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Crustal Structure Modeling Using Regional Gravity in The Tarakan Sub-Basin

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Abstract. The Tarakan Sub-Basin is characterized by heterogeneous structural conditions, including variations in stratigraphy and complex tectonic activity. Although seismic data is accessible, it only covers shallow depths and does not extend to deeper continental boundaries. To acquire an improved understanding of the basin's geological structure and continental boundaries, further techniques, such as the gravity method are required. This research utilizes satellite gravity data from WGM 2012 and 3D seismic data to determine continental and oceanic boundaries, covering both offshore and onshore areas. The structure and boundaries of subsurface anomaly bodies are interpreted through gravity anomaly contrasts obtained by applying Total Horizontal Derivative. Forward modelling gravity is implemented to investigate the depth and boundaries of the continent and oceanic crust. The derived interpretations are validated by seismic data cross-sections. The result shows that the continental crust is located at depths ranging from 10 to 30 km in the western region of the research area, while the oceanic crust is found at depths varying from 15 to 25 km in the eastern part. Although the plate convergence merely indicates the boundary between continental and oceanic crust and there is no subduction activity between the crust, geological features such as toe thrusts in the eastern region are products of the oceanic crust. With this comprehensive approach, the study provides significant contributions to understanding the geological structure and crustal boundaries in the study area, revealing the complexity of the Earth's crust dynamics in the Tarakan Sub-Basin.

1. Introduction

Continental and oceanic boundaries, typically associated with geological structures such as sedimentary basins and faults, play a crucial role in hydrocarbon plays [1, 2]. Seismic data is highly reliable for subsurface imaging. However, it has limitations in penetrating deeper areas as stated by Panea et al. [3], resulting in challenges in acquiring information on the basement and continental boundaries. Gravity methods offer a solution by providing deep coverage, thus providing a more comprehensive understanding of the tectonic settings in these regions [4, 5, 6, 7, 8].

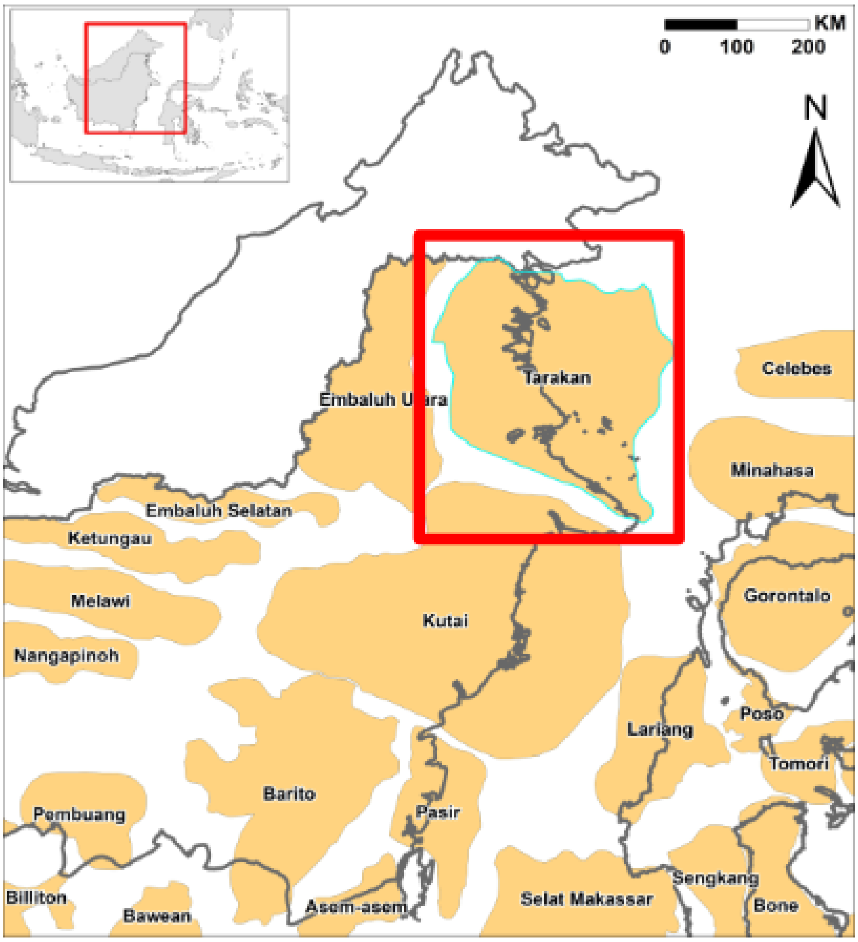

Figure 1. The location of study area in the Tarakan Sub Basin.

