

Subsurface Structure Models Of Sumbawa Island And Flores Back Arc Thrust Based On Gravity Data

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Abstract: Based on the BMKG report on Wednesday, July 29, 2018, at 05.47 WIB, an earthquake with a magnitude of 6.4 SR occurred at the epicenter at a depth of 24 km and was 47 km northeast of the island of Lombok. They are allegedly originating from the Back Arc Thrust Flores, the interaction between the Indo-Australian Plate and the Eurasian plate. This study aims to analyze the subsurface structure of the island of Sumbawa and Flores sea based on the distribution of density values. The analysis was carried out by modeling the subsurface structure based on regional gravity field anomaly data. The data used is secondary data downloaded from the topex.ucsd.edu page 18,400 measuring points. Data processing consists of data correction, separation of anomalies, determination of the Second Vertical Derivative (SVD) value, and 3D and 2D inversion modeling. The data corrections performed are Bouguer correction and terrain correction to produce the total gravity anomaly value. Upward continuation is used to separate regional anomalies and residual anomalies. Analysis of the Second Vertical Derivative (SVD) value was carried out to identify rock contact positions and fault structures. The 3D inversion modeling is done by making a mesh model, and to get a 2D cross-section, six slices are used in the 3D model. The results of the 3D model and 2D cross-section, namely the island of Sumbawa to the Back Arc Thrust zone of Flores, consists of 3 main layers comprised of the upper crust with a density of 2.29 gr/cc - 2.63 gr/cc, the middle crust with a density of 2.64 gr/cc - 2.90 gr/cc, and the lower crust with a density of 2.91 gr/cc - 3.14 gr/cc, and based on the model and SVD value, it shows that the Flores back fault, the reverse fault type, starts at a depth of ± 26 km.

Keywords: back-arc thrust; gravity anomaly; modeling; Sumbawa

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Introduction

The Nusa Tenggara Islands were formed due to the interaction of the Indo-Australian plate moving northward, experiencing subduction under the Eurasian plate, which moves south to form volcanic arc islands. In addition to creating islands, the two plates' interaction also creates a system of enlargement or fault, various types of sedimentary depositional basins such as trenches, forearc basins, inter-mountain or

island basins, and back-arc basins (Darman and Sidi, 2000).

According to Darman (2012), the island of Sumbawa is a volcanic arc of the southeastern Nusa Islands, located between the Sunda arc in the west and the Banda arc in the east in Figure 1. On the island of Sumbawa, several volcanic activities such as Mount Tambora and Sangiang Api, while Sangenges, Soromandi, and Maria had already eroded a quarter of their cones (Sudrajat et al., 1975). In the north of the

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island of Sumbawa, there is a fault rising behind the arc, which is often the center of shallow seismicity

activity around the island of Sumbawa.

