

Identification of the Way Ratai Geothermal System and Menanga Fault Through Derivative Analysis and 3D Modeling of Gravity Data

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Abstract

The gravity method is one of the most commonly used geophysical exploration methods for deep ground structure, especially in the geothermal prospect area. In this study the Way Ratai Geothermal System and Menanga Fault have been successfully identified in Pesawaran Regency, Lampung Province using full Bouguer anomaly information. The interpretation process was also performed through the First Horizontal Derivative (FHD), besides the Second Vertical Derivative (SVD) to emphasize anomalies whilst mapping density contrast limits related with fault and fracture-zones. The subsequent step was to predict the rock density distribution and to assist in interpreting the subsurface geology, 3D modelling was conducted. Results of interpretations show a low density area related to the Way Ratai geothermal system and linear anomaly patterns, which are believed to correspond the Menanga Fault. These results indicate that there are permeable bodies which act as pathways for the hydrothermal fluids to migrate. The tectonic control has been proved to be the significant preparation mechanism for geothermal system. In general, it has proved that the derivative or 3D modeling of the gravity method would be viable in geothermal survey.

Keywords: Gravity method, First Horizontal Derivative (FHD), Second Vertical Derivative (SVD), 3D modeling, geothermal system.

I. INTRODUCTION

Geophysical techniques are crucial to obtain information about the subsurface properties. Gravity method is one of the most commonly employed; such a technique could determine the differences in rock density below the Earth with respect to gravity and requires audio magneto telluric (AMT) data [1]. These density anomalies may be related to different geological structures, (e.g., faults, fracture zones, intrusive rock domes and alteration zones), which are usually closely associated with the geothermal systems [2].

Area of Way Ratai and its surrounding, including Sesar Menanga zone in Lampung, is one of the promising geothermal fields that sited in such a complex geological situation where tectonic and volcanic activities are dominantly presented [3]. The existence of the active fault and surface anomalies, such as hot springs, suggests a large hydrothermal system in this region [4]. In this regard, the gravity method can be employed to delineate subsurface

structures serving as conduits for geothermal fluid movement or as heat reservoirs [5].

By the use of the derivative analyses such as First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) gravity anomalies can be analyzed in finer details to extract short-wavelength features of density contrast boundaries which are frequently related with faults or lithological boundaries [6]. It is valuable to carry out a 3-dimensional solid modeling of the complete residual Bouguer anomaly data, to reveal the internal structural complexity and complement other interpretation of overall geothermal activity that needs consideration also on inter-dependent process [7].

The purpose of this study is to recognize the subsurface in relation to derivative and other methods, do processing with derivative method and horizontal gradient analysis, as well as recognize and interpret the results of processing. The study has been carried out in the geothermal potential area of Way Ratai, administratively located in Pesawaran Regency, Lampung Province, and includes a

surrounding area of Padang Cermin District. The research area belongs to Way Ratai Geothermal Working Area (WKP) Government Determination, with hilly and valley topography, can be reached by the road takes 40–50 km from Bandar Lampung City.

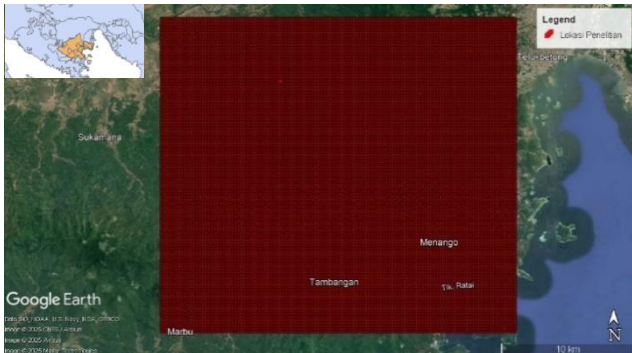


Figure 1. GGMPlus Plot Research Area Location

Geological background The Way Ratai area is situated in the southern part of the Sumatra Island that is affected by strong tectonic and volcanic processes. It belongs to the southern Sunda Volcanic Arc caused by the subduction of Indo-Australian Plate under Eurasian Plate. This mechanism activates and deactivates volcanic fields, as well of geologic features (for instance faults and folds) that almost completely characterize the morphology of the area.

