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Three-Dimensional Subsurface Structural Modeling of a Geothermal Prospect in Banda-Neira, Central Maluku, Based on GGMPlus Gravity Data

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ABSTRAK

Kepulauan Banda terletak di daerah pertemuan tiga lempeng kerak bumi, yaitu lempeng Indo-Australia, Lempeng Eurasia, dan Lempeng Pasifik. Kepulauan Banda Neira memiliki potensi panas bumi yang cukup besar untuk dapat dimanfaatkan. Oleh karena itu, penelitian ini dilakukan dengan tujuan untuk mengetahui struktur bawah permukaan di daerah potensi panas bumi tersebut dengan menggunakan metode gravitasi. Hasil dari analisa *derivative* menunjukkan prospek panas bumi Banda Neira dikontrol oleh patahan yang berbeda, patahan akibat depresi kaldera Banda Neira tua dan patahan lokal yang terkonfirmasi dengan jenis patahan naik *(reverse fault)* dan pada pemodelan 3D teridentifikasi lapisan reservoar panas bumi diperkirakan memiliki densitas sebesar 1,67 – 1,77 gr/cm^3 yang terdiri dari campuran tuff dan minor lava, dimana isi dari reservoar ini adalah dominan air dikarenakan nilai densitas yang relatif rendah dengan kedalaman 150 – 700 m, sedangkan pada *slicing* kedua berarah utara-selatan terlihat bahwa terdapat lapisan *cap rock* dengan kedalaman 0 – 300 m dari titik pengukuran dengan nilai densitas 1,67 – 1,77 gr/cm^3 dan lapisan reservoir berupa batuan vulkanik dengan kedalaman 200 – 700 m dari titik pengukuran dengan nilai densitas 3,57 – 3,67 gr/cm^3.

Keywords:
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The Banda Island is located at the convergence of three major tectonic plates: the Indo-Australian Plate, the Eurasian Plate, and the Pacific Plate. Banda Neira Island holds significant geothermal potential that can be utilized as an energy resource. Therefore, this study was conducted to investigate the subsurface structure of the geothermal prospect area using the gravity method. In the gravity data processing, derivative analysis results indicate that the Banda Neira geothermal prospect is controlled by multiple fault systems: faults associated with the collapse of the older Banda Neira caldera, as well as local faults confirmed to be reverse faults. In the 3D modeling results, a geothermal reservoir layer is identified with an estimated density of 1.67–1.77 g/cm³, interpreted as a mixture of tuff and minor lava. The reservoir is predominantly water-filled, inferred from its relatively low density, and is located at depths of approximately 150–700 meters. In the second slicing profile, oriented north-south, a cap rock layer is observed at depths of 0–300 meters from the measurement point, with a density of 1.67–1.77 g/cm³, overlying a volcanic reservoir layer found at 200–700 meters depth, with higher densities ranging from 3.57–3.67 g/cm³.

I. INTRODUCTION

The collision and movement of Earth's crustal layers generate radioactive processes at depth, leading to the formation of magma with temperatures exceeding 2000°C (Pertamina,2007). A geothermal system is typically associated with volcanic activity that develops along island arcs as a result of plate tectonic movements on the Earth's surface, which give rise to volcanic formations (Suharno,2004). The fundamental requirements for the formation of a geothermal (hydrothermal) system include a substantial heat source, a reservoir to accumulate heat, and a cap rock layer that traps the thermal energy. A productive geothermal reservoir must possess high porosity and permeability, adequate size, elevated temperatures, and sufficient fluid content. An impermeable or low-permeability cap rock overlying the reservoir is essential to prevent the escape of the accumulated hot fluids (Hidayat & Abdul,2011).

Indications of the existence of geothermal system activity in the Banda-Neira area are indicated by the appearance of geothermal manifestations in several locations. Geothermal manifestations include hot springs with temperatures of 35-64 °C, fumaroles with temperatures of 93 0C and alteration rocks. The activity of the geothermal system in this area is most likely related to the volcanic activity of Banda Api Volcano (Aditya Lano et al., 2016). The formation of a complex geothermal system in the Bandaneira area is closely related to the subduction between the Indian Ocean Plate, the Australian Continental Plate, the Eurasian Continental Plate, and the Pacific Ocean Plate with localised plates such as the Halmahera, Sulawesi, and Irian Plates. Referring to the regional geological map of Moa, Damar, and Bandaneira sheets.

