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Distribution of Geological Structures on Java Island Based on Derivative Analysis of Satellite Gravity Data

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Abstract

The island of Java is an interesting place to study geology because of the various tectonic processes that occur starting from volcanic activity, changes in relief, and the relative movement of faults. The aim of this research is to determine the distribution of geological structures spread throughout Java Island based on fault analysis from gravity satellite data. Gravity data was taken via the ICGEM website with a data resolution of 2 km so that 10,000 data were obtained consisting of gravitational disturbances (GD), geoid, and Digital Elevation Model (DEM). The data processing results represent weak zones on the residual anomaly map where fault movement occurs with low anomaly values, namely -55,147 – (-27,175) mGal which stretches from West Java to southern Madura. On the FHD map, it can be seen that the distribution of maximum gravity anomalies is quite numerous and complex with an anomaly value of 1117.18 mGal. It is suspected that the fault near the mountain occurred due to volcanic processes and the southern part occurred due to the shifting process of the Indo-Australian plate and the Eurasian plate. On the TDR map, the weak zones caused by faults spread across Java Island have low gravity anomaly values ranging from -1,353 – (-0.833) mGal. In the Banten to West Java area there are the Baribis Fault and the Cimandiri Fault. In the Central Java region there are the Ajibarang, Ungaran, Baribis Kendeng and Pati faults, as well as parts of the Special Region of Yogyakarta there is the Opak fault. Meanwhile, in the East Java area there are the Baribis Kendeng, Pasuran and Probolinggo faults.

Keywords: *Fault Analysis; Gravity Methods; Geological Structure; Java Island*

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INTRODUCTION

Indonesia is an archipelagic country consisting of thousands of islands and has a fairly large area. The large area and the different conditions of each island cause differences in natural conditions. Geographically, Indonesia is located above the ring of fire which causes frequent earthquakes. With the movement of the three large plates flanking Indonesia (Figure 1), volcanoes and significant tectonic activity have emerged [1,2].

This causes earthquakes to become the most destructive and detrimental natural events in Indonesia [3]. The movement of each different plate has formed a subduction zone and a transform fault zone. In general, tectonic plates in Indonesia divided into two parts, namely west and east. The eastern part has complicated tectonic plate boundaries and the western part has simple and easily recognized tectonic plate boundaries [4].

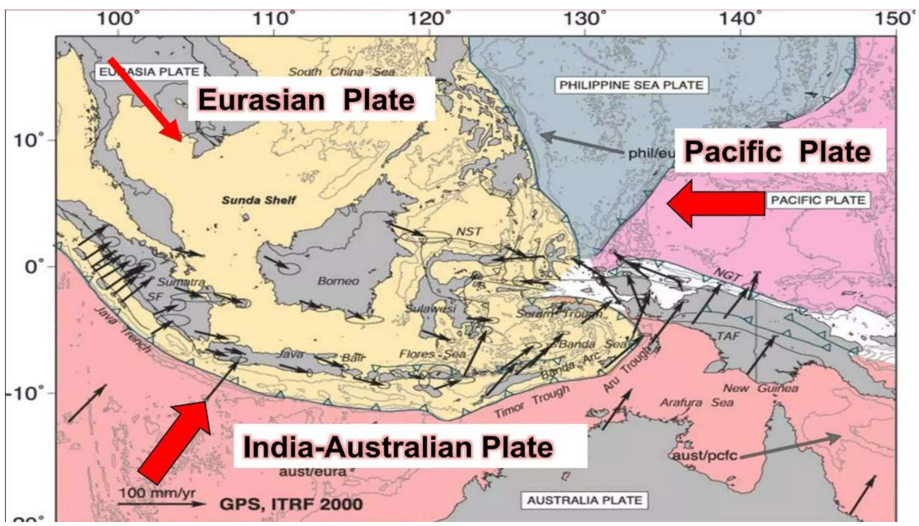


Figure 1. Indonesian Tectonic Plate Model [5]

Java Island is part of the Sunda Arc, which is a volcanic arc of Tertiary to Quaternary age. This volcanic arc was formed because of subduction in the south of Java Island, namely the subduction of the Indian Ocean plate under the Eurasian continental plate. Even though the position of the subduction has progressed towards and away from land, the position of the arc is relatively constant. This tectonic activity causes the formation of various geological structures on the island of Java, one of which is faults [6].

Sources of earthquake hazard originating from subduction earthquake sources around the island of Java which can be seen. Based on the image below, there are 10 sources of subduction earthquakes around the island of Java, namely: Megatrust S. Sumatra, Benioff S. Sumatra, Megatrust Java 1, Benioff Java 1, Megatrust Java 2, Benioff Java 2. Megatrust Java 3, Benioff Java 3, Megatrust Sumba, and Benioff Sumba [7].