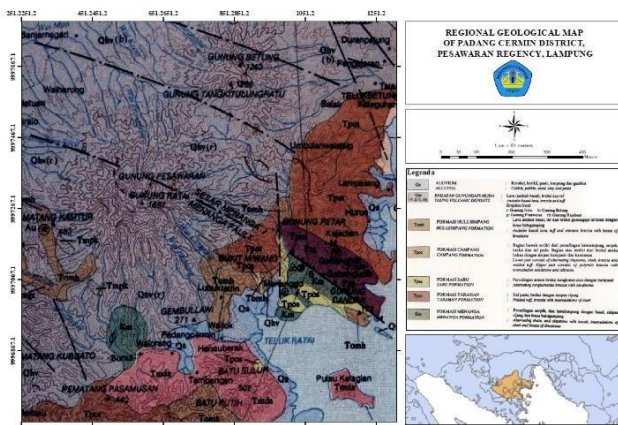


Figure 2. Regional Geological Map

The rock stratigraphy of the Way Ratai area covers several rock units ranging in age from Tertiary to Quaternary, starting from the youngest unit Qa (Alluvium) which is composed of gravel, pebbles, sand, clay and peat by fluvial sedimentation up to young volcanic deposits (Qhv) composing of andesite basalt lava breccias, and tuffs resulting from the eruption activity of Mount Ratai Mount Betung Mount Pesawaran and Mount Rajabasa. older which is the Hulusimpang Formation (Tomh), compsed of andesite-basalt lava, tuff, volcanic breccia and limestone lens which was altered by hydrothermal due to magmatic intrusion. The drill core is the

pivotal section in the geothermal system, since it might possibly be a storage area and metal mineralization. Geothermal manifestations, such as hot springs, rock alteration, and sinters though under-exploited occur are present in this area which suggests the occurrence of hydrothermal activity at shallow depths with Menanga Fault as a major structure that influences the flow of geothermal fluids to the surface.

Previous research has been support the assessment of geothermal potential in Way Ratai. [8] The spectral analysis allowed us to distinguish (i) the regional rock depth of the study area, and (ii) residual gravity anomalies associated with hidden deep geological structures, around a depth of 1.8 km; however, there are located regions with resi dual anomaly where intrusive bodies or faults act as geothermal system controllers. [9] successfully recognized geothermal reservoirs in the Lubuk Badak and Miwung Hills on the basis of low density, by gravity data studies combined with 3D inversion models and resistivity. They identified three other reservoirs in Mount Balirang, Mount Rajabasa and south of Pangkul Hot Spring at depths of 1,000–1,500 m and considered the faults and lithologies to act as separating boundaries between reservoirs. Instead, [10] investigated the rocks' thermal properties at Way Ratai based on thermal conductivity measurements, which reveal substantial differences in mineral composition and porosity among the rock types. In rocks of high conductivity are the good conductors (or “heat pipes”), and in rocks of low conductivity, the cap rocks which retard heat loss to the overlying strata from this source. The findings of these studies are crucial for precise geothermal modeling, positioning the drilling in place and utilizing the geothermal reserves in future.

II. MATERIALS AND METHODS

1.1 Gravity Data Processing

The data used in this study are secondary data obtained from the GGMPlus model released in 2013. The dataset, which covers an area of about 12 km², is made up of gravity disturbance (dg) values that have been processed to create Free-Air Anomaly (FAA) data.