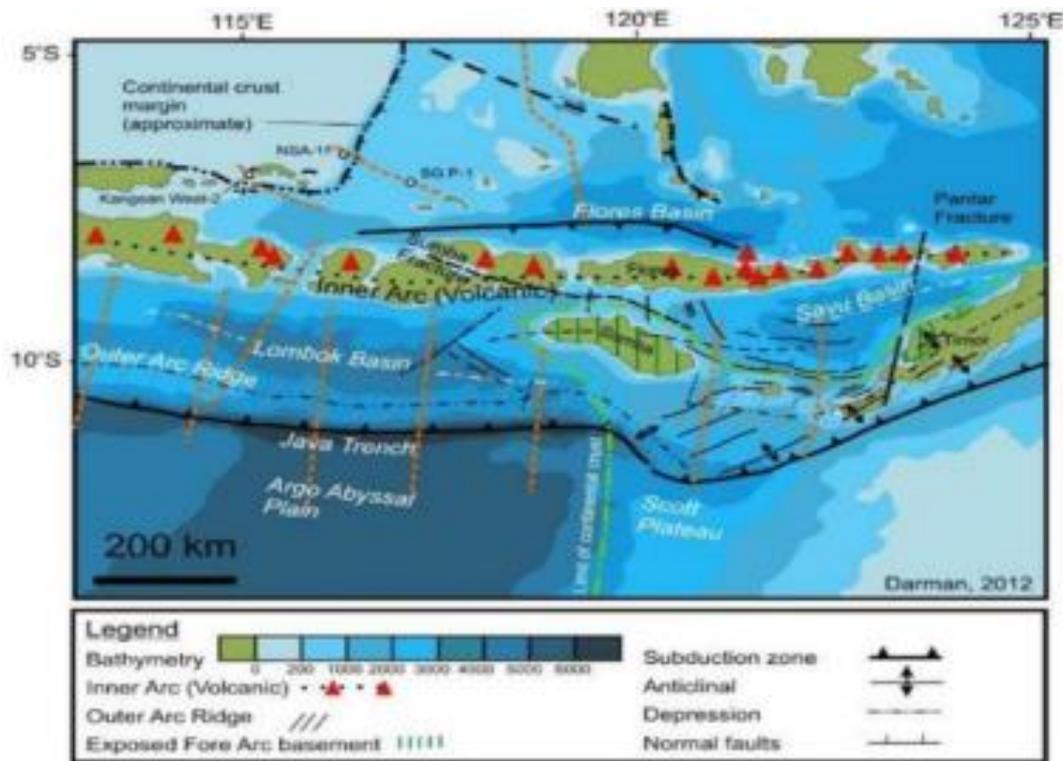


Figure 1 Physiographic and Tectonic Map of the Island of Sumbawa (Darman, 2012)

The back fault of this arc was first reported by Hamilton (1979) based on several reflection profiles found a fault in the north of the islands of Alor and Pantar on the eastern side of the back-arc of the Java subduction zone, which is commonly known as the reverse fault behind the Flores arc. At the same time, Silver et al. (1986) estimated that the fault on the west side of the Flores basin continues to the Bali basin, which is located in the north of the island of Bali.

Based on the earthquake catalog data of the United States Geological Survey (USGS) and the Meteorology, Climatology and Geophysics Agency (BMKG), most of the strong to destructive earthquakes that this back-arc thrust causes rock the Sumbawa area, and some of them are caused by back-arc thrust by plate subduction activity. The western segment of the fault is known as the Flores back arc thrust that stretches from the Northeast of Bali to the north of Flores' island. Flores back arc thrust is a generator of destructive earthquakes that will continue to threaten the arc of the islands of Bali, Lombok, Sumbawa, and Flores. This fault was the cause of the Lombok earthquake (2018), the Sumbawa earthquake (2018), and the Lombok earthquake (2019), which had a very destructive impact.

Research on gravity in Southeastern Nusa and the Flores fault has been studied and identified using

the gravity method by several researchers, including Chamalaun and Grady (1978), Darman (2012), Sari (2010), Titi (2016), and Danniswara (2019). From several previous studies with gravity survey data, no one has specifically modeled the area from the island of Sumbawa to the Flores fault zone in the north of the island of Sumbawa.

The theory that underlies the survey of gravity is Newton's law of the force of attraction between two objects, where the magnitude of the force between two masses m_1 and m_2 separated by a distance of r is (Telford et al., 1990)

$$\vec{F} = -G \frac{m_1 m_2}{r^2} \hat{r} \quad (1)$$

Where F is the force (N), m_1 and m_2 are the mass of the first object and the mass of the second object (kg), r is the distance between two things, \hat{r} is the unit vector from m_1 to m_2 , G is the universal constant of gravity ($6.67 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$) (Telford et al., 1990). The force per unit mass of a particle m_1 which has a distance of r from m_2 is called the gravitational field of the m_1 particle, which can be expressed as:=

$$\vec{g} = -G \frac{M}{r^2} \hat{r} \quad (2)$$

Where g is the gravitational acceleration of the earth, the minus sign indicates that the direction of the force is towards the center of the Earth (Telford et al., 1990).

