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Semarang Subsurface Model Using Airborne Gravity Data

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ABSTRACT

The city of Semarang faults became active again in the Quaternary era. The gravity method has been widely used to identify subsurface conditions in Semarang City and its surroundings, especially the satellite gravity method and land gravity methods. Meanwhile, Semarang City and its surroundings have never used the airborne gravity method. Therefore, this study aims to identify subsurface conditions, especially faults, using airborne gravity data in Semarang and its surroundings. The airborne gravity value is the gravity value at a certain height. Therefore, in this study, the downward continuation process using Molodensky methods on airborne gravity data is useful for obtaining gravity values at topographical heights. Based on the residual anomaly map, there is a low gravity anomaly with a value range of -6.6 – (-0.5) mGal, located between high gravity anomalies, which have a value range of 1.7-7.4 mGal, which is suspected to be associated with a shallow structure in the form of a fault in the research area. Based on the residual anomaly map, the subsurface 2D model uses a forward model in areas identified as faults on the geological map. The model results have an error value of 0.221, representing a fit model that shows a picture of subsurface conditions close to the actual situation with fault structures on the D-D' Line.

Keywords: Airborne gravity, fault, downward continuation, Molodensky method

INTRODUCTION

Semarang has a geological structure consisting of normal, transform, and thrust faults **(1)**. Poedjoprajitno et al **(2)** explained that in the Semarang area, there are faults formed in the Tertiary era; the faults are faults that trend North-South, namely as right-handed faults, faults that trend Northeast-Southwest identified as normal faults and faults that trend West-East which identified as a thrust fault. These faults became active again in the Quaternary era; one is the North-South fault, namely the Kaligarang fault, which is active again as a left fault. The Northeast-Southwest fault consists of the Pengkol River fault and the Kreo River fault as a thrust fault. The West-East fault is also active again as a right-hand fault. There is a change in local stress, which has a Northwest-Southeast direction, causing the reactivation of existing faults. Active fault movements are dangerous because they trigger earthquakes, which can cause ground cracks and movements and allow liquefaction to occur **(3)**.

Geological and geophysical studies in Semarang have been use to identify subsurface structures, especially faults. The gravity method is useful in identifying the geological conditions of Semarang and its surroundings by many researchers. The gravity data in geological and geophysical studies in Semarang and its surroundings use a lot of ground and satellite gravity data. This research is the first to try to use the airborne gravity method in modeling subsurface structures to delineate faults in Semarang. Airborne gravity is data that comes from measuring the value of the gravitational field in the air using aircraft vehicles with a wide range of measurements covering various areas that are difficult to reach by land, such as forests, valleys, and mountains (4). Based on this, according to Hwang et al (5), land gravity measurements are considered less effective, this is because land gravity measurements require a long measurement time and relatively large costs to cover large areas. Meanwhile, airborne gravity measurements require a short time with a comprehensive area coverage and an organized measurement grid. Satellite gravity data can be helpful to measure large areas that are difficult to reach other than airborne gravity. Airborne gravity is terrestrial data based on its measurements because they are carried out directly, thus reflecting the actual situation. In contrast, satellite gravity data is obtained based on mathematical calculations of the actual Earth model (6). Some benefits of using airborne gravity data are usefull for mapping geological prospects and interpreting the subsurface (7). Fitriastuti et al (8) conducted a study to identify subsurface structures around Mount Sumbing and Mount Sindoro, Wonosobo Regency, using airborne gravity data to obtain a contrast value of the gravitational field to detect faults. Airborne gravity also analyzes geological lineament and basement depth (9). No research has used the airborne gravity method to delineate the Semarang fault. Based on this, this study conducted a subsurface model to delineate the Semarang fault and its surroundings using airborne gravity data. This research creates a program for the downward continuation process to obtain Free Air Anomalies (FAA) in topography using the Molodensky method.

