Application of Quantitative Seismic Interpretation Techniques for Prospect Maturation of Part of the Northern Depobelts East Onshore Niger Delta

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ABSTRACT

Onshore hydrocarbon exploration in the Niger delta has continued to decline as major industry players shift attention to offshore environments with massive divestment of onshore assets. This reduction in onshore exploration activities is compounded with the increasing cost of delivering exploration wells, risk of meeting exploration objectives, and reduction in the sizes of the prospects available to be tested. There is therefore a need to properly mature existing prospects before committing scarce financial resources. This study integrates quantitative seismic techniques to prospect maturation through the integration of rock physics, seismic inversion, and amplitude versus offset (AVO) analysis to de-risk prospects and leads in an onshore acreage. The predictive power of the integrated workflow was calibrated with nearby discoveries in the study area to support hydrocarbon detection and prospect de-risking using three-dimensional (3D) seismic data sets and well logs. Seismo-structural interpretation, fault-seal analysis, rock physics and AVO analysis were integrated to improve the understanding of the underlying geology, and the sensitivity of elastic attributes to fluid and lithology. Diagnostic rock physics analysis reveals acoustic impedance (Zp) and Lambda Rho (LR) attributes as the most sensitive attributes for seismic inversion and reservoir characterization within the area of interest. Anomalously low impedance and Lambda Rho responses show good structural conformity for the identified prospect. Also, the AVO analysis of the identified prospects indicates the potential for light hydrocarbon with the classical AVO class III responses. The integrated results from rock physics analysis, seismic inversion and AVO analysis, have improved the ranking of identified exploration prospects, their geological chances of success and speculative resource estimation.

Keywords: Rock Physics, Simultaneous Inversion, AVO analysis, Exploration, Northern Depobelt, Niger Delta.

INTRODUCTION

With the rising cost of exploration activities, the observed reduction in the sizes of the prospects available to be tested and decline in production from existing fields; there is need for proper maturation of new opportunities to ensure higher chances of exploration success. This will ultimately help to sustain production and provide bases for reserves replacement. To achieve this however, it is important to subject these “opportunities” to robust technical scrutiny that will help de-risk them, ensure the intended value is delivered, and reduce surprises.

The previous exploration wells drilled in the block were based on structural closures with little or no history of quantitative study. While most of the exploration wells were successful, quantitative analysis would have helped optimize subsurface targets and well placement in many cases. The key objective of the study includes.

a. To de-risk identified Prospect A and Prospect B
b. To provide additional bases for ranking these prospects in the exploration portfolio.

This study integrates quantitative seismic interpretation methods to the overall prospect maturation process for two prospects (A and B) located in the eastern part of the Northern depobelt, onshore Niger Delta. This includes prospectivity analysis, rock physics analysis, simultaneous seismic inversion and AVO analysis. Importantly, the generated models were calibrated with existing discoveries.

Offset well logs for two offset wells with Gamma ray, Resistivity (Shallow, Mid and Deep), Density, Neutron and Compressional sonic logs, check-shot etc., Full stack seismic data (zero phase, SEG polarity), Angle stacks (0-15deg, 15-30deg, 25-40deg, 30-50deg), seismic gathers, interpreted seismic horizons and Computer Processed Log (CPI) were available for the study.

GEOLOGICAL SETTING

The prospects under study are located in the Northern Depobelt in the onshore Niger- Delta basin (Figure-1a).

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The regional geology is characterized by a tripartite lithostratigraphy units consisting of Benin, Agbada, and Akata Formations within the Niger Delta complex (Avbovbo, 1978). These lithostratigraphic units are diachronous and affected by large scale synsedimentary features such as growth faults, roll-over anticlines and diapirs. Sediment deposition in the Tertiary prograding Niger Delta Basin is complicated by depositional patterns restricted to series of fault controlled sub-basins, referred to as depobelts that strike northwest to southeast, sub-parallel to the present shoreline (Knox and Omatsola, 1989).

