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Integrated Geophysical Characterization of Shallow and Deep Reservoirs in the Wabi Field, Niger Delta

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ABSTRACT

This study conducted an integrated geophysical characterization of the WABI field's shallow and deep reservoirs, utilizing well log and 3D seismic data interpreted with Petrel software. Well logs delineated lithology and identified hydrocarbon presence in both correlated reservoirs (2850SSTLD, 3400SSTVD) (Figure 3, Figure 4). Seismic amplitude maps (Figure 5.1, Figure 5.2) and time structural analysis (Figure 6.1, Figure 6.2) revealed distinct subsurface geometries and fault-assisted trapping mechanisms. Furthermore, 3D Root Mean Square (RMS) amplitude analysis (Figure 7.1, Figure 8.1) identified potential hydrocarbon accumulation zones, while velocity models (Figure 9.1, Figure 9.2) clarified spatial variations linked to reservoir properties. The juxtaposition of these diverse datasets (Figure 7.2, Figure 8.2) provided a comprehensive understanding of reservoir heterogeneity, structural complexity, and fluid distribution. This integrated approach significantly enhances subsurface confidence, crucial for optimized hydrocarbon exploration and production strategies within the WABI field.

Keywords: Petrophysical analysis, Stratigraphic correlation, Acoustic impedance, Isochron maps, Volumetric estimation, Geological modeling, Seismic interpretation, Well placement, Hydrocarbon play, Subsurface imaging.

INTRODUCTION

The global demand for energy continues to drive intensive hydrocarbon exploration and production efforts, necessitating increasingly sophisticated approaches to subsurface reservoir characterization. Accurate reservoir understanding is paramount for optimizing drilling campaigns, enhancing recovery rates, and minimizing economic and environmental risks (Ahmed, 2018). In complex geological settings, such as the Niger Delta Basin, where multiple stacked reservoirs with varying characteristics exist, an integrated approach combining diverse datasets becomes indispensable (Doust & Omatsola, 1990). This study focuses on the WABI field, an area characterized by both shallow and deeper hydrocarbon-bearing intervals, presenting a case study for comprehensive geophysical characterization.

Despite significant exploration in the Niger Delta, challenges persist in precisely delineating and characterizing hydrocarbon reservoirs, particularly those with complex structural configurations and varying depths. Traditional methods relying on single data types often provide insufficient information, leading to uncertainties in reservoir geometry, fluid distribution, and overall productivity. The inherent heterogeneity of deltaic deposits, coupled with the presence of numerous growth faults and associated structures, demands a multi-faceted analytical framework to mitigate exploration and development risks (Weber & Daukoru, 1975). Therefore, a detailed and integrated geophysical characterization is crucial for maximizing hydrocarbon recovery and optimizing field development in such intricate environments.

Numerous studies have underscored the efficacy of integrating well log and seismic data for robust reservoir characterization. Well logs provide high-resolution vertical information on lithology, porosity, and fluid content, while seismic data offer extensive lateral coverage, revealing structural and stratigraphic features (Sheriff & Geldart, 1995). Advances in seismic attribute analysis, including Root Mean Square (RMS) amplitude and time structural mapping, have proven effective in identifying hydrocarbon indicators and delineating reservoir boundaries (Chopra & Marfurt, 2007). Furthermore, the development of 3D velocity models and juxtaposed reservoir interpretation techniques has allowed for a more holistic understanding of subsurface complexity, bridging the gap between seismic responses and petrophysical properties (Telford et al., 1990). This paper aims to integrate these advanced geophysical techniques to provide a comprehensive characterization of the WABI field's shallow and deep reservoirs, addressing the challenges posed by their distinct geological complexities.

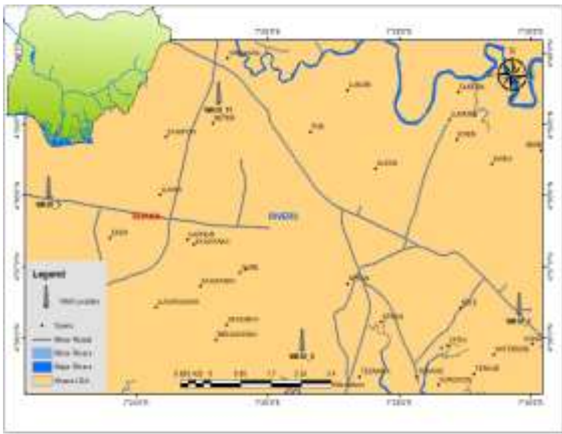
Materials and Methods

1. **Study Area and Dataset**

This study analyzed well log data from four exploration and appraisal wells (WABI-5, WABI-6, WABI-7, and WABI-11) in the WABI field, situated in the Niger Delta basin.

The study area, the WABI field, is located within the Niger Delta, specifically between latitudes 04°35'0''N to 04°40'0''N and longitudes 07°22'0''E to 07°30'0''E (Figure 1). This map also shows the locations of the drilled wells: WAB_5, WAB_6, WAB_7, and WAB_11. The base map of the WABI field (Figure 2) displays seismic grids (inlines and crosslines), representing 3D seismic data. These grids illustrate the actual seismic lines where the drilled wells are positioned.

Key seismic lines—XL1770, XL1820, XL1920, IL11511, IL11556, IL11577, and IL11656—are identified as optimal for interpreting reservoir properties at depth.



