Using Regional Geology & Innovative Technology to Unlock Exploration & Development Opportunities in Deepwater Nigeria

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ABSTRACT

Unlocking the remaining petroleum resources in Deepwater Nigeria requires critical investment decisions. These decisions, such as participating in exploration bid rounds, making Final Investment Decisions on valuable development projects, and drilling Near Field Exploration or frontier wells, rely on credible regional and field-scale geological models, among other technical and economic factors. This paper highlights the technical work conducted in the translational structural geological setting of Deepwater Nigeria to support valuable business decisions. The objective stratigraphic interval spans from the Oligocene to the Messinian. Artificial Intelligence-driven applications were employed for robust regional structural interpretation, generating fault probability cubes, fault sticks, and wall-to-wall horizon interpretations on conditioned broadband seismic data. Stratigraphic attributes/sculpts produced using the interpreted regional events and conditioned seismic data were validated with well data. The results indicate that gravity-induced syn-sedimentary extensional and compressional structures create mini basins within the upper slope environment. Key sand fairways (turbidites) consist of channels, channel margins/levees, aprons (adjacent to structural highs and in mini basins), and Mass Transport Complexes. Most prospects have structural and stratigraphic trap elements, with key risks including trap integrity, fault seal, and access to charge. The main uncertainties are reservoir quality and distribution, particularly within the channel margins and thin beds. This work provided robust regional and field-scale assessments of subsurface geological risks and uncertainties in the area. New exploration leads were identified, and legacy leads were verified. The work also contributed to exploration portfolio ranking, lead-to-prospect maturation, delivery of valuable exploration volumes, seismic impact assessment and effective placement of appraisal/development wells.

Keywords: Regional Geology, Stratigraphic, Mini-Basins, Channels, Sculpts, Mass-Transport Channels, Artificial Intelligence, Attributes

INTRODUCTION

Nigeria ranks among the top ten countries with the largest remaining crude oil and condensate Deepwater (DW) reserves (Sources: www.nuprc.gov.ng & www.offshore-technology.com).

Unlocking these remaining petroleum resources in DW Nigeria requires critical investment decisions based on cutting-edge technology and credible geological models. According to Weimer (2018), "the desire to explore in greater water depths required new seismic technology to accurately image the subsurface, new scientific disciplines to analyze the geology and geophysics, and new technology to drill and develop resources."

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This paper aims to demonstrate how regional geology and high-end geophysical tools are leveraged to support vital business decisions. The regional geological setting of DW Nigeria will be discussed, followed by two case studies: one in an exploration setting (lead generation and prospect maturation) and the other in a development setting (sand distribution and well placement).

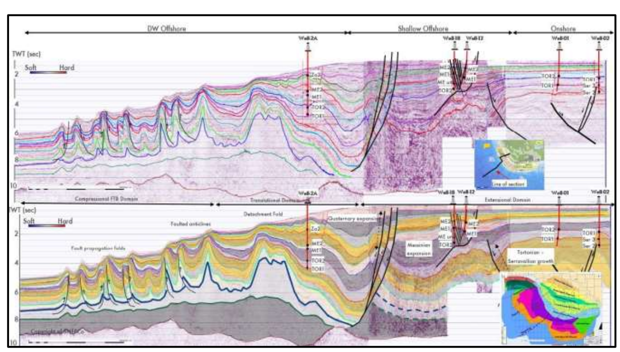

Figure 1: Regional seismic section and interpretation from onshore to DW Nigeria. (Acknowledgment: DW & Shallow Offshore Regional teams).

The objective stratigraphic interval spans from the Oligocene to the Messinian. Figure 1 shows the seismic section from onshore to DW offshore, indicating that extensional structures are dominant onshore and in shallow offshore areas. The structural setting of DW Nigeria is mainly translational to compressional, comprising reverse faults, folds, and thrusts. Figure 1 also illustrates the expansion and growth influenced by the relatively lower mean sea level, leading to the retrogression of the sea and progradation of the shoreline during the Serravallian, Tortonian, and Messinian. Onshore Niger Delta, Afam Canyon, Orubiri Canyon, and Buguma Canyon developed during these periods of relative mean sea level changes. Thus, these ages are most prolific from onshore through shallow offshore and DW offshore Nigeria.