Based on the analysis of the offset wells, two mega plays– Upper Cretaceous mega play and Tertiary mega play were identified. Five other stratigraphic plays were also defined namely, Middle Eocene, Upper Eocene, Lower Oligocene, Upper Oligocene, and Lower Miocene (Ejedawe, J. E., 1989). The Eocene plays are developed in the Northern delta depobelt, while the Oligocene and Miocene plays are developed in the Greater Ughelli depobelt. The plays reflect the episodic shift in depocenters as successive fault trains become active as the delta prograde from north to south across the area.

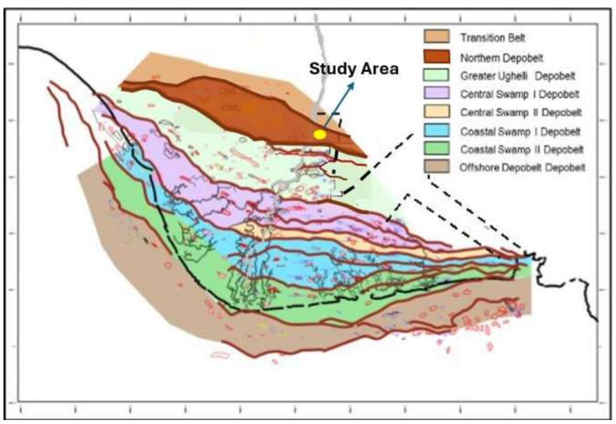


Figure 1: Structural elements of the Niger Delta Basin – Onshore and Offshore and the study area.

METHODOLOGY

The methodology adopted in this study include data review, well and seismic data conditioning, AVO modeling to identify possible AVO effect in the seismic within the Area of Interest (AOI), and seismic amplitude review through the generation of pseudo fluid stack from the available seismic sub-stack (prospectivity analysis). This was followed by rock physics analysis in the offset wells to understand the local geology and identify fluid and lithology sensitive attributes to be inverted from the seismic. Simultaneous seismic inversion was then carried out and stratal slices generated to identify amplitude responses and their structural conformity. AVO analysis (gradient vs intercept plot and amplitude vs angle plots) were then made to analyze the likely causes of the observed amplitude responses and their AVO classes (Aki, K., and P. G. Richards 1980) (Figure 2). All the QI products generated in this study were calibrated by the result of offset discoveries. This enhanced the reliability of the products.

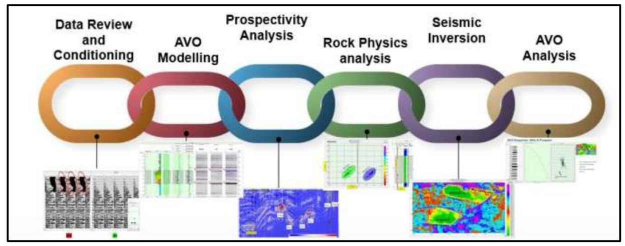


Figure-2: Adopted workflow. Quantitative seismic interpretation workflow adopted for maturation of prospect A and Prospect B.

Avo Modeling

Figure-3 below shows the result of the Amplitude Vs Offset (AVO) modeling for one of the offset wells within the AOI. It was carried out to determine the possibility of AVO effect in the seismic. The insitu fluid in the reservoir is Gas. The gas was replaced with Oil and then brine through Gassmann fluid substitution process to generate the petrophysical log responses for different reservoir fluids. These were used to generate the corresponding synthetic AVO gathers. Observe how the response at the top of the reservoir (trough-blue) brightens from Brine to Oil and to Gas. The base of the reservoir also shows similar responses, as the peak (-red) also brightens from Brine to Oil and then to Gas (Figure-3).

This result indicates that the seismic from the AOI should be sensitive to reservoir fluid changes and AVO responses. This is also supported by the rock physics analysis where the background shale and brine bearing sand shows distinct feature from the hydrocarbon bearing part of the reservoir (Figure 5a to 5d).