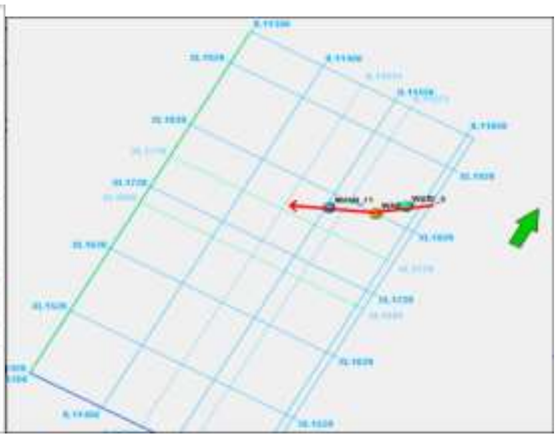


Figure 1: Location map of the study area. **Figure 2:** A base map of 'WABI' field and drilled well grids.

2. Well Log Data Acquisition and Interpretation

Well log data acquired from four wells (WABI-5, WABI-6, WABI-7, WABI-11) constituted the foundational dataset for reservoir delineation. The following key logs were analyzed:

- **Gamma Ray (GR) Logs:** Utilized for lithological discrimination, specifically identifying sand-dominated (low GR) and shale-dominated (high GR) intervals (Figures 3, 4).
- **Resistivity Logs:** Employed to identify potential hydrocarbon-bearing zones through characteristic elevated resistivity responses (Figure 4).

Well correlation was performed within Petrel to achieve precise identification and stratigraphic correlation of the shallow reservoir (top defined at 2850 ft SS true vertical depth subsea [SSTVD]) and the deep reservoir (top defined at 3400 ft SSTVD) across the study area (Figures 3, 4). The high vertical resolution of the shallow reservoir log data facilitated detailed analysis of sand-shale distribution, critical for subsequent volumetric estimation.

3. Seismic Data Interpretation and Attribute Analysis

Post-stack 3D seismic reflection data were imported, processed (for basic conditioning), and interpreted within the Petrel environment. The seismic interpretation workflow comprised the following key stages:

- **Seismic Amplitude Mapping:** Horizon-based amplitude extractions were generated for key reflectors corresponding to the shallow and deep reservoir tops (Figures 5.1, 5.2). These maps highlight spatial variations in acoustic impedance, interpreted as indicative of lithological changes, porosity variations, and fluid content differences.
- **Time Structural Mapping:** Time-structure maps were constructed utilizing 10-millisecond (ms) isochron contours to delineate the structural configuration of both reservoirs. Fault systems, identified as critical elements for hydrocarbon trapping and reservoir compartmentalization, were meticulously interpreted and mapped (Figures 6.1, 6.2).
- **Seismic Attribute Analysis:**
    - **Root Mean Square (RMS) Amplitude Analysis:** 3D RMS amplitude volumes were computed within a window bracketing each reservoir interval (Figures 7.1, 8.1). This attribute provided insights into the overall seismic energy distribution, where anomalously high amplitudes (visually represented by warmer colors) served as potential indicators of hydrocarbon presence.
    - **Integrated Horizon Interpretation:** Comprehensive interpretation of key reservoir horizons was conducted using juxtaposed visualization models (Figures 7.2, 8.2). This integrated approach combined seismic profiles (displaying horizon picks), well log signatures (GR, resistivity) at the intersection points, and 3D amplitude models to characterize the geometry, lithology, and hydrocarbon potential of specific geological layers.

Velocity Model Generation and Interpretation

Three-dimensional interval velocity models were constructed for both the shallow and deep reservoir units (Figures 9.1, 9.2). These models depict the spatial distribution of seismic velocities, which are intrinsically linked to subsurface properties including lithology, porosity, pore fluid type, and pressure. The velocity models were instrumental in:

- **i.** Refining the understanding of structural trapping mechanisms, particularly the geometry of closures and their interaction with sealing faults.
- **ii.** Analyzing systematic variations in velocity distribution with depth between the two reservoir intervals.

Integrated Workflow

The study adopted a synergistic workflow, systematically combining well log-derived lithological and fluid property information, seismic structural and stratigraphic interpretation, and multi-attribute seismic analysis. This integration of diverse geophysical datasets facilitated a comprehensive characterization of the WABI field's complex subsurface architecture, reservoir heterogeneities, and hydrocarbon potential. The resultant insights directly informed the evaluation of optimal well placement strategies and reservoir management decisions.

RESULT

Results of Well Log Models and Stratigraphic Correlations

This study characterized the WABI field's reservoirs using well log data from four wells (WABI-5, WABI-6, WABI-7, and WABI-11) interpreted with Petrel software. Two main reservoirs were identified and correlated: a shallow reservoir (top at 2850SSTLD) and a deep reservoir (top at 3400SSTVD). These correlations are visually represented in Figure 3.

Gamma ray logs were crucial for delineating lithology, identifying sand and shale intervals (Figure 3). Resistivity logs showed strong kicks, indicating hydrocarbon presence within both reservoirs, especially the shallow one (Figure 4). The excellent resolution of the shallow reservoir allowed for detailed analysis of sand-shale variations and confirmed significant hydrocarbon accumulation, ideal for volumetric estimations.

