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2D Surface Structure Modeling in Bengkulu City using Geomagnet Method

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Abstract: Research on 2D modeling of the subsurface structure of the Bengkulu city area was carried out using the geomagnetic method. In this study, we collected data from 130 measurement points using a set of Proton Procession Magnetometers (PPM) to obtain the total magnetic field value. The measurement data were processed by making corrections of daily variations and IGRF (International Geomagnetic Reference Field). We conducted data correction to contour the total magnetic field anomaly. After that, the contour of total magnetic field anomaly was used for the reduction to the poles. This research results from the total magnetic field anomaly show a pair of positive and negative closures. Cross-sections were made on the positive and negative closure pairs to determine the subsurface structure of the area by making a 2-dimensional (2D) model using Mag2DC software. The interpretation of the 2D modeling results shows that three rock layers are continuously arranged. The average susceptibility value of the first layer is 0.00001 cgs which is a sandstone layer at a depth of 0-400 meters; the second layer has an average susceptibility value of 0.002 cgs which is dominated by clay at a depth of 400-700 meters, and; the third layer has an average susceptibility value of 0.006 cgs which is a basalt rock layer at a depth of 700-1000 meters.

Keywords: 2D; Forward Modeling; Geomagnetic; Subsurface Structure

Introduction

The subduction zone of the Indo-Australian and Eurasian plates is near to the location of Bengkulu City. Around 95% of seismic sources are in this area due to the movement of these tectonic plates (BMKG, 2010). This tectonics movement makes Bengkulu City has a high earthquake potential (Hadi et al., 2012). This city is also known as one of Indonesia's most prone to earthquakes (Farid and Mase, 2020), (Misliniyati et al., 2018).

An earthquake as a colossal disaster has damaged and disrupted the built environment, socioeconomic systems and institutions (Adger et al., 2005). Such disturbances and damage have long-term effects in the disaster area (Peng et al., 2020). An earthquake can also trigger other catastrophes, for instance, landslides, liquefaction, soil amplifications, compaction or even tsunami-waves (Theilen-Wilige, 2010). In addition, an earthquake that occurs in an area causes damaged infrastructure and soil (Norio et al., 2011), (Veinović et al. (2007), Mase et al., (2019), Sukkarak et al. (2021). Earthquake damage is mainly influenced by the hardness of the rocks that support the buildings above them, where strong earthquakes cause more damage in areas of hard rock than soft rock area (Chen et al., 2021). One of the efforts in earthquake mitigation in an area is to analyze the subsurface structure to determine the dynamic characteristics of the soil (Sunardi et al., 2017).

Bengkulu City consist with formation Alluvium (Qa), Andesite (Tpan), Reef Limestone (Ql), Swaps Deposits (Qs), Bintunan Formation (QTb), and Alluvium Terraces (Qat). Andesite rock (Tpan) and Bintunan Formation (QTb) are rock formations with Tertiary age (Gafoer et al., 2007). The Andesite Rock (Tpan) is located southeast of the Bengkulu city center, and the Bintunan Formation (QTb) is located northeast of the Bengkulu city center. Alluvium (Qa), Reef Limestone (Ql), Swaps Deposits (Qs), and Alluvium Terraces (Qat) are included in the Quaternary sedimentary sequence. Stratigraphically, this Quaternary sediment is Holocene

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in age. The Alluvium Terraces (Qat) rock formation dominates the study area, and the Reef Limestone (Ql) rock formation is only found south of Muara Cemara Pantai Panjang, Teluk Segara (Gafoer et al., 2012).

Previous research on subsurface rock structures in the Bengkulu city has been researched by Lestari (2018), (Hadi et al., 2021), and (Simbolon et al., 2020). Lestari (2018) conducted research using Multichannel Analysis of Surface Wave (MASW) and USGS data on f0 from microtremor measurements in Bengkulu City. From the calculation of the Vs30 value in general for the Bengkulu City area, the values range from 200 m/s – 800 m/s. The Vs30 values are based on the MASW data on the USGS, which are around 179.75 m/s – 224.29 m/s, while from the direct measurements using the MASW method, the values are around 239.89 m/s – 389.91 m/s. However, the method using the Vs30 value can only identify a soil depth of 30 meters. (Hadi et al., 2021) carried out research in Bengkulu City using the MASW method with a time-term inversion technique to obtain bedrock that varies from the surface to a depth of 17.71 m. While, (Simbolon et al., 2020) showed that they used the geomagnetic method to identify rock structures to a depth of 1 km. Based on previous study, it is vital to analyze the subsurface structure deeper than the methods that have been used. To obtain deeper subsurface structures, we use the geomagnetic method with 2D structure modeling based on magnetic anomaly.

