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IDENTIFICATION SUB-SURFACE STRUCTURE AND SEDIMENT DEPTH ESTIMATION AT THE PROPOSED INDONESIAN NEW CAPITAL CITY

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ABSTRACT

In this study, we employ high-resolution GGMplus gravity satellite data and three-dimensional geological modeling to ascertain sediment thickness and subterranean structures in East Kalimantan, designated as Indonesia's prospective capital. The region's sedimentary basins, specifically the Kutai Basin with up to 14 kilometers of Tertiary sedimentary rocks, are pivotal in assessing seismic risk due to their potential to amplify seismic activity. Through Fourier transformation and power spectrum analysis, we discern the Simple Bouguer Anomaly (SBA) across the region, revealing an inverse relationship between SBA values ranging from -5 mGal to 145 mGal and topographical elevation. The Mangkalihat Peninsula showcases pronounced gravity anomalies corresponding to a complex geological matrix, including a carbonate platform and an extension of the Palukoro Fault system. The three-dimensional inversion modeling, across a 29,000 meters by 27,000 meters grid, identifies varying rock densities from 2.3 g/cm³ to 2.65 g/cm³, and delineates predominant rock types such as igneous granite, claystone, limestone, and sandstone. This is further validated by resistivity measurements, aligning with geological maps. The average regional depth estimates for sediment layers are -15274.93 meters for North-South transects and -13409.25 meters for West-East transects, with residual depth estimates suggesting sediment thickness up to -1988 meters. These granular insights enhance the geological model of East Kalimantan, providing a nuanced understanding of its geophysical framework and informing the developmental blueprint for Indonesia's future capital city.

Keywords: gravity anomaly; GGMplus; Depth of Sediment

INTRODUCTION

Kalimantan is one of the five biggest islands in Indonesia which is proposed as a new capital city. This place is deemed as a better place than Jakarta that faces with some problems such as natural disaster, pollutions, traffic congestion, and number of inhabitants. Following by Indonesian constitution about the nation's capital, the exact location will be located at East Kalimantan spanning in two regencies namely Penajam Paser Utara and Kutai Kartanegara. Total areas of the planned capital city are 252,660 hectares which consist of main area and development area.

Discussion about potential disasters that might be occurred in the new capital city is being widely discussed. Using qualitative studies, [1] found that Kalimantan is not free from natural disasters such as forest fire due to swamp, drought, rob flood, earthquake, and tsunami. Using the same method, [2] concluded that both Penajam Paser Utara and Kutai Kartanegara has a moderate potential disaster and adding landslide as a potential disaster. In addition, using rainfall data analysis, [3] and [4] justified if the capital city has a potential of flood disaster.

Lithologically, there are two main rock groups that make up The Island of Kalimantan, namely the Paleozoic-aged rock group and the Cenozoic-aged rock group [5]. The bedrock that makes up the borneo region is of continental, oceanic and transitional origin. On the territory of the Schwaner Mountains it consists of granite rocks and metamorphic rocks formed from the collision of the Schwaner Arc with the Eurasian Plate. In the northwestern area of Borneo Island, the area is dominated by sedimentary and volcanic rocks. Part of the East Kalimantan region is channeled by the Oceanic crust with the form of chunks ofiolite [6].

Tectonically, Kalimantan is influenced by the kinematics of three plates [7]. The three plates are Eurasian Plate, Pacific Plate and Philippine Plate. Kalimantan is an area in Indonesia that has a low level of seismicity because the location of Kalimantan is quite far from the boundary zone of the plates and is not passed by the Ring of Fire zone. However, it does not mean that Kalimantan is free from earthquake disaster risk. Some studies revealed that the thick sedimentary basin will amplify the ground shaking of earthquake and can make damage even the distance is far away from the source [8], [9], [10]. Because of that, the information about sediment thickness is essential to be considered in the determination of potential disaster.