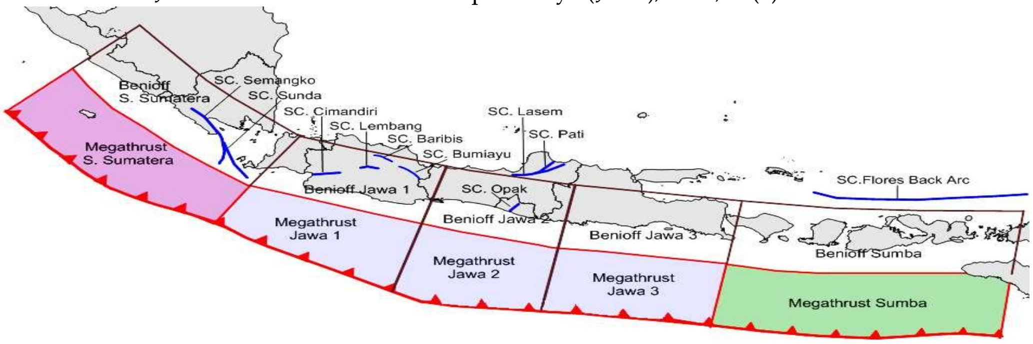


Figure 2. Source of Earthquake [8]

As a result of changes in subduction positions from time to time, this has implications for changes in structural and tectonic patterns on the island of Java. In the central Java area, the dominant structure is a reverse fault structure, while in the eastern part of Java Island it is dominated by normal fault structures [9]. There are many papers and research regarding derivative analysis using satellite data. One of the research by Andini Fitriastuti, which stated on the paper that using First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) in West Java especially Wonosobo that using this method can show Wonosobo district is in a volcanic arc area with a large compressional force that forms a series of rising faults and faults formed in the form of local faults with a fairly random distribution of locations at a depth of 500 meters to 1 kilometer [10]. The difference and novelty in this paper is our research is not based on one district but all of java region, so we want to see the relevance geological structure in Java and correlate it with FHD and SVD method. The application of potential-field methods such as gravity in geophysical prospecting can identifying geological structures of the earth such as faults in Java Island [11,12]. The Gravity Method measures the value of variations in gravitational acceleration on the earth. The Gravity Method measures changes in gravitational acceleration anomalies due to density differences, so it can identify the presence of fault structures [13].

The gravity method is a method that utilizes the density difference between one rock layer and another rock layer. These differences can also be used as an indication of the presence or absence of a geological structure in the form of a fault. Faults can be divided into two types; normal and reverse depending on their movement [14]. The gravity method itself is based on measuring changes in the Earth's gravitational field. The gravity method is a method for investigating changes in the Earth's gravitational field due to differences in the density of rocks beneath the Earth's surface [15]. Newton's Law theory of the attractive force between two objects of masses m_1 and m_2 separated by a distance r is used [16,17].

$$\vec{F} = -G\frac{m_1 m_2}{r^2}\vec{r} \tag{1}$$

With $\vec{F}(r)$ is the force of attraction (N), m_1 is the mass of object 1 (kg), m_2 is the mass of object 2 (kg), r is the distance between two objects (m), and G is the universal gravitational constant (6,67 x 10^{-11} $m^3\,kg^{-1}\,s^{-2}$).

First Horizontal Derivative (FHD) namely Horizontal Gradient. The horizontal gradient of the gravity anomaly is caused by a body tending to show the edge of the body. So, the horizontal gradient method can be used to determine the location of horizontal density contrast contact boundaries from force data [18] [19]. To calculate the FHD value, using equation (2).

$$FHD = \frac{g_{(i+1)} - g_{(i)}}{\Delta x} \tag{2}$$

Tilt Derivative (TDR) is a derivative method used to emphasize the boundaries of gravitational anomalies which is very useful for identifying structures that develop at the research location [24]. This filter limits the frequency of incoming residual anomalies by applying a tangential function. In other words, this filter includes two balances of filtering effects, namely vertical derivative and total horizontal derivative of gravity data [19]. To use this TDR filter, it can be formulated as equation (3):

$$TDR = arctan\left(\frac{\frac{dg}{dz}}{\sqrt{(\frac{dg}{dx})^2 + \sqrt{(\frac{dg}{dy})^2}}}\right) \tag{3}$$

The tectonic development of the island of Java can be studied from geological structural patterns over time. Geological structure is the main factor that controls the shape and direction of hill paths, especially sedimentary hills [20]. The geological structure on the island of Java has regular patterns (Figure 1). Geologically, the island of Java is a complex history of basin subsidence, faulting, folding and volcanism under the influence of different stress regimes from time to time. In general, there are three general structural pattern directions, namely the Northeast – Southwest (NE-SW) direction which is called the Meratus pattern, the North – South (N-S) or Sunda pattern and the East – West (E-W) direction [21]. The change in the Cretaceous Subduction route from Northeast - Southwest (NE-SW) to relatively East - West (E-W) from the Oligocene until now has produced a very complicated Tertiary geological setting on the island of Java as well as raising questions about the mechanism of this change. This complexity can be seen in the structural elements of Java Island and the surrounding area [22].

