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Fault Structures and Lithological Boundaries Study on Weh Island Using Horizontal Gravity Analysis

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Abstract. The horizontal gradient method is a widely used qualitative approach for enhancing the interpretation of gravity anomaly data. This method is particularly effective in delineating lithological boundaries between rock units with contrasting densities, especially where contacts are horizontally aligned. Horizontal gradient calculations are performed by partially differentiating gravity data with respect to its horizontal position. This method was applied to gravity data of Weh Island, the westernmost part of Indonesia, to delineate fault zones and lithological boundaries in the region. The results of the study show that this method can effectively identify rock formations on Weh Island, such as the boundary between coral reef limestone and pyroclastic flow units, as well as tuff sandstone areas and surrounding rocks, including volcanic kulam units and volcanic pumice rocks. Applying the horizontal gradient method to gravity data on Weh Island produced maps that clearly outline rock formations. Combining these with geological maps shows a northwest–southeast trend aligned with the main strike of the Seulimuem Fault, which crosses the island. The results from analyzing horizontal derivatives offer key insights for studies of lithology, faulting, and subsurface layers in complex geological regions like Weh Island.

Keywords: *Gravity Method, Horizontal Gradient, Lithological Boundaries, Land Survey, Weh Island*

Introduction

Gravity method is a geophysical exploration method that measures variations in gravitational force on the Earth's surface to predict the distribution of rock density beneath the surface. The gravity method has been widely used in geophysical research. It can be applied in several fields, including hydrocarbon exploration, regional geological studies, mineral exploration in sediments, geotechnical site investigations, hydrogeological investigations, detection of subsurface voids, and archaeological geophysics (Apeh et al., 2024; Ariyanto and Purba, 2025; Olivier Ntomb Biboum et al., 2021; Reynolds, 2011; Steven et al., 2024; Telford et al., 1990).

The gravity method is often used because it is cheap, practical, and fast. This method is also used as a supporting method due to its regional survey areas (Muhajirin et al., 2020; Oesanna and Ismail, 2018; Sihombing et al., 2024; Wangsa, 2018). Thus, this method is one step in determining more specific research areas. For example, gravity survey is often used as a tool to detect seismic survey locations in oil exploration which is cheaper than seismic method. The results obtained from the gravity method are often used to aid in solving problems in seismic interpretation (Darisma et al., 2019). In mineral exploration, this method is typically employed as a supporting technique, serving as an aid in interpreting magnetic and electromagnetic data to clarify the results obtained from iron ore surveys (Telford et al., 1990).

Interpretation of gravity anomaly data is done through two stages: the qualitative and the quantitative. The quantitative stage involves modeling variations in gravitational acceleration at the ground surface into variations in subsurface density. This quantitative stage involves two types of modeling: forward modeling and inverse modeling (Irwansyah et al., 2013). The qualitative stage involves processing gravity anomaly data to produce more detailed data that accurately represents the anomalies measured on the ground surface. Although this stage cannot explain conditions below the surface, performing is still essential. Compared to the quantitative stage, which requires time for data modeling, this stage can be completed in a relatively short time, making it suitable for field cross-checking (Luo et al., 2025; McGrath, 1991).

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Many approaches can be used for qualitative interpretation, including upward continuation, directional derivatives, horizontal gradient (horizontal derivative), and analytic signal. Horizontal gradient reveals underground rock boundaries (Entezar-Saadat and Motavalli-Anbaran, 2016; Lase, 2024; Wu et al., 2017). It maps rocks below the surface, showing formations or faults due to density contrast differences (Blakely, 1995). These patterns show deviations in the horizontal gravity gradient caused by boundary changes. High gradient values at the edges of rocks indicate anomalies, helping identify sudden lateral density changes from gravitational measurements (Cordell, 1979; Cordell and McCafferty, 1989; Grauch and Cordell, 1987).

