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Gravity Anomaly Evaluation of the Geothermal Field Distribution Around the Seismo-Volcanic Area of Toba Lake

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Gravity Anomaly Evaluation of the Geothermal Field Distribution Around the Seismo-Volcanic Area of Toba Lake

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Abstract. Toba Lake is one of the largest caldera lakes in the world, formed by an enormous eruption about 74,000 years ago. The emergence of hot spring manifestations around Lake Toba is closely related to volcanic activity, which is also controlled by regional geological structures. There are two areas in Lake Toba: Simbolon and Pusuk Buhit, with several geothermal manifestations, such as fumaroles, hot springs, and steaming ground. With the large caldera area, there should be other locations with geothermal potential. Therefore, we analyzed the regional gravity anomaly to find specific patterns that might indicate a possible geothermal field. First, we obtained the data of Free Air Anomaly (FAA) with a resolution of 1.85 km from altimetry satellites and acceleration of gravity anomaly data of 0.1 mGal at 1 minute per grid with an altitude accuracy of 1 meter. In order to acquire the Simple Bouguer Anomaly, the data were corrected. Then, we analyzed the results based on derivative analysis. The result shows that the location has simple Bouguer anomaly values between -26.2 mGal-36.0 mGal with an initial density of 1.74 gr/cc. Furthermore, we speculated that indicated regional patterns of structures and sub-surface properties might be associated with that prospective geothermal.

1. Introduction

In general, geothermal is a form of thermal energy stored in rocks below the earth's surface and the fluids contained therein. The *geothermal system* is a system that allows the occurrence of fluid from the meteoric recharge area into a reservoir above the heat source [1]. According to Santoso [2], geothermal energy is deposit energy as hot water or steam under a specific geological site located several kilometers below the earth's crust. In a geothermal field, there should be a specific hydrological condition of rocks for the availability of geothermal energy.

Geothermal energy is the Indonesian government developing energy to meet the needs of alternative energy throughout Indonesia. One area that has geothermal potential is Lake Toba, North Sumatra. Toba Lake is one of the seismo-volcanic lakes in the world. Modeling subsurface structures around the Lake Toba region can be done using the gravity method to identify subsurface structures in geothermal prospect areas [3,4]. The gravity method is used in geophysics to see or describe structures below the ground surface [5]. The gravity measurement can be done based on the difference in the earth's gravitational field [6,7], which is due to the variation in density laterally. This method can be used as a reference in interpreting and localizing areas suspected to have geothermal potential around the Seismo-Volcanic Lake Toba area [8]. Abdurrahman conducted research in the Lake Toba area [9] with the gravity method resulting in the location of faults and magma chambers around the Lake Toba area. However, this study focused more on looking at the straightness of the faults. Therefore, the study only analyzed the existence of geothermal potential. There has been no discussion regarding the modeling of subsurface structures regarding the distribution of geothermal and geothermal systems, including reservoirs in the Lake Toba region. Therefore, this research needs to be carried out using the gravity method by modeling residual gravity anomalies, and regional gravity anomalies with a broader and deeper coverage area focused on the area.

2. Data and Method

2.1 Data

The data in this research is gravity data from altimetry satellite observation data obtained from TOPEX [10] in the form of Free Air Anomaly (FAA) data. Free-air gravity anomaly changes drastically in the areas with great terrain undulation [11,12]. Data from the altimetry satellite has a resolution of 1.85 km/px, with an accuracy of latitude and longitude for the acceleration of gravity anomaly data of 0.1 mGal at one minute per grid with an accuracy of one-meter height. Figure 1 presents the research area map.

