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UTILIZATION OF SATELLITE GRAVIMETRIC DATA TO ESTIMATE THE LOCATION OF THE MAGMA CHAMBER OF SLAMET VOLCANO, CENTRAL JAVA, INDONESIA

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ABSTRACT

Satellite gravimetric data can be utilized to map the gravity anomaly on the earth's surface, especially for difficult, extreme, and large areas. In this study, satellite gravimetric data has been used to estimate the location of the magma chamber of Slamet volcano, Indonesia. Information on the magma chamber is very useful for knowing the volcanic characteristics and activity, thus helping pre-mitigation efforts to catastrophic eruptions that occur. The stages in the study which have been carried out include data access, correction, reduction, modeling, and interpretation. The satellite gravimetric data that has been accessed is GGMplus data. After several corrections and reductions are done, the complete Bouguer anomalies (CBA) data are obtained with values ranging from 11.889 – 117.429 mGal. Filtering process using the upward continuation has been applied to obtain regional anomalies data. The regional anomalies data are corrected to the CBA data, so that the residual gravity anomalies data are obtained. The lowest gravity anomaly value is located at positions of 109.21967° E and 7.24281° S which is interpreted to be the location of the magma chamber of Slamet Volcano that is currently still active. The result of modeling of the residual gravity anomalies data indicate that the position of the magma chamber of Slamet Volcano is estimated to be relatively under the cone with a density lower than the surrounding rock densities, i.e. 1.50 – 1.75 g/cm^3. The study results have a good match with the geological map of the research area.

Keywords: satellite gravimetric; magma chamber; Slamet Volcano; 3D-modeling

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INTRODUCTION

Slamet Volcano (3.432 m msl) is a type A Strato volcano located in Central Java, Indonesia. Slamet Volcano is located at a geographical position of 7°14'30" S and 109°12'30" E. Administratively, this volcano is located on the border of five regencies, i.e. Tegal, Brebes, Pemalang, Banyumas, and Purbalingga Regencies, Central Java [1]. Slamet Volcano is the highest volcano in Central Java which has four craters. The fourth crater of Slamet Volcano is the last crater that is still active today, where the last activity was at the alert level in mid-2009 [2]. Based on records since the 19th century, this volcano is active and often experiences small-scale eruptions [2]. The last activity was recorded from May to June 2009, when the volcano was still spewing incandescent lava. Previously, this volcano was recorded to have erupted in

1999. In March 2014, Slamet Volcano showed its activity and its status became alert [3]. Record from the Center for Volcanology and Geological Hazard Mitigation has shown that the volcanic activity of Slamet Volcano is still volatile [4].

Like other volcanoes on Java Island, Slamet Volcano is believed to have been formed from the subduction process of the Indo-Australian Plate against the Eurasian Plate in the south of Java Island. The descending Indo-Australian plate is slowly melting due to very high subsurface temperatures. This melt then becomes magma. Cracks in the Eurasian Plate open a pathway for magma to slowly rise to the surface. On its way to the surface, magma can experience a loss of mobility while still in the rock of the earth's crust, thus forming magma chambers before reaching the surface [5]. Magma has a lower density than the surrounding rocks. It causes magma to be pushed to the surface of the earth. Magma that comes out of a volcano is called lava. Pyroclastic material (lava and ash) that comes out during a prolonged eruption will settle and accumulate to form a volcanic body [6]. According to Gudmundsson (2012) the shapes of strato volcano magma chambers can be classified into four shapes, i.e. (1) magma chambers with very irregular surface boundaries and is thermally and mechanically unstable, (2) magma chambers with a vertically extended roughly ellipsoidal shape, generally found beneath several volcanic bodies with relatively narrow cones and steep slopes (3) magma chambers with a spherical shape, which may be common, especially in the later stages of the chamber's evolution, (4) magma chambers with a nearly obtuse ellipsoidal shape laterally, which is probably the most common chamber geometry, to be found in mid-oceanic ridges [7].

