A Novel QI Screening Technique for Identifying Deep-water AVO False Positive: Learnings from Well X

[1] Obinna Chudi, [2] Jaume Hernandez, [2] Chima Chikezie, [1] Austin Anaevune, [2] Stephane Gesbert, [2] Ayodeji Ogunlana, [2] Somime Oguntola, [1] Francesca Osayande, [2] Kolawole Akingbade, [1] Uche Johnbosco, [2] Segun Obilaja; [2] Dipo Falade and [2] Sito Busman.

[1]The Shell Petroleum Development Company

[2]Shell Global Solutions International B.V[4]

ABSTRACT

The quest for hydrocarbon has led explorationist to investigate amplitude anomalies popularly known as direct hydrocarbon indicators (DHI) from seismic data. Although DHI technology has proven to be a reliable tool in reducing exploration risk leading to many discoveries, it is not infallible and therefore can lead to disappointing outcomes of drilling into water bearing reservoirs that are classed as false positives which were characterized at predrill phase as hydrocarbon bearing sands. Hence the effectiveness of DHI's should properly be ranked particularly on the backdrop of sound geological and geophysical models. This paper presents a study from a deep-water field where an integrated QI workflow has revealed a distinction between false positives and conventional hydrocarbon bearing sands. An Exploration well – Well X was recently drilled targeting Body X sand – a channelized lobe displaying high amplitude anomaly and Class II/III AVO signature. The well turned out to be a 78ft thick brine sand with 32% porosity and 100% net-to-gross. A post-mortem rock physics analysis of this sand and other false positives that were previously encountered in the field indicate that false positives show a distinct behavior compared to conventional oil and brine bearing sands. Two elastic properties; – LambdaRho, a fluid indicator and MuRho - a proxy for lithology, formed the basis of this analysis. From the rock physics cross plot, false positives are observed to be more rigid with higher MuRho values compared to conventional hydrocarbon and brine filled sands. LambdaRho and MuRho deterministic seismic inversion attributes were generated directly from broadband angle stacks that highlighted the high rigidity values of the false positives in line with the rock physics cross plot. This technique therefore serves as a first pass screening tool for identifying false positives that could improve our predrill prediction and future risking of potential hydrocarbon opportunities in Nigeria Deep-water operations.

Key words: Amplitude, AVO, Channels, Deepwater, DHI, Exploration, False Positive, Inversion, LambdaRho, MuRho, Porosity, Seismic

INTRODUCTION

The Niger Delta sedimentary basin is noted for its hydrocarbon prolific nature with significant discoveries made both onshore and offshore across mostly Miocene and Younger intervals of the delta system. Majority of these discoveries were made based on strong amplitude anomalies otherwise known as bright spots and supported with AVO (amplitude versus offset) technology from seismic data. Together these techniques have been classified as Direct Hydrocarbon Indicators (DHI). Utilizing these tools has led to major discoveries across the Niger Delta deepwater space such as the Agbami, Akpo, Bonga, Bosi and Ehra fields located in the continental slope of the basin (Cameron and White, 1999). Significant attention has now been given to deep-water exploration in water depth greater than 500m which has culminated in major studies undertaken in this part of the basin in search of bright amplitude anomalies. Although DHI technology has proven to be a reliable tool in reducing exploration risk leading to many discoveries, it is not always dependable and therefore can lead to unexpected outcomes of drilling into water bearing reservoirs or low gas/oil saturation sands that are known as false positives which were hitherto characterized at predrill phase as hydrocarbon bearing sands due to its strong amplitude and AVO signatures.

This study focuses on a deep-water field in the Niger Delta

We wish to express our appreciation to the leadership of Shell Nigeria Exploration and Production Company (SNEPCo) for their support and permission to showcase this article. The Authors are also grateful to NAPE for creating an enabling environment to publish this paper.

where significant discoveries have been made from reservoir sands with high amplitude signatures. However, a Near Field Exploration well (Well X) was drilled targeting Body X sand characterized with bright spot anomaly and strong AVO behavior that turned out to be brine bearing (a false positive). Rock physics integrated with seismic inversion models revealed a distinction between false positive and conventional hydrocarbon and brine bearing sands. The model outcome predicted nicely the Well X results thereby "ground thruthing" the workflow as a novel technique for predicting AVO related false positives. Whilst this paper is centered on seismic quantitative analysis, a view of a postmortem study on the hydrocarbon charge from source kitchen to Body X reservoir is the subject of another paper (Ogunlana *et al.* 2023; Drilling into a charge shadow zone of a prolific Niger Delta Field: Learnings from Well X).

GEOLOGIC SETTING

The study area is in the mid to lower slope deep-water setting, offshore Niger Delta in the Gulf of Guinea, which is situated along the West Africa passive margin (Figure 1). The basin evolution is attributed to the breakup of the South American and African plate in the Mid to Late Cretaceous (Whiteman, 1982). The end of rifting in the Late Cretaceous was followed by a post rift sedimentation phase in the Tertiary, and progradation of the delta seaward from the Eocene. Significant sediment influx from the hinterland into the basin via the Niger-Benue fluvial system in the west and the Cross River in the East was seen from the Late Oligocene and increased steadily up to Plio-Pleistocene times (Whiteman, 1982). A series of canyons developed during the Tertiary that incised into the shelf margin and extended basinward. Canyons like the Mahin, Opuama, Benin, Escravos, Lagos and Ramos Canyons (Burke *et al.,* 1972, Petters 1984) formed major point-sourced conduits for sedimentation in the deep-water environment (Figure 1). These northeast-southwest orientated canyons or the equivalent paleo-canyons actively fed sediment from the delta front and shelf margin staging area to the slope and deeper basin from the onset of delta formation and ocean formation up until the present day. The principal mode of downslope transport was by turbidity currents and associated mass transport processes leading to the deposition of sand-rich turbidites (Adeogba *et al.,* 2005). These form the principal reservoirs and plays for active hydrocarbon exploration and production today. Marine sedimentary unit – the Akata underlies the entire Tertiary Niger delta stratigraphic sequence from onshore to offshore. This Formation is characterised by pelagic silt, mud and shale with an abundance of fauna and flora that has enabled an age assignment of Paleocene to Recent (Doust and Omatsola 1990). The marine mud crops out offshore in the form of mud diapirs that have developed as a result of smectite – rich sediment deposited underneath a rapidly prograding Eocene to Miocene delta complex (Whiteman 1982). This has further resulted in an overpressured condition in the marine sediments (Cohen and McClay, 1996). Diapiric movement of the Akata muds is still active and significant distribution of diapirs has been visible around the continental slope and sea-floor where they are revealed as mud volcanoes (Graue, 2000). This mud diapirs are partly responsible for modifying the slope system leading to the development of both structural and stratigraphic traps particularly within the study area. The Akata Formation is thought to be the primary source rock in the Niger Delta petroleum province, although source rocks have also been encountered in the shallow Agbada shales (Evamy *et al.,* 1978, Ekweozor and Daukoru, 1984, Lambert-Aikhionbare and Ibe, 1984, Bustin, 1988, Haack *et al.,* 2000, Samuel *et al.,* 2009).