The Tarakan Sub-Basin is geologically characterized by two major NW-SE orientated structures: the Sempurna Fault in the north and the Maratua Fault in the south [9, 10]. This region has been divided into two segments: the onshore area in the west and the offshore area in the east. A horst structure is obvious in the onshore area. This site is part of an active delta system characterized by growth faults, which are representative of the structural evolution of this delta. A toe thrust system has developed in the distal region of the eastern part [11, 12]. The Tarakan Sub-Basin mostly consists of sandstone and shale layers with coal intercalations, originating from the Pleistocene to Pliocene.

This study aims to identify the crustal boundary in the Tarakan Sub-basin, which is predicted to host significant subsurface structure and its implication to petroleum system (Fig. 1). To achieve this objective, the First Horizontal Derivative (FHD) edge detection technique was implemented on satellite gravity data from WGM2012. The FHD method enhances lateral boundary definitions of anomalies, providing a clearer and more accurate depiction of geological boundaries within the sub-basin. In addition to FHD, forward modelling techniques were employed to analyse the geometry and depth of the crustal structures. The interpretation of the

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crustal boundary was further validated using both 2D and 3D seismic data to ensure the accuracy of the identified crustal boundaries and its depth.

2. Data and Methodology

To achieve the goals of this study, we used gravity satellite data and seismic techniques. We applied gravity data from WGM2012 to the Greater Tarakan Basin area of 200.460 km2. The gravity data was downloaded at https://bgi.obs-mip.fr/grids-and-models-2/. Additionally, seismic composite line data extends 220.45 km from onshore to offshore. Seismic composite data ranged from 0 ms to -9000 ms, with four well data points along the seismic line. Furthermore, we used interpreted seismic sections to validate these findings. The workflow of this study can be seen in Figure 2.

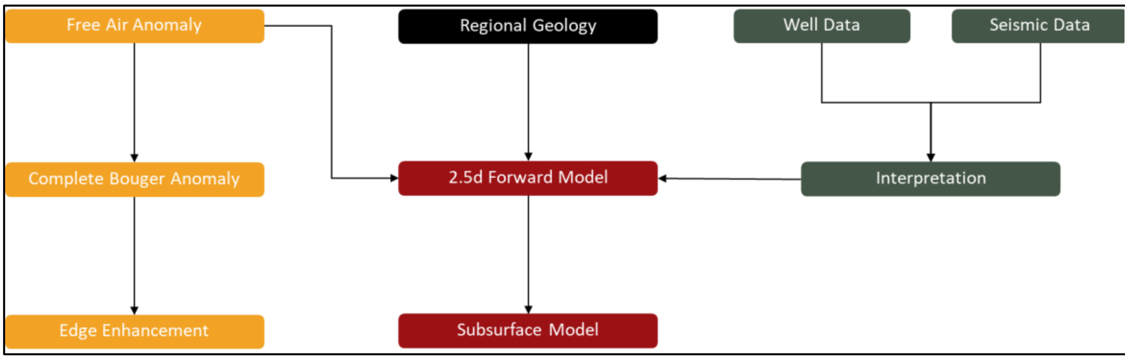

Figure 2. The workflow of this research.

The data acquired from the WGM2012 satellite comprise free air anomaly (FAA) and Complete Bouguer Anomaly (CBA), covering both onshore and offshore areas and total 14734 data points with spacing of each point approximately 2000m. To illustrate the subsurface lithological distribution, mapping of the CBA data was performed with a resolution of 2000m × 2000m. Considering that the CBA represents the total anomaly from subsurface mass distribution, it is necessary to separate shallow and deep anomalies using filtering techniques based on spectral analysis of the CBA data. The separation was accomplished by upward continuation at a height of 10 km. The filtered anomaly was subsequently used as input data for enhancement by the First Horizontal Derivative (FHD) method, establishing the delineation of the boundaries of the plate

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2.2 Example subsection heading

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2.3 First Horizontal Derivative (FHD)

The First Horizontal Derivative (FHD), introduced by Cordell and Grauch [13], is a technique in gravity data analysis that can detect subsurface bodies by considering the first-order horizontal derivative of the potential field, as described by the following equation:

$$FHD = \sqrt{\left(\frac{dg}{dx}\right)^2 + \left(\frac{dg}{dy}\right)^2}$$

with $\frac{dg}{dx}$ and $\frac{dg}{dy}$ demonstrate the derivatives of gravity field in the horizontal directions, x and y. This technique depicts maximum value in the top of anomaly source edge.