The gravity data were processed using Microsoft excel to derive the Average Density, Bouguer Correction (BC) and Simple Bouger Anomaly (SBA), using topographic information observed gravity values. The average surface density was estimated using the Parasnis method, which applies the gradient equation:

$$y = mx + c \quad (1)$$

m : Slope in Parasnig graph, representing subsurface density estimation (g/cm³)

c : Intercept of the linear regression line in Parasnig method

Equation 1 is the equation of a straight line in slope-intercept form.

Where the y-axis is calculated from Free-Air Anomaly (FAA) values (*g_{obs}* - *g_n* + 0.3086*h*), and the x-axis is obtained from elevation multiplied by 0.04192. The slope (*m*) represents the estimated density value. The Parasnig method can also be expressed as:

$$\Delta g = g_{obs} - g_n + 0.3086h - 0.04193\rho_o \quad (2)$$

$$g_{obs} - g_n + 0.3086h = \rho_o(0.04193h) + \Delta g$$

Δg : Gravity anomaly difference or correction value (mGal)

g_{obs} : Observed gravity value at the measurement point (mGal)

g_n : Normal gravity value based on latitude using the reference ellipsoid (mGal)

H : Elevation or station height above sea level (m)

ρ_o : Assumed Bouguer density or crustal density used in calculation (g/cm³)

Equation 2 is the Bouguer Anomaly Equation

The obtained density value was then applied to calculate gravity corrections, including Bouguer Correction (BC), terrain correction, Free-Air Anomaly (FAA), and Free-Air Correction (FAC). These corrections were used to derive the Simple Bouguer Anomaly (SBA) and Complete Bouguer Anomaly (CBA). Subsequently, a contour map of SBA in the study area was generated using Surfer 13 software. Regional-residual anomaly separation was performed through spectral analysis, employing the moving average filter with a window size of 17, determined from the spectral analysis results. The moving average method produced the regional anomaly, while the residual anomaly was obtained by subtracting the CBA from the regional anomaly.

1.2 Gravity Data Interpretation

After obtaining the residual anomaly, derivative analysis was carried out using the First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) with the aid of Oasis Montaj software to

provide a more detailed identification of subsurface fault structures. The FHD method is applied to enhance the boundaries of geological structures that cause gravity anomalies. The first horizontal derivative produces sharp responses in the form of maxima or minima at locations associated with dominant geological structures. The maxima of FHD values can represent the position of faults or other discontinuity zones.

$$FHD = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \quad (3)$$

T : anomaly value

$\frac{\partial g}{\partial x}$: first derivative in the x-direction (east–west)

$\frac{\partial g}{\partial y}$: first derivative in the y-direction

Equation 3 is the First Horizontal Derivative (FHD) Equation

SVD analysis of the residual anomaly was done using the Elkins matrix filter. This technique enhances gravity anomalies resulting from shallow geological structures. Since the SVD is derived from the horizontal derivatives of the residual anomaly data, it enhances the subsurface structural boundaries that could not be clear in the Bouguer anomaly map.

Table 1. Table Matriks Elkins (1951)

0	-0.0833	0	-0.0833	0
-0.0833	-0.0667	-0.0334	-0.0667	-0.0833
0	-0.0334	1.0668	-0.0334	0
-0.0833	-0.0667	-0.0334	-0.0667	-0.0833
0	-0.0833	0	-0.0833	0

It will then be followed by the application of the Second Vertical Derivative analysis, by which the fault types could be identified as either a normal fault or a reverse fault. The identification will be done using mathematical equations representing the relation of SVD values with gravity anomaly gradients, from which the resulting positive and negative patterns can be interpreted to be indicative

of fault structures with particular displacement directions.

