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Identification of Mud Volcano's Structure using Gravity Satellite and Fault Fracture Density Analysis: Case Study Ciuyah Mud Volcano, Kuningan, West Java

(Pengenalpastian Struktur Gunung Berapi Lumpur menggunakan Satelit Graviti dan Analisis Ketumpatan Fraktur Sesar Kajian Kes: Gunung Berapi Lumpur Ciuyah, Kuningan, Jawa Barat)

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ABSTRACT

Mud volcanoes, known as mud extrusion phenomenon, is a geological feature that expels suspended fine-grained sedimentary materials and fluids to the surface due to buoyancy and pressure difference. This geological feature is found almost all over the world and formed in compressional tectonic environments, one of which is the Ciuyah Mud Volcano, Kuningan, Indonesia. Previous studies have shown that the appearance of the mud volcano was influenced by tectonic activity that formed a 'hypothetical' fault structure as a pathway for mud migration and extrusion to the surface. Integration of geophysical studies using satellite gravity and geology using fault fracture density analysis was conducted to prove the existence of the 'hypothetical' fault structure. The results show that the mud volcano site is located in a low to high gravity anomaly pattern associated with significant density contrast differentiation followed by the maximum value of FHD and low-high SVD pattern oriented west southwest - east northeast (WSW - ENE). The gravity anomaly pattern can be associated with the presence of faults. This is reinforced by the fault fracture density map which shows that the mud volcano site is located in a medium to high fracture density zone (weak zone) associated with good permeability conditions below the surface. Thus, the research results have proven the existence of a 'hypothetical' fault as the migration and extrusion pathway of Ciuyah Mud Volcano mud that has been studied previously.

Keywords: Ciuyah Mud Volcano; fault fracture density; GGMPlus; gravity methods

ABSTRAK

Gunung berapi lumpur yang dikenali sebagai fenomena penyemperitan lumpur adalah ciri geologi yang mengeluarkan bahan sedimen halus yang digantung dan cecair ke permukaan kerana perbezaan keapungan dan tekanan. Ciri geologi ini terdapat hampir di seluruh dunia dan terbentuk dalam persekitaran tektonik mampatan, salah satunya ialah Gunung Lumpur Ciuyah, Kuningan, Indonesia. Hasil penyelidikan terdahulu menunjukkan bahawa kemunculan gunung berapi lumpur dipengaruhi oleh aktiviti tektonik yang membentuk struktur kesalahan 'hipotetikal' sebagai laluan penghijrahan dan penyemperitan lumpur ke permukaan. Integrasi kajian geofizik menggunakan graviti dan daya geologi menggunakan analisis ketumpatan patah kerosakan telah dijalankan untuk membuktikan kewujudan struktur kesalahan 'hipotetikal'. Keputusan menunjukkan bahawa tapak gunung berapi lumpur berada dalam corak anomali graviti rendah hingga tinggi yang berkaitan dengan pembezaan kontras ketumpatan yang ketara diikuti oleh nilai FHD maksimum dan corak SVD tinggi rendah berorientasikan barat daya - timur laut (WSW - ENE). Corak graviti anomali sedemikian boleh dikaitkan dengan kehadiran kesalahan. Ini diperkukuhkan oleh peta ketumpatan patah kerosakan yang menunjukkan tapak gunung berapi lumpur yang terletak di zon ketumpatan patah sederhana hingga tinggi yang berkaitan dengan keadaan kebolehtelapan yang baik di bawah permukaan. Oleh itu, hasil kajian telah membuktikan kewujudan kesalahan 'hipotetikal' sebagai laluan penghijrahan dan penyemperitan untuk lumpur Lumpur Gunung Berapi Ciuyah yang telah dikaji sebelum ini.

Kata kunci: GGMPlus; Gunung Lumpur Ciuyah; kaedah graviti; ketumpatan fraktur sesar

Introduction

Mud volcanoes, known as mud extrusion phenomenon, are a geological feature that expels suspended fine-grained sedimentary materials and fluids to the surface due to buoyancy and pressure difference. These geological features are found almost worldwide and formed in compressional tectonic environments and are characterized by rapidly sedimented and overpressured clay material sequences, the presence of gas content, especially methane gas and saline fluid solutions, and associated with regional seismotectonic activity (Isnaniawardhani, Faisal & Faizal 2013; Isnaniawardhani et al. 2020; Muhamadsyah, Sunardi & Isnaniawardhani 2012). In Indonesia, mud volcanoes are found and scattered in 'ellisional' basins along the Java - Madura depression in the Bogor - North Serayu - Kendeng - Madura Strait Zone, one of which is the Ciuyah Mud Volcano, West Java (Isnaniawardhani et al. 2020).

The Ciuyah Mud Volcano is found in Ciniru Subdistrict, Kuningan Regency, and continues to emit mud insignificantly and extends to 22.5 hectares. Tectonically, this site was formed in the axial depression zone of Java - Madura due to the influence of the Indian Ocean plate subduction towards the south of Java Island. As a result of active tectonic conditions, the site was affected by two tectonic phases, namely uplift of the Pemali Formation mudstone facies and Halang Formation sandstone facies followed by igneous intrusion (Middle Miocene) and formation of NW-SE to NE-SW trending strike-slip faults (Plio Pleistocene) (Muhamadsyah, Sunardi & Isnaniawardhani 2012) (Figure 2).

Observations showed that the surface morphological characteristics of the Ciuyah Mud Volcano were found to be a combination of swamp and crater muddy lake that continues to release mud and water followed by gas (in the form of bubbles). Deposits of salt crystals were found in several places as a result of evaporation from the mud extrusion process that occurred (Isnaniawardhani et al. 2020). The mud eruption stages classified by Waluyo (2007) are divided into embryonic, diapirism, mud eruption/syn-eruption, and post-eruption stages, where the observed surface morphological conditions show that this geological site is in the transitional stage from the late syn-eruption phase to post-eruption (dormant phase). Observations show the appearance of bubbling mud phenomenon as a sign of syn-eruption phase and fresh material without bubbles or mud flow indicating dormant phase (Isnaniawardhani et al. 2020). The muddy lake crater site is interpreted to occur as a result of reduced subsurface pressure followed by a partial topographic decrease and indicates the mud volcano site is in the dormant phase (Muhamadsyah, Sunardi & Isnaniawardhani 2012).

Previous studies have shown that the Ciuyah Mud Volcano is affected by active tectonism (Isnaniawardhani, Faisal & Faizal 2013; Isnaniawardhani et al. 2020; Muhamadsyah, Sunardi & Isnaniawardhani 2012). Muhamadsyah, Sunardi and Isnaniawardhani (2012) proposed that the appearance of the Ciuyah Mud Volcano was influenced and controlled by a hypothetical fault as a pathway for groundwater migration and circulation as well as the opening of a regional blocking structure formed by the mudstone facies of the Halang Formation and Pemali Formation. The 'hypothetical' status associated with the fault as the control and migration path of the mud extrusions of the Ciuyah Mud Volcano is an interesting study to be studied further. In the current study, the research focuses on the utilization of geophysical methods to prove and provide further understanding related to the alleged existence of hypothetical faults based on previous research. The research was conducted using geophysical methods that utilize the physical parameter of density, where the presence of structures gives a distinctive heavy force anomaly response and is supported by geological studies using alignment analysis associated with the influence of structures in the study area.

