Geological interpretation of offshore Central Sumatra basin using Topex satellite gravity data

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Abstract. Topex is a geodetic satellite to map earth surface topography with very high precision. Two types of data can be obtained from Topex satellite, namely topographic and free-air gravity field data. Then, it is processed to produce Bouguer anomaly which will be used to interpret the subsurface geology of a specific study area. The purpose of this study was to delineate sedimentary basin and basement configurations. The methods used in this research are spectral analysis, band-pass filter and 2D forward modeling. The spectral analysis results show the average thickness of the sedimentary rocks is 2.1 km. Sub-basin patterns based on the band-pass filter are 7 sedimentary sub-basins and the structural patterns found in this area comprise basement height, graben and fault. The 2D modeling results show that the bedrock in the eastern part of the Central Sumatra basin is granitic with a mass density value of 2.67 gr/cc and the layer above the bedrock is interpreted as a sedimentary rock with a mass density value of 2.35 gr/cc. Analysis of the gravity data shows significant results as initial information to delineate sedimentary sub-basin and regional structure to enhance information to the next stage of hydrocarbon exploration.

Keywords: Bouguer gravity anomaly, geological interpretation, offshore Central Sumatera basin, Topex satellite data

1. Introduction

The Central Sumatra Basin is the tertiary sedimentation basin that produced one of the biggest oil and gas fields in Indonesia. Based on its tectonic position, the Central Sumatra Basin is known as the back-arc basin and relatively elongated in a Northwest-Southeast direction, where its formation is affected by the subduction of the Indian-Australian plate which moved under the Asian plate [1]. Oil and gas exploration activities in the Central Sumatra Basin are mostly carried out in the western area, namely at the land area, while for the eastern region, especially at sea or at the Malacca Strait and its surrounding area is still rare carried out because the sediment layer at eastern region according to [2] was thin. This causes interest in researching the potential sedimentary basins in the eastern part of the Central Sumatera Basin.

One of the geophysical methods used to determine subsurface geological conditions based on physical parameters of mass density is the gravity method. This method is commonly used as a preliminary survey in oil and gas exploration to determine regional geological structure patterns. Nowadays, satellite altimetry such as Topex Poseidon has become an advanced instrument to observe marine gravity anomalies. Some applications of free-air anomaly data and Topex satellite altimetry are to predicting the seafloor depth, knowing undersea volcanoes, oil and gas exploration, tectonic plates and lithosphere structures [3], meanwhile [4] using gravity data derived from the Geosat, ERS-1
and Topex-Poseidon altimetry satellites for a case study application at Reykjanes Ridge, Iceland. The Topex satellite data is also used to determine the structural geological analysis of oil and gas prospects in West Aceh, Indonesia [5]. Analysis of sub-basin patterns and basement configurations hasn’t been done in this area. In hydrocarbon exploration, information about sediment thickness, structure lineament and basement height patterns is needed as initial information to map the depocenter existence which is followed by a more detailed survey such as seismic methods, so that this study is important to do. This research aims to delineate the sedimentary sub-basin, geological structure patterns and knowing the basement configuration in the eastern part of the Central Sumatra Basin based on gravity data derived from free-air anomaly and topography from Topex satellite altimetry.

2. Materials and Methods
The data used in this study are free-air anomaly and topography data taken from Topex satellite [6], which can be accessed via the website http://topex.ucsd.edu/cgi-bin/get_data.cgi with ASCII format. The data has a lateral spacing of about 1 min/grid with free air anomalous data error of 0.1 mGal and a height error of about 1 m [7]. The data format of XYZ position, free air anomaly, and altitude is then converted to gravity (Bouguer) anomaly using the following equation:

\[ BA = FAA - (-2\pi G (2.67 - 1.03)) h \]  

Note:  
- \( BA \) = Bouguer Anomaly (mGal)  
- \( FAA \) = Free air Anomaly (mGal)  
- \( G \) = Gravity constant \( (6.67 \times 10^{-11} \text{ N.m}^2 \text{.kg}^{-2}) \)  
- \( h \) = Depth of bathymetry (m)

Data processing is carried out to convert the free-air anomaly and topography data into Bouguer anomaly. Bouguer anomaly data is a combination of regional and residual anomalies. Regional anomalies are characterized as long wavelengths and originate from anomalies with a deeper depth, while residual anomalies usually have shorter wavelengths and originate from anomalies with the shallower position. The method used to analyze the Bouguer anomaly data is by performing spectral analysis to find the optimal window width and also to estimate the depth of the basement. Furthermore, a band-pass filter will be carried out to separate regional and residual anomalies. Then, subsurface geological models were done by means of 2D forward modeling method. The results of regional and residual anomalies were then used for qualitative analysis to determine the distribution pattern of sedimentary sub-basins, basement height, and graben patterns. Meanwhile, the geological model generated from 2D forward modeling is used for quantitative interpretation, namely to determine the sub-basin model and the basement configuration vertically. By knowing the distribution pattern of the sedimentary sub-basin and basement configuration, it is hoped that new information will be obtained about regional geological concepts based on different data reviews that can be used as a reference for the next stage of oil and gas exploration planning.

