3D model of Krakatau volcano subsurface structure based on gravity data

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Abstract. Krakatau is one of the volcano in Indonesia which has the destructive paroxysmal eruption. Eruption on 1883 was estimated had VEI of 6. The eruption was recorded as one among some most violent volcanic eruption event in the world. Gravity method is one of the geophysical methods that could delineate the subsurface structure base on density variation. Therefore, the objectives of this research are to reconstruct the 3D subsurface structure of the Krakatau volcano especially the approximate location and dimension of the magma chamber. The subsurface model of Krakatau was done by 3D modelling using residual anomaly map. In order to develop the status of magma chamber model, the available information on the geological map of Krakatau and surrounding area was used. Besides that, some information relative to the volcano such as the information derived from earthquake wave attenuation were utilized. The result of the study shows that position its volcano magma chamber is not directly vertical or oblique under the volcano crater and it has multiple chambers which trending northwest-southeast.

1. Introduction

Krakatau or Krakatoa is one of the active volcanoes located in the Sunda Strait, Indonesia [1] (figure 1). The history of the Krakatau Volcano before the 1883 eruption was described by several researchers such as Ecsher [2], Stehn [3] and William [4].

At present, in the area it represents by four main islands called as Krakatau Volcanic Complex. It consists of Rakata, Sertung (Verlaten) and Panjang (Lang) as the remnant of "prehistoric" Krakatau volcano and becoming the rim of caldera and Anak Krakatau as an active volcano. Historically, Rakata is a new cone rice at the southern rim of prehistoric caldera after the possible similar great eruption of 1883, and later two andesitic cones namely Danan and Perboeatan developed and coalesced with Rakata [5]. After the paroxysmal eruption of 1883 the cinder cone of Anak Krakatau appeared in 1927 and has been intermittently active since that time [5]. The cataclysmic eruption in 1883 was estimated had VEI 6.0. As one among the most violent volcanic eruption in the world, the event was heard up to India and Australia and the ash fall covered the Indian Ocean (figure 1). According to Holmes, interpretation
Krakatau is controlled by multi-vent volcanic activities, therefore the subsurface structure relative to this phenomenon will be interested to be studied [6]. An example of the used of gravity to reconstruct subsurface structure of Volcano can be seen for Mt. Pandan in East Java [7]. The objective of this research is to construct the subsurface structure beneath Krakatau Volcanic Complex.

Figure 1. Location Map of Krakatoa or Krakatau [5]

2. Data and Methodology
Morphologically the Krakatau Volcano Complex is formed by the remains of Strato volcanoes and one active volcanic cone. They called as Rakata, Sertung, Panjang and Anak Krakau. Stratigraphically, the rock formations in the area were arranged by stratification of its eruption product. Effendi et al defined that there are 5 periods of activities that produced formation of volcanic rocks in the area [8]. The first called as development of Pre-Historic Krakatau, the second called as destruction of prehistoric Krakatau, the third called as development of Rakata, Danan and Poerboewatan, the forth as destruction of 1883, and the fifth development of Anak Krakatau. The rocks type in the area consist of some dikes, lavas and pyroclastic.

Gravity method works based on the underground density variation. In gravity investigation, the density variation is represented by gravity map known as Complete Bouguer Anomaly Map. In this research, the available data in the area has been published by Deplus [9]. This map can be seen in figure 2.
In order to utilize an available data of Complete Bouguer Anomaly Map of Krakatau as the printed copy by Deplus et al [9], the new digital map was developed. It can be done by defining accurate location and setting the coordinate. After that, the contour gravity value of available map were read to be plotted in the new digital map. The result of new digital Complete Bouguer Anomaly Map which is derived from map of Deplus et al [9] can be seen in figure 3. Using this map, then some processing steps to model subsurface structure could be done.
In general, Complete Bouguer Anomaly Map has the value in the range of +54 to +82 mgal. Considering the high anomaly value as above +76 mgal it can be found in the area of existing islands in the complex such as Rakata, Sertung and Panjang. On the other hand, low anomaly in the range of +54 to +65 mgal mgal make a circular shape located in the middle of studied area.

Regional Anomaly and residual anomaly map can be separated by utilizing new Digital Complete Bouguer Anomaly Map. Separation between regional and residual anomaly was done by spectral analysis followed by moving average method. In this case, at the beginning seven representative sections which assuming represent all anomalies in the area were chosen, then the anomaly curve was transformed to frequency domain by applying Fourier transform. By plotting between wave number against amplitude the dominant trend of anomaly can be identified as the slope linear line of each anomaly, such as regional, residual and “noise”. The intersection of each curve will represent the window size to be used in filtering process between regional and residual anomaly. The result of Regional Anomaly Map derived from respective window can be seen in figure 3, and the result of Residual Anomaly can be seen in figure 4.

![Regional Anomaly Map of Krakatau Volcanic Complex](image)

**Figure 4.** Regional Anomaly Map of Krakatau Volcanic Complex
In order to develop the 3D model, at the beginning the 2.5D model across the important anomaly was constructed. The model was developed based on previous interpretation by some researchers such as Holmes [6], Jaxybulatov et al. [10] and geologic map by Effendi et al. [8]. The first author drawn that Krakatau has several vents, and the second author based on the distribution of velocity ratio wave propagation earthquake as \( \frac{V_p}{V_s} \) he interpreted that Krakatau has multi-magma chambers. These two authors didn’t make their interpretation by modelling of quantitative calculation.