Materials dan Methods

Measurements of gravity methods are carried out by utilizing GGMplus (Global Gravity Model plus) gravity data. GGMplus is a model of gravity data formed based on the results of combining GRACE - GOCE gravity satellite data, EGM 2008, and topographic gravity effects on a short wavelength scale (Hirt et al. 2013). The data are combined and processed through a series of stages, namely the creation of spherical harmonic synthesis of the gravitational field, forward modeling, and calculation of normal gravity at the surface, which results in a high-resolution gravity model (Hirt et al. 2013). In contrast to Topex and BGI data, GGMplus is a gravity satellite that produces data with a resolution of about 200 meters (Hirt et al. 2013; Suprianto et al. 2021). Previous research utilized satellite gravity data to delineate the presence of subsurface structures and provided good results (Indriana et al. 2022; Maghfira & Niasari 2019; Natul & Heliani 2022; Putri et al. 2019; Siombone, Susilo & Maryanto 2022). This makes GGMplus gravity data reliable to use as the main data in this study.

In the research conducted, GGMplus gravity data was collected with coordinate specifications in the UTM Zone 49 S projection, namely Easting: 222982 - 224982 (E) and Northing: 9220084 - 9222084 (S), which covers a research area of 4 km^2 (Figure 1). The GGMplus gravity data, in the form of Free-Air Anomaly (FAA), was further corrected to obtain the Complete Bouguer Anomaly (CBA). The CBA values were separated and analyzed derivatively to get a clearer picture of the presence of structures in the study area. In addition, a geological study was conducted by drawing the alignment of the structure and creating a Fault Fracture Density (FFD) map based on Digital Elevation Model (DEM) data. The application of alignment drawing and FFD analysis has been proven and can be used to show the presence of structures (Darmawan, Daud & Iskandar 2021; Nayoan et al. 2023; Saputra & Novrinda 2016; Siombone, Susilo & Maryanto 2022; Sunan et al. 2021; Widiatmoko, Putri & Sunan 2021).

Fault Fracture Density (FFD) Map

The Fault Fracture Density method is a geospatial analysis approach used to study macro-structure conditions in an area (Saputra & Novrinda 2016; Sunan et al. 2021; Widiatmoko, Putri & Sunan 2021). This method calculates the density pattern of interconnected structural lineations so that weak zones can be identified (Saputra & Novrinda 2016; Sunan et al. 2021). The occurrence of high FFD values may be associated with the presence of fault zones (active tectonic activity), the contrast of hard and soft rock materials, or sedimentary rocks whose layers sink towards the lowlands (Widiatmoko, Putri & Sunan 2021).

The application of this method begins with a straightness inference analysis based on DEMNAS image data at azimuthal illumination angles of 0^o, 45^o, 90^o, amd 135^o with a sunlight height of 50^o. In conducting alignment retraction, the assumption is used that each alignment retraction is related to fractures and faults on the surface (Nayoan et al. 2023). The results of the FFD map in Figure 3 show that the structure in the study area has a dominant direction of west southwest - east

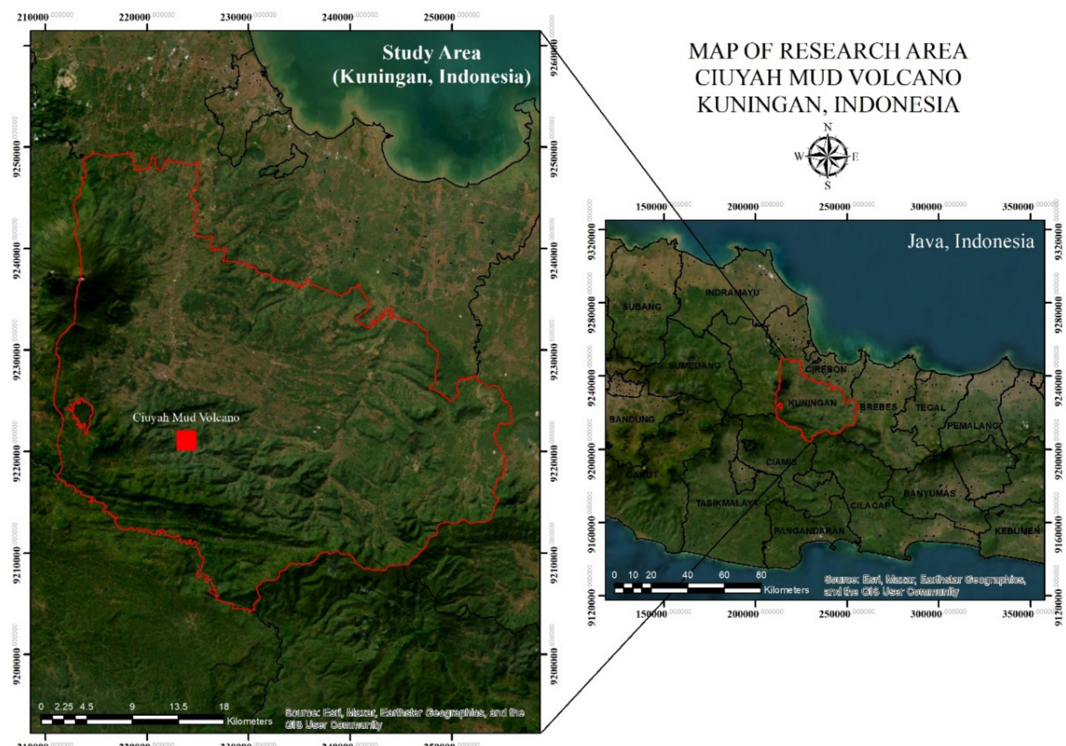


FIGURE 1. Ciuyah Mud Volcano (shown by red box) is located in Kuningan, West Java

northeast (WSW - ESE). The mud volcano site (marked red box) is shown to be in the medium to high fracture density zone. The medium to high fracture density zone can be associated with a weak zone that has good permeability (Nayoan et al. 2023; Polanunu, Sukiyah & Haryanto 2020). This shows that the fault structure becomes the migration path of mud extrusion that occurs in Ciuyah Mud Volcano, Kuningan.

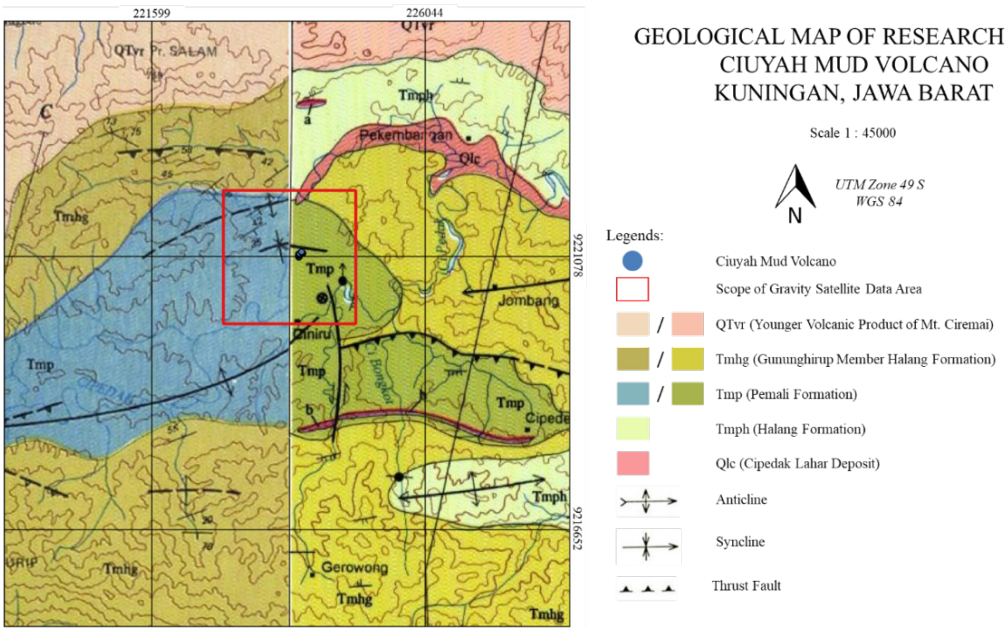


FIGURE 2. Mud Volcano Ciuyah is located in Halang Formation and Pemali Formation. The results of regional geological observations show that the research area is influenced by structures