One of the effective methods in identifying geothermal potential because it can detect variations in rock density values so that it can help to analyse hidden geological structures that are important for geothermal systems and changes in the Earth's gravitational acceleration caused by local anomalous objects. This anomaly is denoted by Δg, when compared to the Earth's gravitational field it is very small ($\Delta g << g$). Gravity anomaly can only be measured with the Earth's gravitational field in the same direction (Gregg et al, 2010).

The study area consists of lava rock, volcanic breccia, and coral limestone of Tertiary to Quaternary age (D. A. Agustiyanto et al., 1994). This study aims to investigate the geothermal potential of Mount Lawu by analyzing its geological structure and tectonic activity. Specifically, it seeks to use gravity methods, such as data from the GRACE, GOCE, and EGM-2008 satellites, to measure gravitational variations, which could provide an early indication of geothermal resources without the need for invasive exploration techniques (Yufajjiru L et al., 2020). The contribution of gravity method to geothermal also shows efficient modelling results and is able to detect the interface between underground rocks and sedimentary cover in the southern part of the Gulf of Suez-Sinai, Egypt (H. Atef et al., 2016).

II. METHOD

2.1 Stratigraphy of Mount Hamiding

The Banda Island consists of a cluster of islands, several of which are classified as major islands, including Lonthor Island, Banda Neira, and Banda Api. This study focuses on the Banda Neira area, which serves as the administrative center of the archipelago. Geologically, Banda Neira is closely associated with Lonthor and Banda Api Islands in the formation of the Banda Api Volcano Complex (Chris, 2010).

Geologically, Lonthor, Neira and Banda Fire Islands are interrelated in terms of the formation of the Banda Fire Mountain Complex. The emergence of geothermal manifestations in the Banda Api Mountain Complex indicates the existence of geothermal potential in the region. To obtain information on the geothermal aspects of the Banda Volcano Complex area, geoscience data such as geological and geochemical data are required (Matahelumual, 1988)

The geological structures found in the investigation area are caldera, crater and fault. The caldera structure found on Neira Island is an almost circular ridge with steep ridges, thought to be the rest of the caldera wall. Crater structures can be found at the summit, slopes and foot of Mount Banda Api (Figure 1). The existence of normal faults is estimated to pass through the summit and several eruption centres on the northern and southern slopes of Mount Banda Api with a relative north-south direction, while the faults around Mount Papen have a relative northwest-southeast direction (Modifikasi dari Agustyanto et al.,1994).

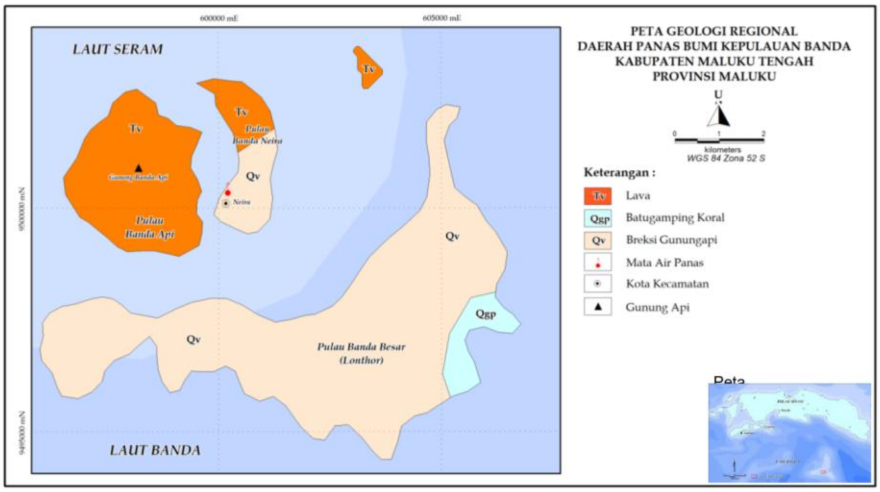

Figure 1. Regional Geological Map of the Banda Island, Central Maluku (Modified from Agustyanto, et al., 1994)

2.2 Gravity Methods

The theory underlying the gravity method is based on the law of gravitation proposed by Sir Isaac Newton, which states that the force between two particles with masses m_1 and m_2 is directly proportional to the product of their masses and inversely proportional to the square of the distance between them, as expressed in the following equation (Dian & Rustadi, 2019):

$$F = G\frac{m_1 m_2}{r^2} \tag{1}$$

The gravity method is processed to yield Complete Bouguer Anomaly (CBA) values. The gravity anomaly data obtained from satellite measurements are already corrected up to the level of free-air correction. Therefore, the additional corrections required include free-air correction, terrain correction, and Bouguer correction, which serve to reduce the gravitational effects of rock masses in the Earth's crust located between the reference spheroid and the measurement point.