Interpreting the horizontal gradient in terms of density and deriving geological information involves several key assumptions. We generally assume that contrasts in physical properties occur along vertical boundaries and are sharply isolated from other sources. However, applying this method to geological problems is often more complex. Density can vary in all directions within geological units, and contacts between units are usually not vertical. Grauch and Cordell (1987) have estimated potential errors that can arise when these basic assumptions are violated. Despite these limitations, the technique has been effective for interpreting regional-scale datasets. Cordell and McCafferty (1989) describe using the horizontal gradient method to identify similar sources from gravity data. Their approach relies on the idea that density within the same layer should remain consistent unless another layer is involved. When density values are added, the results produce a clear visual, transforming the potential field's mountains and valleys into flat planes separated by boundary lines. These boundary lines resemble a map where variations in gravity indicate different areas boundaries.

In this study, the horizontal gradient method will be applied to gravity measurement data from Weh Island. Weh Island is a small island located at the tip of Sumatra Island. Despite its small size, the island has numerous features that warrant study, including faults and volcanoes (Muhammad et al., 2021; Yanis et al., 2019). Studies on faults can help prepare for disaster mitigation caused by earthquakes. Volcanoes, on the other hand, can be utilized as renewable energy sources to support energy needs. With this research, it is hoped that the results of the horizontal gradient analysis can map the geological structure of Weh Island (Pham et al., 2024; Wu et al., 2017). The mapping results can show the condition of faults and rock formation structures in the Weh Island area. The structure of rock formations can be revealed by patterns obtained from the analysis of horizontal gradients.

Methodology

This study utilized gravity measurement data collected from Weh Island to analyze subsurface geological structures using the horizontal gradient method. The research was carried out in two main stages: data acquisition and data analysis. The gravity data acquisition was conducted on Weh Island over a period of 10 days.

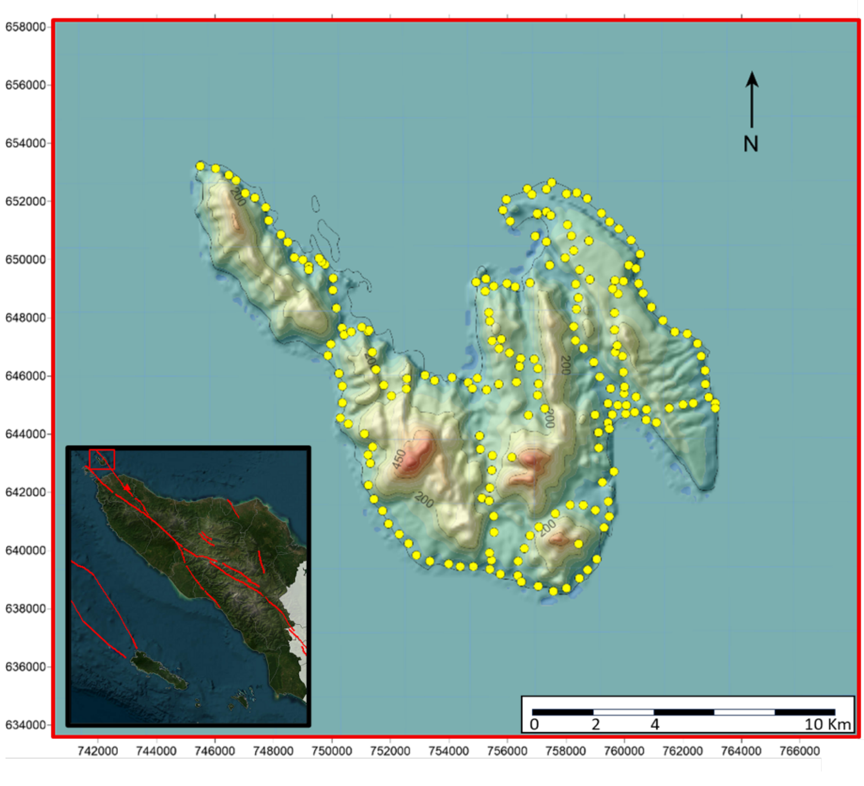

Figure 1 Distributions of gravity measurement points on Weh Island. The inset image shows Aceh Province, with Weh Island located at its northwestern tip.