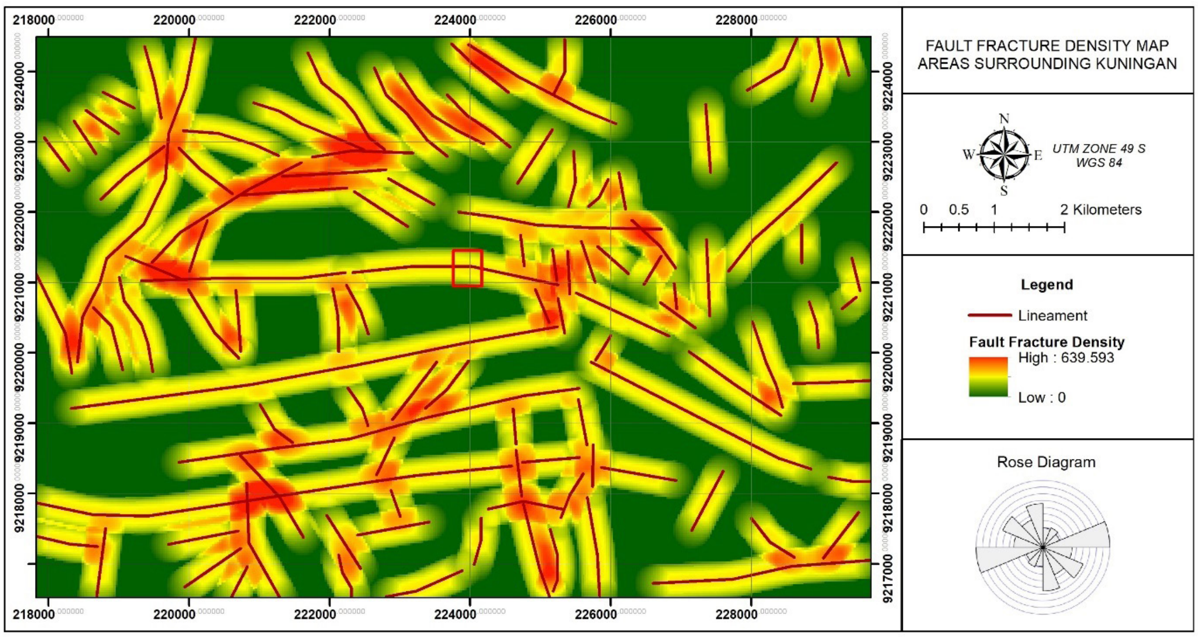
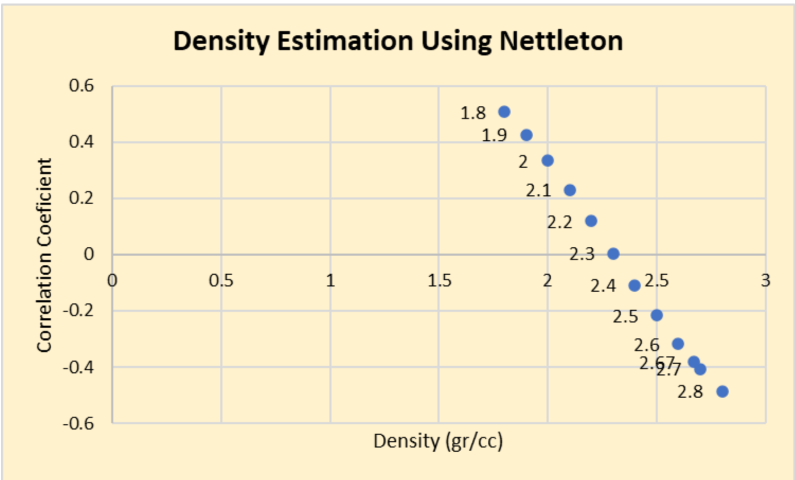


FIGURE 3. Fault Fracture Density Map; the mud volcano site (shown by red box) is shown to be in the medium to high fracture density zone

Estimation of Density

The application of Bouguer's density assumption of 2.67 gr/cc (uniform rock) used in the correction stage needs to be calibrated by estimating the density value that represents the study area. Density estimation is carried out using the Nettleton and Parasnis approaches, where the two values are compared to obtain validation of the best density value that represents the study area.

The uniform rock assumption cannot be used in all conditions because the varying conditions of the earth, both topography and composition, give a gravity anomaly response with a residual value of the gravity anomaly (a constant density value should not give a residual value after correction) (Yuliastuti, Santoko & Yarianto 2016). The Nettleton approach aims to minimize the correlation between topography and the density variation model used. This approach provides isostacy conditions so that the response of a given gravity anomaly is fully influenced by subsurface conditions (Yuliastuti, Santoko & Yarianto 2016). The density variation model that provides the smallest correlation value provides the gravity anomaly response that best represents the geological conditions of the subsurface structure (Rizqia 2022; Yuliastuti, Santoko & Yarianto 2016). As shown in Figure 4, the minimum correlation value between density and topography is obtained, which is associated with a density of 2.3 gr/cc as the density in the study area.



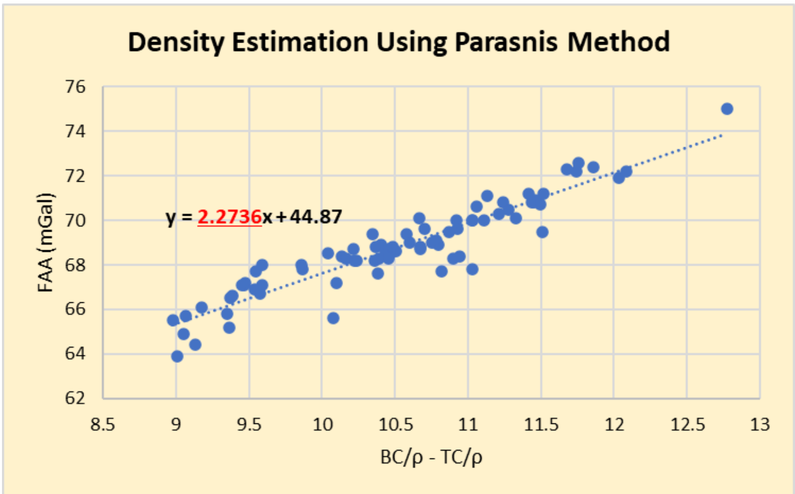


FIGURE 4. Estimated density values representing the study area using the Nettelton (top) and Parasnis (bottom) approaches. Both approaches show a density value of 2.3 gr/cc

The Parasnis approach measures the correlation between free-air gravity (without Bouguer correction) and topography. This approach assumes that the topographic relief and density are homogeneous so that the free-air anomaly can be expressed as a straight-line equation "y = mx + c" and the density value is expressed by the slope component of the line (gradient) (Toushmalani & Rahmati 2014). The application of the Parasnis method is shown by the graph of $\Delta gobs + 3.080h$ against $(-0.0004191h + T)$ and and a density value of 2.27 gr/cc is given. The R^2 value of 0.8729 means that the value obtained for the linear function is consistent with the actual data (Figure 4). Both Nettleton and Parasnis methods show that the study area has a density value of 2.3 gr/cc. This value is thought to be influenced by lithologic conditions dominated by sediments and igneous rock fragments accompanied by developed structures.