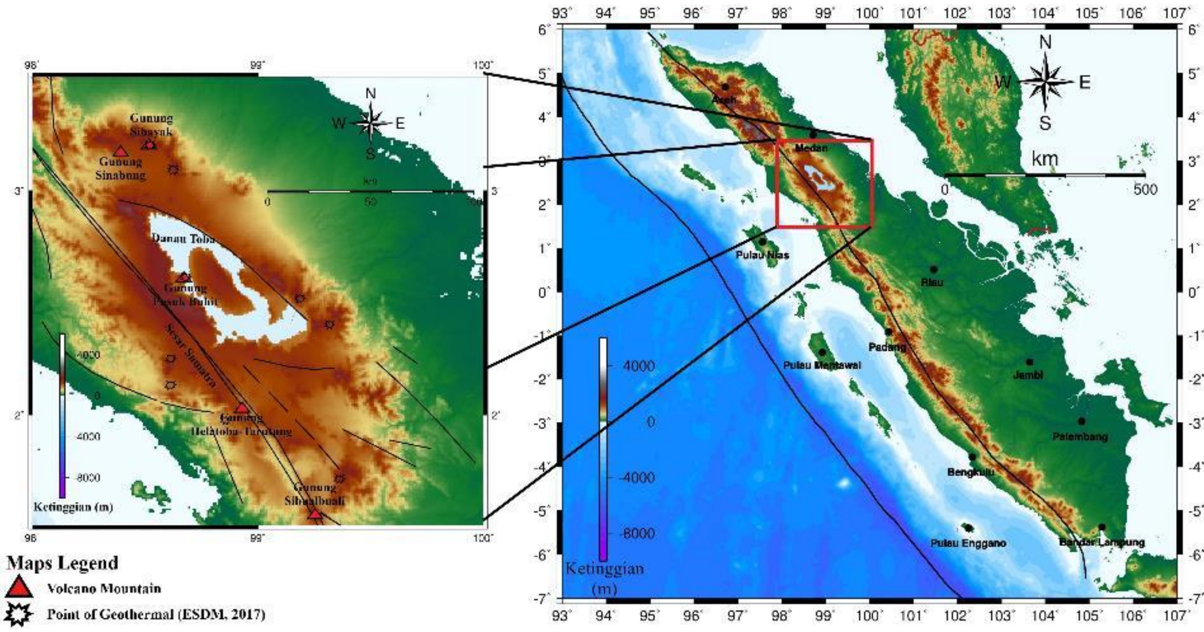


Figure 1. The Research Locations Maps

2.2 Method

We used the TOPEX satellite data, and processed through several corrections. The Bouguer correction was calculated to obtain the Simple Bouguer Anomaly (SBA). First, we need to define the density value to get the Bouguer correction value with the formula:

$$g_{bs} = 2\pi\rho Gh \quad (1)$$

Where G is gravitational constant $(6{,}67 \times 10^{-11} m^3 kg^{-1} s^{-2})$, so equation 2.1 becomes

$$g_{bs} = 0{,}04193\rho h \quad (2)$$

where g_{bs} is bouguer correction (mgal), ρ is rock density $(\frac{kg}{m^3})$, and h is the height of the measurement point (m).

The Bouguer corecction value is used to find the Simple Bouguer Anomaly S_{ba} with the formula:

$$S_{ba} = FAA - g_{bs} \tag{3}$$

where FAA is Free Air Anomaly data, g_{bs} is bouguer correction (mGal)

The effect of topography can also affect the value of the acceleration of gravity in a place, causing an increase or decrease in the value of gravity. To overcome this, the terrain correction obtained through the Hamer Charat equation [13].

$$TC = \frac{2\pi G\rho}{n}\left[R_l - R_D + \sqrt{{R_d}^2 - z^2} - \sqrt{{R_l}^2 - z^2}\right] mGal\ or\ TC = (-0{,}3086 \times h)\ mGal \tag{4}$$

To get the complete bouguer anomaly value, it is calculated using the equation

$$CBA = FFA - g_{bs} + TC \tag{5}$$

where CBA is complate bouguer anomaly, FAA is Free Air Anomaly data, g_{bs} is bouguer correction (mGal) and TC is terrain corections [14].

Then, we used Oasis Montaj software to further analyzed the gravity properties of the area [15].

3. Result

3.1 Simple Bouguer Anomaly (SBA) and Complete Bouguer Anomaly

A simple Bouguer anomaly map for the seismo-volcanic area of Toba Lake is shown in Figure 2. Based on Figure a, areas with high gravitational anomaly values are shown with an interval of 18.7 to 36.0 mGal. In comparison, areas with low gravity anomaly values have an interval of -26.2 to -6.6 mGal. High anomalies are indicated by purple contours, while blue contours indicate low anomalies. Areas indicated to have high anomalies are in the east of the research area, Pusuk Buhit, and around volcanoes and Sumatran fault lines. Based on the results of this 2D simple Bouguer anomaly, it is indicated that Lake Toba's northeast and southwest regions have high anomaly values. Not all geothermal areas and volcanoes are located at high gravity anomaly areas.

Figure 2b is the Complete Bouguer Anomaly (CBA) map obtained after Bouguer and terrain correction. The value of CBA is a total anomaly value that can be separated into several regional and residual anomalies. The distribution of CBA values has a value range from -25.6 mGal to 36.4 mGal. The blue color is the smallest value, the light purple color is the highest, and the yellow color is the medium category value.

