Journal of Geosciences and Geomatics, 2023, Vol.11, No. 3, 67-78
Available online at http://pubs.sciepub.com/jgg/11/3/1
Published byScience and Education Publishing
DOI:10.12691/jgg-11-3-1

Reservoir Characterization: Enhancing Accuracy through Advanced Rock Physics Techniques

Ukpebor Osahon[1], Maju-Oyovwikowhe Gladys Efetobore[2,*]

[1]Department of Geography and Geology, Illinois State University, Normal City, USA
[2]Department of Geology, University of Benin, Benin City, Nigeria
*Corresponding author: efetobore.maju@uniben.edu

Received May 02, 2023; Revised June 03, 2023; Accepted June 22, 2023

Abstract This study focuses on the identification and delineation of hydrocarbon-charged reservoirs in the SJ field of the Niger Delta Basin using an integrated rock physics modeling approach. The study design encompasses the integration of rock physics modeling, shear wave logs, and fluid substitution techniques. The research was conducted in the SJ field of the Niger Delta Basin, spanning from January 2022 to January 2023. Shear wave logs were empirically generated using the Castagna mud rock line relationship, and fluid substitution techniques were applied to obtain accurate log values for hydrocarbon-bearing intervals. P Impedance (Zp) and S Impedance (Zs) were inverted from P wave reflectivity (Rp) and S wave reflectivity (Rs) using a model-based inversion method. Several attributes, including μρ (mu-rho) and λρ (lambda-rho), were generated to discriminate between rock lithologies and differentiate gas-sand from wet-sand reservoirs, based on equations proposed by Castagna. Crossplot analysis of well log data was conducted to validate the presence of gas in the target zone. The results of the crossplot analysis confirmed the presence of gas in the target zone, providing support for the identification of hydrocarbon-charged reservoirs. Additionally, the generated attributes, such as μρ, λρ, and λ/μ, offered valuable insights into the distribution and extent of the gas reservoir. In conclusion, the integrated approach of rock physics modeling, shear wave logs, and fluid substitution techniques proved effective in identifying and delineating hydrocarbon-charged reservoirs in the SJ field of the Niger Delta Basin. The analysis of various attributes derived from inversion and crossplotting techniques facilitated the prediction of the spreading of the gas reservoir, highlighting the significant potential of this approach for reservoir characterization and development.

Keywords:*rock physics modeling, hydrocarbon-charged reservoirs, Niger Delta Basin,rock lithology, gas-sand reservoirs, reservoir characterization.*

Cite This Article: Ukpebor Osahon and Maju-Oyovwikowhe Gladys Efetobore “Reservoir Characterization: Enhancing Accuracy through Advanced Rock Physics Techniques.” *Journal of Geosciences and Geomatics*, vol.11, no. 3 (2023): 67-78.doi:10.12691/jgg-11-3-1.

1. Introduction

The Niger Delta basin, located in the Gulf of Guinea, is recognized as one of the largest and most prolific deltaic systems globally (Figure 1) [1]. Covering an expansive area of approximately 75,000 km2, the sedimentary deposits in this basin have prograded southwestward from the Eocene to the present, resulting in the formation of distinct Depobelts [1].

The Niger Delta basin holds a prominent position in the global petroleum industry, ranking 12th among the most prolific petroleum belts worldwide and occupying the top position in Africa [2]. It is estimated that the basin contains substantial hydrocarbon reserves, with over 34.5 billion barrels (STB) of oil and 93.8 trillion cubic feet (TCF) of recoverable gas [3]. These reserves contribute significantly to the global energy supply, with the Niger Delta accounting for approximately 2% to 5% of the world's sedimentary basins with hydrocarbon resources [3]. The continuous exploration and discovery of hydrocarbon resources within the Niger Delta oil province have stimulated increased exploration and production activities in the region [4]. The presence of significant reserves and the favorable geological characteristics of the Niger Delta make it an attractive area for oil and gas companies seeking to expand their portfolios and meet the growing energy demands. The basin's sedimentary deposits consist of a complex assemblage of sandstones, shales, and conglomerates, reflecting diverse depositional environments and diagenetic processes over millions of years [5]. These geological complexities present challenges in reservoir characterization, as the reservoir properties and fluid distribution can vary considerably within relatively short distances.

Furthermore, the Niger Delta basin is characterized by structural complexities, such as faulting and folding, which further influence reservoir architecture and hydrocarbon distribution [6]. Accurately characterizing these reservoirs and understanding their fluid content is crucial for optimizing exploration and production strategies, as well as for estimating the recoverable reserves and maximizing hydrocarbon recovery. In recent years, advancements in seismic imaging, well logging, and reservoir characterization techniques have significantly contributed to a better understanding of the Niger Delta basin's reservoirs. Sophisticated technologies, such as 3D seismic surveys and advanced well logging tools, enable detailed subsurface imaging and provide valuable data for reservoir characterization studies. Reservoir characterization studies in the Niger Delta have focused on various aspects, including lithological variations, fluid content, reservoir connectivity, and heterogeneity [7]. These studies utilize a combination of seismic attributes, well log data, and geological models to develop comprehensive reservoir models that capture the intricate subsurface architecture and provide insights into the fluid distribution. The reservoir characterization efforts in the Niger Delta have not only improved the accuracy of resource estimation but have also aided in the identification of new exploration targets and the optimization of production strategies. By gaining a better understanding of the reservoir properties and fluid behavior, operators can make informed decisions regarding drilling locations, well completion techniques, and enhanced oil recovery methods.

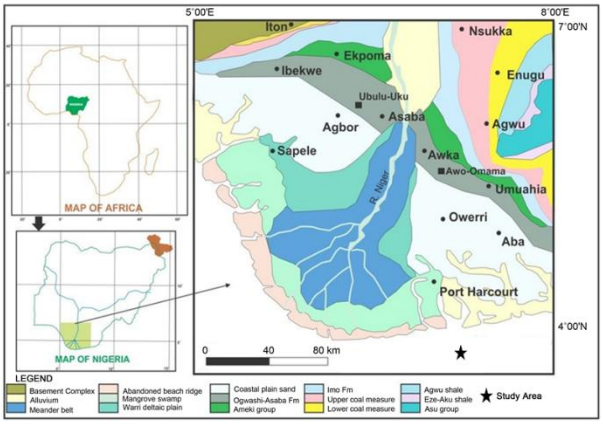

Figure 1. Map of the Niger Delta Basin. After [1]

The Niger Delta is renowned for its significant hydrocarbon potential, with numerous fields contributing to the region's oil and gas production. Among these fields, the SJ Field stands out as a promising area for exploration and production activities [7]. Understanding the reservoir characteristics and fluid content within the SJ Field is of utmost importance for optimizing hydrocarbon recovery and maximizing economic returns.

Seismic reservoir characterization plays a crucial role in the oil and gas industry, providing valuable insights into subsurface reservoir properties. Accurate characterization of lithofacies, fluid content, and elastic properties is essential for optimizing production from existing resources and identifying new subsurface sources. In recent years, significant progress has been made in the field of seismic reservoir characterization, with the introduction of advanced rock physics techniques offering a promising avenue for obtaining more reliable and robust reservoir characterizations.

The traditional approaches to reservoir characterization often rely on the interpretation of velocities or impedances, which can introduce subjective elements and uncertainties into the analysis. To overcome these limitations, researchers have explored alternative methods that provide direct insights into rock physics and avoid indirect interpretation using velocities or impedances.

One notable contribution in seismic reservoir characterization is the work by [8], who established the use of Lamé parameters for seismic reservoir characterization. This approach demonstrated the extraction of Lamé parameter λ and μ, and density ρ, or Lambda-Mu-Rho, to provide interpreters with direct insight into rock physics, enhancing the accuracy of subsurface modeling.