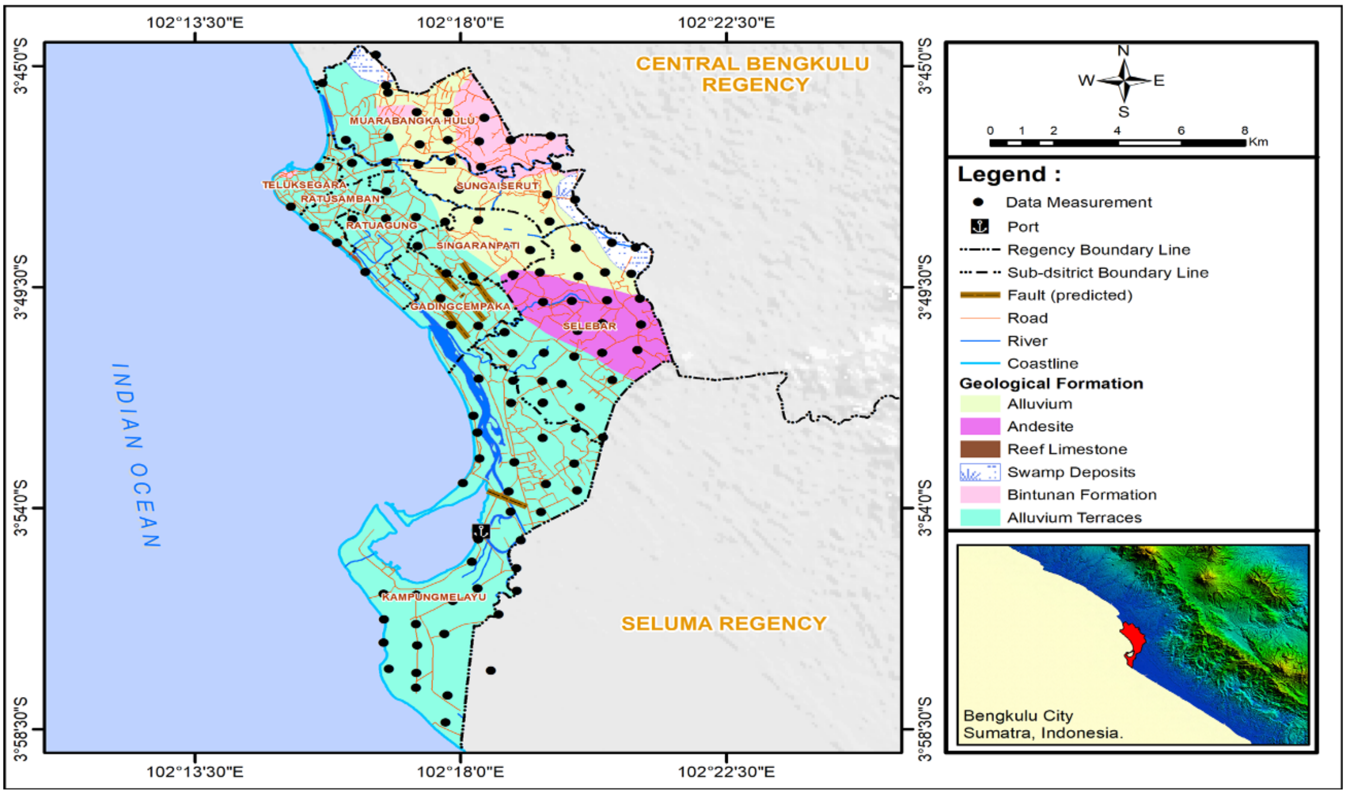

Figure 1. Local geological map of Bengkulu city (Modification of Gafoer et al., 2007).

The magnetic method has a relatively simple operation with easy and fast data acquisition process compared to other geophysical methods. The magnetic method is based on measuring variations in the intensity of the magnetic field on the earth's surface caused by the anomaly of magnetized objects under the earth's surface. The significant difference in magnetic anomaly values is highly effective for the predicted subsurface structures (Susilo and Isdarmadi, 2017), so it is suitable to be used to determine the 2D structure below the surface in the Bengkulu city.

