

INTRODUCTION

The Tulungagung area has prospects for copper and gold (Cu-Au) mineralization, where the high sulfidation epithermal mineral deposit system in the area is characterized by mineralized vuggy quartz and the presence of kaolin minerals as alteration minerals. Metallic minerals found in the study area are dominated by sulfide mineral groups such as enargite, chalcocite, chalcopyrite, covellite, pyrite, and jarosite. Native gold is found associated with enargite (Ali, Winarno, and Jamalulail, 2020). The prospect locations are in the Secang and Pucanglaban Blocks, Tulungagung Regency, East Java Province

Genetically, the high sulfidation epithermal deposit system is formed from two phases: gas and liquid phases. The gas phase is the rise of magmatic vapors with low salinity through fractures and interacts with meteoric water. It then contacts the wall rocks to leach and produce a vuggy silica texture. As for the liquid phase, hydrothermal fluids carrying base metal elements rise to the epithermal environment through fractures or permeable lithologies to deposit the base metal (White and Hedenquist, 1995).

The geomagnetic method is one of the geophysical methods that can be used to delineate alteration zones, mineralization, and structures in the research area. The geomagnetic method is based on the measurement of variations in magnetic field intensity at the Earth's surface, caused by variations in the distribution of magnetized rocks below the Earth's surface (Santosa *et al.*, 2012). Based on the research of Irvine & Smith (1990) which covers several epithermal gold deposit areas such as Bimurra-Conway (northeast Queensland, Australia), Gold Ridge (Solomon Islands), and Ohui (Coromandel Peninsula, New Zealand), then research by Morrell *et al.* (2011) in the Waihi-Waitekauri area (New Zealand) and research by Murakami (2008) in the Kyushu area (Japan), that in general for mineralization zones in epithermal deposit systems are indicated by low magnetic anomaly patterns due to the alteration process that is dominant enough so that the anomaly patterns produced by metal mineralization are reduced. It is supported by the research of Yatini *et al.* (2021) in the Gunung Gupit area (Central Java), which classified magnetic field anomaly, such as a very low magnetic anomaly as a strong mineralization zone (silicified zone), low magnetic anomaly as an intermediate mineralization zone (argillic and advanced argillic mineralization), moderate magnetic anomaly as a weak mineralization zone (propylitic zone), and high magnetic anomaly as fresh igneous rock. The classification is influenced by the intensity of alteration and mineralization, as well as the magnetic mineral content in the study area.

The geomagnetic method is widely used as the preliminary exploration in determining the distribution of alteration zones, mineralization, and subsurface structures.

In this research, the geomagnetic method is used to explore the distribution and geometry of alteration and mineralization zones in Tulungagung, East Java, by building a subsurface model based on rock susceptibility parameters.

GEOLOGICAL SETTING

Regional Geology

The Tulungagung area is a zone of the Eastern Sunda Magmatic Arc, which is the Southern Mountains in the eastern part of Java, formed by the collision between the Indo-Australian Plate which subducts the Eurasian Plate (Van Bemmelen, 1949). These geological activities cause the presence of metallic minerals in the study area.

Based on the Geological Map of the Tulungagung Section (Samodera *et al.*, 1992) (Figure 1), the formations in the study area, from oldest to youngest, consist of Intrusive Rocks, the Mandalika Formation, the Campurdarat Formation, the Nampol Formation, the Wonosari Formation, and Alluvium.

The faults in the research area are dominated by horizontal faults compared to normal faults. The northeast-southwest oriented faults are sinistral strike-slip faults, such as the Puger Fault and the Kambengan Fault. While the northwest-southeast direction faults are dextral strike-slip faults, such as the Ngajaran Fault. Some faults that are thought to reflect the west-east or nearly north-south direction of the alignment are the normal faults (Samodera *et al.*, 1992).

Local Geology

Based on field observations, the lithology in the research area consists of andesite lava, andesite breccia, and polymictic breccia, which are included in the Mandalika Formation in the northwest area of the research area. The intrusive rock breaks through the Mandalika Formation is a dacite intrusion.