METHODOLOGY

The dataset involved key wells, well tops, pressure data, petrophysical data, biostratigraphy data, cores, and core photographs. Regional 2D seismic data and 3D broadband seismic data (full stack, sub-stacks, reflectivity, and relative acoustic impedance seismic volumes) were conditioned to highlight structural and stratigraphic features for quantitative interpretation. The conditioning involved various types of filtering, such as bandpass filtering and AVC. Wide Band Spectral Decomposition (WBSD) volumes were generated using the conditioned broadband full stack reflectivity seismic data.

Two artificial intelligence (AI) driven applications were used for the structural interpretation of the seismic data. One application used the default/in-built fault recognition algorithm database to train the conditioned seismic data. The other AI tool is more interactive, allowing the user to highlight the original fault features/lineaments or planes for the tool to train the data. The tool then highlights "recommended" interpreted faults for user validation and subsequent adoption or rejection. Both tools were used to generate fault probability cubes using full stack conditioned Relative Acoustic Impedance and WBSD volumes. Fault sticks were extracted from the fault probability cubes and augmented with manually interpreted faults when necessary. The interpreted faults were checked for fault geometry consistency and alignment with the regional structural setting using quality control tools and manual inspection (Figures 2 & 3). AI-driven applications were also used to generate wall-to-wall regional interpreted surfaces, and field-scale interpreted events were integrated for field-scale evaluation.

Stratigraphic event-based attributes (sculpts) were generated using WBSD volumes and Near Stack Relative Acoustic Impedance (RAI) volumes when necessary to minimize the impact of fluid fill. Conditioned seismic RAI angle-stacks were further used to generate Stratigraphic

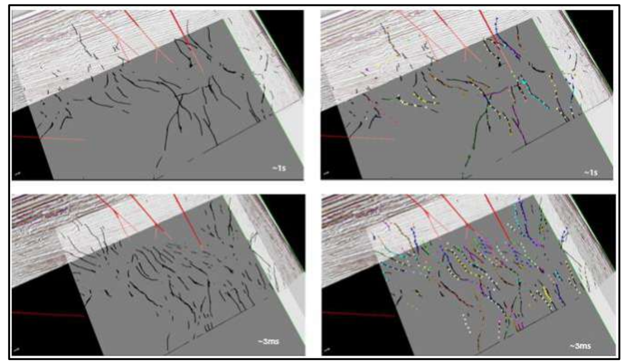

Figure 2: AI-assisted structural interpretation of the study area.

Attribute (AVAEDA) sculpts. These sculpts were created using regional interpreted events and were ground-truthed/calibrated with well data, such as well tops and other reservoir parameters.

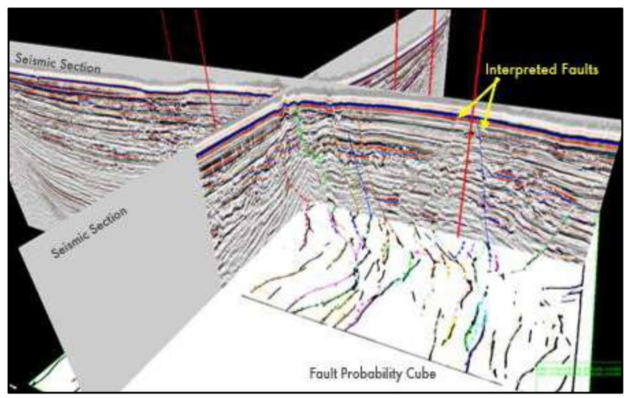

Figure 3: Interpreted faults superimposed on fault probability cube and seismic sections.