However, our knowledge of the deep geological structures (Fig. 1) in the region of Bengkulu remains ambiguous. For this paper, a high-precision geomagnetic survey was performed to more accurately define the deep geological structure of the Bengkulu city limits.

Basic theory

As seen in Figure 2, a rock volume, for instance, an underground rock made of magnetic minerals or materials, can be considered as a magnetic dipole (Telford et al., 1990). An object's magnetization is determined by the magnetic induction it receives from the earth's magnetic field, which is measured while it is in the field. Therefore, Consequently, equation (1) can be used to express the size of the magnetic potential located at a particular location in the rock: (Telford et al., 1990).

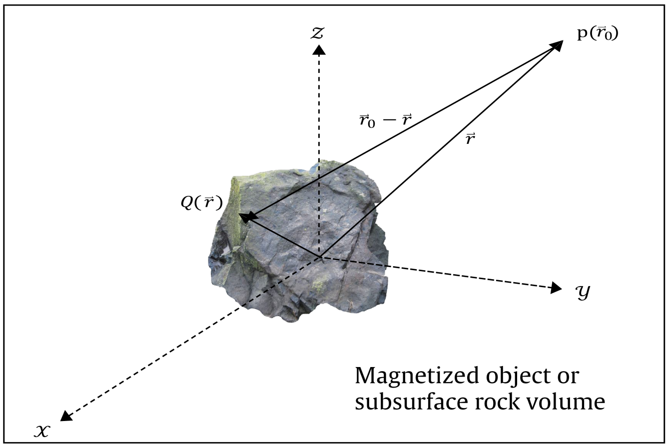

Figure 2. The magnetic value of an object beneath the Earth's surface(Modification of Telford et al., 1990).

$$V = -C_m \vec{m} \cdot \nabla \left[\frac{1}{r}\right] = C_m \frac{m \cos\theta}{r^2} \quad (1)$$

The magnitude of the magnetic potential for all rock volumes can be determined by the integration equation (1) and slightly altering the variables. The result is shown in equation (2).

$$V(\vec{r}_0) = -C_m \int \vec{M}(\vec{r}) \cdot \nabla \left[\frac{1}{|\vec{r}_0 - \vec{r}|}\right] dv \quad (2)$$

Where $\vec{M}(\vec{r})$ is the dipole moment per unit volume andC_m is a constant. The magnetic induction of all rocks can be computed using an integration procedure that can be described by equation (3), if $\vec{M}(\vec{r})$ has a specific value and direction.

$$\vec{B}(\vec{r}_0) = C_m \nabla \int_V \vec{M}(\vec{r}) \cdot \nabla \left[\frac{1}{|\vec{r_0} - \vec{r}|}\right] dV \quad (3)$$

Equation (3) refers to an induced magnetic field as a magnetic anomaly that is continually superposed with the earth's main magnetic field (B_0) Therefore, the number of total magnetic field measured in the magnetometer at a location is a resultant of the main magnetic field and magnetic anomalies (B_{r0}), without considering the external magnetic field. The formula is shown in equation (4).

$$\vec{B}_T = \vec{B}_0 + \vec{B}(\vec{r}_0) \quad (4)$$

However, to obtain a total magnetic anomaly, we needed to conduct the correction process to the collected total magnetic field data. The correction process included daily corrections (B_D) , topographical correction (B_{To}), and main magnetic field correction or IGRF (B_{r0}), The correction equation can be expressed by equation (5) with the total magnetic anomaly written as ΔB (Stella & David, 2015).

$$\Delta B = B_T - B_D - B_0 \quad (5)$$

The main magnetic field of the earth is depicted by the IGRF (International Geomagnetic Reference Field). The surface-level IGRF value varies with latitude and time rather than being constant. By updating and establishing IGRF values on a regular basis, such as every five years, it is possible to understand how changes in magnetic values may affect IGRF (Macmillan & Maus, 2005).