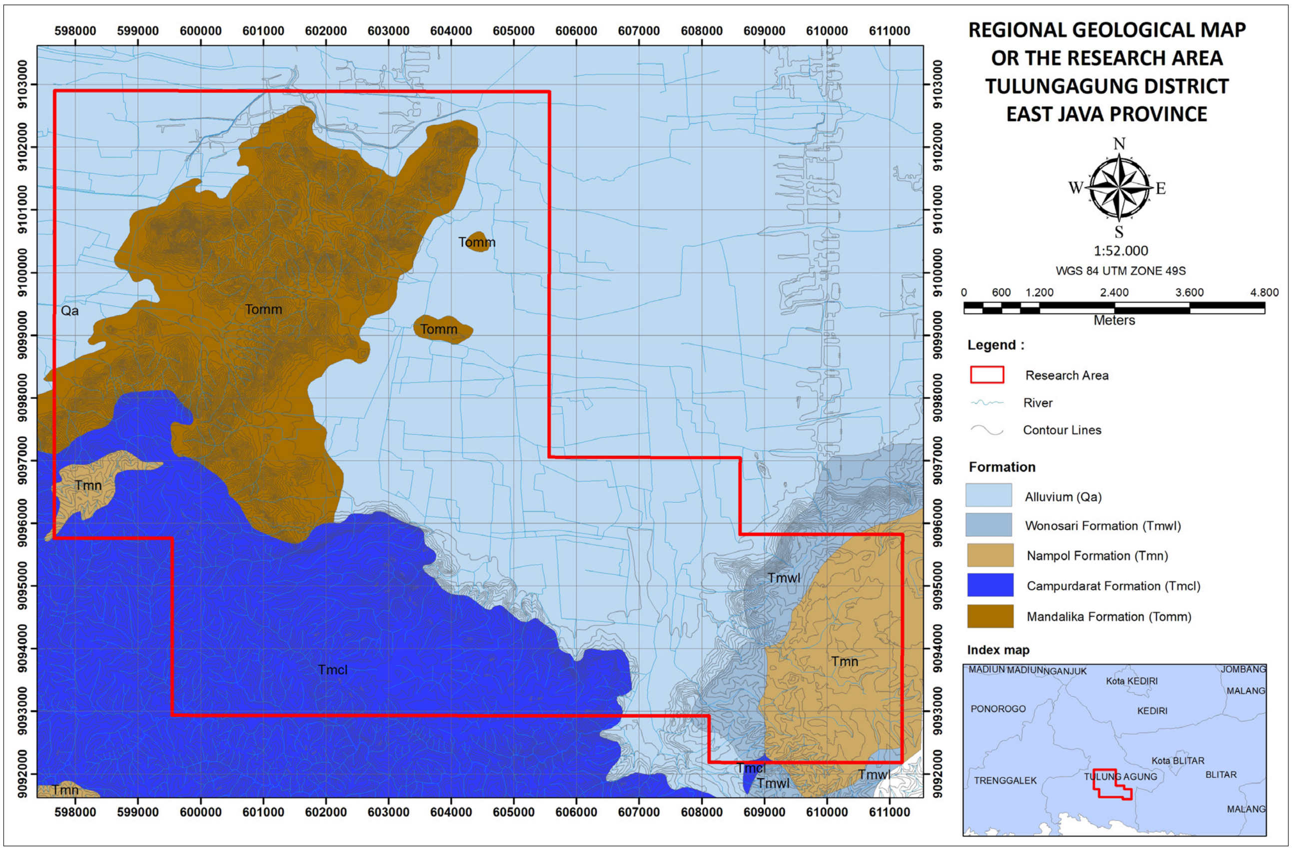

Figure 1. Regional Geological Map of the Research Area (map redrawn from Samodera *et al.*, 1992)

In the southeastern area, there is a quartz diorite unit. Then, there is limestone lithology included in the Campurdarat and Wonosari Formations, and the Alluvium unit deposited above it. The fault structure in the study area has a direction of southwest - northeast and northwest - southeast.

Mineralization in the study area is characterized by the presence of oxide veinlets, pyrite and chalcopyrite sulfide minerals, quartz veins, and magnetite-quartz veinlets. Oxide veinlets are found in andesitic rocks that are altered to clay - silica, with thickness of 0.1 - 0.5 cm, frequency of 15 - 20%, and density of 2 - 3% (Vanessa and Heditama, 2024).

The alteration in the study area consists of propylitic, argillic, advanced argillic, and silicified alterations. Propylitic alteration is characterized by the presence of chlorite and carbonate minerals. Argillic alteration is characterized by the presence of clay minerals such as kaolinite, illite, and smectite. Advanced argillic alteration is characterized by low pH minerals such as alunite, pyrophyllite, and diaspore, as well as the presence of other clay minerals, namely kaolinite and illite (Pratomo *et al.*, 2020). Furthermore, silicification alteration is characterized by vuggy-quartz textures filled with metal sulfide minerals such as chalcopyrite, pyrite, and covellite.

METHODS

The research area is located in Tulungagung Regency, East Java Province, covering an area of approximately 95 km^2. This research employed the geomagnetic method, with a total of 417 measurement points acquired using a random measurement approach. Data collection was conducted using three GSM-19T Proton Precision Magnetometers (Figure 2). Additionally, rock samples were collected to measure their susceptibility values using a Magnetic Susceptibility Meter.

Magnetic Data Correction

The geomagnetic measurement data were corrected to obtain the magnetic anomaly values in the research area. The data corrections performed include the diurnal variation correction to eliminate the influence of external magnetic fields and the IGRF (International Geomagnetic Reference Field) correction to remove the influence of the Earth's main magnetic field.

The equation is as follows:

$$H_{var} = \frac{(t_n - t_{aw})}{(t_{ak} - t_{aw})}(H_{ak} - H_{aw}) + H_{aw} \quad \text{...........(1)}$$

$$H\alpha = H_{rata-rata} - H_{var} - H_{IGRF} \quad \text{...........(2)}$$

Where:

t_n = time at point n
t_{aw} = the time before
t_{ak} = the time after
H_{ak} = magnetic field value at the point after
H_{aw} = magnetic field value at the point before
Hα = total magnetic field anomaly
$H_{rata-rata}$ = the average value of the magnetic field at each station
H_{var} = diurnal variation correction
H_{IGRF} = IGRF correction

Reduce-to-Pole (RTP) Filter

The Reduce-to-Pole (RTP) filter was processed using a gridding technique to generate the magnetic anomaly map. Since the initial results were influenced by dipolar effects, the RTP filter was applied to center the magnetic anomaly directly above the causative body. This filter converts magnetic anomaly values at a given inclination into magnetic anomaly values at 90° inclination and 0° declination (Blakely, 1995). In the study area, the inclination was -32.3114°, the declination was 0.7151°, and the amplitude correction value was 57.6885°.

The equation for converting magnetic anomalies to reduce to pole is as follows:

$$L(\theta) = \frac{1}{[\sin(I) + i\cos(I)\cos(D-\theta)]^2} \quad \text{...............(3)}$$

Where:

L = RTP Operator
I = Magnetic inclination
D = Magnetic declination
θ = Wave number direction

The RTP map results facilitated the identification of alteration zone distributions and lithological variations in the study area.

Spectrum Analysis

The next step involved spectral analysis to determine the regional depth, which was then used to construct a 2.5D model of the high sulfidation epithermal deposit system. The method applied was the Radially Averaged Power Spectrum (RAPS) analysis. The RAPS curve represents the relationship between the natural logarithm of power and frequency, capturing regional, local, and noise anomalies, as illustrated in Figure 3.