Volcanic body evolution and landscape characteristics of Slamet Volcano can be divided into three zones, which include old volcano, intermediate volcano, and young volcano. In the old Slamet Volcano complex, some former craters, andesite lava flows, and deposits of pyroclastic material have undergone hydrothermal alteration in the west and northwest. Volcanic rocks of the intermediate Slamet Volcano spread in the southeast, whereas the young Slamet Volcano rocks spread to the east, northeast, north, and a small part to the northwest [8-9]. The interpretation of the evolution of the body of Slamet Volcano based on landsat imagery analysis is shown in Figure 1 [10]. Overall, Slamet Volcano still shows on going activity in the central crater. The evolution of the volcanic body of Slamet Volcano is estimated to be related to the dynamics of magma flow in the Earth's crust. The dynamics of magma flow can cause the position and depth of the magma chamber to change, even for a long time.

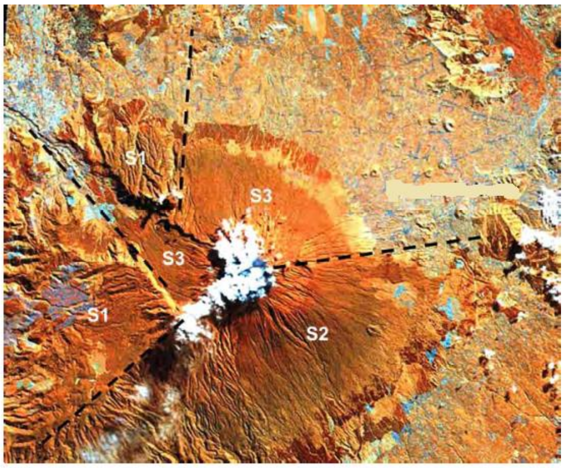

Figure 1. The evolutionary interpretation of the body of Slamet Volcano based on landsat imagery analysis; that indicates the landscape characteristics of the old (S1), intermediate (S2), and young (S3) Slamet volcanoes, and the distribution of cinder cones [10].

Volcanic activity including the magma chamber dynamics of Slamet Volcano is estimated to have been going on since the late Miocene era, which was marked by the presence of the Kumbang formation unit (Tmpk) consisting of volcanic rocks both on land and sea, which occupies the central part of Java Island [10]. Based on the geological information [8], the basement of Slamet Volcano consists of Halang (Tmph) and Rambatan (Tmr) formations which are unconformably overlain by volcanic deposits from the Kumbang formation in the late Miocene and greenish coarse sandstones and conglomerates from the Tapak formation (Tpt) in the Pliocene age. All of these tertiary rocks were then covered by lava and alluvium deposits of Slamet Volcano. It suggests that the body of Slamet Volcano, that is a composite volcano with large diameter (50-60 km), grows on the tertiary rocks [11]. The formations that make up the body of Slamet Volcano consist of lava deposits and undifferentiated volcanic rocks, as shown in Figure 2. The lava deposits (Qvls) are composed of andesitic lava rocks of Slamet Volcano, which are very porous and have numerous cracks. Meanwhile the undifferentiated volcanic rocks (Qvs) consits of breccias, lava, and tuffs. The two formation are from the pleistocene age [8].