The measured variations in the earth's gravitational field are still influenced by several factors, including differences in latitude, differences in elevation/altitude, tidal conditions, effects of topography/surrounding terrain, and variations in subsurface density. (Telford et al., 1990). Mathematically it can be expressed in the following equation:

$$\Delta g(x,y,z) = g_{obs}(x,y,z) - g_{th}(x,y,z) \quad (3)$$

Where $\Delta g(x,y,z)$ is the gravitational field anomaly, $g_{obs}(x,y,z)$ is the observational gravitational field, and $g_{th}(x,y,z)$ is the theoretical gravitational field in the topography.

Only the subsurface density factor is taken into account in the gravity exploration, so other factors must be corrected. If the measurement data used is Satellite Survey data, the required correction consists of Bouguer correction and Terrain correction. The Satellite survey data has been converted to free air correction.

Bouguer Correction is a correction used to eliminate gravitational acceleration due to the mass between the measurement point and the geoid point. The Bouguer correction is given by the equation (Telford et al., 1990):

$$BC = 2\pi G\rho h \quad (4)$$

Terrain Correction (Field corrections) is carried out for areas that have irregular (undulating) topography. At the time of measurement, the elevation around the measurement point, usually within the inner and outer radius. So that the terrain correction (TC) can be written as follows (Reynolds, 1997):

$$TC = \frac{2\pi G\rho}{n} \cdot (r_L - r_D) + (\sqrt{r_L^2 - z^2})(\sqrt{r_D^2 - z^2}) \quad (5)$$

The density value used is the average density value of the earth's crust.

Furthermore, making a 3D Model using Inversion Modeling. Inversion modeling is a process depicted in Figure 2. However, modifying the model to obtain a better match for the computation data and observation data is done automatically. Inversion modeling is often referred to as data fitting because a model parameter is sought, resulting in a fit response to the observed data.

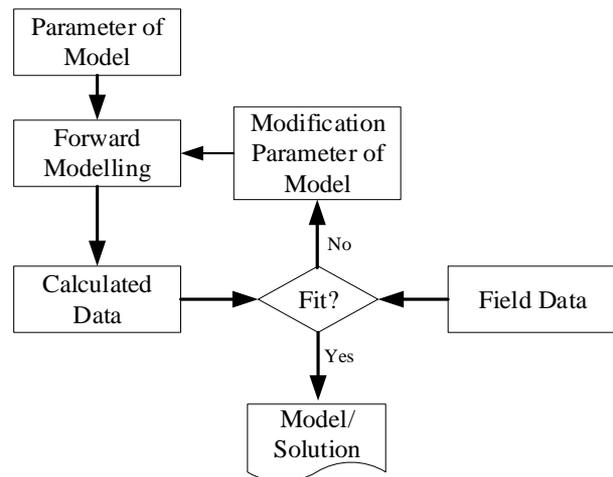


Figure 2. inversion Process

To determine the boundaries of the study area's structure, a Second Vertical Derivative (SVD) filter was used with the Elkins 1951 operator. This filter can separate residual anomalies that cannot be separated by the existing regional - residual separation method. Theoretically, this method is derived from the Laplace equation (Telford et al., 1990):

$$\nabla^2(\Delta g) = 0 \quad (6)$$

Where

$$\nabla^2(\Delta g) = \frac{\partial(\Delta g)}{\partial x^2} + \frac{\partial(\Delta g)}{\partial y^2} + \frac{\partial(\Delta g)}{\partial z^2} \quad (7)$$

Method

The data used in this study is secondary data downloaded from http://topex.ucsd.edu/cgi-bin/get_data.cgi which published by Scripps Institution of Oceanography, University of California San Diego USA. The data used are free air anomaly data (FAA) and topographic data from satellite imagery. The total number of data is 14800, with an area covering Sumbawa Island and its surroundings.

Softwares which used in the processing data are Geosoft v.6.4.2, Google Earth Pro, Surfer v.13, Quantum GIS v.2.18, and UBC.Grav3D. In addition to this software, image processing software such as Corel Draw and MS Visio are also used. Geological information is supported by the Geological Map of Sumbawa and Komodo Islands.