3. Result and Discussion
The Bouguer anomaly pattern that resulted from the conversion of Free Air Anomaly (FAA) and topography from Topex satellite data can be seen in Figure 1a. It can be seen that the gravity anomaly values range from 5 to 35 mGal. The gravity anomaly pattern in the eastern part of the Central Sumatra Basin can be grouped into three different anomaly routes. The first is a high anomaly route that has a value range between 25 to 35 mGal. This anomaly generally occupies the southeast of the research area, namely in the Malacca Strait, Malaysia borders and the east coast of Sumatra Island which is characterized by red color. This anomaly is probably due to the influence of the basement which is a shallower position, this result is following the research conducted by [2] which states that this area has a thin sediment layer. The second anomaly route is a moderate anomaly, with a range of anomaly values from 15 to 24 mGal. This anomaly generally occupies the middle part of the research area,
namely around Bengkalis Island, Padang Island and Rupat Island. The second anomaly route is likely related to sedimentary basins in the eastern part of the Central Sumatra Basin.

The third anomaly is a low anomaly with a range of anomaly values between 5 to 14 mGal. This anomalous path generally occupies the middle of the research area and extends from the Northwest to the southeast in the Malacca Strait area, characterized by blue color. This anomaly is likely caused by the sedimentary rock that fills this basin. However, the Bouguer anomaly cannot be used for direct geological interpretation because it is still a combination of regional and residual anomalies, so it needs to be filtered first. Before filtering, a cross-section of the Bouguer anomaly map is made for spectral analysis with the direction of the trajectory as shown in Figure 1a.

Figure 1. (a) Gravity (Bouguer) anomaly map, (b) example graph of spectral analysis results, and (c) the spectral analysis result of Offshore Central Sumatera Basin and its surrounding area.

Spectral analysis is carried out by performing the Fourier Transform (FFT) of the spatial data on these 9 trajectories. The example of the spectral analysis graph results can be seen in Figure 1b. The spectral analysis graph shows two depth trends anomalous sources, namely regional and residual trends that show two fields of discontinuity, deep and shallow. From the nine trajectories, a table of spectral analysis results is then made, as shown in Figure 1c. It shows the overall results of the spectral analysis of the P1-P9 trajectory consisting of regional depth, residual depth, wave number cutoff, and window width. The calculation result of the spectral analysis shows that the average depth of discontinuity plane (regional) is about 30 km. This depth is interpreted as an undulation plane of the deep structure. In comparison, the depth of the discontinuity field of a shallow source (residual) of about 2 km is interpreted as the basement depth.

The window width from the spectral analysis results is used as the basis for determining the optimal window width for the filtering process. Based on the spectral analysis result, the optimum window width is (60x60) km. This window width is used to determine the optimal window for separating regional and residual anomalies using low pass and band-pass filters. The results of the separation of the regional and the residual anomaly can be seen in Figure 2. Figure 2a shows the regional anomaly pattern resulting from the low-pass filter with a window width (60x60) km, it can be seen that the anomaly value ranges from 10 to 33 mGal. High anomalies in the south, southwest and east area are probably due to the influence of basement which is relatively upward. In contrast, low anomalous in the middle area is probably caused by sedimentary rocks that fill the basin. Figure 2b shows the residual anomaly pattern resulting from the high-pass filter. This anomaly has a relatively short wavelength and reflects a shallower source of the anomaly. The residual anomaly using a high-pass
filter still shows anomalies with a high frequency (which is considered as noise) as shown in Figure 2c, so it needs to be smoothed by applying a band-pass filter so that the results look smoother, as shown in Figure 2d.

![Figure 2](image)

**Figure 2.** (a) Regional anomaly map low-pass filter, (b) residual anomaly map high-pass filter, (c) noise of gravity data, and (d) residual anomaly map band-pass filter of Offshore Central Sumatera Basin and its surrounding area.