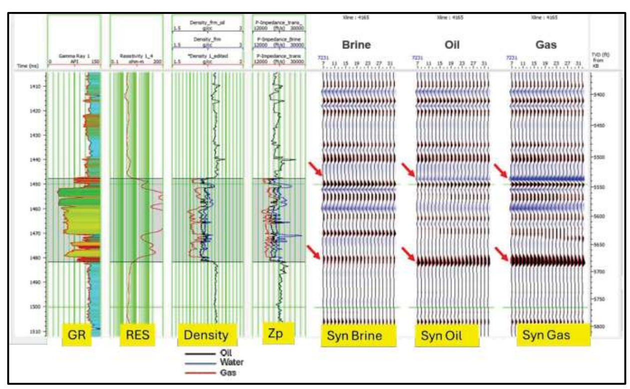


Figure 3: Fluid substitution and Synthetic AVO Gathers. *Log responses for different reservoir fluid generated through fluid substitution. Each combination of logs used to generate synthetic gathers. Large difference in the generated gathers at the top and base of the reservoir I ndicate high reservoir fluid sensitivity and possible AVO presence.*

Prospectivity Analysis

Quick look prospectivity analysis was carried out to identify areas with anomalous amplitude responses within the AOI. It was achieved through pseudo fluid stack volume generated using seismic sub-stacks; by multiplying the difference between the Far and Near angle stack with the Far angle stack. This results in amplified "likely" fluid effect within the seismic volume.

Pseudo Fluid Stack = (F – N) * F

**Where F is the far angle sub stack (30 – 50 deg) and N is Near Angle Sub stack (0-15deg).

The red colored areas show zones of high amplitude while the blue and whitish patches represent the background (Figure 4) The offset discovery in the western part of the area shows decent amplitude responses consistent with the gas find in the well. The unsuccessful exploration well in the eastern part (Figure 5) shows no amplitude response. However, there is a high amplitude response up dip of the well location.

The review of the result at prospects location highlights promising high amplitude responses at Prospect-A, Prospect-B and some other prospects within the area.

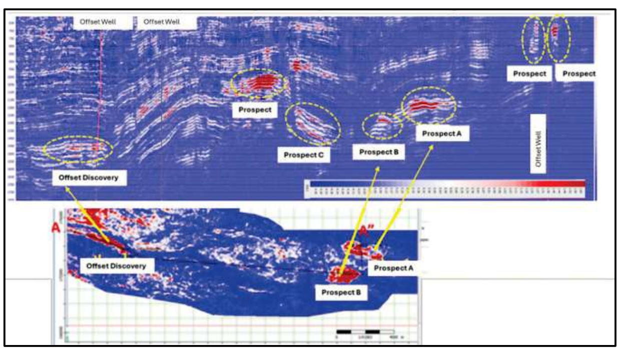


Figure 4: Pseudo Fluid section and stratal slice highlighting offset well-1 discovery and some prospects.
(Anomalous high amplitude responses (Red) represent prospective zones while the bluish zones are the background. The offset well (to the west) with gas discovery shows corresponding high amplitude response. Prospect A and Prospect B also show anomalously high amplitude indicative of possible hydrocarbon presence.).

Rock Physics Analysis

Rock physics analysis was carried out in offset wells to understand the local geology and the sensitivity of elastic rock attribute to fluid and lithology. Several log attributes such as Lambda-Mu rho, acoustic impedance, shear impedance, Vp/Vs ratio, poisson ratio, etc. were generated and cross plotted. Acoustic impedance and Lambda rho attributes show distinctive discriminative ability for reservoir fluid and lithology.

Acoustic impedance depth trend for an offset well shows gradual impedance increase with depth with the shale impedance higher than that of sand. The presence of hydrocarbon in most reservoirs further suppressed the sand impedance responses. These suppressed impedance of hydrocarbon sands resulted in a good contrast between shale/ wet sand and hydrocarbon bearing sand impedance response (Figure 5a).