Free-air correction accounts for the effect of elevation on the Earth's gravitational field. The Free-Air Correction (FAC) is calculated using the expression 0,3085h, which is then combined with the other corrections, resulting in the following equation:

$$FAA(R+h) = g_{obs} - g(R) + 0{,}3085h \tag{2}$$

In the Free-Air Anomaly (FAA) equation, $g\ obs$ represents the observed gravitational acceleration, h denotes the corrected elevation, and $g(R)$ is the gravitational acceleration value corrected for latitude (Helda & Mirtha, 2019).

Bouguer correction is applied to reduce the gravitational effect caused by the presence of rock mass between the measurement point at elevation h above Mean Sea Level (MSL) and the reference level. This is necessary because the measured gravity value is higher than the gravity value that would exist on an equipotential surface (Bagas et al, 2017).

$$BC = 0{,}000419\Delta h\rho \tag{3}$$

BC represents the Bouguer Correction (mGal), Δh is the elevation difference between the measurement point and the datum (m), and ρ is the density (kg/m^3).

Terrain Correction accounts for the influence of surrounding material near the measurement point, which contributes to the observed gravity values. Therefore, topographic correction must be applied, especially in areas with irregular terrain such as mountain ranges or hills. The gravitational effect of a given sector can be calculated using the following formula (Bagas et al, 2017):

$$TC = G\rho\theta\left[\left(r_2 - r_1\right) + \sqrt{r_1^2 + z^2} - \sqrt{r_2^2 + z^2}\right] \tag{4}$$

TC is the Terrain Correction (mGal), G is the universal gravitational constant, ρ is the rock density (kg/m³), θ is the angle formed by the compartment (degrees), *r* is the inner radius (m), *R* is the outer radius (m), and *z* is the height of the hill or depth of the valley (m).

2.3 Derivative Analysis

The First Horizontal Derivative (FHD), also known as the Horizontal Gradient, is used to highlight the edges of a geological body that cause gravity anomalies (Zaenudin et al., 2013). The horizontal gradient method is therefore useful for delineating the location of boundaries marked by horizontal density contrasts in gravity data (Cordell, 1979, cited in Zaenudin et al., 2013). The FHD value can be calculated using the following equation (Krisna,2018):

$$FHD = \frac{g_{(i+1)} - g_{(i)}}{\Delta x} \tag{5}$$

g is the anomaly value (mGal), Δx is the distance interval along the profile (m), and FHD is the First Horizontal Derivative.

The Second Vertical Derivative (SVD) can be used to assist in interpreting structural types from Bouguer anomaly data caused by normal or reverse faults. SVD acts as a high-pass filter, highlighting residual anomalies associated with shallow structures, which helps to identify the type of fault—whether normal or reverse (Setyanta, 2007). Theoretically, this method is derived from Laplace's equation; therefore, the SVD value can be calculated as the second derivative using the following equation:

$$SVD = \frac{g_{(i+1)} - 2g_{(i)} + g_{(i+1)}}{\Delta x^2} \tag{6}$$

Terrain Correction accounts for the influence of surrounding material near the measurement point, which contributes to the observed gravity values. Therefore, topographic correction must be applied, especially in areas with irregular terrain such as mountain ranges or hills. The gravitational effect of a given sector can be calculated using the following formula (Bagas et al., 2017):

$$\Delta g = 2\pi G\rho\left(h_2 - h_1\right)\ln\frac{r_2}{r_1} \tag{7}$$

2.4 Research Stages

The focus of this study is on the Banda Neira region in Central Maluku, one of Indonesia's promising geothermal prospect areas due to its location within a volcanic zone. The formation of the geothermal system in Banda Neira is believed to be associated with volcanic activity originating from Mount Banda Api. To investigate the subsurface structure of this geothermal prospect area, a geophysical method capable of imaging subsurface conditions is required.