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_{max} > \left(\frac{\partial^2 g}{\partial z^2}\right)_{min} \quad \text{Normal Fault}$$

$$\left(\frac{\partial^2 g}{\partial z^2}\right)_{max} < \left(\frac{\partial^2 g}{\partial z^2}\right)_{min} \quad \text{Reverse Fault}$$

III. RESULTS AND DISCUSSIONS

The research of this article does not involve in the field measurement of gravity survey data, however the processing and interpretation on them. The Bouguer anomalies were corrected for Gravity Tidal Correction and processed in Oasis Montaj and Surfer software. Derivative maps including the FHD (First Horizontal Derivative), SVD (Second Vertical Derivative) and regional-residual anomaly ones were constructed to delineate the buried structural edges, density contrasts and possible geothermal anomalies.

Grav3DC and Numeri were used for 3-D modeling of the regional geological data and the reduced anomalies, respectively. The density distributions obtained from inversion showed the intrusives and fracture zones linked with geothermal system. These detections were then linked to surface signals, including hot springs, hydrothermal alteration and topography, to provide an integrated view of the Way Ratai geothermal system.

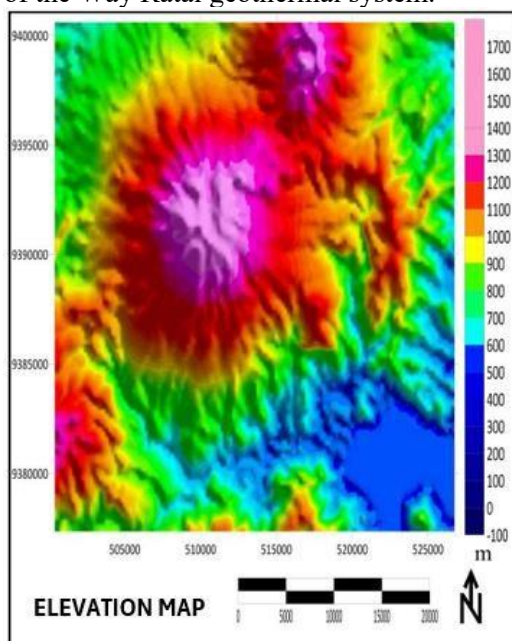


Figure 3. Elevation Map

The CBA map indicates anomaly values from 20–85 mGal. Low anomalies in the central zone, which have values between 20–40 mGal, correspond to the low-density rocks such as tuff and clay interpreted as the geothermal reservoir zones with high porosity and

permeability. Transitional anomalies, with values of 50–65 mGal, represent the fault-related interfaces that facilitate the circulation of geothermal fluids, and high anomalies, with values of 70–85 mGal found in the southwest, reflect dense igneous rocks such as andesite and basalt likely functioning as the heat sources of the systems.

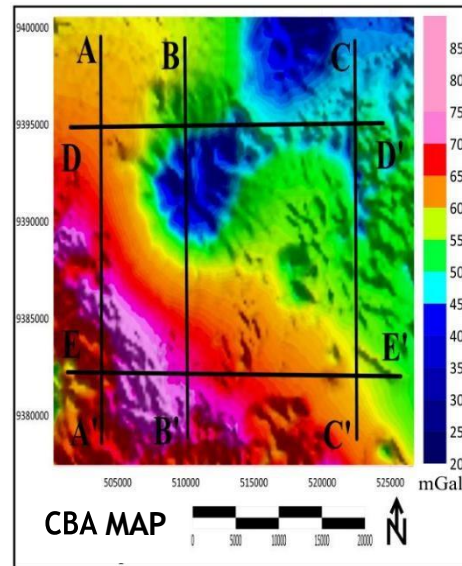


Figure 4. CBA (Complete Bouguer Anomaly) Map

From an interpretative point of view, the lateral high-low anomaly contrast is indicative that deep magmatic intrusions constitute the main thermal engine of this hydrothermal system. This contrast is indicative of a structurally controlled geothermal system in which the interaction between brittle volcanic cap rocks and ductile magmatic bodies controls heat transfer processes.