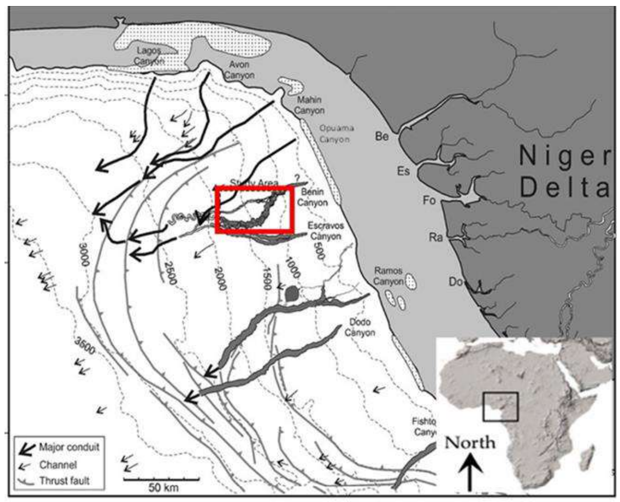

Figure 1: Location of the Western Niger Delta showing bathymetry, major submarine canyons and study area in red rectangle (modified after Deptuck et al. 2007).

DATA AND METHODOLOGY

The 3D seismic data used in this study is a broadband seismic acquired using the streamer technology with a cable length of 10050m (Figure 2A). This data was acquired after the drilling of Well-X. The seismic showcases the structure and stratigraphy within a six second two-way time (TWT). The frequency of this survey is broadband (see Figure 2B). Broadband entailed preserving both the useful low frequency and the noise-free high frequency. This was achieved using several Shell proprietary noise attenuation tools. Some of the noise attenuated include swell noise, random noise, noise trains and residual noise. Velocity model building approach was full waveform inversion (FWI). In addition, an anisotropic velocity model was added as a second pass. The velocity product in the end was properly constrained by geological boundaries – faults and stratigraphy in the final dataset.

The data was processed using Kirchhoff PreSDM algorithm. In comparison to the legacy KLSM (Kirchhoff Least Square Migration) seismic data which underpinned the drilling of Well X, the processing algorithm deployed in the latest seismic data resulted in a broadband frequency content with high resolution, good signal to noise ratio, improved structural imaging, better amplitude balancing and seismic loop continuity. The data is a zero-phase seismic with a negative polarity (anti-SEG) displayed as a trough that characterizes an increase in acoustic impedance. Processing of the data was also performed to obtain high-quality angle stack of near (0° - 10°), mid (10° - 20°), far (20° - 30°) and the ultra-far (30° - 40°).

Several wells have been drilled in the study location with Well X being the most resent exploration well targeting a Near Field Prospect. The study enjoys a good spread of good quality data acquired across the wells with basic logs such as gamma ray, resistivity and acoustic logs – density, compressional and shear sonic logs requisite for quantitative interpretation.

already proven hydrocarbons in stratigraphically equivalent sands north of the prospect, the pre-drill assessment of the petroleum system elements such as structure, reservoir and charge (access to hydrocarbons) was classified as a low risk. The major geologic risk attributed to the prospect was trap. Relying on the stratigraphic trapping element, the pre-drill geologic probability of success (gPOS) was estimated as 57% (Ogunlana et al., 2023).

The Well X (Figure 3B) opportunity was premised around three key value drivers: 1) A robust amplitude signature consistent with amplitude anomalies of proven hydrocarbon bearing reservoirs in the study area particularly north of the Body X opportunity penetrated by Wells K, O & L (see Figure 3A). The amplitude of the prospect was also supported with AVO response from pre-stack gathers showing a Class II/III response at the crest of the structure (similar to the AVO response at the proven oil sand encountered by Well K & O) and decays to a flat AVO response at the flank of the structure consistent with a brine response penetrated by Well P. This additional AVO