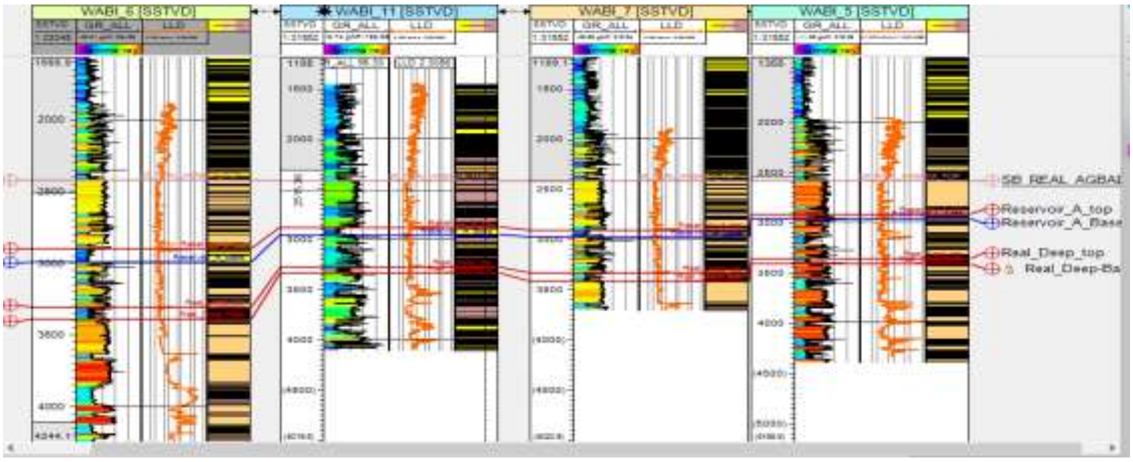


Figure 3: Well correlation of Deep Reservoir across wells; 'WABI_5''WABI_7' and 'WABI_11'.

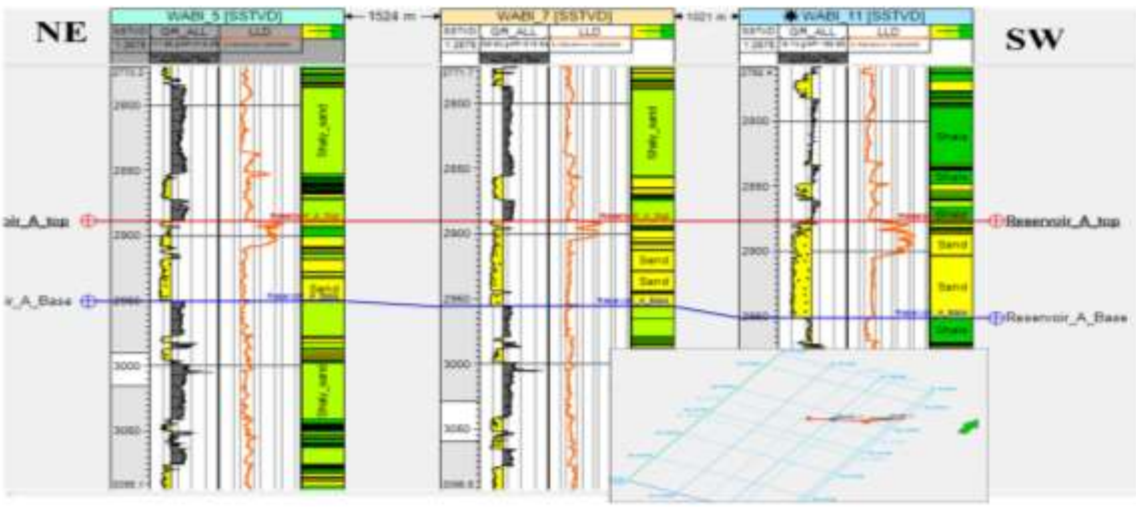


Figure 4: Well correlation of Shallow Reservoir A across wells; 'WABI_5''WABI_7' and 'WABI_11'.

Seismic Grid

Figures 5.1 and 5.2 present integrated visualizations of a shallow and a deeper reservoir, respectively, combining seismic amplitude maps with grid lines and well locations. The seismic amplitude data, represented by color variations, reflects acoustic impedance changes, indicating variations in lithology, porosity, and fluid content.

For the shallow reservoir (Figure 5.1), the map displays seismic data in the time domain (Elevation Time: -2283.00 to -2400.00 ms). Well distribution highlights drilling activity and exploration strategies. The deep reservoir (Figure 5.2) exhibits more complex seismic patterns, suggesting greater structural complexity and a deeper time range (-2500.00 to -3075.00 ms). The consistent grid framework across both figures allows for direct comparison and facilitates reservoir modeling. This integrated approach is crucial for understanding subsurface structures, hydrocarbon indicators, and optimizing well placement in both reservoirs.