The separation of regional, residual, and noise zones allowed the calculation of gradient values for each zone. These gradient values were then used to estimate depth using the equation proposed by Wahaab, Lawal, and Adebayo (2017). The estimated depths for the three zones are presented in Table 1.

$$D = -\frac{m}{4\pi} \quad \text{............(4)}$$

Where:

D = depth
m = slope

Table 1. Depth Estimation of the Regional, Residual, and Noise Zones

Zone	Gradient	Depth (m)
Regional	-6.7747	539.387
Residual	-3.7995	302.508
Noise	-2.0014	159.347

Subsurface Model Construction

Subsurface modeling was conducted using both inverse modeling for 3D visualization and forward modeling for 2.5D representation, based on the previously estimated depth. In the 2.5D modeling, the measured and calculated curves were derived from the RTP map intersections. A 2.5D model was then constructed to represent the geological conditions of the research area through curve fitting, referencing the conceptual model of high sulfidation epithermal (HSE) deposits from Sillitoe (2001), with alteration gradation based on Arribas (1995). This model was further refined using geological and alteration data from field observations and previous studies by Ali *et al.* (2020) and Pratomo *et al.* (2020), along with rock susceptibility values. The results of the 2.5D model provided insights into the depositional environment of the HSE system and the structural controls of alteration and mineralization.

For the 3D model, inversion modeling was carried out to generate a volumetric representation based on susceptibility parameters. The resulting 3D model

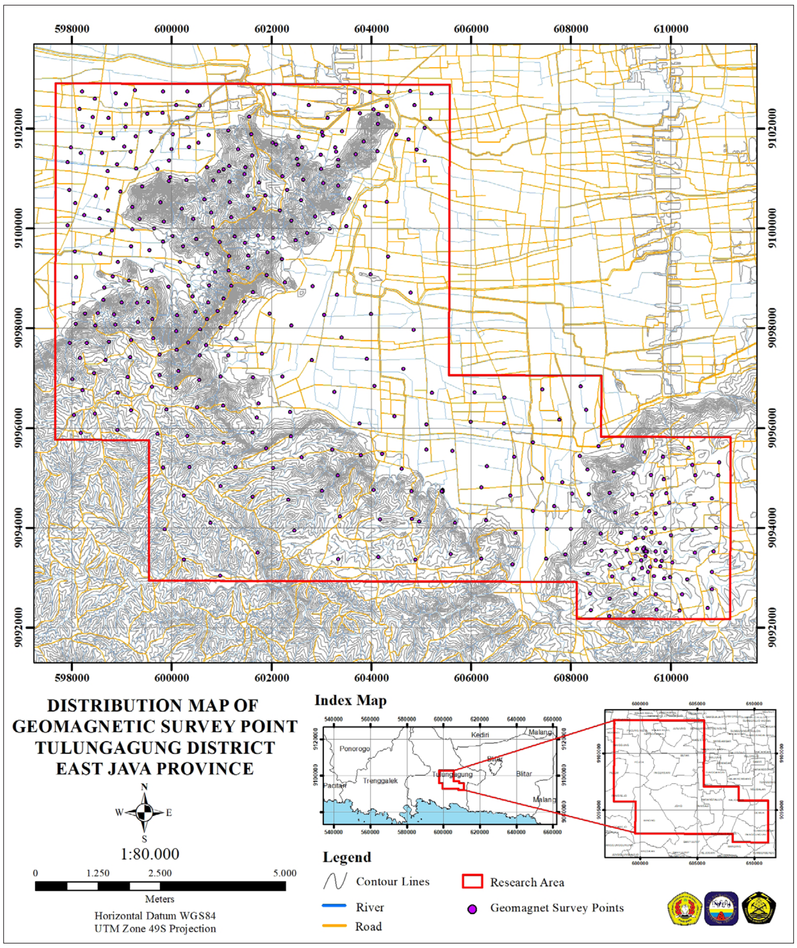

Figure 2. Distribution Map of Geomagnetic Survey Point in the Research Area

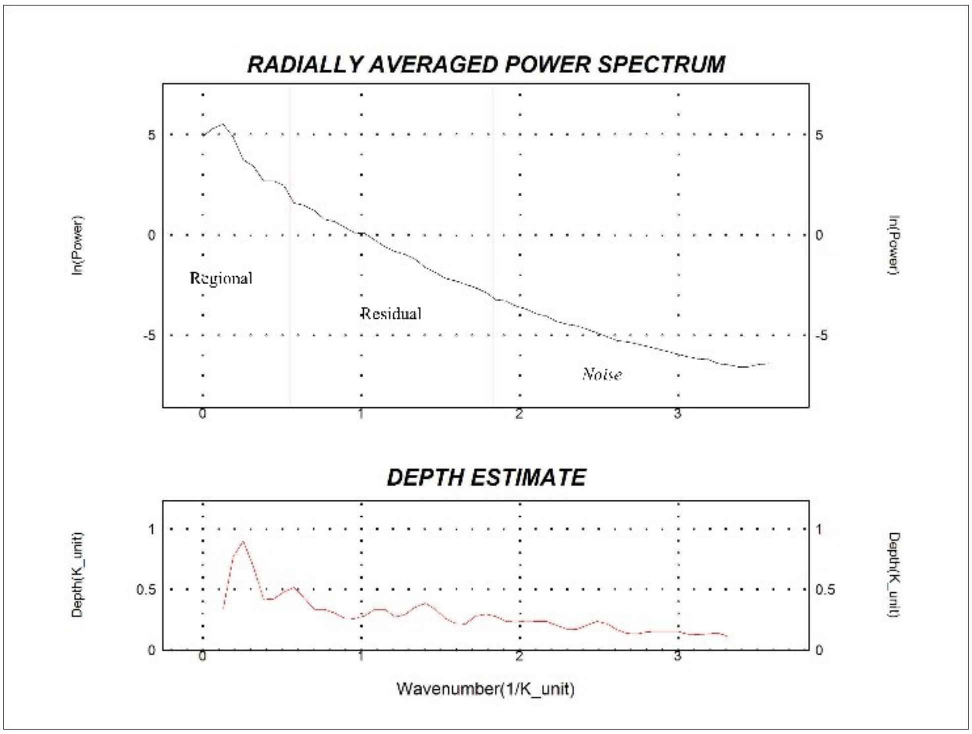

Figure 3. Spectrum Analysis Curve with Regional, Residual, and Noise Zones as the Basis for Depth Calculation

delineated the geometry and distribution of zones potentially hosting metallic mineral deposits within the epithermal system.