Measurements were performed using a Scintrex CG-5 gravimeter, known for its high precision in detecting subtle gravity variations. A total of 210 measurement stations were strategically distributed across the island to ensure comprehensive spatial coverage, with an average spacing of approximately 500 meters between stations. The distribution of these stations is illustrated in Figure 1. The gravity method is one of the methods that generates a significant amount of noise. This noise can originate from the equipment or objects surrounding the measurement point. Once all corrections to the gravity data have been completed, the complete Bouguer anomaly data is obtained. This Bouguer anomaly data was then re-digitized row by row to produce digitized Bouguer anomaly data in the form of lines shown in Figure 2. The digitized data is then processed using the horizontal gradient method to obtain the maximum result at the estimated rock boundary. The magnitude of the horizontal gradient of gravity can be determined using the following equation (Blakely, 1995);

$$h(x,y) = \left[\left(\frac{\partial g_z(x,y)}{\partial x}\right)^2 + \left(\frac{\partial g_z(x,y)}{dy}\right)^2\right]^{\frac{1}{2}} \quad (1)$$

where $h(x,y)$ is the horizontal gradient result and g_z is the gravity anomaly value.

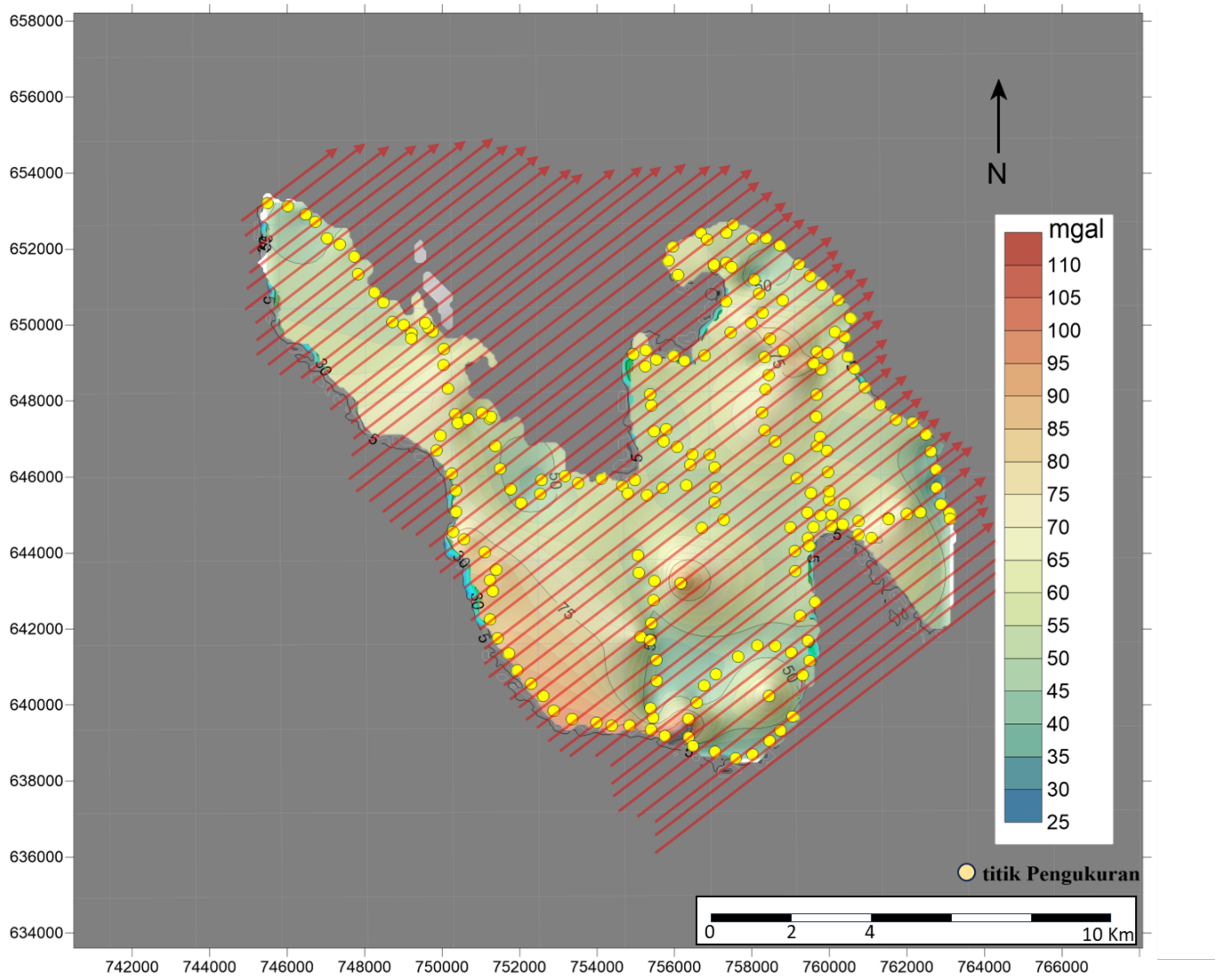

Figure 2 Gravity anomalies on Weh Island. The lines covering the entire island are digitized gravity data.

The horizontal gradient is calculated using finite-difference. This horizontal gradient tends to have a maximum located at the edge of the gravity anomaly, as shown in Figure 3. When applied to two-dimensional surveys, the horizontal gradient tends to indicate steep signs of high-density changes. Finding the maximum value in the horizontal gradient can be accomplished with a simple check. Blakely and Simpson (1986) automated the process using an algorithm that scans the rows and columns of the data grid, recording the location of the maximum in a file for later analysis and plotting. To perform the calculation of equation (1), some modifications are needed to enable the *calculation to be performed automatically by a computer. The modification required is in the partial derivative process, which must be performed using the approach method. One approach method derivative is a center difference method;*

