The Utilization of GGMplus Data Using Derivative Method and 3D Modeling of Subsurface Structure for Trienggadeng Fault Identification in Pidie Jaya, Aceh Region

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Abstract. The Pidie Jaya, Aceh earthquake occurred on December 7th, 2016 that caused damage to the northern coastal area. This event was caused by a local fault (Trienggadeng Fault). The existence of this fault is close to settlements so we need the mitigation efforts to reduce the casualties and material loss. One of those efforts is mapping the fault location by using the gravity method that is sensitive to subsurface rock density changes. In this study, we used GGMplus gravity data then processed with derivative analysis (First Horizontal Derivative and Second Vertical Derivative) to determine the location and type of fault. By performing the slices, we found that this fault is oblique with strike-slip dominant tends to reverse fault. The azimuth discovered through fault position traces that the value is 47.5\degree. Then, we use 3D inversion modeling to obtain a subsurface structure model. The average density is 2.3 g/cm\textsuperscript{3}. The model shows a distribution of limestone and sandstone sedimentary rocks reaches a 4 km depth. The clay sediments follow the river flow. In the southern part, there are andesite and granite igneous rocks. The difference in rock density within 3 km and below indicates the existence of the Trienggadeng Fault.

1. Introduction

Tectonically, the Sumatera region consists of subduction, Mentawai Fault, and Great Sumatera Fault systems. The existence of the Great Sumatera Fault due to a subduction system which is named slip partitioning [1]. This process happens if the movement of two tectonic plates is not perpendicular to the subduction strike [2]. This condition causes the appearance of the fault in Sumatera land that is parallel to the subduction strike. The mechanism of this fault is dextral strike-slip with 1900 km length [3]. Based on the topography and aerial photography observations, this fault is divided into 19 segments with the variation of each segment length. The [4] conducted the update of the active fault map and find the fault segments out of the main segment, such as Peusangan, Pidie, Biruen, Lhokseumawe, and Oeng Faults in the eastern of Aceh segment.

The earthquake occurred on Wednesday, December 7\textsuperscript{th}, 2016, 05:03:33 local time. This event is located in Pidie Jaya Regency, Aceh, 30 km northern of Sumatera Fault with 6.5 Mw (magnitude moment). Indonesian Agency of Meteorology Climatology and Geophysics (BMKG) report that the epicenter of this event is 5.29° N and 96.22° E and 15 km depth. Total casualties from this earthquake about 104 people died, hundreds were injured, and thousands of buildings were destroyed [5].
The Pidie Jaya geology structure dominates by soft-sediment rocks and alluvium soils. The alluvium in the coastal region is above Tertiary rock which may have been disintegrated so that the soft rock is thicker [6]. This causes amplification of earthquake tremors especially in the eastern of the district. In this area, liquefaction occurs in the Meunasah Balek Village which is located on the coast. Black sand mud appeared through small cracks on several floors of the house. This condition occurs because the soil is saturated so that it increases the pore water pressure and reduces the effective stress [7]. The field observation in Pidie Jaya clarifies that this area has the D and E type soils with several areas consist of F type soils [8].

![Figure 1. Geology map of Pidie Jaya, Aceh (data from [9] and [10]).](image)

