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Three-Dimensional Resistivity Modeling of the Hydrothermal Flow System in Tanjung Sakti Pumi Region, Indonesia

Marven Saputra[1], Suhendra[1*], Refrizon[1], Florenzy Ernica Putra[1]
[1] *Physics Department, Faculty of Mathematics and Natural Sciences, University of Bengkulu, Indonesia*

Corresponding Authors E-mail: suhendra@unib.ac.id, refrizon@unib.ac.id

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Abstract

Tanjung Sakti Pumi Subdistrict, Lahat Regency, South Sumatra Province, is characterized by surface geothermal manifestations, particularly hot springs associated with a hydrothermal system. This study aims to evaluate hydrothermal potential and subsurface fluid-flow patterns by analyzing resistivity variations using the Schlumberger Vertical Electrical Sounding (VES) method. An integrated interpretation combining one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) resistivity modeling was applied to improve subsurface characterization. The results reveal low-resistivity zones (< 6 Ωm), interpreted as clay-rich hydrothermal alteration layers (clay cap), while deeper, moderate-to-high-resistivity zones are associated with potential geothermal reservoirs. This multi-dimensional approach enhances the delineation of lateral and vertical continuity of conductive zones, providing a more comprehensive understanding of structurally controlled hydrothermal systems in the study area. The findings demonstrate the effectiveness of integrated resistivity modeling for preliminary geothermal exploration and offer important insights into subsurface geothermal structures in Tanjung Sakti Pumi.

Introduction

Geothermal energy has been widely utilized as a renewable energy source in many countries, including Indonesia, due to declining fossil fuel reserves and increasing energy demand[1]-[2]. Indonesia is located at the convergence of the Indo-Australian, Eurasian, Pacific, and Philippine tectonic plates, creating a complex tectonic setting that controls volcanic and geothermal activity along the Sumatra volcanic arc[3]. This tectonic configuration gives Indonesia an estimated geothermal potential of approximately 29,215 GWe, distributed across more than 285 locations, placing the country among the countries with the largest geothermal resources worldwide[4].

Tanjung Sakti Pumi Subdistrict is located in Lahat Regency, South Sumatra Province, within the Bukit Barisan Mountain range. Geologically, this area is part of the Sumatra volcanic arc and is strongly influenced by regional tectonic structures associated with the Sumatran Fault System, particularly the Manna Segment. Several surface geothermal manifestations, including hot springs with temperatures ranging from approximately 30 to 80 °C, are observed along riverbanks in the study area, indicating an active hydrothermal system. The Manna Segment is interpreted to play an important role in controlling subsurface permeability by acting as a structural pathway for ascending hydrothermal fluids, making the area favorable for geothermal prospecting.

Despite surface manifestations, the subsurface characteristics of the hydrothermal system in Tanjung Sakti Pumi remain poorly constrained. In particular, there is a lack of integrated subsurface imaging capable of resolving the spatial continuity of hydrothermal alteration zones, fluid pathways, clay cap development, and potential geothermal reservoir layers. Previous studies in the area have primarily relied on surface observations and have not applied multi-dimensional resistivity modeling to characterize the geometry of the hydrothermal system.

The geoelectric resistivity method is a geophysical technique that utilizes high-voltage direct current injected into the ground to investigate subsurface electrical properties[5]. Variations in resistivity values are closely related to lithology, porosity, fluid content, and hydrothermal alteration. Recent international studies have demonstrated the effectiveness of resistivity and magnetotelluric methods in delineating geothermal systems in volcanic and tectonically active regions[6], highlighting the importance of integrated geophysical approaches for improving subsurface characterization. In geothermal systems, low resistivity zones are commonly associated with clay-rich alteration layers and fluid-saturated rocks, which may act as a clay cap, whereas deeper zones with relatively higher resistivity are often interpreted as potential geothermal reservoir layers[7].

In this study, the Vertical Electrical Sounding (VES) method with a Schlumberger configuration is applied to investigate subsurface resistivity variations in Tanjung Sakti Pumi Subdistrict. The VES method is particularly suitable for preliminary geothermal exploration due to its ability to resolve vertical resistivity layering and to efficiently estimate investigation depth. By integrating one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) resistivity modeling, this study aims to identify hydrothermal alteration zones, fluid flow pathways, and potential reservoir indicators related to structural control by the Manna Segment. The novelty of this study lies in the integrated multi-dimensional interpretation of VES data (1D, 2D, and 3D) to delineate hydrothermal system characteristics in the Tanjung Sakti Pumi area, where such an approach has not been previously implemented. This integrated approach enables improved delineation of lateral and vertical continuity of conductive zones, which is essential for understanding structurally controlled hydrothermal systems. The results are expected to provide initial subsurface information to support further geothermal exploration and development in the Tanjung Sakti Pumi area.