Data processing includes making Bouguer Anomaly (CBA) complete map, separating anomalies using the upward continuation method, 3D inversion modeling, and making SVD maps. The research stages are shown in Figure 3.

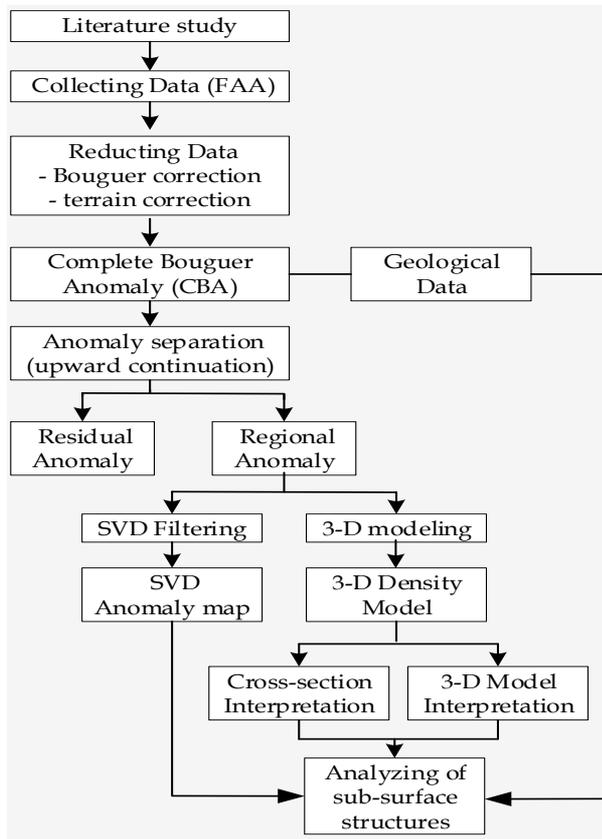


Figure 3. The research stages.

Result and Discussion

The complete Bouguer anomaly map can be seen in Figure 4. This anomaly reflects the distribution pattern of subsurface rock density. The complete Bouguer anomaly map has negative anomaly values ranging from -40 mGal to 464 mGal. The northeastern part of the map shows a high positive anomaly pattern, indicating that the rocks in this area have a high density. Meanwhile, the northwestern part of the island of Sumbawa and around the bay of Cempi shows a low positive anomaly to a negative anomaly which indicates a lower density than the northern part, the back fault Flores and the Flores basin.

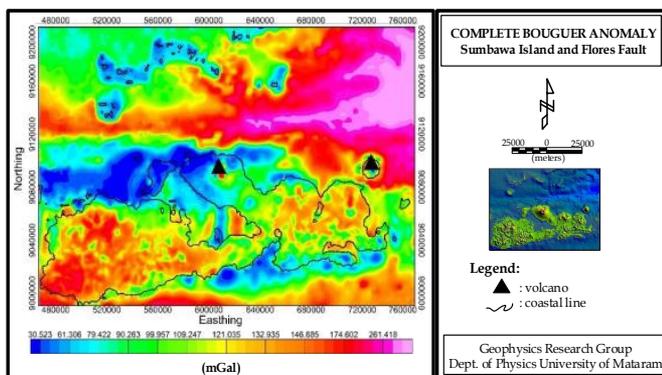


Figure 4. Complete Bouguer Anomaly (CBA) map

The high CBA value is located in the northeast part of the CBA map. Meanwhile, low anomalies in the waters northwest of Sumbawa Island and Cempi Bay are thought to be structures that uplifted at the time quarter.

As a result of the submergence of the oceanic plate, which has a density greater than that of the continental plate, there is a mass accumulation or accumulation in the subduction zone, forming volcanic arcs and basins, and back arcs. The northern part has a high anomaly because the oceanic crust of the Flores basin has plunged south under a volcanic arc. The phenomena cause the mass in the fault area and the basin to get bigger. It is in contrast to the northward subduction of the Australian continental crust.