### 3.1 Qualitative Interpretation

Qualitative interpretation aims to determine the lateral anomaly changes based on the residual anomaly that has been obtained from the band-pass filter results. This qualitative interpretation is usually used to determine the pattern of structural lineament, basement height, and delineation of the sedimentary basins. A qualitative interpretation from residual anomaly pattern based on band-pass filter can be seen in Figure 3. The structural pattern has a relative Northwest-Southeast direction as shown in Figure 3a. This pattern follows the main lineament pattern on the land side of the Central Sumatra Basin. The geological structure patterns in this area are probably due to the influence of regional tectonics. The patterns are formed due to the subduction of the Hindia ocean crust from the southwest direction. The structure pattern which is formed in this area has a direction perpendicular to the subduction, which has a relatively North-Southeast-West direction [1].

Sedimentary rock at the eastern part of the Central Sumatra Basin is relatively thinner than at the western area because the rocks at the eastern region were located on the Sundanese shelf as a continental crust. There were relatively small sedimentary depositions in the eastern area [2]. The height anomaly pattern is shown as red color and the lineament pattern is shown as a line in black color. These patterns show the position of the basement which is relatively upward. The height pattern delimits one subbasin and the others which may have different rock facies. The sub-basin delineation
pattern obtained based on the results of the band-pass filter can be seen in Figure 3b. This sedimentary sub-basin pattern has a relative Northwest-Southeast direction. It can be seen that the sub-basins delineated based on the residual gravity anomaly are 8 sedimentary sub-basins and one sedimentary sub-basin is in the Malaysian territory.

The sedimentary sub-basin is shown as a typical anomaly pattern (blue color) with an anomalous range of -8 to 7 mGal. This basin is classified as a shallow basin. Information about sedimentary basins is important to know as a guide to determine the thickness of the sedimentary rock and basement height in the oil and gas exploration activities. It can be seen that in general, the thicker sedimentary sub-basin is relatively in the area around the Malacca Strait, the thinner those on the mainland of the Sumatra Island. This depocenter gives a place for sedimentary rock to be deposited. If there is a complete petroleum system in this basin, there will likely be the potential for the presence of hydrocarbon [2].

![Figure 3. (a) Structural pattern map, and (b) subbasin delineation map of Offshore Central Sumatera Basin and its surrounding area.](image)

3.2 Quantitative interpretation

The quantitative interpretation aims to determine the subsurface geological model which includes the dimensions or size of the model, the type of rock made based on the physical parameters of rock density. The results of quantitative interpretation are expected to know the depth of the basement and the composition of the sedimentary rock above it. This quantitative interpretation is carried out by doing 2D modeling, and the results of 2D modeling of gravity data can be seen in Figure 4. Three lines namely X-Y, AB, and CD were selected at residual anomaly map to make subsurface geological modeling in the eastern part of Central Sumatra Basin as shown in Figure 4a and Figure 4b are subsurface geological models of gravity data along the X-Y trajectory controlled by HM79-79 seismic line. Figure 4b shows that the basement on this trajectory is around 1300 meters in depth with a mass density value of about 2.67 gr/cc.

This basement is interpreted as a granitic rock. The sedimentary layer based on rock type and depth which obtained from MSF-1 well data, where the Pematang Formation is deposited above the basement with a mass density value of about 2.25 gr/cc, above Pematang Formation is the Sihapas Formation with a density value of 2.3 gr/cc the Telisa Formation deposited above Sihapas Formation with a mass density value of 2.35 gr/cc, above Telisa formation the Petani Formation is deposited with a density value of 2.25 gr/cc. The uppermost layer is the Minas Formation with a mass density value of 2.2 gr/cc. The structure pattern and depocenter of the basin don't appear in the X-Y cross-section because the direction of the trajectory is parallel to the main structure which has a Northwest-Southeast direction. For that reason, we will try to make a subsurface geological model to determine
the configuration of the basement by taking the trajectory direction perpendicular to the main structure, namely the relative Southwest-Northeast direction (AB section) and east-west (CD section), as shown in Figure 4c and Figure 4d.