The mathematical relationship between seismic velocities and lames parameters [9] is as follows;

$$V_s = \sqrt{\frac{\mu}{\rho}}, V_p = \sqrt{\frac{\lambda + 2\mu}{\rho}} = \sqrt{\frac{K_{dry} + K_{pore} + (4/3)\mu}{\rho}} \quad (1)$$

$$\mu\rho = Z_s^2$$

$$\lambda\rho = Z_p^2 - Z_s^2$$

$$K_p\rho = Z_p^2 - 2.233 Z_s^2, \left[\frac{K_{dry}}{\mu_{dry}} = 0.9\right] \quad (2)$$

[10] gave the following physical interpretation of the lambda (λ) and mu(μ) attributes: The λ term, or incompressibility, is sensitive to pore fluid, whereas the μ term, or rigidity, is sensitive to the rock matrix. Kp is the Biot-Gassmann fluid term. As we saw inthe theory, it is impossible to de-couple the effects of density from Kp, λ and μ when extracting this information from seismic data. It is therefore most beneficial to cross-plot λρvsμρ or Kpvs μρ to minimize the effects of density. The basic principles in distinguishing lithology from a Lamé parameter perspective is the ratio between incompressibility (λ) and rigidity (μ). Consider a rock at depth ―feeling‖ an effective stress. The distribution of this effective stress between the Lame parameters is an indication of the manner in which the grains are organized. In instances in which the material is more incompressible than rigid(λ>μ) an anisotropic distribution of stresses deforms the grain shape resulting in large aspect ratios. These grain shapes are usually found in laminated shales. The case where there is an even distribution of stress (λ=μ) implies that the grains have an aspect ratio of 1 or that the grains themselves are randomly organized. This grain behavior is often found in sand. The ratio of lambda to mu is therefore useful in identifying shale versus sand lithologies. This is seen in Figure 2a. Lambda-mu ratios of less than 1 are highlighted as sand zones. From a fluid discrimination perspective, assuming that the rock properties do not change, the onlyLamé parameter affected is λ. In sand the pores can be filled by a variety of fluids. This fluid will decrease the incompressibility of the material. Brine will affect incompressibility the least while gas will affect incompressibility the most. Figure 2b shows how filling sand pores with different fluid will decrease the amount of measured incompressibility (yellow to red circles). Figure 2 consists of two subplots

illustrating the discrimination capability for fluid and lithology using different crossplot techniques.

(a) Ratio Difference Crossplot (Left): The left subplot shows a ratio difference crossplot, which is a graphical representation of the differences in various ratios between different lithologies or fluid types. This crossplot allows for the discrimination and identification of different lithologies and fluids based on their distinct responses in terms of the plotted ratios. The specific ratios used in this crossplot are not mentioned in the provided information but are derived from the well data in the Western Canada Sedimentary Basin (WCSB). The crossplot demonstrates the effectiveness of this technique in discriminating between different lithologies and fluids within the reservoir.

(b) LMR Crossplot (Right): The right subplot displays an LMR crossplot, which combines the Lamé's parameters (λ and μ) and density (ρ) to classify rocks. This crossplot technique utilizes a combination of the [8] and [11] methodologies to calculate the Lamé's parameters and density values. By plotting these parameters, the LMR crossplot enables the classification of rocks based on their λ and μ values, along with the density information. This classification aids in understanding the rock physics behavior and properties within the reservoir.

Both crossplot techniques contribute to the overall rock physics analysis and interpretation in seismic reservoir characterization. They provide valuable insights into lithology discrimination, fluid identification, and the understanding of rock properties based on the plotted parameters and ratios.

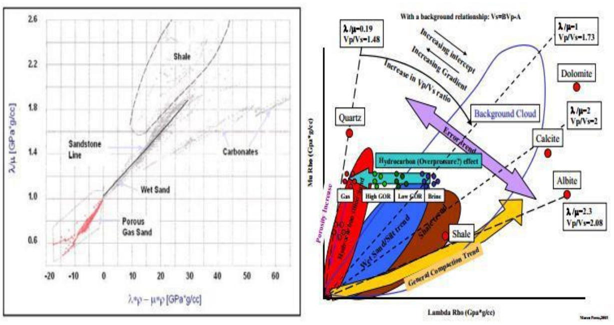

Figure 2. Ratio Difference Crossplot (Left) and LMRCrossplot (Right). Combination of [8,11]

[12] presented a paper on applying statistical rock physics and seismic inversions to map lithofacies and pore fluid probabilities in a North Sea reservoir. Their research demonstrated the optimal combination of near and far offset seismic impedance attributes, well log calibration, and statistical rock physics to classify and map reservoir lithofacies and fluids. By considering uncertainties and assessing the probability of interpretation, their study provided valuable insights into reservoir characterization.

[13] emphasized the increasing demand for hydrocarbons and the need for advanced tools to find new subsurface sources and optimize production from existing resources. Rock physics emerged as one of the key tools for more accurate subsurface modeling. However, challenges and uncertainties in rock physics still exist, presenting opportunities for further research and study.

[14] conducted a study on reservoir sandstones in the Shipwreck Trough, highlighting the influence of quartz cement and pore fluid changes on reservoir properties. They found that the stiffness of the reservoir was substantially affected by quartz cement, while the younger Thylacine Member remained sensitive to pore fluid changes. This research indicated the importance of considering cementation effects and fluid content in reservoir characterization.

To investigate the causes of low Vp:Vs ratios in gas and brine saturated wells, [15] conducted crossplot analysis and compared Vp:Vs ratios with Rock Physics Model (RPM) templates based on Effective Media "Contact Models." Their work illustrated the impact of varying mineral ratios, pore fluids, and grain contact relationships on elastic properties, providing a valuable tool for understanding reservoir behavior.

Furthermore, [16] conducted a study on cross plotting rock properties for fluid and lithology discrimination in a Niger Delta oil field. Their research emphasized the importance of characterizing hydrocarbon reservoirs accurately in terms of fluid properties and lithology. The crossplot analysis of acoustic impedance, Lambda-rho, Murho, and Poisson impedance attributes proved robust in lithology and fluid discrimination within the reservoir.

Recently, the study conducted by [9] focused on the reservoir characterization of the UM field in the Niger Delta using Amplitude Versus Offset (AVO) analysis. The integration of 3D seismic data, well deviation survey data, and checkshot survey data provided a comprehensive understanding of the reservoir properties. AVO analysis, specifically cross-plotting gradient against intercept values, revealed an anomalous deviation from the background trend, indicating the presence of a gas sand reservoir. Seismic stacks and attribute slices further confirmed the amplitude variations at different offsets, supporting the identification of the gas sand reservoir. The study's findings offer valuable insights into the reservoir's seismic response, lithological variations, and fluid content, with implications for reservoir evaluation and exploration activities. [7] also conducted a study on the Majosa field in the Niger Delta to comprehensively characterize the reservoir and analyze fluid behavior. They interpreted well logs, performed fluid replacement modeling, and generated synthetic seismograms for well-to-seismic tie analysis. The study revealed lithology, porosity, and the presence of gas within the reservoir sand located at a depth of approximately 3,392m. Fluid replacement modeling accurately captured the behavior of gas sand observed in the logs. The study's findings have implications for exploration, production, reservoir management, and hydrocarbon recovery strategies.

Building upon the foundations laid by previous works, this research aims to enhance seismic reservoir characterization through the integration of advanced rock physics techniques, statistical analysis, and crossplot analysis. By combining seismic data, well log calibration, and rock physics models, we strive to achieve more accurate and reliable characterization of lithofacies, fluid content and elastic properties within the reservoir. This research aims to mitigate uncertainties and improve reservoir characterization accuracy, supporting effective decision-making in hydrocarbon exploration and production.

The defined problem in seismic reservoir characterization lies in the challenges and uncertainties associated with accurately characterizing lithofacies, fluid content, and elastic properties. Traditional approaches relying on velocities or impedances can introduce subjective elements and may not provide direct insights into rock physics. The need for more reliable and robust reservoir characterizations has led to the exploration of advanced rock physics techniques, statistical analysis, and crossplot analysis.