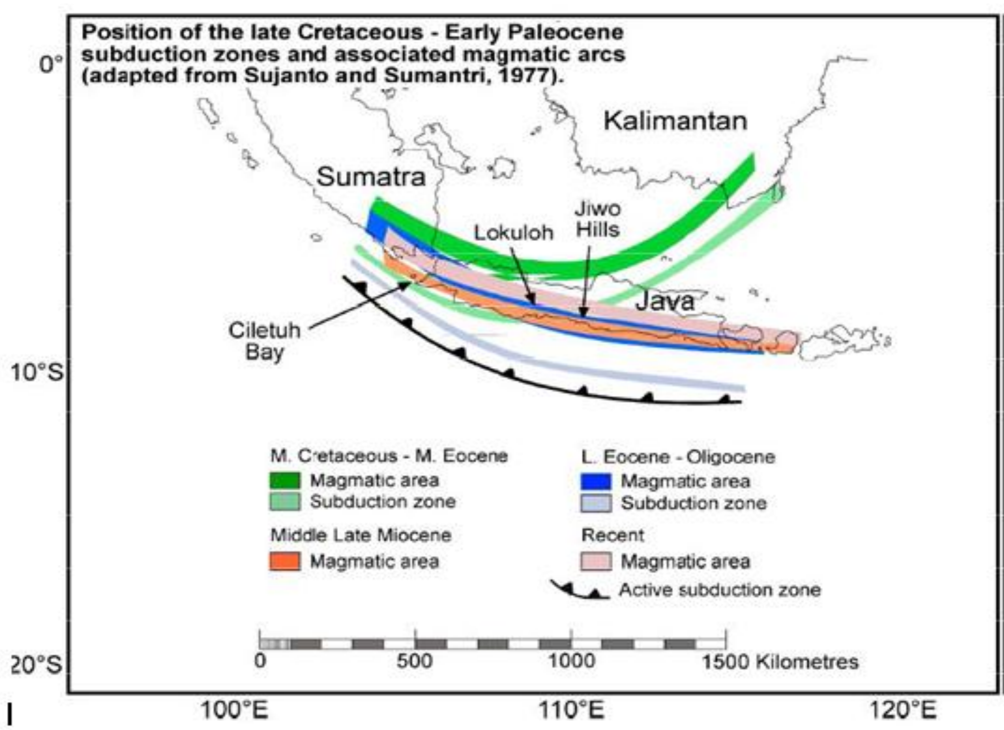


Figure 3. Position of the Late Cretaceous – Early Paleocene Subduction Zones and Associated Arcs [23]

Meratus Pattern in the western part it is expressed in the Cimandiri Fault, in the central part it is expressed in the distribution pattern of pre-Tertiary rock outcrops in the Karang Sambung area. Meanwhile, in the eastern part, it is indicated by the Pati Basin boundary fault, eastern "Florence", "Central Deep". Tuban Basin and is also reflected in the configuration pattern of the Karimun Jawa High, Bawean High and Masalembo High. The Meratus pattern appears to be more dominantly expressed in the eastern part [24].

Sundanese Pattern trending North - South, in the western part it appears more dominant while development towards the east is not expressed. The expression that reflects this pattern is the pattern of boundary faults in the Asri Basin, Sunda Basin and Arjuna Basin. The Sunda pattern in general is a strain structure. The Java pattern in the western part of this pattern is represented by thrust faults such as the Beribis fault and faults in the Bogor Basin. In the middle part, a pattern of faults can be seen in the North Serayu and South Serayu zones. In the eastern part, it is indicated by the direction of the Kendeng Mountains Fault, which is an upward fault. Java Pattern shows the youngest patterns and reactivates all previously existing patterns [25]. Seismic data shows that the thrust fault pattern in a west-east direction is still active today.

Subduction and these structures produce active faults such as the Cimandiri, Lembang, Baribis, Bumiayu, Lasem, Opak, Pati and many more faults. The most common pattern in Java is strike-slip faults/normal faults [20]. One example is the Cimandiri fault. A number of researchers believe it to be a dextral strike-slip fault, namely a normal fault movement that moves to the right [26]. This fault was formed as a result of reactivation of old faults during Cretaceous subduction [27]. Other researchers conclude differently, namely that it is a thrust fault that was formed at the end of the Tertiary [28] or post-Middle Miocene age [29]. Apart from West Java, the Central Java region also has strike-slip faults, namely the Muria-Kebumen Horizontal Fault (southwest-northeast, Meratus direction, sinistral) and the Pramuka-Cilacap horizontal fault (northwest-southeast, Sumatra direction, dextral) cutting through the central part of the island of Java and meet in the southern part of Central Java. The existence of these two regional faults is based on gravity data, surface geology, satellite imagery and seismic and is supported by regional structural and tectonic analysis [30].

In their movement throughout the Tertiary orogenesis period, these two large strike-slip faults have caused: (1) indentation/indentation of the archipelagic structures of the north and south coasts of Central Java, (2) exposure of old rock complexesmelange The Ulo-Karangsambung Lok through a maximum ridge mechanism, and (3) the disappearance of the physiography of the Southern Mountain Route in the southern part of Central Java. All of these symptoms are related to isostatic compensation of the earth's crust [29].

For the East Java area, we know the Kendang fault. Namely, one of the faults that was formed as a result of the Java subduction stress in the eastern part is the Kendeng Fault. The Kendeng Fault stretches from the city of Semarang to the city of Surabaya in a west-east direction. The northern part of the Kendeng Fault is the main part of the Sunda Plate while the southern part is a range of volcanoes. However, the extension of the Kendeng Fault to the east is not known for certain until now [30].