RESULTS & DISCUSSION

Exploration Case Study: Lead Generation & Prospect Maturation

The exploration case study is from the translational zone of DW Nigeria. The objectives of the work were to identify new leads, validate existing leads on newly acquired seismic data, and select the most valuable leads for prospect maturation. The results show that trap configuration and lateral fault seal (due to juxtaposition) are some of the key risks in the study area. Faults with relatively low throws are common and are suspect. There are multiple minor crestal faults with low throws in the area. The gravity-induced syn-sedimentary compressional structures (folds and anticlines) create mini-basins/accommodation within the slope. Combination traps (structural and stratigraphic) are common in the area. The structural components are mostly within the structural highs (folds), and the stratigraphic components (e.g., pinch outs) are dominantly found within the synclines and mini basins on the slope (Figure 4a).

The AI-generated fault probability cubes suitably resolved some of the structural complexities in the study area. Figures 4a and 4b show typical examples of the impact of high-end technologies used in resolving these crucial structural complexities. The yellow fault (from legacy evaluation) was previously interpreted as a deep-seated fault. Current fault interpretation using AI-generated fault probability cubes and broadband seismic data shows that the red fault truncates the yellow fault. The implication on prospect evaluation is profound. A deep-seated yellow fault implies the prospect adjacent to the fault will have direct access to hydrocarbon charge from beneath the field, thus erroneously increasing the chance of success. The current interpretation properly shows that the prospect will most likely have a tortuous path to hydrocarbon charge through carrier beds.

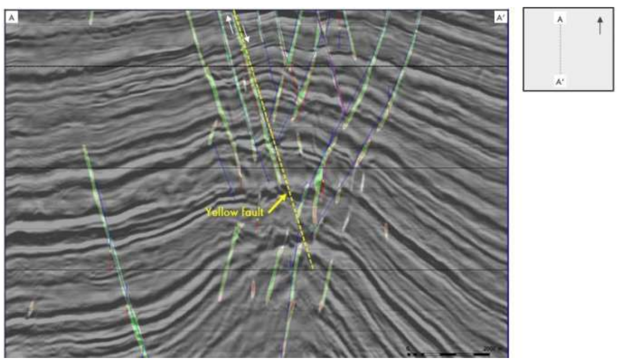

Figure 4a: Seismic section showing legacy interpreted yellow fault as deep-seated fault.

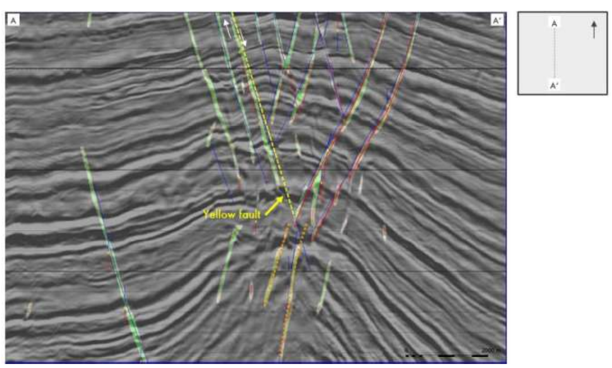

Figure 4b: Seismic section showing yellow fault currently interpreted as truncated by the red fault.

Figure 5 reinforces the value and efficacy of using AI-driven interpretations in conjunction with geology for prospect evaluation. The interpreted yellow event shows that there are at least two phases of structuration in the study area. The lower section below the yellow event shows a combination of thin-skinned compressional and extensional structures, while the upper section above the yellow event is purely extensional. However, the two phases were combined in the fault realization in Figure 6.

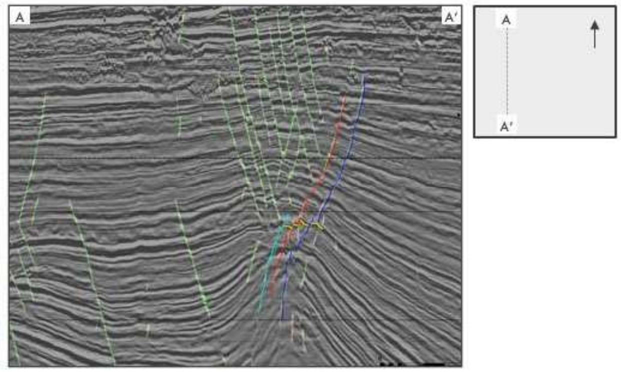

Figure 5: Fault and horizon interpretation showing two structural regimes highlighted by the yellow interpreted event with several relays in the study area.