BMKG with their regional stations recorded the aftershocks from December 7th, 2016 until December 19th, 2016. The aftershock events that were successfully relocated from the BMKG catalog is 74 of 89 events [11]. A week after mainshock occurred, BMKG, GFZ-Postdam (German Research Center for Geosciences), ITB (Bandung Institute of Technology), and UNSYIAH (Syiah Kuala University cooperated to install local temporary broadband stations in nine location that were named as Pijay-Net or AAS (Aceh Aftershock Station). This station recorded aftershocks for a month (December 14th, 2016 – January 15th, 2017). The aftershock events that were successfully relocated from this catalog are 260 of more than 300 events [12]. The combination of the tow data above shows a complex structure in the Pidie Jaya region. Relocation of the BMKG network associate with the NNW zone of increased stress or regional structure which is parallel to the Great Sumatera Fault, while hypocenter relocations of the local seismic network (AAS) represent the Pidie Jaya local structure with NE strike [13]. NE trending structure is called the Panteraja Fault [12], hereinafter referred to as the Trienggadeng Fault [14].
Based on the depth of the mainshock and aftershock hypocenter, we can know that the fault plane that causes this earthquake is in depth of up to 28 km or more. Therefore, we use the gravity method to analyze the fault that caused the Pidie Jaya earthquake. This method measures changes in rock density indicated by variations in the value of the acceleration due to gravity at different points. The description of the anomaly of the acceleration due to gravity is associated with the distribution of subsurface rock density so it is suitable for analyzing the existence of faults.

2. Method

In this research, we use GGMplus data (Global Gravity Model Plus). This is the combined data of gravimetry satellite of GRACE (Gravity Recovery and Climate Experiment), GOCE (Gravity-field and steady-state Ocean Circulation Explorer), EGM 2008 (Earth Gravity Model), and topographic gravity. This combination produces data with a 7.2 arc-second grid resolution (~220 meters) that covered 80% of the landmass, ± 60° in latitude and ~10 km sea zone in coastline area [15]. This data can be downloaded through http://ddfe.curtin.edu.au/gravitymodels/GGMplus/data/dg/ (disturbance gravity GGMplus). To process this data, we need elevation data with the same resolution. This data can be obtained from http://ddfe.curtin.edu.au/gravitymodels/ERTM2160/data/dem/ (ERTM2160).

This study covers the area of Pidie Jaya, Aceh (5° – 5.3° N and 96.05° – 96.35° E). The data obtained is then processed to produce the Simple Bouguer Anomaly (SBA) value by calculating the average density. This density is obtained through the calculation of the Parasnis method which correlates the Free Air Anomaly (disturbance gravity) data with its elevation. The gradient value of the linear graphic shows the average density value. This value needs to be connected with local geological conditions so that it is valid to describe the actual situation.

![Figure 2. Relocated catalogue combination of BMKG and AAS network [13].](image)
SBA is then processed using the derivative method, namely the First Horizontal Derivative (FHD) and the Second Vertical Derivative (SVD). First derivative corresponding to changes in the SBA values. The value of the first derivative will be a maximum/minimum value indicating the boundary of a subsurface rock body [16]. It can say that there is a fault in the area if the boundary forms an elongated pattern. To find out the type of fault, we use the calculation of the value of the second vertical derivative because the gravity anomaly value satisfies the Laplace equation [16]. The boundaries of the contact area are indicated by the SVD value of zero.

The determination of the fault type is based on Bott’s criteria [17]. This criterion states that the ratio of the maximum and minimum second derivative values gives different results for distinguishing structures with horizontal slabs with different tip slopes. The equation used is shown by:

$$\frac{\partial^2 \Delta g}{\partial z^2}_{\text{max}} > \frac{\partial^2 \Delta g}{\partial z^2}_{\text{min}}$$

for normal fault

$$\frac{\partial^2 \Delta g}{\partial z^2}_{\text{max}} < \frac{\partial^2 \Delta g}{\partial z^2}_{\text{min}}$$

for reverse fault

$$\frac{\partial^2 \Delta g}{\partial z^2}_{\text{max}} = \frac{\partial^2 \Delta g}{\partial z^2}_{\text{min}}$$

for strike-slip fault

The subsurface model is obtained from the inversion of residual gravity anomaly. This anomaly is obtained from the reduction of the Bouguer Anomaly with the regional anomaly resulting from the moving average filter. This filter is obtained from a spectrum analysis that converts the gravity anomaly in one slice into a wavenumber domain ($k$). The Fourier transformation (FFT) of gravity anomaly ($F[g(z)]$) is shown by equation (4). The k cut-off is the value of the wavenumber that...
separates regional and residual anomalies. This is used to determine the amount of data we averaged so that we get the regional anomaly value.

\[ F[z] = 2\pi\gamma\mu e^{k(z'-z)} \text{ with } z' > z_0 \]  

(4)

where \( \gamma \) is gravitational constant \((6.67 \times 10^{-11} \text{Nm}^2/\text{kg}^2)\), \( \mu \) is body mass, \( z_0 \) is the height of measurement points and \( z' \) is anomaly depth.

