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RESEARCH ARTICLE

MODELING OF COAL-BEARING ROCK FORMATIONS IN THE KUTAI BASIN, NORTH PANAJAM PASER REGENCY, KALIMANTAN BASED ON SATELLITE GRAVITY ANOMALY DATA

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ABSTRACT

North Panajam Paser Regency, Kalimantan Island, which is traversed by the Kutai Basin has very high coal fuel potential. The geological structure, depth and seam model of coal-bearing rock formations in the research area can be investigated through geophysical surveys using satellite gravity methods. Gravity field data is downloaded from the TOPEX website which comes from Geodesy Satellite (GeoSat) and European Remote Sensing Satellite-1 (ERS-1). The number of gravitational field data downloaded was 785 sets with an area of around 250 km2. The satellite gravity field data processing procedure includes several data corrections and reductions, as well as modeling and interpretation. The modeling and interpretation results show that the coal-bearing rock is estimated to be at a depth of 0 – 2,593.95 m for the AA' section; 0 – 1,877.89 m for the BB' section; and 0 – 1,558.59 m for the CC' section.

KEYWORDS

coal-bearing rock formation, Kutai Basin, satellite gravity anomaly data.

1. INTRODUCTION

Indonesia is an archipelagic country which has a volcanic path due to the activity of tectonic plates. The interaction between these plates resulted in the formation of active volcanic arcs on most of the islands in Indonesia. At the back or front of the volcanic arcs, a basin is formed that functions as a place for sediment deposition that has the potential for hydrocarbon deposits. The existence of these sedimentary basins makes Indonesia one of the countries with the largest hydrocarbon potential in the world (Bintarto et al., 2017). One of the hydrocarbon materials that have very high economic value in addition to oil and gas is coal. Coal-bearing rock formations are spread across all major islands in Indonesia, especially on the Sumatra and Kalimantan islands (Tryono, 2016).

Preliminary exploration of coal natural resources was carried out by the Ministry of Energy and Mineral Resources of the Republic of Indonesia in 2005 in the Longiram and Mentawir regions in West Kutai and North Panajam Paser Districts, East Kalimantan. Exploration results indicate the presence of sedimentary rock formations of Early Oliocene to Plio-Pleistocene age (Sumaatmadja, 2005). These formations include the Pamaluan, Balang Island, Balikpapan, and Kampung Baru Formations, all of which contain coal deposits. North Panajam Paser Regency is estimated to have potential coal resources of 155,376 tons. The quality of coal in this area is quite good based on chemical laboratory tests with a calorific value of 5,183 – 7,256 cal/g (Sumaatmadja, 2005).

Previous research was conducted in 2018 using the gravity method in the Longiram region, East Kalimantan. This research proposes to determine the structural patterns and boundaries of bedrock layers which result in the formation of a basin containing hydrocarbons. The research used the primary gravity method, i.e. gravity method with direct data acquisition in the field (Febriyansyah et al., 2018). The modeling results show that this area has the potential for hydrocarbon deposits at a depth of 1-4 km with three sub-basins which are places for hydrocarbon material formation and maturation. For a long time, this basin area has become a trap zone for hydrocarbon material, including coal. Several faults that appear in this research area function as hydrocarbon migration routes as petroleum (Febriyansyah et al., 2018).

In this research, the exploration method used is the gravity method because it is by the research target. Variations in the density of subsurface rocks (including coal seams) can result in changes in the gravitational field that are measurable at the Earth's surface (Nugraha et al., 2014). However, considering the very large area with extreme conditions, satellite gravity data is used. The satellite gravity method is a development of today's gravity surveys, where to obtain data it is not necessary to measure data in the field, but simply access data from satellites according to the desired location (Yanis et al., 2019). Satellite gravity data accessed from the TOPEX website is the result of measurements from the Geodetic Satellite (GEOSAT) and the European Remote Sensing Satellite-1 (ERS-1) (Sehah et al., 2023). Based on this background, this research proposes to model the subsurface structure of the Kutai Basin area, North Panajam Paser Regency, East Kalimantan based on satellite gravity data, to obtain a model of coal-bearing rock formations and their depth.

2. LITERATURE REVIEW

2.1 Geological Setting

The Kutai Basin is thought to have been formed as a result of the expansion process during the Middle Eocene period which was followed by a flexing phase of the basin floor which ended in the Late Oligen period. This basin is the largest and deepest tertiary age basin in Indonesia. The

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Kutai Basin has a depth of 1,515 km with an area of about 60,000 km^2 (Abhimantra et al., 2015). The rock types in the research area are dominated by limestone, silty claystone with marl insertion as well as claystone with coal insertion (Hidayat and Umar, 1994). Increasing pressure due to the collision of tectonic plates resulted in the uplift of the basin floor towards the northwest, resulting in the regressive cycle of classical sedimentation in the Kutai Basin, which has not changed since the Late Oligocene era until now (Hidayat and Umar, 1994). The geological map of the research area is shown in Figure 1.