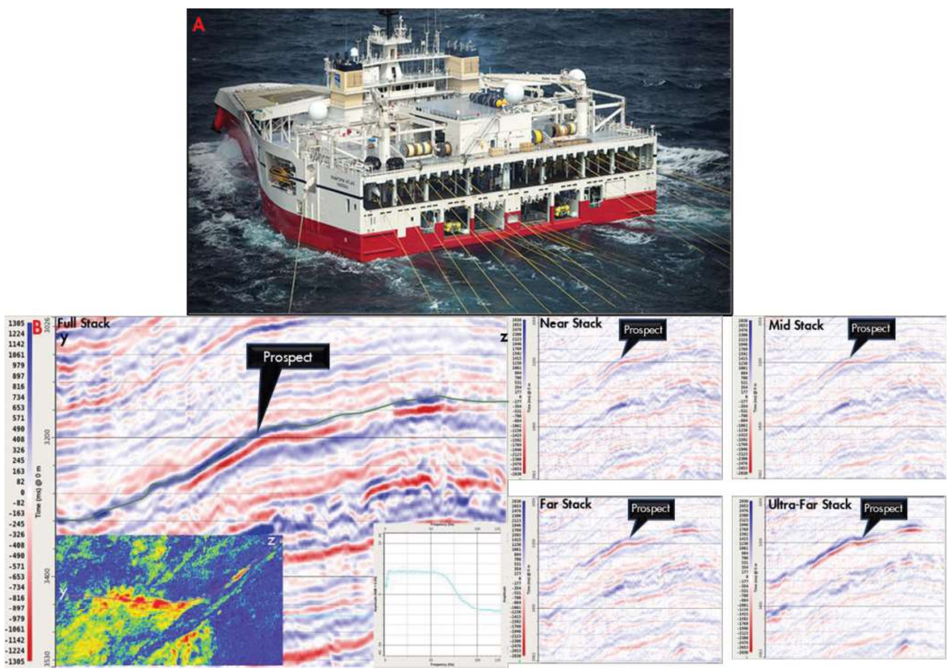

Figure 2: A) Data acquisition at the study location showing streamer lines connected to the seismic vessel. B) Section view from the Post Stack seismic data taken across the Body X reservoir; inserts show bright spot amplitude anomaly and the amplitude spectrum revealing the broadband frequency. Seismic section view of Near, mid, far and ultra far seismic illustrating AVO behaviour at the prospect location.

PREDRILL EVALUATION

Well X was planned targeting Body X – a channelized fan system located South of the prolific Body K structure under a water depth of about a 1000m (Figure 3A). The lateral limit of the Body X sand was pinned down by an earlier well – Well P which was drilled down dip of the structure encountering poor quality brine sands. Having

evidence was the basis for a 13% POS uplift applied to the pre-drill gPOS, translating to a pre-drill posterior POS of 70% (Ogunlana et al., 2023). 2) Well X was considered a quick win being a near filed exploration opportunity that would prove hydrocarbon volumes which would immediately serve as an early tie-back to an existing FPSO located in the vicinity of the study area and 3) the pre-drill economic evaluation was competitive with a robust net-present-value (NPV) and internal rate of return (IRR).

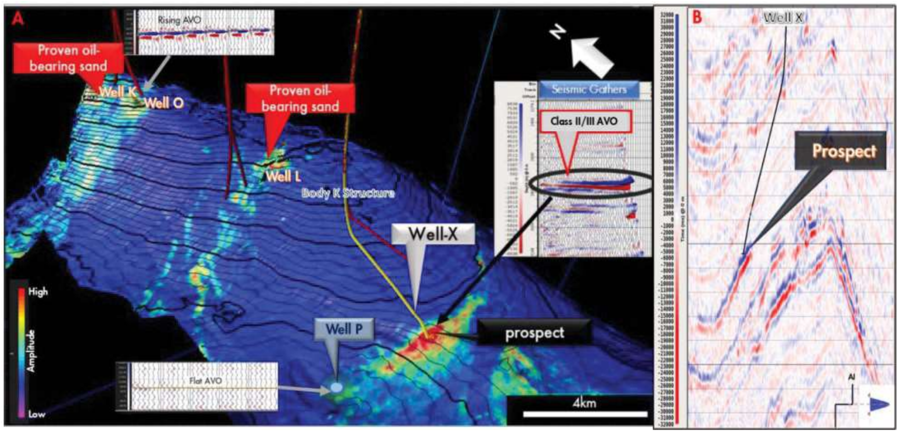

Figure 3: A) Amplitude draped on structure highlighting the bright spot at the location of the Body X prospect relative to proven hydrocarbon penetrated by Wells L, K & O. The Figure also shows the AVO behaviour at the crest of structure comparable with the AVO at the proven oil reservoirs north of the prospect (modified after Ogunlana *et al.* 2023). B) Seismic section showing the well path targeting the prospect.

WELL X OUTCOME

The well discovered excellent reservoir properties of 78ft feet thick sand with 32% porosity and 100% net-to-gross but turned-out brine bearing with no evidence of hydrocarbon. The encountered reservoir properties were better than the prognosticated ranges (Figure 4). There were no indications of thermogenic hydrocarbons in the entire stratigraphic interval drilled by Well-X. All the sands penetrated in this well were brine filled. The mudlogs did not record any gas readings above background C1 (methane) level. No florescence (under UV light) seen from the rock cuttings retrieved from the well-bore which is typically diagnostic of oil presence in the system (Ogunlana *et al.,* 2023). Reservoir fluid pressures acquired from the objective sand lined up with the water-gradient indicating the fluid is brine. A post-mortem study was conducted to understand which failed element of the petroleum system resulted in a wet well outcome which is discussed in another paper (Ogunlana *et al.* 2023; Drilling into a charge shadow zone of a prolific Niger Delta Field: Learnings from Well X).