Regional Geology

The Tanjung Sakti Pumi District is geographically located at 4°10'–4°15' south latitude and 103°00'–103°10' east longitude. It is bordered by the Dempo Utara District to the north, the South Bengkulu Regency to the south, the Tanjung Sakti Pumi District to the west, and the City Agung District to the east. At altitudes between 500 and 1200 meters above sea level, the land in this area is undulating and steep. The morphology of the area is influenced by volcanic and tectonic activity associated with the Semangko Fault System[8]-[9]. This research was conducted in Tanjung Sakti Pumi Subdistrict, Lahat Regency, South Sumatra Province. This location is in the southwestern part of Lahat Regency. It is a hilly area in the Bukit Barisan Mountains. Physiographically, this area is part of a volcanic hill morphology and igneous rock complex formed by tectonic and volcanic activity between the Tertiary and Quaternary periods[9]. Figure 1 shows the geological map of the study area, illustrating the distribution of lithological units and major structural features, particularly the Manna Segment of the Sumatran Fault System. This structural feature is interpreted to play a significant role in controlling permeability and hydrothermal fluid pathways in the Tanjung Sakti Pumi area.

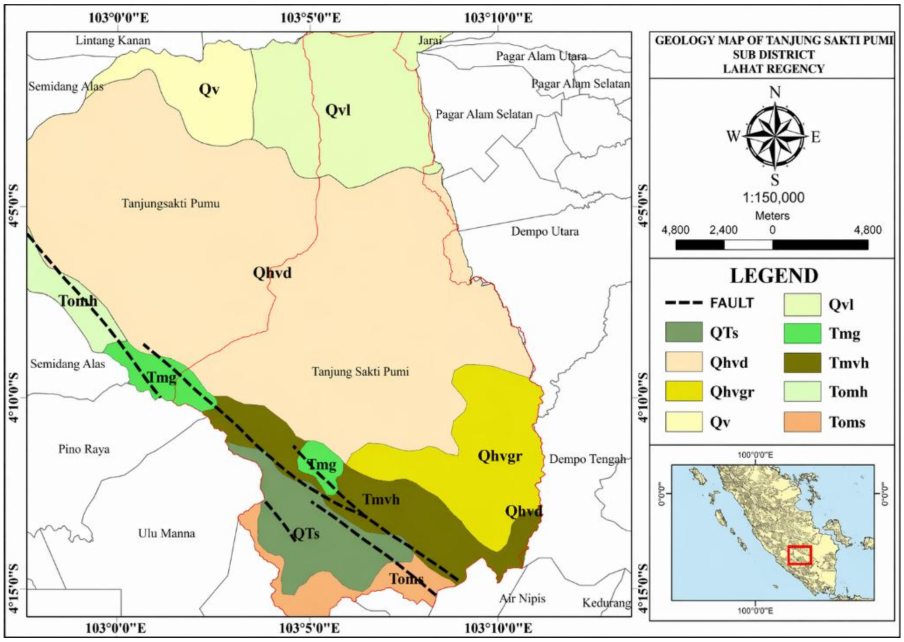

Figure 1. Geological map of Tanjung Sakti Pumi Sub-District, Lahat Regency (Modified from Geomap)

Geothermal and Geoelectric Resistivity

Geothermal heat can be generated by magmatic activity that heats the subsurface layer[10]. Meteoric water that enters through infiltration areas, rock fractures, and crevices causes water to accumulate in reservoirs[11], which are the source of geothermal systems in Indonesia. Water that constantly moves downward due to gravity comes into contact with heat sources, thereby transferring heat, raising its temperature, and reducing its density [12]. Water at higher temperatures rises and is replaced by colder water because it is denser. Springs that appear on the surface indicate that geothermal activity, such as volcanic activity and crustal movement, is occurring beneath the surface[13]. Highly heated geothermal areas are not always available for power generation, even though geothermal sources are widespread on

Earth. Geothermal reservoirs can be divided into various categories, such as hydrothermal reservoirs, geopressured reservoirs, dry hot rock reservoirs, and magma reservoirs[14]. Unlike oil and gas deposits, surface geothermal features such as hot springs, hot mud pools, geysers, and other phenomena often indicate the presence of geothermal resources underground [15].

Ohm's law is the basis of the resistivity method. The geoelectric resistivity method uses the resistivity properties of rocks to determine conditions beneath the Earth's surface[16]. The flow of water through underground rocks is highly dependent on the presence of groundwater and salts[6]. Therefore, this method can be applied to detect aquifers, groundwater contamination, mineral exploration, archaeological surveys, and the discovery of parent rocks in geothermal investigations. The VES method is used to evaluate variations in resistivity values. Resistivity values indicate rock layers beneath the surface. The resistivity value of each rock layer varies depending on the conductivity properties of the material[17]. The ability of a conductor to transfer electrical energy is called conductivity, and the resistance is measured in ohms (Ω). This parameter is known as resistance (R) and is defined as the ratio of voltage (V) to current (I), so it is expressed as[18]

$$R = \frac{v}{i} \text{ or } V = I.R \tag{1}$$

where (R) represents the resistance of the material in ohms, (I) represents the current strength in amperes, and (V) represents the voltage in volts[19]. To measure resistivity, an electric current is injected through a set of electrodes in a Schlumberger configuration. Two current electrodes (C1 and C2) and two voltage electrodes (P1 and P2) are used to inject electric current into the ground, as shown in Figure 2.