GEOLOGICAL SETTING

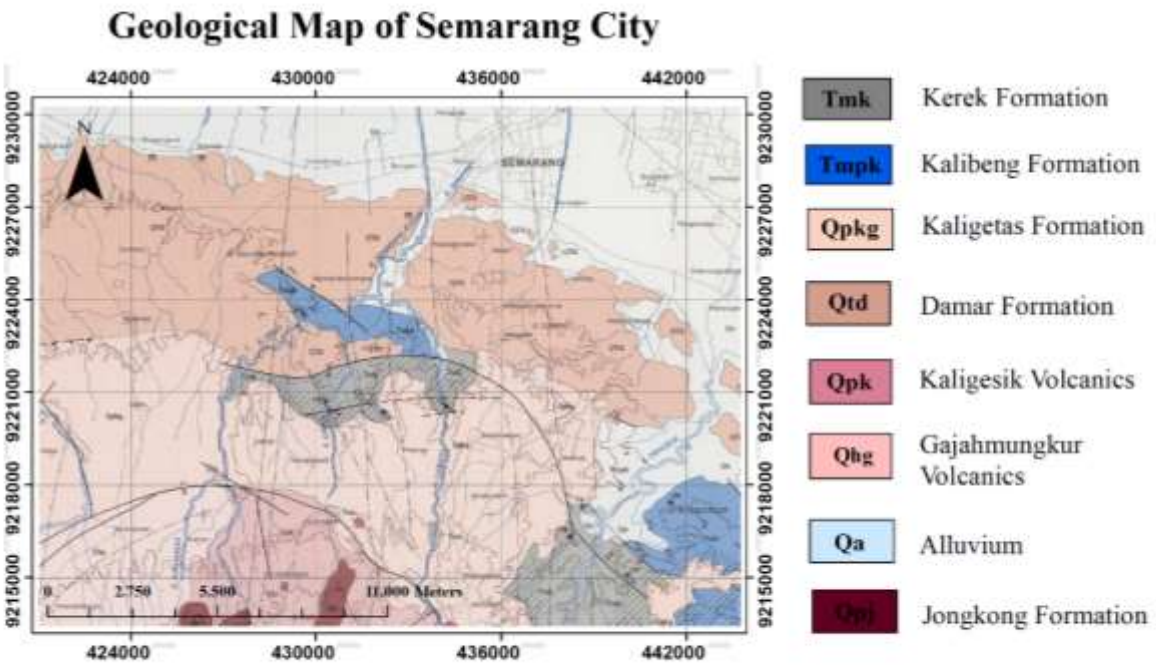

Figure 1. Geological Map of Semarang and Surrounding Areas (Modification of Geological Map of Magelang and Semarang (10)).

Semarang is a part of Central Java province, geographically located at coordinates $109^{0}50$” – $110^{0}35$” E $6^{0}50$” – $7^{0}10$” S. The city of Semarang has an area of 373,7 km^2 (11). Based on the geological map of Magelang and Semarang, Central Java, Semarang has a stratigraphic arrangement from the youngest to the oldest, including alluvium, Gajahmungkur volcanic, Kaligesik volcanic, Jongkong formation, Damar formation, Kaligetas formation, Kalibeng formation, and Kerek formation.

MATERIALS & METHODS

This study uses airborne gravity data and DEM data. Airborne gravity data belong to BIG (Badan Informasi Geospasial), which consists of coordinates of measurement points, free air anomalies, and height of measurement points. The DEM data used comes from the website https://tanahair.indonesia.go.id. DEMNAS data was created based on IFSAR data with a data resolution of 5 m, TERRASAR-X with a resampling resolution of 5 m, which has an original resolution of 5-10 m), and ALOS PALSAR with a resolution of 11.25 m, besides that DEMNAS has mass point data which is usually helpful for creation of Indonesian Topographical maps (RBI). DEMNAS uses the EGM2008 vertical datum and has a 0.27-arcsecond spatial resolution. DEMNAS data consists of several parts according to the Number of Map Sheets (NLP) for each Island or Archipelago. It has a scale of 1:5000 or 1:25000 **(12)**.

Airborne gravity data through the downward continuation process before further data processing. In this research, the downward continuation process uses Molodensky methods. Suppose the airborne gravity data has gone through a downward continuation process. In that case, perform terrain and Bouguer correction processes. Bouguer and terrain correction aim to obtain a complete Bouguer anomaly (CBA) map. For further interpretation, the moving average method helps separate regional and residual anomalies in this study. In conducting subsurface modeling, this study carried out forward modeling using residual anomaly maps.

