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Subsurface Model Of Mt. Sinabung Using The GGM-Plus Satellite Gravity Data And Deconvolution Euler

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Abstract – Mt. Sinabung in Karo Regency, North Sumatra Province, with an altitude of 2450 meters above sea level, became active again in 2010 after a break in volcanic activity for ± 300 years. Since the eruption in 2010 until now, eruptions are still ongoing periodically. The aim of this research is to obtain a model of the subsurface density distribution of Mt. Sinabung. Modeling was carried out using GGM-Plus 2013 satellite gravity data and ERTM2160 topographical data. Bouguer correction and terrain processing use an average density of 2.67 g/cc. After that, the anomaly was separated by using the moving average. Residual anomalies were then analyzed using Euler deconvolution. The results obtained are the existence of a fault structure on the west and three layers of rock obtained which consist of the basement with a density of 2.8 g/cc 3 – 3.3 g/cc, then Toba pyroclastic deposits with a density 1.8 g/cc – 2.3 g/cc and limestone deposits with a density of 2.4 g/cc – 2.7 g/cc.

Keywords – Sinabung, fault, GGM-Plus, Satellite, Gravity, Euler deconvolution

I. INTRODUCTION

One of the active volcanoes in Indonesia is Mt. Sinabung which is in Karo District, North Sumatra Province. Mt. Sinabung first erupted in 800 AD. The Solfatara eruption of Sinabung occurred in 1912. After nearly 100 years of rest, Mt. Sinabung erupted again in 2010. The first eruption in 2010 was on the 27th of August. Sinabung erupted volcanic ash and pyroclastic, so Mt. Sinabung's status changed from a type B volcano to a type A volcano. Type A volcano is a volcano whose eruption has been recorded since 1600, and type B volcano is a volcano whose eruption was recorded before 1600. Mt. Sinabung eruption on 29th August, releasing lava, then erupted again on 3rd September, releasing volcanic ash as high as 3 km and a second eruption occurred simultaneously with a volcanic earthquake which could be felt 25 km away [1].

3 years later, Mt. Sinabung erupted again on September 18 2013 and on November 3 2013 an increase in volcanic activity was detected, so the status of Mt. Sinabung which was previously level II (alert) was raised to level III (standby). The activity of Mt. Sinabung has increased so residents in 21 villages have been evacuated. Increase in level IV (alert) until early 2014 and on 1 February 2014 there was a hot cloud eruption with several fatalities. Two years later Mt. Sinabung erupted again, releasing hot clouds and causing casualties. Mt. Sinabung has erupted several times every year from 2018 to 2021[2],[3].

Several subsurface studies of Mt. Sinabung had previously been carried out using the gravity method based on Topex satellite data prior to the 2010 eruption. The results of the study showed that the Bouguer anomaly in the study area ranged from -100 mGal to 260 mGal, with magma pockets of Mt. Sinabung at a depth of 8 km to 8 km. 23 km and a volume of 3240 km3 [4]. Other gravity research found a Bouguer anomaly value of -56 mGal to. -6 mGal, but not modeled. Another study used the general formula of the Mogi Model to calculate the estimated depth of the center of pressure using continuous real-time GPS data at 3 monitoring points, namely Gurukinayan village, Laukawar village, and Sukanalu Village [5]. The study modeled the magma pocket of Mt. Sinabung using GPS data from 2015 to 2016 using the Very Fast Simulated Annealing (VFSA) method. As a result, the pressure source of Mt. Sinabung is located in a shallow layer 0.5 to 1.5 km below sea level below Mt. Sinabung, and the pressure source fluctuates [6]. The study used the 1D seismic method which is associated with eruption activity and the result of relocating the hypocenter of the volcanic earthquake on Mt. Sinabung was that the magnitude was (2.8≤ML<4.2). Based on the existence of a low-velocity zone, it is suspected that this is molten magma located at a depth of 8 km [7].

Volcanic magma eruptions can result in losses for the people who live around Mt. Sinabung, both materially and fatally. Information for mitigation is needed to minimize the impact of Mt. Sinabung's eruption. One of the actions that can help achieve mitigation is to detect activities and subsurface conditions of Sinabung. To know the state of the subsurface requires data that represents it. Geophysical studies can obtain the data, one of which is about density distribution. Density distribution can be interpreted from the gravity values measured on the surface. This study uses gravity data to determine the subsurface mass distribution model of Mt. Sinabung after the eruption.