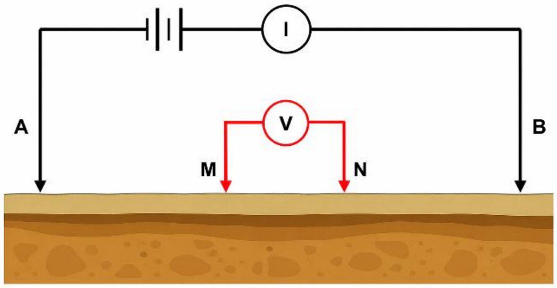

Figure 2. Schlumberger Configuration

Like electrical conductors, rocks have resistivity. Porosity, water content, and mineral content affect rock resistivity. Table 1 shows resistivity values. If a rock has pores filled with water, its electrical resistivity decreases as the water content increases. Conversely, as water content in the rock decreases, its electrical resistivity increases.

Table 1. Rock resistivity values (Telford et al., 1990)

Material	Resistivity (Ωm)
Air	~
Pyrite	0.01-100
Quartz	500-800000
Calcite	$1x10^{12}$ - $1x10^{13}$
Rock salt	30 - $1x10^{13}$
Granite	200 – 10000
Andesite	$1.7x10^{2}$ - $45x10^{4}$
Wet	1000 - $4x10^{4}$
Dry	10 - $1.3x10^{7}$
Limestone	500-10000
Sandstone	200-8000
Shales	20-2000
Sand	1-1000
Clay	1-100
Ground water	0.5-300
Sea water	0.2
Magnetite	0.01-1000
Dry gravel	600-10000
Alluvium	10-800

Experimental Method

The study was conducted in Tanjung Sakti Pumi Subdistrict, Lahat Regency, South Sumatra Province, which is located within the Bukit Barisan mountain range. The area is characterized by hilly to mountainous morphology with elevations ranging from approximately 500 to 1200 m above sea level. This region is part of the Sumatra volcanic arc and is structurally controlled by the Sumatran Fault System, particularly the Manna Segment, which is considered to influence subsurface permeability and hydrothermal fluid circulation. Figure 3 shows the research location map and the distribution of VES measurement points, illustrating the survey's spatial coverage and its relationship to surface geothermal manifestations and structural features. This spatial arrangement supports the interpretation of subsurface resistivity variations in relation to hydrothermal activity. Several tools and materials were used to support the field implementation of geoelectric measurements. The main tool used is the MAE X612 geoelectric device, which functions to obtain subsurface resistivity data. This device is powered by a 12 V battery. The positions and coordinates of the measurement points are determined using GPS, and a distance meter is used to ensure the distance between the electrodes is within the predetermined measurement design.

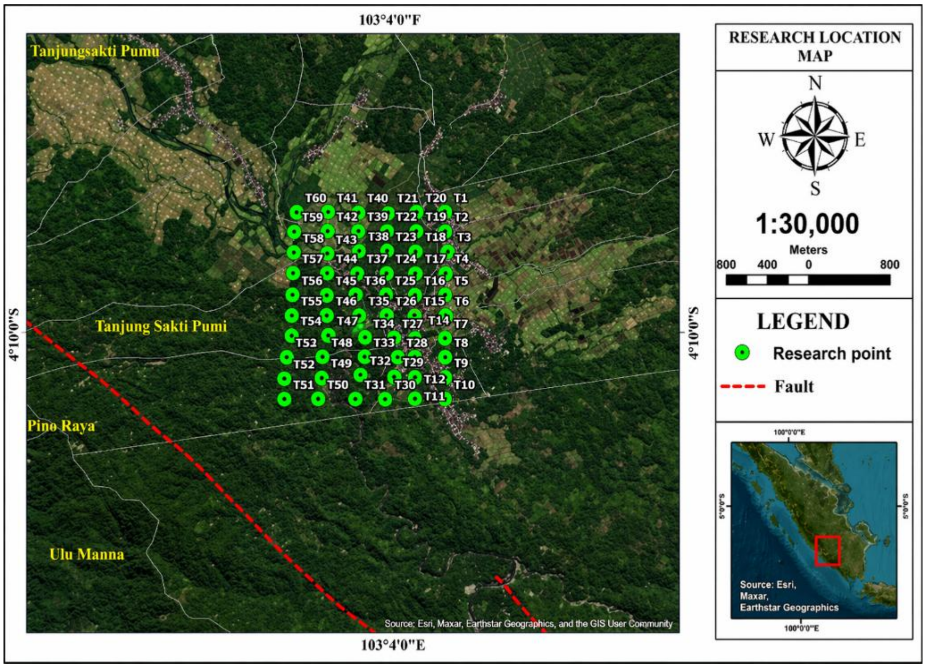

Figure 3. Research map of the research area (Modified from Google Earth)

Geoelectric data were acquired using the Vertical Electrical Sounding (VES) method with a Schlumberger electrode configuration. A total of 60 VES measurement points were distributed across the study area, with an average spacing of approximately 300 m between stations to ensure adequate spatial coverage. At each VES station, two current electrodes (C1 and C2) and two potential electrodes (P1 and P2) were deployed along a straight line. The half-spacing of the current electrodes (AB/2) was progressively increased up to a maximum distance of 150 m on each side, resulting in an estimated investigation depth of approximately 100 m. The potential electrode spacing (MN) was kept relatively small compared to AB to maintain measurement sensitivity and data quality.