To address these challenges, our proposed solution involves the integration of advanced rock physics techniques, statistical analysis, and crossplot analysis. By combining seismic data with well log calibration, we aim to establish a more accurate and comprehensive understanding of the lithofacies, fluid content, and elastic properties within the reservoir. The utilization of rock physics models and statistical analysis will enable us to assess uncertainties and enhance the reliability of the reservoir characterization.

The scope of work undertaken in this research encompasses a thorough literature survey of previous studies and research in the field of seismic reservoir characterization. We have analyzed the contributions of [8] in establishing seismic reservoir characterization using Lamé parameters, [12] in applying statistical rock physics and seismic inversions, [14] in highlighting the role of rock physics integration, [14] in examining the impact of quartz cement and fluid changes, [15] in crossplot analysis of Vp:Vs ratios, [16] in crossplot analysis for fluid and lithology discrimination, [9] in Reservoir characterization using Amplitude Versus Offset (AVO) analysis and [7] Reservoir characterization and analysis of fluid behavior.

By building upon the knowledge and insights gained from these previous works, our research aims to advance the understanding and application of rock physics techniques for seismic reservoir characterization. The combination of seismic data, well log calibration, rock physics models, and statistical analysis will contribute to a more accurate assessment of lithofacies, fluid content and elastic properties. This study seeks to provide a robust framework for reservoir characterization, reducing uncertainties and supporting informed decision-making in hydrocarbon exploration and production.

In conclusion, seismic reservoir characterization is a crucial aspect of the oil and gas industry, enabling accurate assessments of subsurface reservoir properties. By integrating seismic data, well log calibration, statistical analysis, and crossplot analysis, this study aims to enhance reservoir characterization accuracy and provide direct insights into rock physics. Through this study, we aspire to contribute to the advancement of seismic reservoir characterization and support effective decision-making in the oil and gas industry.

1.1. Study Area

1.1.1. Regional Geology of Niger Delta

The Niger Delta, located on the Gulf of Guinea on the west coast of central Africa, is a significant and highly productive petroleum-producing region. It spans between latitudes 3° and 6°N and longitudes 5° and 8°E [17]. With its extensive sedimentary basin covering an area of approximately 75,000 km^2 and extending over 300 km from apex to mouth, the Niger Delta is considered one of the world's most prolific Tertiary deltas.

The basin is characterized by its considerable depth, reaching at least 11 km in its deepest parts. It holds substantial hydrocarbon resources, with a known cumulative production and proved reserves of 34.5 billion barrels of oil (BBO) and 93.8 trillion cubic feet of gas (TCFG) [18]. Currently, most of the petroleum production is concentrated in onshore fields and the continental shelf in water depths less than 200 meters. However, there is a growing exploration focus on the deeper waters of the Niger Delta, driven by significant discoveries such as the Bonga and Agbami Fields, which have substantial reserves of approximately 1 billion barrels of oil (IBBO). Despite the higher exploration and development costs associated with deepwater operations, the prospects in these riskier offshore areas have contributed to the ongoing prosperity of oil exploration in the region. Figure 3 illustrates the paleogeography of the Niger Delta region, depicting the evolution of the area from the Cretaceous period (130.0 to 69.4 million years ago) to the present-day Cenozoic period (50.3 million years ago to the present). In subfigure A, representing the Cretaceous period, the paleogeography shows the opening of the South Atlantic Ocean and the development of the region surrounding the Niger Delta. This period is characterized by the presence of specific geological features and land formations that existed during that time.

Subfigure B represents the Cenozoic period, which encompasses the geological time from 50.3 million years ago to the present. The paleogeography depicted in this subfigure shows the changes and transformations that have occurred in the Niger Delta region during this period.

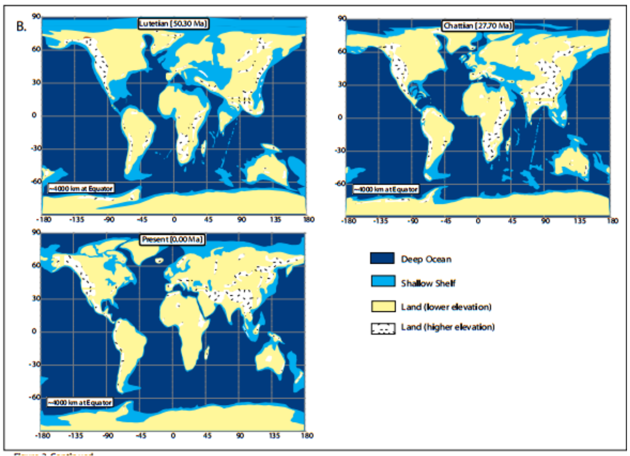

Figure 3. Paleogeography of the Niger Delta region during the Cretaceous and Cenozoic periods. (Figure generated using the PGIS software)

The Niger Delta is characterized by three major lithostratigraphic units: the Akata Formation, the Agbada Formation, and the Benin Formation [19]. The Akata Formation, primarily composed of shale, is recognized as the principal source rock for oil and gas in the region. The Agbada Formation comprises a combination of sands and shales, while the Benin Formation is predominantly composed of coastal plain sands.

The presence of these lithostratigraphic units (Figure 4) in the Niger Delta holds significant implications for petroleum exploration and production. The Akata Formation serves as the major source of hydrocarbons, providing the organic-rich shale necessary for the generation and accumulation of oil and gas. The Agbada Formation, with its sand and shale units, represents reservoirs that can potentially hold significant hydrocarbon accumulations. The Benin Formation, composed of coastal plain sands, also contributes to the overall reservoir potential of the region.

Understanding the regional geology of the Niger Delta, including the distribution and characteristics of these lithostratigraphic units, is crucial for effective exploration and development strategies. It enables petroleum companies to identify favorable areas for hydrocarbon exploration, determine the source-rock potential, evaluate reservoir quality, and optimize drilling and production techniques. By studying the geological framework of the Niger Delta, the petroleum industry can enhance its understanding of the region's subsurface geology and improve the accuracy and success of exploration and production activities.

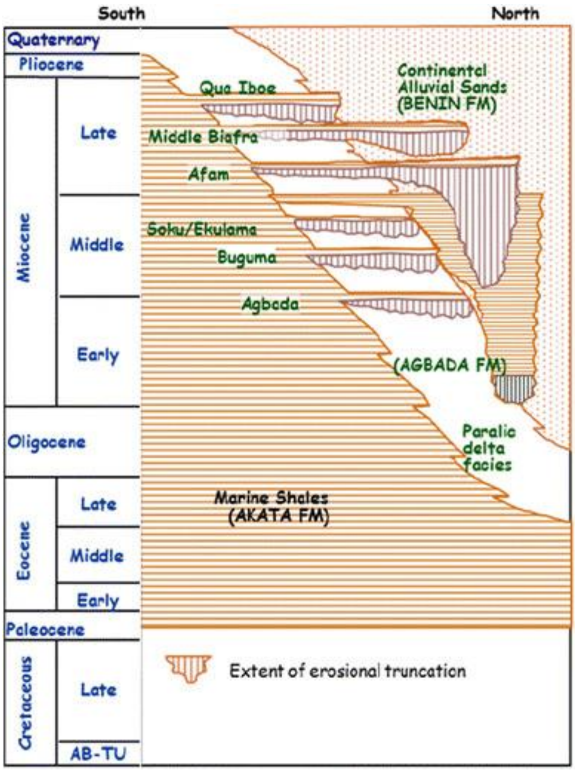

Figure 4. Lithostratigraphic map of the study area [20]

1.1.2. Local Geology of the Study Area

The study area is located in the eastern parts of the Central Swamp Depobelt (Figure 1) of the hydrocarbon-rich Niger Delta Basin of Nigeria. It covers an area extent of about 1171.42 km². Structurally, it is in the extensional zone, and the formations penetrated by this study comprise the Akata, Agbada, and Benin Formations [9].