Complete Bouguer Anomaly

The Complete Bouguer Anomaly map was formed using the best predetermined density value of 2.3 gr/cc. This map can show the variation of subsurface density based on the variation of the gravity field (Figure 5). The CBA values obtained have a varied value range of 45 - 49 mGal. The high anomaly pattern, which is 48 - 49 mGal, is shown to have a distribution pattern in the western and southern parts of the study area. The high anomaly pattern is thought to be influenced by the mountainous area in the study area. The mud volcano site area is shown to have an adjacent low (45 mGal) to high (48 mGal) anomaly pattern. The presence of structures that cause density contrast is thought to give the anomaly pattern (Abdurrahman et al. 2018).

Separation of Gravity Anomaly

Complete Bouguer Anomaly is a superposition of regional anomalies, residuals, and noise. Anomaly separation needs to be carried out to obtain anomaly patterns that represent regional and local influences related to subsurface conditions in the study area. In the research conducted, anomaly separation was carried out using spectrum analysis techniques.

Spectrum analysis technique is an anomaly separation technique that transforms the data domain in spatial functions into the data domain of complex frequency functions (frequency spectrum) consisting

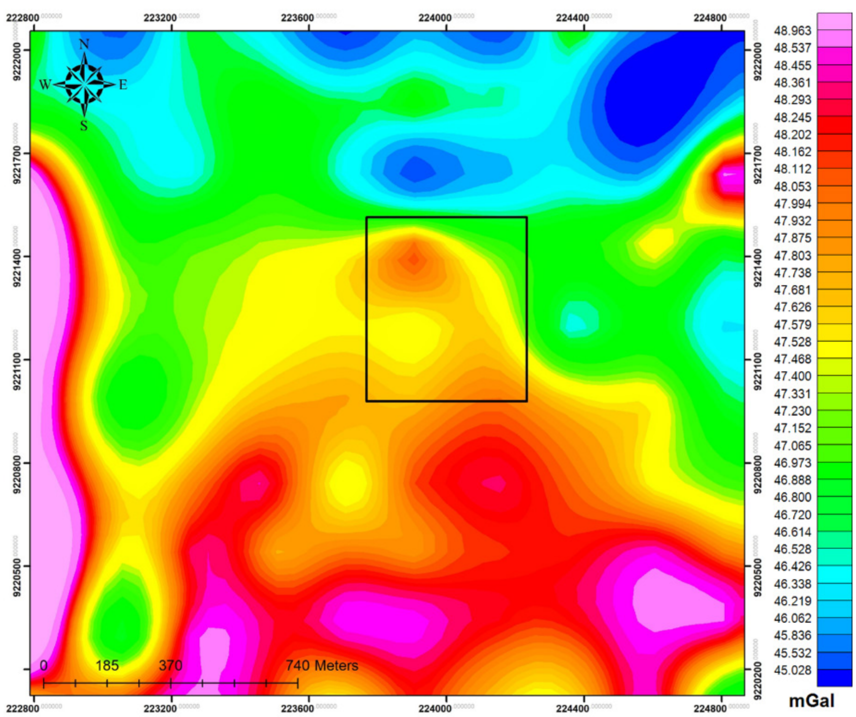


FIGURE 5. CBA map shows mud volcano sites associated with adjacent low - high anomaly patterns

of equivalent amplitude (A) and phase spectra (ϕ). This transformation technique is performed using the Fourier transform or Fast Fourier Transform (FFT). This transformation technique is used to obtain anomaly depth values based on wave number (k) and amplitude (A) variables and is the basis for determining the window width of each anomaly (Gumelar 2022; Rizqia 2022).

In this study, Radially Averaged Power Spectrum (RAPS) is used as a spectral analysis approach that uses the average energy values for all directions in the same wave number in the data (Gumelar 2022). The resulting values in RAPS form the basis for anomaly separation based on the gradient trend of the data. The coefficient of determination is considered as a determinant of the quality of anomaly separation performed, where the coefficient of determination value that is closer to one (1) characterizes the good quality of anomaly separation (Gumelar 2022; Rizqia 2022). The anomaly separation results and cut-off wavelength values as well as depth estimates shown in Figure 6 and Table 1 provide an indication that the anomaly separation is done well. The cut-off wavelength value is used as a parameter to separate the anomalies using a butterworth filter for regional anomalies and a band-pass filter for residual anomalies.

The regional anomaly map shown in Figure 7 has a value distribution of 45.319 - 48.842 mGal. The regional anomaly distribution pattern has a uniform pattern with the CBA map results, where the northern part of the study area has a low gravity anomaly pattern associated with lower mass density values, while the western and southern parts of the study area have a gravity anomaly pattern associated with higher mass density values. As shown in the CBA, the regional high values are thought to be influenced by the mountainous areas in the study area. The mud volcano site area is shown to have a similar anomaly pattern to the CBA pattern. This is thought to be influenced by the presence of structures that cause a high-density contrast compared to the surrounding study area.

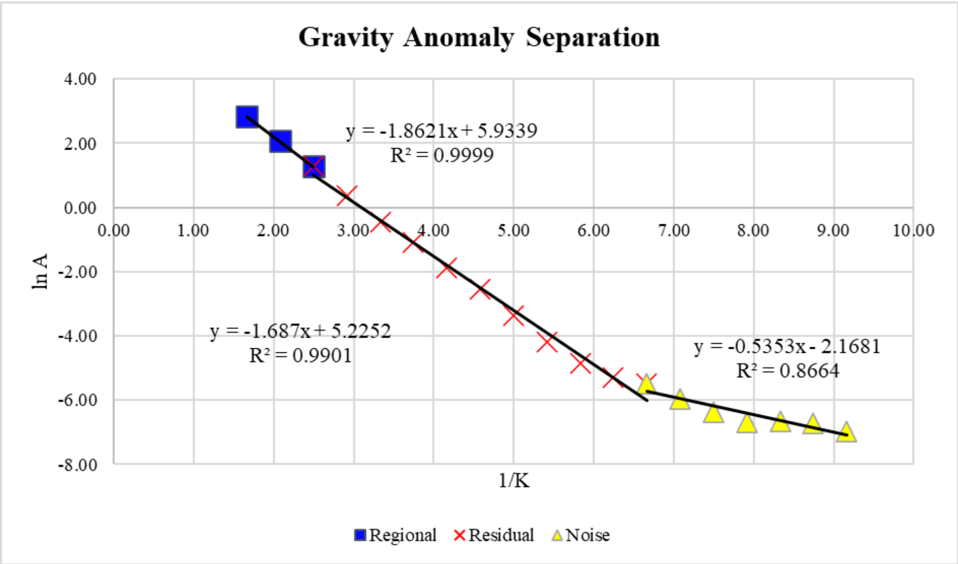


FIGURE 6. A straight-line equation graph of the separation of regional anomalies, residuals, and noise in a Radially Averaged Power Spectrum (RAPS) curve

TABLE 1. Cut-off wavelength value for each anomaly based on spectrum analysis

No	Anomaly	R^2	Cut-off wavelength (rad/m)
1	Regional	0.9999	400.28
2	Residual	0.9901	400.28 - 150.10
3	*Noise*	0.8664	150.10

The residual anomaly map shown in Figure 8 has a distribution of values ranging from -0.612 - 0.484 mGal. The mud volcano site is shown to be in the low to high residual anomaly zone. Abdurrahman et al. (2018) showed that the low to high residual gravity anomaly pattern is associated with the presence of fault structures due to the density contrast caused by the activity of these structures. The low to high residual anomaly pattern at the mud volcano site is thought to be influenced by active tectonic activity between the Indian Ocean and South Java Island plates. Two tectonic phases involving uplift of the Pemali Formation and Halang Formation followed by igneous intrusion and fault formation are thought to give the low to high residual anomaly response. This pattern is found to be similar to the regional anomaly pattern indicating the influence of structures that cause high density contrast values.