RESULT OF STUDY

Response of Magnetic Field Anomaly

In the map of magnetic field anomaly values (Figure 3), the response is influenced by the direction of the magnetic field from the north pole to the south (due to two poles called dipoles). This influence results in the map's magnetic field anomaly pattern not describing objects' positions or conditions below the surface. Therefore, the magnetic field anomaly map is filtered using the reduce-to-pole to describe the subsurface anomaly. The response of magnetic field values is influenced by the mineral composition of rock and geological processes that affect the level of magnetism. The classification of magnetic field anomaly values on the RTP map is shown in Table 2. Furthermore, the interpretation of the RTP map with reference to surface geology data is presented in Table 3.

In Figure 4, the high anomaly is dominant in the northwest to south area of the study area. The high anomaly values are represented by a red to pink color pattern. Low anomaly values are scattered in the eastern and southeastern parts of the study area. Medium anomaly values are indicated by yellow to orange color patterns around the high anomaly patterns. Low anomaly values have green to blue color patterns that dominate the eastern and southeastern areas of the research area.

DISCUSSION

Based on the interpretation of the RTP map (Figure 5), the alteration zone that is suspected of depositing metal minerals is located in a low anomaly response near the fault complex. According to Irvine & Smith (1990) in Clark (2014), precious metal deposits in epithermal systems associated with mafic rocks or intermediate volcanic rocks exhibit a low magnetic response due to alteration that transforms magnetite minerals. The alteration zone is found in andesite lava rocks.

The northwest of the research area appears to have a fairly complex pattern with a dominant structure in the area. Based on surface geological data, this area consists of volcanic rocks such as andesite lava, andesite breccia, and polymictic breccia, as well as the presence of dacite intrusion at the surface. This area contains alteration zones consisting of silicified,

Table 2. Classification of Magnetic Field Anomaly Values on the RTP Map

Classification	Range of RTP Anomaly Value (nT)
Very Low	< -53.1
Low	-53.1 – (-19.7)
Moderate	-19.7 – 26.2
High	26.2 – 60.9
Very High	> 60.9

Table 3. Interpretation of Magnetic Field Anomaly Scale Values on the RTP Map

Classification	Interpretation
Very Low - Low	Alteration Zone
Very Low - Moderate	Aluvium
Very Low – High	Limestone
Moderate - High	Polymict Breccia
High - Very High	Andesite Lava & Andesite Breccia
Very High	Dacite Intrusion

Table 4. Interpretation of Magnetic Field Anomaly Values in Alteration of Epithermal Deposit Systems in the Research Area (Clark, 2014)

Interpretation of Alteration Zone	Classification	Description
Propylitic	Very Low – Very High	*Magnetite-stable, weak altered*
Argillic	Low – Very High	*Partially to totally magnetite-destructive*
Advanced Argillic	Moderate - High	*Partially to totally magnetite-destructive, med-strong oxide*
Silicification	Moderate – Very High	*Partially to totally magnetite-destructive, strong oxide, mineralized*

advanced argillic, argillic, and propylitic alteration, which are classified as part of the high sulfidation epithermal deposit system (HSE). According to Ali, Winarno, and Jamalulail (2020), metallic minerals are present in areas of silicified alteration, dominated by sulfide mineral groups such as chalcocite, chalcopyrite, covellite, jarosite, pyrite, and enargite. Economic metallic minerals, such as native gold (Au), are also associated with enargite.

The classification on the RTP map for alteration zones in the high sulfidation epithermal deposit system is shown in Table 2. The response of magnetic field values to alteration depends on the intensity of the alteration. The table indicates that the further down the table, the higher the alteration intensity. However, if the alteration is exposed to metallic minerals that are magnetic, then the resulting magnetic field anomaly response will have a high magnetic value.

Subsurface Modeling

The 2.5D modeling aimed to describe the environment and geological conditions of the subsurface high sulfidation epithermal deposit system based on susceptibility values in the study area. The susceptibility values were based on measurements from rock samples and previous research conducted in the research area. This 2.5D modeling was created in two sections: A - A' in the northwest - southeast direction (9.6 km) and B-B' in the northeast - southwest direction (8.4 km).

Figure 6 presents the result of the 2.5D modeling of section A-A'. The response of the magnetic field anomaly value varies from high, medium, to low response. Low magnetic features are caused by several factors, such as rocks that do not contain magnetic minerals (alluvium and limestone), the influence of structures, and alterations (propylitic, argillic, advanced argillic, and silicified) present in the study area. The susceptibility values are listed as follows: alluvium, 0.012 x 10^{-3} SI (Nugroho *et al.*, 2021); limestone, 0.465 x 10^{-3} SI; propylitic alteration in andesite breccia, 1.156 x 10^{-3} SI; propylitic alteration in andesite lava, 1.63 x 10^{-3} SI; argillic, 0.686 x 10^{-3} SI; advanced argillic, 0.559 x 10^{-3} SI; and silicification, 0.193 x 10^{-3} SI. Alteration is controlled by permeable lithologies and structures that act as channel ways for hydrothermal fluids, rising to the epithermal environment. In the epithermal environment, hydrothermal fluid reacts with meteoric water and contacts the wall rocks, resulting in leaching and mineral alteration. The alteration of rocks causes the destruction of magnetite, leading to a low anomaly response. Moderate magnetic features are interpreted as andesite lava and andesite breccia lithologies with fresh textures that have not been altered, thus retaining their primary minerals.