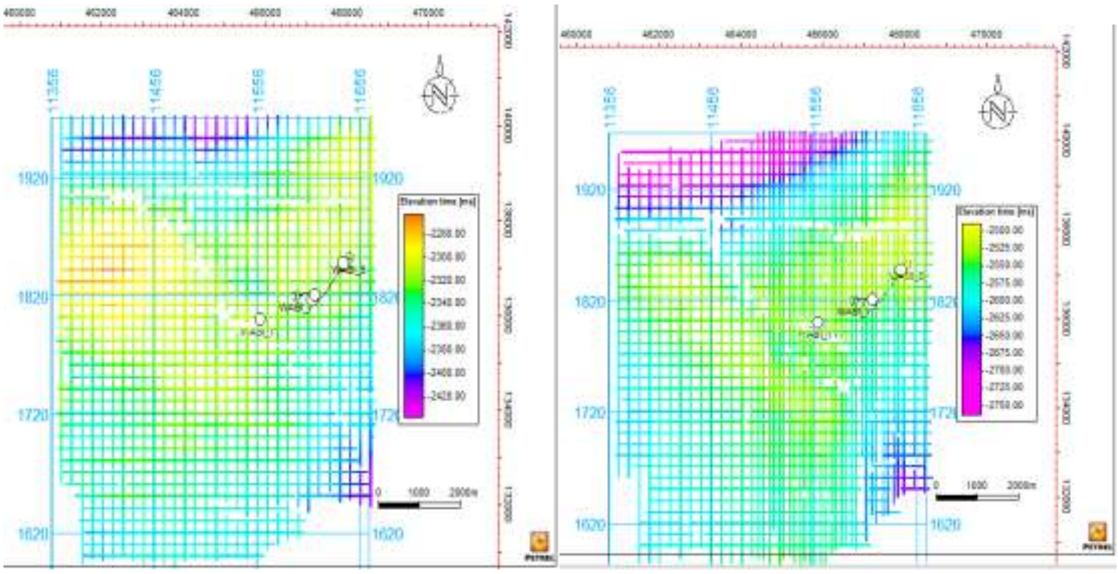


Figure 5.1: Seismic grid for Shallow Reservoir A and **Figure 5.2**: Seismic grid for Deeper Reservoir showing drilled well positions.

Time Structural Map

Figures 6.1 and 6.2 present time structural maps for Shallow Reservoir A and a deeper reservoir, respectively, offering critical insights into their architectural configurations. These maps utilize isochron contours (10m interval) to depict the structural elevation of specific seismic horizons. Warmer colors generally indicate shallower areas, while cooler colors denote deeper regions.

Shallow Reservoir A (Figure 6.1)

The shallow reservoir's time range is -2300 to -2420 ms. Thick white lines delineate interpreted faults, which are crucial for understanding reservoir compartmentalization and potential hydrocarbon trapping. Black dots represent well locations, whose placement relative to contours and faults informs drilling strategies. Dotted black lines outline the reservoir's areal extent.

Deep Reservoir (Figure 6.2)

For the deeper reservoir, the time range extends from -2500 to -2740 ms, confirming its greater depth. Similar to the shallow reservoir, interpreted faults are vital for understanding fluid flow and hydrocarbon accumulation. Well locations provide insights into drilling strategies for this deeper target. Comparing both maps reveals differences in structural style, fault patterns, and potential hydrocarbon distribution between the two zones, which is essential for optimizing well placement and hydrocarbon recovery.