Figure 5c and Figure 5d show the result of lambda rho vs Mu-rho cross plot in two different reservoirs encountered by two different offset wells. Two distinct clusters were observed in both cases. The high lambda rho cluster above 20 Gpa*g/cc (Blue) represents the shale and the and brine filled sand while the low lambda below 20 Gpa*g/cc cluster is the gas filled sand. The high overlap in the Mu-rho axis indicates that the Mu-rho attribute will not be sufficient for lithologic discrimination.

Based on the rock physics analysis, acoustic impedance and lambda rho attributes were selected as the primary attributes for fluid discrimination in this area and were inverted for through the simultaneous seismic inversion process.

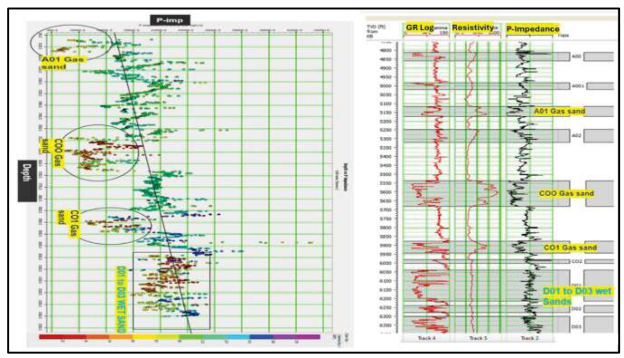
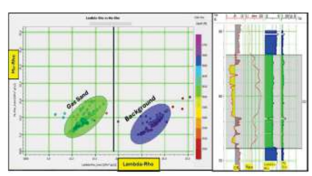


Figure 5a: showing impedance depth trend for offset well-2. **Figure 5b:** Log plot showing the different reservoirs.

(Figure-5a show impedance trend with depth while Figure-5b shows stacks of the different reservoirs encountered by the well. Observe the lower impedance responses within the gas bearing A01, COO and CO1 reservoir and the relatively high impedance response in the brine bearing D01 to D03 reservoirs.)



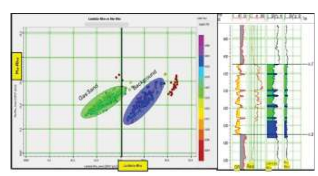


Figure 5c: showing Mu rho Vs Lambda cross plot for offset well-2.

Figure 5d: showing Mu rho Vs Lambda cross plot offset well -1.

*(Lambda Mu rho cross plot for two different wells across two different reservoirs-5c and 5d. Observe clear clusters of low Lambda Rho response (below 20 Gpa*g/cc indicating the gas sand in both cases. Large overlap exists in Mu rho axis showing its poor discriminative ability in this area)*

Seismic Inversion

Model based pre-stack (simultaneous) seismic inversion method was adopted based on the result of rock physics analysis which highlights lambda rho and acoustic impedance attribute as useful attributes for fluid discrimination in this area. The standard workflow for the pre-stack inversion was adopted and is illustrated in (Figure-6a)

The conditioned seismic gather, well logs and regional seismic surfaces are the key input for the inversion process. Two offset wells were used to calibrate the model.

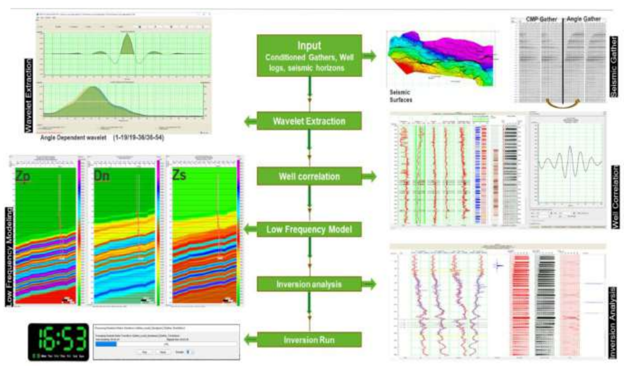


Figure6a: showing adopted workflow for pre-stack inversion.