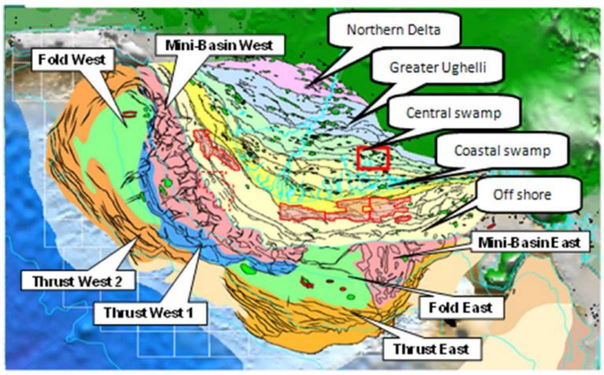

Figure 5. Map of the study area (highlighted by the red box) [21]

The Akata Formation, characterized by its fine-grained sediments, represents the lowermost unit in the study area. It consists of shale, mudstone, and siltstone, indicating a predominantly lacustrine or marine depositional environment. This formation acts as a seal for hydrocarbon reservoirs, preventing upward migration.

Above the Akata Formation lies the Agbada Formation, which comprises alternating layers of sandstone, shale, and clay. The sandstone intervals within this formation serve as potential reservoirs for hydrocarbons. The Agbada Formation reflects a transitional environment, indicating the interplay between fluvial, deltaic, and shallow marine depositional settings.

The uppermost unit in the study area is the Benin Formation, which consists of predominantly shale and minor sandstone layers. This formation represents a deeper marine environment, with organic-rich sediments contributing to the hydrocarbon source rocks within the Niger Delta Basin.

Understanding the geological characteristics and depositional history of the study area is crucial for unraveling the reservoir architecture, sediment distribution, and hydrocarbon potential within the Niger Delta Basin. It provides essential insights into the spatial variations of lithofacies, structural trends, and the complex interplay between tectonic and depositional processes. The local geology of the study area reveals a complex interplay of tectonic and depositional processes. Structural trends and faulting are prominent in this region, which may have influenced the distribution and accumulation of sedimentary deposits. By unraveling the intricacies of the local geology, researchers can gain valuable knowledge about the depositional history, sediment distribution patterns, and structural evolution of the study area. This knowledge is vital for efficient resource exploration and development in the Niger Delta Basin, ultimately contributing to the understanding of the region's geological heritage.

1.2. Rock Physics: Basic Principles and Fuid Substitution Analysis

Rock physics plays a crucial role in bridging the gap between rock and fluid properties and their seismic response. It not only aids in structural imaging but also determines the information content within seismic data. The parameters involved in rock physics are of significant importance but often pose challenges in their acquisition.

Figure 6 illustrates a schematic representation of the strain and stress acting on a siliciclastic rock under normal stress and shear stress conditions. Based on the stress-strain relationship, different rock types such as quartz-rich wet sand, oil sand, gas sand, and clay-rich sand exhibit distinct rock physics constants, leading to varying deformation behaviors.

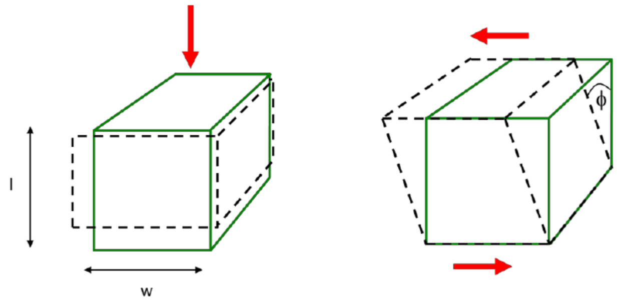

Figure 6. Schematic of the Strain and Stress Acting on a Siliciclastic Rock [9]

Equations (3) through (5) express the basic rock physics parameters and their derived attributes. These equations depict the three-dimensional tensor relationship between stress and strain. In Equation (3), ρ represents density, Vp denotes compressional velocity, Vs signifies shear velocity, and σ represents Poisson's ratio. Equation (4) provides a similar relationship, emphasizing the inverse correlation between compressional and shear velocities.

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1-\sigma)}{(1-2\sigma)}} \quad (3)$$

$$V_s = \sqrt{\frac{{V_p}^2 2(1-\sigma)}{2(1-\sigma)}} \quad (4)$$

$$\sigma = \frac{0.5 - \left(\frac{V_s}{V_p}\right)^2}{1 - \left(\frac{V_s}{V_p}\right)^2} \quad (5)$$

Where ρ = density, Vp= compressional velocity, Vs = shear velocity, σ = poisons ratio [9].

To determine fluid types or saturations using seismic, crosswell, or borehole sonic data, it is necessary to model the effects of fluids on rock velocity and density. Among the various techniques developed for this purpose, Gassmann's equations [22] are widely employed to calculate seismic velocity changes resulting from different fluid saturations in reservoirs [9]. These equations hold significant importance as seismic data increasingly contribute to reservoir monitoring. The seismic response of reservoirs at a specific location is primarily controlled by the compressional (P-wave) and shear (S-wave) velocities, along with densities. Bulk modulus exhibits higher sensitivity to water saturation, as the passage of a seismic wave induces pore volume changes and increases the pressure of pore fluid (water), thereby stiffening the rock and elevating the bulk modulus. In contrast, shear deformation typically does not cause pore volume changes, and differing pore fluids have minimal impact on shear modulus.[9].

Gassmann's equations provide a simplified model for estimating the effect of fluid saturation on bulk modulus.

$$K_s = K_d + \Delta K_d \quad (6)$$

$$\Delta K_d = \frac{K_0\left(1-\frac{K_d}{K_0}\right)}{1-\phi-\frac{K_d}{K_0}+\phi\frac{K_0}{K_f}} \quad (7)$$

$$\mu_s = \mu_d \quad (8)$$

where, K0, Kf, Ks, and Ks, are the bulk moduli of the mineral, fluid, dry rock, and saturated rock frame, respectively Φ is porosity μs and μd are the saturated and dry rock shear moduli. ΔKd is an increment of bulk modulus caused by fluid saturation.

Equations (6) through (8) depict the convenient forms of Gassmann's relations and their physical significance. The incremental change in bulk modulus caused by fluid saturation is denoted as ΔKd. These equations indicate that fluid within pores affects bulk modulus while leaving shear modulus unaffected, consistent with previous discussions. The assumption of shear modulus independence from fluid saturation is a direct consequence of the underlying principles employed in deriving Gassmann's equation, as highlighted by Berryman. Understanding rock physics principles and conducting fluid substitution analyses are crucial in unraveling the complexities of reservoir behavior and optimizing reservoir characterization using seismic data. These techniques facilitate the accurate interpretation of subsurface properties and aid in reservoir monitoring and management.

2. Material and Methods

This current study employed a quantitative approach to provide a comprehensive description of a reservoir in the UM field, located in the Niger Delta. The approach involved integrating all available data from the field to ensure a thorough analysis and understanding of the reservoir's characteristics.

2.1. Data Availability and Quality

The dataset used in this study comprises three main components: 3D seismic data, well deviation survey data, and checkshot survey data. The availability and quality of these datasets are described below:

2.1.1.3D Seismic Data

The UM field was covered by 3-D seismic data, acquired in both swamp and land environments. The seismic data had a bin size/CDP of 25x25m with a nominal 15-fold coverage. The record length was 6 seconds TWT (Two-Way Travel Time) with a sampling interval of 2ms. The data were reprocessed to zero phase reflectivity to 4ms. The seismic processing sequence included three velocity passes, Kirchhoff migration algorithm applied post-stack, and static corrections based on basic LVL (Land Vertical Line) and uphole survey [9]. The UM field in the Niger Delta is characterized by a full coverage of fair to good quality 3D seismic data. The availability of 3D seismic data provided a comprehensive understanding of the subsurface reservoir characteristics. However, it is important to note that the resolution of the seismic data diminishes at deeper levels, specifically beyond 2 seconds. The resolution of seismic data refers to its ability to accurately image and distinguish subsurface features at different depths. In this case, the seismic data's resolution decreases at depths beyond 2 seconds, indicating a lower level of detail and clarity in imaging subsurface structures and reservoir properties. While the seismic data may still provide valuable information and insights for the reservoir characterization, the reduced resolution at deeper levels can pose challenges in accurately identifying and characterizing features such as subtle stratigraphic variations, fault networks, and reservoir boundaries. It is important to consider this limitation when interpreting and analyzing the seismic data and integrate it with other available data sources, such as well logs and core samples, to mitigate the impact of lower-resolution data. Despite the limitation in resolution at deeper levels, the fair to good quality of the 3D seismic data in the UM field allows for meaningful interpretations and analysis within the shallower portions of the reservoir. The integration of multiple data types, including well data and seismic attributes, helped to compensate for the resolution limitation and provide a more comprehensive understanding of the reservoir's subsurface characteristics.