Downward Continuation of Airborne Gravity Using Molodensky Methods

There are two methods for carrying out the downward continuation process using the Molodensky method. Namely the Fourier transformation and least-square collocation. The Fourier transform approach can be calculated based on Equation 1:

$$G_0(u.v) = e^{2\pi\sqrt{u^2+v^2}}\,\mathbf{W}(u,v)\boldsymbol{G}_z \quad 1$$

W is the frequency domain with the value W=1 in Equation 1 and valuable for unfiltered domain space, downward continuation gravity anomaly. Gaussian space filter is helpful for Fourier transform. Equation 2 is a downward continuation process using Least Squares Collocation:

$$\Delta g_0 = C_{oz}(C_g + C_n)^{-1}\Delta g_z \quad 2$$

Δg_0 and Δg_z is the value of gravity anomaly at sea level and z. is the cross-covariance matrix of gravity anomaly at sea level and z. and is the covariant matrix of the signal and noise of which it is a part Δg_z **(13)**.

Bouguer Correction and Terrain Correction

Suppose the FAA is a correction due to height effects without considering mass effects. In that case, the Bouguer correction is a correction to the gravity value considering the mass effect below the measurement point **(14)**. Equation 3 is the calculation used in carrying out the Bouguer correction process **(15)**:

$$\beta = 2\pi G\rho h = 0{,}4192\ \rho h \quad 3$$

ρ is the rock density in $g.cm^{-3}$,β is the Bouguer correction in , G is the value of Newton's gravitational constant, and h is the height in meters.

The Bouguer correction assumes that the earth's surface around the gravity measurement point is a slab, so a terrain correction is needed to remove the effect of mass from around the observation point **(16)**. Equation 4 is the formula used in making terrain corrections **(17)**:

$$TC = 0{,}0491\ \frac{\rho}{n}(r_2 - r_1 + \sqrt{{r_1}^2 + z^2} - \sqrt{{r_2}^2 + z^2} \quad 4$$

Airborne Gravity Anomaly Separation

Complete Bouguer Anomaly is a gravity anomaly map carried out by various correction processes so that the resulting anomaly map is only affected by the mass effect below the earth's surface. A separation process is carried out into regional and residual anomalies to carry out a general interpretation of the complete Bouguer anomaly map **(18)**. Equation 5 is a process for calculating the complete Bouguer anomaly **(19)**:

$$ABL = FAA - BC + TC \quad 5$$

A regional anomaly is an anomaly that has a deeper depth than the residual anomaly. Residual anomalies are shallow anomalies with high frequencies and short wavelengths, while regional anomalies are deep anomalies with low frequencies and long wavelengths **(20)**. In this study, the separation of anomalies using the moving average method. The Moving Average method is a method that separates the Bouguer anomaly by averaging the Bouguer anomaly values. Spectrum analysis aims to obtain a wide window to separate the depth of regional and residual anomalies, which is helpful for the moving average filter process. Equation 6 is a calculation in carrying out the moving average method **(21)**:

$$\Delta g_R(i) = \frac{\Delta g(i-n) + \cdots + \Delta g(i) + \cdots + \Delta g(i+n)}{N} \quad 6$$

Δg_R adalah regional anomaly, N is width of the window, while $n=(N-1)/2$.

Forward Modelling

Forward modeling is a way to obtain field theoretical data based on subsurface parameters. The subsurface model represents subsurface conditions when the model's response matches the data. In general, in forward modeling, to obtain theoretical data that matches the observational data, a trial-and-error process is carried out. Meanwhile, inversion modeling is backward modeling as opposed to forward modeling **(22)**.

RESULT

This research produces a free air anomaly (FAA) map using the Molodensky method, a complete Bouguer anomaly map, regional anomaly, residual anomaly, and a subsurface model based on forward modeling.

Free Air Anomaly (FAA) Map Using the Molodensky Method

Figure 2 shows a free-air anomaly map of the city of Semarang and its surroundings. The FAA map of this study results from downward continuation using the Molodensky method, which has a value range of 9.2-57.1 mGal.

