An Attempt to Depict Deformation Under a Young Volcanic Covered Area Using 3D Gravity Data Inversion in Southern Garut, Indonesia

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Abstract. Active faults earthquakes often cause serious damage due to their close distance to the center of human activities. Dozens of shallow low magnitude earthquakes were felt in recent years in southern Garut, West Java – Indonesia. Two of these earthquakes (2016 and 2017) were reported destructive and interpreted as an indication of an active fault. Our preliminary study uses published gravity data to depict the subsurface structure that may correlate to this recent seismic activity. We implement three techniques to separate the regional-residual anomaly from the Bouguer anomaly, Trend Surface, Butterworth Filtering, and Upward Continuation. The results from the three techniques show a relatively same pattern for the residual anomaly map, a relative N-S trending direction in the southern part of West Java, and corresponds well with the geological information. To further extract subsurface information from this data, 3D inversion modeling is implemented. The density model shows a basin with a NE-SW trending local high observed separating two (western and eastern) sub-basins. The local high is co-located with a magmatic intrusive body and a series of young volcanic bodies in the northeastern end of the basin. It indicates a tectonic-magmatic relationship in this area.

Keywords: *3D inversion; active fault; gravity; Indonesia; southern Garut,.*

1 Introduction

Major earthquakes with large magnitude often occur in convergent plate tectonic margins, especially the subduction zones. However, earthquakes generated from active faults also often cause great devastation, due to their proximity to human activities. In southern Garut, West Java – Indonesia, dozens of shallow low magnitude earthquakes were felt in recent years [1]. Two shallow low magnitude earthquakes in this area (2016 and 2017) were reported to be destructive [2]. These shallow events were interpreted as an indication of an active fault, and the name of Garsela fault was proposed [2,3].

Our knowledge about this interpreted active fault is still very limited. To date, there was no surface expression reported regarding the Garsela fault. The interpreted Garsela active fault line mainly comes from the interpretation of hypocenter relocation and focal mechanism analysis of the earthquake events and topographical lineament interpretation. In a low slip rate deformation regime like Java, fault lines may be hardly recognized until the next major earthquake occurs [4]. Furthermore, surface traces of an active fault in the active volcanic region might be covered by the young volcanic products.

The main objective of earthquake research is to better understand the source of earthquakes and try to reduce their negative impact on human life. Understanding the mechanisms associated with these shallow earthquakes becomes very important as an effort to define the seismic hazard of this area. Here we report our desk study, using available published gravity data, in order to image the subsurface structure that may correlate with the shallow low magnitude earthquakes in the southern Garut area.

2 Geological Setting

Java island is part of a volcanic arc complex in the Sunda-Banda subduction system, Indonesia. The western part of Java is a transition zone between frontal subduction under Java and oblique subduction under Sumatra. The surface morphology of Java does not show a dominant structural pattern as seen on Sumatra, where a regional strike-slip fault spans along the island for more than 1900km [5]. Deformation in Java tends to be accommodated by fairly wide distributed small-scale faults in tens of kilometers order [4]. There are three well-known main active faults in the western part of Java, Cimandiri fault [4,6,7], Lembang fault [8–10], and Baribis fault [11–13].

The interpreted Garsela active fault is located in the southern Garut zone, where the surface geology is dominated by quaternary volcanic products overlying Tertiary age rock formations (Figure II.2) [14,15]. This area shows intensive quaternary volcanism, where active Mount Papandayan, Mount Guntur, and Mount Cikuray take place. There are also three geothermal fields in this area, Wayang Windu, Darajat, and Kamojang. In this circumstance, the active volcanic activity in the southern Garut zone may cover the surface expression of active deformation traces. However, data from these geothermal fields may help to better understand the regional tectonic framework of the area.