POST DRILL EVALUATION

A post-mortem was conducted focused on two key areas. 1) To understand which failed element of the petroleum system resulted in the wet well outcome (Ogunlana et al. 2023) and 2) from geophysical perspective, what is responsible for bright spot and the strong AVO response

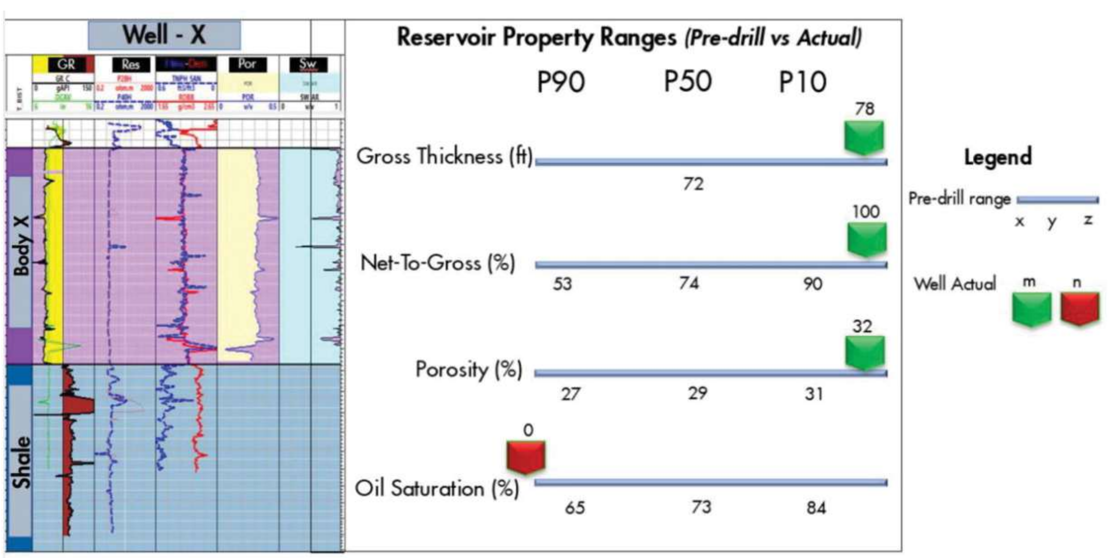

Figure 4: Wireline logs of Well X showing excellent rock properties compared to the pre-drill prediction (modified after Ogunlana et al. 2023).

which turned out to be wet? – this is the focus of this paper.

Rock Physics Analysis

Rock physics trends were investigated across selected wells within the study area. The emphasis was wells that encountered conventional hydrocarbon and brine bearing sands plus wells that penetrated false positive sands including Well X. All reservoir sands being studied (false positives, conventional hydrocarbon and brine sands) are located within the same depth window – less than 9000ftss and therefore have similar porosity distribution. The objective is to investigate elastic properties that can be used to discriminate AVO false positive sands from true hydrocarbon and brine sands.

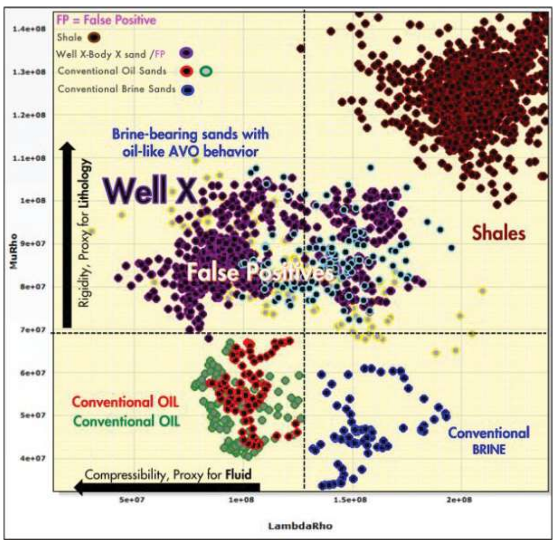

Figure 5: Well log-based rock physics cross plot of MuRho versus LambdaRho revealing the distinct behaviour of all false positive sands including the Well X-Body X sand with anomalously higher MuRho values compared to conventional oil and brine bearing sands.

Two elastic properties showed promising results: – LambdaRho - a measure of compressibility & a fluid indicator and MuRho – a measure of rigidity & a proxy for lithology. LambdaRho and MuRho are derived from P-impedance and S-impedance elastic properties based on equations 1 and 2 below:

LambdaRho $= AI^2 - 2SI^2$ ***(EQU 1)***

MuRho $= SI^2$ ***(EQU 2)***

Note: AI = density × compressional (p) velocity and SI = density × shear velocity

Where AI = Acoustic (P) Impedance and SI = Shear impedance.

From the rock physics cross plot (Figure 5), conventional hydrocarbon bearing sands were characterized with low LambdaRho values including the Body X sand and other sands that have been classed as false positives. In the MuRho space, conventional hydrocarbon and brine bearing sands have low MuRho values, whereas the Body X and other false positives displayed a higher-than-expected MuRho suggesting increased rigidity compared to conventional hydrocarbon and brine filled sands despite similar porosity (Figure 6A). The rock physics results thus indicates that MuRho can serve as a tool for discriminating false positives from true hydrocarbon and brine bearing sands.

Model Limitation: The model breaks down for shaly reservoirs and for reservoirs buried deeper than 9000ftss. This is largely attributed to the effect of compaction and/or diagenesis which kicks in from 9000ftss. Beyond this depth, rocks starts getting stiffer as porosity reduces and the overall acoustic behavior of the rock is significantly controlled by the acoustic nature of the rigid rock matrix and less of the acoustic properties of the pore fluid. So, on the MuRho-LambdaRho cross plot the reservoirs deeper than 9000ftss would display a higher or near similar MuRho values with the false positives which cannot be adequately discriminated (see Figure 6B).