The selection of VES measurement locations was based on integrating geological considerations, including the presence of surface geothermal manifestations, proximity to structural features associated with the Manna Segment, and field accessibility. This approach ensures that the acquired data represent areas with the highest potential for hydrothermal activity.

The measured apparent resistivity data were processed using a one-dimensional (1D) inversion approach to obtain vertical resistivity layering at each VES station. The inversion of VES data was performed using an iterative least-squares algorithm to obtain the best-fit subsurface resistivity model. The inversion process was constrained to minimize the root-mean-square (RMS) error, with acceptable errors maintained below 5%. Several iterations were conducted until a stable model was achieved, ensuring consistency between observed and calculated apparent resistivity curves. The inversion results provide information on the resistivity values, thicknesses, and depths of subsurface layers. To analyze lateral variations, the 1D inversion results from adjacent stations were interpolated to construct two-dimensional (2D) resistivity sections along selected profiles. Furthermore, all interpreted resistivity layers were integrated into a three-dimensional (3D) resistivity model to visualize the spatial distribution of resistivity anomalies and hydrothermal features throughout the study area.

ArcGIS, Voxler, and Strater software were used to support spatial analysis, visualization, and construction of 2D and 3D resistivity models, facilitating the interpretation of subsurface structures.

Resistivity interpretation was conducted based on established geothermal resistivity characteristics. Low resistivity values (generally < 6 Ωm) were interpreted as clay-rich alteration zones or hydrothermally fluid-saturated rocks, as such values are commonly associated with conductive clay minerals (e.g., smectite and illite) and high-ionic-content fluids in geothermal systems. These zones are typically interpreted as clay caps that act as semi-impermeable layers.

However, it should be noted that low resistivity values are not uniquely indicative of hydrothermal systems and may also result from groundwater saturation or clay-rich lithologies unrelated to hydrothermal alteration[20]. Therefore, the interpretation in this study is supported by the spatial correlation between resistivity anomalies, surface geothermal manifestations, and regional geological structures, particularly the Manna Segment, which is inferred to control hydrothermal fluid pathways. Moderate to relatively higher resistivity values at greater depths were interpreted as potential geothermal reservoir layers, while high resistivity zones were associated with unaltered volcanic or igneous rocks.

It should be noted that resistivity inversion is inherently non-unique, meaning that different subsurface models may produce similar responses. In addition, the depth of investigation is limited by the electrode configuration used in the survey. Therefore, the results of this study represent a preliminary interpretation that requires further validation using complementary geophysical and geochemical methods. The initial model parameters were adjusted based on field data characteristics to ensure convergence and stability of the inversion results.

Result and Discussion

The Tanjung Sakti Pumi research area is geologically and tectonically favorable for the development of a hydrothermal geothermal system. Regionally, the study area is located in close proximity to the Manna Segment, which forms part of the active Sumatra Fault System. This fault segment plays a significant role in controlling subsurface geological conditions by generating faults and fracture zones that act as permeability pathways for hydrothermal fluid circulation from depth toward the surface. The interpretation of resistivity data obtained using the Vertical Electrical Sounding (VES) method with a Schlumberger configuration reveals significant vertical variations in subsurface resistivity. From a total of 60 sounding points, 21 points exhibit very low resistivity values (< 6 Ωm), which are interpreted as hydrothermal-related anomalies. These low-resistivity zones are predominantly distributed in the southern and southwestern parts of the study area and show a close spatial relationship with surface geothermal manifestations, such as hot water discharges[21].