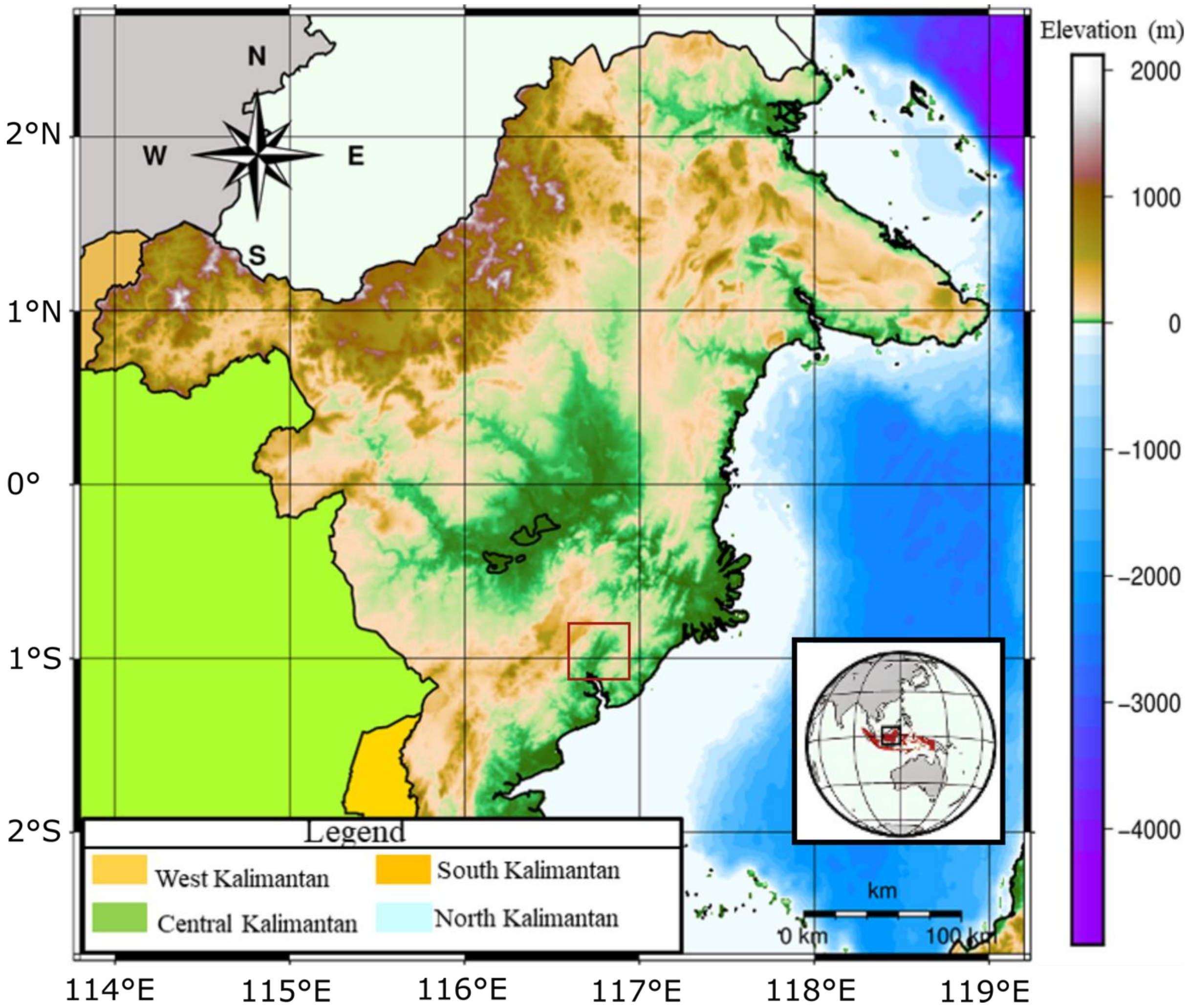

Figure 1. Research area in East Kalimantan with topography profile and surrounding region. The red triangle marks the Sepaku subdistrict location used for 3-D gravity modelling

There are some methods to identify the sediment thickness both using direct measurement (drilling) or using geophysical technique. For the low-cost purposes, geophysical technique for sediment thickness determination is preferable in conjunction with any availability of geophysical data such as seismic [11], [12], [13], [14] and gravity [15-20]. In this study, gravity satellite data from GGMplus [21], [22] will be used to determine the sediment thickness. In addition, 3D modelling based on gravity data is applied to depict subsurface structures in the small region (Sepaku District) as part of the new capital city's region.

METHOD

The research presented herein utilizes gravity disturbance data or Free Air Anomaly (FAA) derived from the GGMplus gravity model. GGMplus represents a high-resolution model for delineating Earth's gravitational field, which integrates a tripartite dataset comprising the GRACE/GOCE satellite, the EGM 2008 model, and topographic gravity data [21]. Then, the elevation data are derived from ERTM2160 model [22]. Both gravity disturbance and elevation date are downloaded with the same area of East Kalimantan with coordinate 115,6° E – 119° E and 1,1° S – 2,1° N. The map of the location can be seen in Figure 1.

The next step is to compute Simple Bouguer Anomaly (SBA) using Equation 1. To compute SBA, we need Bouguer Correction ($0.04193\rho h$) which need elevation (h) and Bulk Density (ρ). Bulk density is then calculated using Parasnis Method [23] by determined slope between ($0.04193h$) and the elevation. It is found that the bulk density is 2.5 gr/cm^3

$$SBA = FAA - 0.04193ph \tag{1}$$

After SBA determined, the values are then interpolated and mapped as can be seen in Figure 2 and 4. As note, the SBA values are interpolated using kriging method [24] in the surfer software package. Horizontal cross-section (East-West) and vertical cross-section (North-South) are then made as can be seen in Figure 2. There are nine cross-sections for North-South direction and twelve cross-sections for East-West direction. Gravity anomaly in cross-sections is in space domain and then they are converted to frequency domain in the similar way when converted time to frequency domain or wavenumber. Then Fourier's transformation forms to frequency domain are:

$$F(k) = \int_{-\infty}^{\infty} f(x)e^{-ilx}dx \tag{2}$$

which $f(x)$ is gravity anomaly in space domain, $F(k)$ is converted gravity anomaly in frequency domain and wave number is denoted by symbol k [25]. In this paper, the Fourier's transformation is applied using spread sheet package (Microsoft Excel) in the data analysis menu. The transformation only run for specific number of data, 2^n data, so for 1364 data in A4-A4' profile as example, we only compute 1024 data (2^{10}). It is should be noted that real and imaginary numbers are existing in the Fourier transformation (Equation 3) where A is the amplitude.

$$|F(k)| = F(k) + F(k)\,i = \sqrt{[\{F(k)\}^2 + \{F(k)\,i\}^2]} = A \tag{3}$$

Wave number can be accomplished by $k = \frac{2\pi}{\lambda} = 2\pi f$. Frequency is calculated by divided number of data by two times of total distance ($f = \frac{n}{2L}$). If the data about anomalies is random and lacks any specific pattern, then performing a Fourier transform yields:

$$A = Ce^{|k|(h_0 - h)} \tag{4}$$

where C is constant, h_0 is height of the point of gravity and h is depth anomaly. By applying the Equation 4, there will be a direct relationship between Amplitude, wave number, and depth $(h_0 - h)$. Thus, a straight line equation is found between the amplitude spectrum $(\ln \ln A)$ and the wave number (k) as indicated by the Equation 5.