During the Middle Miocene age, the uplift of the basin floor started from the western part of the Kutai Basin which moved progressively eastward all the time and was the center of deposition. In addition, there was a natural event in the form of sea shrinkage which continued continuously until the Late Miocene. The rock material deposited comes from the southern, western, and northern basins from the Warukin Formation, Palubalang Formation, and Balikpapan Formation (Susiati et al., 2022). The Kutai Basin in East Kalimantan has the main structure in the form of an anticline that trends north-northeast. This is marked by the presence of asymmetric anticlines separated by very wide synclines containing Miocene-aged siliciclastic with trail axes reaching 20-50 km along straight-to-curved trends. The structure of the anticline changes gradually from east to west, with little to no uplift, to complex folds or normal fault lines with uplift, as well as erosion in the western part. The regressive sequence in the basin includes classic deltaic to paralic layers which contain many seams of coal and lignite (Hidayat and Umar, 1994).

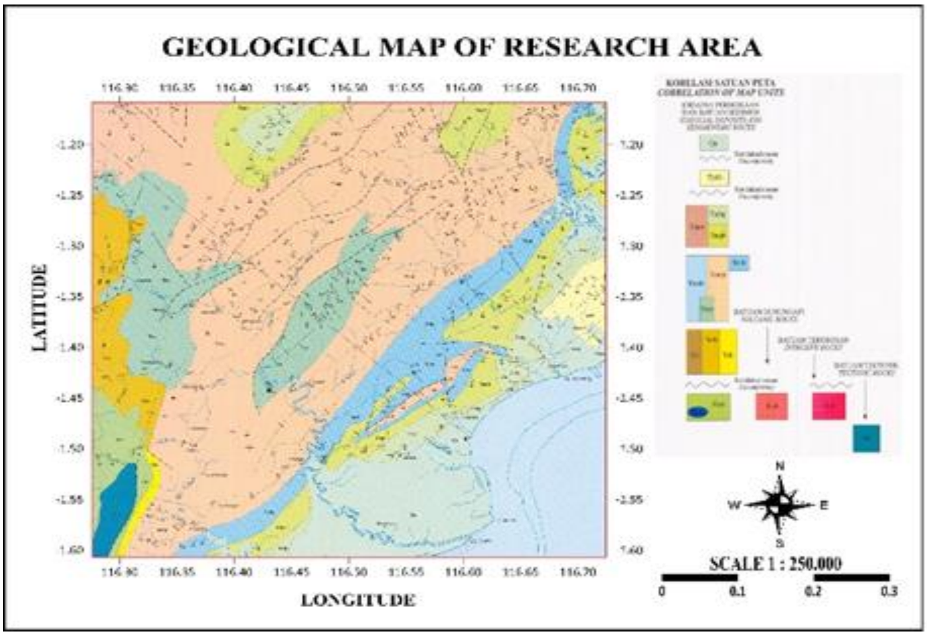

Figure 1: The geological map of the research area; Kutai Basin, East Kalimantan (Hidayat dan Umar, 1994).

2.2 Gravity Method

The gravity method is one of the oldest geophysical methods that is utilized to solve many geological problems. This method is based on Newton's law of attraction between two mass points. The value of the force between two mass points can be written by equation:

$$\vec{F}(\vec{r}) \;=\; -G\,\frac{m_1 m_2}{r^2}\,\hat{r} \tag{1}$$

where F is the force (N), r is the distance between two masses points (m), m_1 and m_2 are the masses of each point or object (kg), and G is the universal gravitational constant (i.e. 6.67 × 10^{-11} Nm^2/kg^2). A group researchers have described Equation (1) to obtain the gravitational potential value at point P outside volume V as shown in Figure 2, so that the following equation is obtained (Telford et al., 1990):

$$U_P(\vec{r}) \;=\; -\int_V \frac{G}{\left|\vec{r}^2-\vec{r}_0^{\,2}\right|}dm \;=\; -G\int_V \frac{\rho(\vec{r}_0)}{\left|\vec{r}^2-\vec{r}_0^{\,2}\right|}d^3\vec{r}_0 \tag{2}$$

where $\left|\vec{r}^2-\vec{r}_0^{\,2}\right| \;=\; \sqrt{r^2+r_0^{\,2}-2rr_0\cos\gamma}$

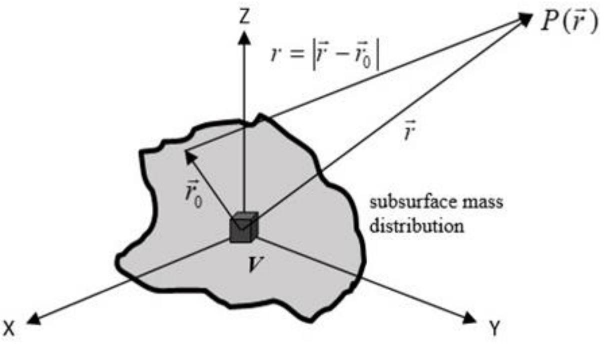

Figure 2: The gravitational potential at point P on the Earth's surface due to the continuous distribution of mass in the subsurface (Telford et al., 1990).