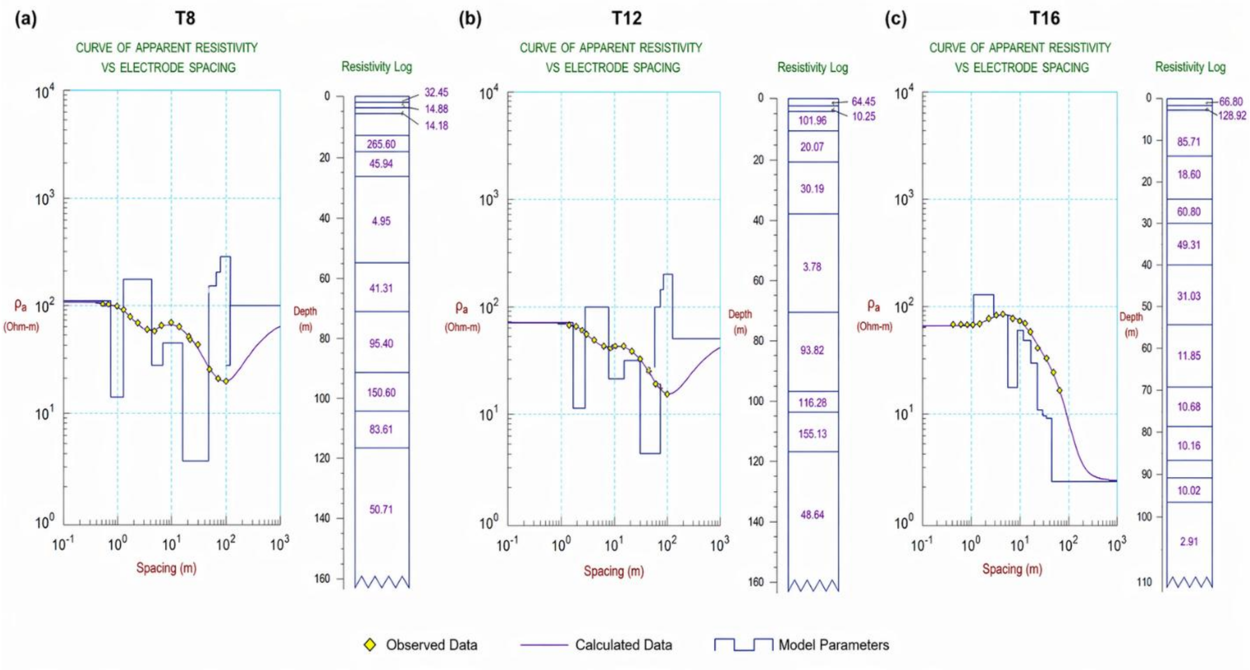

Figure 4. 1D VES model (Research Points 8, 12, and 16)

Figure 4 shows the representative 1D resistivity models at selected VES stations (Points 8, 12, and 16), illustrating the vertical variation of resistivity with depth. These models highlight low-resistivity layers at different depths, interpreted as hydrothermal alteration zones, as well as underlying higher-resistivity layers that may indicate potential geothermal reservoirs. The 1D resistivity models at representative sounding locations (Points 8, 12, and 16) indicate that low-resistivity layers occur at shallow to moderate depths with variable thicknesses. At Point 8, a very low resistivity layer (4.95 Ωm) is identified at depths of approximately 26–55 m, with an estimated thickness of about 29 m. At Point 12, a low resistivity zone (3.78 Ωm) appears at depths of approximately 39–70 m, with a thickness of around 31 m. Meanwhile, at Point 16, the lowest resistivity layer (2.91 Ωm) occurs at greater depths, ranging from approximately 73–100 m, with an estimated thickness of 27 m.

Representative VES points (Points 8, 12, and 16) were selected based on their ability to capture the variability of resistivity responses across the study area, including shallow, intermediate, and deeper conductive zones. These points are considered representative of the overall subsurface conditions and are located in areas with significant hydrothermal indications.