Figure 2c is a cross-section of the complete Bouguer anomaly. The cross-section is used to see the condition of the surface contours in the area where the cross-section line passes. The image also shows a complete Bouguer anomaly 3D contour, and the regional and residual anomaly will be separated using the moving average filter [16].

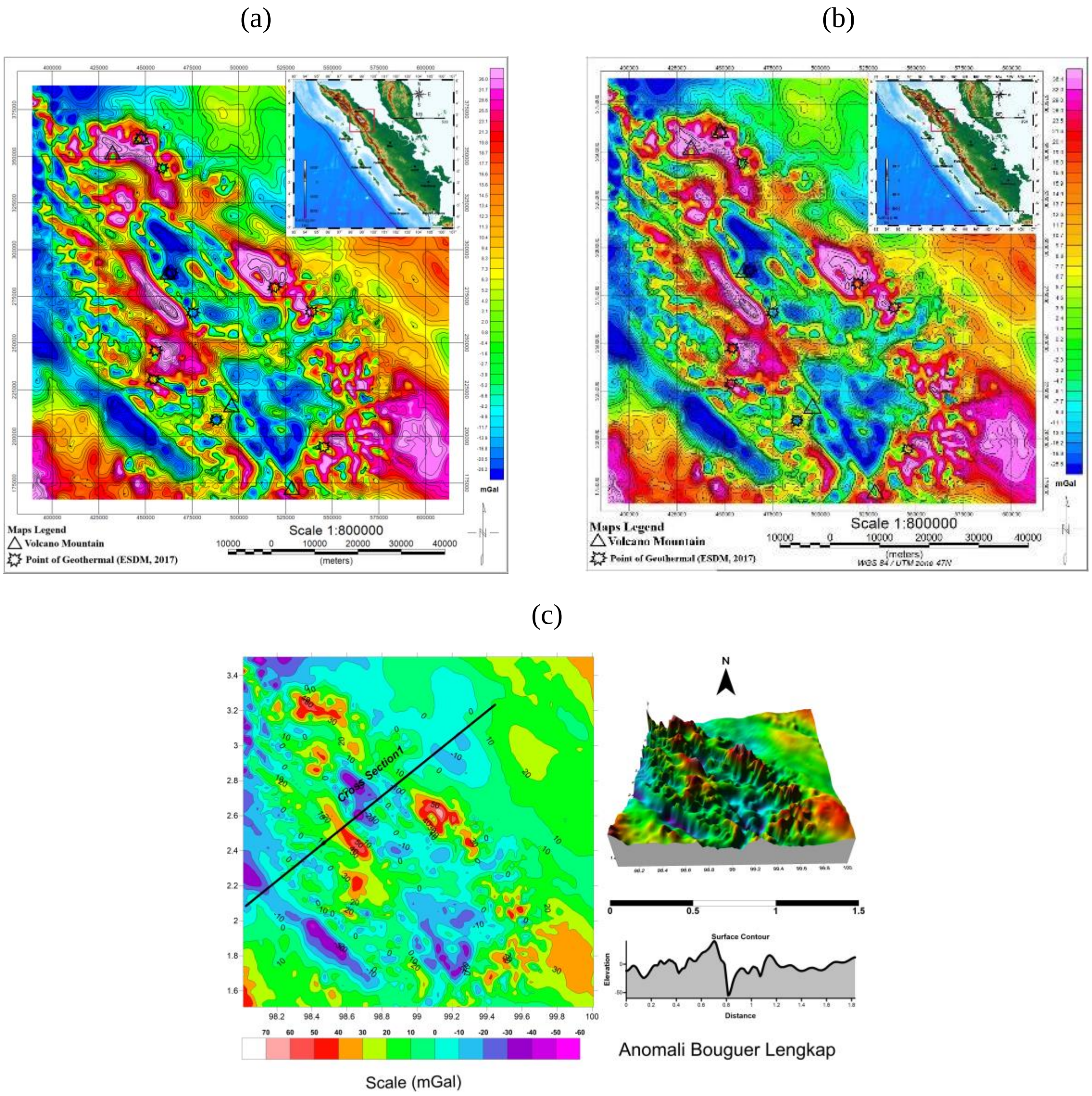
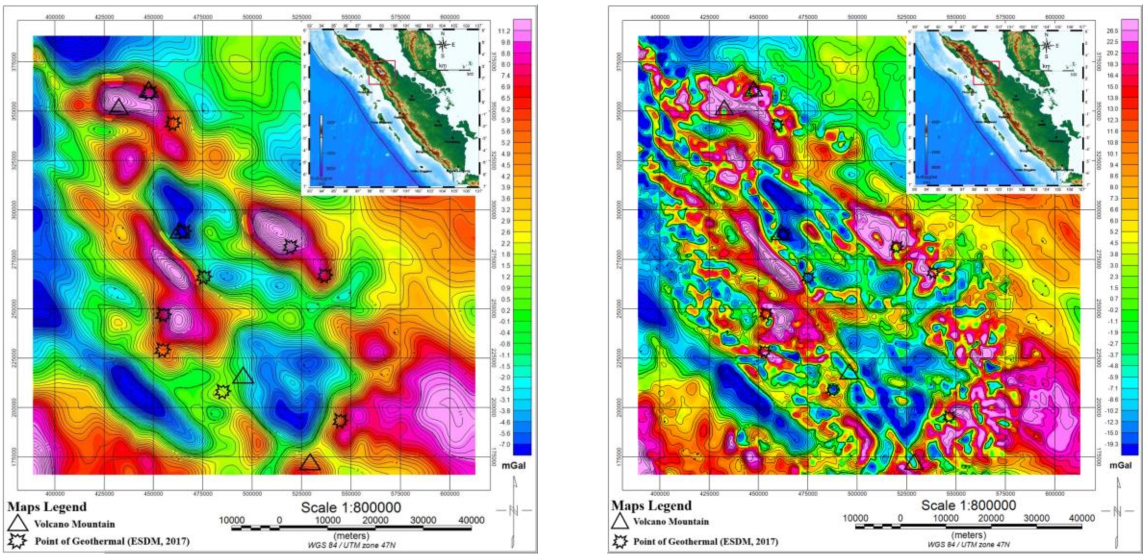