When the volume integral is applied to the overall volume of the Earth, so the gravitational potential at the Earth's surface can be determined. Further, the gravitational field magnitude can be obtained by differentiating the gravitational potential as shown in Equation (3) (Telford et al., 1990):

$$\vec{E}(\vec{r}) \;=\; |-\nabla U_P(\vec{r})| \tag{3}$$

The Earth's gravitational field is often called the gravitational acceleration and is symbolized by g. Based on Equation (3), the Earth's gravitational field value can be stated by Equation (4):

$$g(\vec{r}) = \left|-\vec{E}(\vec{r})\right| = \left|\nabla U_P(\vec{r})\right| \tag{4}$$

Equation (4) can be written more completely by describing the gravitational potential gradient, as shown in Equation (5) (Telford et al., 1990):

$$\boldsymbol{g}(\vec{\boldsymbol{r}}) \;=\; -\boldsymbol{G}\int_V \frac{\rho(\vec{r}_0)zd^3\vec{r}_0}{(x^2+y^2+z^2)^{3/2}} \tag{5}$$

$$\boldsymbol{g}(\vec{\boldsymbol{r}}) \;=\; -\boldsymbol{G}\int_V \frac{\rho(\vec{r}_0)(z_0-z)d^3\vec{r}_0}{[(x-x_0)^2+(y-y_0)^2+(z-z_0)^2)]^{3/2}} \tag{6}$$

Equation (6) shows that the magnitude of the Earth's gravitational field is a function of position (latitude, longitude, elevation) and the density of objects in the subsurface. The gravitational field on the Earth's surface is also influenced by rocks with varying densities, geological structures, and the unevenness of the Earth's surface relief (rough topography). In the gravity method, the value of the gravity field resulting from data acquisition is expressed in gal units (where 1 gal = 10^{-5} m/s^2). However, gravity anomaly values acquired from data measurements in the field are generally very small, i.e. in the milligal range (Lichoro, 2016).

3. RESEARCH METHOD

3.1 Location and Time of Research

The location of the research area is at coordinates 1°09'41.50” -

1°36'55.20” S and 116°16'48.20” - 116°43'46.30” E as shown in Figure 3. This study was carried out from September 2021 to February 2022 at the Geophysical Laboratory, Department of Physics, Faculty of Mathematics and Natural Sciences, Jenderal Sudirman University, Central Java, Indonesia. Satellite gravity field anomaly data for each measuring point have been accessed from the website provided by Scripps Institution of Oceanography, University of California San Diego USA (Sandwell and Smith, 2009).

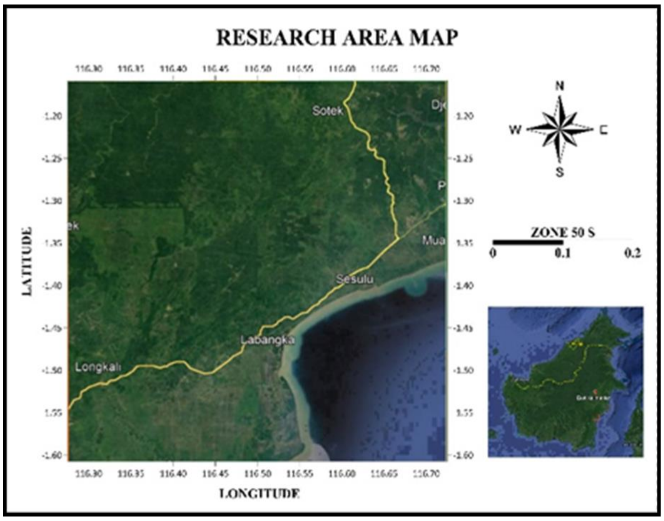

Figure 3: Map showing the location of the research area; North Panajam Paser Regency, East Kalimantan.

3.2 Research Equipment

Several pieces of equipment used in this research consist of a personal computer (PC) to download the gravity anomalies data and the geographical position data, Google Earth to create a research design and determine the boundaries of the study area, and a geological map as a guide in modeling and interpretation. Meanwhile, several software and application program used in the laboratory consist of Microsoft Excel 2019 for Bouguer correction, Gravity 900 for terrain correction, Fortran 77 for processing gravity anomalies data, Surfer 2017 for mapping topographic and gravity anomalies data, and Oasis Montaj (free version) for forward modeling of subsurface anomalous sources in two dimensional.