The research results of Koulali, et al (2016) using GNSS (Global Navigation Satellite System) technology estimated the shear rate of the Kendeng Fault at 2.3 – 4.1 mm/year in the sinistral component. Meanwhile, the normal component of the fault shows compression as accommodation for the Java subduction [31].

In addition, there have been several previous studies regarding geological structures using gravity data such as geological estimates which include regional and residual structures in the oil and gas area, Aceh [32] [33] [34]. Gravity data can also produce 3D models to determine geothermal potential based on the results of the second Vertical Derivative (SVD) analysis [24][35] [36] [37] [38] Lineament analysis of gravity data using techniques such as fast sigmoid edge detection (FSED) and Eulerian deconvolution with GGMPlus satellite data [39] [40] Knowing subsurface structures can identify structural fault lines during disaster mitigation [33][41] [42]. Gravity data can also be used to identify the formation of springs and maars with geological indications of linemeants structures [43] [44].

However, in the article, Abakar, Darisma D, Marwan M and Ismail N [32] estimates of subsurface geological structures in oil and gas prospect areas are carried out by utilizing gravity field anomalies from satellite gravity data. This research aims to analyze satellite gravity data to obtain geological features which include deep and shallow structures or faults around oil and gas prospect areas, while this article discusses the distribution of faults which are not only in one area but also covers the island of Java by producing an FHD map for determine fault zones and TDR maps to identify weak zones due to faults. Because by identifying the distribution of fault zones on the island of Java, locations that are prone to earthquakes can also be identified.

METHOD

The research location is on the island of Java, Indonesia with an area of ± 128,297 km2 (Figure 4). The data used is gravity satellite data taken via the ICGEM website (https://icgem.gfz-potsdam.de/home) with the SGG-UGM-2 2020 model version. This website is open source, accessible at any time, and serves as a platform for collecting and archiving all existing global gravity field models, thus imposing no restrictions on data usage.

The data accuracy is influenced by its resolution; in this case, satellite gravity data has a resolution ranging from ±5 km to ±100 m. This high resolution makes the data more sensitive to small variations in the gravity field, making it highly suitable for regional fault studies. However, such resolution can also produce noise, necessitating gravity corrections. Some of the gravity corrections applied include Bouguer Correction (BC) to remove gravitational effects between the measurement point and the reference point, Free Air Correction (FAC) to account for altitude influences on the measured gravity values, and Terrain Correction (TC) to eliminate the gravitational effects of topography around the measurement location [45].

The data processing in this study begins with collecting satellite gravity data, totaling 10,000 data points comprising Gravity Disturbance (GD), geoid data, and Digital Elevation Model (DEM). Gravity corrections are then applied to produce a Complete Bouguer Anomaly (CBA) map. Subsequently, the CBA map is used to separate anomalies into regional anomalies, which reflect trends of deep and large-scale geological structures, and residual anomalies, which illustrate local variations from shallow and small-scale geological effects. The residual anomalies are further processed into a First Horizontal Derivative (FHD) map to delineate the boundaries of geological structures and a Total Derivative Reduction (TDR) map to support deeper interpretation. The results of the analysis from these maps are then correlated with previous geological structure data and interpreted to produce final conclusions regarding the geological structures in the study area (Figure 5).