The regional anomaly map shows differences of deep-rooted densities from low-density volcanic units (Qhv and Tpot Formations) to higher density intrusive rocks (Tomh and Tpos Formations). The steep anomaly gradient results from the Menanga Fault, which is one of the dominant structures regulating subsurface heat flow. The residual anomaly map outlines shallow features, with negative values (–13 to –7 mGal) characterizing modified and/or fractured rocks acting as fluid reservoirs and positive anomalies (+2 to +7 mGal) delineating dense intrusions that may function as local heat sources. Interpretatively, the spatial combination of these anomaly patterns indicates an active fault–fracture system that promotes vertical and lateral flow of heat. This relationship suggests that geothermal activity of Way Ratai volcano was dominantly controlled by structural corridors maintaining the connectivity pathways between deep magmatic heat and shallow reservoir levels.

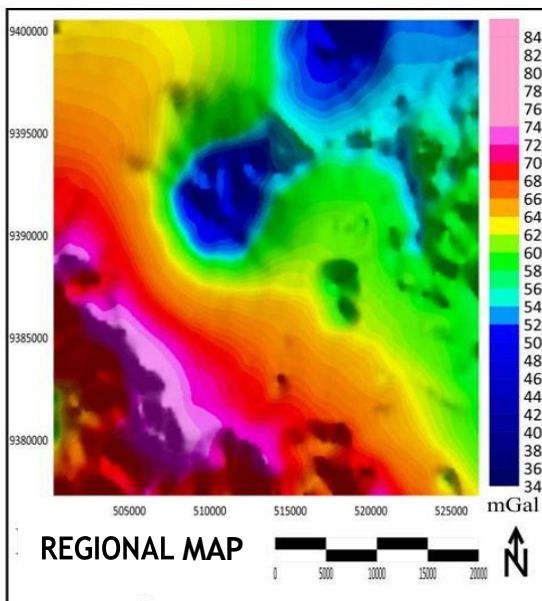


Figure 5. Regional Map

Analysis of regional maps of the Way Ratai area based on regional Bouguer anomaly values shows differences in gravity values from low to high, representing the distribution of deeper rock densities. Dark blue to light blue colors in the central to northern parts of the map indicate low anomalies ranging from 34 to 52 mGal, which indicate the presence of low-density rocks at depth, such as altered rocks, tuffs, and clays belonging to the Qhv (Young Volcanic Deposits) and Tpot (Tarahan Formation) formations. These two formations consist of breccia, tuff, and lava, which at great depths can undergo further weathering and hydrothermal alteration that reduces their density.

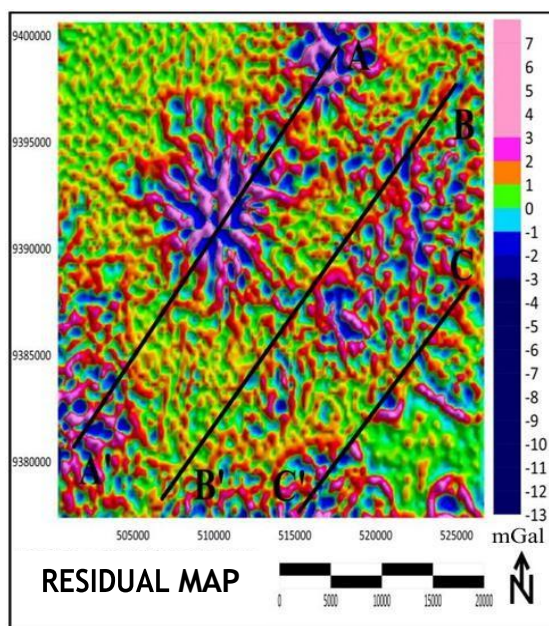


Figure 6. Residual Map

The FHD response shows clear lateral density contrasts in the vicinity of important structural boundaries. A–A' section exhibits a lithological