3.3 Research Procedure

Satellite data obtained in this research are free-air gravity anomalies data. These data do not require free-air correction because the data acquisition is done at the same elevation datum. The latitude correction is also not needed because the satellites have calculated the gravity effect on differences in latitude positions. In addition, with the large distance between the Earth's center of mass and the satellite's orbital trajectories, differences in gravity acceleration values caused by differences in latitude have no effect. Then, some corrections commonly carried out such as equipment height correction and drift correction are also not needed (Maulana and Prasetyo, 2019). Based on this, only bougeur and terrain corrections were applied in data processing to obtain the complete Bouguer anomalies (CBA) data (Putri et al., 2019).

The CBA data obtained are still spread over an uneven topographic surface, so mathematically it can be written in the form $\Delta g(\lambda,\vartheta,h)$. Reduction of anomaly data to a horizontal surface has to be carried out because the data have to be spread at a horizontal surface for further data processing (Blakely, 1995). One method that can be applied to reduce anomaly data to a horizontal surface is the Taylor series approach which can be expressed as an equation (Blakely, 1995):

$$\boldsymbol{\Delta g(\lambda,\vartheta,h_0)^{[i+1]}} = \boldsymbol{\Delta g(\lambda,\vartheta,h)} - \sum_{n=0}^{\infty} \frac{(h-h_0)^n}{n!} \frac{\partial^n}{\partial h^n} \boldsymbol{\Delta g(\lambda,\vartheta,h_0)^{[i]}} \tag{9}$$

The basic mechanism of the Taylor series is to use a derivative function at a point to extrapolate the function around that point. Thus, this method can be used to estimate the gravity anomalies data at points outside the observation field. Equation (9) has been written in the form of iteration; where $\Delta g(\lambda,\vartheta,h_0)$ are CBA data that are distributed on the horizontal surface. The CBA data can be estimated by an approach; i.e. $\Delta g(\lambda,\vartheta,h_0)$ data acquired from i-th iteration are used to obtain $\Delta g(\lambda,\vartheta,h_0)$ data in the (i+1)-th iteration. The iteration can be applied sufficiently to reach convergent values (Blakely, 1995). In many cases, convergence of Equation (9) can be achieved quickly, if z_0 value is taken at the average topographical elevation of the research area. For the initial guess values before iteration, so $\Delta g(\lambda,\vartheta,h_0)$ on the right of Equation (9) can be filled by $\Delta g(\lambda,\vartheta,h)$ data (Blakely, 1995).

The CBA data which are resulted from Equation (9) are still affected by rock densities originating from the deep and wide sources, which are called regional gravity anomalies. Hence, the regional gravity anomalies data have to be separated from CBA data to obtain the residual gravity anomalies data (Sehah et al., 2022). The regional anomalies data can be obtained by the upward continuation process to a certain height so that the anomalous data intervals show very smooth patterns (Guo et al., 2013). The regional anomalies data that are acquired, then corrected to the CBA data which have been distributed on the horizontal surface to acquire the residual anomalies data as written in the following equation (Blakely, 1995; Sehah et al., 2023):

$$\boldsymbol{\Delta g_{res}(\lambda',\vartheta',h_0)} = \boldsymbol{\Delta g(\lambda,\vartheta,h_0)} - \frac{\Delta h}{2\pi} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \frac{\Delta g(\lambda,\vartheta,h_0)}{\sqrt{[(\lambda'-\lambda)^2+(\vartheta'-\vartheta)^2+\Delta h^2]^3}} \, d\lambda d\vartheta \tag{10}$$

The right term is the regional gravity anomalies data, meanwhile, Δh is the height of the upward continuation. The residual anomalies data in the left term are assumed to only come from the local anomalous sources which are the research target (Quesnel et al., 2008).

The final stage of the research is modeling the residual anomaly data and interpreting the results so that a subsurface model which is the research target is obtained in the research area. Modeling and interpretation of the gravity anomalies data are directly related to subsurface rocks physical properties, i.e. the density, and are very useful to field geologists and geophysicists in the mapping and identification of various rock types, including coal-bearing rock in the research area.

4. RESULTS AND DISCUSSION

4.1 Results of Processing Data

Satellite gravity field anomalies data have been accessed for 785 points spread over a research area of 250 km^2. The anomalies data obtained have been corrected up to the free air correction as shown in Figure 4. The free air anomalies data (FAA) have a value range between -5 – 75 mGal. The distribution of high anomalous values is in the northwest as a result of topographic effects in the form of highlands (Wibawa and Wachidah, 2022). The distribution of low gravity anomaly values is in the southeastern part of the study area which is dominated by lowlands such as beaches and river deltas (Nur et al., 2015). Bouguer and terrain corrections are carried out on FAA data so that Complete Bouger Anomalies (CBA) data are obtained, as shown in Figure 5. The CBA value shows the difference between the expected value of gravity at a given location and its actual value.