The anomaly separation process is carried out by the upward continuation method. The results of upward continuation carried out at an altitude of 6,000 meters are shown in Figure 5. The regional anomaly values are in the range of 40 mGal to 400 mGal

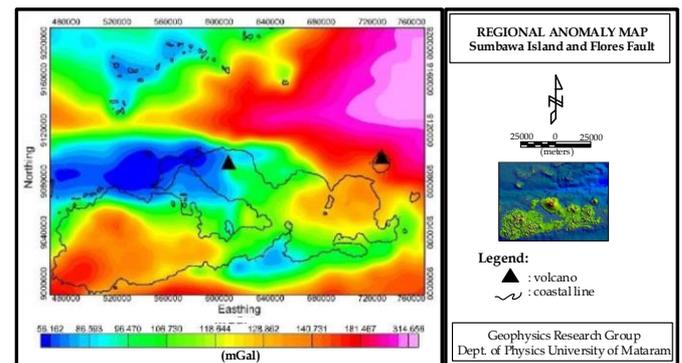


Figure 5. Regional anomaly map as a result in upward continuation at altitude 6000 meters

The sub-surface 3D modeling of the back fault zone of Flores and the volcanic arc of the island of Sumbawa based on regional anomalies are shown in Figure 6. The results of the modeling are three-dimensional layers composed of blocks with a depth of ± 35 km. Based on the inversion results that have been carried out, the value range of rock density values is (2.29 - 3.14) gr/cc. Meanwhile, based on the Crustal data information, the density value model with a depth of up to ± 35 km ranges (2.02 - 3.04) gr/ cc

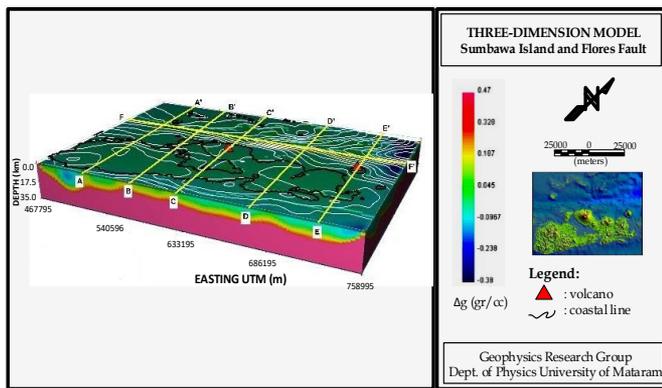


Figure 6. The subsurface 3D model based on anomaly modeling regional lift of 6000 meters

Based on the three-dimensional model in Figure 6, the research area consists of 3 the main layer consisting of the upper crust, middle crust, and lower crust. Third layer thickness varies across study sites. For value, The density of the three layers can be seen in Table 1 below.

Table 1. Types of Rocks for each Layer in the Three-Dimensional Model

| No | Layer | Density (gr /cc) | Thickness (km) |
|----|--------------|------------------|----------------|
| 1 | Upper Crust | 2.29 - 2.63 | ± 13 |
| 2 | Middle Crust | 2.64 - 2.90 | ± 10 |
| 3 | Lower Crust | 2.91 - 3.14 | ± 12 |

From the results of the 3D model obtained, for further interpretation, a model is made the cross-section profile is north-south and west-east, aiming to find out more it is clear the gravity anomaly in the Flores fault area is caused by submergence of the plate. There are six cross-section models, namely one cross-section model east-west and 5 model cross-section direction North-South. Result model cross-section selected some model cross-section that considered could represent a model that other. The result model cross-section could be seen in Figures 7a, 7b, and 7c.

