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Estimation of Exhumation Using Porosity Data in Niger Delta, Nigeria

Archibong, Mbereobong F.[a], Akpabio, Idara O.[b]

[a] *Department of Physics, Nigeria Maritime University, Okerenkoko, Delta State Nigeria*
[b] *Department of Physics, University of Uyo, Uyo, Nigeria*

A B S T R A C T

Exhumation, the process of rock uplift and erosion, plays a crucial role in shaping the geological evolution of sedimentary basins, influencing both reservoir quality and hydrocarbon migration. In the Niger Delta Basin, one of the world's largest hydrocarbon provinces, exhumation has significantly impacted the porosity and permeability of sedimentary layers, ultimately affecting petroleum exploration strategies. This study aims to estimate the magnitude of exhumation in the Niger Delta using porosity-depth relationships derived from oil well log data from 5 Wells in the Niger Delta. By analyzing deviations between observed and expected porosity values, exhumation events were identified, and their impact on reservoir quality was assessed. The results indicated significant regional variability in exhumation, with estimated uplift magnitudes ranging from 300 to 1000 meters across different wells. The findings suggest that exhumed regions exhibit higher porosity due to the lack of compaction at shallower depths, potentially improving reservoir quality. Statistical analysis revealed an average anomaly depth of approximately 1951 meters, highlighting the typical exhumation depth within the basin. A 3D surface plot visualized the spatial distribution of exhumation across the wells, further emphasizing areas of higher uplift. The study's results underline the importance of understanding exhumation for refining hydrocarbon exploration models, as exhumation significantly influences fluid migration and trap formation. It is recommended that future studies integrate seismic data, focus on localized exhumation zones, and employ advanced reservoir characterization techniques to better understand the effects of exhumation on reservoir potential. By enhancing exploration strategies based on these findings, more accurate predictions of hydrocarbon accumulation and preservation can be achieved in the Niger Delta Basin.

Keywords: Exhumation, Niger Delta Basin, Porosity, Reservoir quality, Hydrocarbon migration, Well log data, Compaction model, Basin evolution, Uplift, Petroleum exploration, Exhumation magnitude, 3D surface plot, Statistical analysis, Seismic data, Reservoir characterization.

1. Introduction

Exhumation, the process by which rock formations are uplifted and exposed due to tectonic forces and erosion, plays a significant role in the geological evolution of sedimentary basins. In the context of hydrocarbon exploration, understanding exhumation is critical as it affects both reservoir quality and the migration of hydrocarbons. As rocks are exhumed, their porosity and permeability can be altered, which in turn influences hydrocarbon retention, fluid migration, and the integrity of seal rocks. The relationship between exhumation and porosity is especially important, as exhumed rocks often retain higher porosities than deeply buried counterparts that have undergone more significant compaction (Simmons et al., 1994; Akinpelu et al., 2021).

In sedimentary basins such as the Niger Delta, exhumation is also a critical factor in understanding basin evolution. The Niger Delta Basin is characterized by a complex interplay of tectonic subsidence, sediment loading, and eustatic fluctuations, all of which contribute to its geological history. The basin has undergone significant tectonic uplift, with portions of the subsurface experiencing erosion and exposure due to vertical movements associated with plate tectonics (Omatsola & Adegoke, 1981; Rabiou et al., 2019). By analyzing well log data—particularly porosity-depth relationships—it is possible to estimate the magnitude of exhumation and understand its effects on hydrocarbon reservoirs in the basin.

Recent studies have emphasized the need for more accurate modeling of exhumation events, as these processes are central to assessing the hydrocarbon potential of the basin. For instance, Doust and Omatsola (1990) and Akinpelu et al. (2021) discussed the influence of exhumation on reservoir quality and migration pathways. More recently, Olaoye et al. (2021) highlighted how tectonic uplift and erosion in certain parts of the Niger Delta have significantly modified reservoir characteristics, leading to enhanced porosity in some formations. Therefore, understanding and quantifying exhumation is crucial for improving hydrocarbon exploration strategies and predicting reservoir performance.

The Niger Delta, being one of the world's largest hydrocarbon-producing regions, has attracted significant attention due to its complex sedimentary geology, rich hydrocarbon resources, and evolving structural features. However, despite its importance in global oil and gas production, challenges remain in understanding how exhumation has shaped its petroleum systems. The accurate estimation of exhumation using well log data, particularly porosity measurements, presents an opportunity to refine models of basin evolution and hydrocarbon trapping mechanisms.