$$\ln \ln A = |k|(h_0 - h) \quad (5)$$

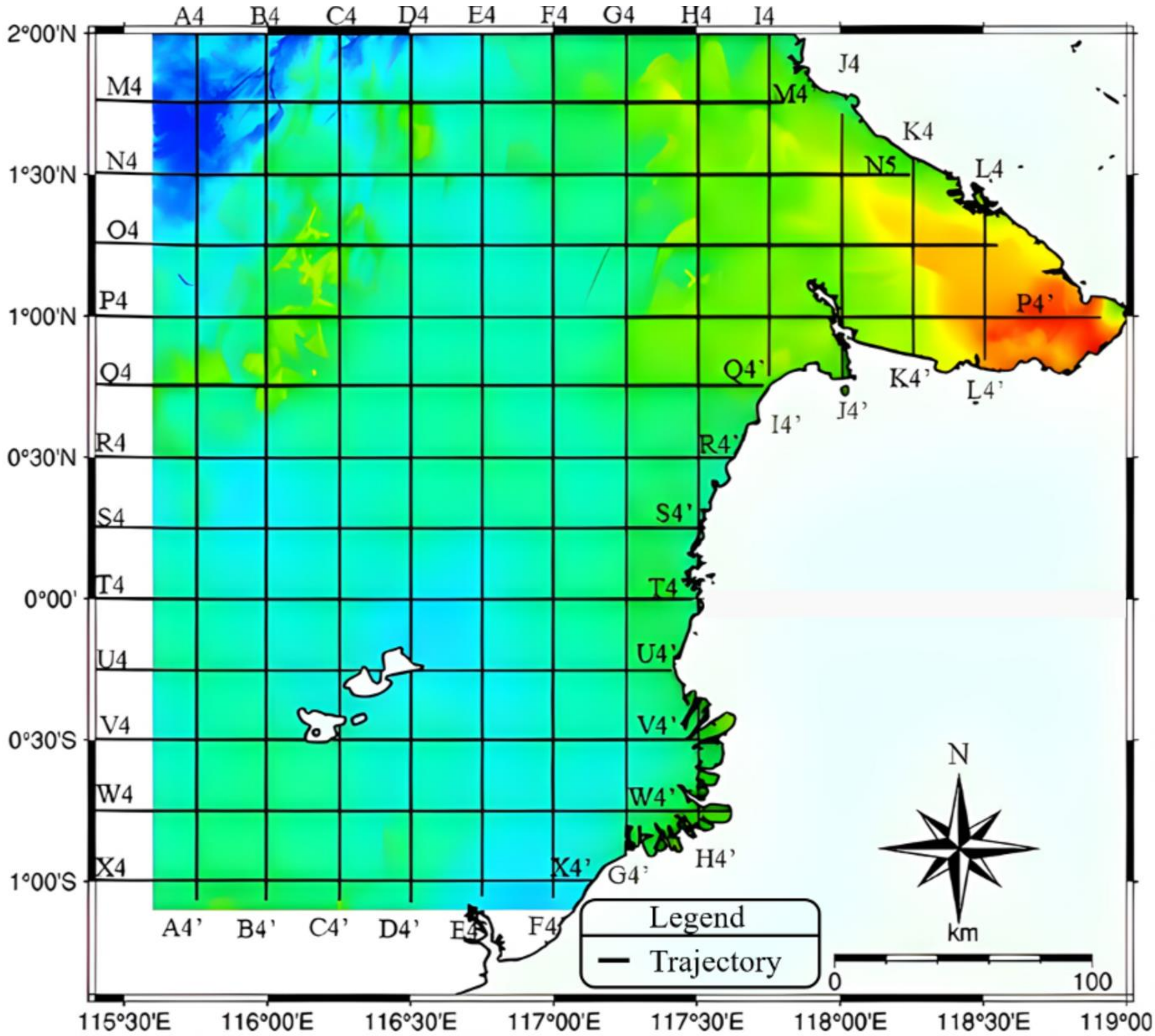

Figure 2. The Map of East Kalimantan Anomaly that has been sliced by nine lines for the East-West and twelve sliced for North-South direction to obtain the profile of anomalies. Slicing in the horizontal direction (East-West) will interpret the North-South depth profile, while Slicing in the vertical direction (North-South) will interpret the anomalous profile of the East-West depth.

The depth associated with different types of anomaly data can be determined by executing a linear regression analysis within each specified zone, as referenced in Equation 5 and illustrated in Figure 3. Utilizing Equation 5, one can compare the patterns that emerge from the Fourier transform results between $(\ln \ln A)$ and (k). This comparative analysis helps to categorize the depth demarcations distinguishing regional from residual anomalies. The transects were deliberately designed to be vertical (12 lines) and horizontal (13 lines) and further divided into six segments encompassing the Kalimantan region, with the aim of attaining more precise results. With the distance between transects set at 27.75 km, this spacing is deemed sufficient to represent the sediment depth values in Kalimantan on a regional scale. Additionally, this segmentation not only enhances the accuracy of the results but also simplifies the data processing for the author, allowing for a phased approach to the analysis. An example of Fourier's transformation for the A4-A4' profile can be found in the attachment of this paper.

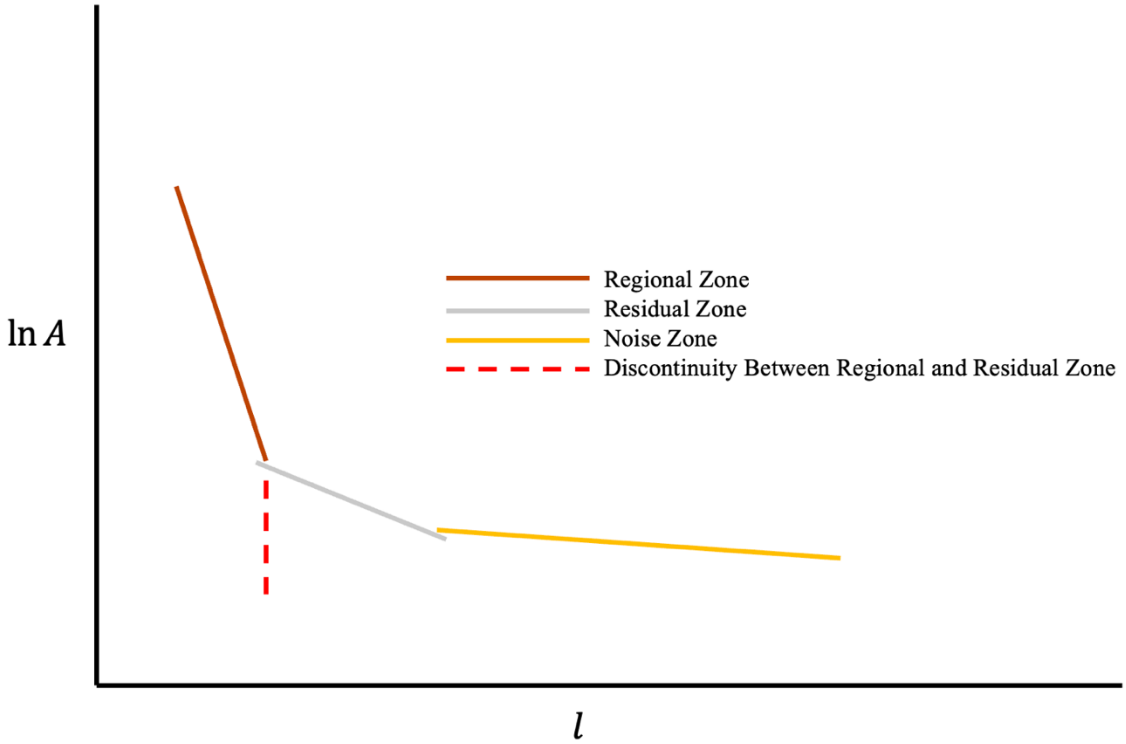

Figure 3. The transformation pattern in the spatial domain used to estimate depth. The pattern shows connection between wave number and amplitude of transformation in invers logarithmic function.

Grav3D is a software tool employed for three-dimensional geological modelling in this paper. In the three-dimensional modeling process, the utilized data consist of residual anomaly. These residual anomaly data are obtained through the application of a moving average filter to divide between regional and residual anomaly. The area selected for three-dimensional modeling spans 29,000 meters by 27,000 meters which is cover Sepaku District region. For the three-dimensional modeling to take place, a mesh composed of numerous cubic cells is required. This mesh is constructed with dimensions of 100 x 100 x 50, so that each cubic cell represents 290 meters in the X-direction and 270 meters in the Y-direction. In the Z-direction, each cell represents a vertical distance of 120 meters, which means the depth considered during the three-dimensional modeling extends down to 6 kilometers.