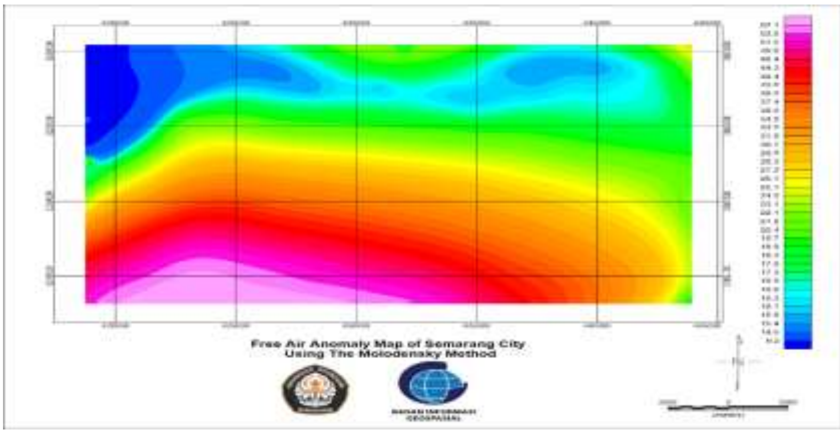

Figure 2. Free Air Anomaly (FAA) Map of Semarang City Using the Molodensky Method

Complete Bouguer Anomaly Map (CBA)

Figure 3 shows a complete Bouguer anomaly map in Semarang and its surroundings. The complete Bouguer anomaly map is an anomaly map that has been corrected for drift, latitude, tidal, terrain, and Bouguer, while the range of values on the CBA map ranges from 10.4 to 29.8 mGal.

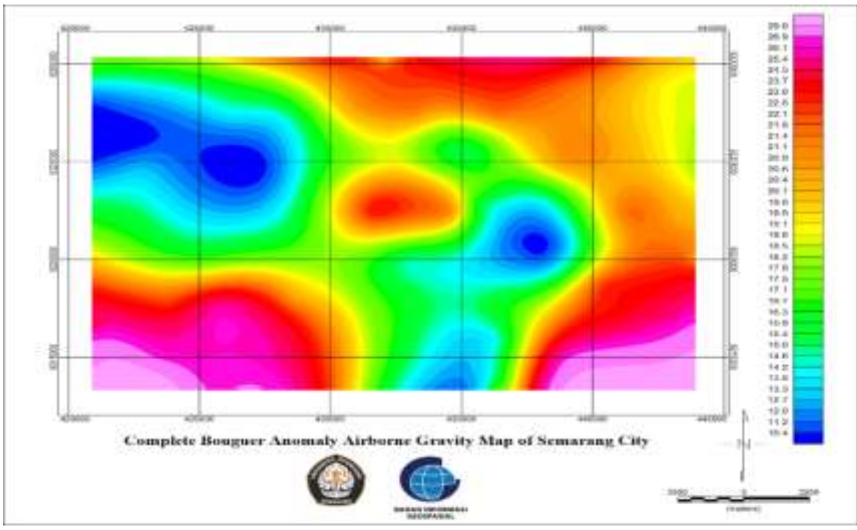

Figure 3. Complete Anomaly Bouguer (CBA) Airborne Gravity Map of Semarang City

Regional Airborne Gravity Anomaly Map

Figure 4 Is a regional anomaly map of the city of Semarang. Separating regional and residual anomalies in this study uses the moving average method. On the regional anomaly map, the range of anomaly values ranges from 14.9 to 22.7 mGal.