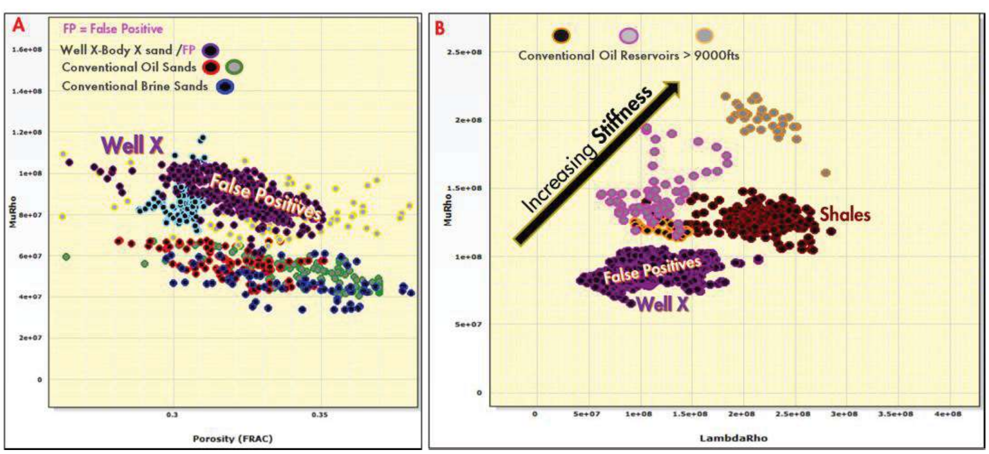

Figure 6: A) Cross plot of MuRho versus porosity calculated from well logs showing similar porosity distribution of false positive sands including Well X-Body X sand and conventional oil and brine sands. B) Cross plot illustrates hydrocarbon bearing sands deeper than 9000ftss expressing near similar or higher stiffness compared to false positive sand.

Seismic inversion

Considering that rock physics analysis revealed MuRho in conjunction with LambdaRho as elastic tools for discriminating false positives from convention hydrocarbon and brine sands, simultaneous inversion also known as pre-stack AVO inversion technique was deployed to calculate both elastic properties from 3D seismic data. Simultaneous inversion typically utilises a set of three or more angle stacks each with their estimated wavelet, low frequency models for P-impedance, S-impedance and density to estimate simultaneously, inversion volumes for P-impedance, S-impedance and density (Brown, 2011). In the study area 3D cubes of P-impedance, S-impedance and density was modelled by performing simultaneous inversion on four angle stacks - the near (0° - 10°), mid (10° - 20°), far (20° - 30°) and the ultra-far (30° - 40°) seismic volumes. The P-impedance and S-impedance cubes where mathematically integrated using equations 1 and 2 above to generate LambdaRho and MuRho seismic volumes.

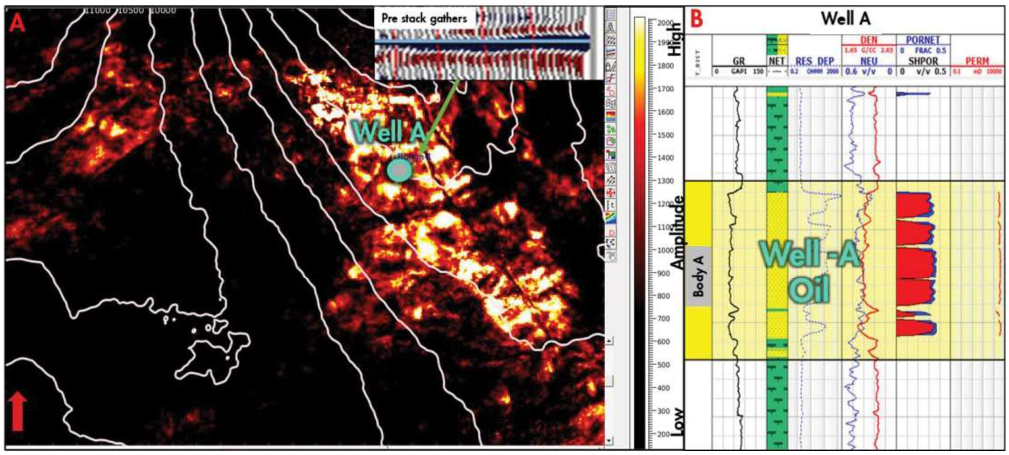

Figure 7: A) Amplitude draped on Body A structure showing bright spot and Class III AVO behaviour from pre-stack gathers. B) Logs of Well A drilled into the structure encountered 115ft oil bearing sands and 34% average porosity.

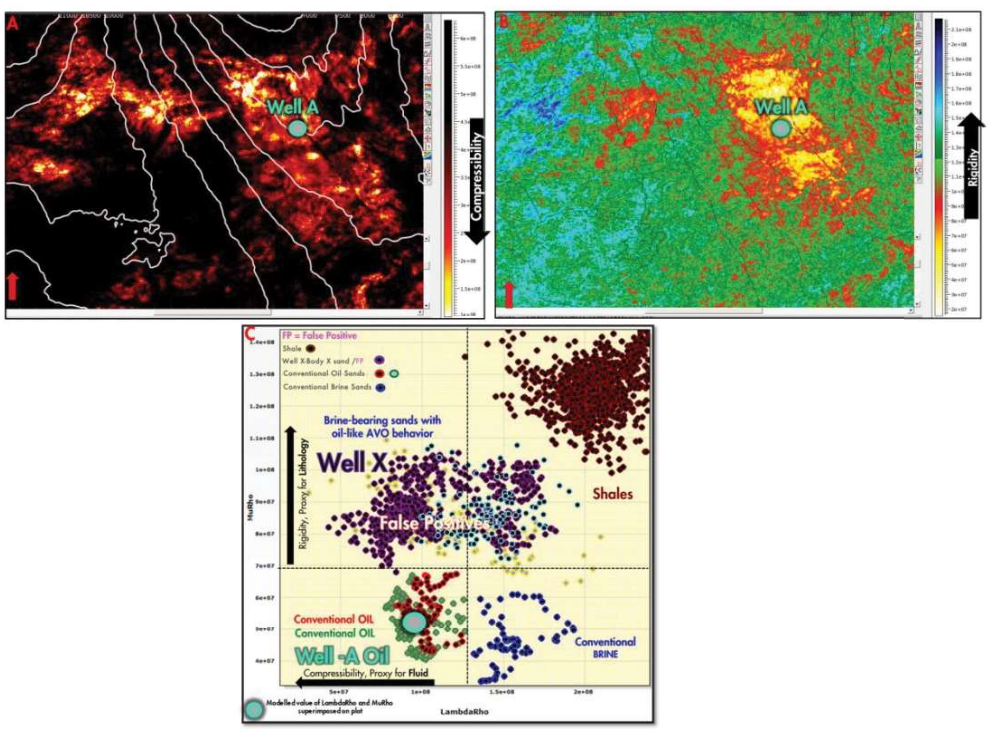

Figure 8: A) LambdaRho map showing low values for the Body A sands indicating high compressibility for the hydrocarbon sands. B) MuRho map showing low values indicating soft or less rigid sands. C) The cross plot highlights the absolute value of MuRho and LambdaRho from the inversion model (bright green circle) seats nicely on the same quadrant as the log-based data of Body A from Well A.