Accordingly, the 2.5D forward modelling based on the multi-magma chamber of Krakatau was constructed. The direction of sections is chosen directed northeast-southwest across the lowest anomaly, Anak Krakatau and Panjang and northwest-southeast across Rakata, lowest anomaly and Sertung. In order to develop the 3D model using Grav3D, the area should be divided into some 3D orthogonal mesh contains its density contrast in each cell. In this case 3D modelling was done using big number of cells, the model was calculated for the elevation of 0 meters with 220 for west to east direction, 220 for the north to south direction, and 80 for vertical direction. Magma chamber is modelled by ellipsoid cell and volcanic vent approach by cuboid cell. Guided by 2.5D model the 3D model was directed northwest-southeast. The 3D model was developed can be seen as figure 6-8.

**Figure 5.** Residual Anomaly Map of Krakatau Volcanic Complex
Figure 6. Slice appearance as diagonal direction of 3D model

The slice of 3D (figure 6) can be described as the top layer which was assumed as pyroclastic flow with density contrast of -0.06 gr/cc of approximately 800 m depth, underneath by density contrast of -0.12 gr/cc which was assumed as andesitic lava flows with the maximum thickness of approximately 1800 m. The deepest part of the model was assumed as basement with density contrast of +0.23 gr/cc. Surrounding magma chambers pyroclastic deposits was assumed has density contrast the same as liquid magma of -0.17 gr/cc. Molten magma chamber assuming sealed by solid magma with density contrast of -0.07 gr/cc.

The 3D model of magma chambers which shows multi-magma chambers with multi vents could be seen in figure 7, and the appearance of magma chamber from above can be seen in figure 8.

Figure 7. The appearance of magma chamber and its vent by 3D model from south toward north
Based on the methodology as mentioned on this Section 2, the synthetic map of Residual Anomaly Map of Krakatau Volcanic Complex was constructed as seen in figure 9.

According to Complete Bouguer Anomaly Map of Krakatau Volcanic Complex (figure 3), it can be seen that most of the area is covered by positive anomaly based on Bouguer density 2.67 gr/cc. As Krakatau Volcanic Complex located in the Sunda Strait that the influence of oceanic slab is significant. On the other hand, additional remnant of product of prehistoric Krakatau also will appear as high gravity value. These high gravity value can be identified as the relatively above +76 mgal which are situated in the location of Rakata, Sertung and Panjang Island.
In order to draw subsurface structure in the region, the residual anomaly should be developed. The result shows that most of the area covered by negative gravity anomaly except the area of the remnant prehistoric Krakatau (figure 5). The lowest anomaly value of less than -5 mgal is found in the middle of the studied area. Assuming that this anomaly is related to magma chamber, then the volcanic vent of Anak Krakatau is inclined toward southwest.

As mentioned in the Section 2, the geological consideration as shown by geologic map to be used as an approximation of subsurface model in order to assume of the density contrast of each rock unit (figure 6). As shown by the Synthetic Complete Bouguer Anomaly Map of the model the interpretation of the subsurface structure could be confirm relative to a subsurface condition. This justification was made due to similarity between the Original Complete Bouguer Anomaly Map and the Synthetic Complete Bouguer anomaly Map that developed by forward 3D model using Grav3D software (see figure 3 and figure 9).

Accordingly, the most important finding of this study are the existing multi-magma chambers and vents below Krakatau Volcanic that feed the Anak Krakatau simultaneously. On the other hand, the volcanic vent of this volcano is not located vertical below Anak Krakatau, but inclined toward Southwest (see figure 7).

Utilizing all of evidence found by this study, the geological model of the subsurface Krakatau Volcanic Complex could be drawn as shown on figure 10. According to the model, the origin of the volcano could be explained that the basement rock was intruded by magma from the deepest part as a result of subduction process, then it made some magma chambers. Multi magma-chambers could be happen because Krakatau is located in the intersection of frontal subduction collision of Java and oblique collision of Sumatra, then it may made numerous significant fractures.

Figure 10. 3D Geological model of Karakatau Volcanic Complex model based on gravity data

These magma chambers produce prehistoric Krakatau which exploded with probably similar size to the 1883 eruption. After the eruption of 1883 the Danan and Poerboewatan were destructed and the new caldera was developed. At present the pyroclastic deposit of Anak Krakatau (purple colour) is still deposited. As it is understanding that Anak Krakatau is one among most active volcano in Indonesia,
then the 4D gravity survey [11] in order to understand the dynamic of the subsurface condition will be interest to be study.

4. Conclusions
Based on gravity model some conclusion could be explained as follows:
- Considering the location of Krakatau relative to the nearest magma chamber, it can be seen that the magma chamber isn’t located directly vertical under the Krakatau, but inclined or oblique toward southwest.
- Krakatau Volcanic Complex is controlled by multi-volcanic vents simultaneously.
- Beside has some volcanic vents Krakatau Volcanic Complex also controlled by multi-magma chambers.
- The origin of multi-magma chambers was caused by location of Krakatau in the intersection of frontal subduction collision of Java and oblique collision of Sumatra.

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