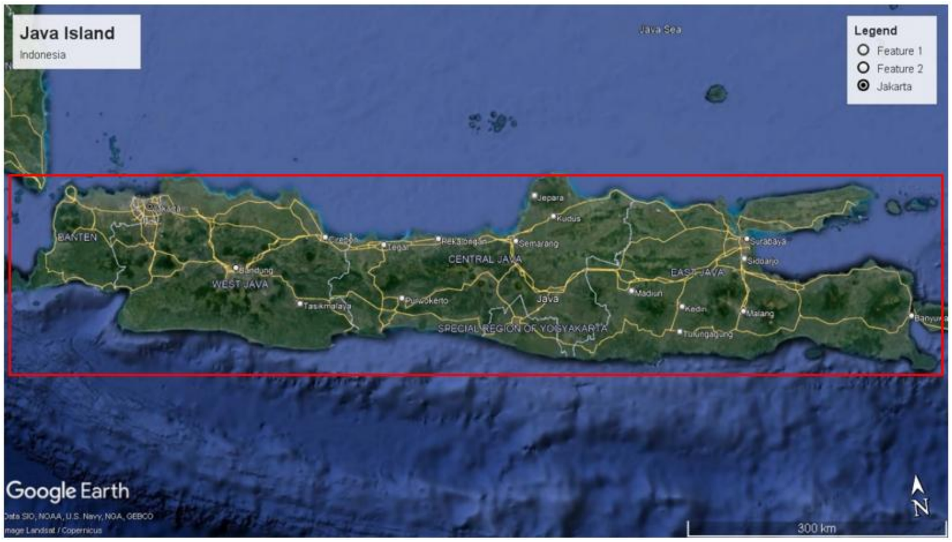


Figure 4. Research Location

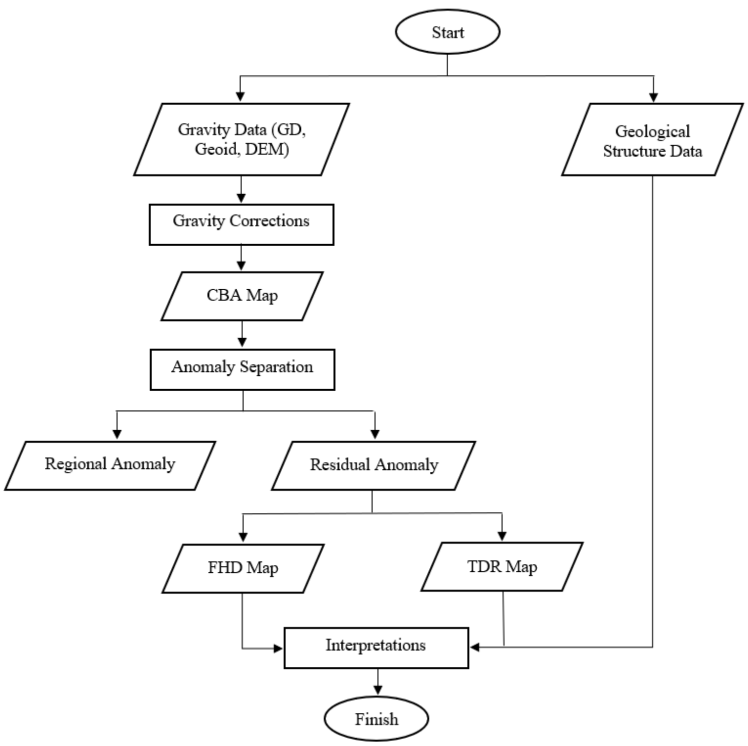


Figure 5. Flow Chart

RESULTS AND DISCUSSION

This research is very important to carry out as additional information for disaster mitigation purposes, especially land shifts due to geological structures in Indonesia, and also makes it possible to find suspected new geological structures in an area that could damage the area. In previous research, the gravity method was used to identify the existence of the Palu - Koro fault using FHD and SVD filters, this has also been done by many other researchers, so for an update in this research the FHD and TDR filters were used to identify regional geological structures on the island of Java [46].

The results of the Topographic Map Analysis (Figure 6) can be seen that the research area, namely the island of Java, has quite complex topography with a topographic value of 3.11 – 1138.62 m and there are many mountains and hills formed due to the collision of tectonic activity between the Indo-Australian plate and the Eurasian plate. It can be seen that the dominant distribution of faults (white polygons) on the island of Java is in a west to east direction.

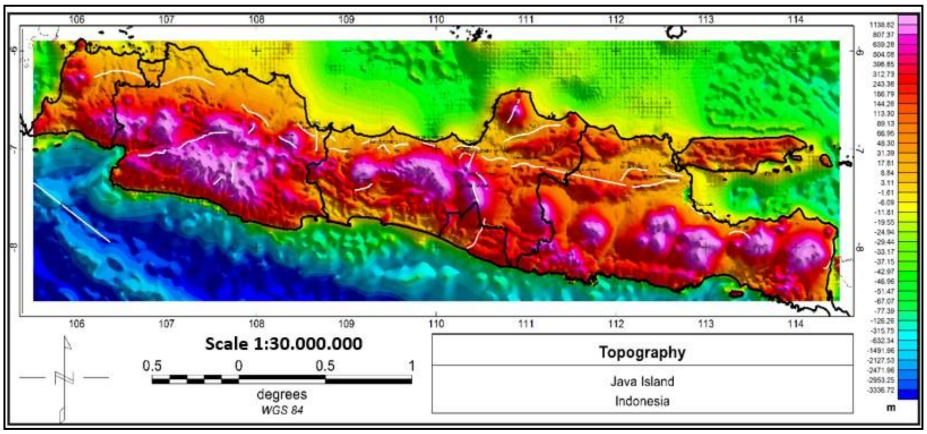


Figure 6. Topography Map

On the Complete Bouguer Anomaly map in the research area (Figure 7) it can be seen that the distribution of gravitational field anomalies has a value of -8.03 – 321.95 mGal, in the northern part of the island of Java which stretches from West Java to the southern part of Madura it has a low gravitational field anomaly value of -8.03 – 38.58 mGal which is thought to be a sedimentary basin area or weak zone due to fault movement (white polygon) which results in rock deformation so that the density of the rock decreases and the southern part of Java Island which stretches from Banten to East Java has a sufficient gravity field anomaly value high, namely 123.40 – 321.95 mGal, which is thought to be the subduction zone between the Indo-Australian plate and the Eurasian plate. However, this CBA map still has ambiguity in interpretation because the CBA map still contains regional (deep) and residual (shallow) anomalies, so the next stage must be to separate the anomalies so that further interpretation can be carried out.