The data used in this research is the GGM-plus 2013 gravity satellite data. Gravity satellite data was chosen because it can be a new alternative for obtaining data for a very large area. The research that has been done shows that with the same location and amount of data, the GGM-plus disturbance gravity anomaly data has a better resolution than the free-air anomaly data from other gravity satellites. GGM-plus which has a resolution of ±220 m can be used as an initial study of an area before the acquisition of terrestrial data [8], [9], [10].

II. Method

Mt. Sinabung is a stratovolcano with a peak altitude of 2,450 meters above sea level and the highest peak in North Sumatra. Mt. Sinabung is located in Karo District, North Sumatra Province. The peak of Mt. Sinabung is located at coordinates 3°10' N and 98°23.5' E. The Sinabung volcano formed on the northwestern fault of the old Toba basin. The old Toba fault is a long fault that at the top forms Mt. Sinabung and Mt. Sibayak. The fault structure around Sinabung is a normal fault in the Lake Kawar area. In addition to fault structures, other geological structures were also found, such as crater structures and straightness [11].

Figure 1. Sinabung

Bouguer anomaly is an anomaly caused by lateral variations in rock density in the earth's crust. Basically, the Bouguer anomaly is the result of the difference in data between the gravity value and the theoretical gravity value. Complete Bouguer Anomaly (CBA) is a value that has removed the effect of the gravitational field that arises around the measurement point [12]. The ambient gravity value that has been removed causes the CBA value at a measurement point to describe or represent the presence of subsurface geology at the measurement point.

$$CBA = g_{obs} - (g_n + g_{FA} + g_b - TC)$$

$$CBA = (FAA - g_b + TC)$$

where $g_{obs}$is the observed gravity value (mGal), g_n is the normal gravity value (mGal), g_{FA} is the free air correction (mGal), g_b is the Bourger correction (mGal), *TC* is the field correction and *FAA* is a free-air anomaly (mGal) [13].

Bouguer anomaly is the sum of the regional anomaly and residual anomaly. These two anomalies interact and cause overlapping anomalies. Therefore, these anomalies must be separated from one another, so a method is needed to separate regional anomalies from residual anomalies. The moving average is one method that can be used to separate regional and residual anomalies. The moving average method produces regional anomaly as a result of averaging the *CBA* value, while the residual anomaly is the difference between the *CBA* value and the regional anomaly. The moving average equation for 1D can be expressed mathematically as follows:

$$\Delta g_{reg}(i) = \frac{\Delta g(i-n) + \cdots + \Delta g(i) + \cdots + \Delta g(i+n)}{N}$$

$$\Delta g_{res} = \Delta g - \Delta g_{reg}$$

where Δg_{res} is the residual anomaly value, Δg is the Bouguer anomaly value and Δg_{reg} is the regional anomaly value [14]

The results of the separation are then modeled to determine the subsurface geology. Modeling is done using 3-dimension inversion Grablox free software. (Purnomo et al., 2013) [15].

The analysis was completed by another method, the next processing is carried out using the method of Euler deconvolution. Some of the results of Euler's deconvolution are the position values of the anomalous objects and the approximate depth and geometry of the anomalous objects. Data processing using the Euler deconvolution method requires the selection of several parameters. One of the parameters is the structure index value [16]. The structure index value depends on the type of structure identified. The parameters of the source of the anomaly resulting from the Euler deconvolution analysis can strengthen the subsurface model analysis obtained [17]. The deconvolution Euler equation is shown below:

$$(x - x_o)\left(\frac{\partial G}{\partial x}\right) + (y - y_o)\left(\frac{\partial G}{\partial y}\right) + (z - z_o)\left(\frac{\partial G}{\partial z}\right) = N(B - G)$$

The source of the anomaly $(x_0, y_0, z_{0)}$ and B is obtained by solving the linear equation. Where (x_0, y_0, z_0) is the location of the detected gravitational field source at coordinates $(x\ \ , y\ \ , z\ \ )$, *N* is the index structure (0 for dykes, 1 for faults, 2 for spheres), *B* is the potential field anomaly value and *G* is the observed gravity value.