Method

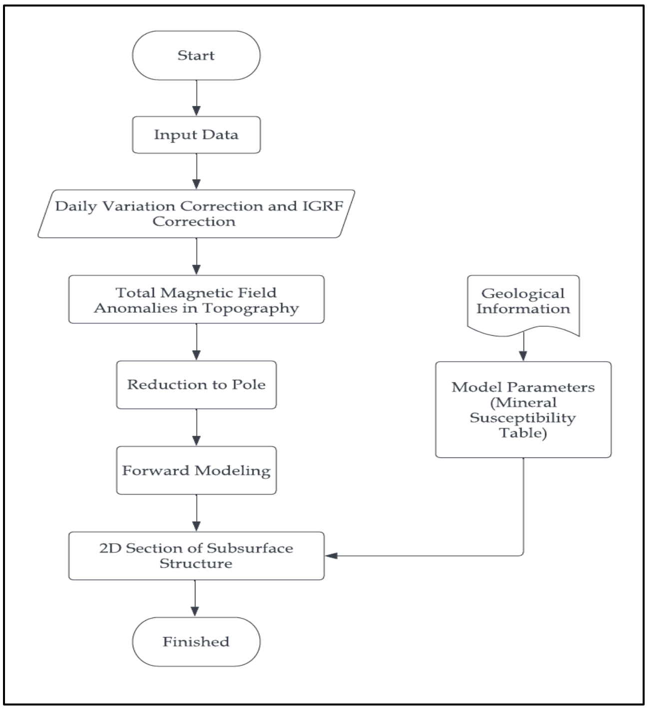

Figure 3. Flow chart of research methodology.

Retrieval of geomagnetic data in this study was carried out by measuring the magnitude of the total magnetic field at predetermined points in the research area using a Proton Procession Magnetometer. Data collection was carried out on 02 – 15 January 2022. The number of measurement points was 130, with a distance of 1 km between points.

The research area covers nine sub-districts in Bengkulu city: Muara Bangka Hulu sub-district, Sungai Serut sub-district, Teluk Segara sub-district, Ratu Agung sub-district, Ratu Samban sub-district, Singaran Pati sub-district, Selebar sub-district, Kampung Melayu sub-district, and GadingCempaka sub-district.

Research began with data collection. After obtaining the data, several corrections were made, including daily and IGRF corrections to find the total field anomaly data. All magnetic anomaly data were spread over the topographical plane and must be reduced to a horizontal plane because the magnetic anomaly data must be distributed horizontally for further processing (Blakely, 1996). After that, we conducted data correction of the magnetic anomaly data from the influence of regional magnetic anomalies to get the value of local magnetic anomaly data(Telford et al., 1990).

The total magnetic anomaly data shown in equation (5) is spread over the topographical surface, meaning the total magnetic anomaly data is a function of longitude (x), latitude (y), and altitude (h). Next, the anomaly data were lifted to a horizontal plane (h_0) of topography using the Taylor series equation in equation (6). Iterative form can be used to write equation (6), where $\Delta B\ (x, y, h_0)$ the magnetic anomaly data dispersed in a flat plane were obtain through an approach; $\Delta B\ (x, y, h_0)$ from the iteration I could be used to get a value of $\Delta B\ (x, y, h_0)$ on $(i+1)$-iteration. The iteration processes were carried out adequately to obtain the of value $\Delta B\ (x, y, h_0)$ that showed convergence (Blakely, 1996).

$$\Delta B(x, y, h_0)^{[i+l]} = \Delta B(x, y, h) - \sum_{n=0}^{\infty} \frac{(h-h_0)^n}{n!} \frac{\partial^n}{\partial z^n} \Delta B(x, y, h_0) \quad (6)$$

Regional magnetic anomalies had an impact on magnetic anomaly data that was dispersed in the horizontal plane. Therefore, because this research targeted underground structures, it was necessary to reduce regional magnetic anomaly data. By extending the magnetic anomaly data spread horizontally upwards to a specific height $(h_0 + \Delta h)$,regional magnetic anomaly data were obtained, so changes to the anomalous data show a smooth trend. The following anomaly data formula was taken from Green's Second Identity Theorem (Blakely, 1996) and can be expressed in Equation (7).

$$\Delta B(x, y, h_0)^{[i+l]} = \Delta B(x, y, h) - \sum_{\infty=0}^{\infty} \frac{(h-h_0)^n}{n!} \frac{\partial^n}{\partial z^n} \Delta B(x, y, h_0)^{[i]} \quad (7)$$

$\Delta B(x', y', h_0 + \Delta h)$ is the regional magnetic anomaly data, corrected using equation (8)(Stella & David, 2015).

$$\Delta B_{Local} = \Delta B(x, y, h_0) - \Delta B(x', y', h_0) \quad (8)$$

The local magnetic anomaly data obtained is a magnetic anomaly data that describes underground conditions.