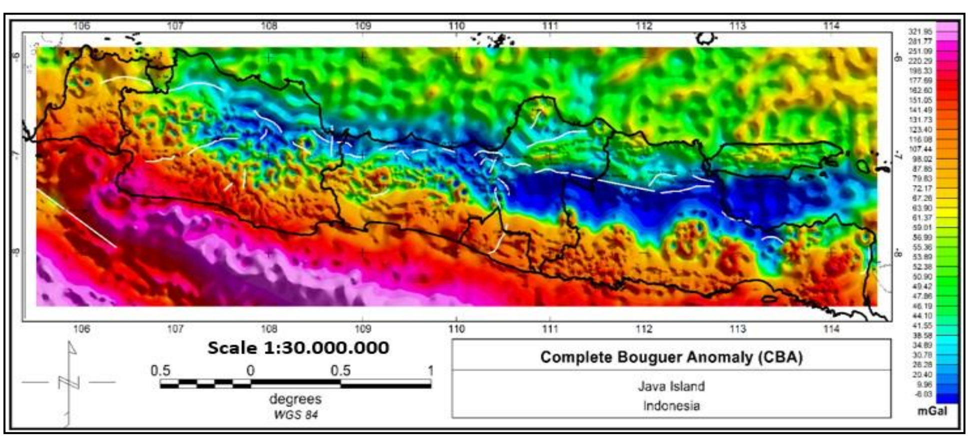


Figure 7. Complete Bouguer Anomaly (CBA) Map

In the regional anomaly map (Figure 8) it can be explained that the contours tend to be smoother than the CBA map, because the regional anomaly map depicts the response or conditions of the subsurface which is quite deep, in the study area it can be seen that the distribution of gravity field anomalies has a value of 39,741 – 255,036 mGal, in the northern part of the island of Java, which stretches from West Java to the southern part of Madura, it has a moderate gravity field anomaly value, namely 57,709 - 83,709 mGal. In the southern part of Java, which stretches from Banten to East Java, it has a quite high gravity field anomaly value, namely 98,734 - 255,036 The mGal is thought to be a subduction zone between the Indo-Australian plate and the Eurasian plate which is very deep far below the earth's surface.

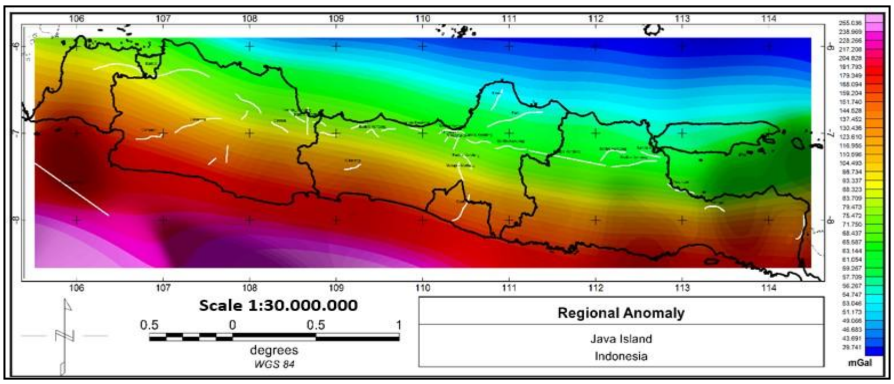


Figure 8. Regional Anomaly Map

In the residual anomaly map (Figure 9) it can be explained that it has contours that tend to spread and vary, because the residual anomaly map describes the subsurface response or conditions close to the earth's surface, in the research area it can be seen that the distribution of the gravity field anomaly has a value of -55,147 – 53,445 mGal, in the northern part of the island of Java which stretches from West Java to the southern part of Madura has a low gravity field anomaly value, namely -55,147 – (-27,175) mGal which is thought to be weak zones or deformation caused by faults on the island of Java (white polygon), it can be seen that the fault shp data is correlated with low gravity field anomalies, the southern part of Java Island which stretches from Banten to East Java has quite high gravity field anomaly values, namely 10,837 – 53,445 mGal which is thought to be a subduction zone between the Indo-Australia Plate and the Eurasian plate.