III. RESULT AND DISCUSSION

The data used in this study is secondary data from the GGM-Plus satellite. The data can be obtained from the official GGM-Plus website (http://ddfe.curtin.edu.au/gravitymodels/). The data that has been downloaded is then extracted using the Matlab software with the script provided by GGM-Plus. The extract results obtained position coordinate data in latitude, longitude, and gravity disturbance data which is equivalent to the free air anomaly and elevation data in the study area which has a distance between points of ±220 m. Elevation values at Mt. Sinabung range from 728 m to. 2427 m. The Free air anomaly of Mt. Sinabung is 47.1 mGal to 182.9 mGal, as mapped in Fig. 2. Low anomalous areas are colored blue with values 47.1 mGal to 95 mGal, anomalies colored green-yellow are colored 95 mGal to 145 mGal, and high anomalous areas are graded red-white, with a value of 145 mGal up to 182.9 mGal. Mt. area Sinabung has a high anomaly value to the northwest and a low anomaly from the south to the southwest.

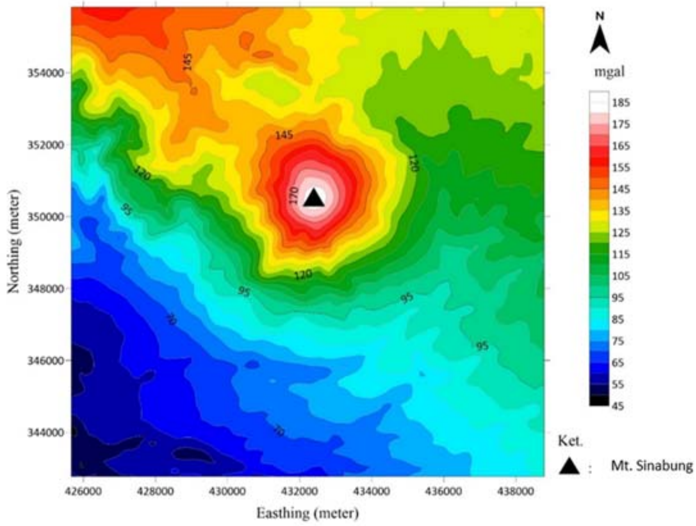


Figure 2. Free air anomaly of Mt. Sinabung based on GGMPlus data

The complete Bouguer Anomaly (CBA) contour map provides information about the distribution of the anomaly in the research area. To obtain the CBA value, a correction process is carried out which is generally carried out using the gravity method. The corrections made are Bouguer corrections and terrain corrections. The free air anomaly value is corrected with both to obtain the CBA value. The average density value used in this study was 2.67 g/cc. The distribution of Bouguer anomaly values is mapped in Figure 3. CBA value are -45.89 mGal to -19.69mGal. In Figure 3, the distribution of anomaly values is mapped as follows: low anomalies in black-blue colors, with values are -45.89 mGal to -35 mGal, yellow contour color of anomalies with values -35 mGal to -26 mGal, and high anomalies are colored in red to white with value -26 mGal to -19.69 mGal.

The negative Bouguer anomaly value geologically can be caused because the area has very deep bedrock and the top is filled with low-density rock, for example, sedimentary rock. Based on previous research on Mt. Sinabung, explain that the above bedrock of Mt. Sinabung consists of lava flows and pyroclastic deposits which are supported by deposits from the Toba caldera [18]. This negative anomaly value is also found on Mt. Sibayak which is ± 15 km from Mt. Sinabung, the CBA value is 0 to -42 mGal, then in the southwestern and northeastern parts of Lake Toba have Bouguer anomaly values of -40 mGal to 30 mGal [19],[20],[21].