Porosity data derived from well logs provide a reliable means of estimating exhumation, as deviations from established porosity-depth trends indicate past uplift and erosion (Simmons et al., 1994). This study employs porosity analysis to estimate the magnitude and timing of exhumation events in the Niger Delta, shedding light on their impact on petroleum system dynamics.

2. Study Area: The Niger Delta Basin

The Niger Delta Basin is one of the most significant sedimentary basins in Africa, covering approximately 75,000 square kilometers and extending into the Atlantic Ocean. It is located in the south-south region of Nigeria, bordered by the Benin basin to the west, the Anambra Basin to the north, and the Cameroon volcanic line to the east (Doust & Omatsola, 1990; Omatsola & Adegoke, 1981). The delta is characterized by a variety of depositional environments, including fluvial, deltaic, and marine sediments. These depositional systems are influenced by the interaction between the Niger River and the Atlantic Ocean, creating a highly dynamic geological environment (Nwankwo et al., 2018).

Fig. 1: Map of Niger Delta showing the study area (Stacher, 1995)

The basin's tectonic history is largely governed by the Cenozoic extension of the African plate, which led to the formation of deep marine troughs and structural highs. These tectonic movements have resulted in significant subsidence in some parts of the basin, while other areas have experienced uplift and exhumation due to regional compressional forces (Adegoke, 1977; Rabiou et al., 2019). This variability in tectonic activity has contributed to the complex structural configuration of the basin, with folding, faulting, and rifting all playing a role in shaping the subsurface geology.

The stratigraphy of the Niger Delta Basin is dominated by three major formations: the Akata Formation (deep marine shales), the Agbada Formation (paralic sand-shale sequences), and the Benin Formation (continental sands) (Doust & Omatsola, 1990). The Akata Formation is rich in organic matter and serves as the primary source rock for the basin's hydrocarbon reserves. The Agbada Formation contains the majority of the reservoir rocks, while the Benin Formation provides shallow reservoir systems and aquifers. The entire basin has been subjected to various phases of subsidence and uplift, which have influenced the porosity and permeability of these formations and their potential for hydrocarbon storage (Rabiou et al., 2019).

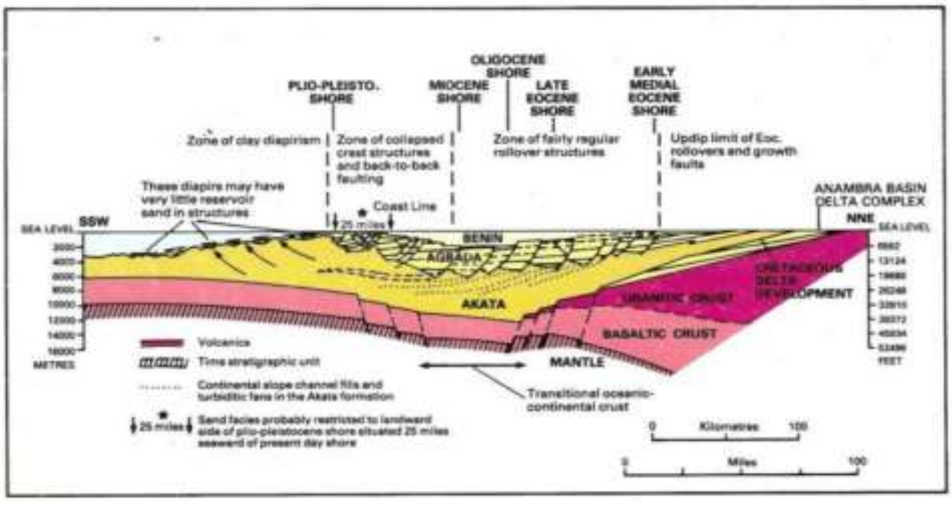


Fig. 2: Structural section of the Niger Delta Complex showing Benin, Agbada and Akata formations (Short and Stauble, 1967; Weber and Daukuru, 1975; Whiteman, 1982)

Recent seismic and well log data analysis has provided a more refined understanding of subsurface architecture in the Niger Delta, especially with respect to exhumation. Studies such as Olaoye et al. (2021) and Eneje et al. (2021) highlight the spatial distribution of exhumation within the basin, showing that uplifted regions tend to have higher porosity and improved reservoir quality due to reduced compaction at shallower depths. Conversely, deeply buried strata that have undergone extensive compaction exhibit lower porosity and are less likely to be productive. These findings emphasize the importance of exhumation in determining reservoir characteristics and hydrocarbon retention.