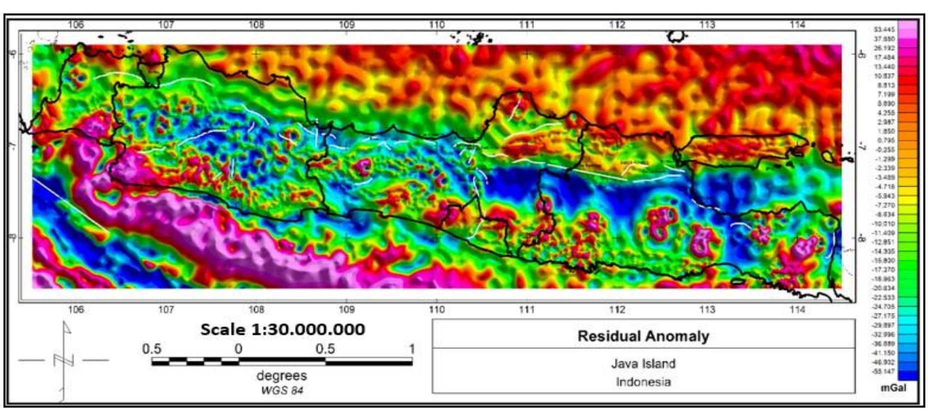


Figure 9. Residual Anomaly Map

In the First Horizontal Derivative (FHD) map (Figure 10), it can be seen that there is quite a large and complex distribution of maximum gravity field anomalies. In the FHD map to determine the fault zone, the maximum anomaly value is found. In the research area, the distribution of gravity field values is 22.89 - 1117.18 mGal, where in all parts of the island of Java there is a maximum FHD value (1117.18 mGal) or suspected faults which are estimated to be near mountains which are caused by volcanic processes and in the southern part which are caused by the process of shifting the Indo-Australian plate and the Eurasian plate, it can also be seen that the faults on the island of Java (white polygons) are correlated with the maximum anomaly on the FHD map.

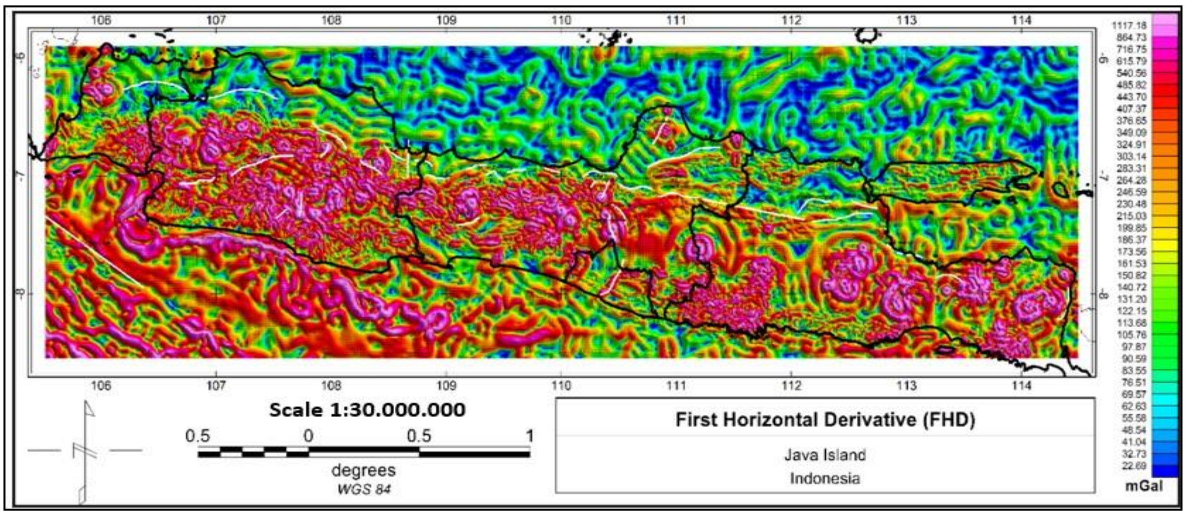
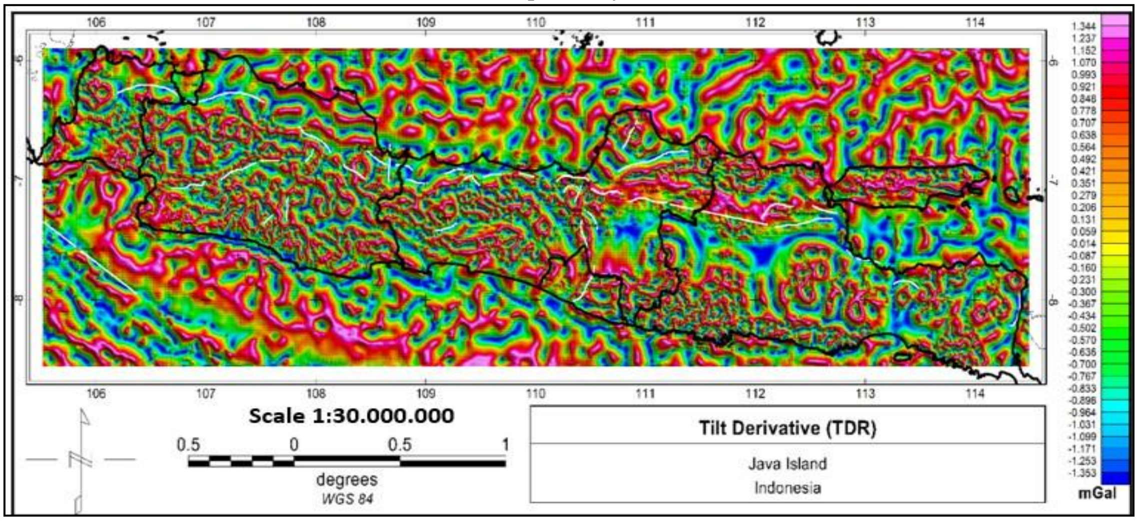
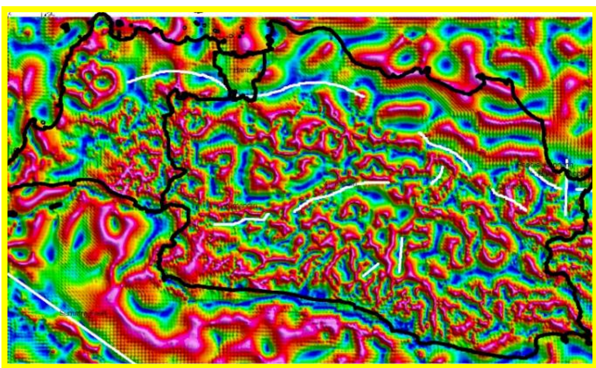