RESULTS and DISCUSSION

The model was first tested on Body A - a proven conventional hydrocarbon bearing sands as proof of concept. On seismic it shows up with a classic bright spot anomaly and a Class III AVO behaviour (see Figure 7A). The reservoir sand is a 115ft sand with porosity of 34% encountered by Well A (Figure 7B). The results seen from the LambdaRho map indicates highly compressible fluid with low values as expected (Figure 8A). The MuRho values are also low indicating soft sands (Figure 8B). The results are all consistent with the rock physics cross plot for a hydrocarbon bearing sands as the absolute values of modelled LambdaRho and MuRho plots on the same quadrant as the log-based values (Figure 8C), hence validating the model.

Well X: The Body X sand encountered by well X as highlighted earlier was initial evaluated pre-drill as a hydrocarbon bearing sands considering the high amplitude anomaly and the Class II/III AVO response (Figure 3, page 6). However, the post drill outcome turned out a thick brine sands with 100% net-to-gross and 32% porosity (Figure 4). The LambdaRho model on the map view reveals low values like a hydrocarbon bearing sand (Figure 9A) but the MuRho models clearly shows that the Body X sand is a false positive with high MuRho values (Figure 9B) as predicted from the Rock physics cross plot (Figure 9C). On the cross plot both the absolute values from the model and the log based lambdaRho and MuRho values seats in the same quadrant.

The model was further "ground truthed" as a predictive tool for false positive by testing two false positive sands – Body B and C which were interpreted at pre-drill as oil bearing. Both sands were penetrated by Well B and C respectively. The sands showed the classic bright spot anomaly on the amplitude map with a strong Class III AVO response (Figure 10A and 12A) but when drilled they turned out to be brine sands (Figure 10B and 12B). The inversion models result for the Body B and C sands reflects low LambdaRho values as expected for a false positive (Figure 11A and 13A). However, the MuRho map shows high values (Figure 11B and 13B) just like the Body X sand penetrated by Well X. The absolute values of LambdaRho and MuRho from the inversion model superimposes on the same quadrant as the log data from Well B and C (see Figure 11C and 13C respectively).

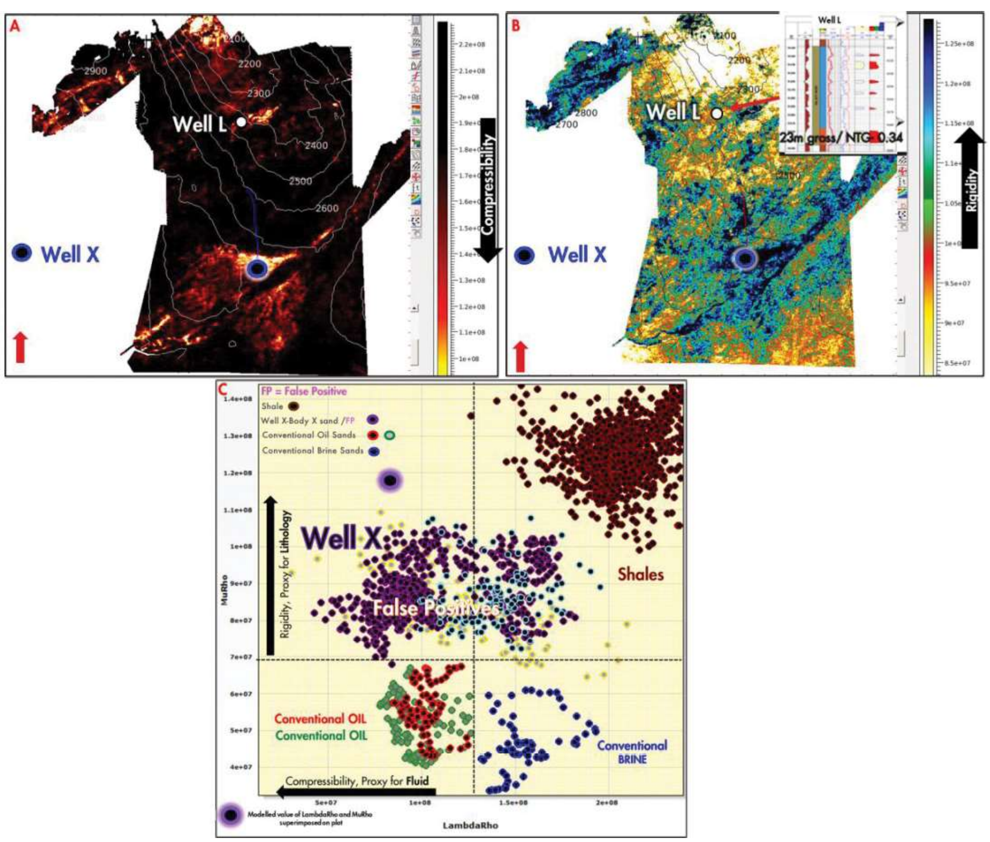

Figure 9: A) LambdaRho map showing low values for the Body X sands indicating high compressibility like hydrocarbon sands. B) MuRho map with higher-than-expected values indicating rigid sands, thus confirming a false positive. C) The cross plot highlights the absolute value of MuRho and LambdaRho from the inversion model (bright purple circle) although slightly higher but seats nicely on the same quadrant as the log-based data of Body X from Well X.