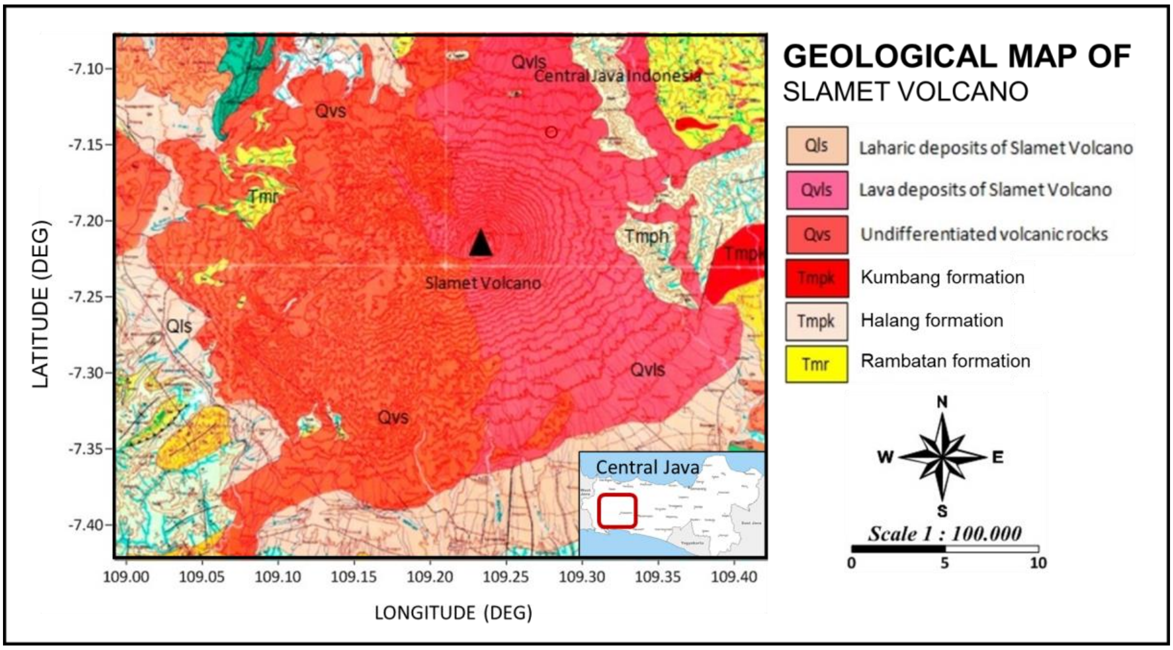

Figure 2. Geological map of Slamet Volcano and its surrounding areas [8].

One of the geophysical methods that can be used to determine the distribution of subsurface rocks and geological structures is gravity method. The gravity method is based on measuring variations in the value of the gravity field anomaly on the earth's surface. The variations are due to differences in the density of the subsurface rocks. The contrasting density differences between the target and the surrounding rocks such as magma chambers can be studied very easily with this gravity method. Currently, data acquisition technique in the gravity method has developed into using gravimetric satellites, completed with the geographical position data of all measuring points on the earth's surface. The satellite gravity anomalies data are extracted from the Global Gravity Model Plus (GGMPlus) data. The GGMPlus data have several advantages, one of which is having the best spatial resolution compared to other satellite gravity anomalies data, such as TOPEX [12]. These data have a spatial distance of 22 The GGMPlus data have several advantages, one of which is having the best spatial resolution compared to other satellite gravity anomalies data, such as TOPEX 0 m [12] and can be utilized for initial mapping of an area to get an overview before taking more specific primary data. Therefore, GGM Plus data have good accuracy in determining indications of subsurface geological structures, including estimating the position of the magma chamber of Slamet Volcano which has a very extreme landscape.

In this paper, we will estimate the position of the magma chamber of Slamet Volcano based on the residual gravity anomaly map. The data can be obtained through the separation of regional-residual anomalies data using the upward continuation technique. The upward continuation is a filtering technique that aims to continue the gravity anomaly data from one horizontal surface to another surface above it [13]. Upward continuation will be applied on Complete Bouguer Anomaly (CBA) data that have been distributed in a horizontal surface. This process is done step-by-step, thus forming a regional anomalous pattern. The regional anomaly contour map has a smooth pattern, which means that the anomaly value interval between one data point and other points around is very small. The regional anomaly contour pattern obtained from the research area is estimated to originate from a deep and wide geological structure [14]. In general, the upward continuation equation originates from the second identity of Green's theorem, which after being further elaborated by Blakely (1995), the following equation is obtained [15]

$$U(x, y, z_0 - \Delta z) = \frac{\Delta z}{2\pi} \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{U(x', y', z_0)}{\sqrt{[(x-x')^2 + (y-y')^2 + \Delta z^2]^3}} dx' dy' \quad (1)$$

For the upward continuation, $\Delta z > 0$. The regional gravity anomalies data that have been obtained from Equation (1) are then corrected to the CBA data which have been distributed on a horizontal surface to obtain residual gravity anomalies data. Equation (1) can be solved efficiently and quickly using computations in the Fourier domain, provided that the equation is a simple 2D-convolution [15]. Therefore, Equation (1) can be expressed as

$$U(x, y, z_0 - \Delta z) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} U(x', y', z_0)\, \Psi_u (x - x', y - y', \Delta z) dx' dy' \quad (2)$$

where $\Psi_u(x, y, \Delta z) = \frac{\Delta z}{2\pi} \frac{1}{(x^2 + y^2 + \Delta z^2)^{3/2}}$

Thus, the Fourier domain representation is formed by transforming both sides of Equation (2) into the Fourier domain, so that the equation can be expressed as [15]

$$F[U_u] = F[U] F[\Psi_u] \quad (3)$$

After modification of Equation (3), Equation (1) can be written as [15]:

$$F[U_u] = F[U] e^{-\Delta z |k|}, \quad \Delta z > 0 \quad (4)$$

Equation (4) can be used to continuate potential field data including gravity anomalies data from one horizontal surface to another horizontal surface above it [15].

