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RESEARCH ARTICLE

3D Modeling of Subsurface Lawanopo Fault in Southeast Sulawesi, Indonesia Using Grablox and its Consequence to Geohazard

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Abstract. Lawanopo Fault is a horizontal shear fault (sinistral strike-slip) found in Southeast Sulawesi province and is thought to be active during Plio-Pleistocene or mid-late Miocene to the present. This study has been carried out which aims to find out the geometric shapes below the surface of the Lawanopo fault using complete Bouguer anomaly (ABL) data. The ABL data is projected onto a flat plane using the Dampney method at an altitude of 8 km, and the separation of local and regional anomalies is carried out using the upward continuation method at an altitude of 60 km. Three-dimensional (3D) modeling under the surface of the Lawanopo fault is done using the computer program Grablox. Data processing techniques using Singular Value Decomposition (SVD) and Occam inversion. The results showed that a high gravity anomaly of 190-225 mGal was caused by an igneous rock below the surface with a density of 2.7-3.33 gr/cm^3 and a thickness of about 13 km, a moderate anomaly of 175-187 mGal caused by Paleozoic igneous rocks aged Carbon with a density of 2.6-2.9 gr/cm3 and a thickness of about 25 km. Low anomaly 115-160 mGal is caused by rocks with a density of 2.0-2.5 gr/cm3 and a thickness of about 22-23 km. The Lawanopo fault constituent rocks consist of alkaline rocks in the basement covered by sediment and metamorphic with a depth of Lawanopo fault more than 15 km and begin to be seen at a depth of 4.3 km of the surface. it is known that the area around the Lawanopo fault is an area prone to earthquakes. But, based on the soil and rock structure around the Lawanopo fault, the compactness and attenuation levels in reducing earthquake waves are quite good, so that land use around the Lawanopo fault tends to be safe.

1. Introduction

In the last decade, the intensity of earthquakes in Indonesia has increased. Many researchers conclude that earthquake intensity increases due to tectonic plate movements (Putra et al. 2012). One of the regions in Indonesia, which has quite a large number of plates, is the central part of Indonesia (Holloway and Hall 1998). Sulawesi Island is located in the confluence zone of three large tectonic plates, namely the western Eurasia plate, the EasternPacific plate, and the Philippine plate shown in Figure 1 (Boen 2008). The interaction between the three plates causes the shape of the island of Sulawesi to be unique, resembling the letter "K" formed in the final Cretaceous (Natawidjaja and Daryono2016). Tectonic developments in the Sulawesi Island region have been going on since the Miocene era (Zufialdi et al. 2018), including the most active areas in Indonesia and complex and complex geological phenomena (Van Gorsel 2013). One manifestation of the movement of the plate in the presence of a fault (Valkaniotis et al., 2018).

Faults found on tectonic plates in their development also experience movement and will contribute to earthquake events (Farid et al., 2016). The magnitude of the earthquake that occurs due to the mechanism of the movement of the fault depends on the area of the asperity area where the greater the area of asperity (Arunee et al. 2019), the greater the probability of the earthquake occurring (Rusydi et al. 2018). The mechanism of this fault movement can be in the form of strike-slip, reverse, and normal (Irsyam et.al. 2010).Sulawesi island tectonics is dominated by several sinistral strike-slip faults, including the Palu-Koro fault, Matano fault, Lawanopo fault, Walanae fault, and Gorontalo fault (Natawidjaja and Daryono 2016). In these faults, various types of rocks are mixed so that the stratigraphic position becomes very complicated. The object of this research is Lawanopo Fault, as shown in Figure 2 (Hall and Wilson 2000). This fault is thought to have been active during Plio-Pleistocene or during the mid-late Miocene to the present, as evidenced by the presence of hot springs on the Holocene reef limestones on the fault line in the Tinobu Southeast (Natawidjaja and Daryono 2016). (Masri et al. 2011) and (Valkaniotis et al. 2018) have mapped the level of the threat of an earthquake in Kolaka Subdistrict, Southeast Sulawesi Province.

Other than that, (Burhan 2012) has done two-dimensional (2D) modeling and one-dimensional (1D) spectrum analysis to determine the subsurface structure of the Palu-Koro system based on vertical gradient analysis of gravity anomaly data (Nurpratama and Darusman 2015). The results obtained were the depth of the basement in Southeast Sulawesi, especially in the Kolaka area, about 5 km down to the northwest to a depth of more than 20 km. The decrease in basement depth in North Kolaka is thought to be related to the Palu-Koro-Matano fault and the Lawanopo-Kolaka fault system (Saibi et al. 2006). The shape of the subsurface structure of the Palu Koro-Lawanopo-Matanofault system area is a rock coating consisting of a basement dominated by alkaline and ultramafic rocks and covered by sediment and metamorph. Further research is needed, regarding subsurface mapping in the Palu-Koro-Lawanopo-Matano fault area in 3D to reinforce the suspicion of the existence, depth, and type of rock in the area (Gou et al. 2016). Whereas the Matarombeo Mountains are one of the mountains in the Southeast arm of Sulawesi Island, restricted by the Matano Fault in the north and the Lawanopo Fault in the Southwest - South, which produces a very complex geological structure.

In this study, we carried out observations, analysis, and interpretation to determine the dimension subsurface model of the suspected Lawanopo fault area in Southeast Sulawesi Province using Grablox and Bloxer software based on regional gravity anomaly data. Also, any bedrock that

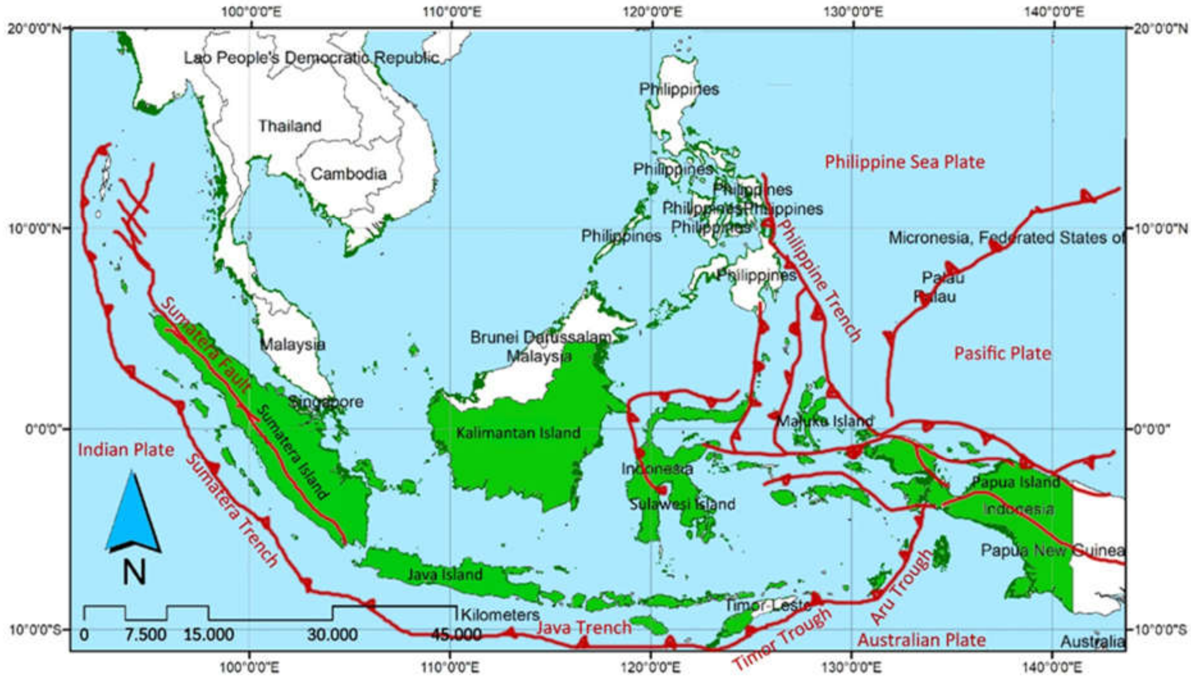

Figure 1. Meeting of the three-continent plates (Irsyam et.al. 2010)