Figure 2. (a) Simple Bouguer Anomaly (SBA) maps, (b)The Complete Bouguer Anomaly maps and (c) the results of the cross section to get surface contour in the Seismo-Volcanic of Lake Toba

3.2 Regional Anomaly and Residual Anomaly

The measured gravity anomalies in the field are a merger of regional and residual anomalies that can be separated by the moving average method. The anomaly separation aims to obtain the source of regional and residual anomalies. The moving average method resulted in the regional anomalies (Figure 3a), and the subtracting of the Bouger anomaly resulted in the residual anomalies from the regional anomalies [17], as shown in Figure 3b.

Figure 3a is a regional anomaly generated from a moving average filter with a window width of 35. The regional anomalies obtained by the spectrum analysis method have values between -7.0 mGal and 11.2 mGal. Based on the depth, the regional anomalies are deeper than residual anomalies, and the noise is shallower than residual anomalies. The residual anomalies are caused by shallow anomalies that have high frequencies and short wavelengths. In contrast, regional anomalies have high frequencies and short wavelengths caused by deep anomalies that have low frequencies and long wavelengths [18]. The moving average method was chosen to separate regional and residual anomalies. In this method, the separation is conducted by calculating the average value of the Bouguer anomaly. The average value is a regional anomaly. Furthermore, the residual anomaly is the difference between the Bouguer and the regional anomaly [19].



(a) (b)

Figure 3. (a) The regional anomaly and (b) residual anomaly maps in the Seismo-Volcanic of Lake Toba

The complete Bouguer anomaly was subtracted from regional anomalies to obtain residual anomalies. From Figure 3b, the residual anomaly value ranges from -19.3 mGal to 26.5 mGal. Mapping residual anomalies can explain the distribution of more specific structures in shallow areas. Although on the residual map, there is negative and positive anomaly value, the anomaly is influenced by several parameters such as the rock body position, density, and size that yield the anomaly.

3.3 FHD Residual

The FHD process is carried out by slicing the zones suspected to be faults from the residual anomaly data. The data to be obtained is the residual Bouger anomaly value as $f(x)$ and the difference in distance between data points. The value $\Delta x$of is 1 because the data are taken sequentially continuously. The next step is to plot the FHD value against the difference in distance between data points, but it cannot be directly analyzed because it is necessary to confirm with SVD data [20].

The FHD residual anomaly map is shown in Figure 5. The FHD filter generated an anomaly map that presents the continuity of a under surface anomaly based on the first derivative horizontally. So that the boundaries of the anomaly can be seen clearly.