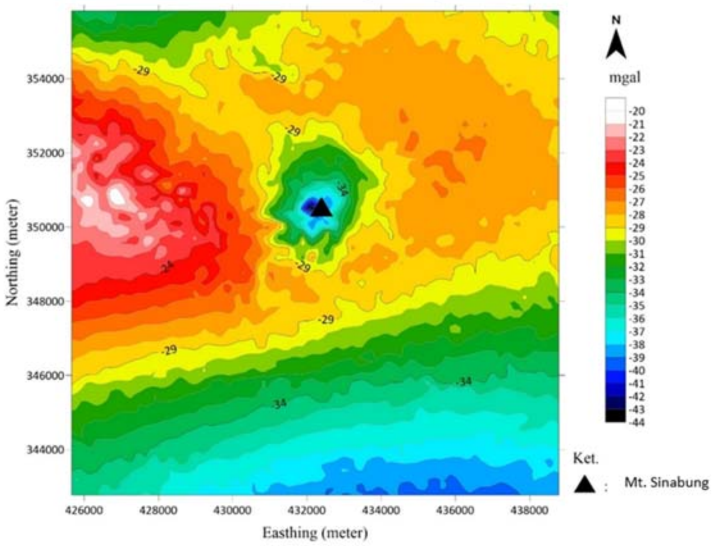
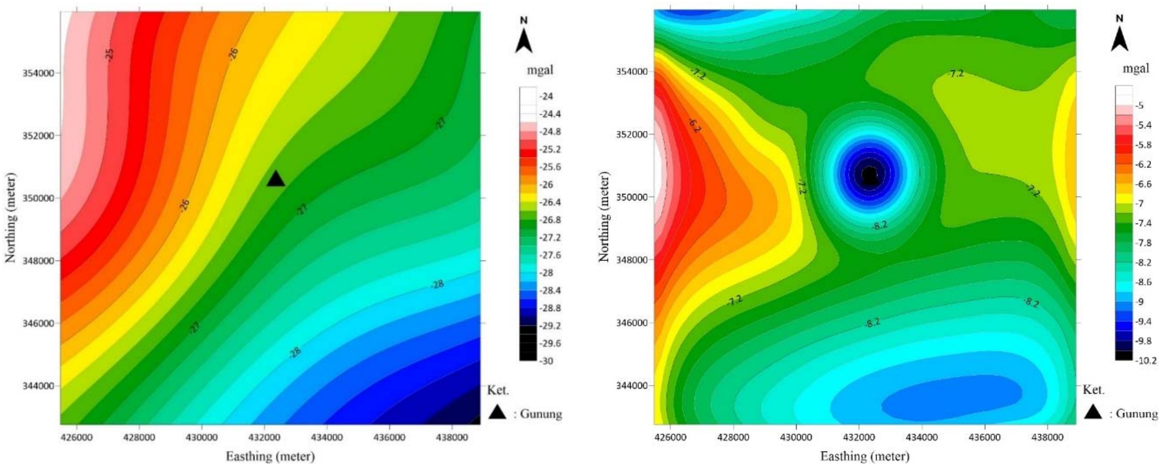


Figure 3. Complete Bouguer Anomaly of Mt. Sinabung

CBA is the sum of regional and residual anomalies. The two anomalies interact and produce superimposed values. Therefore, it is necessary to separate these anomalies. Local anomalies are caused by shallow and small sources, while regional anomalies represent deeper and larger sources. Separation of anomalies use the moving average method. The result of the separation is a regional and local anomaly as shown in Figure 4.



a. Regional b. Local

Figure 4. Regional and local anomaly based on moving average method

The results of separating the anomalies using the moving average method are residual anomalies of -5 mGal to -10.2 mGal and regional anomaly values of -24 mGal to -30 mGal. The distribution of low local anomaly values represented by blue color gradations is found in the Sinabung peak area and the southeast. The red gradation which presented a high anomaly, spread to the west and east area. The low regional anomaly is mapped to the southeast and the high anomaly trending west to north. The consistency of regional-local low anomaly values illustrates the existence of the same structure both regionally and locally. The low anomaly value is thought to correspond to a lower density which can also be suspected as a very deep bedrock. When referring to previous research, shows that the southeast area is a continuous part of the Toba basin.

The low density is thought to be the rock that is the result of Toba eruption deposits such as pyroclastic deposits and other sedimentary deposits. To be able to know the description of rock distribution, modeling is needed. The modeling results can provide information on the subsurface layers of Sinabung. The modeling done is inverse modeling so that more valid results are obtained because it is based on a mathematical model.