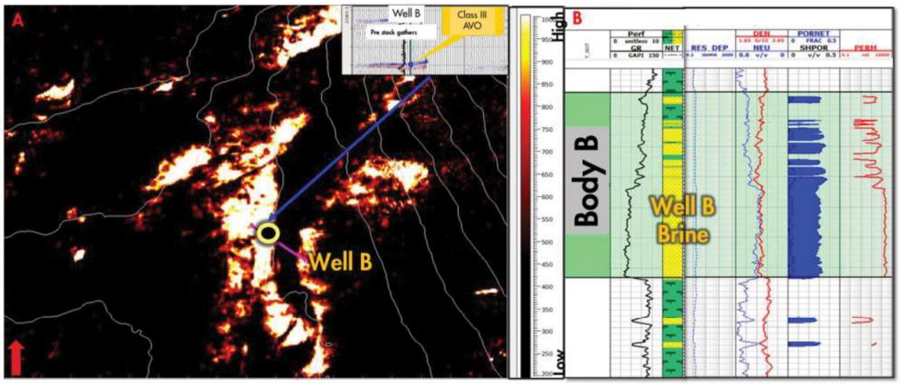

Figure 10: A) Amplitude draped on Body B structure showing bright spot and Class III AVO behaviour from pre-stack gathers. B) Logs of Well B drilled into the structure encountered 150ft of brine sands and average porosity of 35%.

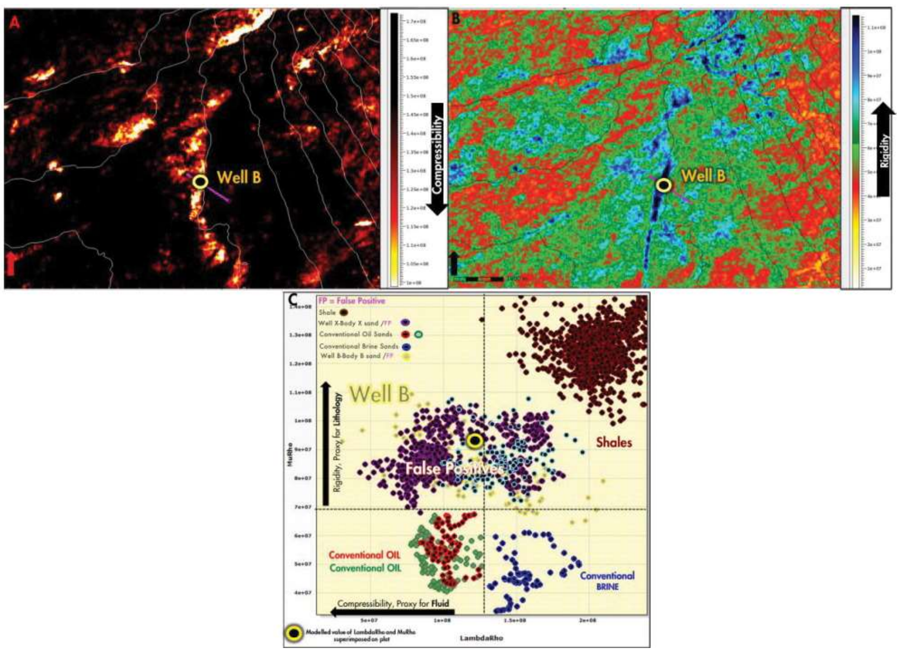

Figure 11: A) LambdaRho map showing low values for the Body B sands at the location of Well B indicating high compressibility similar to hydrocarbon sands. B) MuRho map with higher-than-expected values indicating rigid sands, thus confirming a false positive. C) The cross plot highlights the absolute value of MuRho and LambdaRho from the inversion model (bright yellow circle) seats nicely on the same quadrant as the log-based data of Body B sand from Well B.

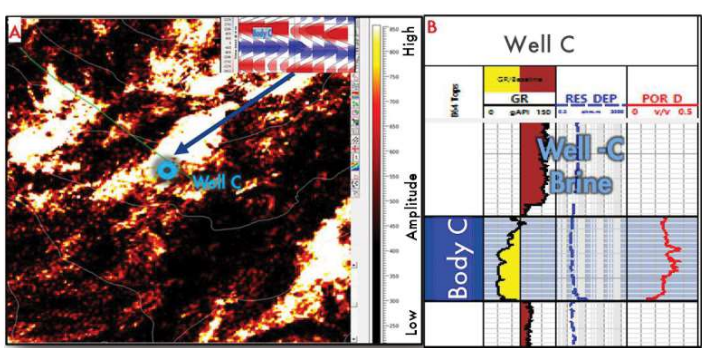

Figure 12: A) Amplitude draped on Body C structure showing bright spot and Class III AVO behaviour from pre-stack gathers. B) Logs of Well C drilled into the structure encountered 55ft of brine sands and average porosity of 34%.