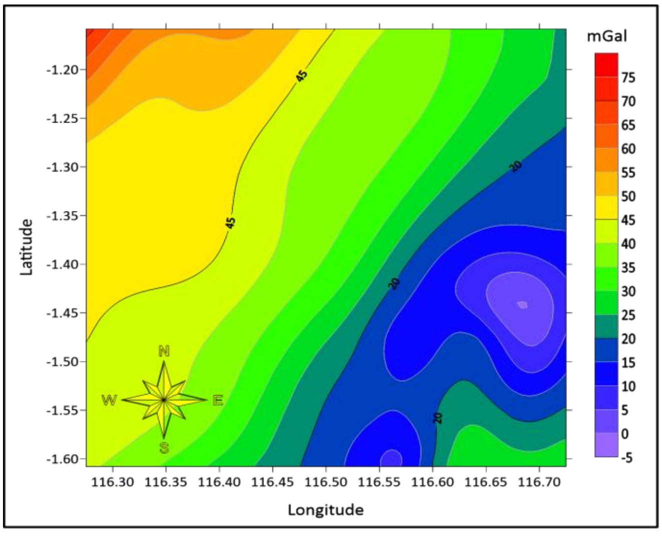

Figure 4: Free air anomaly contour map of the research area; North Panajam Paser Regency, East Kalimantan.

The next process is data reduction to a horizontal surface using the Taylor Series approach method. The result is a CBA contour map on a horizontal surface (average topographic height) which has a value range from 0 – 70 mGal, with the contour map shown in Figure 5 (Sehah et al., 2022). The lineament pattern seen on the CBA contour map is thought to be a fault, which is also the target of the research.

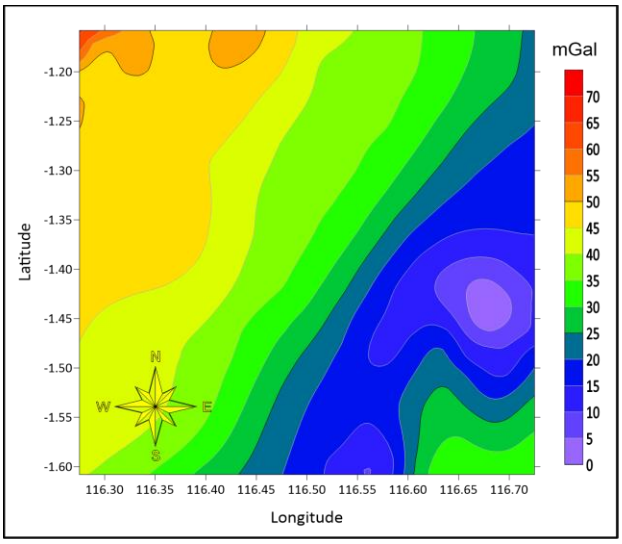

Figure 5: Complete Bouguer anomaly contour map spread over the average topographic height of the research area.

The next process is the separation of regional and residual anomalies using the upward continuation method (Blakely, 1995; Sehah et al., 2021). The residual anomalies shown in Figure 6 are used in the process of modeling and interpreting the subsurface geological structure of the study area. The distribution of high anomaly values is in the northwest, meanwhile low anomalies are in the southeast. The residual gravity anomaly has a value range between -35 – 35 mGal.

4.2 Results of Modeling Data

The subsurface geological structure of the study area can be described through forward modeling which is supported by geological information of the research area. Modeling was carried out using residual anomalies data on three trajectories, i.e. trajectory AA′, trajectory BB′, and trajectory CC′ as shown in Figure 6. The positions of these trajectories were adjusted to study areas that were predicted to contain coal prospects. Several well-known rock formations have high coal potential, i.e. Pamaluan, Balang Island, Balikpapan, and Kampung Baru formations (Sumaatmadja, 2005).

The residual gravity anomaly contour map shows a lineament pattern with a northeast-southwest orientation, so forward modeling must be carried out in a northwest-southeast direction which is perpendicular to the orientation of the lineament which is estimated to be a fault. Thus, the fault model in the research area can be described easily (Indriana, et al., 2021). The geological map shows that the study area has a very complex structure with many rock formations and small faults that are close to each other (Hidayat and Umar, 1994).