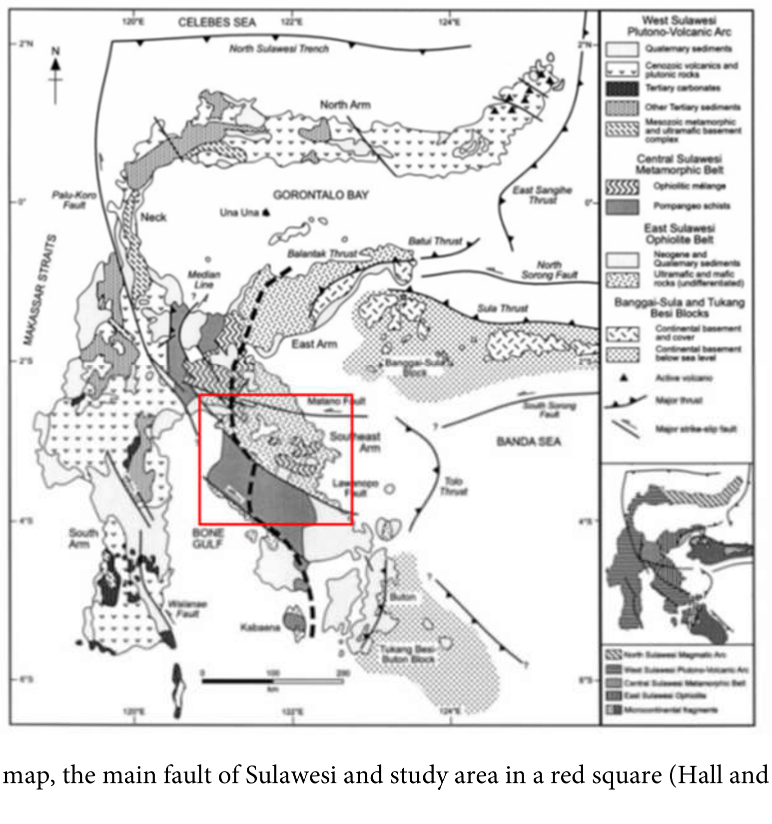

Figure 2. Geological map, the main fault of Sulawesi and study area in a red square (Hall and Wilson 2000)

composes the Lawanopo fault will be sought in this study and also the magnitude of the Lawanopo fault depth.

2. Method

The research area covers Southeast Sulawesi, which is geographically located in a position 3.0915o LU - 3,8490o LS and 121,1685° BB-122,2893° BT with the area of the study is 124 km × 83 km (Figure 2). The gravity data used is secondary data sourced from the Bureau of Gravimetrigue International (BGI) which is part of the IGSF (International Gravity Field Service). BGI is a collection, archiving, and distribution of gravity data throughout the world. This gravity data comes from several satellite surveys including GRACE and GOCE (http://www.bgi.omp.obs-mip.fr/data-products/grids-and-models/regional) gravity anomaly grids.

To facilitate understanding of the stages in this study, outline the procedures or stages in processing the data stated in the flow diagram such as; Secondary data obtained from BGI are in the form of Complete Bouguer anomalies (ABL). Geographical coordinates (degrees) are converted into UTM (meter) coordinates using the *Surfer* software. Based on topographical maps of Indonesia issued by the National Survey and Mapping Coordinating Board (Badan Informasi Geospatial), the Southeast Sulawesi Province is in Zone 51.

Then a gravity anomaly contour map is created using the *Surfer* software. The ABL that is still in the topography is then reduced to a flat plane with a regular grid using the Dampney mass point equivalent method. The ABL data, need to be carried out upward continuation which aims to separate local and regional anomalies. This continuation is carried out gradually upward until a contour is considered stable (unchanged). Upward continuation is done using the Magpick software. The results are used to obtain regional and local anomalies for further interpretation.

Regional and local anomalies from the results of upward continuation are then modeled in 3D using the Grablox and Bloxer software (Pirttijavi 2008, 2012). In this study, 3D modeling was carried out in 2 stages, namely forward modeling and inversion modeling. The modeling phases are done by making an input model and an initial block model of subsurface density.

The input model and initial block model can be made directly on Grablox by trial and error by entering several parameters such as the Bouguer density of the study area, block size, maximum and minimum X and Y values, and the depth of the target (Sudarmaji et al., 2016). After entering these parameters, it is then calculated, so that the theoretical data of the model is obtained with the smallest error rate. Inversion modeling is the opposite of forwarding modeling. At this stage, several stages of inversion are carried out using the Grablox software which starts with base optimization, density (ρ), Occam density, block height, and Occam height. This stage of optimization is done to get a match between model data and measurement data or reduce errors in the modeling process. Then the subsurface interpretation is based on geological information sources. In this study, the source of the geological information used was the regional geological map of the Kolaka-Lasusua sheet with a scale of 1: 250,000. To determine the trend of the Lawanopo fault, it is done by using the Rockwork software by inputting several parameters such as maximum and minimum X and Y values, rock density, and target depth. The input density value is the low rock density value obtained from the results of 3D modeling on Grablox which is the presence of faults.

3.Result and Discussion

Complete Bouguer anomaly is an anomalous value somewhere, as a result of the difference in density (ρ) between one rock to another. Bouguer anomaly is the difference from the value of the gravitational acceleration of observation with its normal value. The results of data processing carried out in the form of a complete Bouguer anomaly map to describe the subsurface geometry of the Lawanopo fault in the Southeast Sulawesi Province are shown in Figure 3 with a gravity anomaly value of around 115 mGal to 235 mGal.

Based on the complete Bouguer anomaly map, it can be explained that the high gravity anomaly is around 190 mGal - 225 mGal which is marked with red scattered in the east-northeast part of the Matarombeo mountain range, Hialu mountains, Morombo mountains, Bulu Tolinku, Bulu Ranawuwu, Bulu Buhusemale. This gives information that the rocks that make up the subsurface structure have a high density. The high value of gravitational anomalies in this area is thought to be caused by sedimentary rocks of the ocean (igneous) which are of late Cretaceous age (Hartantyo et al., 2014). This rock is dominated by peridotite, harzburgite, dunite, gabbro, and serpentinite. In addition to the east-northeast, high gravity anomalies are also found in the south -southwest and west-southwest with gravitational anomalies of around 190 mGal - 225 mGal which spread from the Lapaopao, Ululapaopao, and Tanjung Tobuso regions.