The susceptibility value of andesite lava is 14.2 x 10^{-3} SI, while andesite breccia is 11.7 x 10^{-3} SI. High magnetic features are interpreted as andesite intrusions, as the mineral composition of the rock contains ferromagnetic minerals such as magnetite, which forms primarily and retains a fresh, unaltered texture. The susceptibility value for dacite intrusion is 27.5 x 10^{-3} SI (Nugroho *et al.*, 2021).

The 2.5D modeling of the B-B' section is shown in Figure 7. The magnetic anomaly response is more fluctuating, indicating that the geological environment of the study area is quite complex. The section begins with a high magnetic feature, which indicates the presence of dacite intrusion in the subsurface. Dacite intrusions are igneous rock intrusions containing ferromagnetic minerals such as magnetite, which form primarily with fresh, unaltered textures, resulting in high magnetic features. The susceptibility value of the dacite intrusion is 27.5 x 10^{-3} SI (Nugroho *et al.*, 2021). The model also identifies moderate magnetic features, such as andesite lava rock units (14.2 x 10^{-3} SI), andesite breccia (6.7 x 10^{-3} SI), and polymictic breccia (5.04 x 10^{-3} SI). The low magnetic feature is influenced by fault structures and lithologies such as limestone (0.465 x 10^{-3} SI) and alluvium (0.012 x 10^{-3} SI) (Nugroho *et al.*, 2021). The section also reveals propylitic alteration in the andesite breccia area. Figure 8 presents the 3D inversion modeling using susceptibility parameter values. The 3D inversion model illustrates the geometry and distribution of zones potentially enriched with metallic minerals based on susceptibility values. Zones suspected of containing metal minerals exhibit low susceptibility values (<2 x 10^{-3} SI). High susceptibility values (>15 x 10^{-3} SI) correspond to dacite intrusions, which serve as host rocks for hydrothermal fluids. The study area is classified as a high sulfidation epithermal deposit system, with alteration and mineralization zones located near the surface. The target zone is interpreted at approximately 200 meters below the surface. The subsurface model indicates that alteration and mineralization are predominantly distributed in the northwest area. This interpretation is supported by surface geological data and the reduce-to-pole map, which confirm alteration and mineralization processes in this region. Metallic sulfide and oxide minerals present in the area include gray sulfide, pyrite, goethite, hematite, veinlet sulfide, and chalcopyrite (Vanessa & Heditama, 2024).

CONCLUSION

The prospective zone of high sulfidation epithermal deposits is located in the northwest of the research area with a low magnetic anomaly response. This response is due to a widely dominant zone of strong alteration and a complex fault system. Moderate magnetic anomaly responses correspond to polymictic breccia and limestone, while high anomaly responses are associated with volcanic rocks or dacite intrusions.

The subsurface modeling in this research consists of both 2.5D and 3D models. The 2.5D modeling was conducted to analyze the presence of alteration and mineralization, which are controlled by the fault structure as a channel way for hydrothermal fluid to escape into the epithermal environment. The results show that this environment is characterized by a low susceptibility value (< 2 x 10-3 SI). Host rocks that carry hydrothermal fluids are interpreted as intrusions of dacite or andesite lava that have high susceptibility values (> 15 x 10-3 SI). In addition, the 3D modeling results show the geometry and distribution of zones suspected to be the depositional area of metallic minerals from the epithermal deposit system.