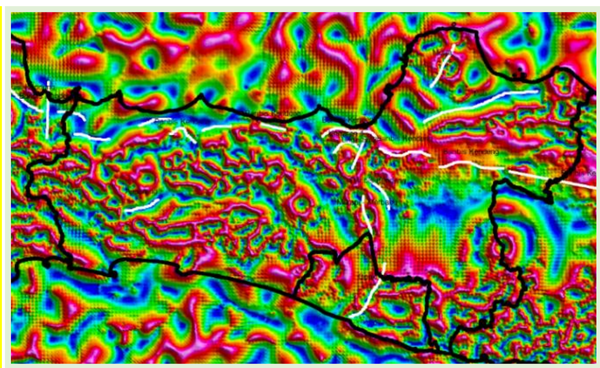
Figure 10. First Horizontal Derivative (FHD) Map

The Tilt Derivative (TDR) map (Figure 11) functions to clearly show the lithological contact boundaries in the research area. This TDR map is sourced from a residual anomaly map carried out by a tilt derivative filter so that it produces quite clear lithological contact boundary anomalies. The TDR map in this research area determines the zones. weak due to faults having low gravitational field anomaly values ranging from -1,353 – (-0.833) mGal, it can be seen that the faults spread across the island of Java are correlated with low gravitational field anomalies.

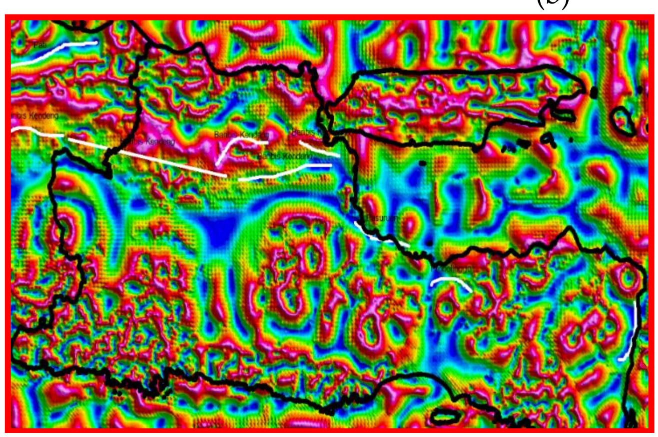
In figure 11(a), in the Banten to West Java area, there is a very long fault, namely the Baribis Fault, which correlates with low anomaly values in the research area. There is also the Cimandiri Fault in the southern part of West Java, which correlates with low anomaly values. In figure 11(b), in the Central Java region there are the Ajibarang, Ungaran, Baribis Kendeng and Pati faults which correlate with low anomaly values in the research area and in the Yogyakarta Special Region there are the Opak faults which correlate with low anomaly values. In figure 11(c) in the East Java area there are the Baribis Kendeng, Pasuran and Probolinggo faults which correlate with low anomaly values in the study area.







(a) (b)



(c)

Figure 11. Tilt Derivative (TDR) Map (a) Banten, DKI Jakarta and West Java, (b) Yogyakarta Special Region and Central Java, (c) East Java

CONCLUSION

The residual anomaly map reveals weak zones associated with fault movements, with low gravity anomaly values ranging from -55.147 to -27.175 mGal, extending from West Java to southern Madura. The First Horizontal Derivative (FHD) map highlights a complex distribution of maximum gravitational anomalies, with a peak value of 1117.18 mGal, indicating fault zones influenced by volcanic activity near mountainous regions and tectonic shifts caused by the interaction between the Indo-Australian and Eurasian plates. The Total Derivative (TDR) map further identifies weak fault zones with low gravity anomaly values between -1.353 and -0.833 mGal, correlating with major fault structures such as the Baribis and Cimandiri faults in West Java, the Ajibarang, Ungaran, Baribis Kendeng, Pati, and Opak faults in Central Java, and the Baribis Kendeng, Pasuruan, and Probolinggo faults in East Java. The strong correlation between these geological structures and the identified anomalies confirms the effectiveness of FHD and TDR filters in delineating fault zones, demonstrating that gravity anomaly analysis is a valuable tool for mapping geological structures and understanding regional tectonic activity.

AUTHOR CONTRIBUTIONS

Nanda Ridki Permana: Conceptualization, Software, Validation, Formal Analysis, Investigation, Data Curation, Supervision, Funding Acquisition, Writing - Original Draft; Dhika Faiz Fadrian: Resources, Project Administration, Writing - Original Draft; Belista Gunawan: Methodology, Resources, Visualization, Writing - Original Draft; Amara Wulandari: Writing - Review & Editing.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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