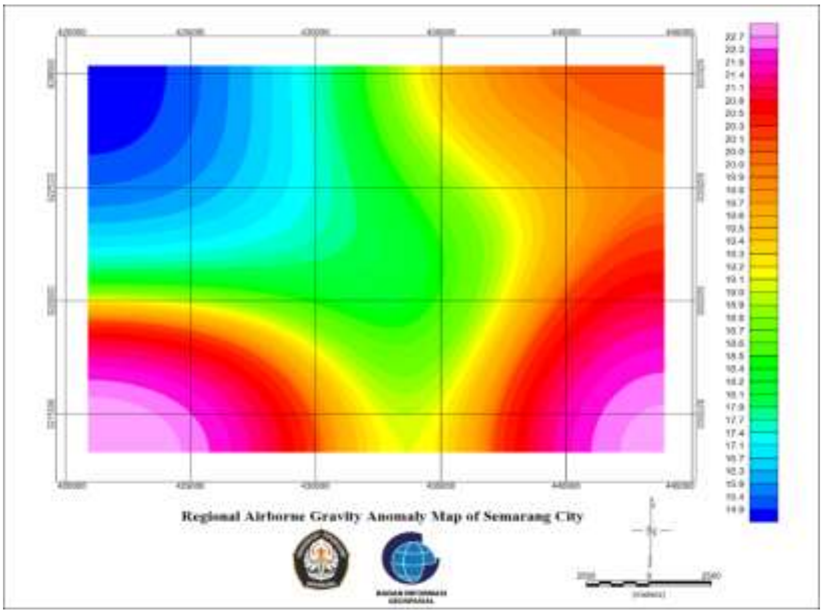

Figure 4 Regional Airborne Gravity Anomaly Map of Semarang City

Residual Airborne Gravity Anomaly Map

Figure 5 maps the residual airborne gravity anomaly in Semarang and its surroundings. Subtracting the complete Bouguer anomaly from the regional anomaly produces a residual anomaly. The residual anomaly has a range of values ranging from -6.6 to 7.4 mGal.

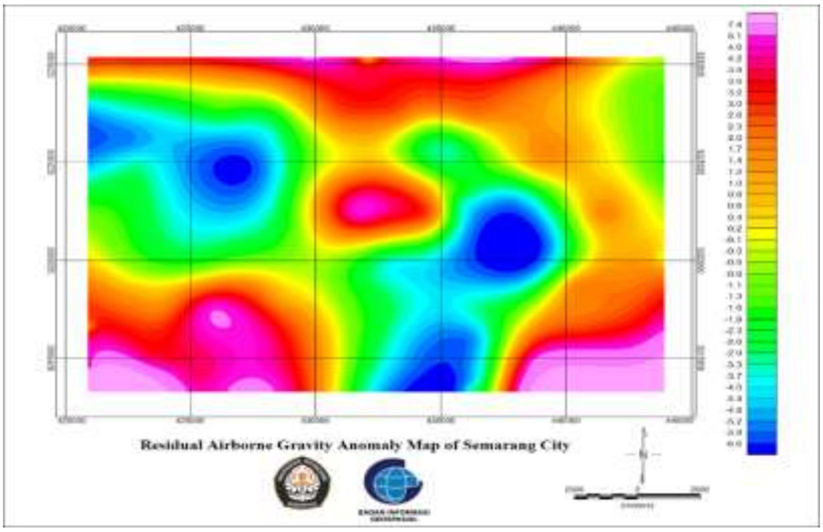

Figure 5 Residual Airborne Gravity Anomaly Map of Semarang City

Forward Modelling Airborne Gravity

Figure 6 is the Line D-D' in modeling that intersects from the North-South direction of the city of Semarang and its surroundings, with a track length of 25000 m. Wardhana et al (2014) modeled the subsurface structure of Semarang City using the land gravity method, while the density values in the modeling were alluvium 1.85 g/cc^3, Damar formation 2.2 g/cc^3, Kaligetas Formation 2.3 g/cc^3, Kalibeng Formation 2.45 g/cc^3, Kerek Formation 2.6 g/cc^3 and Basement 2.85 g/cc^3. Based on these references, this study uses the density values as written in Table 1, which are the input for the density values of each layer in making subsurface models. Meanwhile, Figure 7 results from forward modeling on Line D-D'.

Table 1. Rock Density Values in Rock Arrangements as Forward Modeling Parameters

Rock Structure	Rock Density (g/cc^3)
Alluvium	1,85
Damar Formation	2,1
Kaligetas Formation	2,25
Kalibeng Formation	2,4
Kerek Formation	2.6
Basement	2,8