The existence of the structure is further analyzed using derivative analysis. Derivative analysis can show the edge of a discontinuity plane that correlates with the contact boundary of mass density contrast to characterize the presence of subsurface structures in the form of fault structures (Zaenudin et al. 2021). In the study conducted, First Horizontal Derivative (FHD) and Second Vertical Derivative (SVD) approaches were applied.

First Horizontal Derivative (FHD)

The First Horizontal Derivative is a method used to determine the presence of a density contrast boundary by detecting edge effects due to fault structures or other geological boundary features (Daud et al. 2018; Gumelar 2022; Rizqia 2022). This method is applied based on the understanding that the horizontal gradient of the gravity anomaly is caused by tabular bodies impinging on the edges of vertical bodies and is well separated from each other (Daud et al. 2018). This method can be regarded as a high-pass filter based on the horizontal and vertical derivatives of the gravity anomaly (Daud et al. 2018). The FHD component can be calculated based on the following equation.

$$FHD = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \tag{1}$$

where ($\partial g/\partial x$) and ($\partial g/\partial y$)is the horizontal derivative of the gravity anomaly in the x and y directions. This method is not susceptible to noise, where the maximum value of FHD can be used as an indicator of the position of the edge of the anomaly source. The presence of fault structures can be indicated by the maximum FHD value and provides a good match of the results to the actual data (Daud et al. 2018; Gumelar 2022; Rizqia 2022).

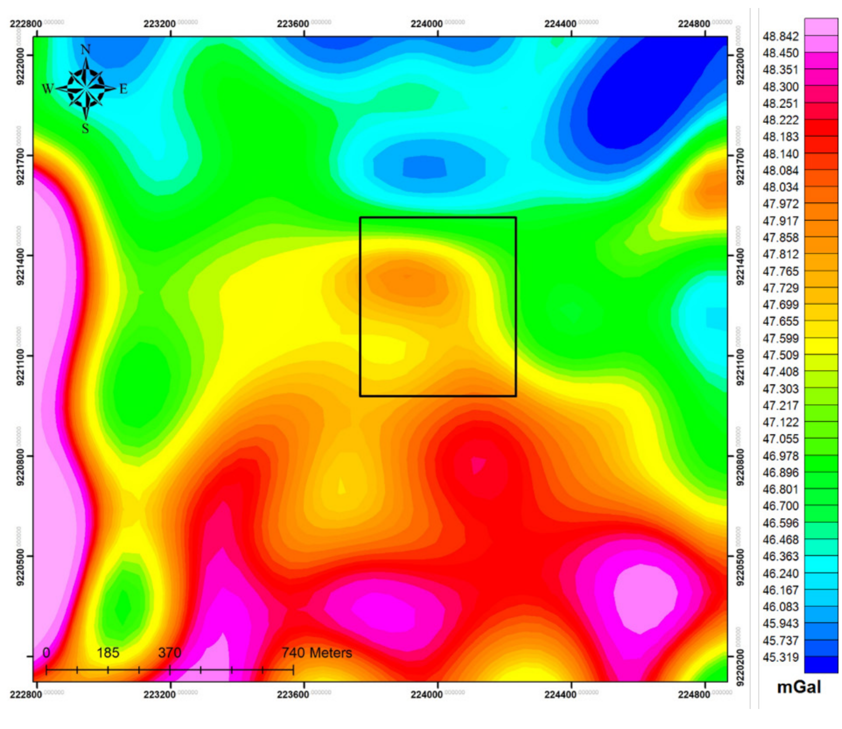


FIGURE 7. Regional gravity anomaly map generated using butterworh filter using cut-off wavelength according to Table 1

The FHD results shown in Figure 9 have values ranging from 58.557 - 1663.954 mGal/km. The rock density contrast is shown by the pattern of high anomalous values in the black dashed line zonation (Figure 9). High FHD values are found to have a southwest - northeast (WSW - ENE) orientation and are thought to be caused by structures formed in the study area.

Second Vertical Derivative

The SVD method is used to obtain the presence of local or shallow anomalies associated with subsurface fault structures (Gumelar 2022). Sumintadireja, Dahrin and Grandis (2018) showed that this method cannot be used to determine the type of fault because the gravity anomaly pattern tends to be asymmetrical and has an overlapping pattern that can provide interpretation errors. This method can only be used to determine the direction of the layer slope and density change of a fault plane. In the Fourier domain, the SVD components can be calculated based on the following equation.

$$\frac{\partial^2 g_z}{\partial z^2} = F^{-1}(|\boldsymbol{k}|^2 G_z);\ |k|^2 = k_x^2 + k_y^2 \qquad (2)$$

where G_z is the Fourier transform of g_z, k_x and k_y are the wave numbers in the x and y directions, while F^{-1} is the Fourier transform inverse operator. This equation shows that this method enhances the high-frequency components contained in the data so that the displayed results appear noisy compared to the actual data.

The SVD results shown in Figure 10 have values ranging from -0.7 - 0.4 mGal/km^2. The high and low anomaly patterns are associated with high-and-low-density values, respectively (Sumintadireja, Dahrin & Grandis 2018). However, SVD interpretation is not recommended to be done directly given that this method enhances high-frequency components, including noise, so caution is needed in doing so. FHD and SVD components can be integrated to overcome these problems and provide a better understanding of the presence of structures. In this case, an incision is made that intersects the high anomaly pattern shown by FHD and the low - high pattern shown by SVD. In recent studies, the presence of faults is indicated by adjacent low-high anomaly patterns, and this is the basis for choosing the incision pattern (Gumelar 2022; Rizqia 2022).

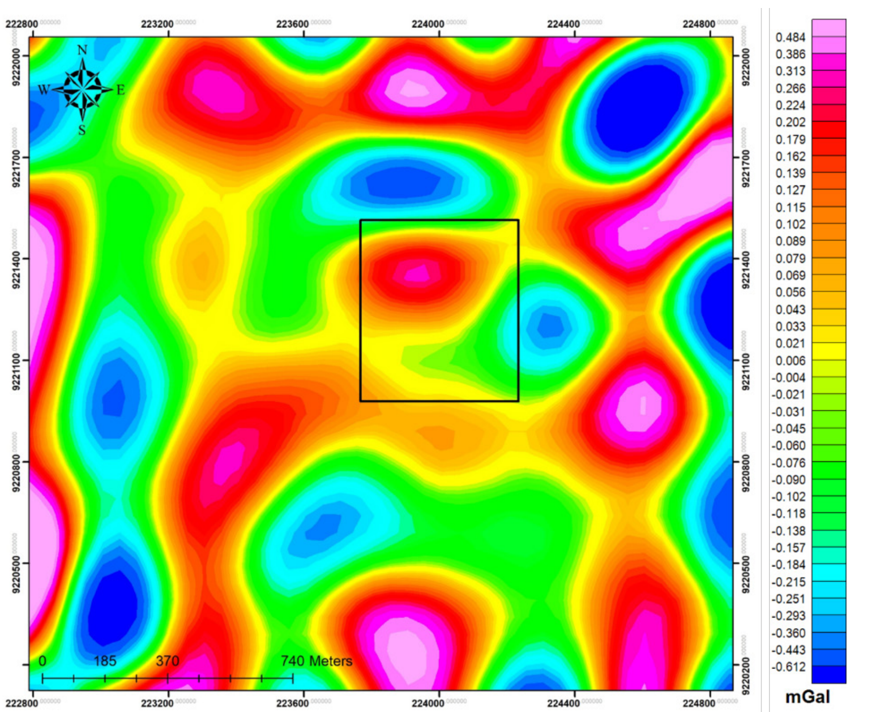


FIGURE 8. The residual gravity anomaly map generated using the band-pass filter using the cut-off wavelength is in accordance with Table 1