Moderate gravity anomalies (175 mGal - 187 mGal) which are marked in green, spread from the east-southeast to south-southeast, including the Asera, Tambua, Bulu Abuki, Abuki Mountains, Tinobu, Molawe, Laiwui, Sambeani, Ambepela, and Osao. This moderate gravity anomaly is thought to be caused by valleys and Paleozoic marble. Paleozoic marble rocks are exposed to Paleozoic rocks that are scattered in the Tinondo lane. Paleozoic gravel rocks are dominated by schist, genes, phyla, quartzite, and little marble (Hartantyo et al., 2015).

In the east-southeast to the south-southeast, the rock beneath it is thought to be composed of Permo-Trias-aged Meluhu rock formations which overlap in harmony with the Paleozoic metamorphic rocks, and at the same time, the Tokala formation is deposited in the Meluhu formation. The Meluhu Formation is dominated by sandstones, quartzite, black shale, red shale, phyllite, and siltstone.

The low gravity anomaly pattern (115 mGal - 160 mGal) is marked in purple, scattered in the northwest-southeastern part starting from the Tangkeleboke Mountains, Mount Tangkesawua, Asera, and Tambua. The low gravity anomaly gives information that the constituent rocks below the surface are thought to be Meluhu formations and Tokala formations. Both of these formations are rocks that overlap inconsistently with Paleozoic metamorphics rocks and are thought to be Permo-Trias. Low gravity anomalies in this area are thought to be Lawanopo fault zones, Kolaka faults, and Matarombeo faults.

Complete Bouguer Anomaly data that is still exposed to the surface of the topography, is located at irregular points with varying heights. This variation in altitude can distort gravity data. To minimize distortion, a process is carried out, namely, the complete Bouguer anomaly data is projected onto a flat plane with a certain height and the results of these

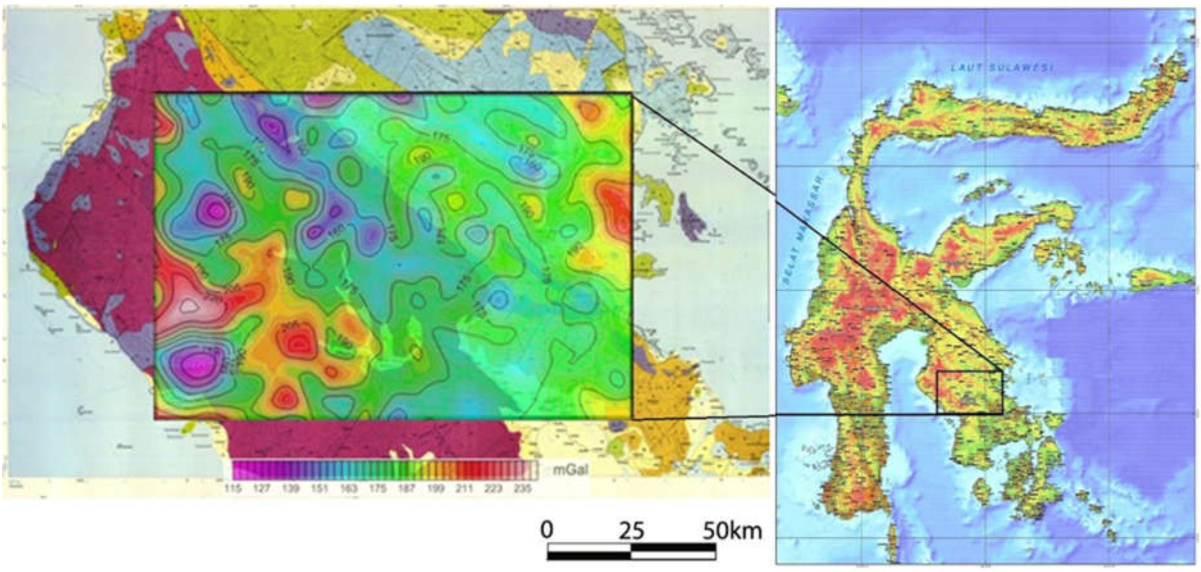

Figure 3. Complete Bouguer anomaly map

projections are convergent. Projection to flat fields using the Dampney method or mass point equivalent method (Dampney 1969). Based on the Dampney equation that the difference in distance between the sources of the point mass and the height of the flat plane of the reference spheroid is at least 2.5 times the grid space and a maximum of 6 times the grid space.

In this study, the average distance between the survey points was 1256 m, with a maximum height of 2110 m. The range of source depth values equivalent to mass point h is obtained by calculating using the Dampney equation which is between 5250 m to 9646 m. Projections are carried out for the equivalent depth of the mass point, which is 6 km, 7 km, 8 km, and 9 km. Based on the results of these calculations, the h value used in the reduction operation to a flat plane is 8 km below the reference spheroid, so that a complete Bouguer anomaly contour map is obtained after reduction to a flat plane as shown in Figure 5. The projection of the gravitational field to the flat plane is greatly affected by the difference in the source depth equivalent to the mass point, because the Earth's gravitational field is inversely proportional to the square of distance which is the greater the distance from the center of the earth, the smaller the value of the gravitational field (Irawan, S., Sismanto,, and Sukmatiawan, A. 2014).

Based on the complete Bouguer anomaly map the results of the reduction to the flat plane (Figure 4) show a reduction in the value of gravity anomalies. This is because, in the flat plane reduction, complete Bouguer anomaly data that is still exposed in the topography is carried to a flat plane with a certain height so that distance is increased. This is consistent with the concept that the greater the distance with the center of the earth the smaller the value of the gravitational field.

The range of the gravity anomaly after reduction to the flat plane is 10 mGal - 200 mGal. High gravity anomalies (160 mGal - 200 mGal) spread from the northeast to the southeast, namely Matarombeo mountains, Hialu mountains, Morombo mountains, Bulu Ranawuwu, Bulu Buhusemale, Abuki mountains, Bulu Abuki, Laiwui, and Latoma mountains. This anomaly is a response from constituent rocks that are below the surface that has high density, it is thought that rocks that have high density are igneous.Moderate gravity anomalies (110 mGal - 140 mGal) which are marked in green are scattered in the middle of the study area, which is thought to