![Figure 4. Quantitative interpretation (a) section direction map of the model, (b) subsurface model along X-Y, (c) subsurface model along A-B and (d) subsurface model along C-D.](image)

The AB cross-section extends along the Southwest-Northeast direction, starting from Sumatra Island to the northeast, namely the Malacca Strait in the Eastern part of Malaysia. The subsurface geological model of the AB section as shown in Figure 4c shows that the basement consisting of the granitic crust was located at a depth of about 2 km and has a density value of 2.67 gr/cc. Above the basement is a sedimentary rock model, in general with a mass density value of 2.35 gr/cc. In this model, we only want to know the basement configuration pattern, the basin depocenter filled by sedimentary rocks, basement high and structural alignment patterns in this area. From this model, it can be seen that there is some depocenter, namely in the southwest, southeast of Rupat Island, and northeast around the waters of the Malacca Strait. The subsurface geological model of the CD cross-
section as shown in Figure 4d shows that the basement is granitic same as the AB cross-section with a mass density value of 2.67 gr/cc, above the basement was deposited sedimentary rock with a density value of 2.35 gr/cc. The direction of the trajectory of this cross-section modeling is relatively west-east through high and lows gravity anomaly so that it can be seen that several depocenters are filled with a thick sedimentary layer in the south of Rupat Island and around the southeast of Bengkalis Island. The few wells penetrated a basement in the Malaka Strait area [2], generally shown by granites. Based on regional settings these rocks are interpreted as a part of Sundaland Craton [1].

The results of qualitative analysis from the gravity data at the offshore Central Sumatran basin show that the basin pattern has a relatively northwest-southeast direction. The lineament pattern of this basin follows the pattern of the regional structure of Sumatra. Central Sumatran Basin is a back-arc basin due to the subduction activity of the Hindia Ocean plate to the Sundaland Craton [1]. The pattern of the offshore central Sumatran basin is a basin located at the east of the central Sumatra basin so that the basin is thinner than sedimentary rocks at the west area [2]. However, the results of the quantitative analysis show that there are many depocenters and basement high that probably as the place for hydrocarbon indication. While the results of the quantitative analysis show that the basement in this area is granitic rock, this is under information [1] which states that the basement of this area is the continental crust of the Sundaland Craton. The sediment thickness ranges from (1 to 2) km. This is quite interesting as a place for the petroleum system indication which includes source rocks, reservoir, trap, and sealing rocks [2].

4. Conclusion
The structural pattern that appears in the study area based on the results of qualitative analysis of residual anomalies shows a relative Northwest-Southeast direction. This pattern follows the regional pattern caused by the subduction of the Hindia ocean crust from the southwest under the Asian Continental Plate. The results of the spectral analysis showed that the depth of the basement in the study area was about 2.1 km. The number of sedimentary sub-basins that can be delineated based on this gravity data analysis is 7. The basement underlies the research area is interpreted as continental crust Sundaland rocks with a mass density value of about 2.67 gr/cc. Based on the results of the gravity analysis, it can be seen that there are several depocenters filled by sedimentary rocks which are quite interesting as a place for hydrocarbon indication, such as in the sub-basin between the Bengkalis Islands and Sumatra which extends in a relatively Northwest-Southeast direction. Another interesting sub-basin is in the Malacca Strait bordering Malaysia which extends in a relatively Northwest-Southeast direction. On the right and left of the basins, several basement heights are probably potential for hydrocarbon migration.

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References
[1] Eubank R T and Makki A C 1981 Structural geology of the central sumatera back-arc basin, Proc. Indonesian Petroleum. Assoc. 10th Annual Convention and Exhibition May 1981 p 153-196
[2] Lee R A 1982 Petroleum geology of the malacca strait contract area (central sumatera basin), Proc. Indonesian Petroleum. Assoc. 11th Annual Convention and Exhibition June 1982 p 280-297
[3] Sandwell D T and Smith W H 1997 Marine gravity from geosat and ers-1 satellite altimetry J. Geoph. Research: Solid Earth 102 0039-10054
[4] Hwang C and Parsons B 1995 Gravity anomaly derived from seasat, geosat, ers-1, and topex/poseidon altimetry and ship gravity: a case study over the reykjanes ridge Geoph. J. Int. 122 551-568
[5] Darisma D, Marwan and Ismail N 2019 Geological structure analysis of satellite gravity data in oil and gas prospect area of west Aceh-Indonesia J. Aceh Phys. Soc. 8(1) 1-5
[6] Topex.ucsd.edu 2021 Free air anomaly and bathymetry of eastern part of central sumatera basin Topex.ucsd.edu/cgi-bin/get_data.cgi, accessed on February 3rd, 2021
[7] Sandwell D T and Smith W H 2009 Global marine gravity from retracked geosat and ers-1 altimetry: Ridge segmentation versus spreading rate J. Geoph. Research Atmospheres 114 (B01411) 1-18