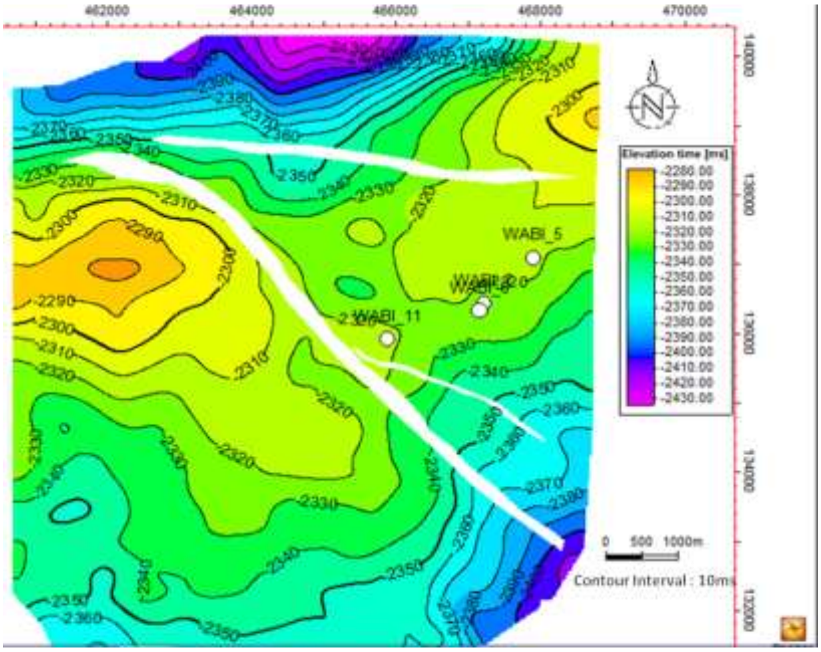


Figure 6.1: Time structural map for Shallow Reservoir_

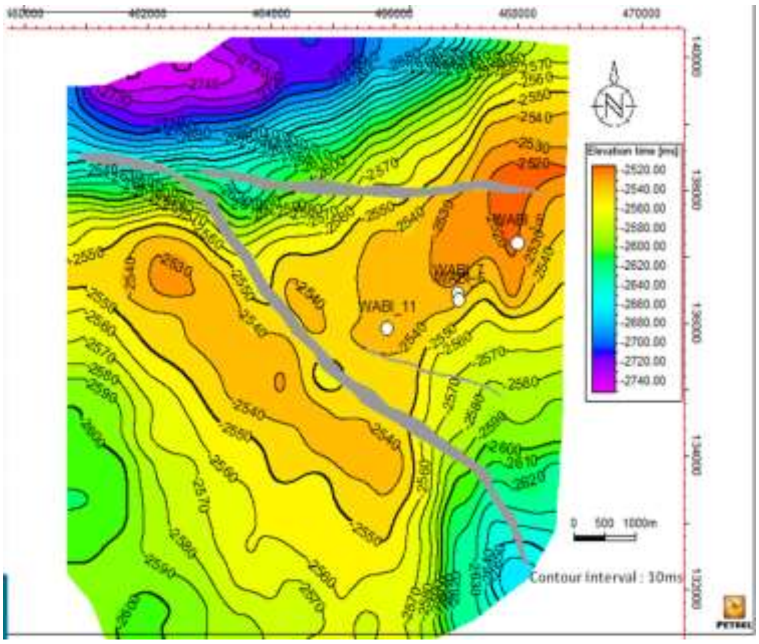


Figure 6.2: Time structural map for Deep reservoir showing the trapping mechanism of faults across reservoir closures.

Interpretation of Seismic Attributes and Reservoir Models

Figures 7.1 and 7.2 provide complementary 3D visualizations for Shallow Reservoir A, deepening our understanding of its structure and potential hydrocarbon presence. Figure 7.1 showcases a 3D Root Mean Square (RMS) amplitude analysis, where warmer colors (red/yellow) signify higher seismic energy. These high amplitudes often indicate hydrocarbons, though lithological changes can also contribute. Integrated well trajectories (e.g., WABI 11, WAP167) highlight their positions within these high-amplitude zones, aiding in production assessment and identifying potential hydrocarbon accumulation areas. Figure 7.2 offers a sophisticated reservoir horizon interpretation by juxtaposing three crucial datasets: a seismic profile showing an interpreted horizon, well logs detailing petrophysical properties at that horizon, and a 3D amplitude model illustrating spatial amplitude distribution. This multi-data integration allows for a comprehensive characterization of the geological layer, including its geometry, lithology, and hydrocarbon potential, enabling highly accurate reservoir interpretation.

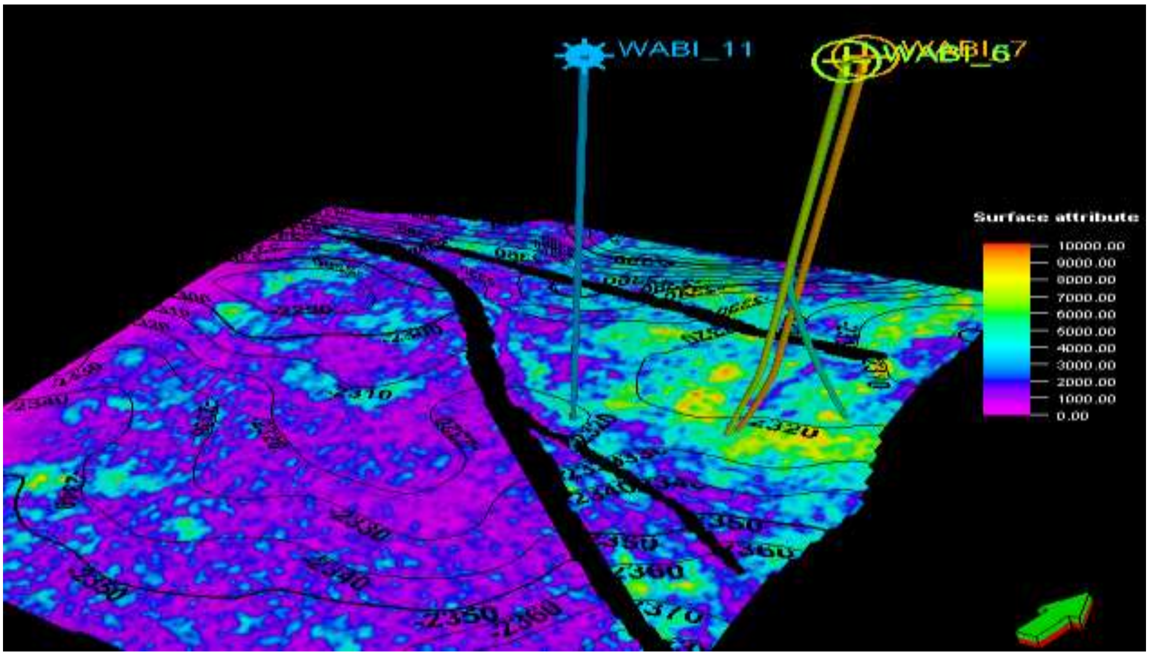


Figure 7.1: Root Mean Square (RMS) amplitude analysis for Shallow Reservoir_A.