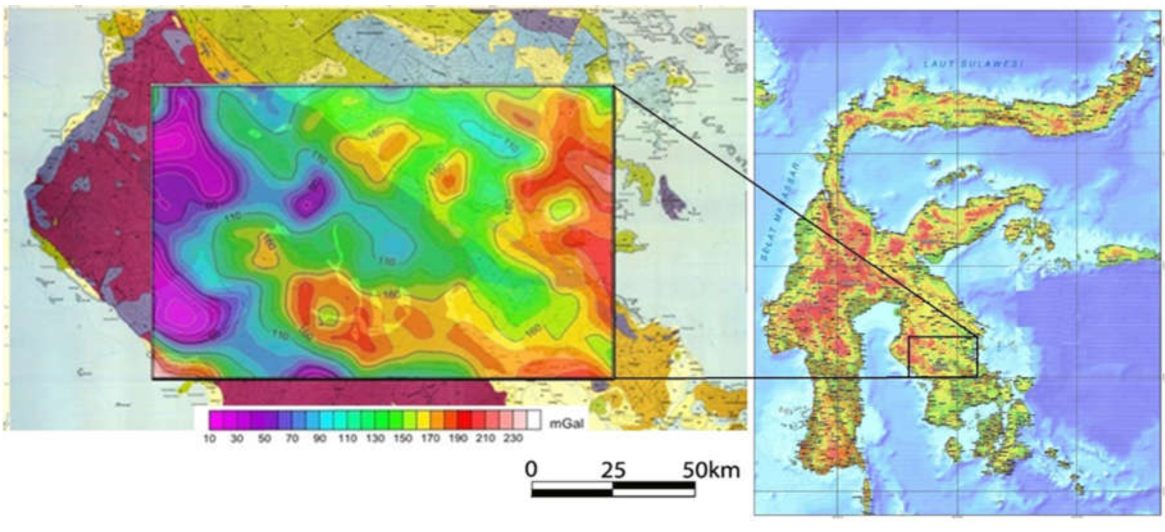

Figure 4. Complete Bouguer anomaly map after reduction to a flat plane

be a response to rocks that have a moderate density which is Paleozoic igneous rocks (metamorphic rocks) that are thought to be Carbon.

Low gravity anomalies are marked in purple with an anomalous range of about 10 mGal - 60 mGal scattered in the western and north-western areas of the study covering the area of Kondea and Lanipa. This low-density rock is thought to be the Lawanopo, Kolaka, and Matano fault zones.

Complete Bouguer anomaly that has been projected onto a flat plane is a combination of local and regional anomalies. To facilitate interpretation and further modeling, local and regional anomalies must be separated. One method used to separate local and regional anomalies is the upward continuation method using the Magpick software. In this study, the study was conducted to find out how the geometric shape under the surface of the Lawanopo fault using 3D modeling. The anomalies used from the results of upward continuation are a combination of local and regional anomalies so that it is expected to clearly describe the geometric shape of the Lawanopo fault surface.

The upward continuation process is carried out by trial and error and gradually each height so that regional contours of anomalies are found which have no influence from local anomalies and show a constant anomalous contour pattern. In this study, appointments were made from 10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 70 km, and 80 km. At an altitude of 60 km, there are fixed regional and local anomalous contours and are shown in Figures 5(a) and 5(b). Regional anomalous contours from upward continuation are then used for three-dimensional (3D) modeling of the subsurface structure of the Lawanopo fault using the Grablox program.

In Figure 5(a) regional anomalies resulting from the upward continuation show positive anomalous values which are around 125 mal to 138 mgal. This shows that the constituent rocks below the earth's surface have a positive density value. High anomalies are indicated by red contours in the northeast to southeastern and low anomalies are indicated by purple contours in the northwestern part of the study area.

Figure 5(b) shows local anomalies from the upward continuation with negative and positive anomalies with anomalous values ranging from -120 mGal to 70 mGal. This provides information that the rocks that make up the subsurface structure of the earth have density contrast values that vary from negative to positive anomalies. Negative gravity anomalies are thought to be caused by rocks of low density ie sedimentary rocks. While positive gravity anomalies are thought to be caused by rocks that have medium to high density, namely metamorphic and igneous rocks.

Three-dimensional Model (3D)

The results of inversion calculations using the SVD method and Occam inversion produce a three-dimensional (3D) model of the subsurface structure of the Lawanopo fault zone. The first step to create a 3D model is to make a cross-section on the regional anomaly contour map from the upward continuation. The overall inversion results in a 3D model of the subsurface structure of the Lawanopo fault shown in Figure 6-9. The cross-section in the 3D model is made perpendicular to the direction of Z, so that the depth of each layer can be obtained and the density of the rock from each layer can be known. In this process, the cross-section model is made to a depth of 25 km and is divided into 7 layers of depth ranging from 4.3 km, 6.7 km, 9.5 km, 12.6 km, 16 km, and 19, 8 km with varying contrast density at each depth.

Depth of 0 – 2,5 km

The horizontal 3D cross-section model with a depth of 0 -2.5 km is shown in Figure 6a. At a depth of 0 km, it is dominated by rocks with an average density of around 2.6 gr/cm³. This rock is a Paleozoic (a metamorphic rock), that is Carbon age and spread along the Tinondo line. At a depth of 2.5 km, it starts to show the contrast of rock density ranging from low to moderate density. Low-density rocks (blue and light blue) are Meluhu and Tokala formation rocks with an average density of around 2.0-2.5 gr/cm³. Medium-density (green) is a metamorphic rock with an average density of around 2.6-2.9 gr/cm3. At this depth, the Lawanopo fault zone is not yet visible.

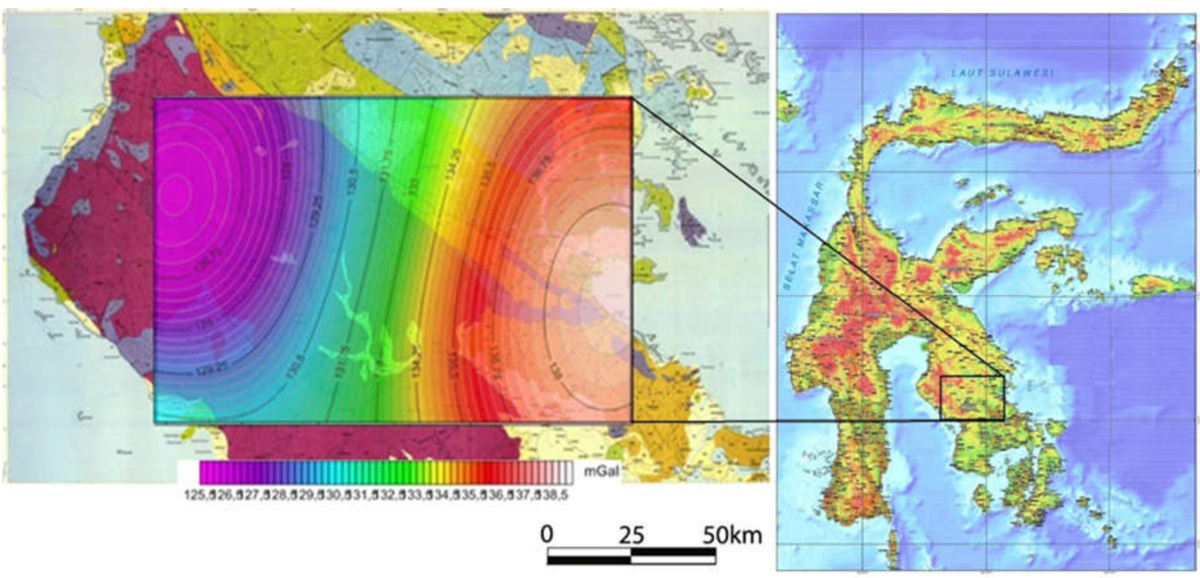

Figure 5 (a). Regional Anomaly contour map at the appointment of 60 km.