METHOD

Location of Research

This research has been carried out in the Laboratory of Electronics, Instrumentation, and Geophysics, Department of Physics, Faculty of Mathematics and Natural Sciences, Jenderal Soedirman University, Purwokerto. The data used in this study is satellite gravity anomaly data covering the Slamet Volcano and the surrounding area, that lie within the geographical coordinates of 108.993° – 109.401° E and 7.021° – 7.403° S.

Equipments and Materials

The equipment used for this study includes a laptop or personal computer (PC), equipped with some software and applications, which includes: Microsoft Excel 2019, Surfer 17, Fortran 77, Gravity 900, Grablox 1.7, Voxler 4.0, and the geological map of the research area. Whereas, the material used in this study is free-air satellite gravity anomalies data from GGMplus, that includes gravity disturbance data, geographical position data of the research area, and quasi-geoid elevation data [16].

Procedure of Research

Satellite gravity anomalies data complemented with topographic data are accessed from the GGMplus website: https://bgi.obs-mip.fr/data-products/grids-and-models/modele-global-ggmplus2013/ that is provided by Bureau Gravimetrique International (BGI) as a scientific service of International Association of Geodesy (IAG), International Gravity Field Service (IGFS), and International Union of Geodesy and Geophysics (IUGG) [12]. The data can be accessed according to the boundaries of the study area using the Matlab. The data obtained are then stored in the Microsoft Excel. Data processing begins with applying the bougeur and terrain corrections to the free-air gravity anomalies data to obtain the bougeur anomalies data (CBA). The CBA data which are still distributed on the topographical surface, are then reduced to a horizontal surface using the Taylor series approach, given in Equation (5) [15, 17]

$$\Delta g\left(x,y,h_0\right)^{[i+1]} = \Delta g\left(x,y,h\right) - \sum_{n=0}^{\infty} \frac{\left(h-h_0\right)^n}{n!} \frac{\partial^n}{\partial z^n} \Delta g\left(x,y,h_0\right)^{[i]} \tag{5}$$

Equation (5) can be stated in the form of iteration; $\Delta g(x,y,h_0)$ is CBA data distributed on a horizontal surface. The data can be calculated through an approximation, i.e. $\Delta g(x,y,h_0)$ data acquired from i-th iteration can be used to acquire $\Delta B(x,y,h_0)$ data in the $(i+1)$-th iteration. The iteration is carried out until the values reach convergence. For the initial values before iteration, the $\Delta g(x,y,h_0)$ values on the right of equation are filled by $\Delta g(x,y,h)$ values which are the CBA data distributed on the topographic surface. Convergence of Equation (5) can be reached quickly if h_0 is taken at the average value of topographic elevation [15].

The CBA data distributed on the horizontal surface are superposition of local and regional anomalies data [13]. Upward continuation process can be applied step-by-step to CBA data to obtain regional anomalies data. The higher the upward continuation, the local anomalous patterns are getting lost, meanwhile the regional anomalous patterns are getting stronger. Regional anomalies data are obtained at a certain height, where the anomaly value interval between one grid point and the surrounding grid points is very small [18]. Mathematically, the upward continuation formulation has been writen in Equations (1) to Equation (4). When this equation is applied to the CBA data, the equation can be written as follows [14, 17]

$$\Delta g\,(x',y',h_0+\Delta h)=\frac{\Delta h}{2\pi}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{\Delta g(x,y,h_0)}{\sqrt{\left((x'-x)^2+(y'-y)^2+\Delta h^2\right)^{3/2}}}\,dx\,dy \qquad (6)$$

where $\Delta g(x',y',h_0+\Delta h)$ are the regional anomalies data. The regional anomaly contour map has a fairly smooth pattern and there are no local anomalous closures [18]. These anomalies data which have been obtained from Equation (6) are corrected to the CBA data, in order to obtain residual gravity anomalies data. Residual anomalies can be modeled using Grablox and Voxler to estimate the location of the currently active Slamet Volcano magma chamber.