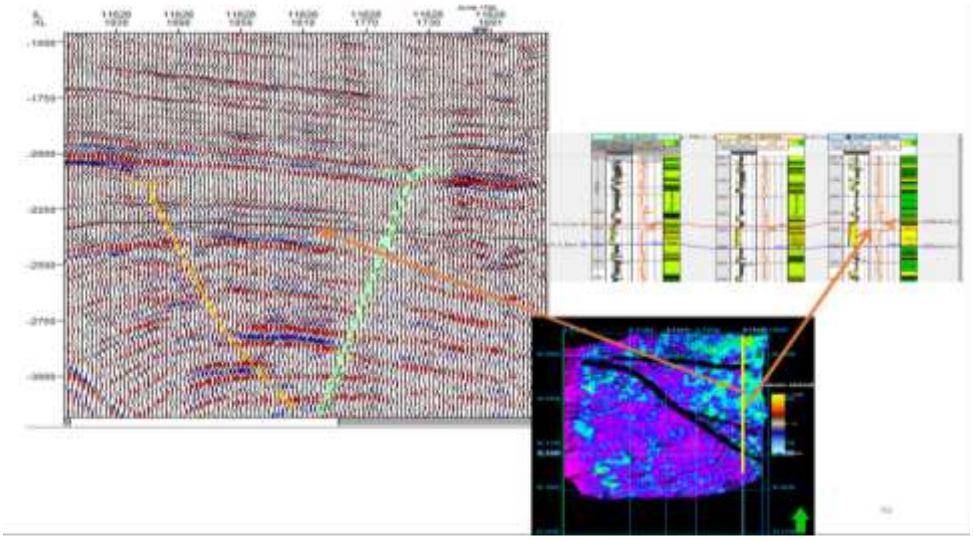


Figure 7.2: Interpretation of reservoir horizon for Shallow Reservoir A

Figures 8.1 and 8.2 offer critical, complementary 3D insights into the Deep Reservoir's intricate architecture and hydrocarbon potential. Figure 8.1 specifically presents a 3D Root Mean Square (RMS) amplitude analysis, where warmer colors (red/yellow) indicate higher seismic energy, often suggesting thicker pay zones or higher hydrocarbon saturation. Well trajectories are integrated, their placement relative to these high-amplitude zones being crucial for assessing production. For instance, Block A shows amplitude conforming to structure, implying a structural trap. However, Block B exhibits no significant amplitude anomaly, indicating low pay contrast or poor reservoir quality. While Figure 8.1 focuses on overall energy, Figure 8.2 provides an advanced integrated interpretation of a reservoir horizon. This is achieved by juxtaposing a seismic profile with an interpreted horizon, well logs detailing petrophysical properties, and a 3D amplitude model. This multi-data approach allows for a comprehensive characterization of the geological layer, including its geometry, lithology, and hydrocarbon content. Furthermore, the analysis of Block A again confirms amplitude conformity with structure, while Block B shows weak amplitude, consistent with resistivity logs, highlighting the spatial variability in hydrocarbon potential. This combined visualization is essential for informed well placement and effective reservoir management.

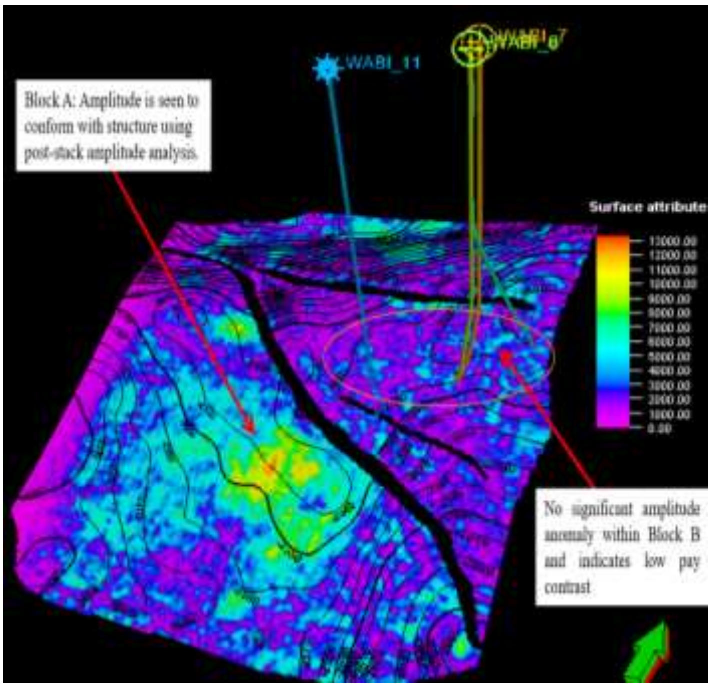


Figure 8.1: Root Mean Square (RMS) amplitude analysis for Deep Reservoir.