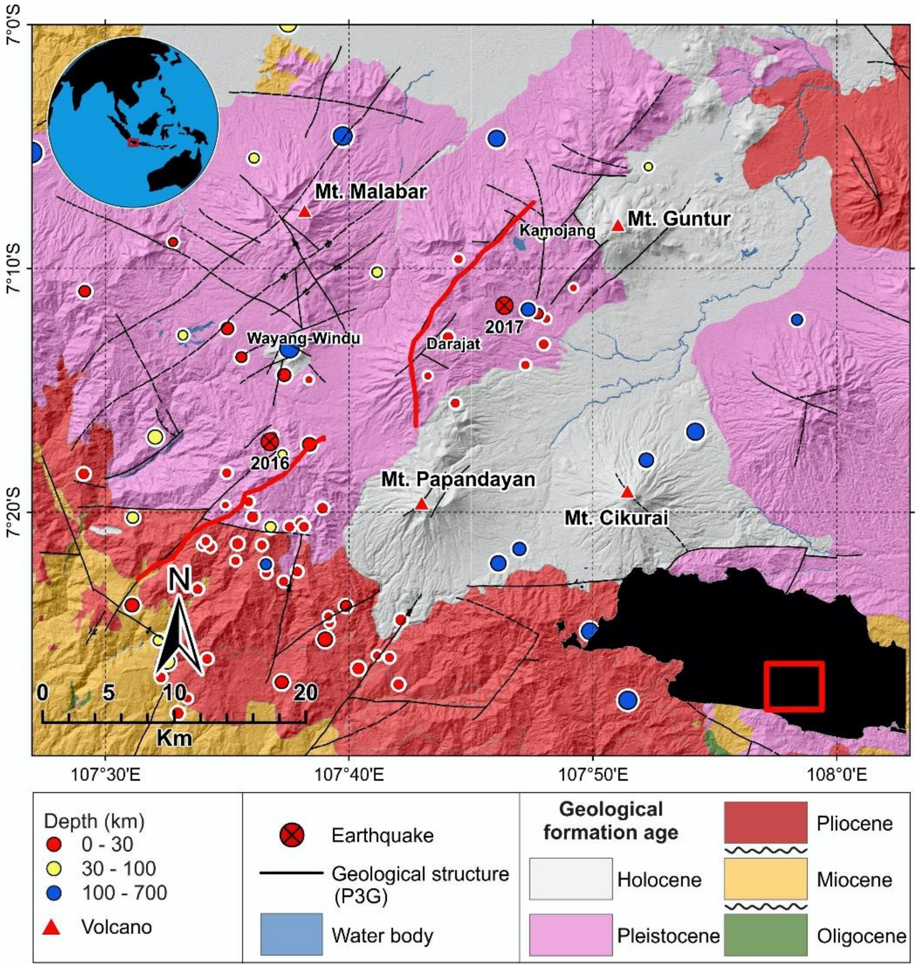

Figure 1 Surface geology of the study area, dominated by quaternary volcanic products overlying Tertiary age rock formations (Alzwar et al., 1992; Koesmono et al., 1996). Seismicities: Nugraha et al. In [16], Pesicek et al.in [17], Supendi et al. (2018b).

Kamojang and Darajat geothermal fields are located in a NE-SW volcanic eruption centers series between Mount Rakutak and Mount Guntur [18]. The effective fracture in the Darajat reservoir shows N10-30E strike direction dominance [19], in line with the regional SHmax of Java Island which is in the NNE-SSW direction [20]. In the Wayang Windu area, which is close to the 2016 earthquake, the dominant geological structure is NE and NW direction [21]. The NE trending fault is estimated to be a regional shear fault that has been reactivated into a normal fault. Information from these three geothermal sites is in line with the geological research from Sribudiyani et al. In [22] that concludes the dominant basement structure pattern in West Java is NE-SW, while the surface structure pattern is more diverse with the dominance of N-S direction.

3 Data and Method

The gravity method has been widely used to describe subsurface structures, in the sense of rocks density. This method basically measures a small variation of earth gravitation field (anomaly) that is caused by the subsurface rocks density variation. Thus, subsurface geological structure can be delineated based on the contrast anomaly. This method has been widely used in the study of crustal and lithospheric modeling, basement of a in petroleum basin, geothermal exploration, subsidence and cavities and to delineate fault geometry, especially when the fault surface traces are hardly recognized [23–28]

We use the available published Java Bouguer anomaly map from the Geological Agency [29]. This map can be classified as a regional scale map, whereas the measurement interval ranges about 4-5 kilometers. This dataset has been carefully digitized previously using its contour line as the guideline [30]. Figure 2 shows that the 2016 earthquake is located on the edge of a high gravity anomaly, while the 2017 earthquake is located at a local high that separates two low gravity anomalies. The low gravity anomalies tend to be elliptical in shape with the main axis direction relative to NE-SW.