3. Data and Methodology

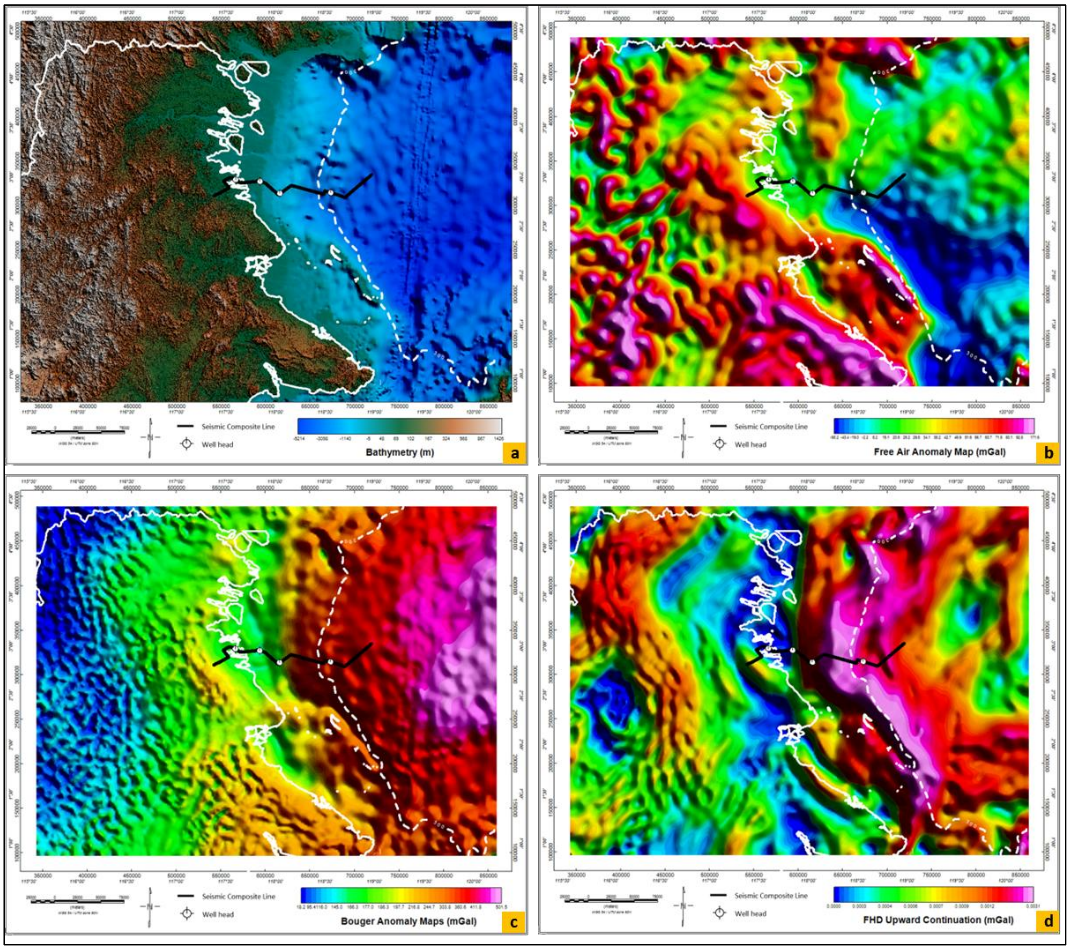

Figure 3. (a) Bathymetry Map, (b) FAA Map, (c) CBA Map, (d) FHD Filtred Map.

The gravity anomaly map (Fig. 3) depicts the distribution of subsurface lithological densities. The FAA map indicates that anomalies within the study area range from -100 mGal to 172 mGal (Figure 3b). Low anomalies are observed in offshore, while high anomalies are presented in onshore. In contrast, the CBA map, illustrated in Figure 3c, reveals high anomalies in offshore and low anomalies in onshore. The CBA values exhibit a wider range than the FAA, variying from 18 mGal to 501.5 mGal, suggesting that CBA is affected by both terrain and subsurface density variations. To improve edge effects related to lithological boundaries, we employed the FHD technique, with results displayed in Figure 3.d. In the FHD analysis, the maximum response values signify lithological boundaries potentially associated to crustal boundaries, oriented relatively N-S, with an anomaly value of 0.0031 mGal. Further, all gravity data maps are overlayed with white dash line (300 mGal of CBA) interpreted with oceanic and continental plate boundary. On the continental basement region, Bouguer anomaly values are usually below 220 mGal, while on the oceanic regions, they are commonly over 300 mGal as conducted by Druet et al [4].