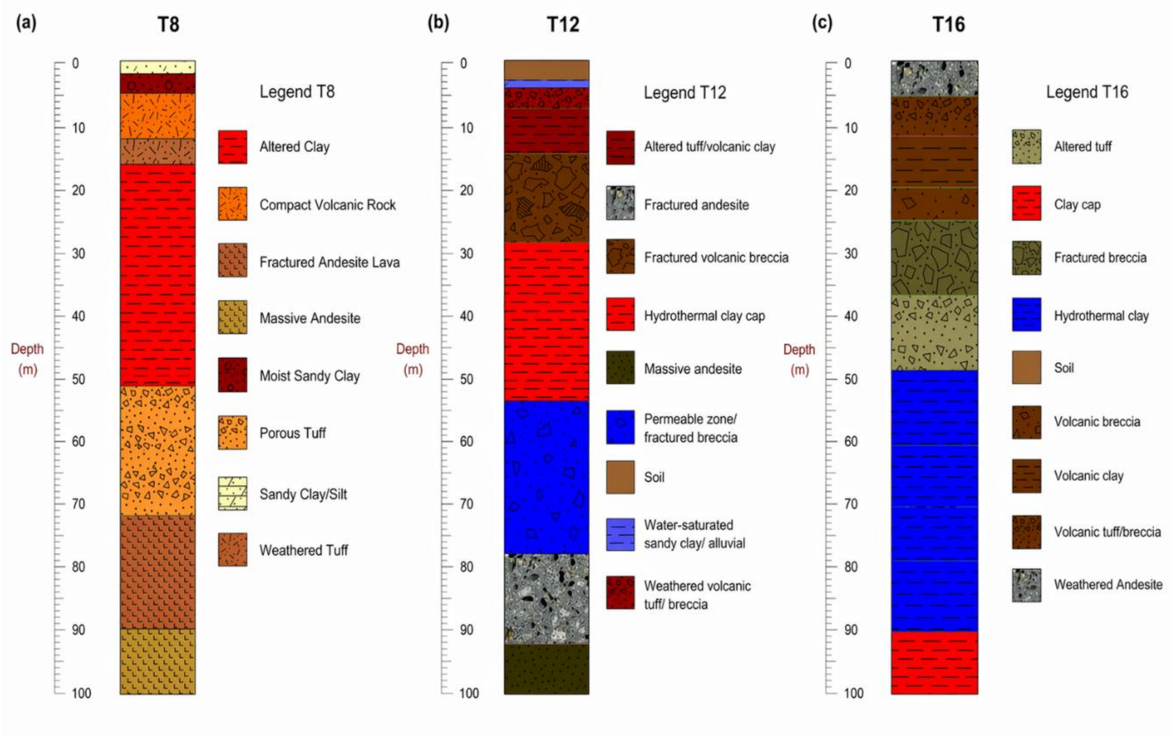

Figure 5. Rock Lithology

Figure 5 shows the interpreted lithological models derived from the 1D resistivity results at representative VES points (Points 8, 12, and 16), illustrating the relationship between resistivity variations and subsurface lithology. The conductive layers are interpreted as clay-rich hydrothermal alteration zones (clay cap), while the underlying higher-resistivity layers are associated with fractured volcanic and volcaniclastic rocks that may act as potential geothermal reservoirs. These low-resistivity layers are interpreted as a clay cap zone, which commonly forms in geothermal systems due to intensive hydrothermal alteration that produces conductive clay minerals. The presence of this clay-rich layer acts as an impermeable or semi-impermeable layer[22] cover that traps hydrothermal fluids beneath it. The observed variation in depth and thickness of the clay cap (approximately 20–35 m) suggests heterogeneous alteration intensity, strongly influenced by local lithology and structural conditions.

Beneath the clay cap, layers with relatively higher resistivity values are interpreted as the geothermal reservoir zone. This zone is estimated to occur at depths greater than 40 m and to extend to approximately 100 m within the investigated range. The higher resistivity values are associated with fractured volcanic and volcaniclastic rocks that retain sufficient permeability to store and transmit hydrothermal fluids. The presence of fractures and faults significantly enhances reservoir permeability, allowing the accumulation and lateral flow of hot fluids.

The identified resistivity structure can be interpreted within a conceptual geothermal system framework. The shallow, low-resistivity zones (< 6 Ωm) are interpreted as clay cap layers formed by hydrothermal alteration and act as semi-impermeable barriers. Beneath these layers, the relatively higher-resistivity zones are interpreted as potential geothermal reservoirs associated with fractured volcanic and volcaniclastic rocks [23].

The presence of structurally controlled conductive zones, particularly those aligned with the Manna Segment, suggests that faults and fractures play a critical role in controlling hydrothermal fluid flow. These structures likely function as upflow pathways, allowing hot fluids to migrate from depth toward the surface, as evidenced by the spatial association with surface geothermal manifestations.

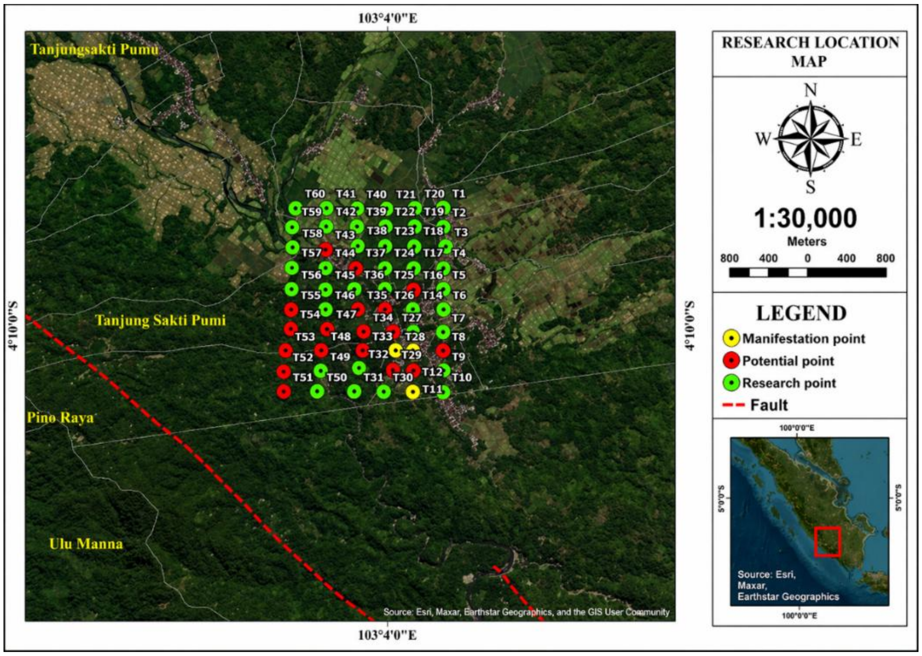

Figure 6. Potential hydrothermal locations (Modified from Google Earth)

Figure 6 shows the areas with hydrothermal potential. The yellow research points indicate locations with geothermal manifestations and hot water outlets. There are three locations: research points 11, 28, and 29. The red research points indicate areas with indicated hydrothermal potential.