2.1.2. Well Data

We had access to well-log curves from five wells in the UM field. The well logs included gamma ray, resistivity, P-wave sonic, density, caliper, neutron porosity, and spontaneous potential (SP). Check-shot data was available for wells 1, 2, and 3, while well 1 had a substantial amount of footage covered by DT (Delta-T) and RHOB (Bulk Density) logs in the entire UM Field macrostructure [7,9]. To estimate the shear wave data, we empirically generated shear wave logs using the Castagna mud rock line relationship [23]. We then verified these logs by performing fluid substitution using the Biot-Gassmann method. This was reported in [7] over the hydrocarbon-bearing intervals.

2.1.3. Well Data

Checkshot velocity data was acquired in the available well within the UM field. The purpose of collecting checkshot data was to establish a seismic-to-well tie during horizon interpretation. Checkshot surveys involve measuring the travel times of seismic waves from the surface to various depths within the wellbore. By comparing the measured travel times with the corresponding seismic data, the interval velocities of the subsurface layers can be estimated. This velocity information is crucial for accurately positioning seismic reflectors and correlating them with the well data. In this study, the checkshot data obtained from the available well played a critical role in the interpretation of seismic horizons. The checkshot velocity data was used to calibrate and align the seismic data with the well log data, ensuring accurate depth positioning of seismic reflectors. This seismic-to-well tie improves the correlation between the seismic data and the subsurface features observed in the well, enhancing the accuracy of the reservoir interpretation and modeling. By incorporating the checkshot data into the analysis, the study benefited from a more robust and reliable seismic interpretation. The checkshot data provided valuable information for velocity modeling, depth conversion, and improved understanding of the subsurface structure. The seismic-to-well tie established using the checkshot data enabled more accurate mapping and characterization of the reservoir horizons and improved the overall integration of well data and seismic information.[maju]. The acquired checkshot data was carefully quality checked and processed to ensure its accuracy and reliability. Any necessary corrections or adjustments were made to the data to enhance its suitability for the seismic interpretation and subsequent analysis. This was also reported in [7].

2.2. Rock Physics Parameters and Crossplots

After empirically generating shear wave data from the available logs and verifying the results through fluid substitution using the Biot-Gassmann method [7], cross-plots of elastic rock properties were generated. The elastic rock properties included Lambda (λ), Mu (μ), and Rho (ρ) derived from the well logs. Combinations of these properties, such as λρ, μρ, λ/μ, and others, were also plotted. The cross-plots provided insights into the relationships between different elastic rock properties and their variations within the reservoir [23]. The patterns observed in the cross-plots at known well locations were utilized to further investigate cluster patterns at potential locations beyond the existing wells. This analysis aimed to identify similar patterns that could indicate the presence of favorable reservoir conditions in those areas. To expand the analysis beyond the well locations, a Lambda (λ) - Mu (μ) - Rho (ρ) inversion of the partial-stack seismic data was performed. This inversion process generated seismic-derived volumes of Acoustic Impedance (AI), Shear Impedance (SI), and Density (Rho). From these volumes, additional rock physics parameters such as LambdaRho (λρ) = AI2 - 2SI2 and MuRho (μρ) = SI2 were computed. The generated cross-plots using the rock physics parameters were then used to evaluate which of these parameters served as better indicators of pore fluids within the reservoir. By analyzing the cluster patterns and relationships observed in the cross-plots, it was possible to identify zones that exhibited characteristics associated with hydrocarbon-bearing intervals. Data slices extracted from the elastic rock parameter volumes, including

Acoustic Impedance, Shear Impedance, and Density, were used to study the characteristics of known hydrocarbon-bearing intervals. Additionally, these data slices helped in locating other potential hydrocarbon-bearing areas away from the existing well locations.

Figure 7 illustrates a crossplot of the Vp-Vs ratio against P-impedance, specifically focusing on the insitu reservoir fluid. The crossplot provides a graphical representation of the relationship between these two parameters, which are derived from the elastic properties of the reservoir. The Vp-Vs ratio represents the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs). It is a significant parameter in rock physics analysis as it can provide insights into the lithology and fluid content of the reservoir. The P-impedance, on the other hand, is a measure of the acoustic impedance of the rock, which is influenced by the density and compressional wave velocity. By crossplotting the Vp-Vs ratio against P-impedance, distinct patterns or clusters emerged, indicating different fluid types or lithological variations within the reservoir. These patterns were used as indicators to identify potential hydrocarbon-bearing intervals or zones [23]. [23] reported that the use of Vp/Vs ratio as a lithology indicator was popularized by [24]. They also reported the use of Vp, Vs, and Vp/Vs in seismic exploration for estimation of lithology and saturating fluids in particular stratigraphic intervals. Because the P-wave velocity is more sensitive to fluid changes than the S-wave velocity, changes in fluid type result in changes in Vp/Vs.

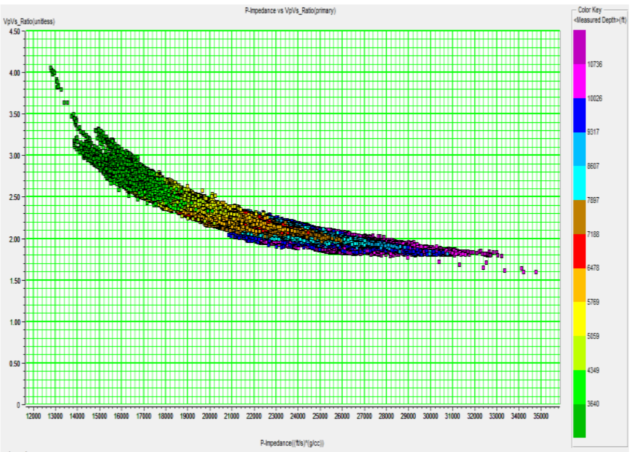

Figure 7. Crossplot of Vp-Vs Ratio against P-Impedance for the Insitu Reservoir Fluid

Figure 8 displays a crossplot of the Vp-Vs ratio against P-impedance specifically for the three-phase reservoir fluid. The crossplot visually represents the relationship between these two elastic parameters derived from the reservoir data. The Vp-Vs ratio represents the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs) and serves as an essential indicator for lithology and fluid content within the reservoir. The P-impedance, on the other hand, is a measure of the acoustic impedance of the rock, influenced by factors such as density and compressional wave velocity. By plotting the Vp-Vs ratio against P-impedance, distinctive patterns or clusters emerged, providing insights into the fluid content and lithological variations within the reservoir. These patterns aided in the identification and characterization of different fluid phases present in the reservoir, such as hydrocarbons, water, and gas. It showcases the distribution of data points representing the relationship between the Vp-Vs ratio and P-impedance for the three-phase reservoir fluid. The observed clusters or trends in the crossplot offered valuable information for reservoir analysis and fluid identification. By examining the location and behavior of data points, we were able to assess the fluid composition and make predictions about the presence and distribution of different fluid phases.