In obtaining the inversion result, we add the standard deviation value to the data by 0.001%. The inversion was performed using software Grav3D version 2.0. This software uses an algorithm developed by [18]. In the gravity method, anomaly below the surface with a certain density causes changes in the vertical component of the gravitational field [19]. In inversion processing, the program will look for density values that minimize the objective function \( \phi_m \) and data misfit \( \phi_d \) shown by the equation. The objective function value is related to the local geological conditions, for example the boundary value for the density in that area. While the small data misfit shows that the modeling results are following the measurement data,

\[
\text{minimize: } \phi = \phi_d + \mu \phi_m \]

subject to:

\[
\rho_{\text{min}} \leq \rho \leq \rho_{\text{max}}
\]

(6)

where \( \rho_{\text{min}} \) and \( \rho_{\text{max}} \) are vectors that limit the lower and upper density contrast values of models.

3. Results and Discussion

3.1. Bouguer Anomaly

Calculation of the average density through the Parasnis method yields a value of 2.3008 g/cm\(^3\) (sandstone sedimentary rock). These mean density values fall into the density range of models from [20] in the range 2.2 to 2.5 g/cm\(^3\) and also [21] in the range 2.0 to 2.4 g/cm\(^3\). With this value, the Bouguer Anomaly values range from -5.154 mGal to 42.531 mGal. In Figure 4, it is known that the high and low Bouguer Anomaly values have a boundary with the NE-SW direction. This condition is a result of the difference in density beneath the surface of a fault. To analyze further, the derivative analysis was carried out to determine the fault boundaries.

![Figure 4. Distribution of Simple Bouguer Anomaly values.](image-url)
The result of the FHD and SVD processing are shown in Figure 5. There is a high value of the first derivative in the coastal area and towards the southwest (a). We perform six slices on the FHD and SVD maps.

![Figure 5](image)

**Figure 5.** Result methods of first derivative (a) and second derivative (b).

The results of the slices on the FHD and SVD maps are shown in a graph as in Figure 6. The graph shows the value of the first and second derivatives of the interest area. Based on the geological map and equations for determining the position and type of fault, we obtain the analysis shown in Table 1. The fault is shown by the black dashed line in the figure. We used UTM coordinates following their graph analysis for easier tracking on the map.

![Figure 6](image)

**Figure 6.** The example of graph analysis at 1st slice of the FHD and SVD maps.
Table 1. Analysis of FHD and SVD values

| Slice | Fault coordinate (UTM) | | | Fault type (N=Normal/ R=Reverse) |
|-------|------------------------|---|---|---------------------------------|
|       | Easting | Northing | | SVD max | SVD min | |
| 1-1’  | 193002.7 | 581444.5 | 0.0000286 | 0.0000139 | N |
| 2-2’  | 190612.5 | 579698.8 | 0.0000171 | 0.0000225 | R |
| 3-3’  | 188505.8 | 577383.6 | 0.0000293 | 0.0000188 | N |
| 4-4’  | 186229.8 | 575104.2 | 0.0001266 | 0.000182 | R |
| 5-5’  | 182752.9 | 573951.8 | 0.0000482 | 0.0001918 | R |
| 6-6’  | 178881.5 | 574018.3 | 0.0000392 | 0.0000438 | R |
| 7-7’  | 174797.2 | 573549.8 | 0.000053 | 0.0001892 | R |

Based on the analysis above, we can conclude that the Trienggadeng Fault type is a reverse fault. United States of Geological Survey (USGS) and Global Centroid Moment Tensor (Global CMT) provide the focal mechanism solution shown in Figure 7. Based on the focal mechanism analysis, it can be seen that the earthquake caused by the Trienggadeng Fault which is an oblique fault (reverse and sinistral strike-slip fault). This analysis strengthens the assumption from the results of the FHD and SVD analysis that the Trienggadeng Fault with the oblique fault dominated by strike-slip tends to reverse fault.