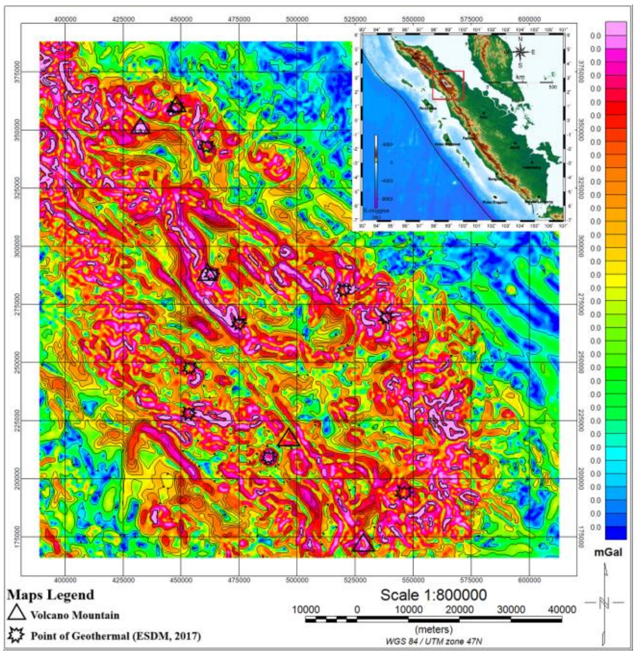


Figure 4. The FHD residual anomaly maps in the Seismo-Volcanic of Lake Toba

4. Discussion

The result of this simple bouguer anomaly (SBA) is indicated by the mGal unit scale, where 1 mGal is equivalent to $10^{-5}\ \mathrm{m/s^2}$. The value represents the response of gravity to rock density, where in this study the average rock density was 1.74 gr/cc. The variation of rock density is influenced by the heterogeneous constituent materials of the earth layer. The high and low value of SBA is also influenced by the mass's position, the tool's density, and the mass's volume. In the area where the fault passes, the SBA value tends to be high due to the surface temperature rise caused by fractures. In the seismic-volcanic area of Lake Toba, there are several faults caused by tectonic activity. The number of faults results in the existence of a fracture zone, where this fracture will cause water to penetrate the hot rock. The water is stored for a long time, then gets hotter and turns into hot steam. Due to the tremendous pressure below the surface, the water and steam come out toward the earth's surface. This indicates that there is geothermal potential that can be utilized as alternative energy in the future.

Based on the results of the qualitative interpretation of the contours of the Bouguer correction and the Simple Bouguer anomaly, the high anomaly is located in the area adjacent to the Sumatran fault, Mount Sinabung, and around the Toba Lake area. The anomaly is in the eastern region of Lake Toba, which is thought to be correlated with the pattern of geothermal potential around the Lake Toba area. The low anomaly occurs because the rocks around the area are volcanic rocks that have undergone sedimentation. The volcanic breccia is considered the reservoir rock in the area, and the cap rock is a tuffaceous clay retaining fluid heat. The total of the residual and regional anomaly is the Bouguer anomaly. Both anomalies interact and cause overlapping anomalies. Therefore, these anomalies must be separated from each other. So we need a regional anomaly separation method with a reasonably good residual anomaly to obtain an accurate residual anomaly for geological modeling below the earth's surface [21]. The complete Bouguer anomaly was subtracted from regional anomalies to obtain residual anomalies. From Figure 3b, the residual anomaly value ranges from -19.3 mGal to 26.5 mGal. The residual anomaly map indicated the distribution of more specific structures in shallow areas. However, the anomaly is influenced by several parameters such as the rock body position, density, and size that yield the anomaly.

5. Conclusion

The simple Bouguer anomaly (SBA) interpretation has indicated that areas with high anomalies are marked with anomaly values between 18.7 to 36.0 mGal located in the southwest of the Pusuk Buhit, Mount Sinabung, and northeast of the Lake Toba area. Meanwhile, areas with low anomaly values ranged from -26.2 to -6.6 mGal. The region suspected of having high anomaly values on the Bouguer correction and SBA maps are marked in purple color, while areas of the low anomaly are in blue color. Based on the interpretation results of the Bouguer correction map and SBA, the areas indicated to be areas that have geothermal potential are southwest-southwest of Pusuk Buhit, northeast of Lake Toba, and the area around Mount Sinabung. This area is a geothermal prospect in the future.

6. Acknowledgement

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