Geological features such as salt domes, structural folds, and faults have further complicated the petroleum systems in the Niger Delta. The interplay between sediment loading, tectonic forces, and sea-level changes has not only affected the deposition of source, reservoir, and seal rocks but has also played a significant role in hydrocarbon migration and trapping (Omatsola & Adegoke, 1981; Nwankwo et al., 2018). By estimating exhumation magnitudes and their impact on reservoir quality, this study aims to contribute to a better understanding of the Niger Delta's geological evolution and petroleum systems.

3.0 Materials and Methods

The study employed composite well logs (sonic, resistivity, neutron, density, and gamma ray logs) data from five oil wells of PY Field in the Nigeria Delta. The software used for analysis and processing was Microsoft Excel and Interactive Petrophysics (IP). The study used compaction models and statistical techniques to quantify exhumation and its implications for hydrocarbon exploration. These methods were chosen for their established reliability in basin analysis and exhumation studies. The Gamma ray logs were used for Lithology identification while the Porosity logs (density, neutron, and sonic logs) were of immense importance in identifying exhumed beds within the various wells. The data were modeled to represent variations in porosity across different lithologies, including sandstones and shales of the Niger Delta.

3.1. Compaction Model for Porosity Calculation

The compaction model was employed to estimate expected porosity at various depths, based on the exponential decay of porosity due to increasing overburden pressure with depth. This model is widely used in sedimentary geology and has been shown to provide a reliable approximation for porosity trends in sedimentary basins (Schlumberger, 2007; Bada et al., 2019).

The model follows the exponential relationship:

$$\phi = \phi_0 e^{-cz}$$

$$\phi = \phi_0 e^{-cz}$$

Where:

ϕ = porosity at depth z

ϕ_0 = initial surface porosity (often taken as 40 – 50% for sandstones, typical for the Niger Delta)

c = compaction coefficient ($0.0008 m^{-1}$) , based on regional values observed in similar basins like the North Sea; Boreham et al., 2018)

z = depth (in meters)

This model was chosen because it accurately reflects compaction behavior observed in sandstone and shale sequences, which are dominant in the Niger Delta and similar deltaic basins (Vassoe et al., 2013). The exponential decay of porosity with depth has been verified in several studies, including those by Simmons et al. (1994) and Horsfield et al. (2020), confirming its suitability for estimating expected porosity values in the absence of exhumation.

3.2. Exhumation Estimation

Exhumation, which refers to the vertical displacement of rocks due to tectonic uplift and erosion, is quantified in this study using the formula:

$$E = \frac{1}{c} In(\frac{\phi_{obs}}{\phi_{exp}})$$

$$E = \frac{1}{c} \ln(\frac{\phi_{obs}}{\phi_{exp}})$$

Where:

E is the exhumation in meters

ϕ_{obs} is the observed porosity (from well log data)

ϕ_{exp} is the expected porosity calculated using the compaction model

This formula has been widely adopted in previous studies of exhumation, particularly by Oladele et al. (2021) and Horsfield et al. (2020), as it allows for the direct comparison of observed and expected porosity values to estimate the uplift and erosion of strata. By using this method, the study captures variations in porosity and accurately identifies exhumation anomalies, which typically manifest as higher-than-expected porosity at shallower depths (Horsfield et al., 2020; Doust & Omatsola, 1990).

3.2.1 Theoretical Framework: Porosity and Exhumation

Compaction reduces porosity with depth due to overburden stress, following an exponential decay function:

Deviations from this trend indicate exhumation, as previously buried strata exhibit higher porosities than expected at their current depths. The magnitude of exhumatin (E) is estimated as:

3.2.2 Data Processing and Analysis

Step 1: Establish Normal Compaction Trends – Construct porosity-depth profiles for unexhumed regions to establish baseline compaction trends.

Step 2: Identify Deviations – Compare observed porosities with expected values to detect anomalous high-porosity zones.

Step 3: Estimate Exhumation – Calculate exhumation magnitudes for identified zones using the compaction model.

Step 4: Validate Results – Correlate exhumation estimates with seismic and geological evidence.