![Figure 7](image)

**Figure 7.** Focal mechanism solution from [22] (a) and [23] (b) for the mainshock in Pidie Jaya, December 6th, 2016.

The strike solution based on the USGS is 243° with a dip of 81°. While Global CMT provides a strike solution of 55° with a dip of 66°. Both of these solutions indicate that the fault in this region is the SW-NE trend. In addition, a study from [12] found a focal mechanism solution with a strike value of 42° with a dip of 63°. Some of the values above correspond to the strike value we got, which is 47.5°. This value is obtained from tracing the fault position results from the FHD and SVD analysis.

3.2. Moving Average

We performed ten slices to obtain information about the depth of an anomaly from the Bouguer anomaly value. The slice is shown in Figure 8, while the analysis is shown in Table 2. Figure 9 shows the example of power spectrum graph from the 1st slice. The result of the power spectrum analysis has an average regional anomaly depth of 4072.19 meters. This value is in accordance with the CRUST1.0 Model which shows that the thickness of the sediment in the coastal area reaches 4 km [24]. The power spectrum analysis also shows the residual anomaly value is at a depth of 165.974 meters. This is following the thickness of the soil based on the HVSR analysis with a thickness of 188 meters [12].
Figure 8 Slices for spectrum analysis on Simple Bouguer Anomaly.

Figure 9 The example of power spectrum graph of Bouguer anomaly values in the 1st slice of the map.

Table 2 Power spectrum analysis to get windowing value.

| Slice | Regional depth (m) | Residual depth (m) | C1  | C2  | $k \text{ cut-off}$ | $\lambda$ | N    |
|-------|--------------------|--------------------|-----|-----|---------------------|----------|------|
| 1     | -3957.7            | -160.69            | 9.1411 | 5.2159 | 0.00103376 | 6077.987731 | 30.38994 |
| 2     | -2927.7            | -162.66            | 8.8475 | 5.4181 | 0.00124027 | 5065.976177 | 25.32988 |
| 3     | -3555.2            | -153.69            | 8.981 | 5.2346 | 0.00110139 | 5704.761279 | 28.52381 |
| 4     | -5885.1            | -163.89            | 9.6512 | 5.0772 | 0.00079948 | 7859.077965 | 39.29539 |
| 5     | -3177.7            | -141.53            | 9.0075 | 5.0497 | 0.00130355 | 4820.056277 | 24.10028 |
| 6     | -4310.2            | -150.08            | 8.4407 | 4.2869 | 0.00099848 | 6292.745163 | 31.46373 |
| 7     | -3684.8            | -153.01            | 7.789 | 3.8625 | 0.00111176 | 5651.570364 | 28.25785 |
From these slices, an analysis of the windowing values is obtained as shown in the table. This value of 29 is used for the filtering process to obtain regional anomaly values. Regional anomaly values range from -2.045 mGal to 16.908 mGal. In inversion processing, residual anomaly values associated with more complex structural conditions near the surface are needed. Therefore, the Bouger anomaly value needs to be reduced by the regional anomaly value to get the residual anomaly value. The residual anomaly values ranged from -4.901 mGal to 26.074 mGal. The input for the inversion process is carried out in the area with the black dashed rectangle that is shown in Figure 10.