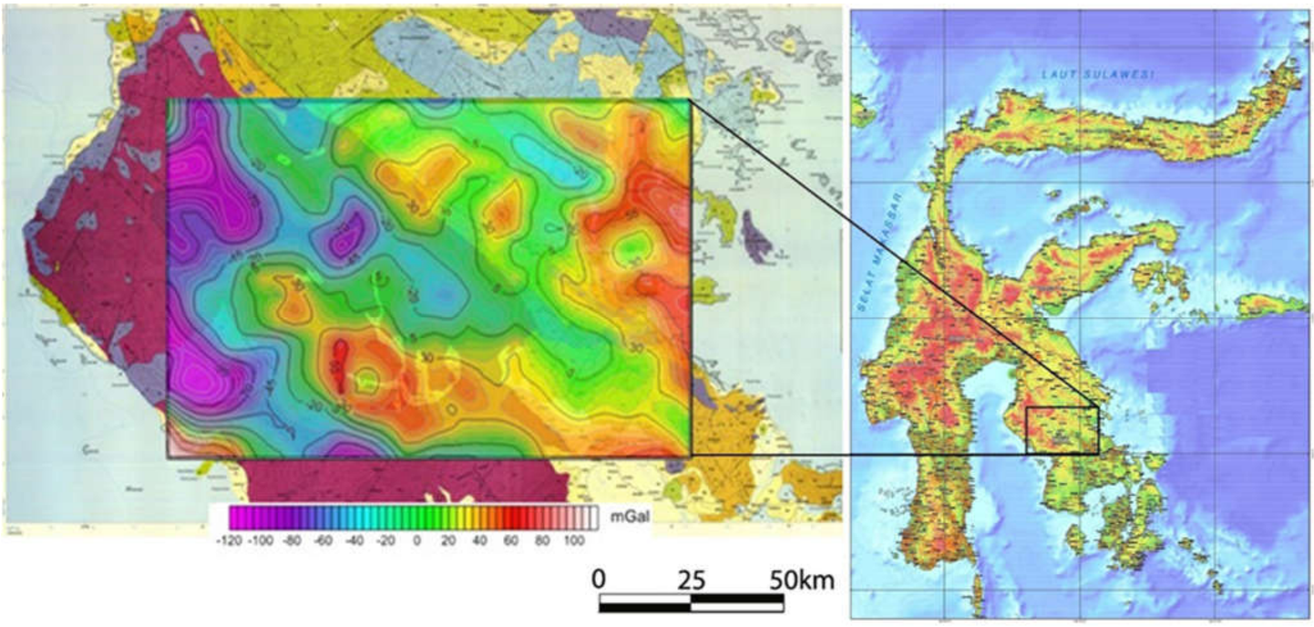

Figure 5 (b). Local Anomaly contour map after subtracting contour regional at an altitude of 60 km

Depth of 4.3 km

At a depth of 4.3 km, the contrast of density is increasingly apparent as shown in Figure 6b. At this depth, it is still dominated by rocks of moderate density which are marked in green-yellow which are Paleozoic igneous rocks (metamorphic rocks) and have an average density average of around 2.6-2.9 gr/cm^3. Whereas low-density rocks which are marked in blue and light blue, scattered in the northwest-southeast direction, these rocks are Meluhu formations and Tokala formations which have an average density of around 2.0-2.5 gr/cm^{3}which is aged Permo-Trias and overlapping in incompatible Paleozoic rocks. At this depth, the Lawanopo, Kolaka, and Matano fault zones begin to be visible marked in blue and light blue. Based on Figure 6b, the rock thickened in the northwest and southeast of the study area. Whereas the center is still filled with other rocks that have a higher density. Low-density rocks located in the northwest and southeast are Lawanopo, Kolaka, and Matano fault zones. This is following the 3D model of the cross-section perpendicular to the Z-axis.

Depth of 6.7 km

Low-density rocks marked with blue and light blue begin to dominate at this depth as shown in Figure 6c. The rocks found at this depth are Meluhu and Tokala formation rocks which are thought to be Permo-Trias with an average density of around 2,0-2.5 gr/cm^3 which is spread along the northwest to the southeast which is the Lawanopo, Kolaka, and Matano fault zones. Fault zones are usually characterized by rocks that have a lower density than the surrounding rock due to destruction in the zone. Medium-density rocks around 2.6-2.9 gr/cm^3 are also seen at this depth which is marked with green and yellow which are Paleozoic bleached rocks that are thought to be of Carbon age. These rocks are overlapped unconformable by Meluhu and Tokala formation rocks. Meluhu and Tokala formation rocks are seen thickening in the northwest and southeast while in the middle it looks thin.

Depth of 9.5 km

Rocks at this depth have very varied densities as shown in Figure 6d. Composite rock structures are very complex ranging from rocks of low to high density. Low-density rocks (blue and light blue) are seen more clearly at a depth of 9.5 km. This rock is a Meluhu and Tokala formation that is thought to be Permo-Triassic and overlaps with the Paleozoic igneous rock in the Tinondo line with an average density of around 2.0-2.5 gr/cm^3. Paleozoic speckles (green) are scattered in the central part of the study area, which shows that these rocks are overlapped by other rocks of lower density. In the eastern part of the study area, rocks of high density (red) begin to appear at this depth. These rocks are sedimentary rocks of oceanic crust which are scattered along the Hialu lane and have an average density of around 2.7-3.33 gr/cm^3.

Depth of 12.6 km

Figure 6e shows that at this depth it is increasingly apparent that the Lawanopo, Kolaka, and Matano fault zones are characterized by low-density rocks (blue and light blue). Medium-density (green) and high (red) are also present at this depth. Low-density rock is spread along the northwest to the southeast which is the Lawanopo fault. Parallel to the Lawanopo fault, there is a Kolaka fault and a Matano minor fault. Low-density rock in this fault zone is Meluhu and Tokala formation rock with a density of 2.0-2.5 gr/cm^3. Medium-density rocks at this depth are carbon-aged metamorphic rocks with an average density of 2.6-2.9 gr/cm^3. These rocks are overlapped unconformably by Meluhu and Tokala formations scattered in the Tinondo line. High-density rocks at this depth are increasingly visible, these rocks are igneous in the Hialu line. These igneous rocks are bedrock (basement), which is composed of Lawanopo, Kolaka, and Matano faults, which are dominated by alkaline and ultramafic rocks with a density of about 2.7-3.3 gr/cm^3.