RESULTS AND DISCUSSION

Results of Data Procession

Access to satellite gravity anomalies data for Slamet Volcano area, with position boundaries has been described in the Methods section. The GGMplus data accessed is free-air gravity anomalies data. The gravity anomalies data ranges from 27.345 – 322.642 mGal. After the bouguer and terrain corrections are applied to free-air gravity anomalies data, the CBA data are obtained with values of 11.889 – 117.429 mGal. The low anomalous value around the volcanic cone on the CBA contour map is indicative of the position of the magma chamber of the young Slamet Volcano that is currently still active [2]. The high anomalous value in the northwest region of the volcanic cone is interpreted as andesite rock from the old Slamet Volcano [19] with a very high density. For further processing, the CBA data is reduced to a horizontal surface using the Taylor Series approximation, as described in the Methods [15]. The free-air gravity anomaly map and the CBA map distributed on a horizontal surface (at an average topographical height of 572.58 m) are shown in Figure 3.

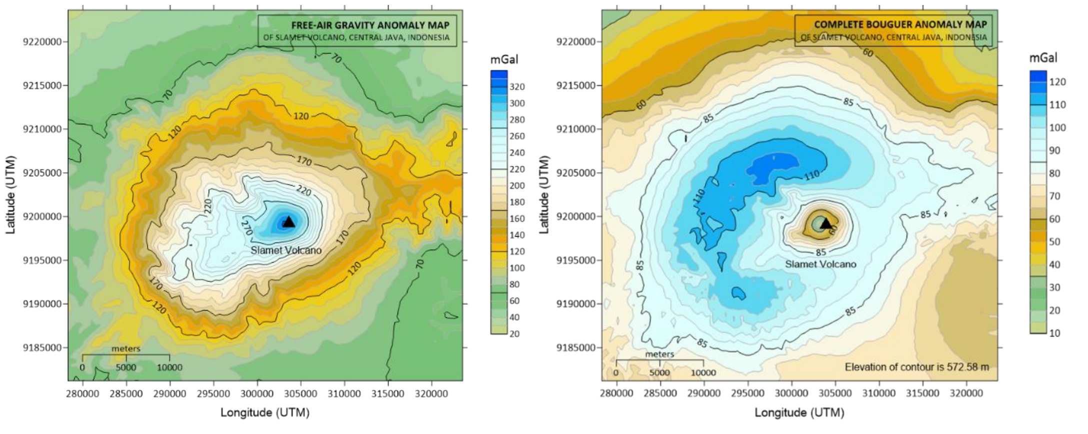

Figure 3. The free-air gravity anomaly map and the CBA map distributed on a horizontal surface.

CBA data that have been distributed on the horizontal surface (average topographical height) are a superposition of local and regional anomalies data. An upward continuation has been applied to the CBA data to obtain a step-by-step regional anomaly pattern. This filter will reduce the anomaly value with respect to wavelength; the shorter the wavelength, the greater the attenuation. Therefore, this filter can be applied to visually display anomalies originating from deep sources of Slamet Volcano by reducing anomalies originating from shallow and near surface sources [20]. When the upward continuation is higher, the local anomaly patterns are getting lost and the regional anomaly patterns are getting stronger. The final result of the upward continuation process (at an altitude of 30,000 m) is a regional gravity anomaly map with values ranging from77.805 – 78.712 mGal, which represents deep anomalous sources. The deep anomalous sources are interpreted as originating from the bedrock of Slamet Volcano, including magma intrusion that breaks through the Earth's crust. The separation of regional anomalies data from CBA data has resulted in residual anomalies data that have values ranging from -67.569 – 38.808 mGal. The regional and residual gravity anomaly contour maps are shown in Figure 4.

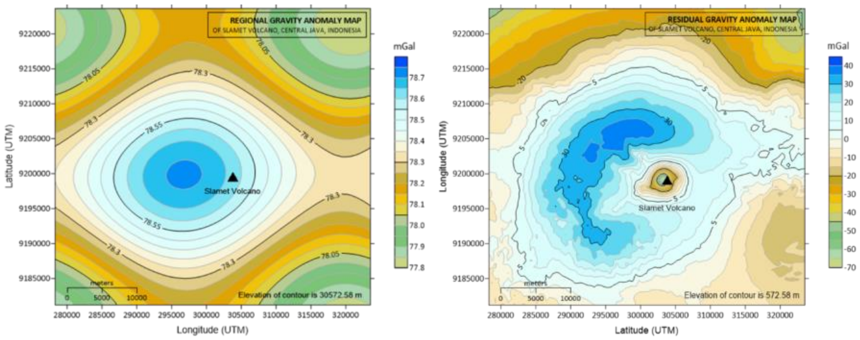

Figure 4. The regional and residual gravity anomaly maps of Slamet Volcano area.