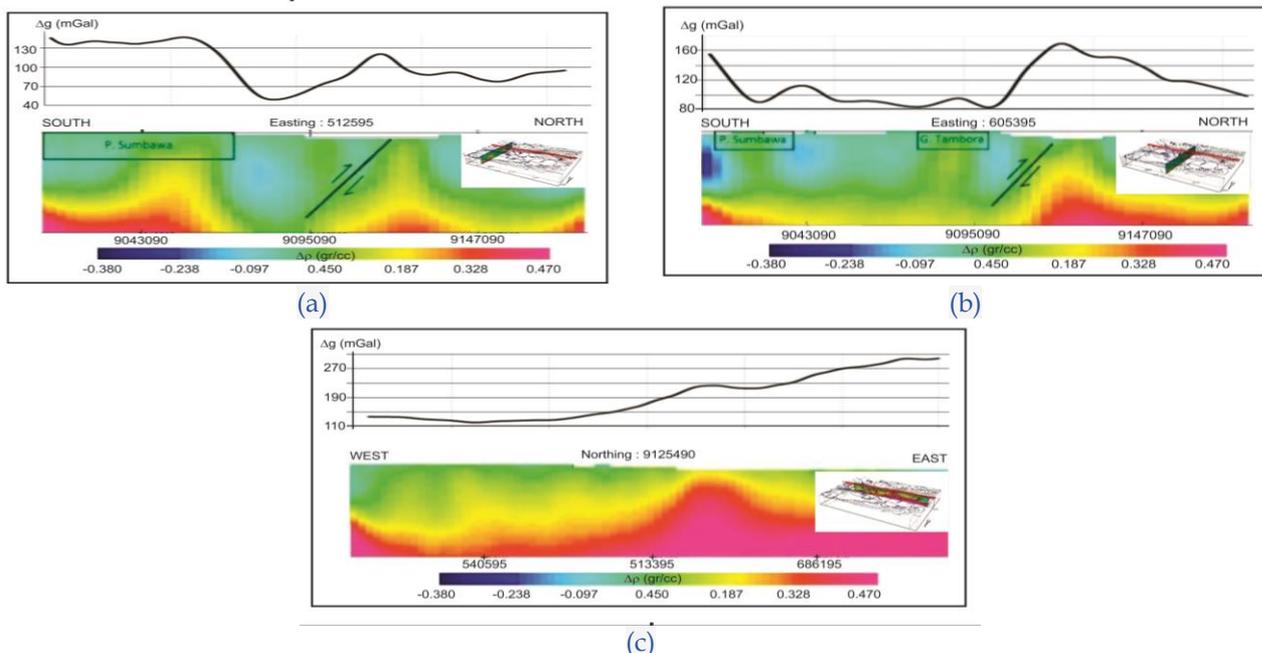


Figure 7. The result model cross-section of (a) AA', (b) BB', and (c) FF'

Figures 7a, 7b, and 7c show that the structure of the Flores Reverse Fault extends from East to West with an average increase of 26 km to the surface and has the same density composition so that it is possible that the rocks the constituents are the same. This is under the information from the BMKG (Widyarta et al., 2020) that the earthquake on August 9, 2018, with a magnitude of 6.9, had a hypocenter depth of 16.1 km, indicated to have originated from the Flores Reverse Fault as well as the earthquake incident on July 29, 2018, with a magnitude 6.4 has a hypocenter depth of 24 km

(Hidayati et al., 2018) that, the earthquake is thought to have originated from the Flores Reverse Fault..

Furthermore, the cross-section of gravity modeling results (Figure 8a) is compared with the 6 Seismic cross-section profiles from Yang et al., 2020 study in Figure 8b with the same coordinates. This is done to validate the inversion data model gravity with the result of a Seismic section.