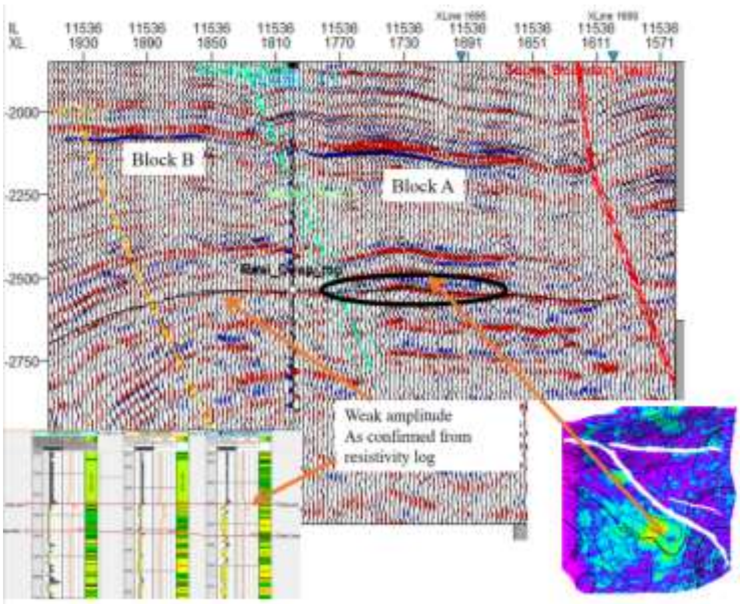


Figure 8.2: Interpretation of reservoir horizon for Deep reservoir using juxtaposed models of seismic reflectors, well log signatures and 3D amplitude reservoir model.

Interpretation of Velocity Models

Figures 9.1 and 9.2 present crucial 3D velocity models for Shallow Reservoir A and a Deep Reservoir, respectively. These models are fundamental for accurate seismic interpretation and comprehensive reservoir characterization, as they illustrate the spatial distribution of seismic velocities within the subsurface. Warmer colors (red, orange, yellow) generally signify higher velocities, while cooler colors (blues, purples) indicate lower velocities. Velocity variations are directly related to crucial reservoir properties like lithology, porosity, and fluid content.

Figure 9.1, focusing on the shallow reservoir, explicitly highlights a reservoir closure and structural faults as potential hydrocarbon trapping mechanisms, indicating the direct application of velocity models in identifying such features. However, Figure 9.2, representing the deeper reservoir, reveals a more structurally intricate environment, a characteristic often associated with deeper geological formations. While direct annotations for structural features like faults or closures might not be explicitly present, the color patterns and the complex geometry within Figure 9.2 implicitly reflect the deeper reservoir's structural framework, potentially revealing fault zones or areas of distinct velocity signatures. Comparing these two figures allows for a direct analysis of how velocity distribution changes with depth, offering invaluable insights into the distinct characteristics and hydrocarbon potential of both shallow and deep reservoir zones.

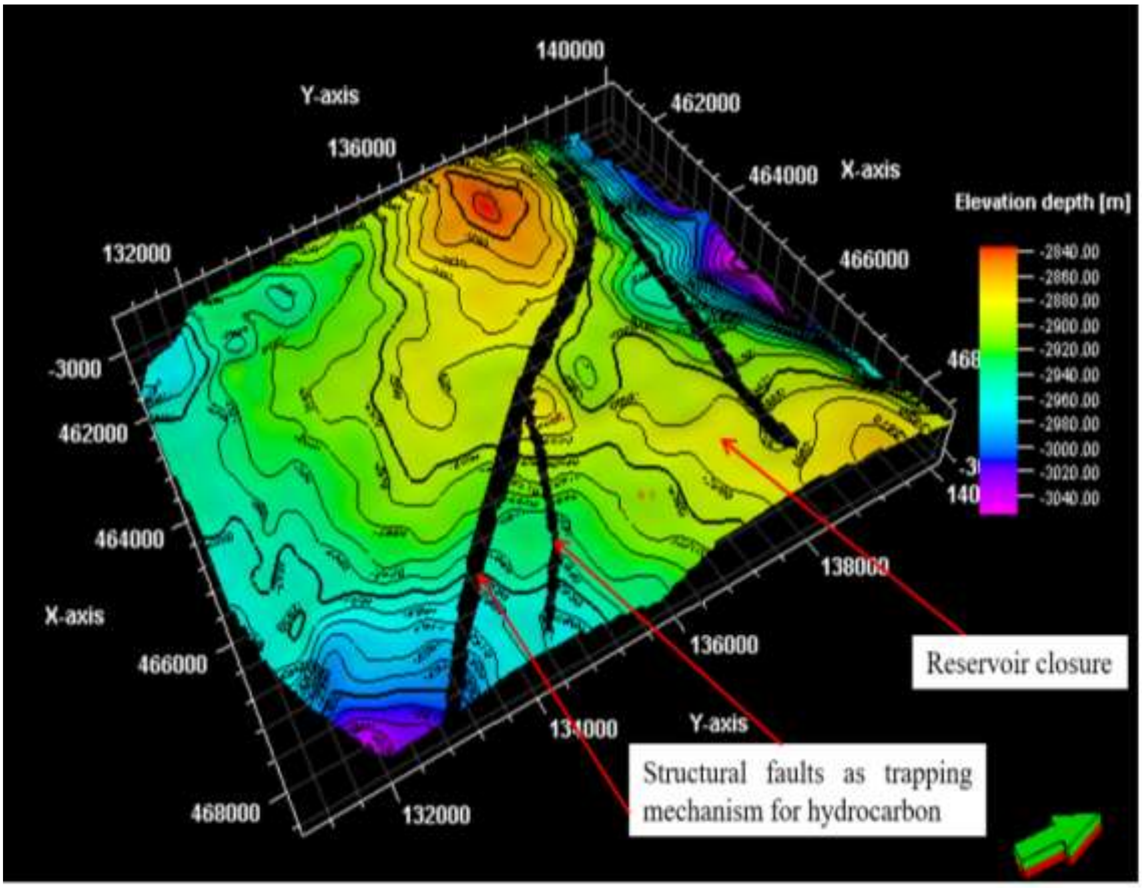


Figure 9.1: Velocity model for Shallow Reservoir A.