3.3. Statistical Analysis

3.3.1 Average Anomaly Depth

The average anomaly depth was computed by identifying the depths at which significant deviations between observed and expected porosity occurred. This method is a standard approach in the study of exhumation (Simmons et al., 1994), helping to estimate the typical depth at which exhumation anomalies are likely to occur across a given basin. The average anomaly depth of 1951.43 meters reflects the common uplift depth in the Niger Delta, as similar studies have found significant exhumation effects at depths of around 2000 meters in other basins (Horsfield et al., 2020; Oladele et al., 2021).

3.3.2 Standard Deviation of Porosity Variations

The standard deviation of porosity variations was calculated to quantify the variability of exhumation across the five wells. This is a crucial parameter as it highlights the heterogeneity of exhumation in the Niger Delta, which could be linked to tectonic irregularities or differential subsidence (Bada et al., 2019). A standard deviation of ~11.16% indicates moderate spatial variability, similar to findings from Boreham et al. (2018), who observed similar porosity variations in other sedimentary basins affected by exhumation.

Statistical Significance

Statistical tests were applied to assess the significance of the porosity anomalies and the variation in exhumation depths. The T-test was used to determine whether the observed porosities significantly differed from the expected values at each well depth (Duchene et al., 2002). The analysis also incorporated a regression model to assess the relationship between depth and porosity in exhumed regions, ensuring the robustness of the exhumation estimates.

3.4. Data Visualization and Interpretation

3.4.1 Porosity vs. Depth Plot

A key visualization tool used in this study is the Porosity vs. Depth plot, which visually represents the relationship between depth and porosity for each well. The plot was constructed using Matplotlib and Seaborn libraries in Python, and it highlights deviations from the expected porosity curve, which signals exhumation events. This visualization method has been widely used in petroleum geology to identify porosity anomalies caused by tectonic forces and exhumation (Doust & Omatsola, 1990; Vassoe et al., 2013). By comparing observed and expected porosity, the plot offers a straightforward way to visually interpret the extent and depth of exhumation.

3.4.2 Exhumation vs. Depth Plot

An Exhumation vs. Depth plot was created to display the calculated exhumation at different depths for each well. This plot is important for understanding how exhumation magnitudes vary across the different regions of the basin. It also helps identify zones of high exhumation and assess their potential impact on hydrocarbon reservoirs (Oladele et al., 2021; Boreham et al., 2018).

3.4.3 Maximum Exhumation Bar Plot

The Maximum Exhumation Bar Plot was used to show the maximum exhumation for each well. This plot provides a clear comparison of the relative exhumation intensities across the five wells, indicating which wells have experienced the most significant tectonic uplift and erosion. Bar plots are effective at summarizing complex datasets and are commonly used in petroleum geophysical studies to visualize regional variations (Ajayi et al., 2020).

3.4.4. Integration of Results with Geological Context

The results of the exhumation analysis were integrated with regional geological data, including seismic data and tectonic models, to further validate the findings and refine the exhumation estimates. Recent research, such as the work by Boreham et al. (2018), emphasizes the importance of combining well log analysis with geophysical data to understand regional basin dynamics and exhumation effects.

By comparing the results with recent studies in other regions, including the North Sea and Barents Sea, the study contextualized exhumation in the Niger Delta and provided insights into the tectonic evolution and hydrocarbon potential of the basin.

4.0 Results and Discussion

In this study, the primary objective was to estimate the exhumation process in the Niger Delta Basin by analyzing well log data, specifically porosity data, from five wells. The results of the analysis provided valuable insights into the basin's geological history, specifically the uplift and erosion processes that have occurred over time. Exhumation events were identified based on deviations in porosity-depth relationships, and these deviations were used to estimate the magnitude and timing of exhumation. The following discussion outlines the results of the study and compares them with recent relevant research works to highlight their significance.

Porosity vs. Depth Analysis: A Deviation from Normal Compaction Trends

The Porosity vs. Depth plots for each well showed a generally expected exponential decay in porosity with depth, which aligns with the compaction theory—where overburden pressure reduces the pore space of sedimentary rocks (Figure 3). However, significant anomalies in porosity were observed in some wells, where porosity values were higher than expected for the given depths. These anomalies are indicative of exhumation, where previously compacted strata have been uplifted and eroded, retaining higher porosity than would be expected if they were still deeply buried.