$$\frac{\partial f(x)}{\partial x} = \frac{f(x+1)-f(x-1)}{2\Delta x} \tag{2}$$

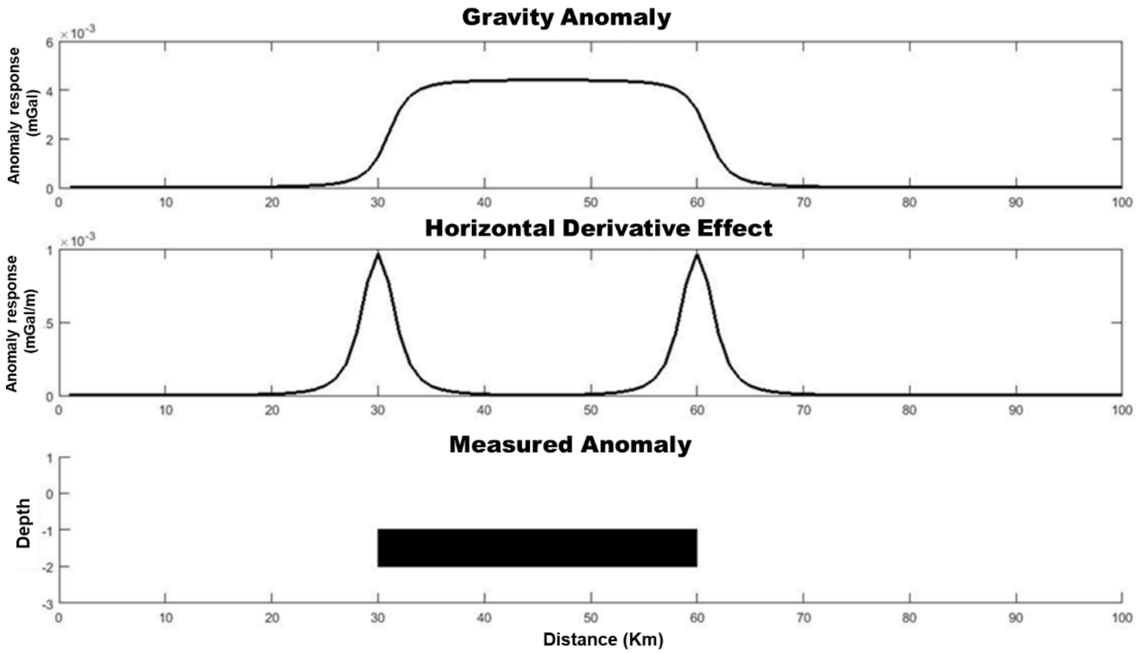

Figure 3 Gravitational anomaly and horizontal gradient above a tabular object, modified from Blakely (1995).

from equation (2) for the derivative $g_z(x,y)$ *concerning x and y;*

$$\frac{\partial g_z(x,y)}{\partial x} = \frac{g_z(x+1,y)-g_z(x-1,y)}{2\Delta x} \tag{3}$$

$$\frac{\partial g_z(x,y)}{\partial y} = \frac{g_z(x,y+1)-g_z(x,y-1)}{2\Delta y} \tag{4}$$

Equations (3) and (4) are equations used to perform horizontal gradient processing on each field component (x-axis and y-axis). If processing is only performed on one data profile on the measurement path, then horizontal gradient processing is only required for the x-axis. Therefore, equation (1) can be modified for use in calculations as follows:

$$h(x) = \left[\left(\frac{\partial g_z(x)}{\partial x}\right)^2\right]^{\frac{1}{2}} \tag{5}$$

Therefore, the derivative $g_z(x)$ *of equation (5) can be written as*

$$\frac{\partial g_z(x)}{\partial x} = \frac{g_z(x+1)-g_z(x-1)}{2\Delta x} \tag{6}$$

The horizontal gradient analysis was automatically conducted using the algorithm developed by Blakely (1995). This algorithm was implemented as a complete program run through a Fortran compiler. Since Fortran processes data in vector form, the data must be digitized one line at a time. The total number of data rows (N) needs to be known to input all data into the Fortran program. The program subsequently iterates over these N data points, loading each one from the data file, and performs the calculation based on equation (6). In this equation, g(x-1) poses an issue because Fortran arrays begin at index 1. To fix this, the function is adjusted by adding one to it. Consequently, the derivative with respect to x becomes:

$$gx = \frac{g(x+2)-g(x)}{2\Delta x} \tag{7}$$

Equation (7) is used to analyze horizontal gradients in a specific direction. The chosen direction aligns with the digitization line that intersects the fault on Weh Island. This line is selected based on the assumption that the fault-induced changes will be contrasting.

Results

The gravity data were obtained from measurements taken along roads covering the entire island, with the distribution of station points shown in Figure 2. The anomaly data obtained were not arranged in a good grid. To organize the data into a neat grid, the data was first corrected to obtain complete Bouguer anomalies and digitized in a line direction, as shown in Figure 3. The Bouguer anomaly values indicate variations in density beneath the surface. Areas with low anomaly values indicate low rock density contrast, while high anomaly values indicate high-density contrast. A critical change from low to high anomalies is observed in the southwest part of the island, which is attributed to the presence of two rocks with significant density differences or a fault in that area. To obtain more information on the measurement data on Weh Island, horizontal gradient calculations were performed on the complete Bouguer anomaly data. The initial assumption of the results obtained is the boundary area between anomalies with high and low gravity values.