Result and Discussion

The magnetic field measurement results are influenced by the external magnetic field, the main magnetic field, and the magnetic field anomaly. We removed the external magnetic field using daily variation correction to get the magnitude of the obtained magnetic field anomaly in the field. The main magnetic field was removed using IGRF correction (Firmansyah & Budiman, 2019). IGRF values can be obtained from the online website of the National Geophysical Data Center (NGDC). The IGRF value obtained for the research area is 43800.49 nano Tesla.

Qualitative Interpretation

Qualitative interpretation is based on magnetic field anomaly patterns originating from the distribution of rocks and minerals that are integrated into the subsurface geological structure of the earth (Awaliyatun & Hutahaean, 2015).

After correcting the magnetic field data, magnetic anomaly data were obtained and processed with Mag2DC software. The results were used to produce magnetic anomaly maps in Figure 4. Figure 4 shows that the magnetic anomaly at the research location is in the range of -2028.15 to 2666 .94 nano Tesla. In this case, the magnetic anomalies can be grouped into two parts: magnetic anomalies with positive values and anomalies with negative values. The positive anomaly values range from 0 to 2666.94 nano Tesla and negative anomalies range from -2028.15 to <0 nano Tesla.

Quantitative interpretation

A quantitative interpretation was carried out to describe the subsurface structure from the measured data in the field with two-dimensional (2D) mathematical modeling using Mag2DC software. By creating a 2D model, the subsurface structure could be identified based on the susceptibility value of each rock scattered in the study area.

From the magnetic anomaly map in Figure 4.a, cross-sections were made to obtain data in making a two-dimensional (2D) model from the cross-sectional data on the magnetic anomaly map representing magnetic anomalies below the surface.

The cross-sections in Figure 4.b were sliced across all magnetic anomalies in the study area to determine and correlate each rock model obtained.

Making a model with Mag2DC software was conducted using the forward modeling method. This method requires researchers to conduct trial and error while modeling the rock layering structure (Setiadi et al., 2016).

To create a model, we input a declination value of 0.0921 degrees and an inclination value of -25.054 degrees from the National Geophysical Data Center (NGDC) website. Meanwhile, the maximum depth displayed is 1000 meters, and the rock or mineral susceptibility value follows the research location's geological conditions and the IGRF value. The parameters were changed to get an overview of the rock layer structure were the model's shape, depth, and susceptibility values.