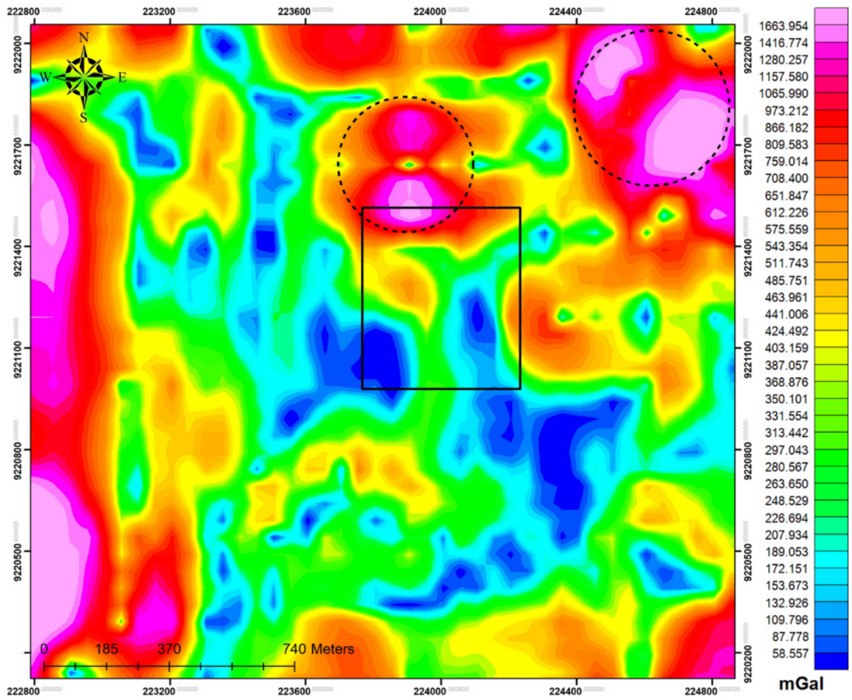


FIGURE 9. The resulting First Horizontal Derivative (FHD) map shows an indication of the presence of structures based on the maximum FHD value (shown by black circle)

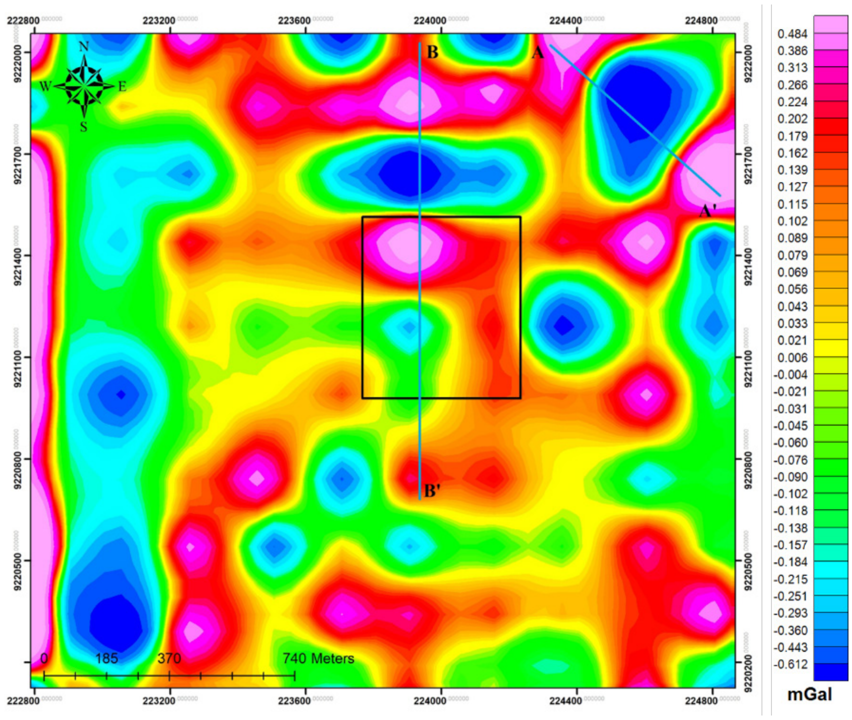


FIGURE 10. The resulting Second Vertical Derivative (SVD) map shows an indication of the presence of structures based on adjacent high - low anomaly patterns. Incision A - A' and B - B' to analyze the presence of 'hypothetical' structures at the mud volcano site

As shown in the Figure 10, the incision is divided into incision A - A' oriented northwest - southeast (NW - SE) and incision B - B' oriented north - south (N - S). The orientation of the incision was chosen to intersect with the direction of the hypothetical fault structure controlling mud extrusion (oriented southwest – northeast (SW - NE). Determination of the presence of fault structures is carried out at the zero value between the extreme values of the maximum and minimum amplitudes as a discontinuity boundary and an indication of the presence of fault structures (Gumelar 2022).

RESULTS AND DISCUSSION

The results of incision A-A' shown in the comparison graph of FHD and SVD values in Figure 11, indicate the presence of a fault structure with a southwest - northeast trend (WSW-ENE). This is indicated by the extreme values of FHD with maximum amplitude values of 809 - 1664 mGal/km and validated by zero values located at both extreme values of maximum and minimum amplitude in SVD. The incision results on the FHD and SVD maps are divided into two segments. The FHD graph shows the maximum amplitude values for each segment