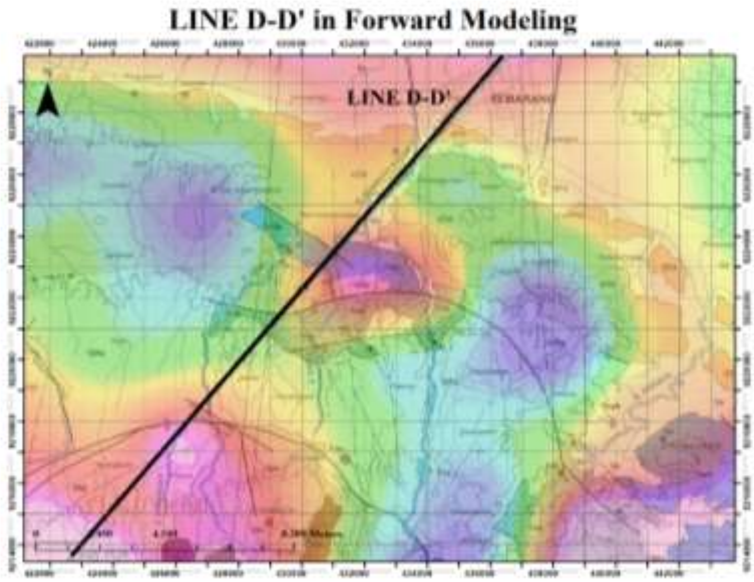

Figure 6. Line D-D' in Forward Modelling

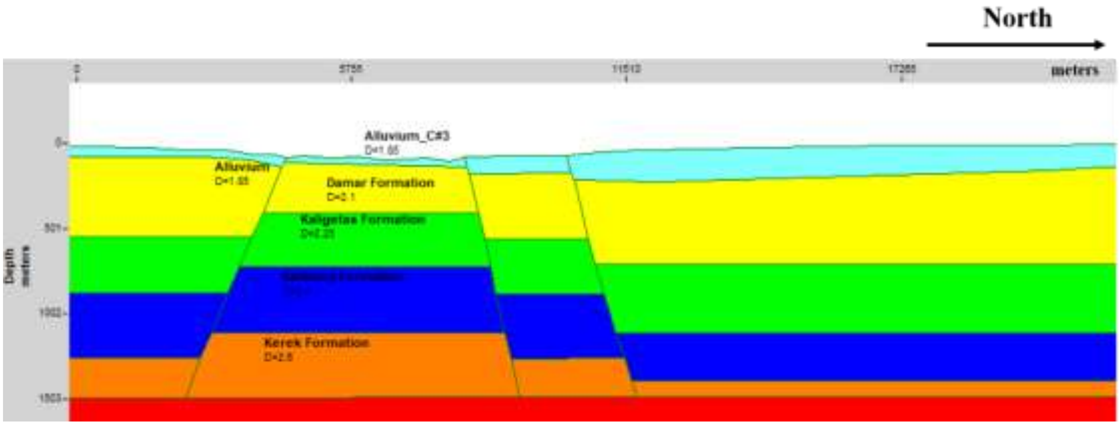

Figure 7. Subsurface Model of Line D-D'

DISCUSSION

The Bouguer anomaly represents the true gravitational force of the earth at a point on the earth's surface of all the earth's inhomogeneities above and below a datum. Generally, a negative Bouguer anomaly indicates a mass with a low density compared to the surrounding density. In contrast, a positive Bouguer anomaly indicates a mass with a high density compared to the density of the surrounding rock **(24)**. The high anomaly on the CBA map represents shallow bedrock, while the low anomaly represents a deep basin **(1)**. Separation of regional and residual anomalies is helpful for further interpretation of the Bouguer anomaly map. Regional Bouguer anomaly is valuable to indicate a basin, while residual Bouguer anomaly qualitatively describes the geological structure, especially faults **(25)**.

Figure 2 is a free-air anomaly map resulting from a downward continuation process using Molodensky methods. Low anomalies are represented by dark blue to light green contours with a range of 9.7-23.1 mGal, and medium anomalies are represented by light green to orange contours with a range of 23.1-39 mGal and high anomalies are represented by orange contours to pink with a value range of 39-57.1 mGal. Low anomalies dominate the Northern part, while high anomalies dominate the Southern part. In this study, the FAA anomaly pattern was similar to the terrestrial gravity FAA anomaly pattern in a study by Liana **(14)**. High anomaly represents high density compared to its surroundings, and low anomaly represents low density compared to its surroundings. Based on the FAA map, the value of the anomaly is higher to the South, which indicates that the subsurface structure is decreasing to the South.

Figure 3 shows a complete Bouguer anomaly map in Semarang and its surroundings. The complete Bouguer anomaly airborne gravity map has a value range of 10.4–29.8 mGal. This value represents the variation in rock density beneath the earth's surface. The anomaly values consist of three types of anomalies, namely low anomalies, with dark blue to light green contours with a 10.4-17.8 mGal value range. Medium anomaly have light green to orange contours with a value range of 17.8-21.1 mGal, and high anomalies have orange to pink contours with values ranging from 21.1 to 29.8 mGal. Based on the CBA map, the high anomaly dominates the Southwest and North, spreading to the East and South. Meanwhile, low anomalies dominate in the central and Northwestern parts. High anomaly represents high density compared to its surroundings, and low anomaly represents low density compared to its surroundings **(14)**.