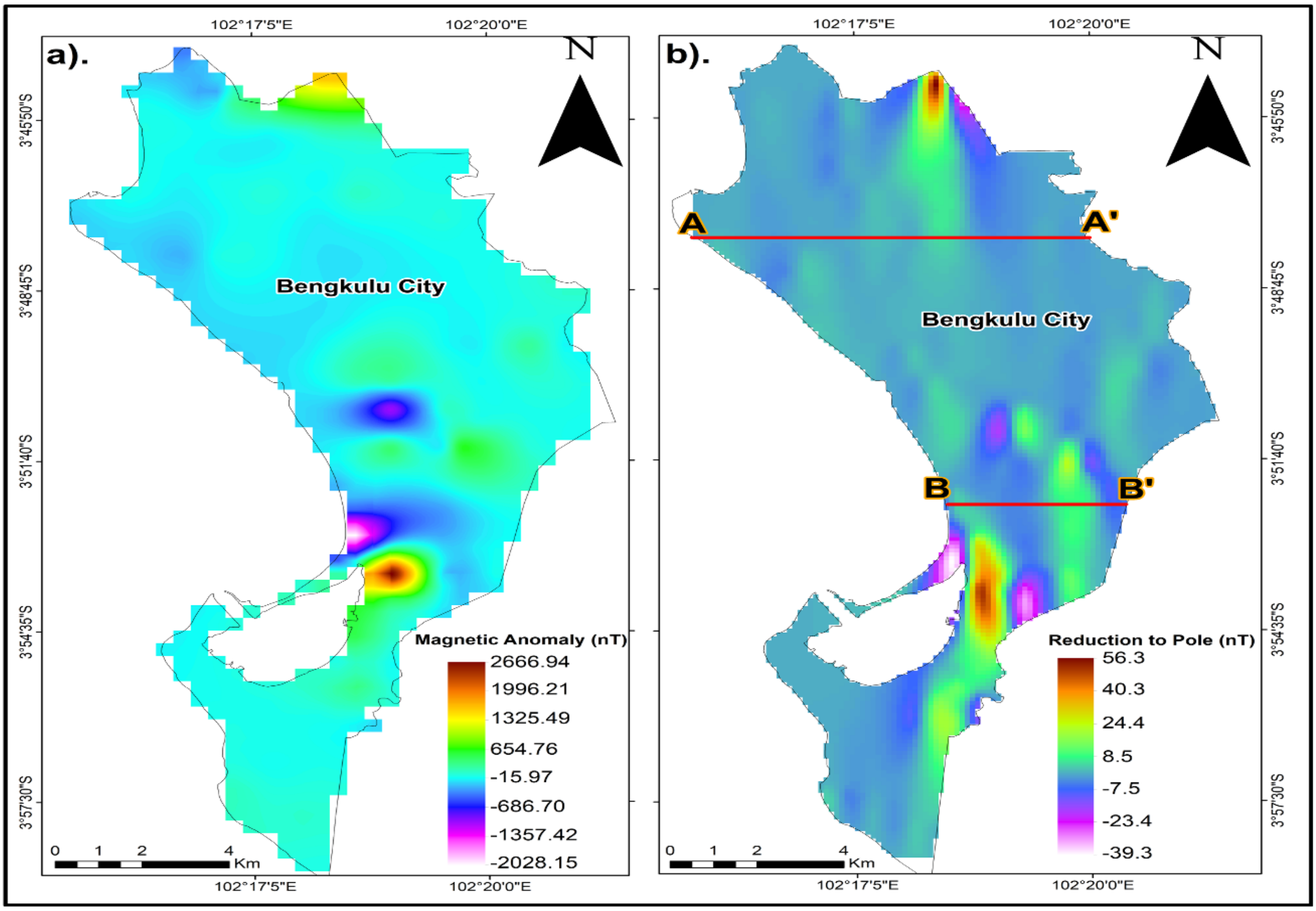

Figure 4. a. Total Anomaly Distribution Map, b. Map of the Distribution of Polar Reduction as well as A-A' and B-B' sections