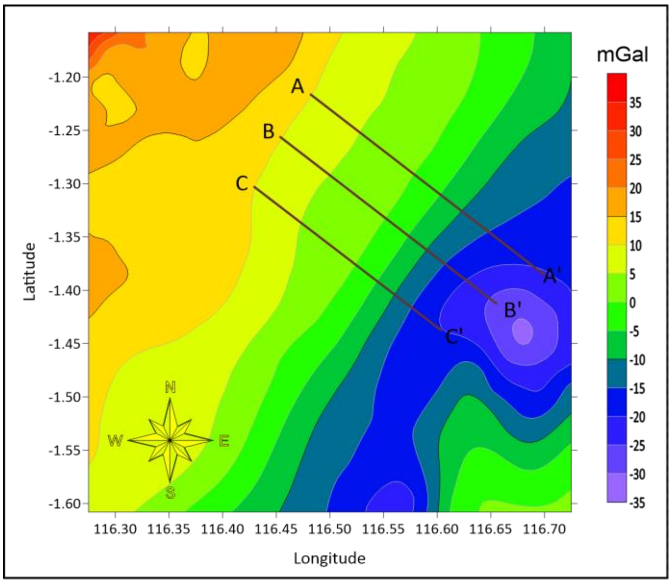

Figure 6: Residual gravity anomaly contour map of the research area with three modeling trajectories.

The forward modeling method can be carried out by translating data from a model by calculating the theoretical response and distribution of the properties of the anomaly source. The modeling is carried out by matching the observation curve and the model curve to achieve a small error value. The results of the modeling of the residual anomalies data along these trajectories will result in the geometric shape and structure of subsurface rock (Setiadi and Pratama, 2018). The modeling results on the AA′ trajectory, BB′ trajectory, and CC′ trajectory are shown in Figure 7, Figure 8, and Figure 9. While, the interpretation results are shown in Table 1, Table 2, and Table 3. The AA′ trajectory stretches at geographical coordinates of 1.233° - 1.400° S and 116.466° - 116.716° E. The BB′ trajectory stretches at geographical position of 1.266° - 1.416° S and 116.450° - 116.650° E. While the CC′ trajectory stretches at geographical coordinates of 1.300° - 1.433° S and 116.416° - 116.600° E. The forward modeling purpose is to identify depth estimates and seam models of coal-bearing rock formations along the AA, BB, and CC cross-sections. In general, rocks containing coal are generally deposited in fluvial, delta, and coastal plain environments.

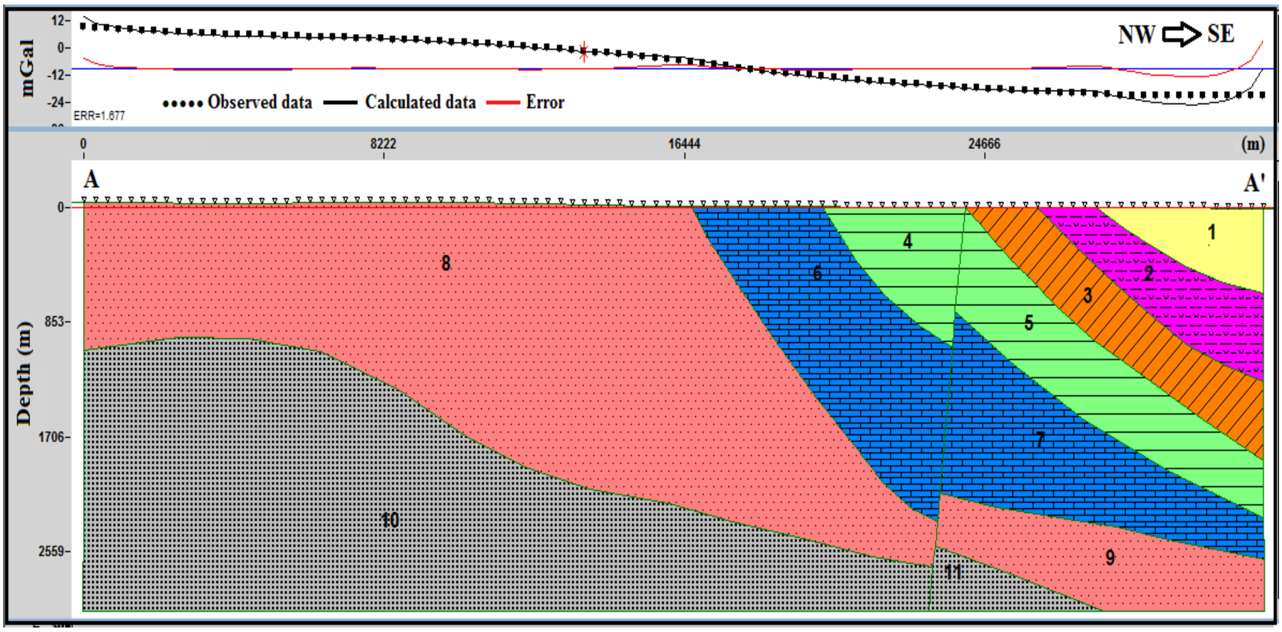

Figure 7: Cross-section of the subsurface rock formation model resulting from forward modeling of residual anomalies data on the AA′ trajectory.