Bouguer anomaly is a combined response of various masses in the subsurface at different depth levels, which are simplified as sources at shallow and deep levels. Relatively deep features contribute to low frequencies (regional), while relatively shallow and local features contribute to high frequencies (residual). Many techniques are available to decompose the Bouguer anomaly, additional efforts are needed to determine which technique best represents the geology of the area. We use three techniques available in the Geosoft Oasis Montaj package to separate the regional and residual anomaly from the Bouguer anomaly map and compare its result. The three techniques are Trend Surface (TS), Butterworth Filtering (BF), and Upward Continuation (UC).

TS uses least-squares fitting of low order polynomial surfaces to approximate the regional component of the gravity field [31]. The larger the order of TS indicates more heterogeneous conditions and is associated with shallower depths. Butterworth filter was first described in a classic paper [32]. It is known as a maximally flat magnitude filter and considered as a smoother version of a simple band-pass filter. BF is often used due to its simplicity to control the degree of filter roll-off to avoid ringing, in this study order of 8 (default) is used in low-pass mode. Another technique used is the UC which transforms the gravitational anomaly at one position (observation station; X_1, Y_1, Z_1) to a greater height flat surface (X_1, Y_1, Z_2; with $Z_1 > Z_1$) [33]. Changes in altitude (distance from the source of the anomalous mass) will have an effect on the magnitude of the gravitational attraction per unit mass.

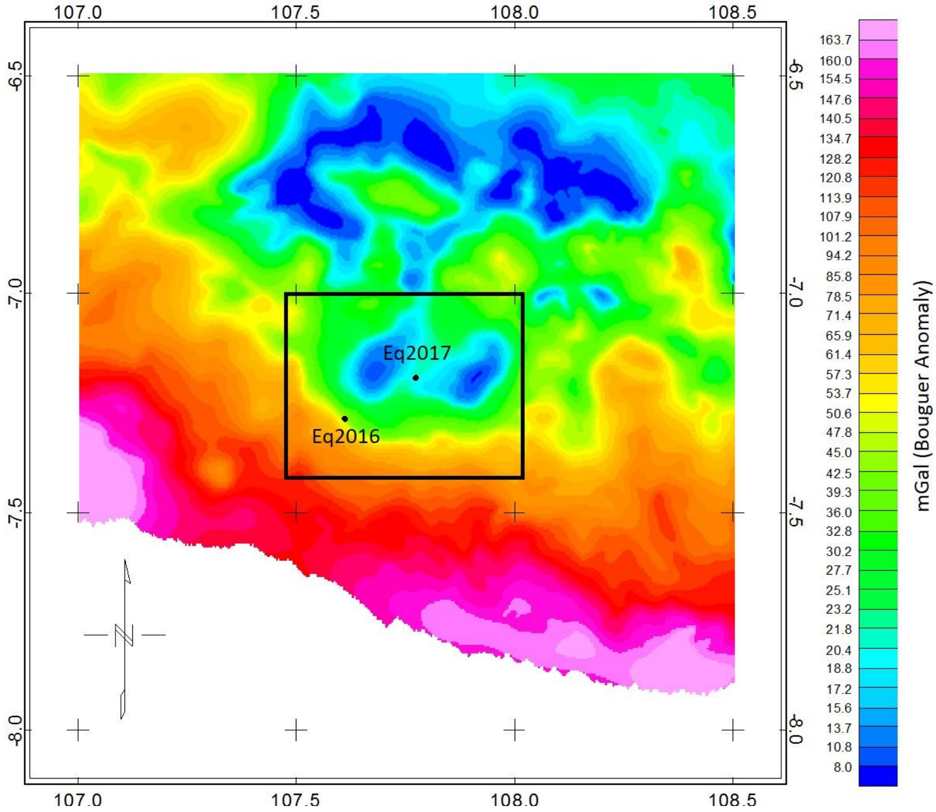

Figure 2 Gravity map of the research area, digitized from the Bouguer Anomaly Map of Java Island [29]. Black dots represent the location of the 2016 and 2017 earthquakes.