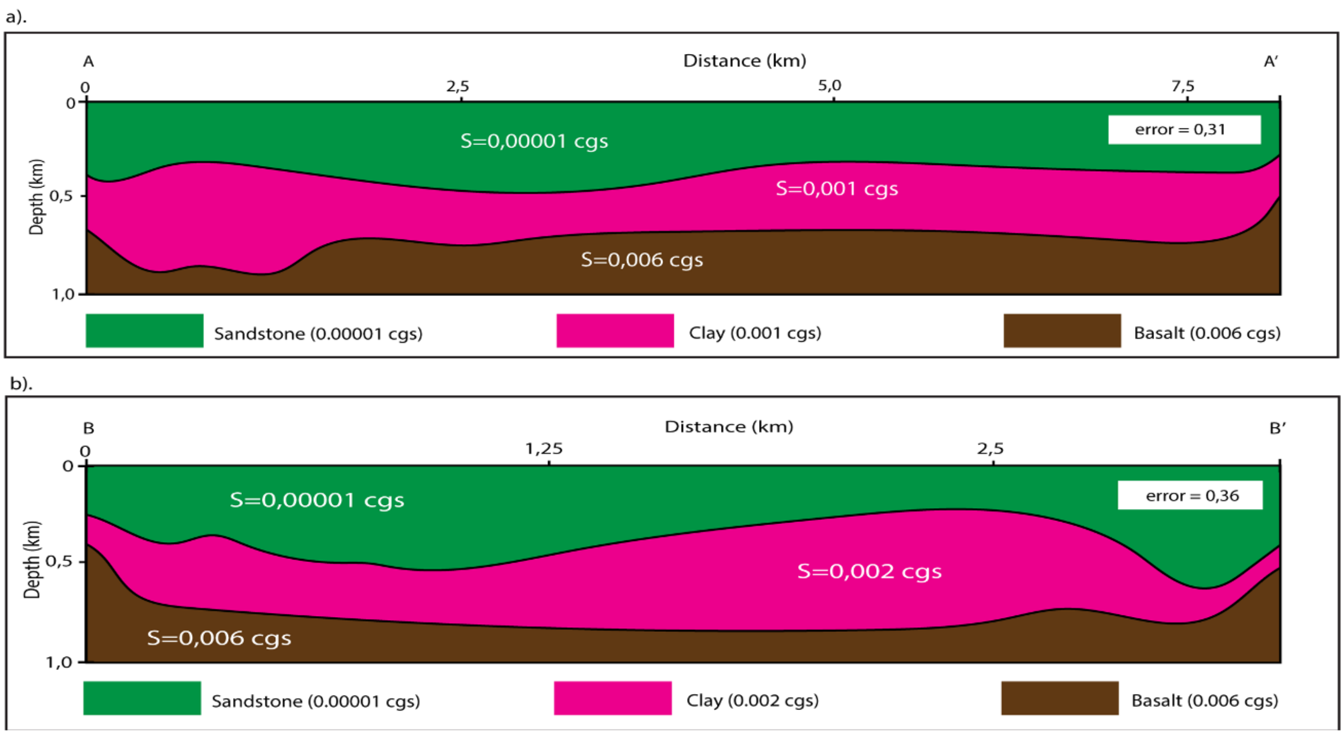

Figure 5. a. 2D modeling results on polar reduction anomaly data along the trajectory A-A', b. 2D modeling results on polar reduction anomaly data along the B-B' path

Changing these parameters was carried out continuously until the experimental anomaly value approached the anomaly value of the measurement results at the research location (forward modeling method). This was indicated by overlapping the test anomaly graphs with the measurement results from anomaly graphs at the study site (Deniyatno, 2010). Suppose the two graphs coincide with each other. In that case, it can be concluded that the subsurface rock layering model is close to the actual conditions, so the susceptibility value of each polygon is taken to interpret the rock types modeled by comparing the susceptibility value of each polygon with the standard rock susceptibility table.

The susceptibility values of the modeling results were in the CGS units, so they must be converted to SI units, which are multiplied by 10^{-6} . Finally, the susceptibility values of the conversion results were adjusted to the standard value of rock susceptibility to interpret the rock type.

Table 1. The list of rock and mineral susceptibility (Modification from Telford, 1990)

Types of Rocks / Minerals	Susceptibility (x 10^{-6} emu)	
	Intervals	Average
Sedimentary Rock		
Dolomites	0 – 75	10
Limestone	2 – 280	25
Sandstone	0 – 1660	30
Clay	5 – 1480	50
Av. Sedimentary	0 – 4000	75

The A-A section results, with a length of 7.8 km (figure 5.a), produce three-layer models with different susceptibility values. The first layer is green with a susceptibility value of 0.00001 cgs, estimated as a type of sandstone with a thickness of 400 m. The second layer is pink with a susceptibility value of 0.001 cgs, estimated as clay with a thickness of 350 m. The third layer is brown with a susceptibility value of 0.006 cgs, estimated as basalt with a thickness of 250 m.

The results of the B-B' section, with a length of 2.9 km, produce three-layer models with different susceptibility values (figure 5.b). The first layer is green with a susceptibility value of 0.00001 cgs, estimated as sandstone with a thickness of ±450 m. The second layer is pink with a susceptibility value of 0.002 cgs, estimated as clay with a thickness of 300 m. The third layer is brown with a susceptibility value of 0.006 cgs, which is estimated as basalt rock with a thickness of 250 m.

In the arrangement of the cross-section (figure 4), It is understood that the study area's rock types have a similar rock with a pattern in respect to the horizontal and vertical axes. The pattern was relative to the horizontal means that the sandstone sedimentary rock layers in the A-A' cross-section are similar to the sandstone sedimentary pattern in the B-B' cross-section, while what is meant by relative to the vertical is that the shape of the layers of each cross-section is almost similar to one another.

Conclusion

After the acquisition, processing, and interpretation of the data, it is known that the total magnetic field contour was corrected for daily variations, and IGRF obtained a magnetic dipole which indicates an anomaly in the study location. The total magnetic field anomaly on the contour shows pairs of positive and negative closures, with a magnitude of the magnetic field in the positive closures of about 1224.7 nano Tesla and the magnetic field of negative closures of around -4634 nano Tesla. Interpretation based on the outcomes of the processed data shows that Bengkulu City has three rock layers. The average value in the first layer is 0.00001 cgs which is sandstone. The average value for the second layer is 0.002 cgs, in which is dominated by clay. While, the average value of the third layer is 0.006 cgs, in which is basalt rock layer.

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