RESULTS AND DISCUSSION

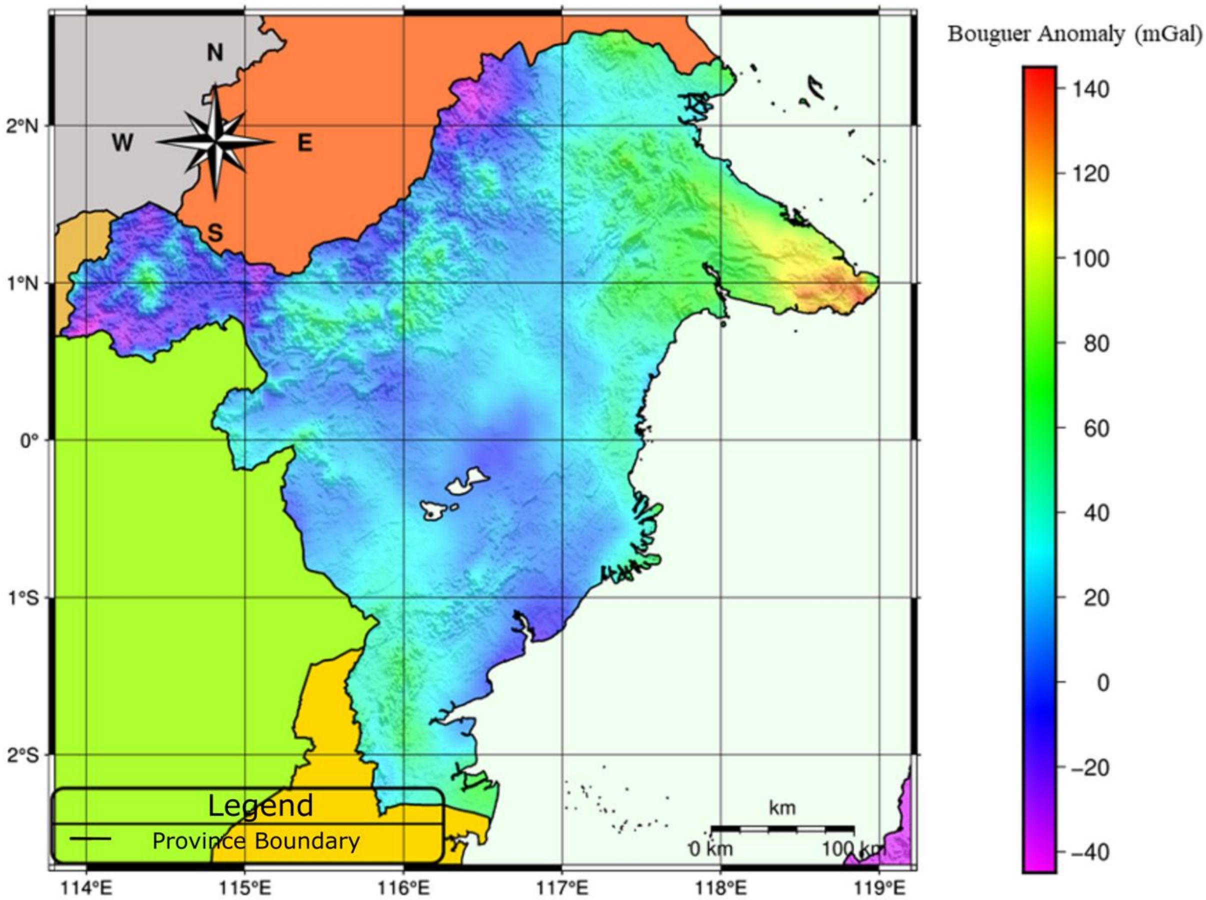

Figure 4. Simple Bouguer Anomaly at East Kalimantan Region. The SBA mapping is smoothed using Kriging interpolation.

Figure 4 illustrates the spatial distribution of Simple Bouguer Anomaly (SBA) values across East Kalimantan, which range from -5 mGal to 145 mGal. The SBA is influenced by the topographical elevation of a region; as noted by [26], there is an inverse relationship between SBA values and the elevation of a given area. This correlation is a consequence of the Bouguer correction that accounts for the gravitational attraction of mass at the measurement site. Regions of high elevation typically exhibit lower SBA values due to the distance from the mass causing the attraction, whereas areas of low elevation are characterized by higher SBA values. The Northwestern part of East Kalimantan is distinguished by a lower anomaly, indicative of its relatively higher elevation compared to other regions and is situated along the boundary with North Kalimantan. interestingly, The Northeast region of East Kalimantan is notable for its high Anomaly. This area corresponds geographically to the Mangkalihat Peninsula and its adjacent territories.

From the result of Simple Bouguer Anomaly, it is evident that the anomaly feature is significant in the mangkalihat Peninsula. The Mangkalihat Peninsula, situated between the Kutai and Tarakan Basins, is distinguished by a carbonate platform, as detailed by [5]. This geological feature is understood to have supplied a modest volume of clastic carbonates to the edges of both basins, a contribution that is primarily constrained to the slopes near the peninsula. Moreover, this locality is recognized as a segment of a strike-slip fault structure, which extends over 100 kilometers in length and is considered a continuation of the Palukoro Fault, as reported by [27]. Consequently, the significant gravity anomaly detected in East Kalimantan may be linked to the dynamic geological structures within this region.

Each horizontal and vertical transect has been subjected to power spectrum analysis, yielding a relationship between the wave number (k) and $\ln \ln A$ (the natural logarithm of Amplitude). The transects were deliberately designed to be vertical and horizontal and further divided into six segments encompassing the Kalimantan region, with the aim of attaining more precise results. With the distance between transects set at 27.75 km, this spacing is deemed sufficient to represent the sediment depth values in Kalimantan on a regional scale. Additionally, this segmentation not only enhances the accuracy of the results but also simplifies the data processing for the author, allowing for a phased approach to the analysis.