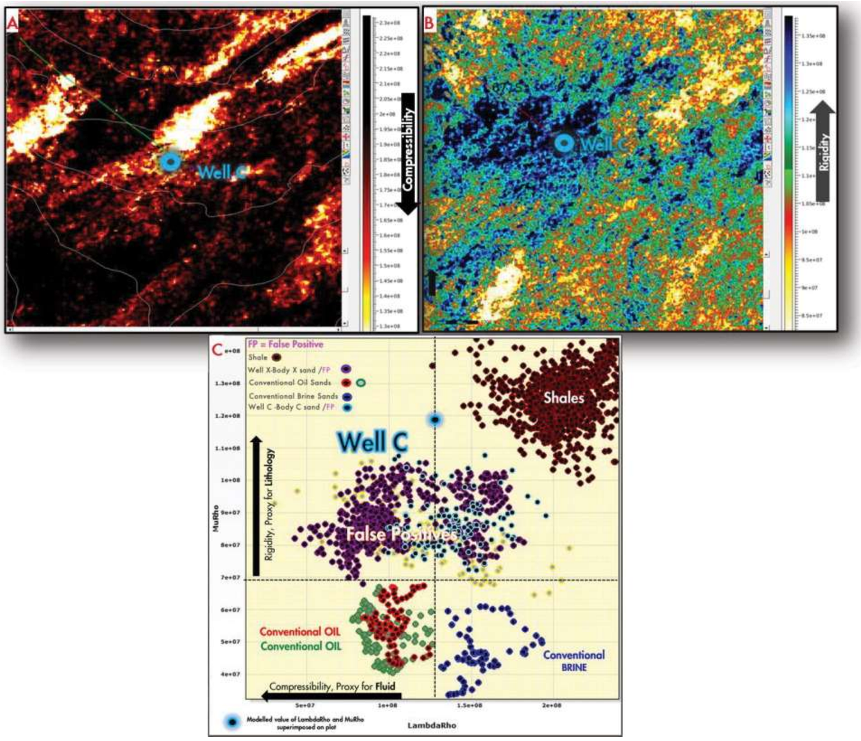

Figure 13: A) LambdaRho map showing low values for the Body C sands at the location of Well C indicating high compressibility similar to hydrocarbon sands. B) MuRho map with higher-than-expected values indicating rigid sands, thus confirming a false positive. C) The cross plot highlights the absolute value of MuRho and LambdaRho from the inversion model (bright blue circle) seats on the same quadrant as the log-based data of Body C sand from Well C.

CONCLUSION

The DHI tool integrated with AVO technology would continue to be a valuable technique for predicting pay sands. However, their limitations should be built into any subsurface evaluation and the opportunity risked appropriately capturing potential failure scenarios. Brine sands displaying similar AVO behaviour like hydrocarbon bearing sands, popularly known as false positive would continue to be a risk in subsurface evaluation except when reliable tools are deployed that can discriminate these false positives from true hydrocarbon bearing sands. The study reveals that AVO is not controlled by fluid but largely dictated by lithology and rock quality, considering brines sands have been observed to display similar AVO class as hydrocarbon bearing reservoirs. The technique presented in this paper clearly demonstrates the value of seismic inversion for LambdaRho and MuRho elastic properties in polarizing false positives. These false positives are characterized by higher-than-normal MuRho values compared to true hydrocarbon bearing sands, albeit the display similar LambdaRho signatures like hydrocarbon sands. This therefore suggests that the technique is potentially a game changer in de-risking potential hydrocarbon reservoirs in deepwater Nigeria.

REFERENCES CITED

Adeogba, A. A., Mchargue, T. R. & Graham, S. A. (2005). Transient fan architecture and depositional controls from near-surface 3-D seismic data, Niger Delta continental slope. AAPG bulletin, 89, 627-643.

Brown, A. R. (2011). Interpretation of three-dimensional seismic data. AAPG Memoir, 42, 295-308.

Burke, K. (1972). Longshore drift, submarine canyons, and submarine fans in development of Niger Delta. AAPG Bulletin, 56, 1975-1983.

Bustin, R. (1988). Sedimentology and characteristics of dispersed organic matter in Tertiary Niger Delta: origin of source rocks in a deltaic environment. AAPG Bulletin, 72, 277-298

Cameron, N. & White, K. (1999). Exploration Opportunities in Offshore Deepwater Africa. IBC 'Oil and Gas Developments in West Africa', London, UK, 25-26.

Cohen, H. A. & Mcclay, K. (1996). Sedimentation and shale tectonics of the northwestern Niger Delta front. Marine and Petroleum Geology, 13, 313-328.

Deptuck, M. E., Piper, D. J., Savoye, B. & Gervais, A. (2008). Dimensions and architecture of late Pleistocene submarine lobes off the northern margin of East Corsica. Sedimentology, 55, 869-898.

Doust, H. & Omatsola, E. 1990. Niger Delta. In: Edwards,J.D., Santogrossi, P.A (Eds), Divergent/Passive Margin Basins. American Assoiciation of Petroleum Geologist, 4, 239-248.

Ekweozor, C. & Daukoru, E. (1984). Petroleum source-bed evaluation of Tertiary Niger Delta: reply. AAPG Bulletin, 68, 390-394.

Evamy, B. D., Haremboure, J., Kamerling, P., Knaap, W. A., Molly, F. A. & Rowlands, P. H. (1978). Hydrocarbon habitat of Tertiary Niger Delta. American Association of Petroleum Geologists Bulletin, 62, 1-39.

Graue, K. 2000. Mud volcanoes in deepwater Nigeria. Marine and Petroleum Geology, 17, 959-974.

Haack, R. C., Sundararaman, P., Diedjomahor, J. O., Xiao, H., Gant, N. J., May, E. D. & Kelsch, K. (2000). AAPG Memoir 73, Chapter 16: Niger Delta Petroleum Systems, Nigeria.

Lambert-Aikhionbare, D. & Ibe, A. (1984). Petroleum source-bed evaluation of Tertiary Niger delta: discussion. AAPG Bulletin, 68, 387-389.

Ogunlana, A., Akingbade, K., Oladipo, F., Obilaja, O., Chikezie C., Farran. H., Jenakumo, T., & Orakwue, A. (2023). Drilling into a charge shadow zone of a prolific Niger Delta Field: Learnings from Well-X. SPE, SPE-217127-MS.

Petters, S. 1984. An ancient submarine canyon in the Oligocene-Miocene of the western Niger Delta. Sedimentology, 31, 805-810.

Samuel, O. J., Cornford, C., Jones, M., Adekeye, O. A. & Akande, S. O. (2009). Improved understanding of the petroleum systems of the Niger Delta Basin, Nigeria. Organic Geochemistry, 40, 461-483.

Whiteman, A. (1982). Nigeria: Its petroleum geology, resources and potential vol 1.