Inversion Analysis

Inversion analysis was carried out at the offset well locations to calibrate and optimize inversion parameters before applying them to the entire seismic data. The model-based inversion starts with the equation of convolutional model; S=W*R +N where the seismic trace (S) and the Wavelet (W) are known, and the noise is uncorrelatable and difficult to quantify. The reflectivity series is then solved iteratively. The reflectivity series which generates a synthetic seismic that matches the actual seismic is assumed to be correct (HRS manual v 13.1 2023).

Figure-6b shows the inversion analysis at one of the offsets well locations. Tracks 1 to 4 show the input log (blue) versus model log (red) comparison for Zp, Zs, Density and Vp/Vs ratio respectively. Tracks 6 and 7 are the synthetic and actual seismic trace while track 9 shows the difference between the synthetics and the seismic trace. The smaller the error, the more representative the model is.

The analysis is quality checked by comparing the Zp responses from the log to that of the model and the differences between the synthetic and the actual seismic traces at all well locations. 7% error was obtained at the offset well location.

DISCUSSION OF RESULTS

OFFSET DISCOVERY

Description: An offset discovery located about 7km west of the prospect A and B was used for the calibration of the model. The well was drilled in 1996 discovered one gas bearing sand with gross thickness of about 170ft and net gas sand of 130ft (Figure 7a). It is a fault dependent

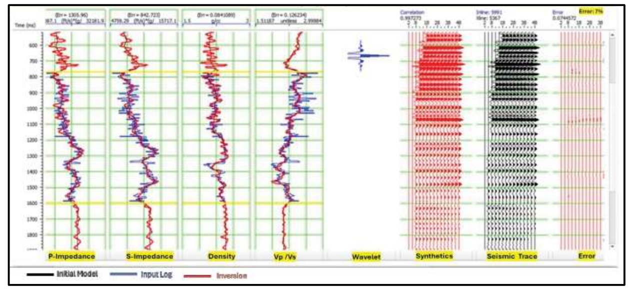


Figure 6b: Panel showing inversion analysis at offset well-1. (Observe the match between the input logs in blue and the inversion result in red. Also, the synthetic (inversion) and the input seismic. Analysis indicates good calibration at offset well location)

elongate NW-SE trending structure.

Amplitude Response: The gas sand is clearly highlighted by the pseudo fluid stack volume as a distinct high amplitude response. The stratal slices from the impedance and lambda rho volume show the gas sand as a low impedance and low lambda rho expression which is structurally conformable (Figure 7a). The distinct amplitude switch-off conforms with the Gas-Water-Contact (GWC) already seen by the well and hence used to delineate the extent of the gas for this level.

AVO Response: The amplitude response of the gas sand was tested for AVO effect. An AVO point was selected within the low impedance expression and the result shows a strong variation of amplitude with offset, consistent with a typical gas sand response. The intercept vs gradient cross plot also shows a class III AVO response with the AVO point away from the background indicating lighter end hydrocarbon (Figure 7d) (Fobster *et al* 2010). A confirmatory test point taken around the high impedance area, away from the hydrocarbon accumulation show no AVO response. This indicates a brine response (Figure-7c). This result is consistent with the gas discovery and helped in the calibration of both the impedance model and the AVO model.

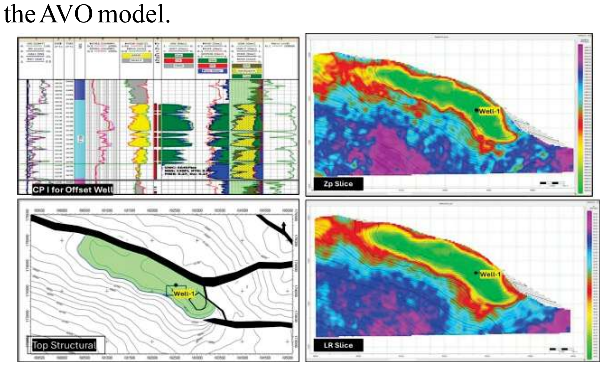


Figure 7a: Impedance section and stratal slices for Impedance (Zp) and lambda rho (LR) attribute.