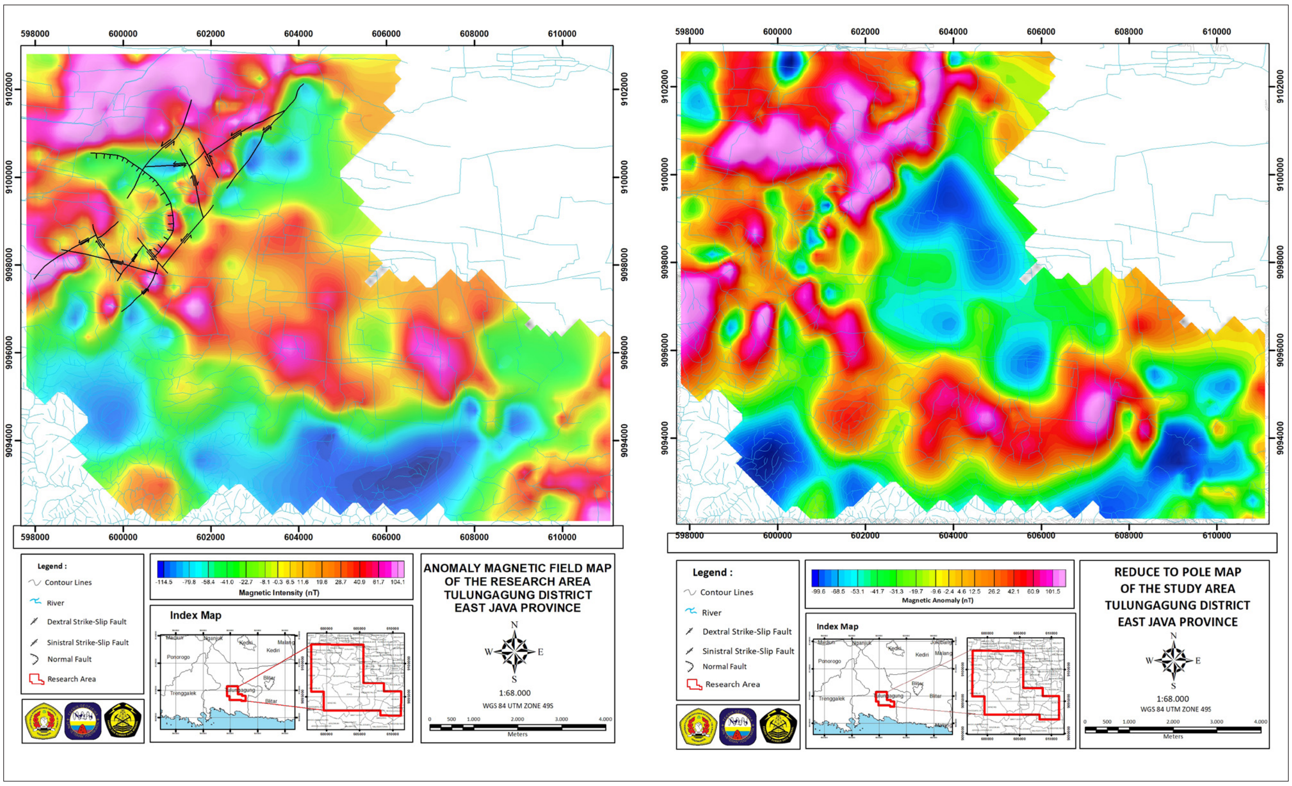

Figure 4. (a) Magnetic Field Anomaly Map, (b) Reduce-to-Pole (RTP) Map

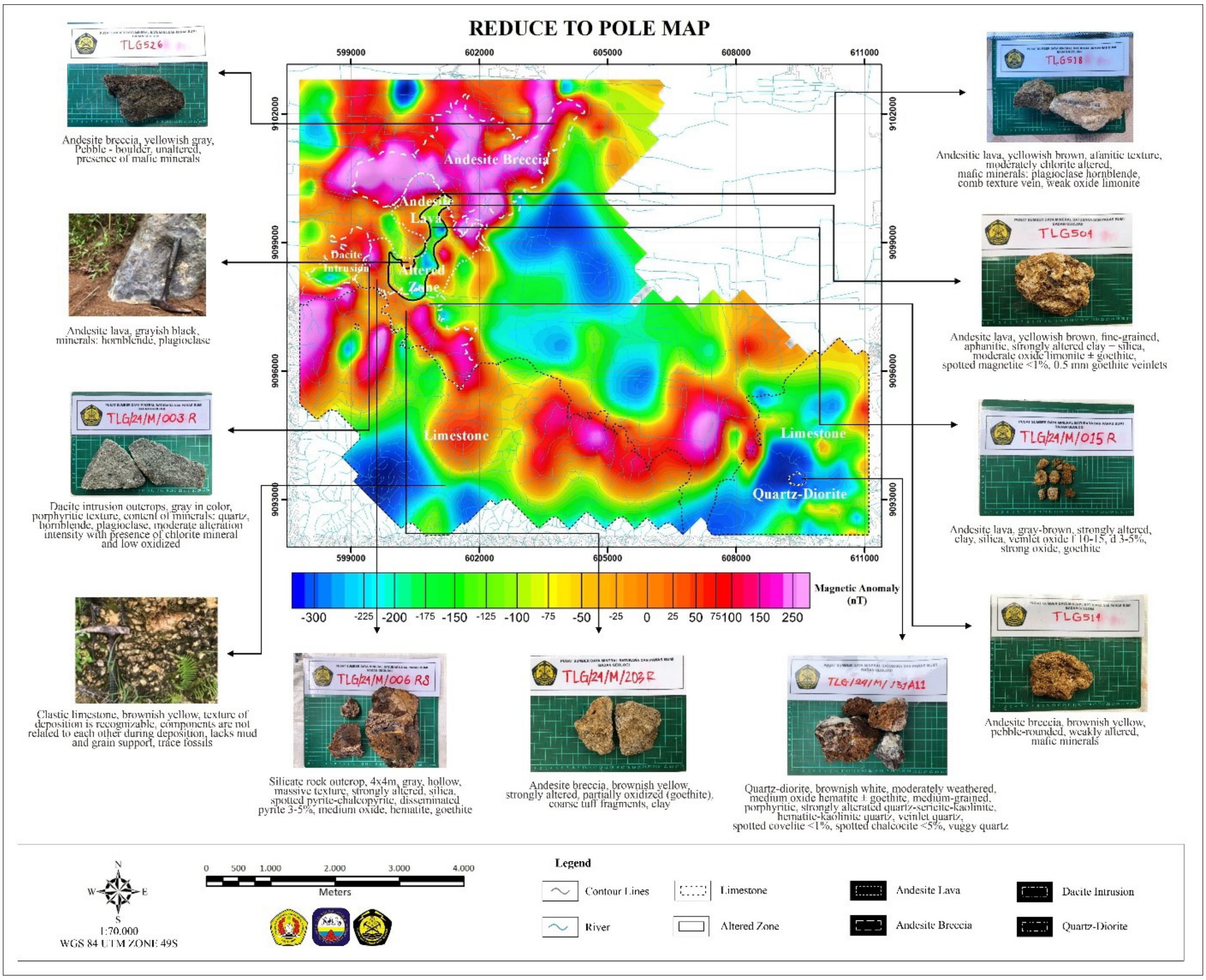

Figure 5. Interpretation of the Reduce-to-Pole Map with Surface Geological Data of the Research Area