To further extract subsurface information from this dataset, we have done 3D inversion modeling using Grablox [34] where the optimization method is based on linearized inversion. Considering the measurement interval, we discretize the grid model into 2km horizontally and an increasing vertical grid size to a maximum depth of 10km. To simplify the modeling, we use a flat top grid at 1400meter (average elevation in this area). We use the result of regional anomaly from upward continuation 7500m as the base anomaly parameter (the reason can be found in the discussion section). After several trials, we choose to use the Occam scheme [35] in the inversion where the roughness of the model is minimized together with the data misfit. The final model presented here was obtained with both 3 iterations of Occam-h and Occam-d.

4 Result and Discussion

Figure 3 shows the regional-residual separation using the TS technique. The residuals of order-2 and order-3 are observed to be almost the same pattern, while order-1 shows a different pattern in the northwest. In the TS technique, higher polynomial order is associated with a shallower depth. Thus the chosen regional anomaly is the lowest order, in this case, the preferred regional anomaly is order-2. Figure 4 shows the result of the BF technique, which has an overall same pattern with TS for the central wavelength of infinity and 100km. When the central wavelength value was reduced to 50km, the residual anomaly did not show a clear significant pattern. Thus, the most suitable regional anomaly for the BF technique is the one with a 100km central wavelength.

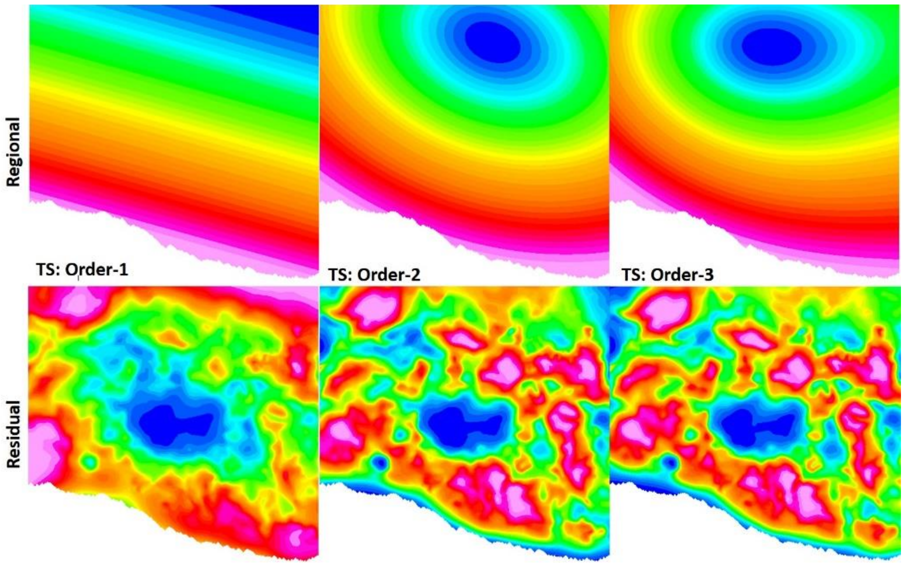

Figure 3 Regional (top) and residual (bottom) anomaly separation, based on TS technique order-1, order-2, and order-3.

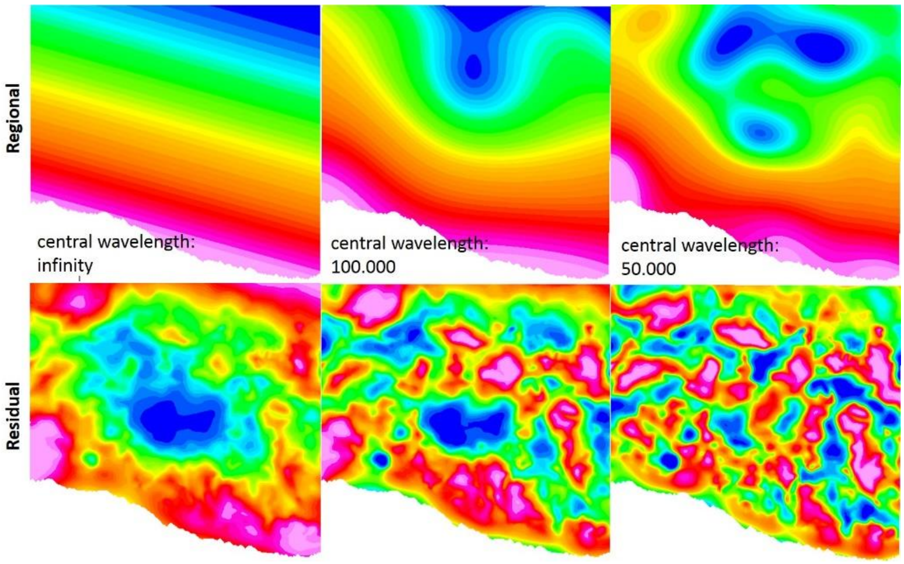

Figure 4 Regional (top) and residual (bottom) anomaly separation, based on BF technique with the central wavelength value of infinity, 100km, and 50km respectively.