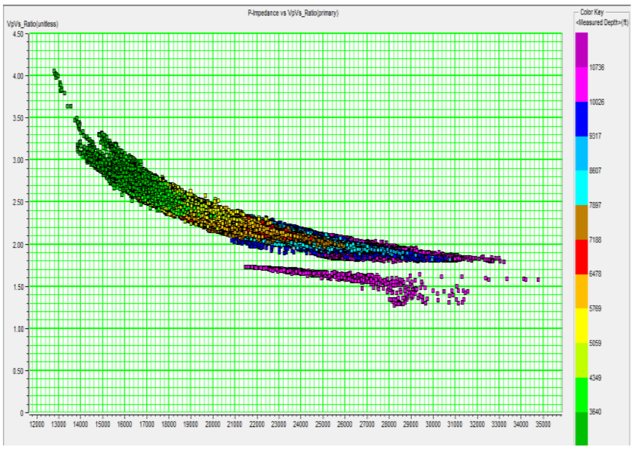

Figure 8. Crossplot of Vp-Vs Ratio against P-Impedance for the Three-Phase Reservoir Fluid

Figure 9 illustrates a crossplot of the Vp-Vs ratio against P-impedance specifically for the two-phase reservoir fluid. The crossplot visually represents the relationship between these two elastic parameters derived from the reservoir data. The Vp-Vs ratio, representing the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs), is a critical parameter for lithology and fluid identification within the reservoir. The P-impedance, on the other hand, is a measure of the acoustic impedance of the rock, influenced by factors such as density and compressional wave velocity. By plotting the Vp-Vs ratio against P-impedance, distinct patterns or clusters emerged, providing insights into the fluid content and lithological variations within the reservoir. These patterns helped us to identify and characterize the two-phase fluid present in the reservoir, typically representing a combination of hydrocarbons and water. It displayed the distribution of data points representing the relationship between the Vp-Vs ratio and P-impedance for the two-phase reservoir fluid. The observed clusters or trends in the crossplot provided valuable information for reservoir analysis and fluid identification. By examining the location and behavior of data points, we were able to assess the fluid composition and make predictions about the distribution and characteristics of the two-phase fluid within the reservoir.

Conclusively, in Figure 7, we presented a crossplot of Vp-Vs ratio against P-Impedance for the insitu reservoir fluid. This crossplot allowed us to identify the characteristic patterns associated with different fluid types in the reservoir. It helps in discriminating hydrocarbon-bearing sand from non-hydrocarbon-bearing sand [25].

Figure 8 showed the crossplot of Vp-Vs ratio against P-Impedance for the three-phase reservoir fluid. This crossplot provides insights into the fluid distribution within the reservoir and helps in identifying potential hydrocarbon-bearing intervals.

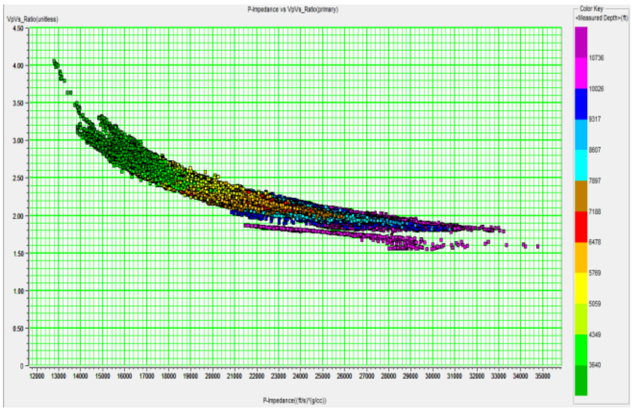

Figure 9. Crossplot of Vp-Vs Ratio against P-Impedance for the two phase reservoir Fluid.

Figure 9 displays the crossplot of Vp-Vs ratio against P-Impedance for the two-phase reservoir fluid. This crossplot aids in understanding the fluid content and distribution in the reservoir and assists in the identification of gas-sand and wet-sand intervals. These figures demonstrate the utility of crossplots in distinguishing different fluid types and identifying hydrocarbon-bearing intervals within the field[16].

3. Results and Discussion

3.1. Rock Physics Analysis

The rock physics analysis in this study aimed to investigate the relationship between various rock properties and fluid distributions within the reservoir. By integrating seismic data and well log information, the rock physics parameters were derived and analyzed to gain insights into the reservoir characteristics. It involved estimating zero offset P-wave reflectivity (RP) using the intercept (A) and assuming a Vp/Vs ratio of 2 to estimate zero offset S-wave reflectivity (RS) by subtracting B from A. The estimated RP and RS values were then inverted to obtain acoustic impedance (Zp = ρVp) and S-wave impedance (Zs = ρVs), respectively. The inverted sections were further crossplotted to explore the relationships between various rock physics parameters. [26] provided a physical interpretation of the lambda (λ) and mu (μ) attributes, where λ represents incompressibility sensitive to pore fluid, and μ represents rigidity sensitive to the rock matrix. The rock physics crossplots were performed to minimize the effects of density and highlight the variations in these attributes. Crossplots of λρvsμρ or Kpvsμρ were used to analyze the data.

3.1.1. Estimation of Zero Offset Reflectivity

The intercept (A) was utilized to estimate the zero offset P-wave reflectivity (RP), providing valuable information about subsurface reflectivity patterns (Figure 10). The assumption of Vp/Vs = 2 was made to estimate the zero offset S-wave reflectivity (RS) by subtracting B from A.

3.1.2. Inversion of RP and RS

RP and RS were inverted to obtain acoustic impedance (Zp = ρVp) and S-wave impedance (Zs = ρVs), respectively. These inverted sections were further analyzed to understand the subsurface rock properties and fluid distributions.

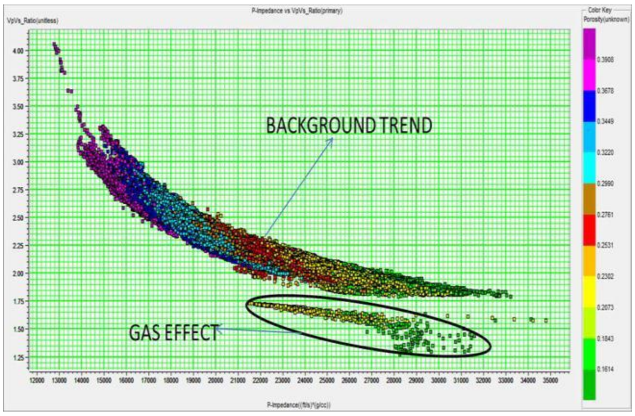

Figure 10. Crossplot – Vp-Vs ratio vs P-Impedance

3.1.3.Crossplot Analysis

Crossplots were generated to explore the relationships between different rock physics parameters and identify patterns deviating from the background trend. The rock physics results for the study interval indicated a low Vs/Vp ratio, low Mu-Rho, and low Lambda-Rho values compared to the background trend, confirming the amplitude-versus-offset (AVO) response given in [9,27]. The crossplots of rock physics parameters (Figures 11, 12, and 13) revealed distinctive patterns where gas sands plotted away from the background trend. In Figure 11, crossplots are presented showing the relationship between Poisson's ratio and P-Impedance. These crossplots provide valuable insights into the elastic properties and behavior of the studied rock formations. The variations in Poisson's ratio with respect to P-Impedance can offer important information about lithology, pore fluid content, and rock deformation characteristics. The crossplot of Poisson's ratio against P-impedance (Figure 11) revealed a distinct plot away from the background trend, indicating the presence of gas sands.