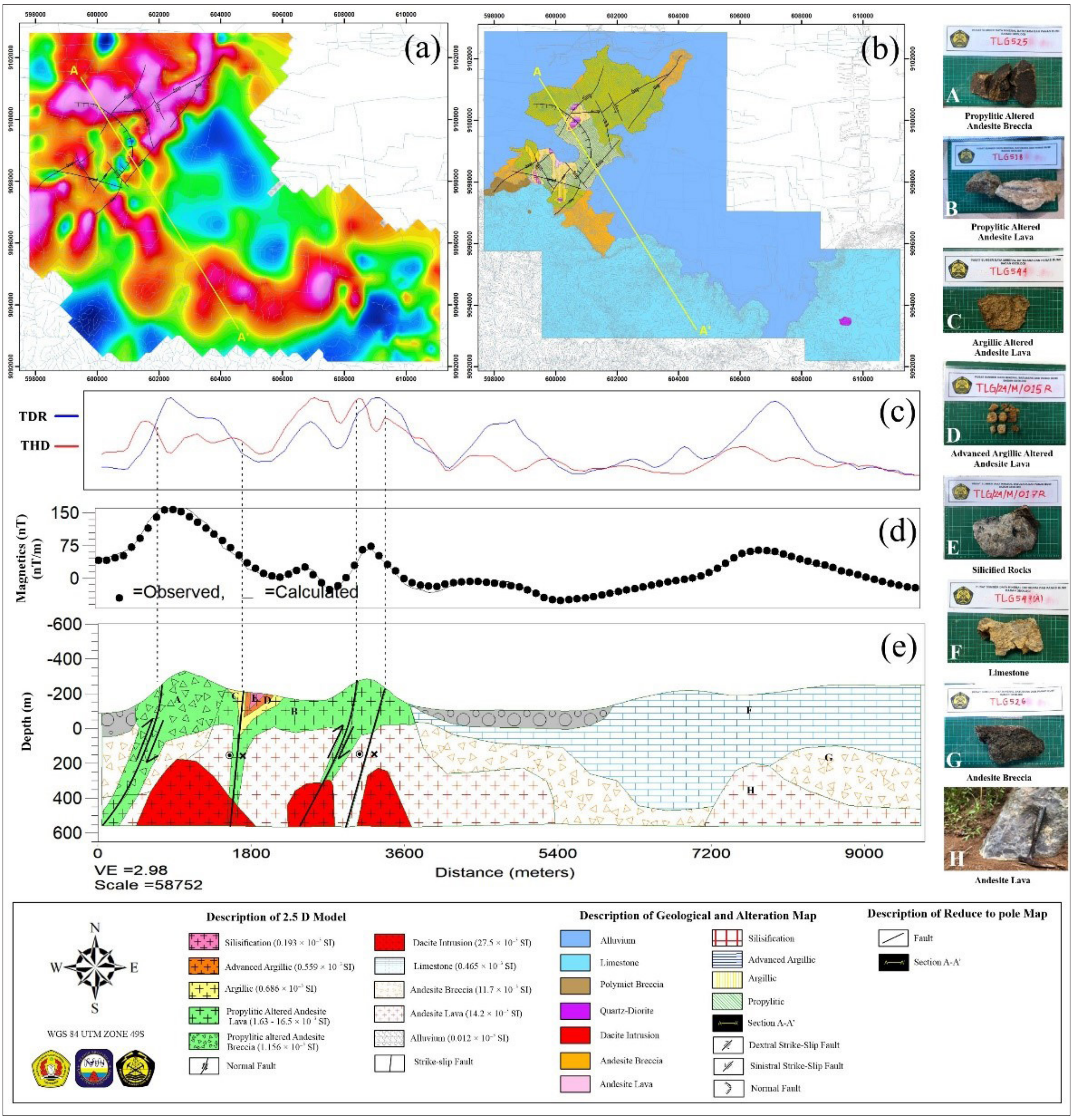

Figure 6. The 2.5D Modeling of Section A-A’, (a) The RTP map with the presence of fault structures and A-A’ modeling section, (b) Geology and alteration map (Vanessa and Heditama, 2024) with A-A’ modeling section, (c) Response of tilt derivative and total horizontal derivative in section A-A’, (d) Response of RTP values (calculated) and observations (observed), (e) Forward subsurface modeling of section A-A’.