(Left figures- show the discovered gas by the offset well and the depth structure map. Right figures- show Impedance (Zp) and Lambda Rho (LR) extracted for the gas sand. Observe the conformity of the amplitude to structure and the clear amplitude switch off which corresponds to the know GWC from the well)

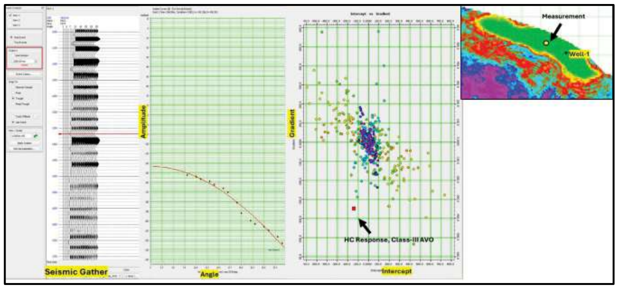


Figure 7b: AVO response within amplitude anomaly – offset discovery.

(AVO measurement point taken within the low impedance gas sand. Observe the amplitude change with angle in the amplitude vs Angle plot. And the AVO point in the gradient vs intercept plot. This indicate that the gas discovery is consistent with the expected AVO response (Foster et al 2010)).

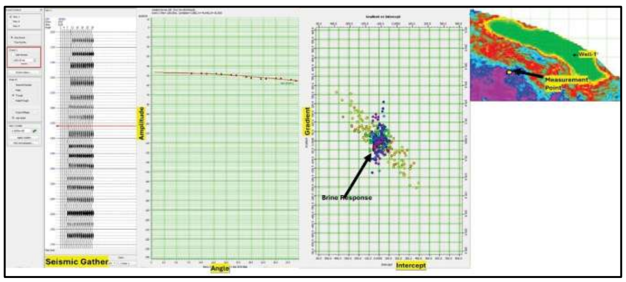


Figure 7c : AVO response within amplitude anomaly - measurement 2 (water leg)

(A confirmatory test point taken in the water leg. Observe the poor amplitude variation with angle in the Amplitude vs angle plot and the AVO plot in the gradient vs intercept plot which lies within the background. This indicates a typical brine response).

PROSPECT A AND B

Prospect A and B are two independent prospects separated by a fault. They are located about 7km east of the offset well. They are fault assisted structural closures. Fault seal analysis carried out on the prospects indicates that the faults are potentially sealing.

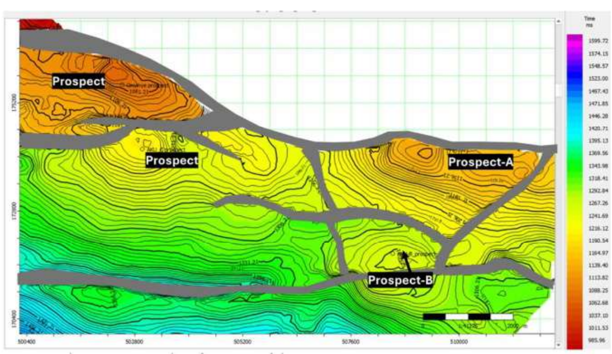


Figure 8a: Showing structural configuration of the prospects.

Amplitude Response: The review of the fluid stack volume shows distinct and stacked high amplitude response in prospect A and B (Figure 4). Stratal slices from the impedance and lambda rho volume show an anomalous low impedance and low lambda rho expression. Prospect A and B show good structural conformity with clear amplitude switch-off which is interpreted as the possible HC water contact (Figure 8b) and used to optimize the resource volume estimate for these prospects. The observed responses are within same range as those of the offset discovery. Local impedance variation exist in both prospect which is attributed to local facies variation within the prospects.

Figure 8c is the stratal slices for Impedance lambda rho and density attributes showing the similarity between the response at the offset well and those of prospect A and Prospect B.