In Fig. 5 it can be seen that the bedrock beneath Mount Sinabung forms a basin-like structure which is thought to be part of the Toba caldera structure which is then filled with tuff-type pyroclastic rock deposits. Geological research explains the presence of volcanic rock consisting of pyroclastic overlapping unconformably on the Toba tuff rock [20]. Pyroclastic rock containing volcanic ash which is then released when a volcanic eruption occurs. These pyroclastic rocks are thought to result from the mechanism of the Toba volcanic eruption. According to previous research, the Toba tuff occupies an area of 20,000 to 30,000 km^2, which shows that the Toba tuff is the largest deposit in the world [19]. Based on the modeling, the southern Sinabung bedrock is at a depth of 2 km, so the layer of pyroclastic sediment above it is thinner than the northern part. The further north the bedrock layers get deeper to a depth of 4 km. On the cross-section which passes through the peak of Mt. Sinabung, the rock layer above it becomes thicker.

Based on geological information, the study area is dominated by pyroclastic flows, lava flows, limestone, alluvium, and Toba pyroclastic flows. The modeling results show that the rocks that Sinabung have a density of 1.8 g/cc to 3.3 g/cc. There are three layers of rock with different densities. The yellow layer, 2.4 g/cc to 2.7 g/cc, is a limestone deposit. The blue layers, 1.8 g/cc to 2.3 g/cc, are pyroclastic deposits. The red rock layer with a density of 2.8 g/cc to 3.3 g/cc is thought to be bedrock. However, in this modeling, there are no fractures and no visible magma chamber of Mt. Sinabung. Based on seismic research, the magma chamber of Mt. Sinabung is estimated to be at a depth of 12 km below sea level [22].

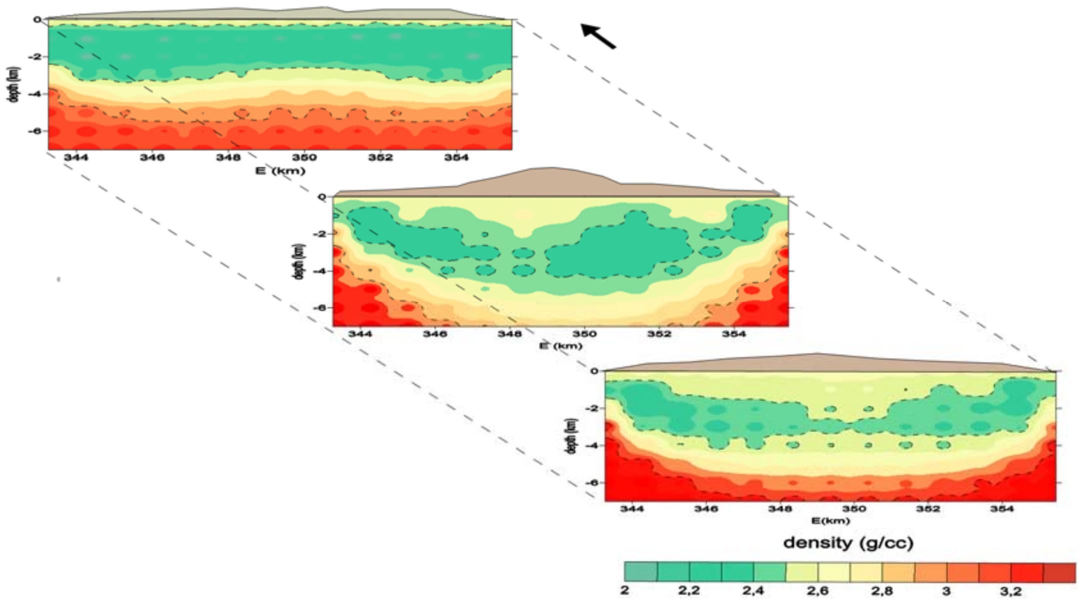


Figure 5. Inverse density model of Mt. Sinabung based on CBA

The results of the Euler deconvolution as shown in Fig. 6, the distribution of Euler is to the west, south to the east of Sinabung, and around the mountain body. Based on the results of the Euler deconvolution, there is a match between the mapped fault positions and the Euler results. The fault is in the western part of Sinabung.

The results of Euler's analysis show that the depth of the structure is 1509 m to 2336 m. The fault location obtained is in the west, south to east of Mount Sinabung, and around the body of the mountain. Based on the Euler deconvolution result, one fault matches the geological map in the western part of Mount Sinabung.