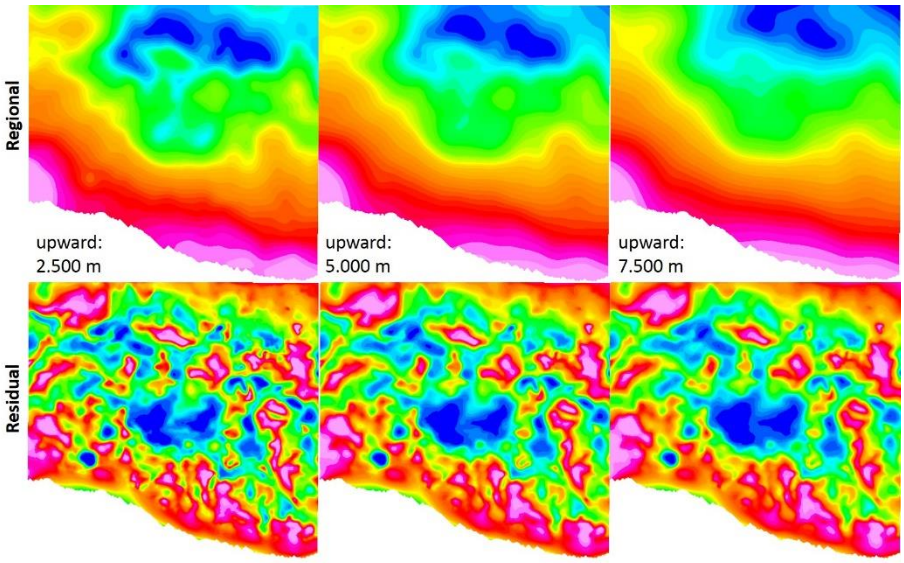

Figure 5 Regional (top) and residual (bottom) anomaly separation, based on UC technique with 2500m, 5000m, 7500m transformation respectively.

Figure 5 shows regional and residual anomalies based on the UC technique with elevation changes of 2500, 5000, and 7500 meters. The transformation of 7500 meters shows that all high-frequency features in the low gravity anomaly around the Garut zone have disappeared. Therefore the selected regional anomaly is the one resulting from the 7500 meter UC.

Figure 6 shows a comparison of the regional-residual anomaly separation of the three techniques used. It can be seen that the three techniques produce similar residual anomaly patterns. However, the regional anomaly that best represents the Bouguer anomaly is the result of UC 7500meter. Therefore the UC 7500meter residual anomaly was selected for use in the subsequent analysis. The residual anomaly map, which depicts the local shallow structure, shows a relatively N-S trending direction in the southern part of West Java. This result corresponds well with geological information from [22].