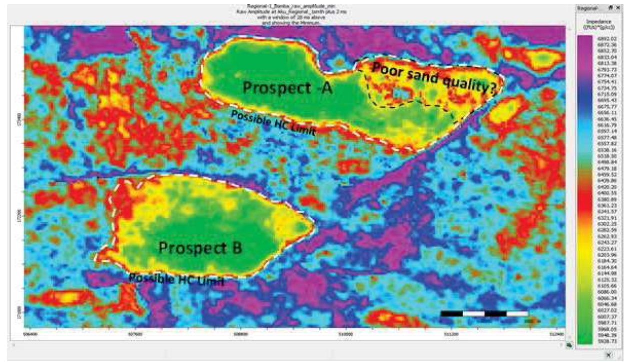


Figure 8b: showing the impedance stratal slice for Prospect A and B.

(Impedance slice showing the impedance responses at prospect A and Prospect B. observe the low impedance response in both prospect with good structural conformity. The amplitude switch-off indicate the likely hydrocarbon water contact in these prospects)

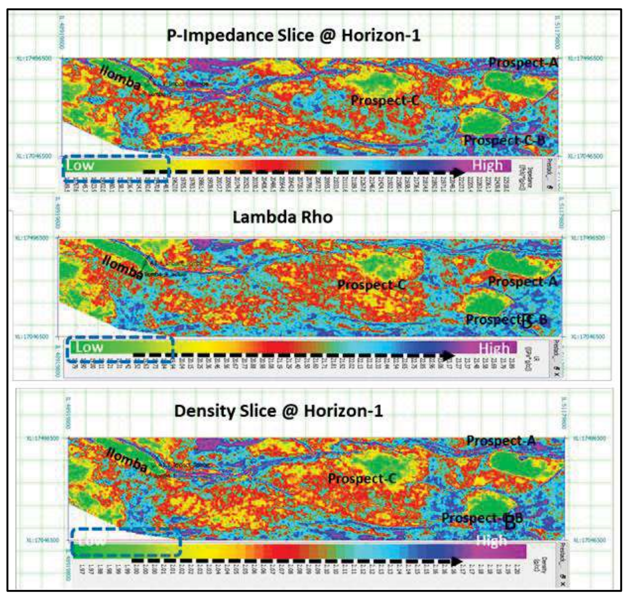


Figure 8c: Showing stratal slices for Impedance, Lambda Rho and Density.

AVO Response: The result of AVO analysis within the low impedance response shows a class III AVO response at all analyzed levels in prospect A and B indicating a high likelihood of a light hydrocarbon (Figure 8d, 8e). A confirmatory point of measurement taken around the high impedance area gave a brine response (Figure 8f). This implies that the low impedance zone is responding to possible hydrocarbon presence (Castagna, J.P. and Swan, H.W., 1997).

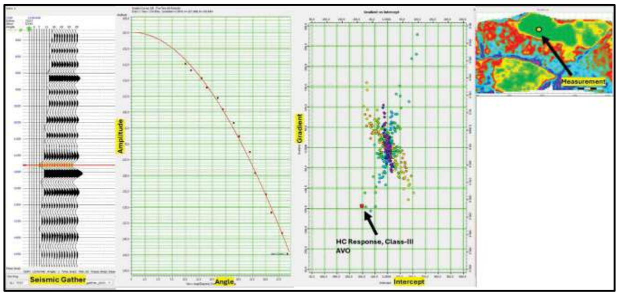


Figure 8d: AVO response within amplitude anomaly – Prospect A

(AVO measurement point taken within the low impedance response in prospect A. Observe the amplitude change with angle in the amplitude vs Angle plot and the AVO point in the gradient vs intercept plot. This indicates a class III AVO response. The AVO plot-away from the background cluster in the gradient vs intercept plot indicate a light hydrocarbon (Foster et al 2010)).