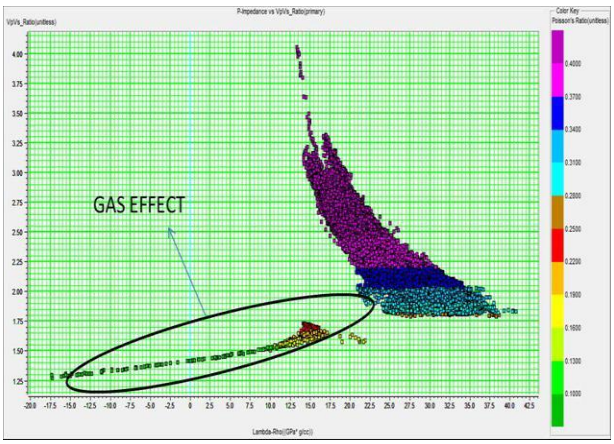

Figure11. Crossplots – poison's vs P-Impedance

The crossplot of Vp-Vs ratio against Lambda-Rho (Figure 12) reveals a distinctive plot pattern that serves as further confirmation of the presence of gas-bearing intervals within the reservoir. The Vp-Vs ratio represents the ratio of compressional wave velocity (Vp) to shear wave velocity (Vs), while Lambda-Rho represents the product of Lamé's first parameter (lambda) and density (rho). The distinct plot pattern observed in Figure 12 indicates the response of the rock formation to the presence of gas. Gas-bearing intervals typically exhibit a specific range of Vp-Vs ratio and Lambda-Rho values due to the contrasting elastic properties of gas compared to other fluid phases, such as water or oil. Gas has a lower density and higher compressibility compared to liquid phases [27], resulting in lower Vp-Vs ratios and Lambda-Rho values. By analyzing the crossplot, we identified clusters or trends that correspond to gas-bearing intervals. These clusters appeared as distinct groupings within the overall data distribution. The presence these clusters suggests the potential presence of gas accumulations within the reservoir. Therefore, the distinctive plot pattern observed in the Vp-Vs ratio against Lambda-Rho crossplot (Figure 12) serves as further evidence supporting the identification of gas-bearing intervals within the studied reservoir. It provides valuable information for reservoir characterization and aids in the understanding of the fluid content and behavior of the subsurface formations.

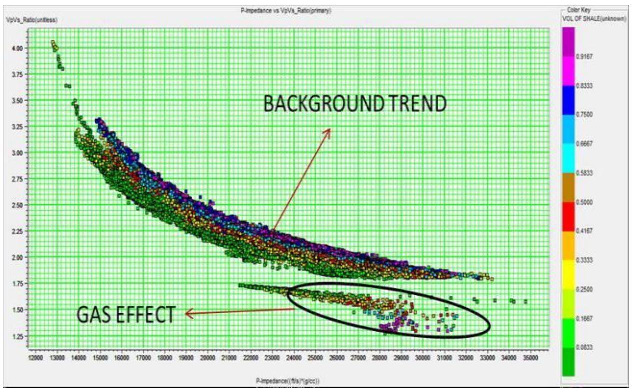

Figure 12. Crossplots– Vp-Vs ratio vs lambda rho

The crossplot of Mu-Rho against Lambda-Rho (Figure 13) reveals an interesting observation with a portion of the plot deviating from the general background trend. This deviation provides additional evidence for the presence of gas-bearing intervals within the studied reservoir. Mu-Rho represents the product of shear modulus (mu) and density (rho), while Lambda-Rho represents the product of Lamé's first parameter (lambda) and density (rho). The crossplot allows us to examine the relationship between these two parameters and identify any anomalies or distinct patterns that may indicate the presence of gas. The portion of the plot that deviates from the general background trend suggests a variation in the elastic properties of the rock formation. This deviation is likely due to the influence of gas within the reservoir. Gas exhibits different elastic properties compared to other fluid phases, such as water or oil. It has a lower shear modulus (mu) and density (rho), which can result in a specific range of Mu-Rho and Lambda-Rho values for gas-bearing intervals. By identifying this deviation in the crossplot, we gained additional evidence for the presence of gas within the reservoir. This information is valuable for reservoir characterization and can assist in determining the distribution and behavior of gas accumulations. Overall, the crossplot of Mu-Rho against Lambda-Rho (Figure 13) highlights a specific portion of the plot that deviates from the general background trend, providing further support for the presence of gas-bearing intervals within the studied reservoir.

The crossplot of Mu-Rho against Lambda-Rho (Figure 13) provided additional insights into the characteristics of the reservoir sand. In this plot, there are two portions that deviate from the general background trend, indicating distinctive behavior. One portion of the plot, where the water saturation occurs, is away from the background trend. This further confirms that it is gas sand. The presence of gas within the reservoir affects the elastic properties, leading to a different response in terms of Mu-Rho and Lambda-Rho values. The deviation from the background trend in this portion indicates the influence of gas saturation.

Moreover, Figure 13 also shows another portion that plots away from the general background trend. The reservoir sand falls within this distinctive plot, suggesting a gas effect. This means that the reservoir sand is characterized by specific elastic properties that are consistent with the presence of gas. The color representation in the crossplot helps to highlight these distinct portions where deviations occur. By observing the location of the reservoir sand in relation to these distinctive plots, we further confirmed the gas effect and its impact on the elastic properties of the reservoir.

Overall, the crossplot of Mu-Rho against Lambda-Rho (Figure 13) demonstrates the presence of two portions that deviate from the general background trend. The water saturation of the reservoir sand occurs within one of these portions, confirming it as gas sand. The identification of these distinctive plots provides valuable information for understanding the gas effect and its influence on the reservoir's elastic properties.

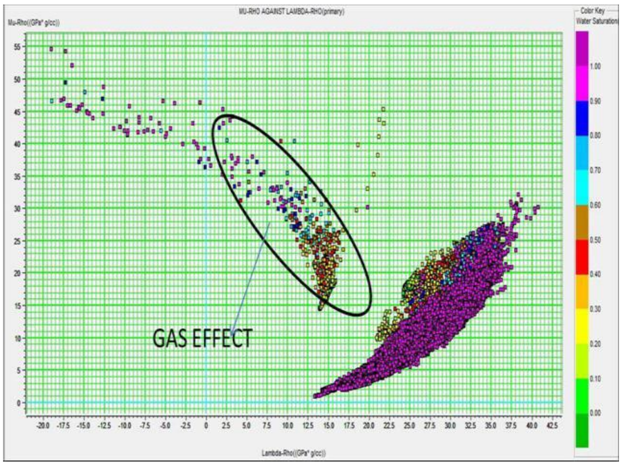

Figure 13. Crossplots – Mu-Rho vs Lambda Rho

In conclusion, the rock physics analysis, including the crossplots of various rock properties, has provided valuable insights into the reservoir's fluid distribution. The observed patterns align with previous research and contribute to a more accurate reservoir characterization. Figure 11 displayed the crossplot of Poisson's ratio against

P-impedance, showing distinct deviations from the general background trend. This crossplot provided additional evidence of gas sand presence. The crossplot in Figure 12 depicted the relationship between Vp-Vs ratio and Lambda-Rho, further highlighting the distinctive behavior of the reservoir sand. The portion of the plot where the reservoir sand fell indicated a gas effect. In Figure 13, the crossplot of Mu-Rho against Lambda-Rho showed another portion of the plot deviating from the general background trend.

The reservoir sand also fell within this distinctive plot, confirming its gas-bearing nature. The identification of gas sands and the confirmation of the water saturation occurring within the portion of the crossplots that deviated from the background trend provided strong evidence of the reservoir being gas sand. These findings align with the expected fluid distribution within the reservoir and contribute to a better understanding of the reservoir's properties [9; 7]. Overall, the rock physics analysis and the interpretation of the crossplots supported the identification of gas-bearing intervals within the reservoir [9] and [7] provided valuable insights into the fluid distribution and lithological variations. These findings are consistent with the work of [27] and contribute to the understanding of the reservoir's hydrocarbon potential.