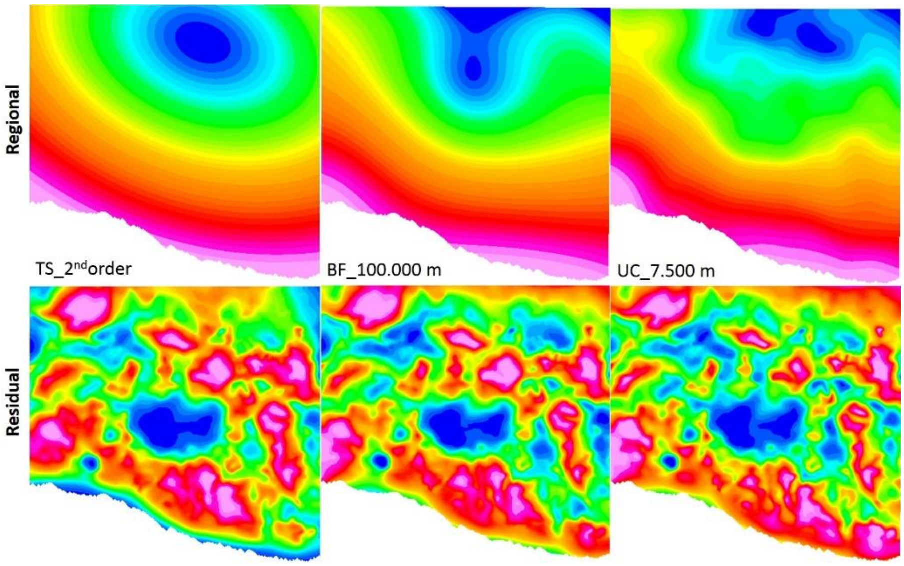

Figure 6 Regional (top) and residual (bottom) anomaly separation, based on TS, BF, and UC techniques respectively. The regional anomaly of UC 7500m best represents the Bouguer anomaly.

A closer look at the interest area shows that the low anomaly can be divided into two "sub-basins", separated by a NE-SW trending local high anomaly. This moderate anomaly lineament co-located with the lineament of young volcanic bodies on the surface and may indicate a close relationship among them [36]. The eastern sub-basin seems to be shifted toward northeast, in this point of view the low gravity anomaly can be interpreted as a pull-apart basin formed by a left-lateral strike-slip fault. This interpretation corroborates previous work that interpreted the existence of a NE-SW regional left-lateral strike-slip fault in the past, which then transforms to a localized normal fault in Wayang Windu area due to a regional scale tectonic reorganization [21].

Figure 8 shows the measured, regional, computed, and misfit maps of the inversion modeling results. It can be seen that the highest misfit was observed in the NE section, although it was still within a fairly low-value limit. This is probably due to intensive topographic differences, while in this model we use a flat topography. In general, the results of the inversion have modeled the data quite well.

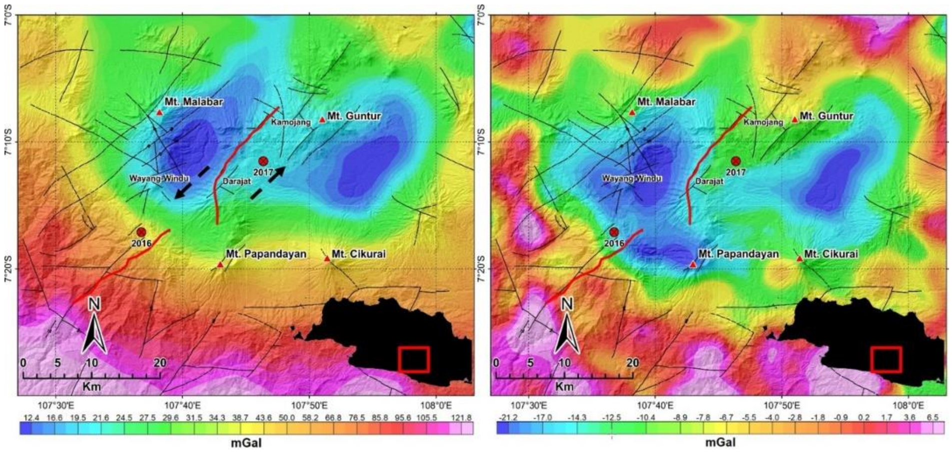

Figure 7 The Bouguer anomaly map (left) and residual anomaly (right) around the study area correspond to the direction of the NE-SW structure. In addition, the regional anomaly map also highlights the conformity to the NW-SE and W-E structure directions.

The 3D gravity inversion result shows a basin consisting of 2 sub-basins, with the deepest part being at about 7km, while the shallowest part at about 3km. This result reinforces the interpretation of the pull-apart basin and correlates well with the resistivity model from magnetotelluric (MT) data that show this area as a horst-graben system. However, 3D joint inversion of gravity, MT, and micro-earthquake (MEq) data, reveal that the local high gravity anomaly in the Darajat area corresponds with the granodiorite intrusion [19]. This information suggests that the ridge of the local high Bouguer anomaly might be composed of a series of volcanic bodies. This interpretation is also plausible since the moderate anomaly lineament co-located with a series of young volcanic bodies lineament observed at the surface [36]. Another possibility is the combination of both, the local-high is a horst which is later intruded by the younger magmatic product. In this context, volcanic intrusion arises at the main displacement zone of the fault as observed by Mukti in [37] after reinterpreting 2D seismic section in the Semangko Semangko pull-apart basin.