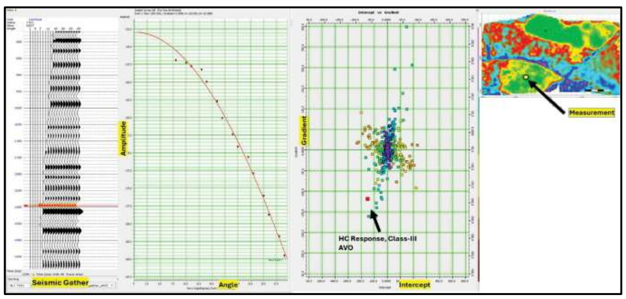


Figure 8e: AVO response within amplitude anomaly – Prospect B

(AVO measurement point taken within the low impedance response in prospect B. Observe the amplitude change with angle in the amplitude vs Angle plot and the AVO point in the gradient vs intercept plot. This indicates a class III AVO response. The AVO plot-away from the background cluster in the gradient vs intercept plot indicate a light hydrocarbon (Foster et al 2010)).

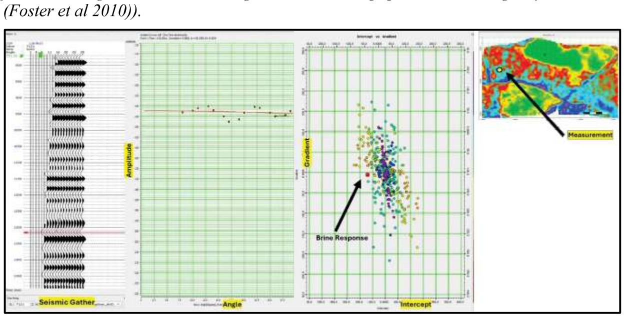


Figure 8f: AVO response within amplitude anomaly – Prospect B

(AVO measurement point taken within the low impedance response in prospect B. Observe the amplitude change with angle in the amplitude vs Angle plot and the AVO point in the gradient vs intercept plot. This indicates a class III AVO response. The AVO plot-away from the background cluster in the gradient vs intercept plot indicate a light hydrocarbon(Foster et al 2010)).

LIMITATIONS AND UNCERTAINTY

- Shear sonic was not acquired in the offset wells. Shear wave used was modelled from the P-wave.
- Seismic inversion is non-unique as there are many geological scenarios that can give rise to a given inversion result.
- Gas response can be obtained in a formation with non-commercial gas saturation.
- The result of the AVO analysis is highly dependent on the accuracy of the seismic Gather processing which was done independent of this study.

CONCLUSION

Quantitative seismic interpretation methodology was integrated to the maturation process of Prospect A and Prospect B, eastern part of the Northern Depobelt, Onshore Niger delta. AVO modelling and rock physics analysis carried out in the offset wells show that seismic gathers are sensitive to changes in reservoir fluid with lambda rho and acoustic impedance being the most sensitive attribute for fluid discrimination in the area of study. Prospectivity analysis highlight good amplitude response at the known gas discoveries with similar responses seen in the prospects. Simultaneous seismic inversion highlights the anomalously low impedance and low lambda rho response of the gas discovery in the offset well. Similar responses were seen at each of the prospects with good structural conformity. The clear amplitude switch-off seen in the prospects indicates the likely hydrocarbon water contact in the structures. To confirm the possible cause of the anomalous responses, AVO analysis was carried out. A Class III AVO response indicative of light hydrocarbon was observed at the offset discovery and in the prospects. The presence of an amplitude anomaly, the conformity of the amplitude to structure and the Class III AVO responses seen in prospects-A and Prospect-B is an indication of possible hydrocarbon presence in the prospects. These responses are similar to those seen in the offset discoveries within the AOI.

This evaluation helped to further de-risk the prospects, increase the geological chances of success (COS) and optimize volumetric assessments. Other prospects in the exploration portfolio were subjected to similar quantitative analysis given a comprehensive template for the ranking of all prospects within the acreage. Within this portfolio, Prospect-A and Prospect-B ranked first and second respectively amongst a basket of 11 other prospects.

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