The three-dimensional resistivity model, as shown in Figure 7, highlights low-resistivity zones (red) that are distinctly lower than the surrounding subsurface layers. In the Schlumberger Vertical Electrical Sounding configuration, vertical resistivity variations are highly sensitive to changes in subsurface physical properties at specific depth intervals, allowing conductive zones to be effectively identified. Resistivity values below 6 Ωm are interpreted as hydrothermally altered, fluid-saturated layers, commonly associated with clay-rich alteration products and ion-rich geothermal fluids. Similar resistivity ranges have been reported in previous geothermal studies, where low resistivity values (< 10 Ωm) are commonly associated with clay-rich alteration zones formed by hydrothermal processes. For example, magnetotelluric studies in volcanic geothermal systems have identified conductive clay caps overlying resistive reservoir zones. Therefore, the interpretation of low resistivity values in this study as hydrothermal alteration zones is consistent with established geothermal models[24].

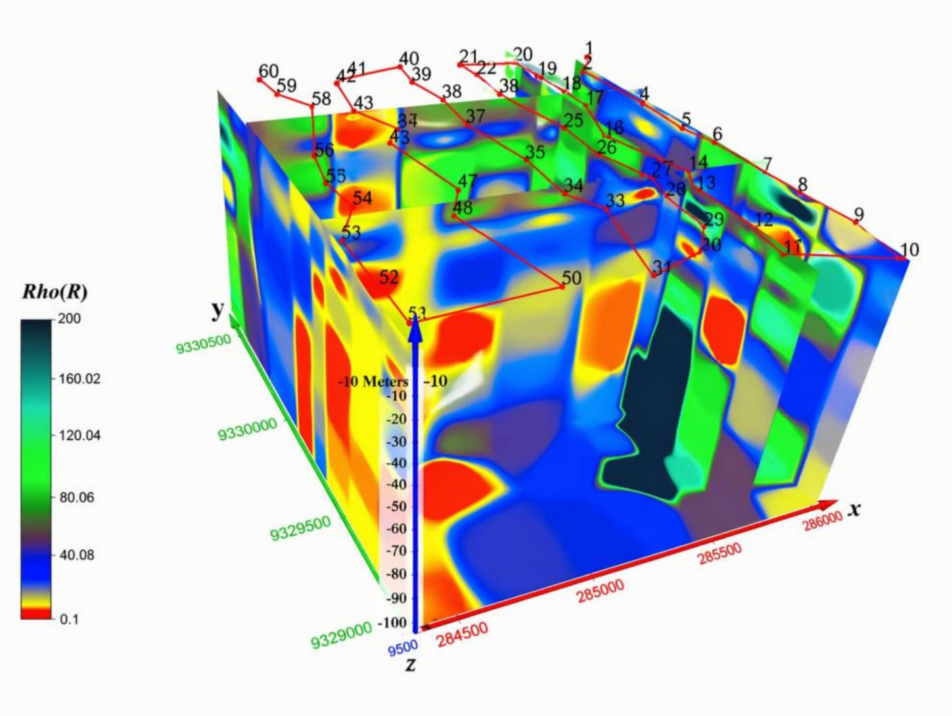

Figure 7. 3D cross-section of hydrothermal flow

In the geological setting of the Tanjung Sakti Pumi area, which is dominated by Quaternary to Tertiary volcanic and volcaniclastic rocks, resistivity contrasts are strongly controlled by alteration intensity, fracture intensity, porosity, and fluid saturation. The presence of hydrothermal fluids with elevated ionic content within pores and fractures significantly enhances electrical conductivity, resulting in the observed low-resistivity anomalies[25].

The 3D resistivity model indicates that low-resistivity zones extend laterally across several hundred meters and vertically from shallow depths (~10 m) to approximately 100 m. These conductive zones exhibit partial connectivity, suggesting the presence of interconnected pathways that may represent hydrothermal upflow zones[26].

Based on the 3D resistivity model, the spatial distribution of these low-resistivity anomalies shows a preferential alignment following the regional structural trend associated with the Manna Segment of the Sumatra Fault System. The anomalies are not randomly distributed but form laterally connected conductive zones that extend both horizontally and vertically within the subsurface. Several of these conductive zones appear to cluster along interpreted fault traces, indicating that these structures act as primary pathways for hydrothermal fluid migration. The observed vertical continuity of low-resistivity zones further supports the presence of upward fluid flow controlled by fracture systems.

The identification of these structural controls is based on integrating geological information, including mapped fault orientations, with geophysical evidence derived from resistivity contrasts, lateral connectivity, and vertical continuity observed in the 3D model. This combined interpretation strengthens the inference that the anomalies are structurally controlled rather than randomly distributed.