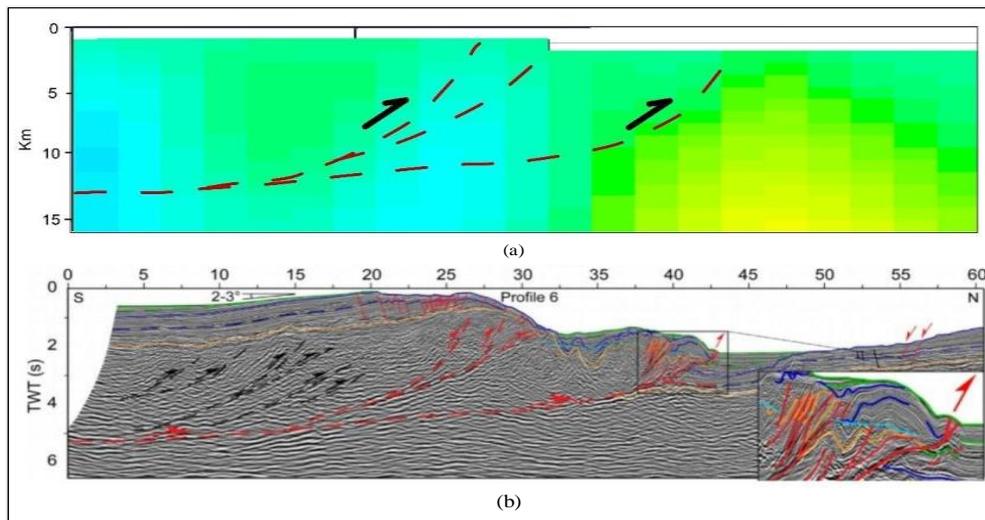


Figure 8. a). Section of Gravity b). Seismic cross-section based on research by Yang et al. (2020)

In the Gravity cross-section, a rock with a density of $\pm 2.52 \text{ gr/cc}$ (blue color) is identified as Andesite rocks, while rocks with a density of $\pm 2.68 \text{ gr/cc}$ (green color) identified as basalt rock. As for the seismic section of the top layer (delimited by the green line) identified as Pliocene sediments, later layers the second (delimited by brown line) was identified as the upper Miocene sedimentary layer Limestone, the two layers in the Gravity section cannot be identified, this is because the modeling is done with anomalous data regional which is an anomaly caused by the deep structure. While the lowest layer is identified as the basalt layer, there is a Fault Ascend Flores and identified to a depth of 10 km. In contrast, on the model, the gravity of the Flores Fault was identified up to 26 km.

Based on the comparison of gravity and seismic sections, it can be concluded that the Flores Reverse Fault is located in basalt rock, where the south side has a relative increase compared to the north side.

Filtering using the SVD method is carried out to determine the location and type of fault structure. From the SVD contour map, anomaly values ranged from -0.170 mGal to 0.157 mGal . The existence of a fault can be indicated by the second derivative of the regional anomaly, which is equal to zero. The SVD contour map is shown in Figure 9, and the results of the cross-sections are shown in Figure 10. In this study, the determination of the fault type only focused on the Flores Back arc thrust zone.