boundary between dense igneous rocks (Tomh/Tpos) and light volcanic rocks (Qhv), being understood to be a thrust fault zone. Localised high FHD zones, identified again on the B–B' and C–C' lines throughout much of the survey, suggests multiple parallel fault traces indicating a complex, fractured subsurface that acts to facilitate fluid pathway migrations. The SVD map highlights short wavelength structural variations with regions of negative and positive anomalies, marking radial and concentric patterns. Negative areas are equivalent to the disrupted and fractured rocks, while positive areas stand for solid non-altered formation. This radial arrangement is probably a palaeo-caldera that has been reactivated by tectonism. Such reactivation would have increased the permeability of the host rocks and hence allow for hydrothermal fluids to circulate in this geothermal field.

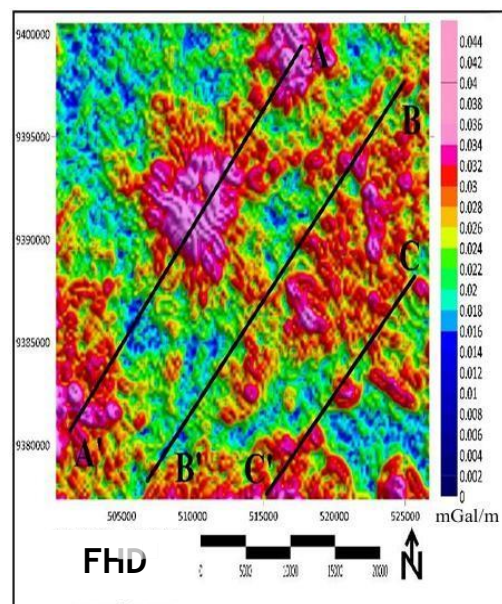


Figure 7. FHD (First Horizontal Derivative) Map

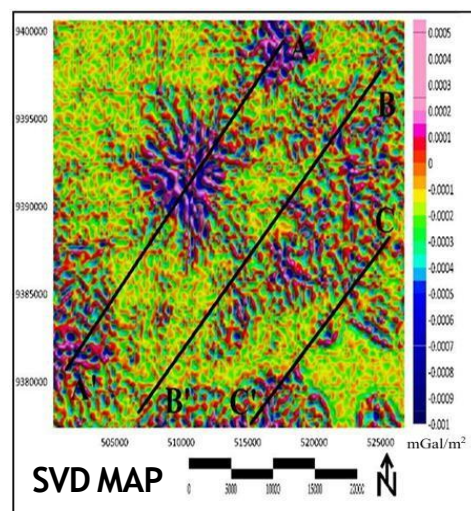


Figure 8. SVD (Second Vertical Derivative) Map

The 2D subsurface model presents a marked contrast between the dense rocks of Tomh/Tpos and the lighter volcanic deposits of Qhv/Tpot. A major interpreted fault, probably part of the Menanga Fault system, cuts both aforementioned formations and is acting as a conduit for heat flow upwards. The inclination of this fault plane reflects extensional tectonic conditions, consistent with geothermal dynamics. The 3D model provides further insight into the spatial relationships of geothermal components. The blue zone in the center indicates the reservoir hosted in the Tomh Formation. The rocks are dominated by porous and permeable lithologies, which constitute the caprock at the top of the Qhv Formation, albeit relatively less permeable. At the bottom lies the red zone made up of high-density intrusive rocks, Tpos/Tomh, interpreted as the principal heat source. Vertical structuring attests to a thermally integrated system in which faults and fractures link deep magmatic heat sources with shallow hydrothermal reservoirs.