Based on the residual gravity anomaly contour map, the position of the magma chamber of Slamet Volcano which is still active right now is estimated to be located below the lowest anomaly zone with a value of -67,569 mGal at positions of 109.21967° E and 7.24281° S. Magma with high temperatures has caused its density to decrease, so the residual anomaly value is low [21] as shown in Figure 4. The spatial position of the lowest anomaly value on the residual gravity anomaly map which is interpreted as the magma chamber of Slamet Volcano only shifts slightly from the position of the active crater which is located at the coordinates of 109.20500° E and 7.23833° S [1]. The results of this study are supported by the results of study about the magma dynamics based on the analysis of volcanic tremor of Slamet Volcano, which concluded that the pipe connecting the magma chamber to the crater of Slamet Volcano is not perfectly vertical but has a certain slope [22]. Three dimension modeling of subsurface structures has been done to a depth of 5,000 m below the average topographical height of the research area, i.e. 572.58 m. Before the modeling, the residual anomaly contour area is cut according to the position boundary of the area to be modeled as shown in Figure 5. The 3D-model resulted is shown in Figure 6, whereas the sections along the paths of AB and CD are shown in Figure 7 and Figure 8.

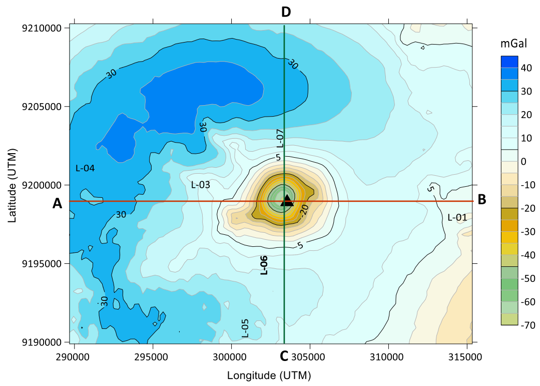

Figure 5. Slices AB and CD on the residual gravity anomaly map for 3D-modeling.

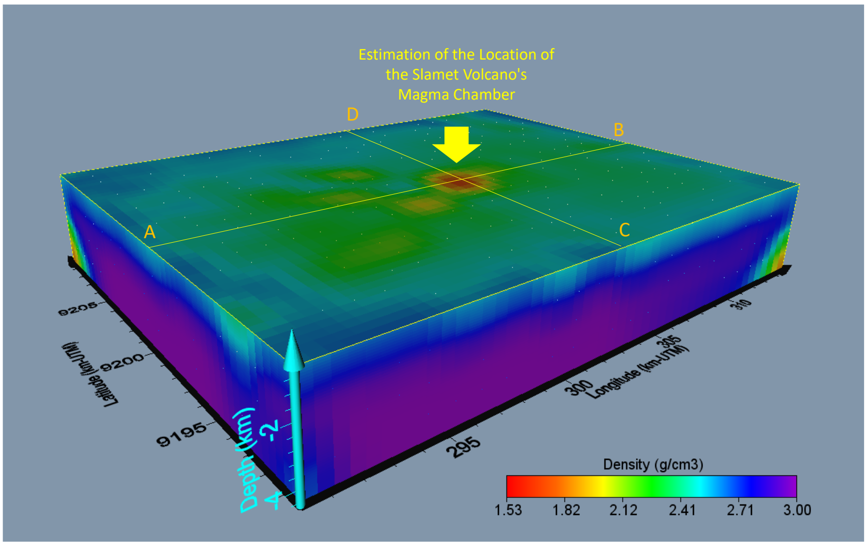

Figure 6. Estimation of the location of the Slamet Volcano magma chamber based on a 3D model of subsurface rock density (at longitude of 303,270 m UTM and latitude of 9,198,950 m UTM).