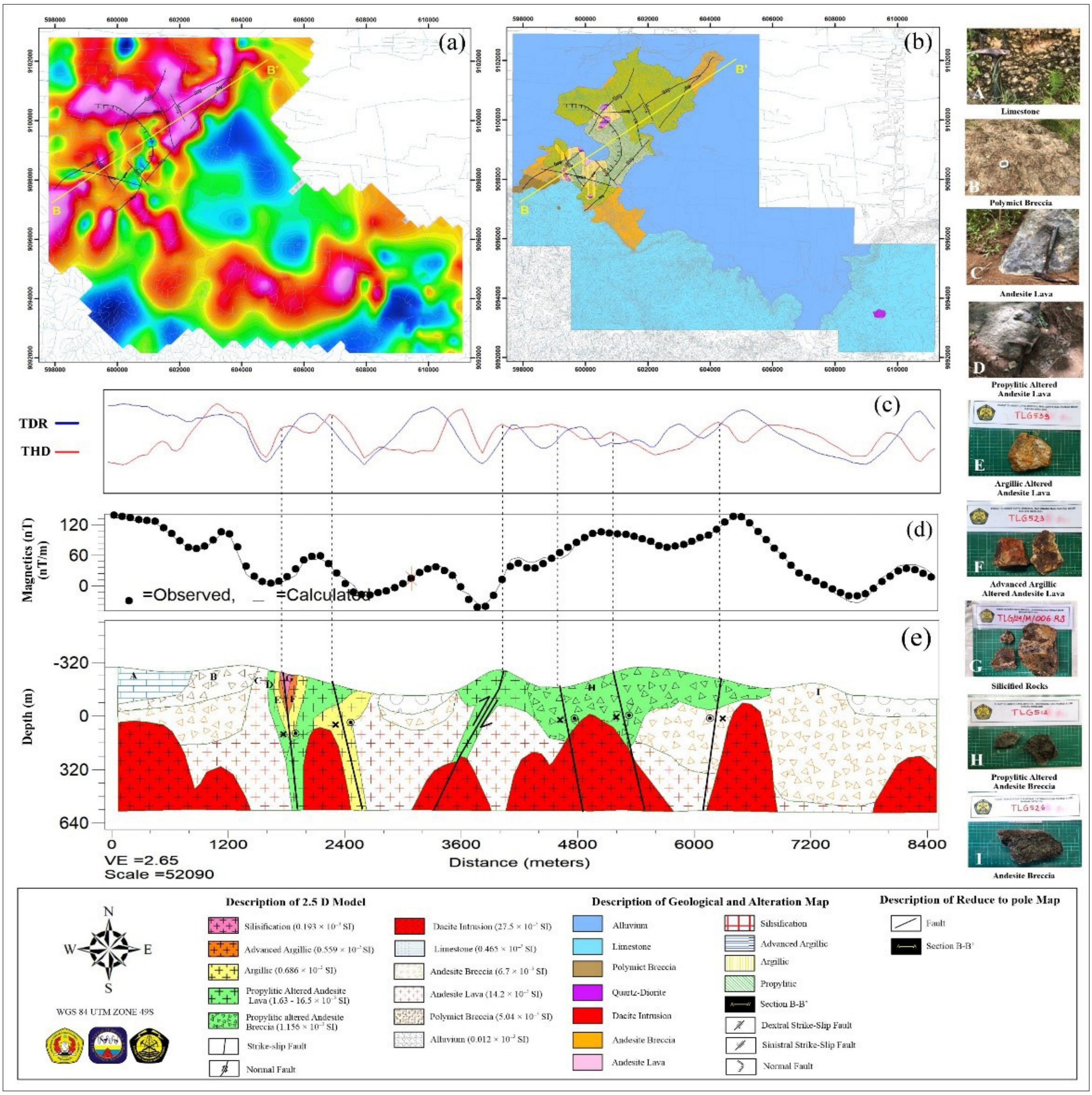

Figure 7. The 2.5D Modeling of Section B-B', (a) The RTP map with the presence of fault structures and B-B' modeling section, (b) Geology and alteration map (Vanessa and Heditama, 2024) with B-B' modeling section, (c) Response of tilt derivative and total horizontal derivative in section B-B', (d) Response of RTP values (calculated) and observations (observed), (e) Forward subsurface modeling of section B-B'.

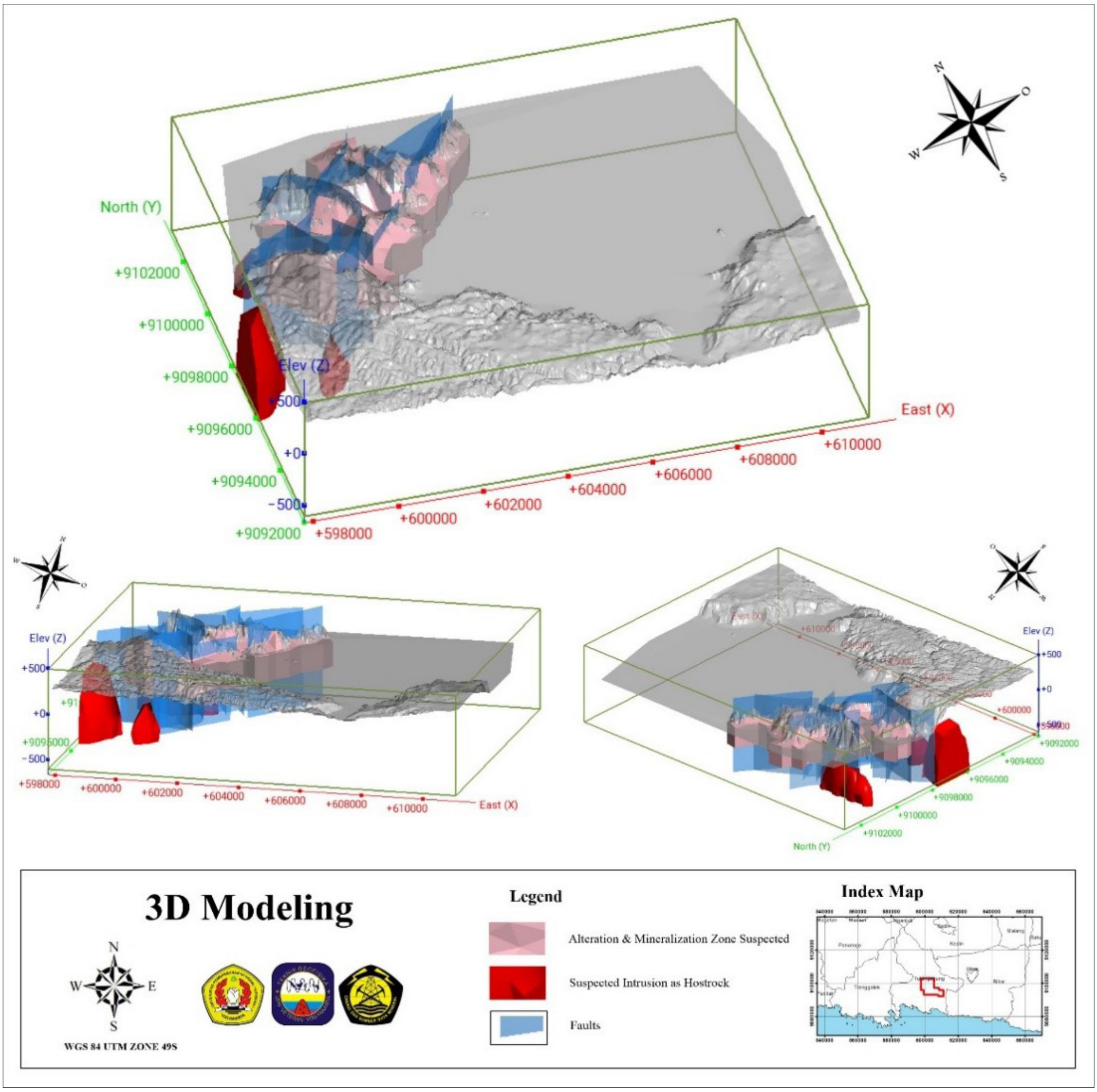

Figure 8. The 3D Isosurface Modeling Illustrates Mineralization Zones

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