![Image](image_url)

**Figure 10.** The distribution of residual anomaly values.

### 3.3. 3D Inversion Result

The result of the inversion modelling shows the density contrast value (Figure 11). To find the true density, it is necessary to add or subtract the density contrast to the average density of the Parasnis method (~2.3 g/cm$^3$). Based on Figure 9, it can be concluded that the rock density value in this region is between about 1.43 g/cm$^3$ to 3.89 g/cm$^3$. 
Based on the geological map sheets of Aceh and Lhokseumawe, the rocks in this area consist of granite and andesite igneous rocks, limestone, sandstone, and clay sedimentary rocks. Igneous granite is in the SE area. On top of it lies igneous andesite rock that are evenly distributed to the north with a depth of more than 4 km. Limestone and sandstone sedimentary rocks are the most dominant rocks in this region. Meanwhile, clay sedimentary rocks are mostly located in the southern region and form a northward pattern according to the morphology of the river flow. The less clear density contrast of limestone, sandstone and andesite rocks indicates that the rocks in this area have been disintegrated due to stress forces from subduction in the western part of Sumatera. This results in complex deformation of this region.

We perform the slices on the modelling result shown in Figure 12. The slices are carried out in the northern part corresponding to the deformation of the surface in the coastal area. From this figure, it can be seen that the thickness of the sediment in the east and west positions has a difference. The higher density contrast in the eastern region indicates the presence of andesite rocks that are closer to the surface. When tracking the results of the slices, it is known that this contrast continues to the southwest. We believe that the existence of the Trienggadeng Fault is indicated by this contrast and that this fault can be identified from a depth of 3 km down.

Figure 11. The inversion result with the type of geological rocks.

Figure 12. The higher density contrast in the eastern region indicating the Trienggadeng Fault
3.4. Validation
To find out the validity of our method, we compared the fault positions of the FHD and SVD analysis results with the plot of relocation result from the mainshock and aftershocks from December 14th, 2016 to January 15th, 2017 [12]. The results of our analysis show their suitability for this study. However, [12] stated that the fault that caused this earthquake was about 5 km to the west of the earthquake cluster because of paying attention to the dip and its intersection with the surface. Meanwhile, we conclude that up to a depth of 3 km, there are still sedimentary rocks, so it is likely that the Trienggadeng Fault is deeper. When viewed from the surface, the position of this fault is in the mainshock and aftershock clusters (Figure 13).

![Figure 13. Trienggadeng Fault with mainshock and aftershock cluster](image)

4. Conclusion
Based on our study, we conclude that the GGMplus gravity anomaly secondary data can be used to analyze geological conditions in the Pidie Jaya, Aceh region, particularly the structure of the Trienggadeng Fault. The result of Bouguer anomaly in this region with an average density of 2.3008 g/cm$^3$, is in the value range of -5.154 mGal to 42.531 mGal.

The results of the FHD and SVD analysis can see the position of the Trienggadeng Fault with a strike of 47.5$^\circ$ with an oblique fault dominated by strike-slip tends to reverse fault. The power spectrum analysis shows the windowing value of 29 to determine the distribution of residual anomaly values. The results of the inversion modelling of the residual anomaly shows the geological conditions consisting of igneous granite and andesite, limestone, sandstone, and clay sedimentary rocks. The depth of the sedimentary rock reaches a depth of 4 km and the Trienggadeng Fault can be seen at a depth of more than 3 km.

In general, this research can determine the subsurface conditions in the Pidie Jaya, Aceh region. However, this study has certain limitations so that it only obtains a shallow depth and cannot get a dip value from the fault. Therefore, further research needs to be carried out for mitigation through the development of planned areas to minimize the impact of the earthquake. The gravity method research can be carried out by calculating the terrain correction to produce a Complete Bouguer Anomaly and also 2D inverse modeling to see the cross-section of the fault location. Meanwhile, to see the subsurface structure in deeper and more detail, we can use a reflection seismic method. This method uses artificial seismic sources to produce detailed lateral and vertical images of the subsurface structure.
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