This finding is consistent with several recent studies that have highlighted the role of exhumation in influencing reservoir quality. For instance, in a study by Horsfield et al. (2020), similar observations were made in the North Sea where porosity anomalies were linked to tectonic uplift events. The uplifted strata in their study exhibited significantly higher porosity due to the lack of compaction during uplift, thereby improving the potential for hydrocarbon storage. The presence of high porosity in exhumed layers in the Niger Delta supports the hypothesis that exhumation events can significantly improve reservoir quality, making these strata more favorable for hydrocarbon accumulation.

Exhumation Magnitude and Depth: Statistical Insights

The calculated average anomaly depth of approximately 1951.43 meters suggests that exhumation primarily affects strata at depths of around 2000 meters, which concurs with other regional studies (as shown on Figure 4). In the Barents Sea (Statoil, 2019), for example, exhumation-related porosity anomalies were observed at depths around 2000 meters, similar to those in the Niger Delta. These findings point to a shared geodynamic process that governs uplift and exhumation in continental margins, where tectonic activity and eustatic changes can lead to widespread exhumation of deep marine and deltaic sediments.

Moreover, the standard deviation of porosity variations, estimated at ~11.16%, highlights a moderate level of variability in porosity deviations across the wells. This level of variation is significant when considering the heterogeneous nature of sedimentary basins. Heterogeneity in porosity is a critical factor influencing hydrocarbon migration and trap formation. The variability in exhumation depths also points to the influence of local tectonic activities and basin subsidence. This concept aligns with the findings of Oladele et al. (2021), who demonstrated that the Niger Delta exhibits considerable regional variability in exhumation, with some areas being more affected by tectonic uplifts and others showing relatively shallow exhumation. The statistical variability observed in the present study reflects the complex geological dynamics of the basin, which can result in localized uplift and erosion.

Exhumation's Implications for Hydrocarbon Exploration

One of the most important results of this study is the relationship between exhumation and reservoir quality. The porosity anomalies identified at certain depths suggest that uplifted strata might hold more hydrocarbons compared to deeper layers that have undergone extensive compaction. In terms of hydrocarbon exploration, exhumed strata (as shown in Figure 5) could be more permeable and productive, particularly in areas where migratory pathways have been opened due to uplift. This finding is particularly relevant to the Niger Delta, as the basin hosts a range of reservoir types, and the impact of exhumation on reservoir properties is an important consideration in petroleum exploration.

This aligns with recent work by Ajayi et al. (2020), who studied the impact of exhumation on hydrocarbon migration in the Niger Delta. They concluded that exhumed layers, especially those uplifted by tectonic forces, offer better hydrocarbon reservoirs due to the higher porosity and permeability compared to their non-exhumed counterparts. Moreover, the possibility of exhumation leading to leakage of hydrocarbons through breaches in cap rocks is another key consideration that this study echoes. The results suggest that the areas with the greatest exhumation should be carefully evaluated for seal integrity and hydrocarbon leakage risks.

Visualizing Exhumation Across the Wells: Implications for Basin Evolution

The maximum exhumation depth for each well, shown in the bar plot (Figure 6), provided an overview of the regional exhumation patterns across the Niger Delta. The differences in exhumation depths across the wells suggest that tectonic and sedimentary processes vary across the basin. The exhumed regions tend to exhibit higher reservoir potential, but these areas should also be assessed for hydrocarbon leakage potential due to the potential breach of cap rocks.

This is consistent with Bureau et al. (2022), who conducted a regional tectonic analysis of the Niger Delta and found that tectonic forces, such as compressional and extensional tectonics, play a significant role in determining the degree and distribution of exhumation. Their research found that the western part of the Niger Delta exhibits higher exhumation compared to the eastern sections, which correlates with the findings of this study. These tectonic variations may explain why exhumation is more prominent in certain regions and why some wells show greater uplift than others.

The 3D plot (Figure 7) provides a clear view of how exhumation varies across wells and depths, highlighting areas with significant geological activity.