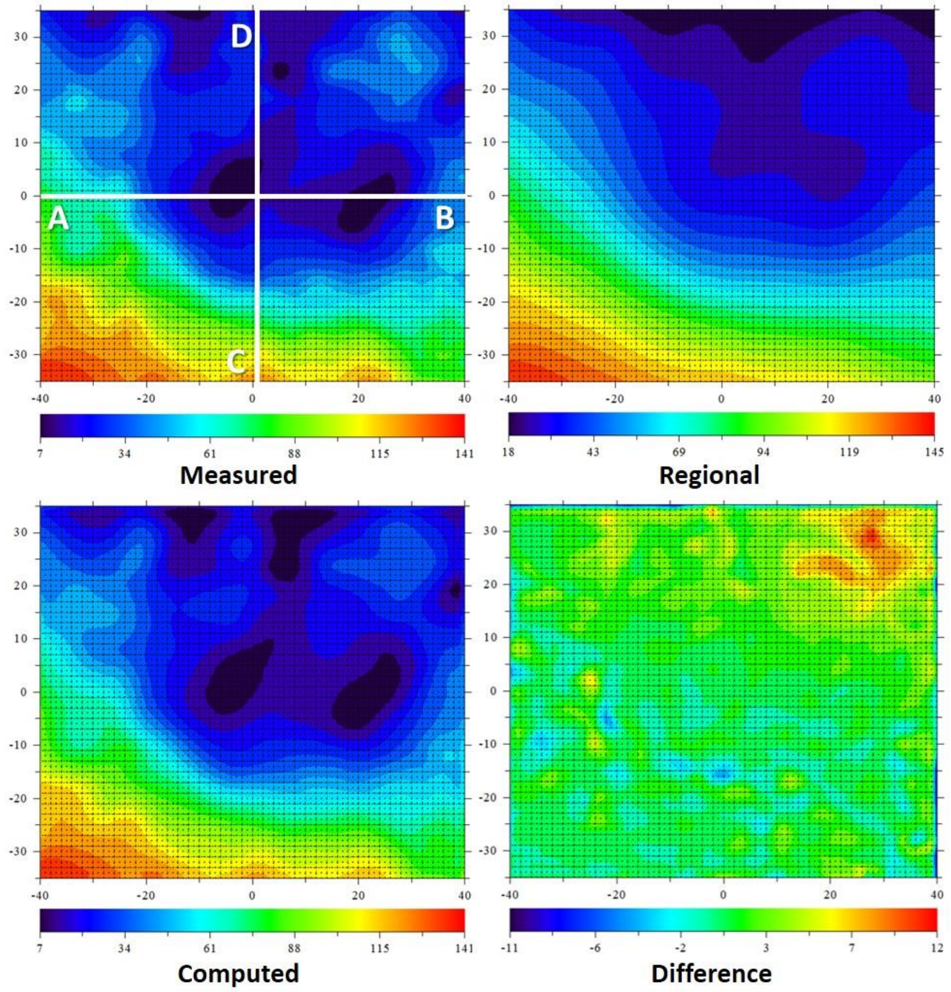

Figure 8 The measured, regional, computed, and misfit maps of the 3D inversion modeling results. The bold white line marks the position of Line A-B and Line C-D whose cross-sections are shown in Figure 9

The northeastern part of Garsela fault, Rakutak segment, was also known as the Gagak Fault in geothermal exploration [18,19]. The cross-section of the 3D joint-inversion of MT - gravity - and MEq data at Darajat [19] shows that the Gagak fault is characterized as a discontinuity that cuts the resistive layer at the surface to a depth of 1.5km. The discontinuity is then disappeared and replaced by a high resistivity body at depth which is interpreted as a Plio-Pleistocene intrusion. This means that the interpreted pull-apart basin was formed prior to the Pliocene, and overprinted by younger volcanism activity in the Plio-Pleistocene.