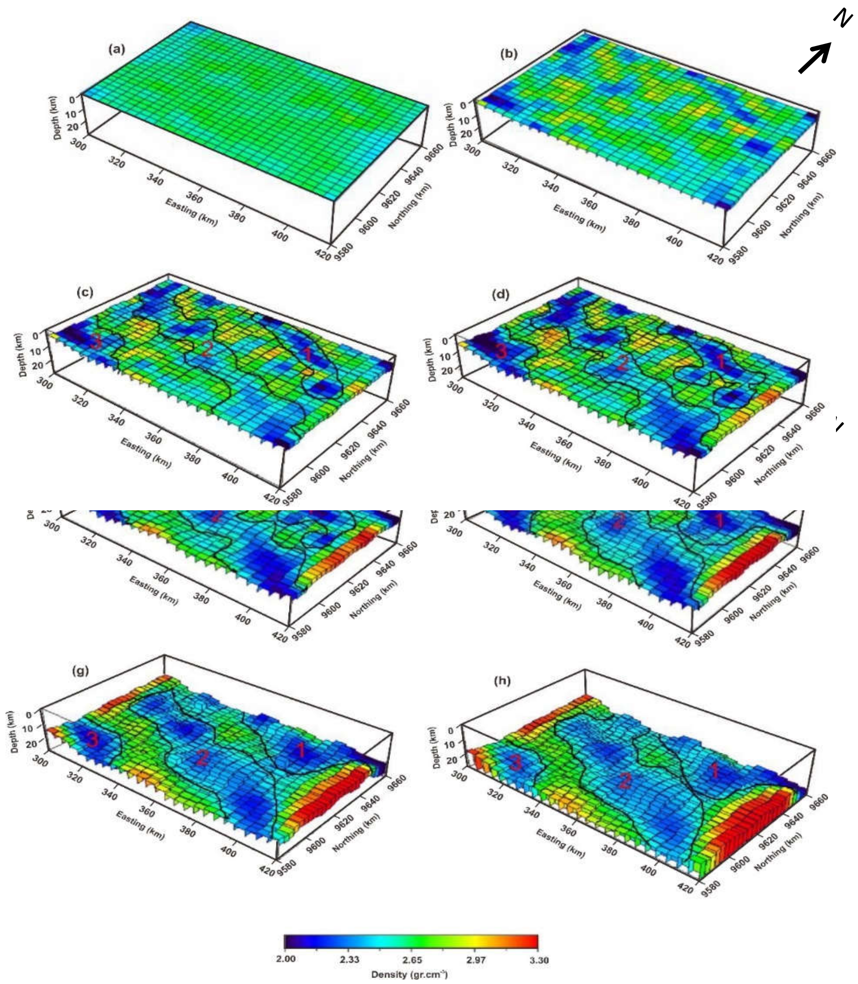

Figure 6. Gravity modeling on density for each slice depth (3 is a trend area for Kolaka fault; 2 is a trend area for Lawanopo fault, and 1 is a trend area for Matano fault) at depth 0 km (a),2.5 km (b), 4.3 km (c), 6.7 km (d), 9.5 km (e), and 12.6 km (f), 16 km (g), 19.8 km (h).

Depth of 16 km

Figure 6f shows that at this depth, high-density rocks (red) which are igneous are located in the west and east of the study area. As the depth increases, these rocks are increasingly seen thickening in the east. This rock is an oceanic crust sedimentary rock that is thought to be Cretaceous and spread along the Hialu line with an average density of 2.7-3.33 gr/cm^3. At this depth, the Lawanopo, Kolaka, and Matano fault zones are marked with blue and light blue extending from northwest to southeast. The rocks found along this fault zone are Meluhu and Tokala formations which are thought to be Permo-Trias. At this depth, low-density rocks appear thinning in the northwest.

Depth of 19.8 km

Based on Figure 6g also, it can be seen that rocks with low density spread evenly on the surface along the northwest to southeast direction. In the northwest, the Meluhu rock formations look thinner while in the southeastern part the two faults appear to be fused. The igneous rocks that have a high density (red) are increasingly visible in the east and west. This rock is the basement of the Lawanopo fault cretaceous. This rock distribution starts from Bulu Tolinku, Buhusemale fur, Bulu Ranawuwu, Hialu mountains, and Morombo mountains.

Figure 6. Gravity modeling on density for each slice depth (3 is a trend area for Kolaka fault; 2 is a trend area for Lawanopo fault, and 1 is a trend area for Matano fault) at depth 0 km (a),2.5 km (b), 4.3 km (c), 6.7 km (d), 9.5 km (e), and 12.6 km (f), 16 km (g), 19.8 km (h).

Medium-density rock (green) is still visible at this depth which is a Paleozoic rock with density2,6-2,9 gr/cm^3. This rock spread starts from the Tangkeleboke mountains, Mount Latoma, Mount Tangkesawua, Purau, Anggoea, Alaaha, Andalaki, and Watumencanga. In the northeastern part, the dominating rock is the Matano formation rock which is at the end of the Cretaceous, this rock overlaps with incompatible igneous rocks in the Hialu line.

The Matano formation rock consists of layered limestone inserts with a flange at the bottom. In addition to the Matano formation, there are also molasses-type sedimentary rocks which are thought to be late Miocene-early Pliocene which formed the Pandua formation consisting of conglomerates, sandstones, and claystone. At a depth of 16 to 19.8 km, it can be seen that the position of the Lawanopo fault has shifted from the previous position on the surface. Based on Figure 6, it can be seen that at that depth the Lawanopo fault zone is not right in the northwest-southeast direction.

3D density model distribution

The rock found in the study area is a melange mixed rock produced as a result of the process of a collision between plates, this resulted in a very complicated stratigraphy of the area. The rock has a very varied density ranging from rocks with low to high density. Low-density rocks which are around 2.0-2.3 gr/cm³ which are marked in blue are shown in Figure 7(a). These rocks are sedimentary or called sedimentary melange and consist of sand, sandstone, meta sediment, breccia, and volcanic which is the lowest density rock that spreads from the northwest to the southeast with an uneven thickness in the study area which is around 22-23 km. This low-density rock is the Lawanopo, Kolaka, and Matano fault zones. The Lawanopo fault is parallel to the southern segment of the Palu-Koro fault. The end of the Lawanopo fault is at the end of the Gulf of Bone, presumably that the movement of the Lawanopo fault causes the opening of the Bone Bay (Koesnama 2014). Based on the figure, it is seen that the Lawanopo fault does not coalesce in the southeast. It is suspected that the Lawanopo fault is an old-age fault and has never been active. When the fault is inactive, the sedimentation process occurs in the lower part (southeast) so that the lower part is covered with other rocks (Zuhdi et al., 2018).

Figure 7(b) shows the thickness of the rock with a density of about 2.3-2.5 gr/cm³ which is marked in light blue. This rock is a Meluhu and Tokala formation that is Permo-Trias aged and spread unevenly in the research area with a thickness which is around 23-24 km. The thickness of the rock with a density of about 2.6-2.9 gr/cm³ is shown in Figure 8a.

This rock is a Paleozoic metamorphic rock (metamorphic rock) which is marked with green-yellowish color, this rock is thought to be of the Carbon age and dominated by schist fillit, quartzite, and a little marble. Metamorphics rocks are intermediate rocks, rocks that are not acidic and also not alkaline. This rock distribution is not evenly distributed in the study area starting from the basement to the surface. In the western part, the thickness of this rock is about 25 km and thinning in the middle to the east. Figure 8b shows the thickness of igneous rock which is marked in red with a density of about 3.0-3.3 gr/cm³ spread over the western and eastern parts of the study area with a thickness of about 13 km. These rocks are sedimentary rocks of the oceanic crust and are basement rocks which are interpreted as ultrasound