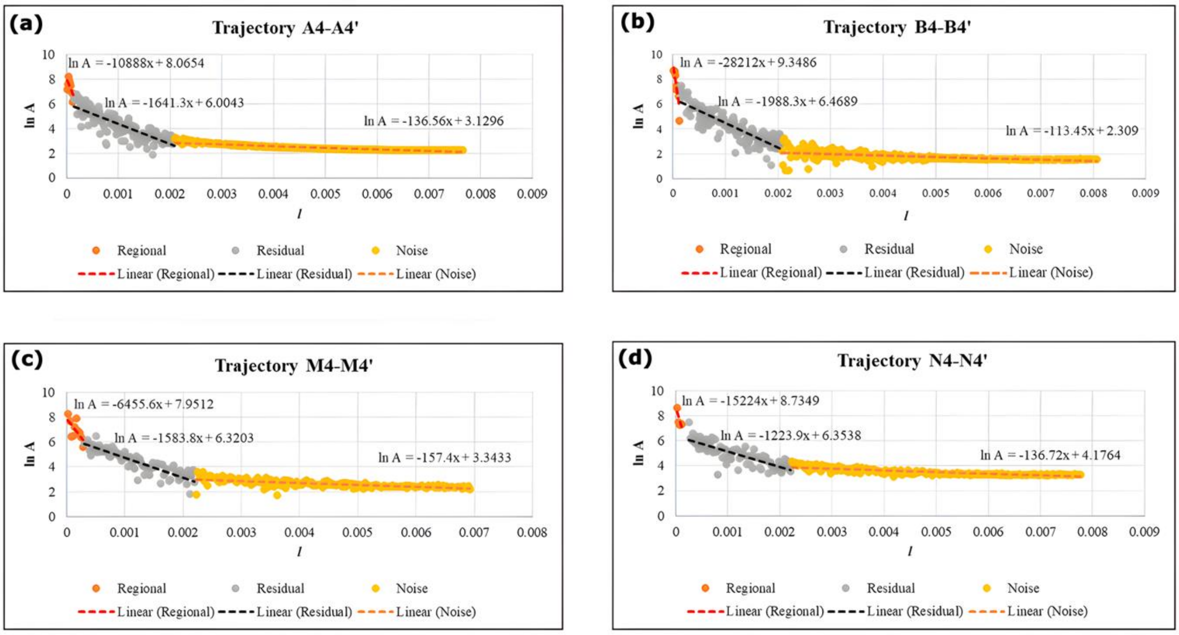

Figure 5. Power Spectrum Analysis of Horizontal and Vertical Trajectories for four example slices: M4-M4’, N4-N4’, B1-B1’, A4-A4’.

Figure 5 depicts an example of four trajectories of gravity anomaly data in wave number domain in horizontal and vertical trajectory. For horizontal trajectories (East-West) are M4-M4’ and N4-N4’ and for vertical trajectory (North-South) are B1-B1’ and A4-A4’. From the results, the linear pattern can depict the regional and residual components clearly. The trajectory analysis of each transects, whether oriented North-South or West-East, has yielded depth estimations for both regional and residual structures along each transect section. The result of depth estimation can be seen in Table 1 and Table 2.

Table 1. The estimation of the depth of regional and residual anomalies for the North-South transect area.

Trajectory	Regional Depth (m)	Residual Depth (m)
A4 - A4'	-10888	-1641,3
B4 - B4'	-28212	-1988,3
C4 - C4'	-16643	-1601,3
D4 - D4'	-24461	-1509,4

E4 - E4'	-25547	-1387,3
F4 - F4'	-21643	-1651,5
G4 - G4'	-14336	-1234,2
H4 - H4'	-14616	-1427,2
I4 - I4'	-8458,4	-1382,1
J4 - J4'	-5692,4	-1448,5
K4 - K4'	-6769,4	-1125,7
L4 - L4'	-6270,6	-1220,9
Average Depth	-15274,93	-1468,14

Table 2. The estimation of the depth of regional and residual anomalies for the East-West transect area

Trajectory	Regional Depth (m)	Residual Depth (m)
M4 - M4'	-6455,6	-1583
N4 - N4'	-15224	-1223,9
O4 - O4'	-11380	-1123,5
P4 - P4'	-25404	-1159,1
Q4 - Q4'	-24224	-1323,6
R4 - R4'	-9225,6	-1644,9
S4 - S4'	-7862,7	-1494
T4 - T4'	-8169,4	-1182
U4 - U4'	-18067	-1354,7
V4 - V4'	-13050	-1484,8
W4 - W4'	-12836	-1482,8
X4 - X4'	-12248	-1546,6
Y4 - Y4'	-10174	-1439,3
Average Depth	-13409,25	-1387,86

Based on Tables 1 and Table 2, the average regional depth estimates associated with deeper sources and the residual depth estimates linked to sediment thickness can be discerned. For the North-South transects, the average regional depth estimate is -15274.93 meters, and the average residual depth estimate is -1468.14 meters. In contrast, for the West-East transects, the average regional depth estimate is -13409.25 meters, and the average residual depth estimate is -1387.96 meters. The profile of the sediment depth estimation for the North-South and West-East transects can be seen in Figure 6 and Figure 7 respectively. Regional depth is associated with the depth bodies and the residual depth is associated with sediment thickness which are to be objective in this paper.

From the power spectrum analysis conducted in the East Kalimantan region, the estimated depths for residual anomalies along the North-South transect (Figure 6) range from -1125.7 meters to -1988.3 meters. For the West-East transect (Figure 7), the estimated residual depths range from -1123.5 meters to -1583 meters. The North-South transect reveals the deepest sediment depth estimates, with transect B4 - B4’ showing the greatest sediment thickness, approximately -1988 meters. Meanwhile, for the West-East transect, the deepest sediment thickness estimate is indicated by transect R4 - R4’, with a value of around -1650 meters.

Transects Q4 through S4 exhibit a pattern resembling a depression zone or sedimentary basin. The final sediment thickness at East Kalimantan region then can be seen in Figure 8.