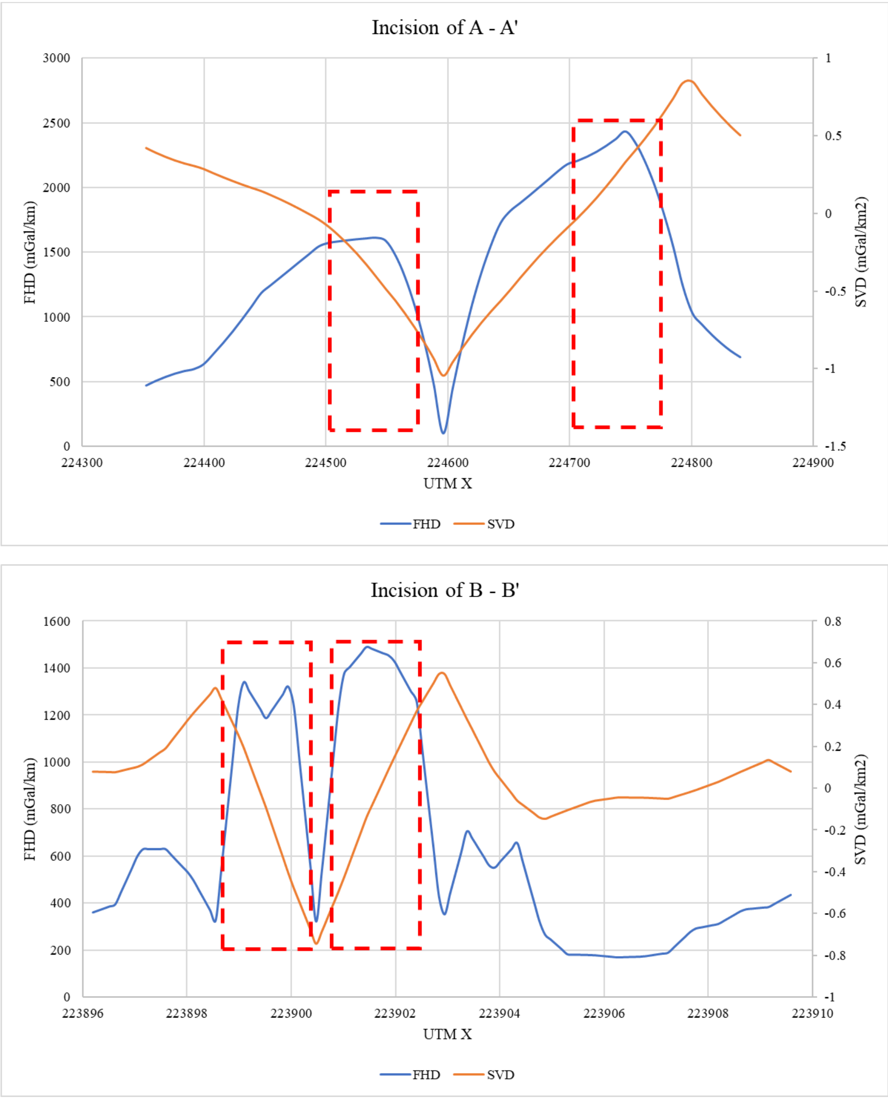


FIGURE 11. An indication of the presence of structure is indicated by the maximum FHD value and zero value between the maximum and minimum values in the SVD in Incision A - A' (top) and Incision B - B' (bottom)

of 1500 and 2500 mGal/km, respectively, as the fault structure boundary. The first segment shows a maximum SVD value or |+SVD| of 0.4 mGal/km^2 which is smaller than the minimum SVD value or |-SVD| of -1.0 mGal/km^2 indicating that the foot-wall is at |-SVD| and the hanging-wall is at |+SVD|. The second segment shows a maximum SVD or |+SVD| value of 0.8 mGal/km^2 which is smaller than the minimum SVD or |-SVD| value of -0.7 mGal/km^2 indicating that the foot-wall is |-SVD| and the hanging-wall is |+SVD|. In this case too, the density value of |+SVD| is greater than |-SVD|.

The results of incision B-B' shown in the comparison graph of FHD and SVD values in Figure 11, indicate the presence of a fault structure with a West-East trend. This is indicated by the extreme value of the first-order horizontal derivative with a maximum amplitude value of 809 - 1664 mGal/km and validated by the zero-value located at both extreme values of the maximum and minimum amplitude of the second-order vertical derivative. The incision results taken from the first-order horizontal derivative map and SVD are divided into two segments. The first-order horizontal derivative graph shows the maximum amplitude values for each segment of 1203.5 and 1469 mGal/km as the fault structure boundary, respectively. The first segment shows a maximum SVD value or |+SVD| of 0.4 mGal/km^2 which is smaller than the minimum SVD value or |-SVD| of -0.7 mGal/km2 indicating that the foot-wall is at |-SVD| and the hanging-wall is at |+SVD|. The second segment shows a maximum SVD or |+SVD| value of 0.5 mGal/km^2 which is smaller than the minimum SVD or |-SVD| value of -0.7 mGal/km^2 indicating that the foot-wall is |-SVD| and the hanging-wall is |+SVD|. In this case too, the density value of |+SVD| is greater than |-SVD|.

The CBA map and anomaly separation results show a low to high anomaly pattern at the mud volcano site. This pattern can be associated with density contrast occurring significantly in the study area and is thought to be caused by fault structures. The results of the FHD and SVD incisions show indications of the presence of a fault structure oriented west southwest - east northeast (WSW-ENE) characterized by the maximum value of FHD associated with the high - low pattern on the SVD (Figure 12). This structure is thought to have formed due to compressional forces between the Australian and Indo-Australian plates that intersected the main anticline structure. The FFD map also shows the influence of the fault structure on the mud volcano site, where the site is found to be in the medium to high fracture density zone, indicating a weak zone associated with good permeability conditions in the subsurface. This indicates the influence of the structure as a pathway for fluid

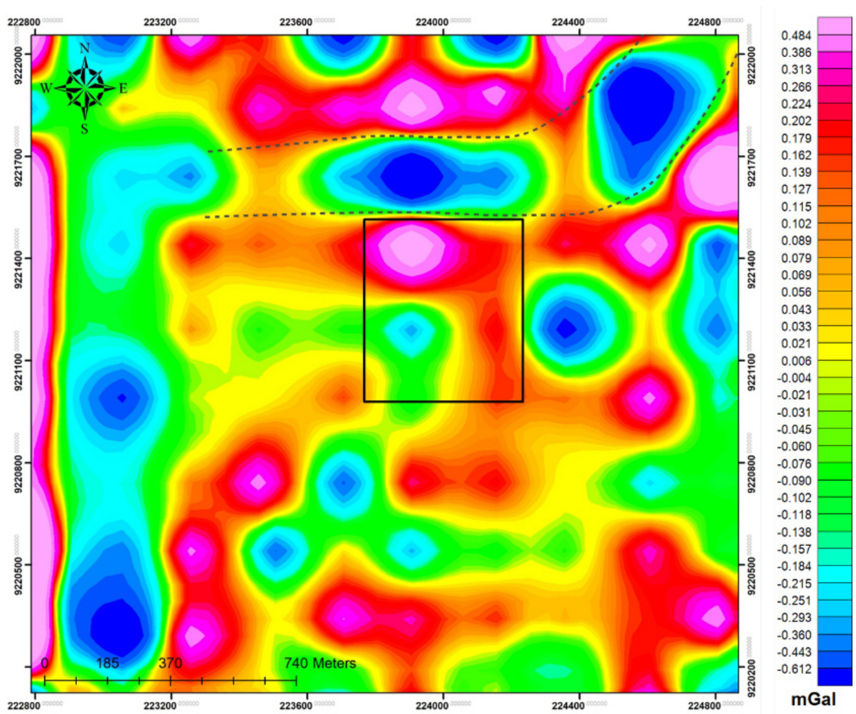


FIGURE 12. The results of FHD and SVD analysis show the presence of fault structures associated with the high - low anomaly pattern and are depicted using dashed black lines. The fault structure pattern is found to have an orientation of west southwest - east northeast (WSW - ESE) in accordance with previous research (Muhamadsyah, Sunardi & Isnaniawardhani 2012)

migration and extrusion of Ciuyah mud to the surface. These results also confirm the results of the geological study by Muhamadsyah, Sunardi and Isnaniawardhani (2012). The fault structure controls the migration path and subsurface fluid circulation. These migration paths provide an outlet for subsurface materials and fluids, especially clay materials to elute and form mud volcano intrusions at the surface (Isnaniawardhani et al. 2020; Muhamadsyah, Sunardi & Isnaniawardhani 2012). However, the geophysical and geological studies conducted have not been able to provide information related to the type of fault that affects the mud volcano site. Obviously, geological and geophysical approaches on a local scale are needed and is expected to provide information related to the type of fault that affects the mud volcano site in Ciuyah, Kuningan.