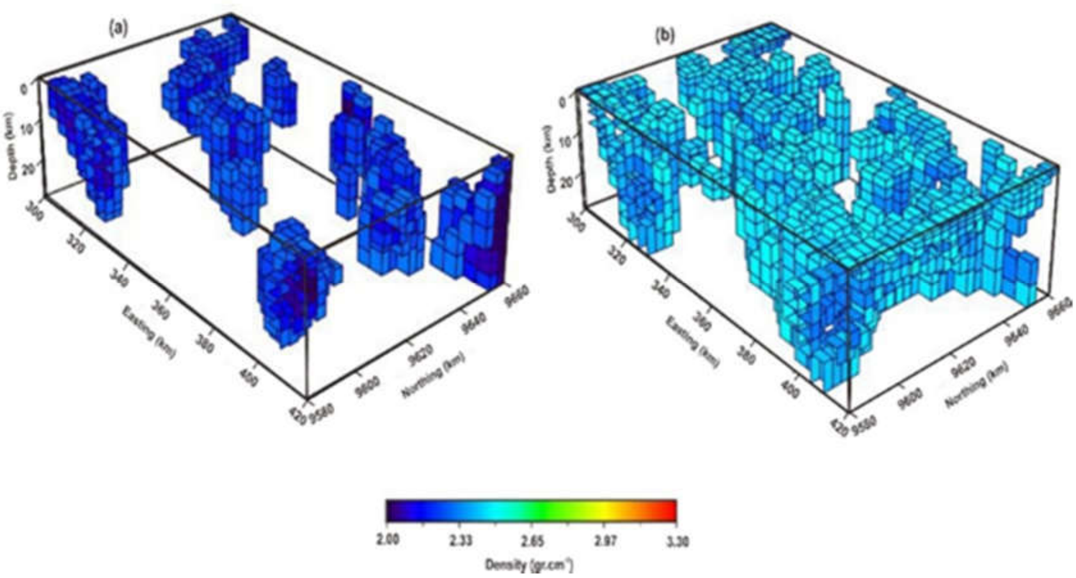

Figure 7.Distribution of density model 2,0–2,3 gr/cm³(a) and 2,3–2,5 gr/cm³(b)

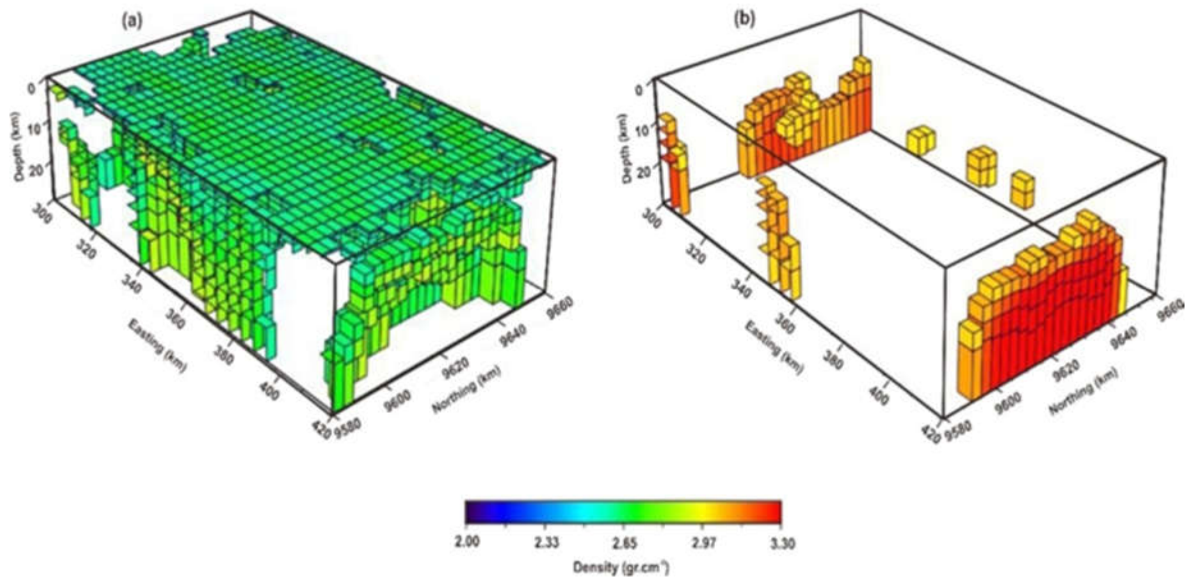

Figure 8. Distribution of density model 2,6 – 2,9 gr/cm³(a) and 3,0 – 3,3 gr/cm³ (b)

peridotite, basalt, dunite, and gabbro which contain ferromagnetic or basaltic minerals (Rizqi et al. 2019).

3D model of Lawanopo fault based on density

Figure 9a shows a 3D model of trends in the Lawanopo, Kolaka, and Matano faults at a depth of 4.3 km. Rocks found in the Lawanopo fault are igneous rocks in the Hialu line which are overlapped unconformably by the Matano formation rock which is thought to be Cretaceous. In addition to the Matano formation, there are also Molasa type sedimentary rocks that are late Miocene-early Pliocene which formed the Pandua formation. Other rocks that are also found along the Lawanopo fault zone are Meluhu rock formations and deposits of Tokala formations which are thought to be Permo-Trias.

At this depth, it can be seen that the trend of the Lawanopo fault has not converged, this is since at this depth there are still Paleozoic igneous rocks, where these metamorphic rocks are squeezed out of harmony with the two formations. Meluhu formation rock thickens in the northwest and thinned in the southeast with a density of about 2.0-2.5 gr/cm^3 which is marked with purple and light blue in the figure. Based on the results of data analysis and parameters of an earthquake caused by faults on the island of Sulawesi (Irsyam et al. 2010), the value of the slip-rate of the Lawanopo fault is around 25 mm/year with a dip angle formed between the fault and the horizontal plane is around 70^o, the depth of the Lawanopo fault is around 15 km, this is by the results of 3D modeling for cross-sections perpendicular to the Z-axis, where the trend of faults begins to be seen at a depth of 4.3 km to 19.8 km. The Lawanopo fault trend extends from northwest to southeast with a length of about 303 km starting from Mount Tangkeleboke, Kuete, Lewulo, Asera, Tambua, Longu, Abuki, and Tinobu. In line with the direction of the Lawanopo fault, there are also other faults in the study area, namely the Matano fault and the Kolaka fault which traverses northwest-southeast.

The rock found in this fault is an igneous rock found in the Hialu line, which is crushed in harmony with the Matano formation which is thought to be of late Cretaceous age and is dominated by layered limestone with heating at the bottom.