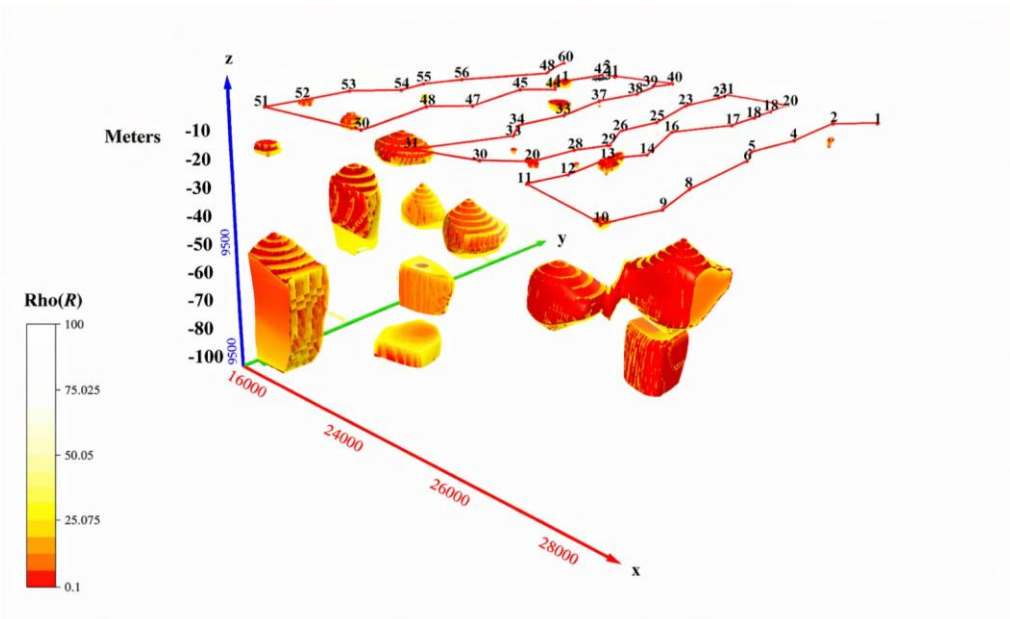

Figure 8. 3D appearance of hydrothermal potential

The spatial distribution of resistivity zones lower than 6 Ωm, as shown in Figure 8, reveals predominantly localized anomalies; however, several zones exhibit both lateral and vertical connectivity. This connectivity suggests the presence of subsurface pathways that facilitate the migration of hydrothermal fluids.

Low resistivity zones with values below 6 Ωm identified in this study are not uniquely indicative of hydrothermal systems and may also be associated with clay-rich lithologies, groundwater saturation, or saline fluids. However, in the geological context of the Tanjung Sakti Pumi area, which is dominated by volcanic and volcaniclastic rocks, these low resistivity values are more plausibly interpreted as hydrothermally altered clay zones.

This interpretation is supported by several factors, including the spatial association between low-resistivity anomalies and surface geothermal manifestations, their occurrence at moderate depths (approximately 12–100 m) with thicknesses of 25–33 m, and their structural control by faults and fractures related to the Manna Segment of the Sumatra Fault System, which provides pathways for hydrothermal fluid circulation.

The resistivity characteristics identified in this study are consistent with previous geothermal investigations in volcanic and structurally controlled settings. Low-resistivity zones (< 6 Ωm) interpreted as clay cap layers have also been reported in other geothermal fields, where hydrothermal alteration produces conductive clay minerals that overlie potential reservoir zones[25].

Compared with previous studies, the present work provides a more detailed spatial characterization by integrating 1D, 2D, and 3D resistivity modeling. This multi-dimensional approach allows better visualization of the lateral and vertical continuity of conductive zones, which is essential for identifying structurally controlled fluid pathways. As a result, the interpretation of hydrothermal flow systems in this study is more comprehensive than conventional single-dimensional analyses.

Although low-resistivity anomalies are interpreted as hydrothermal alteration zones, alternative explanations, such as groundwater saturation or clay-rich lithologies, cannot be entirely ruled out. However, the strong spatial correlation between the anomalies, surface geothermal manifestations, and structural features supports the hydrothermal interpretation as the most plausible explanation in this geological setting.

Conclusion

This study demonstrates that integrating 1D, 2D, and 3D resistivity models derived from VES data provides a more comprehensive understanding of subsurface hydrothermal systems than conventional single-dimensional approaches. The multi-dimensional interpretation enables improved visualization of both vertical layering and lateral connectivity of resistivity anomalies, which is essential for identifying structurally controlled fluid pathways. The results indicate the presence of low-resistivity zones (< 6 Ωm), interpreted as hydrothermal alteration (clay cap), and deeper moderate-to-high resistivity zones that may represent potential geothermal reservoirs. The spatial distribution and alignment of these anomalies suggest strong structural control by the Manna Segment of the Sumatra Fault System, which likely serves as a major pathway for hydrothermal fluid migration. However, due to the non-uniqueness of resistivity data, the interpretation of reservoir zones should be considered preliminary. Further investigations using complementary geophysical methods and geochemical analyses are required to confirm the reservoir characteristics and heat source. Overall, this study highlights the effectiveness of integrated resistivity modeling for preliminary geothermal exploration and provides important insights into the hydrothermal system in the Tanjung Sakti Pumi area. The approach applied in this study can be used as a reference for similar geothermal investigations in structurally controlled volcanic regions.

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