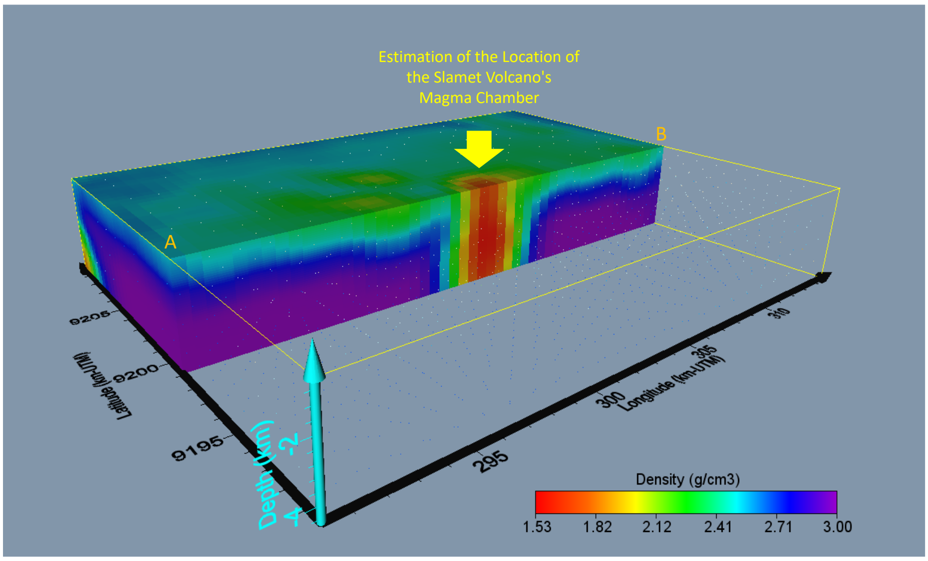

Figure 7. Cross-section of subsurface rock density model along AB path (at latitude of 9.198.950 m UTM).

The position of the magma chamber of Slamet Volcano, which is still active at this time has been successfully estimated through three dimensional (3D) modeling. The modeling results show that the position of the magma chamber of Slamet Volcano is under the volcanic cone with a density lower than the average density of rocks in the earth's crust, which is around 1.50 – 1.75 g/cm^3. The magma rises through cracks from below and across the earth's crust because it is less dense than the surrounding rocks. When magma cannot find its way up, it pools in the magma chambers. These magma chambers are usually formed over time, by continuous injection of magma liquid from below. As a result, the pressure inside the magma chamber increases, causing magma material to be pushed to the surface. In general, the modeling and interpretation results have a good match with the landsat imagery analysis map of the Slamet Volcano surface and the geological map of the research area.

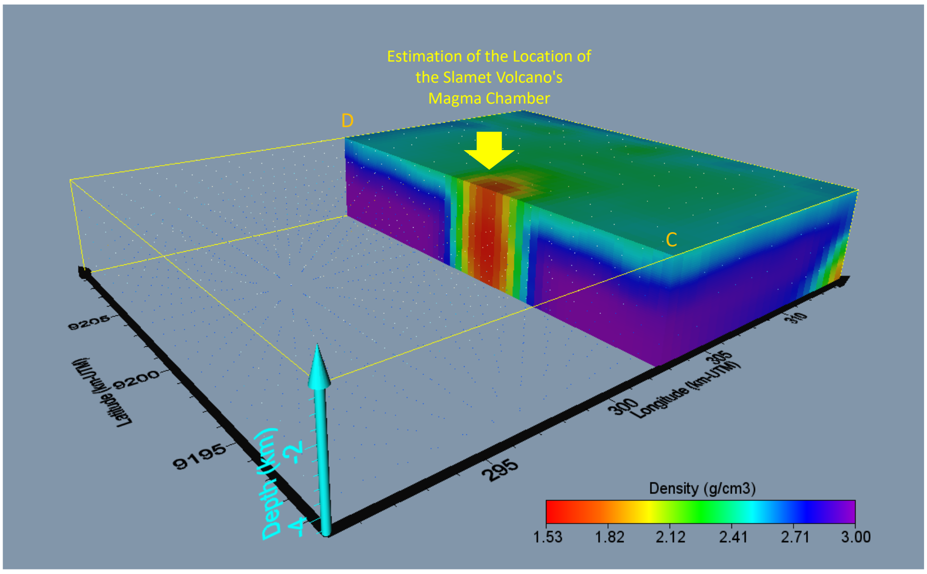

Figure 8. Cross-section of subsurface rock density model along CD path (at longitude of 303,270 m UTM)