The result of horizontal gradient processing is in the form of digitized line files. Before plotting the data, it must first be combined into a single file. The plot of the horizontal gradient analysis data consists of points that form a pattern, as shown in Figure 4.

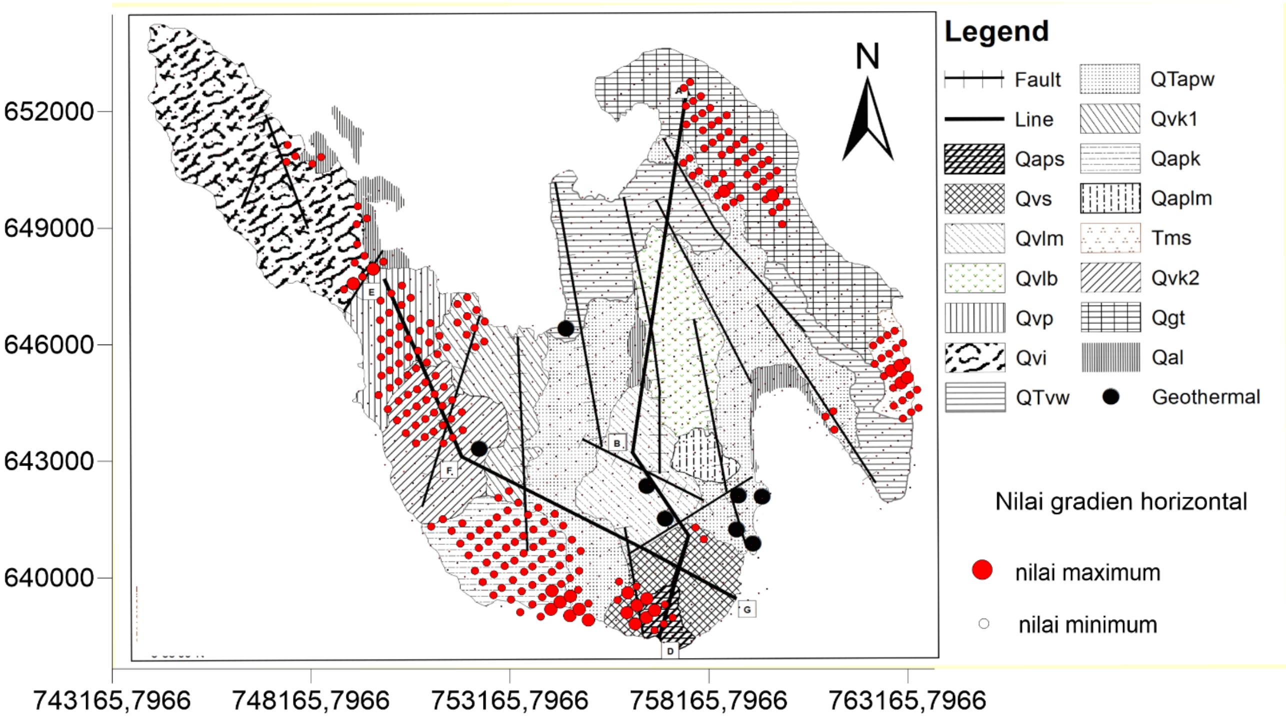

Figure 4 Geological map of Weh Island with horizontal gradient patterns, modified from Dirasutisna and Hasan (2005).

Figure 4 shows a plot of circles distributed across the island. The variation in the size of the circles indicates the degree of difference in the anomaly response values in the area, which can also be interpreted as the variation in the contrast of rock density in the area. The pattern obtained from the analysis is oriented in a northwest-southeast direction across the island, similar to the orientation of the rock formations on Weh Island. Dirasutisna and Hasan (2005) describe Weh Island's lithology: Tertiary and Quaternary rocks, including Tertiary Sedimentary Rock (Miocene), Old Volcanic Rock (Quaternary-Tertiary) with lava and pyroclastic flows, Young Volcanic Rock (Quaternary) from recent cones aligned NW-SE and N-S, and Coral Reef Limestone Group. The direction of these rock formations is shown in Figure 4. This direction is indicated by three distinct patterns: east, central, and west of the island. In the southwest part of the island, circular deposits spread out to form an area where rocks with significantly different densities from their surroundings are present. On the other hand, in the northeast direction of the island, there are circular accumulations arranged in an elongated pattern, and the orientation of their distribution is parallel to the Sumatra fault line, which runs northwest-southeast. The patterns suggest that the data in this area indicates the presence of a fault or fracture.