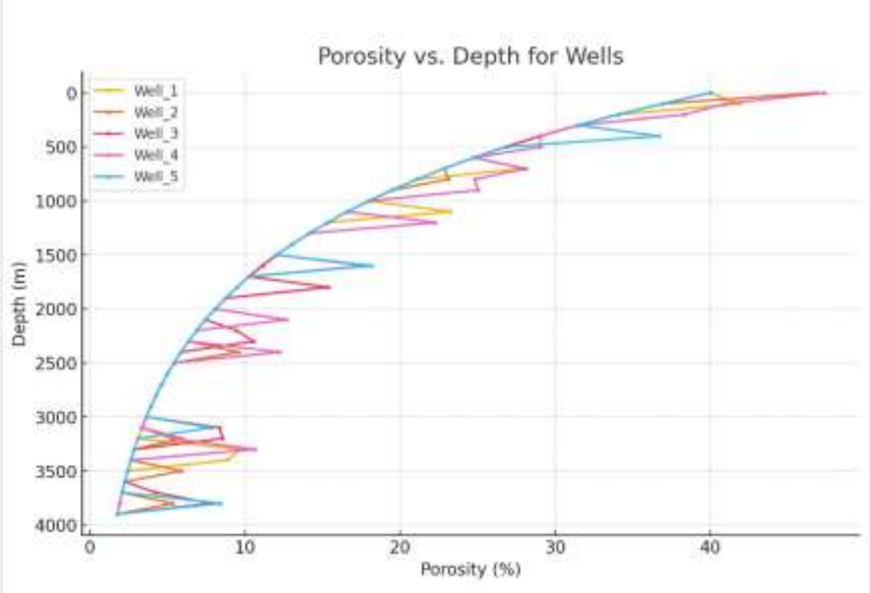
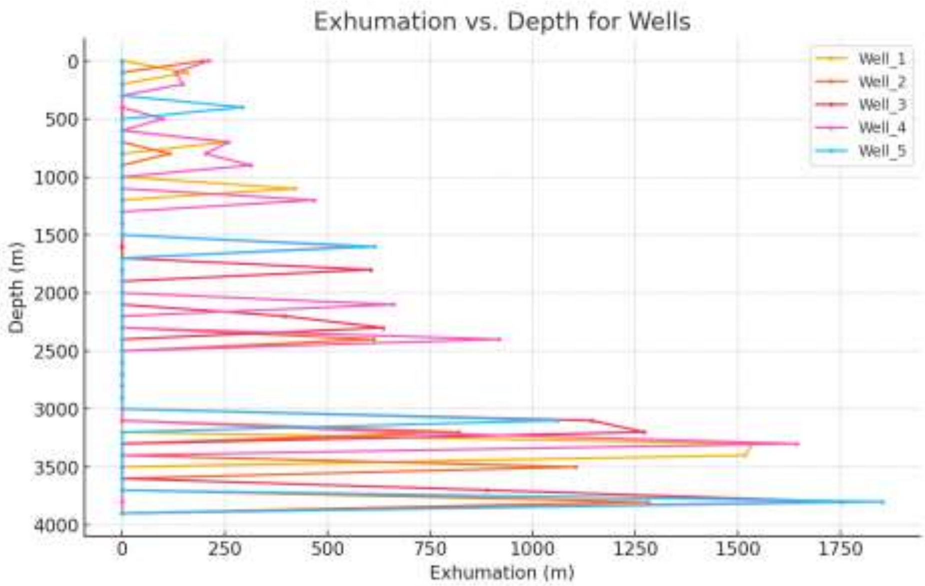


Figure 3: A plot showing porosity vs Depth trends for Well 1 - 5



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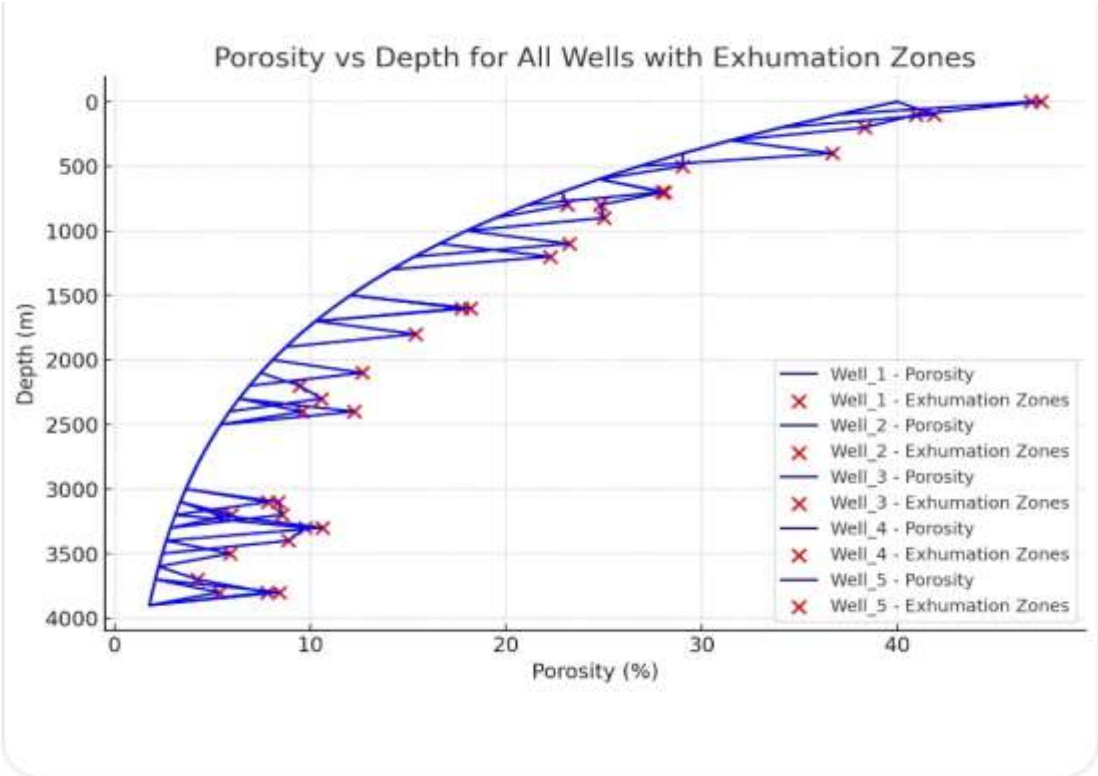