Discussion

The residual gravity anomaly map shown in Figure 5 have a good match with Figure 1, that shows the results of the analysis of the landsat image of the surface of Slamet Volcano [10]. The landsat image analysis as shown in Figure 1 indicates the existence of the old Slamet Volcano complex located in the northwest and west of the current Slamet Volcano crater. In Figure 5 (right), this area is marked by a high anomalous complex (in blue) interpreted as andesitic lava-rock, based on the geological information [8]. This high-gravity anomaly zone is estimated to be lava of old Slamet Volcano which has frozen, because high-gravity anomaly values generally indicate high density [21]. Based on Figure 1, the southwest, south, southeast, and east are the rock complexes of intermediate Slamet Volcano which have medium to low gravity anomaly values, as shown in Figure 5. Whereas the north, northeast, and a small part of the west are the rock complexes of young Slamet Volcano which are characterized by high, medium, and low anomalous values. The evolutionary journey of Slamet Volcano was initiated from the marine environment, and its eruption has produced basaltic lava. In the next period, there was a change from basaltic lava to andesitic-basaltic lava, until finally turning into andesitic lava, which was accompanied by a changes in the volcanic environment from marine to land [11].

The facts in the field show that the intensity of the eruption of the Slamet Volcano is not too large compared to several other active volcanoes on Java Island. Therefore, the pyroclastic material released is not too much, with a relatively short eruption period. The volume of magma flow from the magma chamber, that is not too large, can be a key factor in assessing the eruption characteristics of Slamet Volcano [22]. The low eruption intensity is believed to be related to the leakage of magma in the volcanic body, causing the pressure in the pipe weakens and some of the magma liquid freezes in the magma chambers [22]. The part of the magma chamber that has frozen will be left behind by the magma liquid. Liquid magma coming from the lithosphere will look for cracks in the side of the old magma chamber to break through to the surface. When magma moves towards the earth's surface, this magma liquid will form a new magma chamber inside the body of Slamet Volcano and freeze inside. This event is likely to keep repeating itself so that the position and depth of the magma chamber of Slamet Volcano changes from the old volcano to the young volcano.

According to information from the Geological Agency of the Republic of Indonesia, Slamet Volcano has weak eruption characteristics and sometimes only lava flows are accompanied by eruptions of ash and scoria [23]. Generally, this type of eruption indicates that the current depth of the magma chamber of Slamet Volcano is relatively shallow [23]. This is relatively consistent with the results of this research showing that the depth of the magma chamber of Slamet volcano is relatively shallow. The results of this research are also in accordance with information from the Center for Volcanology and Geological Hazard Mitigation [23] which states that the depth of the magma chamber of Slamet Volcano is no more than 2 km. Even if volcanic activity increases, magma can rise to a depth of 1 km below the crater.

CONCLUSION

The estimation of the location of the magma chamber of the Slamet Volcano, Central Java, Indonesia, has been carried out using satellite gravimetric data. Information on the magma chamber of a volcano is very useful for understanding the eruption characteristics and vulcanic activities of a volcano, thus helping pre-mitigation efforts to catastrophic eruptions that can occur at any time. The satellite gravimetric data used is GGM Plus data which has better accuracy than other gravimetric satellite data. The complete Bouguer anomalies (CBA) data have been obtained after applying some corrections, with values ranging from 11.889 – 117.429 mGal. Upward continuation have been applied to obtain a regional anomaly data. The upward continuation was carried out to an altitude of 30,000 m so that regional anomalies data are obtained with values ranging from 77.805 – 78.712 mGal. After correction of regional anomalies data to the CBA data, the residual gravity anomalies data are obtained with values ranging from -67.569 – 38.808 mGal. The residual anomaly map shows that the lowest gravity anomaly value is located under the active crater at positions of 109.21967° E and 7.24281° S. This zone is interpreted to be the location of the magma chamber of Slamet Volcano which is currently still active. The results of 3D-modeling of the residual gravity anomalies data indicate that the position of the magma chamber of Slamet Volcano is estimated to be relatively under the cone with a density lower than the average density of the surrounding rocks, i.e. 1.50 – 1.75 g/cm^3. In general, the study results have a good match with the geological map of the research area.

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