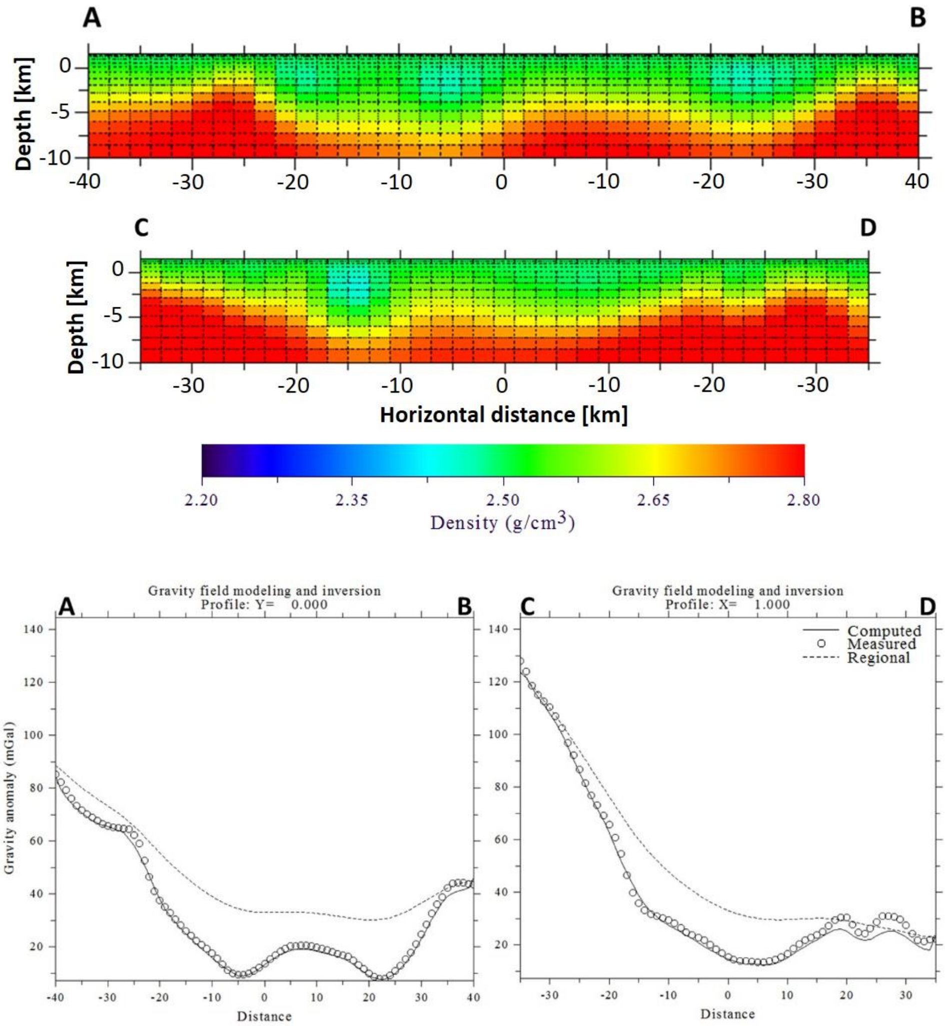

Figure 9 Top: Cross-section of A-B and C-D, sliced from 3D inversion modeling. Bottom: profile fitting data vs model of line A-B and C-D. Position of Line A-B and Line C-D can be seen in Figure 8

The result of this preliminary study, yet cannot answer the source and mechanism of recent seismic activity in Southern Garut. Hakim et al. in [38] show a seismicity cluster around 2016 earthquake position and due to its depth, they are interpreted as tectonic related. Another seismicity cluster was observed around Darajat and Kamojang and interpreted as related to the geothermal activity. However, the result of hypocenter relocation [2] indicates that the 2017 earthquake is too deep to be related to geothermal activity.

We realize that gravity data has a dominant ambiguity in the vertical direction, and inverting the gravity data alone without strict constraint would also raise ambiguity. However, this preliminary study resulted in such a model that arguably related to the previous studies and shed new insight on the tectonic framework of this area.

5 Conclusion

Here we report our preliminary study using published gravity data in order to better understand the source and mechanism of recent seismic activity in the southern Garut area. We used three regional-residual anomaly separation techniques, Trend Surface Analysis (TSA), Butterworth Low-pass Filtering (BLF), and Upward Continuation (UC), and gained a relatively same pattern for the residual anomaly map. The residual anomaly map shows a relative N-S trending direction in the southern part of West Java, and corresponds well with the geological information. The 3D inversion resulted in a basin with a NE-SW trending local high observed separating two (western and eastern) sub-basins. The local high is co-located with a magmatic intrusive body and a series of young volcanic bodies in the northeastern end of the basin from previous work. It indicates a tectonic-magmatic activities relationship in this area.

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