On Weh Island, rock formations generally trend northwest-southeast, as shown in Figure 4. In the east, coral limestone (Qgt) covers the coast, forming low hills extending north. North of this, tuff sandstone (Tms) lies beside the Pulau Weh lava flow unit (QTvw). To the west are the Pulau Weh pyroclastic flow (QTapw). The western area features Iboih volcanic rocks (Qvi), surrounded east by alluvial rocks (Qa) and south by Pawang volcanic rocks (Qvp). The central region contains volcanic and pyroclastic rocks from north to south: the Weh Island lava flow (QTvw), Labu Ba'u volcanic (Qvlb), Weh Island pyroclastic flow (QTapw), Old Kulam volcanic (Qvk1), Young Kulam volcanic (Qvk2), Kulam pyroclastic flow (Qapk), Leumo Matee volcanic (Qvlm), Leumo Matee pyroclastic flow (Qaplm), Semeureuguh volcanic (Qvs), and Semeureuguh pyroclastic flow (Qaps) (Dirasutisna and Hasan, 2005).

The horizontal gradient dot pattern in Figure 4 is compared with the geological structure. In that case, it can be assumed that the circle located in the northeast direction of the island is the boundary between the reef limestone (QgT) and the Weh Island pyroclastic flow unit (QTapw). The circular pattern to the south of the coral reef limestone indicates the boundary between the tuff sandstone area and the surrounding rocks. Meanwhile, to the southwest of the island, this circular pattern indicates an area. The area indicated by this pattern is composed of volcanic kulam units and volcanic pawang rocks. The pattern in this area can be considered the boundary of the volcanic rock area, as these rocks exhibit contrasting density differences.

Additionally, the area may have formed due to the island's topography. In the rocks in the northwest direction of the island, no differences are observed because only one type of rock is present. However, when viewed to the south, this rock has a boundary that serves as a separator between the rock itself and the rocks below it. Meanwhile, in the central area of the island, there are no clear rock boundaries. The lack of contrast in these boundaries is due to the area having rocks with slight variations in density. As a result, the boundaries between rocks in this area are not visible. Some errors resulting from calculations, such as overly large circular patterns, may occur due to the presence of points without data, which can cause significant contrast in their values. This calculation process may also lead to interpretation errors, as the data processed for Pulau Weh is digitized from contour results. The digitized data obtained is interpolated data from each measurement point. When compared with topography and faults, the match obtained is the direction of the faults and topography. The pattern indicating the position of the faults is not visible because the density differences caused by the faults are minimal compared to the density differences caused by the rocks.

Conclusion

This study concludes that horizontal gradients can delineate subsurface layer structures by showing boundaries in rocks beneath the surface. In the case of Weh Island, the maximum pattern was only observed in certain areas due to the island's predominantly volcanic rock composition. Therefore, the differences in gravity anomaly values are not contrasting. In the southwest part of the island, beneath the surface, there is a rock with a high-density difference from its surroundings. The area contains the oldest volcanic rock on the island. Furthermore, in the northeast part of the island, the pattern shows maximum values. The pattern appears elongated, suggesting that a fault may be present in that area. To improve the accuracy of horizontal gradient analysis, data collection with a more precise grid is required. The results obtained from a more accurate grid will be more contrasting than those from digitization. For comparison with this horizontal gradient analysis, it would be better to perform another analysis.

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