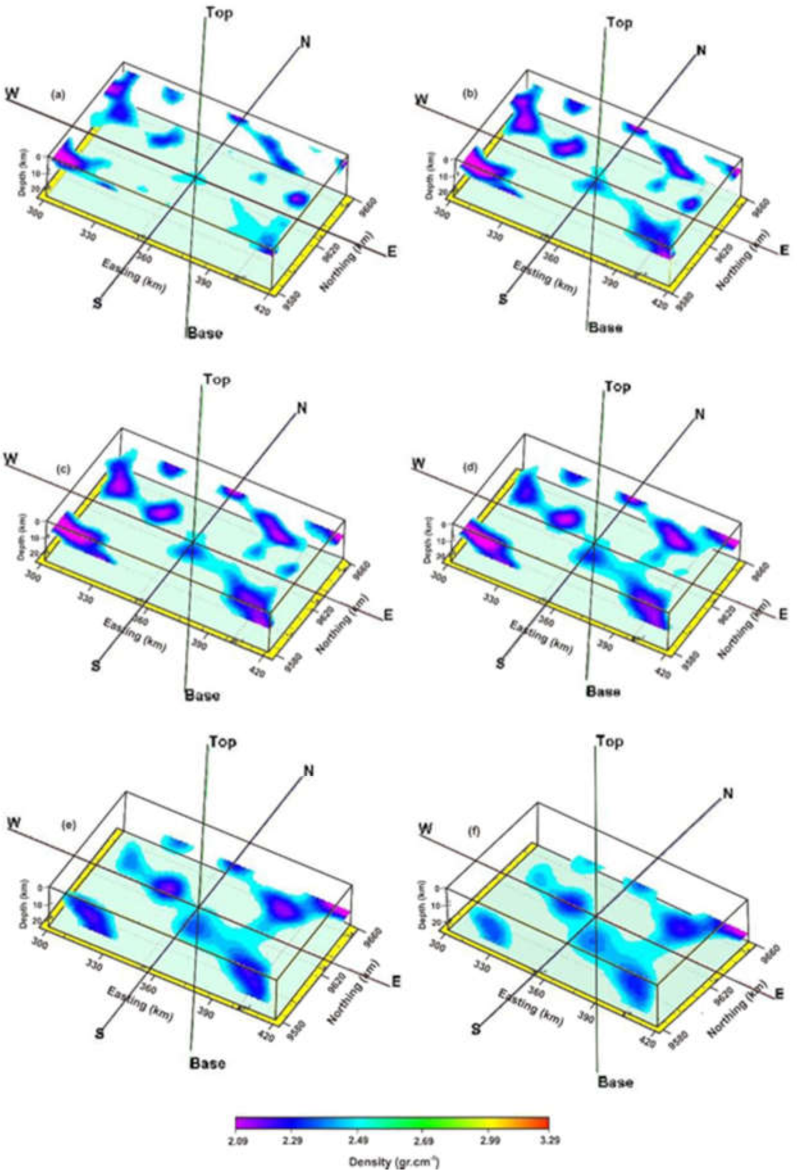

Figure 9. Trend of Lawanopo fault at 4.3 km (a), 6.7 km (b), 9.5 km (c), 12.6 km (d), 16 km (e), and 19.8 km (f) depths (blue line is a trend for Kolaka fault; the orange line is a trend for Lawanopo fault, and the black line is a trend for Matano fault).

At a depth of 6.7 km and 9.5 km the trend of faults began to be seen clearly, the Meluhu and Tokala formation rocks were thickened in the northwest and southeast while in the middle of the two rock formations it was seen to be fused as shown in Figures 9b and 9c.

At a depth of 12.6 km, it can be seen that the Meluhu and Tokala rock formations which have low densities begin to thin out in the northwest and merge in the southeast. At this depth, the Matano minor fault appears to merge with the Lawanopo fault. The Matano fault is a Minor fault found in the Hialu lane and its direction is parallel to the direction of the Lawanopo fault, which is directed northwest-southeast. The rocks contained in the Hialu line are igneous rocks with a density of about 2.7-3.3 gr/cm^3 which consists of peridotite, harzburgite, dunite, and gabbro. This rock is suppressed unconformably by the Matano formation which is thought to be Cretaceous and consists of limestone inserts with flanges at the bottom. Molasa type sedimentary rocks which are thought to be late Miocene-early Pliocene form the Pandua formation, this formation overlaps not aligned with all older formations both in the Hialu line and in the Tinondo line. The rock density found in the Lawanopo, Kolaka and Matano faults is around 2.0-2.5 gr/cm^3 as shown in Figure 9d.

Figures 9e and 9f show the Lawanopo fault trend at a depth of 16 km and 19.8 km. In the northwest, to the southeast, the rock layers of the Meluhu and Tokala formations are thinning. At this depth, the Lawanopo, Kolaka, and Matano faults are increasingly evident and in the southeast part of the Lawanopo fault connect with the Matano fault.

Geohazard risk

The existence of the Lawanopo fault can be a source of earthquakes, if triggered by a large earthquake source nearby, for example, the Palu-Koro fault. The source of the Lawanopo fault caused ground motion on the surface of the area around the fault. The ground motion that occurs due to earthquake events can be in a short time but can also occur over a long period of time. The difference in the length of time an earthquake occurs is due to differences in the amplitude, and frequency of the earthquake waves. The strong ground motion will greatly affect infrastructure facilities. The amount of ground motion caused by the earthquake is greatly influenced by the amount of energy released when an earthquake occurs. The amount of energy released during an earthquake has a direct relationship with the magnitude of the earthquake strength recorded at the earthquake recording station. The characteristics of the ground motion are very important to know because the damage caused by the earthquake is very much influenced by the characteristics of the motion. In general, the characteristics of earthquake motion include amplitude, frequency, and duration. The results of identification and evaluation of the characteristics of the earthquake motion will affect the ground motion parameters which include the history of displacement time, the time history of velocity, and the time history of acceleration. Parameters of ground motion can be acceleration, velocity, and displacement, or a combination of the three. From the interpretation results (Figures 6 - 9) and the correlation between fault distribution and subduction zones in the Sulawesi region (Figure 1-2), it is estimated that the area around the Lawanopo fault is an area prone to earthquakes. Although vulnerable to earthquakes, based on the soil and rock structure around the Lawanopo fault (Figure 2), the compactness and attenuation levels in reducing earthquake waves are quite good, so that land use around the Lawanopo fault tends to be safe. On the other hand, it is necessary to analyze the level of land use around the Lawanopo fault, especially activities in the process of soil processing and building strong structures to determine the level of disaster risk around the Lawanopo fault.

4. Conclusion

Based on the results of 3D modeling that has been done to see how the subsurface geometry model of Lawanopo fault in Southeast Sulawesi Province is based on analysis of gravity anomalies, the following results are obtained:

High gravity anomalies (190-225 mGal) are thought to be caused by rocks with a density of about 2.7-3.33 gr/cm^{3}ie igneous rocks that are thought to be Cretaceous, this rock is dominated by peridotite, harzburgite, dunite, gabbro, and serpentinite with a thickness of about 13 km. Moderate gravity anomalies (175-187 mGal) are thought to be caused by Paleozoic rocks (metamorphic rocks) which are thought to be of the carbon age and have a density of about 2.6-2.9 gr/cm^3. This rock is dominated by schist, genes, fillit, quartzite, and a little marble with a thickness of about 25 km. Low gravity anomalies (115-160 mGal) in the northwest-southeast are thought to be caused by Meluhu and Tokala rock formations which have a density of about 2.0-2.5 gr/cm^3. This rock is a sedimentary rock that is Triassic in age and is dominated by sandstones, limestones, calcilutite, shale, and marl with a thickness of about 22-23 km.

Lawanopo fault compiler rocks consist of igneous rock as the basement which is dominated by peridotite, gregro, harzburgite, dunite, and serpentinite and coated with sediment and metamorphic rocks. Lawanopo fault depth is more than 15 km and begins to appear at a depth of 4.3 km to 19.8 km. it is estimated that the area around the Lawanopo fault is an area prone to earthquakes. But, based on the soil and rock structure around the Lawanopo fault, the compactness and attenuation levels in reducing earthquake waves are quite good, so that land use around the Lawanopo fault tends to be safe.

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