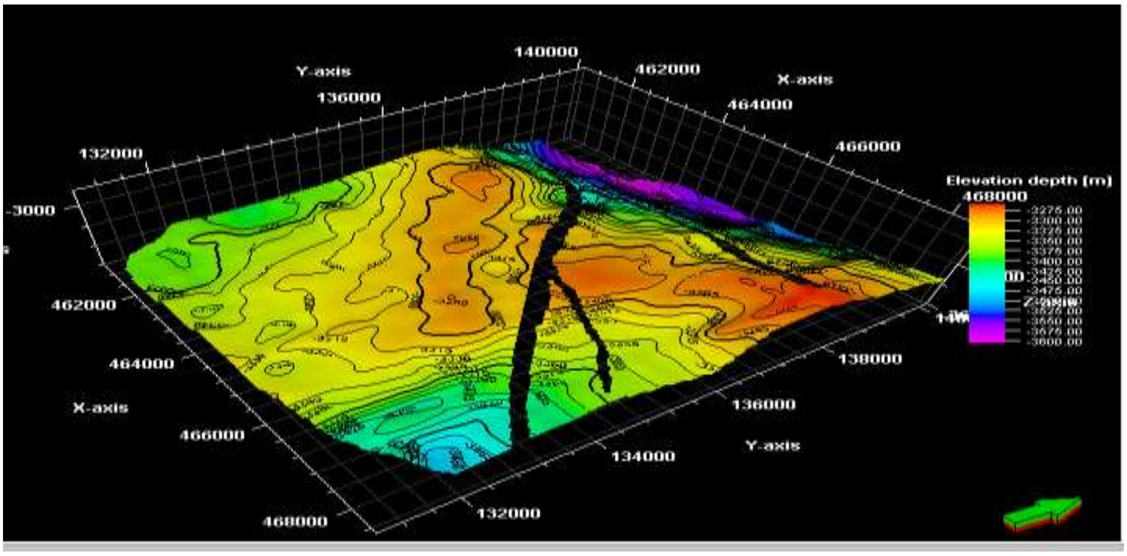


Figure 9.2: Velocity model for Deep Reservoir.

Discussion

The integrated geophysical characterization of the WABI field's shallow and deep reservoirs establishes a robust framework for evaluating its hydrocarbon potential. Well log analysis, particularly utilizing gamma ray and resistivity logs (Figures 3, 4), was instrumental in delineating lithology and identifying hydrocarbon-bearing intervals. This analysis proved especially effective within the highly resolved shallow reservoir, providing the necessary data for volumetric estimations. Seismic data significantly augmented this understanding. Amplitude maps (Figures 5.1, 5.2) revealed variations in acoustic impedance, indicative of lithological changes, porosity variations, and fluid content. A contrast in complexity was observed: the shallow reservoir exhibited relatively simple seismic patterns (Figure 5.1), whereas the deeper reservoir demonstrated greater structural complexity (Figure 5.2).

Time structural maps, incorporating isochron contours and interpreted faults (Figures 6.1, 6.2), elucidated trapping mechanisms. Faults within both reservoir units were identified as critical elements governing compartmentalization and hydrocarbon accumulation.

Furthermore, 3D Root Mean Square (RMS) amplitude analysis (Figures 7.1, 8.1) provided visual indicators of potential hydrocarbon accumulations, with warmer hues correlating to higher seismic energy that is frequently associated with hydrocarbon presence. The integration of well trajectories within these 3D models enabled a direct assessment of well placement efficacy. Advanced interpretation techniques, specifically the juxtaposition of seismic profiles, well logs, and 3D amplitude models (Figures 7.2, 8.2), yielded detailed characterization of specific geological layers. Velocity models (Figures 9.1, 9.2) provided further refinement to the interpretation, illustrating spatial variations in seismic velocities linked to reservoir properties and structural features. A comparative analysis of the shallow versus deep reservoir velocity models (Figure 9.1 vs. Figure 9.2) revealed systematic variations in these properties with depth, thereby optimizing future exploration and development strategies.

This comprehensive multi-disciplinary approach, synthesizing diverse datasets, significantly mitigates exploration risk and enhances reservoir management efficacy.

CONCLUSION

This integrated geophysical characterization successfully illuminated the complex architecture and hydrocarbon potential of the WABI field's shallow and deep reservoirs. Through comprehensive well log and seismic data analysis, we confirmed the presence of distinct sand and shale intervals and identified significant hydrocarbon accumulations, particularly in the shallow reservoir. The integration of seismic amplitude and time structural maps clearly delineated reservoir geometries and highlighted the crucial role of faults in hydrocarbon trapping and compartmentalization. Furthermore, advanced 3D RMS amplitude and velocity models provided vital insights into fluid distribution and subsurface heterogeneity. This multi-data approach substantially reduced geological uncertainties, offering a robust framework for informed decision-making in future drilling operations and reservoir management strategies, ultimately enhancing hydrocarbon recovery efficiency within the WABI field.

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