The results of the rock physics analysis offer significant insights into the reservoir's fluid distribution and provide a basis for interpretation. The distinctive plot patterns observed in the crossplots of Poisson's ratio against P-impedance (Figure 11) and Vp-Vs ratio against Lambda-Rho (Figure 12) align with previous studies [27; 16; 28; 29). These patterns indicate the presence of gas sands within the reservoir. Furthermore, the crossplot of Mu-Rho against Lambda-Rho (Figure 13) exhibits another portion of the plot deviating from the background trend, supporting the existence of gas-bearing intervals. The confirmation of water saturation occurring within the deviating portions of the crossplots reinforces the interpretation that the reservoir sands are primarily gas-bearing intervals. These findings have significant implications for reservoir characterization, development planning, and production optimization. Understanding the fluid distribution within the reservoir is crucial for making informed decisions regarding drilling, production strategies, and reservoir management.

4. Conclusion

In conclusion, this study focused on seismic reservoir characterization and aimed to enhance accuracy through the application of advanced rock physics techniques. The analysis and interpretation of rock physics parameters, along with the generation of crossplots, provided valuable insights into the reservoir properties and fluid distribution within the studied field. Through the integration of seismic data, well logs, and rock physics models, we gained a deeper understanding of the reservoir's behavior and characteristics. The deviations observed from the background trend in the crossplots proved to be significant in identifying potential hydrocarbon-bearing intervals. The distinctive patterns exhibited by gas sands in the crossplots confirmed their gas-bearing nature, further enhancing our reservoir characterization efforts. By leveraging the information derived from rock physics analysis, such as Vp-Vs ratio, P-impedance, Lambda-Rho, and Mu-Rho, we were able to differentiate fluid types and contribute to the identification of reservoir zones with varying fluid saturations. This knowledge is crucial for optimizing exploration strategies, well placement decisions, and overall reservoir management. The application of advanced rock physics techniques in this study has proven instrumental in enhancing the accuracy of seismic reservoir characterization. The findings presented here contribute to the body of knowledge surrounding reservoir properties and serve as a valuable resource for future exploration and production activities. By leveraging the power of rock physics analysis and its integration with seismic data, this study paves the way for more accurate reservoir characterization, leading to improved decision-making processes and optimized production strategies.

Acknowledgements

We would like to express our gratitude to all individuals and organizations that have contributed to the successful completion of this study on seismic reservoir characterization and rock physics analysis.

Competing Interests

Authors have declared that no competing interests exist.

References

[1] Nwajide CS. Geology of Nigeria's Sedimentary Basins. Lagos: CSS Bookshops Limited; 2013.

[2] Tuttle ML, Charpentier RR, Brownfield ME. The Niger Delta Petroleum System: Niger Delta Province, Nigeria, Cameroon, and Equatorial Guinea, Africa. US Department of the Interior, US Geological Survey; 1999. Report No.: OFR 99-50H. Available from: https://doi.org/10.3133/ofr9950H.

[3] Reijers TA. Selected chapters in geology. Warri, Nigeria: SPDC Corporate Geographic Service; 1996. p. 194.

[4] Corredor F, Shaw JH, Bilotti F. Structural Styles in the Deepwater Fold and Thrust Belts of the Niger Delta. Bull Am Assoc Petrol Geol. 2005;89:753-780. Available from: https://doi.org/10.1306/02170504074.

[5] Avbovbo AA. Tertiary lithostratigraphy of Niger Delta. AAPG Bull. 1978;62:295-300.

[6] Doust H, Omatsola E. Niger Delta. In: Edwards JD, Santogrossi PA, editors. Divergent/Passive Margin Basins. AAPG Memoir 48. Tulsa: American Association of Petroleum Geologists; 1990. p. 239-248.

[7] Maju-Oyovwikowhe G, Ukpebor O. Reservoir Characterization and Fluid Analysis of the Majosa Field in the Niger Delta. J GeosciGeomatics. 2023;11(2):39-55. doi: 10.12691/jgg-11-2-2.

[8] Goodway B. AVO and Lamé constants for rock parameterization and fluid detection. CSEG Recorder. 2001;26(6):39-60.

[9] Ukpebor O, Maju-Oyovwikowhe G. Reservoir Characterization of the UM Field in the Niger Delta Using AVO Analysis. J GeosciGeomatics. 2023;11(2):56-66. doi: 10.12691/jgg-11-2-3.

[10] Goodway B, Chen T, Downton J. Improved AVO fluid detection and lithology discrimination using Lamépetrophysical parameters; "λρ", "μρ", & "λ/μ fluid stack", from P and S inversions. In: SEG Technical Program Expanded Abstracts 1997. Tulsa: Society of Exploration Geophysicists; 1997. p. 183-186.

[11] Downton JE, Russell BH, Lines LR. AVO for managers: pitfalls and solutions. CREWES Research Report. 2000.

[12] Mukerji T, Jørstad A, Avseth P, Mavko G, Granli JR. Mapping lithofacies and pore-fluid probabilities in a North Sea reservoir: Seismic inversions and statistical rock physics. Geophysics. 2001;66(4):988-1001.

[13] Mohammad RS. Rock Physics Integration: From Petrophysics to Simulation. In: Proceedings of the 10th Biennial International Conference & Exposition; [date unknown]; City, Country. p. 444.

[14] Close D, Taylor R, Nixon S. Rock physics and quantitative interpretation using lambda-mu-rho in the Shipwreck Trough, Otway Basin. ASEG Extended Abstracts. 2015;2015(1):1-4.

[15] Avseth P, Bachrac R. Seismic properties of unconsolidated sands: Tangential stiffness, Vp/Vs ratios and diagenesis. In: 2005 SEG Annual Meeting; 2005 Nov 6; [location unknown]. OnePetro.

[16] Rasaq B, Igwenagu CL, OnifadeYS. Cross plotting of rock properties for fluid and lithology discrimination using well data in a Niger Delta oil field. J ApplSci Environ Manage. 2015;19(3):539-546.

[17] ReijersTJ, Petters SW, Nwajide CS. The Niger Delta basin. In: Selley RC, editor. Sedimentary Basins of the World. Vol. 3. Amsterdam: Elsevier; 1997. p. 151-172.

[18] Petroconsultants. Petroleum exploration and production database. Houston, Texas: Petroconsultants, Inc.; 1996. [database available from Petroconsultants, Inc., P.O. Box 740619, Houston, TX 77274-0619].

[19] Aigbedion I, Iyayi SE. Diversifying Nigeria's petroleum industry. Int J Phys Sci. 2007;2(10):263-270.

[20] Ozumba B. Geology of the Niger Delta: An Overview for Geophysics Processors. SPDC presentation for geologists in Nigeria. 2013.

[21] Obiadi I, Ozumba B, Osterloff P. Regional Sequence Stratigraphic Framework and Structural Evolution of Parts of the Eastern Central Swamp Depobelt of the Niger Delta, Nigeria. NAPE Bulletin. 2012;24:95-103.

[22] Gassmann F. Elastic waves through a packing of spheres. Geophysics. 1951;16:673-685.

[23] Castagna JP, Batzle ML, Eastwood RL. Relationships between compression wave and shear-wave velocities in clastic silicate rocks. Geophysics. 1985;50:571-581.

[24] Pickett GR. Acoustic character logs and their application in formation evaluation. J Petr Tech. 1963;659-667.

[25] Omudu LM, Ebeniro JO. Cross plot of rock properties for fluid discrimination, using well data in offshore Niger Delta. Niger J Phys. 2005;17:16-20.

[26] Goodway B, Varsek J, Abaco C. Isotropic AVO methods to detect fracture prone zones in tight gas resource plays. In: CSPG/CSEGGeoConvention; 2007. p. 14-7.

[27] Inyang CB. AVO Analysis and Impedance Inversion for Fluid Prediction in Hoover Field, Gulf of Mexico. Houston: University of Houston; 2009. Available from: https://books.google.com.ng/books?id=aS4xcgAACAAJ.

[28] Dewar J. Rock physics for the rest of us: An informal discussion. Can SocExplorGeophys Rec. 2001;5:43-49.

[29] Golyan MF. Compaction rock property evolution and rock physics diagnostics of Askeladd discovery, Norwegian Barents Sea. [cited 2023 June 25]. Available from: http://urn.nb.no/URN:NBN:no-32607.