Conclusions

Geological and geophysical studies show that the appearance of Mud Volcano Ciuyah Kuningan site is influenced by fault structures. This fault structure is thought to be a pathway for groundwater migration and circulation as well as the opening of a regional blocking structure formed by the mudstone facies of the Halang Formation and Pemali Formation. Gravity anomaly values show that the mud volcano site is located in the high - low gravity anomaly zone associated with significant density contrast differentiation. This is also validated by the maximum FHD value associated with significant density changes and the SVD pattern and incision which shows a high - low gravity anomaly pattern with an orientation of west southwest - east northeast (WSW - ENE). This pattern can be associated with the presence of fault structures, where the presence of faults is characterized by significant density contrast due to tectonic activity. Geological studies also show indications of the presence of structures at the mud volcano site. Straightness and FFD analysis show that the mud volcano site is located in a medium to high fracture density zone or weak zone. This zone indicates that the mud volcano site is affected by high intensity fault structure activity. This makes the mud volcano site in a zone with good permeability so that mud extrusion can occur through the faults formed.

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References

Abdurrahman, D., Santoso, D., A. Kadir, W.G., Dahrin, D., Setianingsih & Alawiya, S. 2018. Using gravity fault identification data in Bandung Basin. *AIP Conference Proceedings* 1987(1): 020062.

Darmawan, D., Daud, Y. & Iskandar, C. 2021. Identification of geological structure based on gravity and remote sensing data in "X" geothermal field. *AIP Conference Proceedings*. 2320(1): 040004.

Daud, Y., Sulistyo, A., Fahmi, F., Nuqramadha, W.A., Fitrianita, Sesesega, R.S., Rosid, S., Pati, P.G., Maulana, M.R., Khoiroh, M., Rahman, K.R. & Subroto, W. 2018. First horizontal derivative and Euler Deconvolution in application for reconstructing structural signature over the Blawan – Ijen Geothermal Area. *IOP Conf. Ser.: Earth Environ. Sci*. 254: 012008.

Gumelar, F. 2022. *Skripsi*. Identifikasi Kondisi Struktur Geologi Bawah Permukaan di Kawasan Gunung Api Tangkuban Parahu Berdasarkan Data Geomagnetik. Bandung: Universitas Padjadjaran.

Hirt, C., Claessens, S., Fecher, T., Kuhn, M., Pail, R. & Rexer, M. 2013. New ultrahigh-resolution picture of Earth's gravity field. *Geophysical Research Letters* 40(16): 4279-4283.

Indriana et al. 2022. gravity interpretation of mud volcano based on satellite data (study case Kuwu and Cangkring Mud Volcano).

Isnaniawardhani, V., Faisal, H. & Faizal, M. 2013. Stratigraphy and structural geology of Ciuyah mud volcanoes in Ciniru Area, West Java. *International Journal of Science and Research* 4(4): 3223-3226.

Isnaniawardhani, V., Natasia, N., Effendi, T.K., Syah Alam, B.Y.C.S.S., Ismawan & Sulaksana, N. 2020. Mud eruption dynamic in Ciuyah, Java, Indonesia. *International Journal of GEOMATE* 19(75): 92-99.

Maghfira, P.D. & Niasari, S.W. 2019. Gravity satellite data analysis for subsurface modelling in Mount Merapi – Merbabu, Java, Indonesia. *E3S Web of Conferences* 76: 03003.

Muhamadsyah, F., Sunardi, E. & Isnaniawardhani, V. 2012. Karakteristik geologi daerah gunungan lumpur Ciuyah. *Bulletin of Scientific Contribution* 10(2): 59-76.

Natul, A.S. & Heliani, L.S. 2022. A comparison of geologic structure detection of Sumatera Island using goce satellite gravity data and Sgg- Ugm-2 data. *Journal of Geoscience, Engineering, Environment, and Techonology* 7(3): 95-101.

Nayoan, A.G.P., Pranatikta, K.A., Anil, Hendrasto, F. & Yuniasih, S. 2023. Upflow-outflow zone identification based on geochemistry indicator and fault fracture density correlation analysis in Mt. Gede geothermal case, West Java. *IOP Conf. Ser.: Earth Environ. Sci.* 1159: 012003.

Polanunu, T.T., Sukiyah, E. & Haryanto, A.D. 2020. Analisis kerapatan kelurusan (*lineament density*) untuk pendugaan zona permeabilitas di Daerah Gunung Patuhan. *Padjadjaran Geoscience Journal* 4(5): 393-400.

Putri, D.R., Nanda, M., Rizal, S., Idroes, R. & Ismail, N. 2019. Interpretation of gravity satellite data to delineate structural features connected to geothermal resources at Bur Ni Geureudong geothermal field. *IOP Conf. Ser.: Earth Environ. Sci.* 364: 012003.

Rizqia, M.N. 2022. *Skripsi*. Identifikasi Kondisi Geologi Bawah Permukaan Di Bagian Khuluk Gunung Tangkuban Parahu Menggunakan Metode Gravitasi. Bandung: Universitas Padjadjaran.

Saputra, I. & Novrinda, R. 2016. Metode fault fracture density untuk potensi gerakan tanah di Kota Kendari Provinsi Sulawesi Tenggara. *Prosiding Seminar Nasional XI. Rekayasa Teknologi Industri dan Informasi*. pp. 138-142.

Siombone, S.H., Susilo, A. & Maryanto, S. 2022. Integration of Topex Satellite Gravity and Digital Elevation Model Shuttle Radar Topography Mission (DEM SRTM) imagery for subsurface structure identification at Tiris Geothermal Area. *POSITRON* 12(2): 98-111.

Sumintadireja, P., Dahrin, D. & Grandis, H. 2018. A note on the use of the Second Vertical Derivative (SVD) of gravity data with reference to Indonesian cases. *Journal of Engineering and Technological Sciences* 50(1): 127-139.

Sunan, H.L., Khahlil Gibran, A., Rizki Aditama, M., Iswahyudi, S., Widiatmoko, F.R., Widagdo, A. & Anjar Tri Laksono, FX. 2021. Interpretasi struktur geologi berdasarkan *fault fracture density* (ffd) dan implikasinya terhadap potensi likuefaksi di Daerah Kalibening, Kabupaten Banjarnegara, Jawa Tengah. *Eksplorium* 42(1): 47-54.

Suprianto, A., Supriyadi, Priyantari, N. & Eko Cahyono, B. 2021. Correlation between GGMPlus, Topex, and BGI gravity data in volcanic areas of Java Island. *J. Phys.: Conf. Ser*. 1825: 012023.

Toushmalani, R. & Rahmati, A. 2014. A new inversion method of estimation simultaneous near surface bulk density variations and terrain correction across the Bandar Charak (Hormozgan – Iran). *SpringerPlus* 3: 135.

Waluyo. 2007. Pertamina. Personal Communication (Unpublished).

Widiatmoko, F.R., Putri, R.H.K. & Sunan, H.L. 2021. The relation of fault density with the residual gravity; case study in Muria. *Journal of Earth of Marine Technology* 1(2): 105-110.

Yuliastuti, Santoko, H. & Yarianto, S.B.S. 2016. Bouguer density analysis using Nettleton Method at Banten NPP Site. *Jurnal Pengembangan Energi Nuklir* 19(1): 43-49.

Zaenudin, A., Karyanto, Kurniasih, A. & Catur Wibowo, R. 2021. Analisis struktur patahan Daerah Suoh menggunakan metode gravitasi dan penentuan kerapatan patahan. *POSITRON* 11(2): 95-103.

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