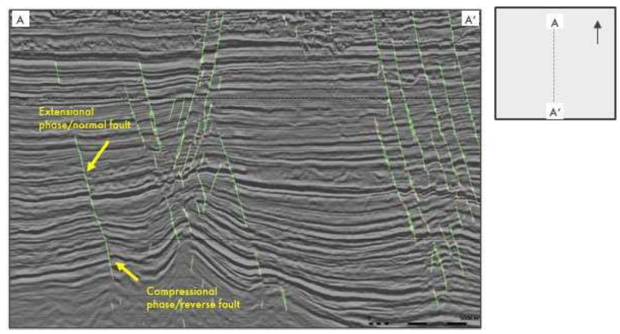

Figure 6: First-pass AI-backed fault interpretation showing the combination of normal and reverse faults.

Such errors are usually resolved by further training the data to recognize these patterns.

Figures 7 & 8 show a by-passed Mid-Miocene lead identified using the AVAEDA stratigraphic attribute. A legacy Well-001 drilled in the area missed the opportunity.

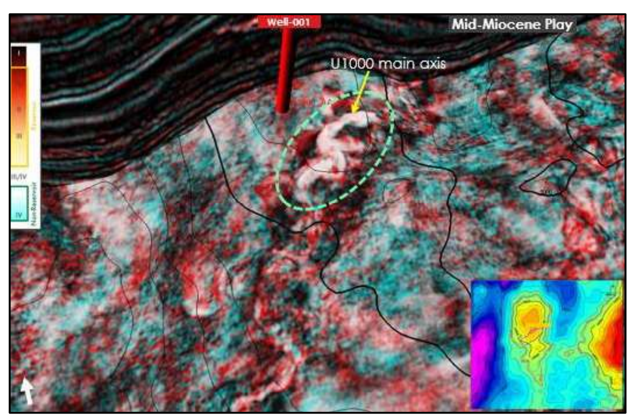

Figure 7: AVAEDA stratigraphic attribute showing quality sand fairway missed by Well-001. Yellowish AVAEDA colors are AVO Class 3 sands & reddish colors depict AVO Class 2/2P sands. Cyan color represents non-reservoir facies.

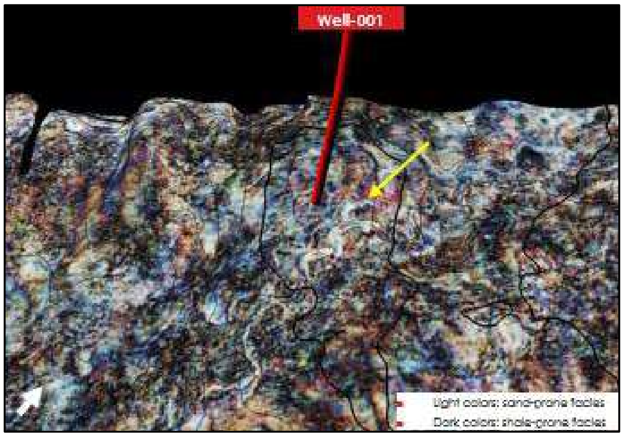

Figure 8: ED stratigraphic attribute map showing quality sand fairway missed by Well-001. Bright smooth colors of the attribute represent sand-prone facies and dark colors represent shale-prone facies.

Development Case Study

Seismic Impact Assessment on Field Development Plan

The key objectives of this work were to evaluate the probable impact of the newly acquired broadband seismic data on the understanding of the depositional architecture of the reservoirs in the study area. This assessment would dovetail into the seismic impact evaluation on hydrocarbon volumes and field development costs, including the number of producer-injector well pairs required. Consequently, some critical business decisions depended on the results of this assessment. The evaluation schedule was tight.