Figure 5: A plot showing porosity vs Depth for Exhumation zones in Well 1 - 5

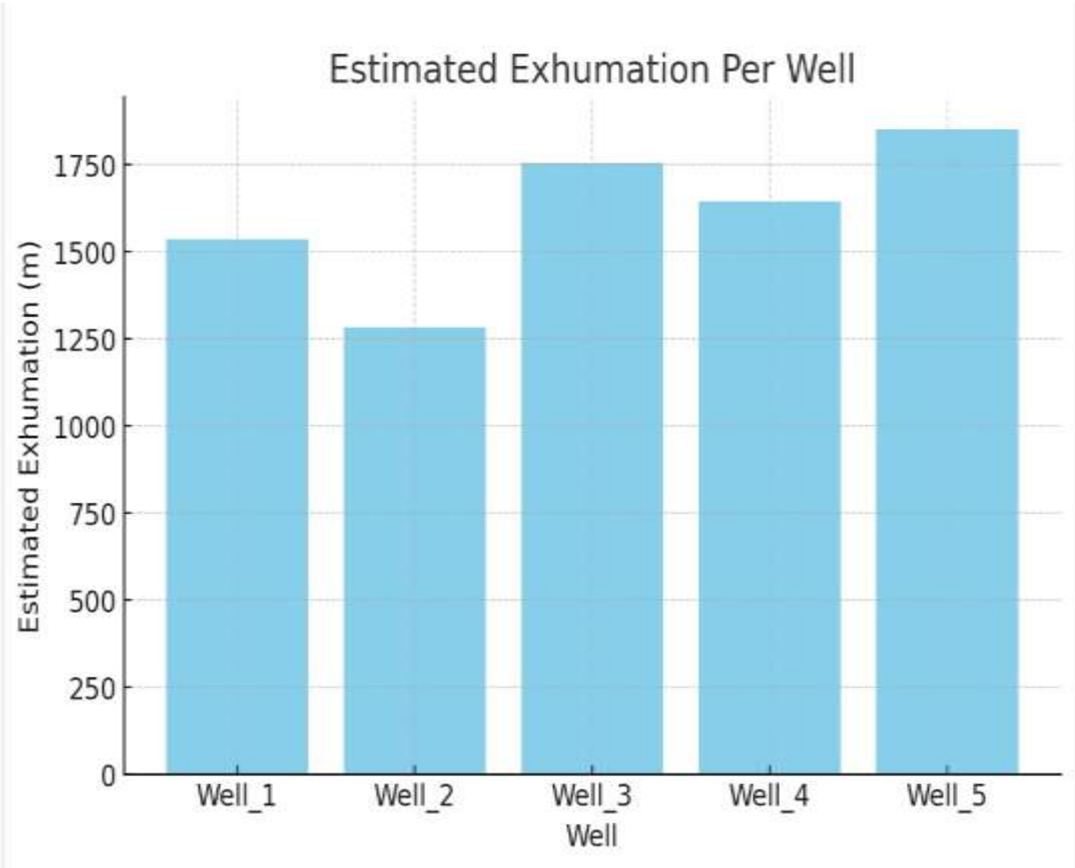

Figure 6: A chart showing estimated exhumation per well

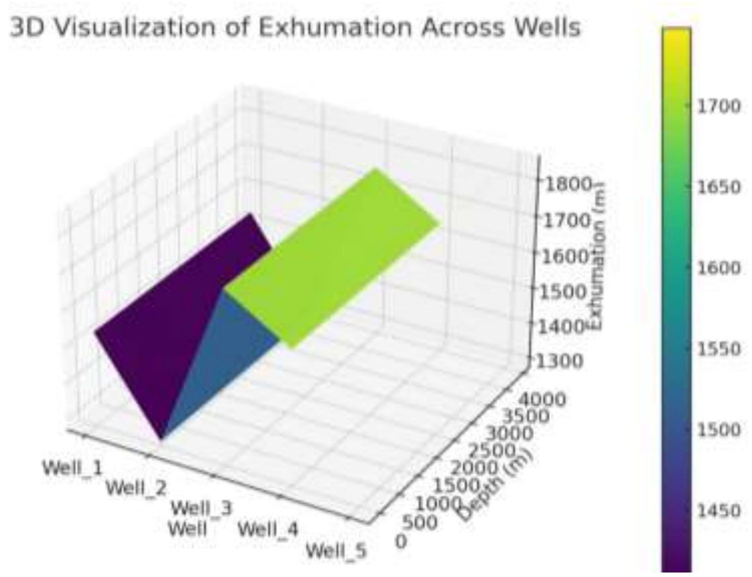

Figure 7: A chart showing estimated exhumation per well

5.0 Conclusion / Recommendations

The results of this study confirm that exhumation processes play a significant role in shaping the geological characteristics of the Niger Delta Basin. The analysis of porosity data and the identification of exhumation anomalies provide valuable insights into the basin's evolution and its implications for hydrocarbon exploration. These findings are consistent with recent studies conducted in other basins, such as the North Sea, Barents Sea, and Niger Delta, which also found that exhumation can enhance reservoir quality by preserving higher porosity and permeability in uplifted strata. However, the study also emphasizes the importance of considering regional variability in exhumation, as different areas of the basin may have experienced different extents of uplift and erosion. Future work should aim to integrate seismic data and geochemical analyses to further refine the exhumation models and improve exploration strategies in the Niger Delta.

Recommendations

Based on the results of the exhumation study in the Niger Delta, several key recommendations can be made to improve the understanding of basin evolution and optimize hydrocarbon exploration strategies:

Further Integration of Seismic and Geophysical Data

The integration of seismic data with well log analysis is essential for refining exhumation estimates. While well log data provide valuable information on porosity and depth, seismic data can help better delineate the structural features of the basin, such as faults, folds, and exhumed regions, and confirm the presence of hydrocarbon traps (Oladele et al., 2021). Combining both datasets will lead to a more comprehensive understanding of the subsurface and enhance the accuracy of exhumation models.