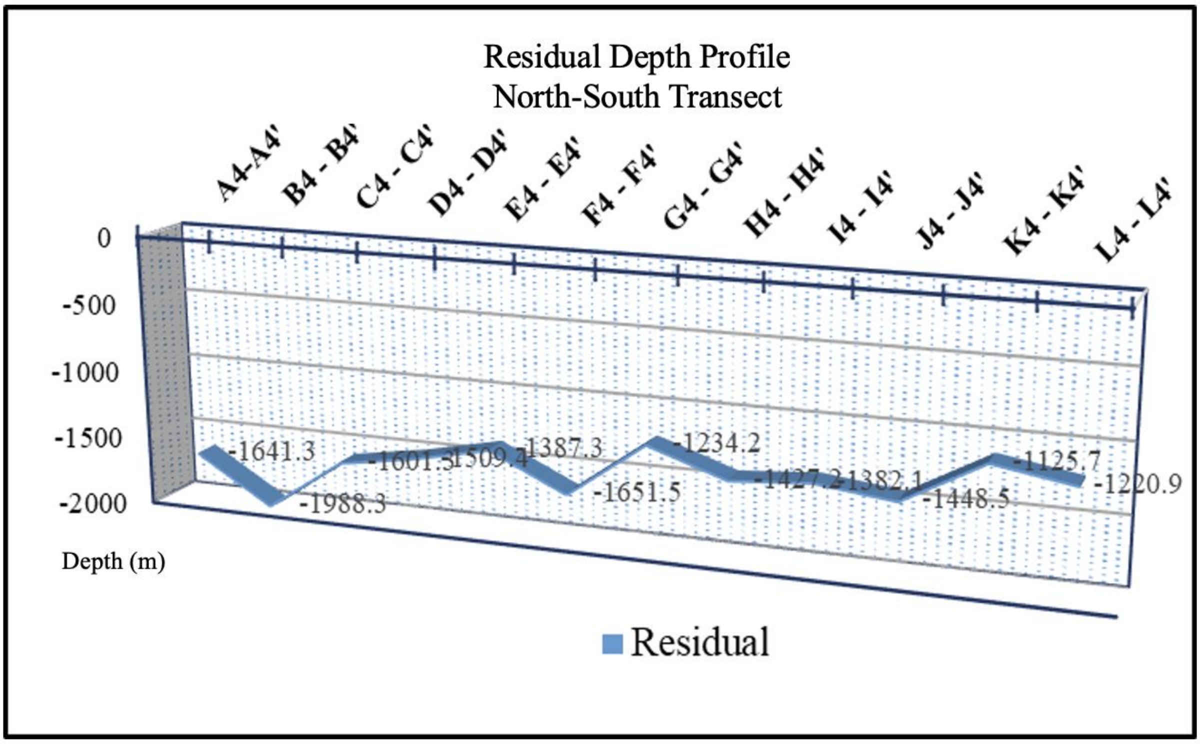

Figure 6. Sediment depth estimation at East Kalimantan Region North-South Transect

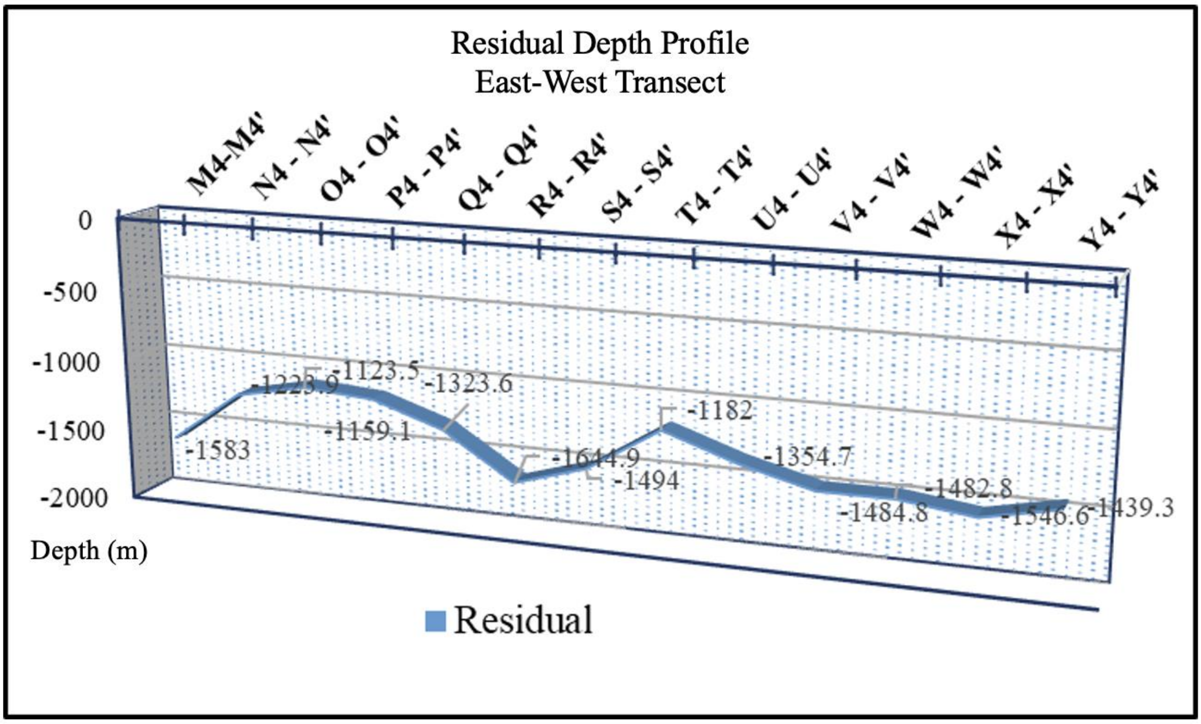

Figure 7. Sediment depth estimation at East Kalimantan Region East-West Transect

In East Kalimantan, there exists a significant sedimentary basin, the Kutai Basin. According to the [28]. Kutai Basin is one of the Tertiary age basins filled with up to 14 kilometres of Tertiary sedimentary rocks. This basin is the most extensive and deepest in the western part of Indonesia and contains substantial reserves of oil, coal, and gas [29] suggest that the Kutai Basin was formed by rifting processes that occurred during the Middle Eocene, involving the expansion of the northern Makassar Strait and the Sulawesi Sea.