Figure 4 Is a regional anomaly map of the city of Semarang, with an anomaly value range of 14.9-22.7 mGal. Low anomaly has a value range of 14.9-18.7 mGal, medium anomaly has a value range of 18.7-20 mGal, and high anomaly has a value range of 20-22.7 mGal. The regional anomaly map has an anomaly contour similar to the CBA map, where high anomalies dominate the eastern part from North to South. On the regional map, the high anomaly is still visible in the Southwestern part, and low anomalies dominate in the Northwestern part. Meanwhile, the low anomaly in the center of the CBA map appears missing on the regional anomaly map. Figure 4 is a regional anomaly map for Semarang City, with an anomalous value range of 14.9-22.7 mGal. Low anomaly has a value range of 14.9-18.7 mGal, medium anomaly has a value range of 18.7-20 mGal, and high anomaly has a value range of 20-22.7 mGal. High anomaly is associated with high rock density, presumably due to shallow bedrock. In contrast, low anomaly represents low rock density, presumably due to being associated with deep basins **(14)**.

Figure 5 maps the residual airborne gravity anomaly in Semarang and its surroundings. The residual anomaly includes shallow depths compared to regional anomalies. Residual anomaly maps qualitatively describe the subsurface structure of the earth and faults, with positive and negative anomalies forming a lineament pattern with density contours presumably due to faults **(14)**. Meanwhile, according to Prihatiwi **(26)**, the fault has the characteristics of a low anomaly located between high gravity anomalies. A low gravity anomaly on a fault is caused by a brittle zone when the rock experiences movement, resulting in a reduction in density compared to the surrounding rocks. The residual anomaly has a range of values ranging from (-6.6) – 7.4 mGal. Low anomalies are depicted by dark blue to light green contours with a value range of (-6.6)-(-0.5) mGal, and medium anomalies are depicted by light green to orange contours with a value range of (-0.5) -1 .7 mGal. The high anomaly has orange to pink contours with values ranging from 1.7 to 7.4 mGal. The Southwest and Southeast have high anomaly values. Based on the Geological map of Semarang by Thanden et al **(10)**, the height anomaly is in volcanic rock formations. Therefore, the high anomaly in this area is presumably due to being associated with volcanic rocks. Meanwhile, in the southern part, there is a positive anomaly presumably due to being associated with mountainous areas, namely Ungaran. The Northwest-Southeast part, including the Kreo River, Kaligarang, and Pengkol River, shows low and high anomaly contrasts, presumably due to being associated with a geological structure in the form of a fault. The statement of Poedjoprajitno et al **(2)** strengthens research results that Semarang has reactivated faults, including the Pengkol River Fault, Kaligarang Fault, and Kreo River Fault. Low and high anomaly contrasts also occur in the Northwest and Southwest areas, which are suspected to be associated with faults in the Ungaran area. Forward modeling helps model the subsurface using airborne gravity.

Figure 6 is the D-D' Line in modeling that cuts from the North-South direction of Semarang and its surroundings, with a track length of 21000 m. This study's subsurface model consists of six layers: alluvial deposits, Damar Formation, Kaligetas Formation, Kalibeng Formation, Kerek Formation, and bedrock. Table 1 shows the amount of density of each layer that is input in making the subsurface model. Figure 7 is the result of modeling carried out on Line D-D', the modeling results have an error value of 0.221. This line represents two types of faults: normal and thrust with a north-south direction. Previous research conducted by Wardhana et al **(1)** also found faults based on subsurface modeling of the city of Semarang using land gravity data. His research found two transform faults and a thrust fault with a north-south direction.

CONCLUSION

Based on the research results, airborne data is helpful for geophysical studies, especially in identifying faults. Based on the residual anomaly map, there is a low gravity anomaly with a value range of -6.6 – (-0.5) mGal l between high gravity anomalies located, which has a value range of 1.7-7.4 mGal, which is suspected to be associated with a shallow structure in the form of a fault in the research area. The fault found on the geological map is then known as the D-D' line and used for forward modeling. This line represents two types of faults: normal and thrust faults trending north-south. The modeling results have an error value of 0.221. A fit model shows a picture of subsurface conditions close to the actual situation with fault structures on the D-D' Line.

Declaration by Authors

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