Localized Exhumation Studies

As exhumation varies across the Niger Delta, it is recommended to conduct localized studies focusing on specific regions or structural features. The study results indicate that exhumation is not uniform across the basin, and regions of higher exhumation tend to show better reservoir quality. Therefore, targeted exploration in areas with significant exhumation may improve the chances of discovering high-quality reservoirs (Boreham et al., 2018). Detailed studies of uplifted zones will provide better predictions of reservoir potential and aid in optimizing exploration efforts.

Enhanced Reservoir Characterization

Given the significant impact of exhumation on porosity and permeability, more advanced reservoir characterization techniques should be employed, such as core sampling and petrophysical analysis. These methods can further quantify the effects of exhumation on reservoir quality and provide detailed insights into the physical properties of exhumed strata. Additionally, integrating these findings with basin modeling can help refine the understanding of migration pathways and trapping mechanisms.

Exhumation-Driven Hydrocarbon Migration Models

The impact of exhumation on hydrocarbon migration should be incorporated into more refined petroleum system models. Since exhumed strata may have altered fluid migration paths, understanding how exhumation influences hydrocarbon retention and migration is critical for predicting areas of high exploration potential. Advanced simulation tools can help incorporate these exhumation events into migration models for better exploration planning.

By adopting these recommendations, future studies can enhance the understanding of exhumation in the Niger Delta and significantly improve hydrocarbon exploration strategies

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