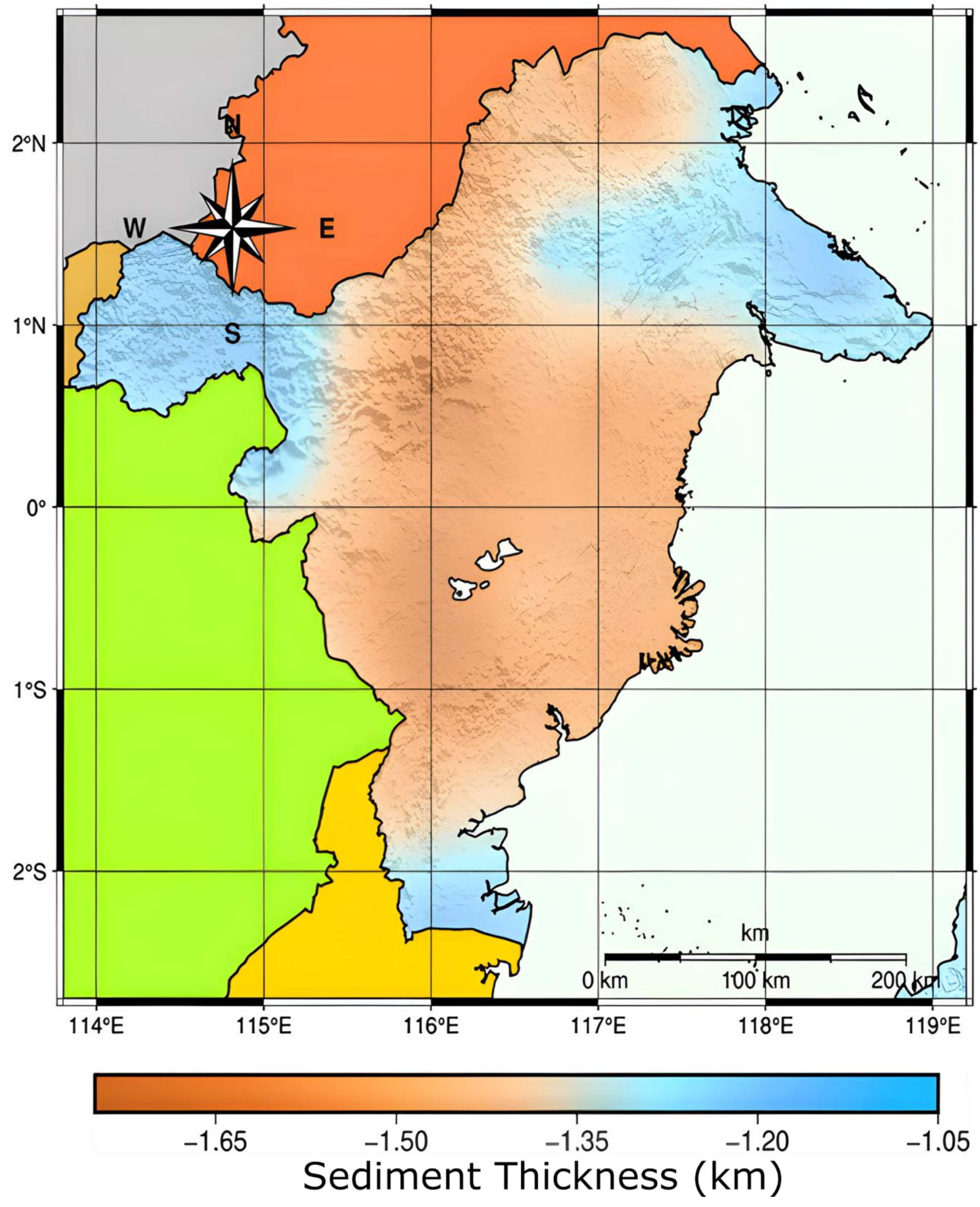

Figure 8. Sediment Thickness at East Kalimantan Region.

The principle that gravity anomaly interpretation inherently yields non-unique solutions is well-recognized in the field of geophysics [25], [30], [31]. Hence, corroborating results obtained from gravity anomaly data with those from alternative methodologies is crucial for validation and comparison. In the case of sediment thickness in the East Kalimantan region, the use of the receiver function method by [12] has indicated an average sediment depth of 5-10 km. This figure contrasts with the results obtained through gravity anomaly data in this research, suggesting a discrepancy that is nearly twofold.

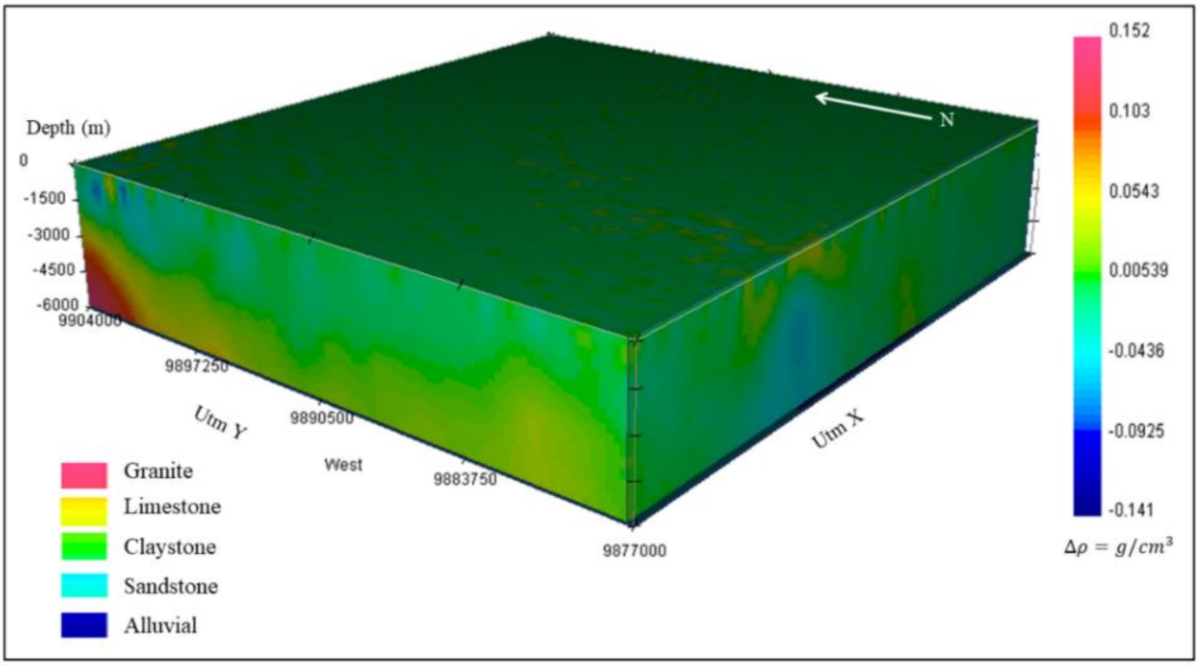

Figure 9. Three-dimensional model resulting from inversion of gravity anomaly data at Sepaku District, East Kalimantan

Furthermore, the application of the Horizontal to Vertical Spectral Ratio (HVSR) technique to seismic signals by [13] reveals that the area designated for the proposed capital city is underlain by a very thick sediment layer, exceeding 30 meters. Despite these differences, there remains a level of confidence in the sediment thickness results as determined by gravity anomaly data. This confidence stems from understanding the inherent limitations of geophysical methods and the value of integrating multiple lines of evidence to derive a more comprehensive geoscientific understanding.

The inversion modeling results based on residual anomaly data are displayed in Figure 9. The outcomes represent the density contrasts between different rock types. Density contrasts are ranging from -0.141 g/cm³ to 0.152835 g/cm³. From these contrast values, it is determined that the rock density in the study area varies from 2.3 g/cm³ to 2.65 g/cm³. To ascertain the actual density values, it is necessary to perform adjustments on the average density results by applying subtraction and addition using the Parasnis method. From the results of the three-dimensional modeling of the research area, the constituent rocks in the area under study have been identified as igneous granite and sedimentary rocks such as claystone, limestone, sandstone, and alluvial deposits. These findings can then be integrated with the topographic map to observe the overall distribution of the rock layers in the Sepaku Subdistrict area, as shown in Figure 10.