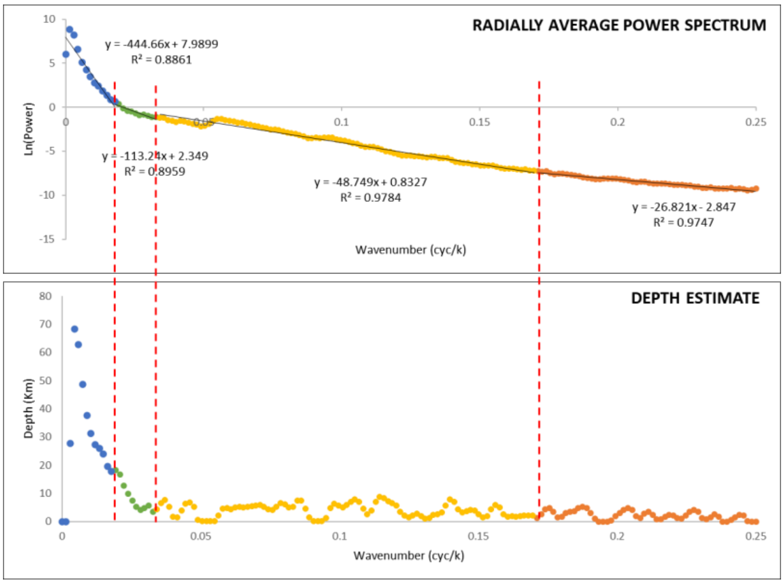

Figure 4. Radially Average Power Spectrum Graphics.

Figure 4 shows the analysis of crustal depth using gravity data spectra. Spectrum analysis is utilized to differentiate between deep (regional) and shallow (residual) anomalies. The graph indicates that the crust correlates with the regional anomaly shown in green dots, estimated to occur at a depth of 9 km.

The gravity anomaly in the study area exhibits CBA and FAA responses, as depicted in Figure 5(a). In the onshore region, located in the western part of the study area, FAA values are higher, ranging from 5 to 50 mGal, likely influenced by topographic effects. In contrast, the offshore area to the east shows lower values (-20 up to 10 mGal), due to the superposition of seawater density and bathymetric effects. Based on CBA values, the onshore to transitional areas display anomalies varying from 200 to 250 mGal, associated with the formation of growth faults, whereas the offshore region is dominated by toe thrust structures, with anomalies reached 270 up to 400 mGal. Moving eastward into the offshore zone, there is a significant increase in gravity response, which may be associated to the presence of dense rock bodies of deep anomalies.

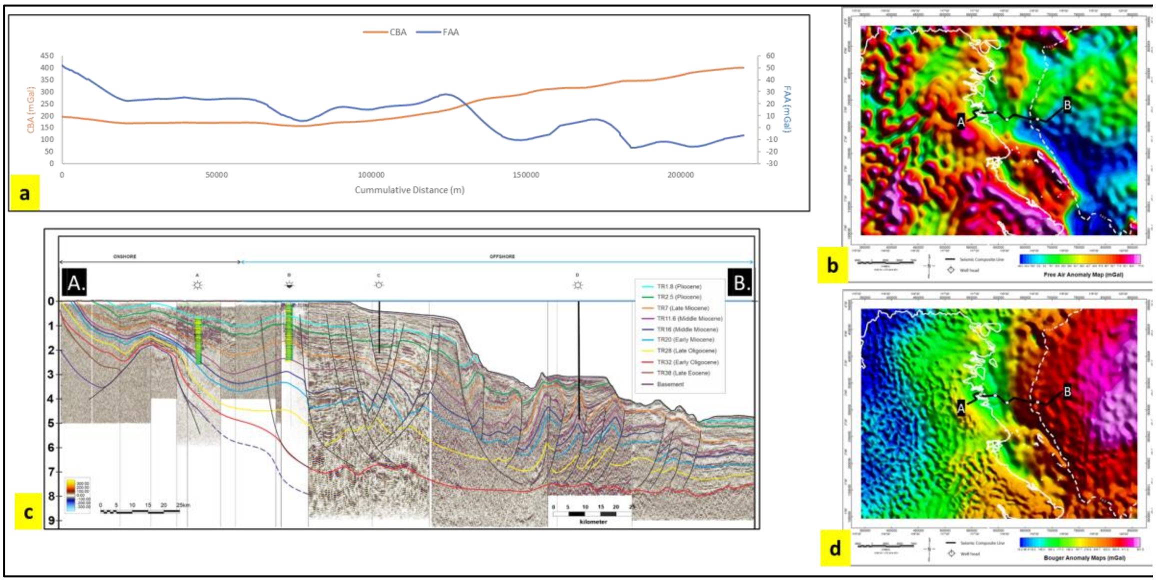

Figure 5. Comparisson between seismic line and gravity profile.