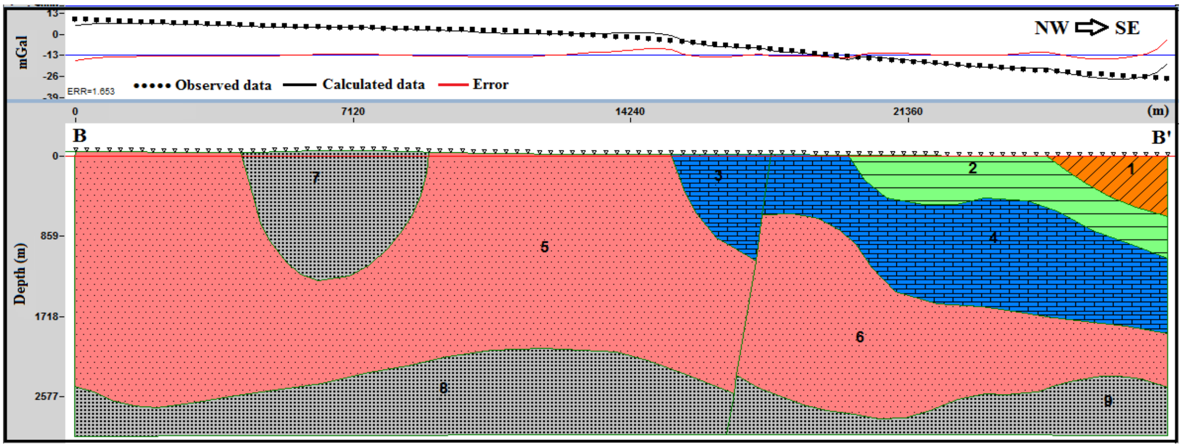

Figure 8: Cross-section of the subsurface rock formation model resulting from forward modeling of residual anomalies data on the BB′ trajectory.

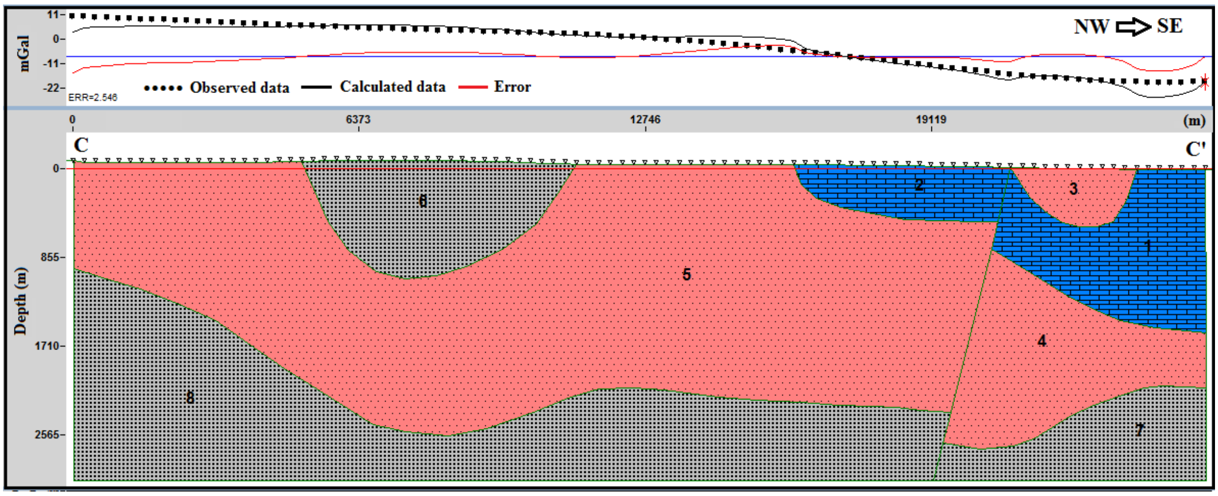

Figure 9: Cross-section of the subsurface rock formation model resulting from forward modeling of residual anomalies data on the CC′ trajectory

Table 1: Results of lithological interpretation of modeling results on the AA′ cross section

No. Body	Density (g/cm³)	Rock Formation (Symbol)
1	1.82	Aluvium (Qa)
2	2.30	Kampung Baru (Tpkb)
3	2.29	Balikpapan (Tmbp)
4	2.34	Pulau Balang (Tmpb)
5	2.30	
6	2.31	Bebulu (Tmbl)
7	2.28	
8	2.46	Pamaluan (Tomp)
9	2.50	
10	2.58	Tuyu (Toty)
11	2.66	

Table 2: Results of lithological interpretation of modeling results on the BB′ cross section

No Body	Density (g/cm³)	Rock Formation (Symbol)
1	1.92	Balikpapan (Tmbp)
2	2.59	Pulau Balang (Tmpb)
3	2.38	Bebulu (Tmbl)
4	2.14	
5	2.76	Pamaluan (Tomp)
6	2.79	
7	2.71	Tuyu (Toty)
8	2.40	
9	2.79	