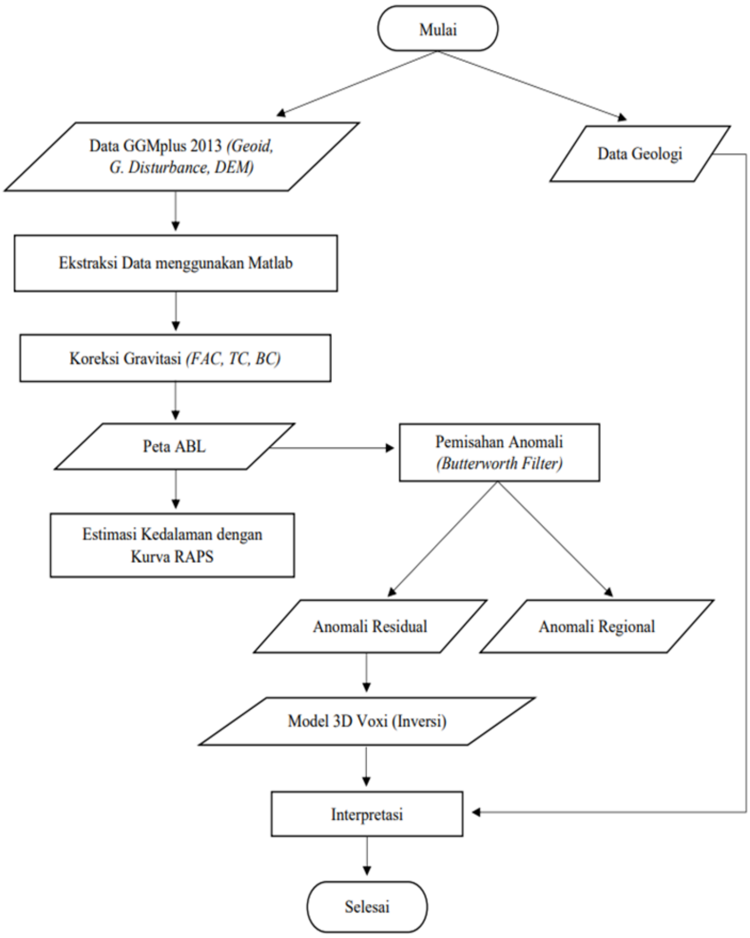

Figure 2. Research Flow chart

III. RESULT AND DISCUSSION

3.1 Complete Bouguer Anomaly (CBA)

After applying the free-air correction, Bouguer correction, and terrain correction, the resulting Complete Bouguer Anomaly (CBA) represents the distribution of gravity anomalies and rock density contrasts in the study area namely, the Banda Neira Volcano region 4°31'23.9" LS and 129°53'17.9" EL, its surroundings caused by subsurface density variations (Figure 3).

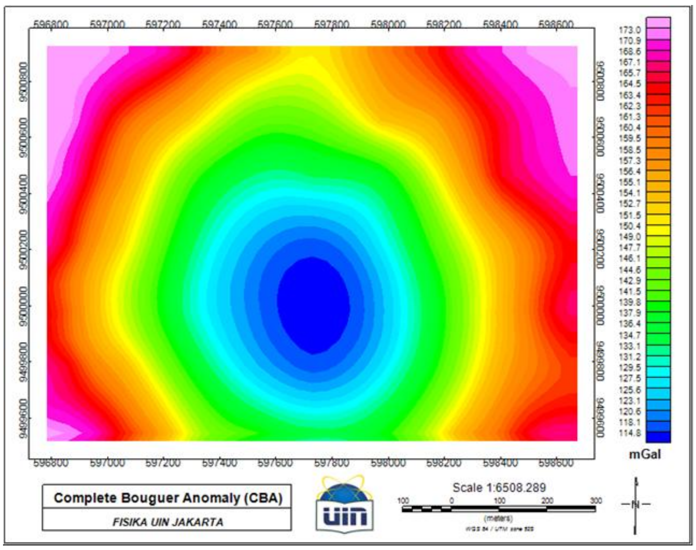

Figure 3. Complete Bouguer Anomaly (CBA) Map

The Complete Bouguer Anomaly (CBA) map shows the presence of both low and high anomalies, indicated by variations in CBA values and contour colors. The resulting CBA values range from 114,8 to 173 mGal. Low anomaly values, ranging from 114,8 to 149 mGal, are located in the central part of the map, represented by blue to green colors. Moderate anomaly values range from 150,4 to 161,3 mGal, while high anomaly values range from 162,3 to 173 mGal. The anomaly contours tend to decrease toward the center. According to the Parasnis method, the average rock density in the study area is relatively high, at 2,67 g/cm³. However, this CBA map still contains a mixture of residual (shallow) and regional (deep) anomalies. These regional and residual anomalies interact and overlap, which can lead to ambiguous interpretations. Therefore, separating the regional and residual anomalies is necessary to eliminate this ambiguity.