Mount Sinabung is thought to have arisen due to orogenesis followed by volcanic activity. Sinabung is a Quaternary Volcano that is not explosive but is more effusive. After a long absence of eruptions, the types of eruptions that are now occurring are explosive and Strombolian

Mount Sinabung is part of the Brastagi plateau which is part of the East Bukit Barisan Mountains. Based on its physiography, Sinabung is a solitary volcano, growing from the Pleistocene to the Holocene. The long period produced a lot of lava flows on the slopes, especially the south - southeast. The regional structure describes the relationship between Mount Sinabung, Mount Sibayak and Lake Toba. Sinabung and Sibayak's activities are thought to be related to Toba's activities in the past. These two mountains are at the end of the Toba basin. The rocks found in the Sinabung, Sibayak and Toba areas are pyroxene andesitic lava rock, lava, agglomerate.

On the geological map as in Fig. 6, the rocks of Mt. Sinabung and its surroundings are composed of lava flows marked in red, pyroclastic rocks marked with green, Toba pyroclastic deposits and alluvium deposits marked with white, lava deposits marked with orange, and limestone deposits marked with the color blue. The geological structure in the area of Mt. Sinabung has faults in the west, north, southwest, and northeast of Mt. Sinabung and the crater structure at the peak [21]. The lithology composition of Mt. Sinabung consists of volcanic ash, volcanic rock, and solidified lava that takes a long time. Volcanic rocks on Mt. Sinabung have an andesitic to basaltic composition [23]. The results of the Euler deconvolution map a lot of depth values in area from the east circular to the west. Various depth values are suspected to be related to various lithologies in the area.

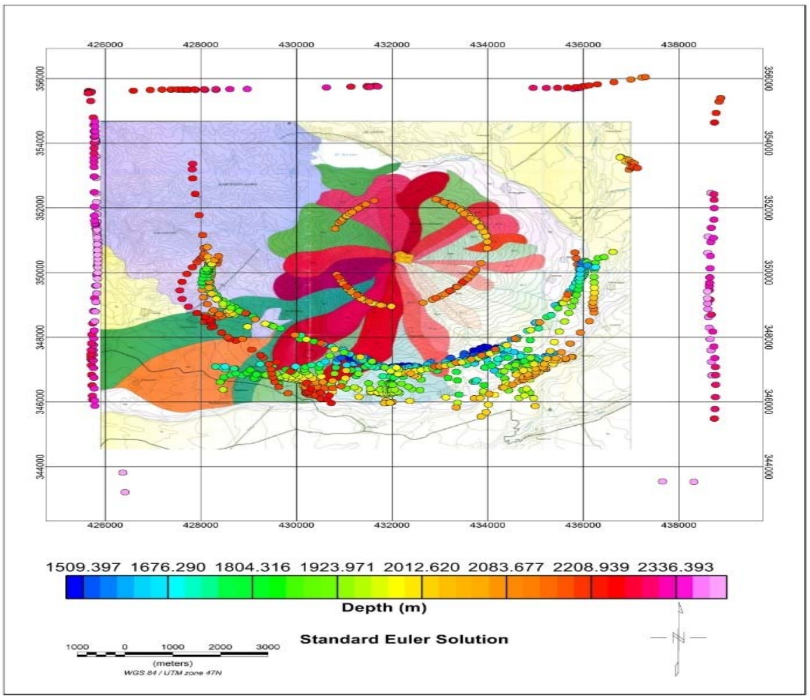


Figure 6. Euler deconvolution map overlay with geology map of Sinabung [1]

IV. Conclusion

The CBA of the study area produced an anomaly of -31.14 mGal to -31.14 mGal to -20.13mGal. Negative Bouguer anomaly values indicate deep bedrock and Mt. Sinabung was formed on top of limestone deposits, pyroclastic deposits, and the Toba caldera. Euler deconvolution analysis of the residual anomaly obtains an overview of the fault structure at a depth of 1581 m to 2387 m. The results of the residual anomaly modeling show that there are three rock layers consisting of bedrock with a density of 2.8 g/cc to 3.3 g/cc, then the Toba pyroclastic rock deposits are of the tuff type containing volcanic ash with a density of 1.8 g/cc to 2.3 g/cc and limestone deposits with a density of 2.4 g/cc to 2.7 g/cc.

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