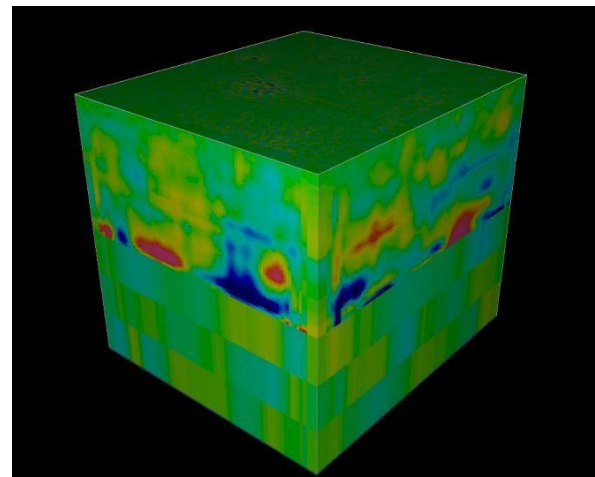


Figure 10. 3D Gravity Inversion Model

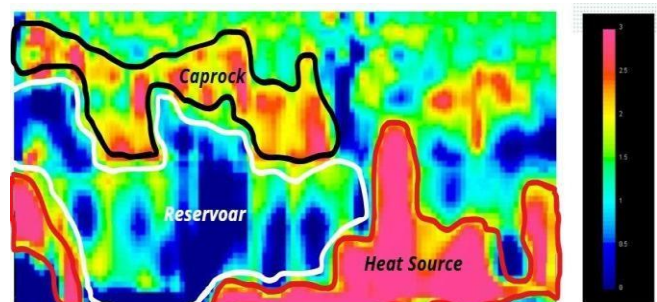


Figure 11. 3D Cross-Section

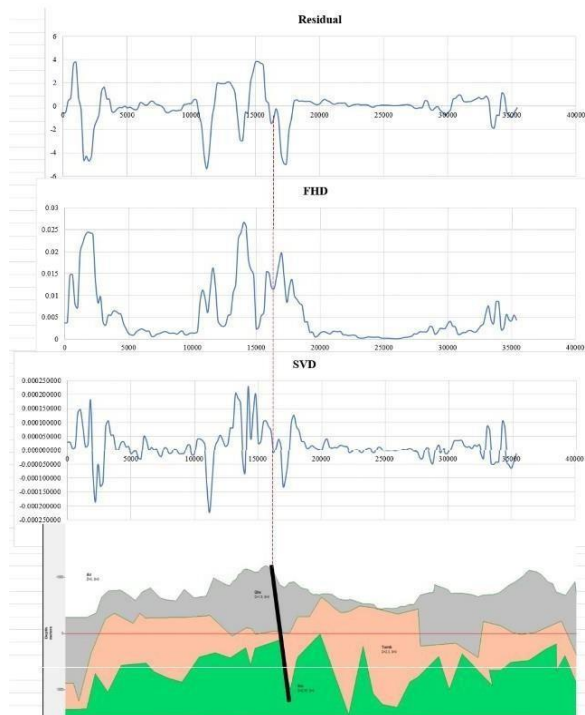


Figure 9. 2D Cross-Section Results

IV. CONCLUSIONS

Based on regional geological conditions, the Way Ratai area is part of a Quaternary volcanic complex dominated by volcanic products from Mount Ratai and its fracture system. The results of the derivative analysis show that this method is able to clearly describe the existence of major faults and low-density geothermal zones, which appear as high-value linear features on the FHD map with a dominant northwest-southeast and northeast-southwest direction. The application of derivative methods, specifically First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD), effectively confirms the density contrast boundaries associated with fault structures and fracture zones, enabling a more detailed interpretation of subsurface discordances. These results were then reinforced by 3D modeling that confirmed the subsurface configuration of the geothermal system, revealing a clear spatial relationship between the reservoir zone, cap rock, and heat source at depth. From these interpretation results, the Menanga Fault was identified as the main fluid pathway controlling the circulation and migration of hydrothermal fluids in the Way Ratai geothermal system.

Overall, the integrated application of the FHD–SVD–3D approach has been proven to improve the accuracy and reliability of subsurface interpretation, while providing a strong geophysical basis for exploration and assessment of geothermal resource potential in the Way Ratai region.

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