3.2 Regional Anomalies and Residual Anomalies

After applying anomaly separation using the Butterworth filter, residual anomalies (shallow anomalies) and regional anomalies (deep anomalies) were obtained (Figure 4). As shown on the residual anomaly map (Figure 4.a), the distribution of gravity anomalies exhibits significant heterogeneity at the surface due to the shallow nature of these anomalies, which are caused by near-surface rocks or layers. The regional anomaly contours appear smoother and resemble the CBA contours, indicating variations in deeper rock formations. On the residual anomaly map, the gravity anomaly values range from -36,7 to 16,4 mGal. The residual anomaly contours are rough and heterogeneous, reflecting variations in shallow rock formations. In a more refined residual anomaly map, the gravity anomaly values range from -2,5 to 2,6 mGal.

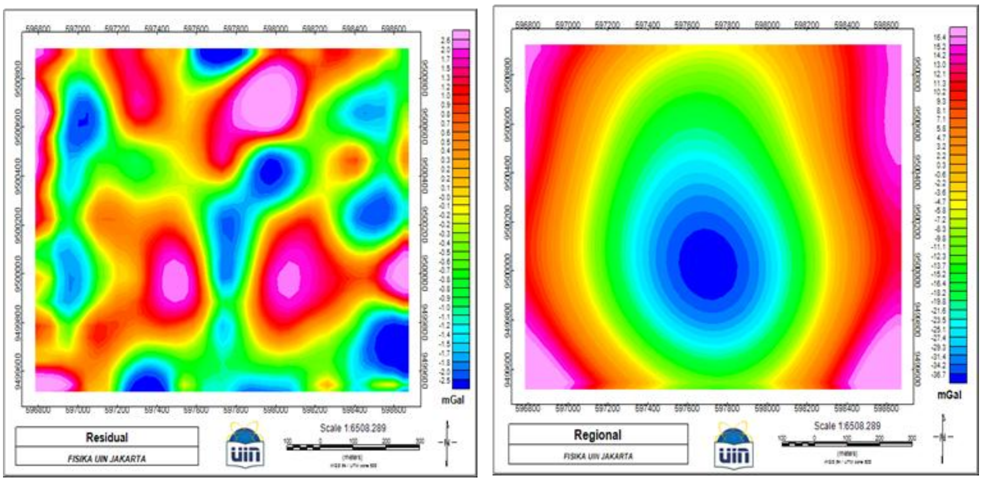

Figure 4. (a) Residual Anomaly (b) Regional Anomaly

There are two key focus areas identified on the residual anomaly map. The first, in the southwest, indicates that the geothermal system is likely controlled by the old Neira caldera or the Neira depression, which forms a circular pattern around Mount Banda Neira. This structure creates subsurface fractures that serve as pathways for fluid flow. The second focus area, in the northeast, shows a low anomaly (marked with a black circle), interpreted as a weak zone or an area of rock alteration.

3.3 3D Modeling

In this 3D modeling, two slices were made on the residual anomaly map to validate the 3D model results. The first slice (A-A') is oriented from west to east (W–E), and the second slice (B-B') is oriented from north to southe (N–S). These slice directions were chosen based on the location of low anomaly targets, which are interpreted as reservoir layers dominated by liquid fluids, as liquid fluids typically have low density (Figure 5).

3D inversion modeling was conducted to illustrate the subsurface structure of the Banda Neira geothermal system. In the A–A' model, oriented west to east, a cap rock layer is observed at depths of 0 to 150 m from the measurement point, with a density value of 1,67 to 1,77 g/cm³. Below this, the reservoir layer, consisting of volcanic rocks, is found at depths of 150 to 700 m with density values ranging from 3,57 to 3,67 g/cm³. The error obtained from the inversion modeling result is 9,7.