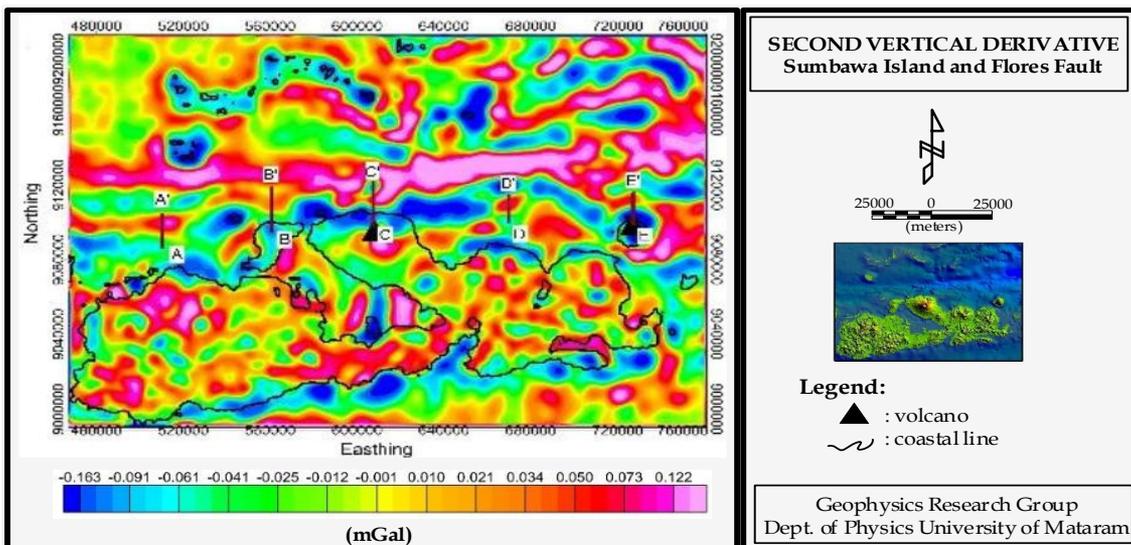


Figure 9. Map of SVD Regional Anomaly with the position of cross-sections

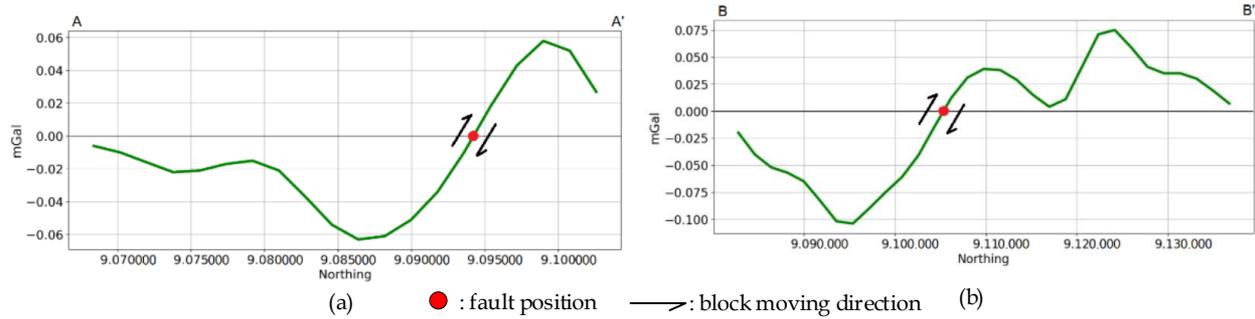


Figure 10. Graph of cross-sections A-A' (a) and B-B' (b) on the Map SVD Filter Elkins 1951

Based on the results of the five cross-sections, the SVD value shows that the Flores Fault is an Up Fault, this can be seen in the absolute value of the second derivative of the five cross-sections, where the absolute value of the minimum SVD is greater than the absolute value of the maximum SVD. The average is located in the vicinity coordinate $y = 9106000.0$ UTM. The value of the results of the five cross-sections can be seen in Table 2 below.

Table 2. Absolut value of SVD

| No | Cross-section | $ SVD _{max}$ | $ SVD _{min}$ | Norting Position (m - UTM) |
|----|---------------|---------------|---------------|----------------------------|
| 1 | A - A' | 0.058 | 0,063 | 9093579 |
| 2 | B - B' | 0.075 | 0.104 | 9106179 |
| 3 | C - C' | 0.098 | 0.121 | 9107979 |
| 4 | D - D' | 0.077 | 0.169 | 9104976 |
| 5 | E - E' | 0.068 | 0.183 | 9107979 |

Conclusion

Based on the analysis of gravitational anomaly data and three-dimensional modeling of the subsurface structure of the Flores back fault zone and the island of Flores volcano arc can be concluded that Sumbawa island to the fault zone behind the Flores arc, three main layers are consisting of the upper crust layer with a density of (2.29 - 2.81) gr/cc composed of Granite, Andesite and Basalt rocks, the middle crust with a density range of (2.82 - 2.91) gr/cc composed of Basalt, Diorite rocks, and Granodiorite, as well as the lower crust with a density range of (2.92 - 3.14) gr/cc composed of basalt, gabbro, and lava rocks. The Flores Reverse Fault is estimated to be from a depth of 26 km to the seafloor's surface, located in a different layer composed of Basalt, Granite and Diorite rocks.

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