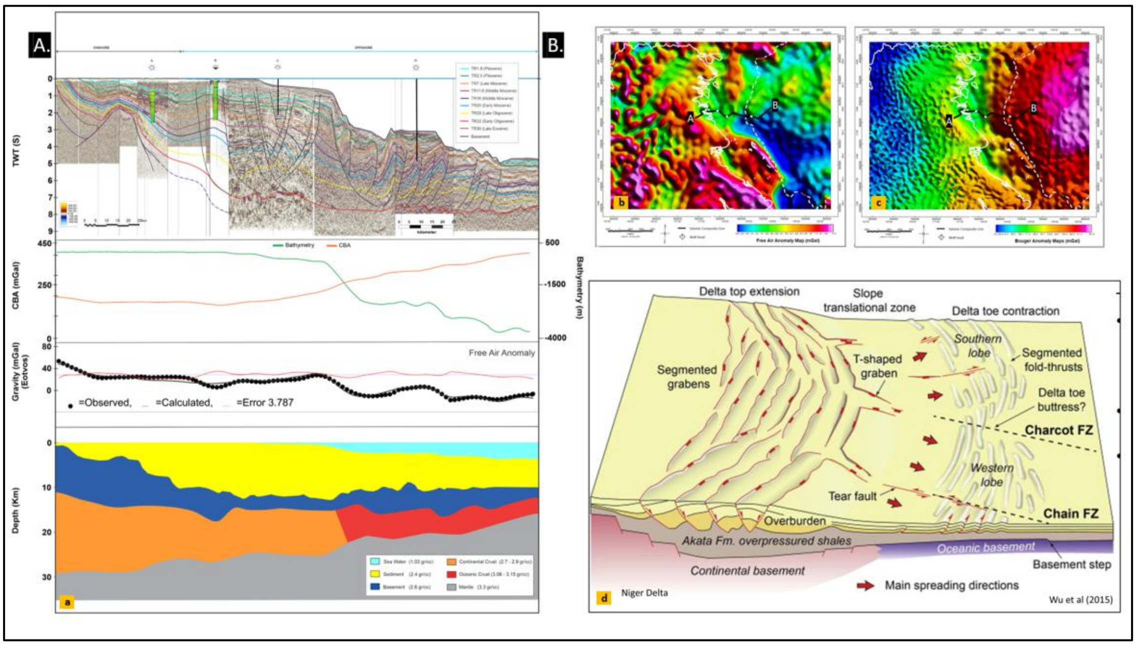

Figure 6. (a). 2.5D Forward Model (b). FAA (c). CBA (d). Conceptual model of structures at the Niger Delta by Wu et al. 2015 [14].

The results from the integration of multiple datasets were modeled using 2.5D forward modeling, as shown in Figure 6a. This model was constructed to a depth of 35 km, based on FAA values, CBA data for determining plate boundaries, the basement layer interpreted from seismic data, and rock density values from various literature sources. The model reveals several layers: the sedimentary layer (yellow area) with a density of 2.4 g/cc, representing the youngest rock formation, followed by the basement (2.6 g/cc, shown in blue). Beneath this lies the continental crust in the western section, with a density range of 2.7–2.9 g/cc (orange), adjoining the oceanic crust (red layer) on the eastern side, which has a higher density of approximately 3.06–3.15 g/cc. The oldest layer is the mantle, with a density of 3.3 g/cc, represented in gray.

The model highlights the subsurface configuration, where the boundary between the continental and oceanic crust is located in the transition zone between the growth fault system and the toe thrust system. The oceanic crust, situated beneath the toe thrust system, has a thickness ranging from 3 to 10 km, with a depth range of 10–20 km below sea level. In contrast, the continental crust, located in the growth fault system zone, has a thickness ranging from 10 to 20 km, with depths between 10 and 30 km below the surface. The model indicates the absence of subduction activity between the oceanic and continental crust, with the two crusts merely adjoining along their boundary layers. This model is further supported by several studies, such as Wu et al [14], whose findings, depicted in Figure 6d, map a geological configuration similar to the growth fault system and toe thrust system, with the oceanic and continental boundaries located in the transition zone.

4. Conclusions

Based on forward modelling data, continental crust thickness around 10-20 km and oceanic crust thickness around 3-10 Km with a depth around 10-30 Km below the surface. Oceanic and continental boundary is located between growth fault system and toe thrust system where oceanic crust located below toe thrust system and continental crust located below growth fault system.

Acknowledgments

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