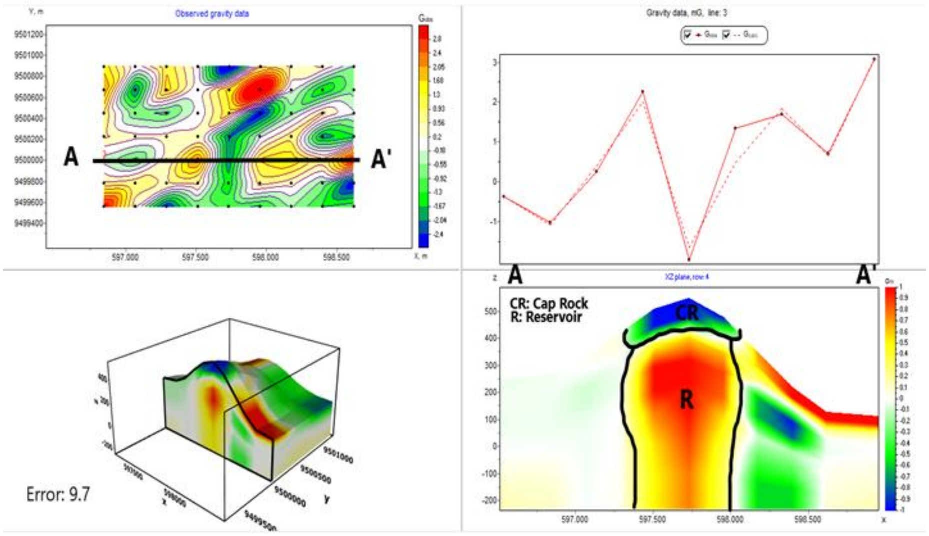

Figure 5. 3D Model Slicing A – A'

In the B–B' model, oriented north–south, a cap rock layer is observed at depths of 0 to 300 m from the measurement point, with density values ranging from 1,67 to 1,77 g/cm³. Beneath this, a reservoir layer composed of volcanic rocks is identified at depths of 200 to 700 m, with density values ranging from 3,57 to 3,67 g/cm³. The inversion modeling resulted in an error value of 9,7.

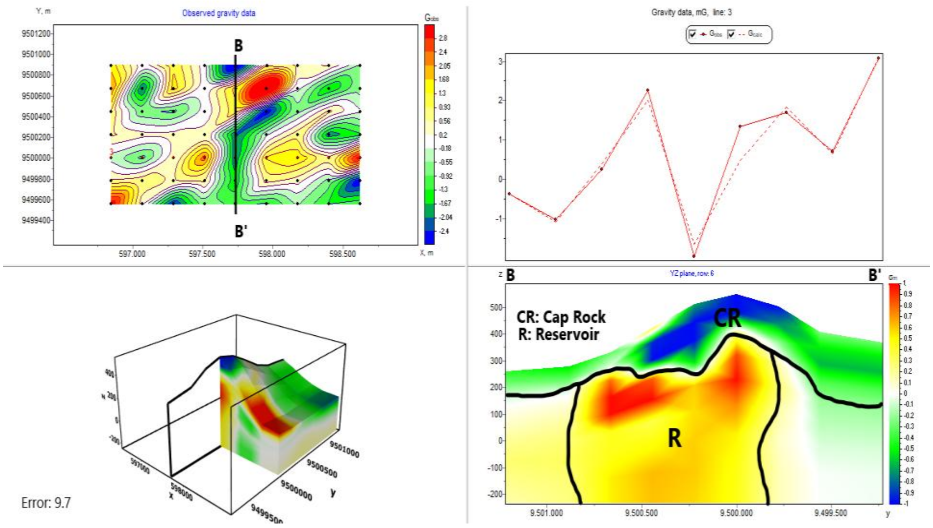

Figure 6. 3D Model Slicing B – B'

IV. CONCLUSION

Based on the results of the gravity-based investigation conducted in the Banda Neira area, it can be concluded that the derivative analysis indicates that the geothermal prospect in Banda Neira is controlled by multiple fault systems—namely, faults associated with the caldera depression of the older Banda Neira system and confirmed local faults of the reverse type. The 3D modeling identifies a geothermal reservoir layer with an estimated density ranging from 1,67 to 1,77 g/cm³, composed of a mixture of tuff and minor lava. The first slice is oriented from southwest to northeast show the reservoir is inferred to be predominantly water-filled, as indicated by its relatively low density, and is located at depths between 150 and 700 meters. In the second slicing, oriented from northwest to southeast, a cap rock layer is observed at depths of 0 to 300 meters from the measurement point, with a density of 1,67 to 1,77 g/cm³, and a volcanic reservoir layer is found at depths of 200 to 700 meters with a higher density range of 3,57 to 3,67 g/cm³.

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