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Table 3: Results of lithological interpretation of modeling results on the CC′ cross section

No. Body	Density (g/cm³)	Rock Formation Name
1	2.24	Bebulu (Tmbl)
2	2.22	
3	2.68	Pamaluan (Tomp)
4	2.65	
5	2.68	
6	2.64	Tuyu (Toty)
7	2.72	
8	2.82	

5. ANALYSIS AND DISCUSSION

Coal is an organic mineral that can burn, formed from the remains of ancient plants that settle and then change shape due to physical and chemical processes that take place over a long time. Coal that is formed usually occurs in wet and swampy forests, so when the trees in the forest die and fall, they immediately sink into the swamp and the remaining plants do not decompose completely and eventually become plant fossils that form organic sediment. The process that turns plants into coal is called coalification. Several factors that influence the coal formation process include the ancient plant types, the location where ancient plants grow and develop, the location of plant deposition, pressure from surrounding rocks, heat from the Earth, and geological dynamics below the Earth's surface. Hence, the characteristics of coal that occur vary, according to the conditions of the coalfield and seam (Fauzan et al., 2024).

The initial process of forming coal is that plant sediments turn into peat, which then turns into light coal (lignite) also known as brown coal. Young coal is coal with a type of low organic maturity. After being continuously influenced by temperature and pressure over a very long period and undergoing ongoing chemical and physical changes, young coal becomes harder and blacker in color and forms bituminous or even anthracite. Several coal seams also form anthracite over a longer period, which has the lowest structure and water content among other coals. The history of coal basins largely depends on the geotectonic position that influences the development of coal and coal basins. The formation of coal in basins generally experiences deformation by tectonic forces, that will produce coal seams with certain shapes (Ju et al., 2012).

Based on Figure 7, the coal-bearing layers on the AA′ cross-section are estimated to be at a depth of 0 – 2,593.95 m with a thickness in the vertical direction of 2,593.95 m and the lateral direction of 15,583.33 m. The rock formations that make up these rock layers include the Kampung Baru Formation (Tpkb), the Balang Island Formation (Tmpb), the Balikpapan Formation (Tmbp), and the Bebulu Formation (Tmbl). The geological information of the research area shows that these rock formations are mostly composed of quartz sandstone, sandstone, limestone, silty mudstone with a few marl inserts, and mudstone with coal inserts. The modeling results also show that there is a normal fault that can function as a migration route for hydrocarbon substances from the source rock to the reservoir (Hidayat dan Umar, 1994).

Meanwhile, based on Figure 8, the coal-bearing rock layers on the BB′ cross-section are at a depth of 0 – 1,877.89 m with a thickness in the vertical direction of 1,877.89 m and the lateral direction of 12,657.9 m. The rock formations that make up these layers include the Balikpapan Formation (Tmbp), the Bebulu Formation (Tmbl), and the Balang Island Formation (Tmpb). The geological information of the research area shows that these rock layers are dominated by rock types such as quartz sandstone, limestone, silty mudstone with a few marl inserts, sandstone, and mudstone with coal inserts. Furthermore, based on Figure 9, the coal-bearing rock layers on the CC′ cross-section are at a depth of 0 – 1,558.59 m with a thickness in the vertical direction of 1,558.59 m and lateral direction of 9,137.59 m. The rock formation that makes up this rock layer is the Bebulu Formation (Tmbl). The geological map of the research area indicates that this rock formation is dominated by limestone, silty claystone with a few marl inserts, as well as claystone with coal inserts (Hidayat dan Umar, 1994).

6. CONCLUSION

2D-modeling of coal-bearing rock formations has been successfully carried out for the Kutai Basin, Panajam Paser Regency, North Kalimantan based on satellite imagery gravity anomaly data with the following conclusions:

1. The gravity anomalies data used in the research amounted to 785 points in an area of 250 km2, that were downloaded from the Topex website sourced from GeoSat and ERS-1.

2. The satellite gravity anomaly data processing procedures which have been carried out include Bouguer and terrain corrections, reduction to a horizontal surface, separation of regional and residual anomalies data, as well as modeling and interpretation.

3. The modeling and interpretation results show that the coal-bearing rocks are estimated to be at a depth of 0 – 2,593.95 m for the AA' cross-section; 0 – 1,877.89 m for BB' cross-section; and 0 – 1,558.59 m for the CC cross-section.

4. The coal-bearing formations are interpreted as the Kampung Baru Formation (Tpkb), Balang Island Formation (Tmpb), Bebulu Formation (Tmbl), and Balikpapan Formation (Tmbp) which lithologically are mostly composed of quartz sandstone, sandstone, limestone, silty mudstone with little marl inserts, and mudstone with coal inserts.

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