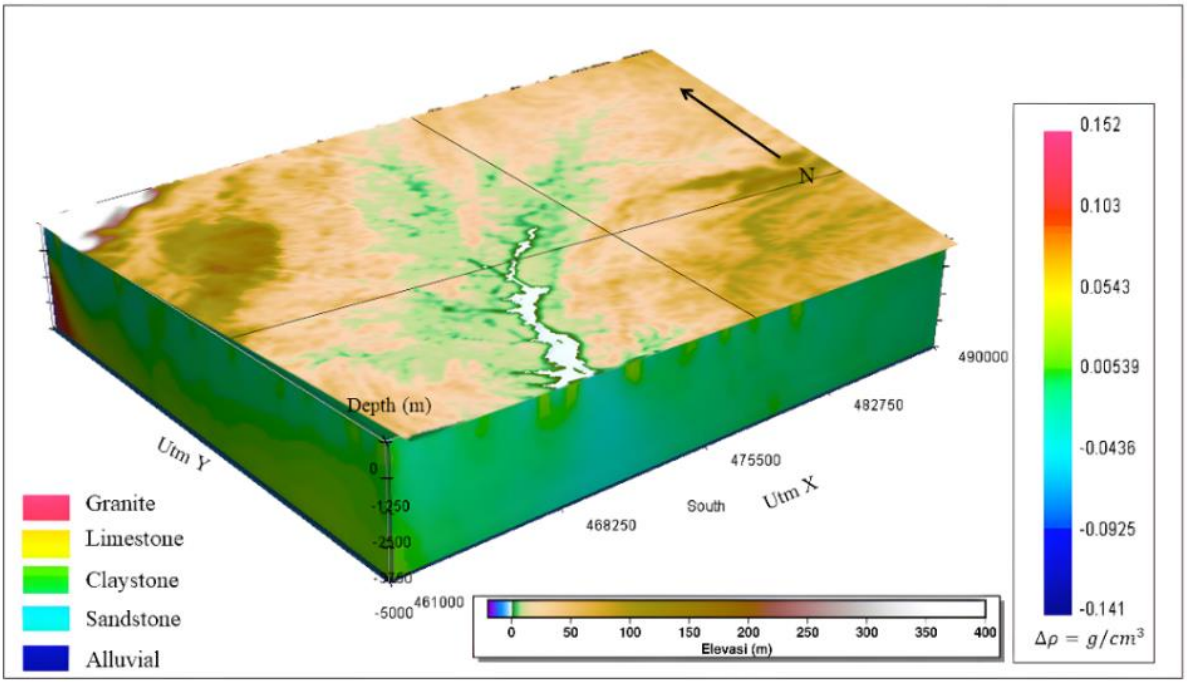

Figure 10. Modelling result with topography layer (top) at Sepaku District, East Kalimantan

Based on the layout of the three-dimensional model integrated with the topographic map, as shown in Figure 10, it is evident that the distribution of rock layers corresponds with the existing topographical conditions. This is observable in the southern region of Sepaku Subdistrict, where the Sepaku River is located. The three-dimensional modeling reveals a zone of low-density contrast, indicated by blue coloring, which suggests the presence of alluvial deposits in the river's vicinity. In the Northwestern area of the Sepaku Subdistrict, the three-dimensional model shows a shallow layer of granite, marked by light red coloring, which is associated with the higher topographical elevations in the region. To further investigate the distribution of density contrast values within the Sepaku Subdistrict, a cross-section that bisects the central part of the three-dimensional model is created as depicted in Figure 11.

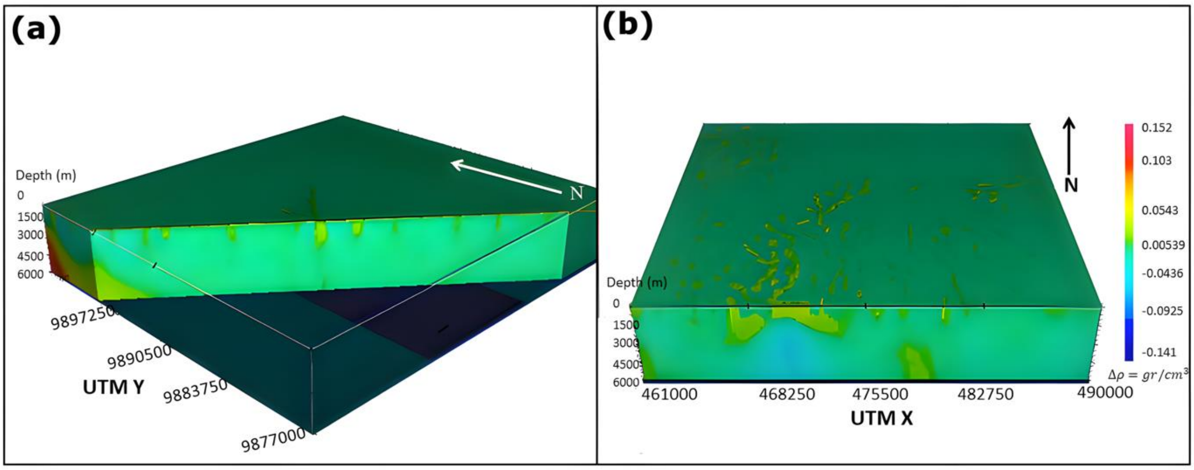

Figure 11. 3D modelling front view from South to North point of view.

The results of the three-dimensional subsurface structure modeling, as depicted in Figure 11, indicate that claystone and sandstone, represented by green and light blue colors respectively, are the predominant rock types in the research area. These findings can be validated against the geological map of the East Kalimantan sheet, which shows that the location under study is composed of the Pamaluan Formation, Palubalang Formation, Bebulu Formation, Balikpapan Formation, and alluvial deposits. The Pamaluan Formation is characterized by sandstone with interbeds of claystone, shale, siltstone, and tuff. The Palubalang Formation is marked by the presence of claystone with interbeds of quartz sandstone and coal. The Bebulu Formation consists primarily of limestone with interbeds of clayey siltstone and minor asphalt. The Balikpapan Formation is composed of quartz sandstone, clayey siltstone, shale with interbeds of asphalt, limestone, and coal.

The results of the three-dimensional modeling in the research area have received validation from resistivity measurements performed by [32] in the village of Sukomulyo, located in the Sepaku Subdistrict. The findings of [32] indicate that the Sukomulyo area comprises stratified layers of claystone, limestone, quartz sandstone, and claystone with interspersed coal seams. These geological features corroborate the results from the three-dimensional inversion analysis carried out in this research, which also identified claystone, limestone, and sandstone as the prevalent rock types within the area of study.

CONCLUSION

Our geophysical investigation in East Kalimantan delineates the Simple Bouguer Anomaly (SBA), underscoring the inverse relationship between SBA values and elevation, which aligns with established theoretical frameworks. The distinctive anomalies in the Northwest and the pronounced values in the Mangkalihat Peninsula reveal complex underlying geological structures, including the carbonate platform and fault systems akin to the Palukoro Fault. Through power spectrum analysis and three-dimensional inversion modeling, we have refined the regional sediment depth estimates, presenting a contrast with previous studies and emphasizing the non-uniqueness of geophysical data interpretation. The integration of our findings with topographical and geological maps, as well as independent resistivity measurements, affirms the presence of diverse rock formations and provides new insights into the geology of the Sepaku Subdistrict and the broader East Kalimantan region. This study enhances the geological model of East Kalimantan, contributing to a more nuanced understanding of its sedimentary basins and resource potential. It also advocates for the integration of multiple geophysical methods to strengthen the reliability of subsurface interpretations in similar geological settings.

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