It was important to understand the regional depositional setting of the area, including the source of sediment inputs and the general sand fairways. Wall-to-wall interpreted events were used with cutting-edge stratigraphic attributes to successfully identify the regional sand fairways. Figure 9 is the ED attribute sculpt near the R-708 reservoir in the study area. The key sand fairways consist of channels, channel margins/levees, aprons, and mass transport complexes (MTCs). The ED attribute also shows the entry points of the feeder channels in the area, illustrating the relationship between structuration and sedimentation. The anticlinal structure (fold) to the east of Well-001 clearly influenced sedimentation in the area. Some reservoirs are draped on the folds, providing key channel-over-nose trap configurations. Other channels are draped on the sides of the folds as aprons/lobes, while some turbidites are deposited as basin floor fans. The late-stage channels are significant as they usually truncate existing sand fairways, thereby creating stratigraphic traps, baffles, and/or compartments. Some stratigraphic traps exist within the synclines in the mini basins. The petrophysical properties of the reservoirs show that some are acoustically soft, while others are acoustically hard, depending on the depth below mudline, presence of overpressure, and other diagenetic factors in the area.

Second, it was necessary to assess the reservoir units on a field scale. AVAEDA and ED attributes were used to evaluate the reservoirs (Figures 10a & 10b). The results show that one of the reservoir units (BD-108) consists of apron/channel facies. The wide channel belt facies in the NNE/SSW direction indicate that BD-108 most likely consists of amalgamated channels. The BD2_ST2 well penetrated the margin of the channel. The late-stage channels seen in BD-108 are not necessarily barriers, as shown in the relative impedance sections (Figure 10b). The results of this work, coupled with the results of other high-end quantitative interpretation assessments, among other factors, ultimately underpinned the positive business decision taken on the project.

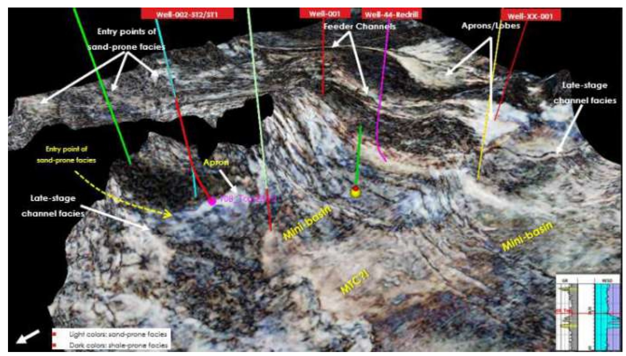

Figure 9: Regional ED stratigraphic attribute map near the R-708 reservoir. The inset to the right shows the gamma ray log and resistivity log from Well-002 ST1 near the R-708 reservoir. Bright smooth ED attribute colors represent sand-prone facies, and dark colors represent shale-prone facies.

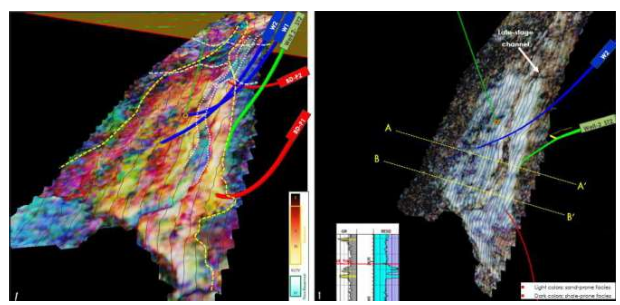

Figure 10a: AVAEDA (left) and ED (right) stratigraphic attributes of BD-108 reservoir. Yellowish AVAEDA colors are AVO class 3 sands & reddish colors depict AVO Class 2/2P sands. Bright smooth ED attribute colors represent sand-prone facies and dark colors represent shale-prone facies. Cyan color represents non-reservoir facies.

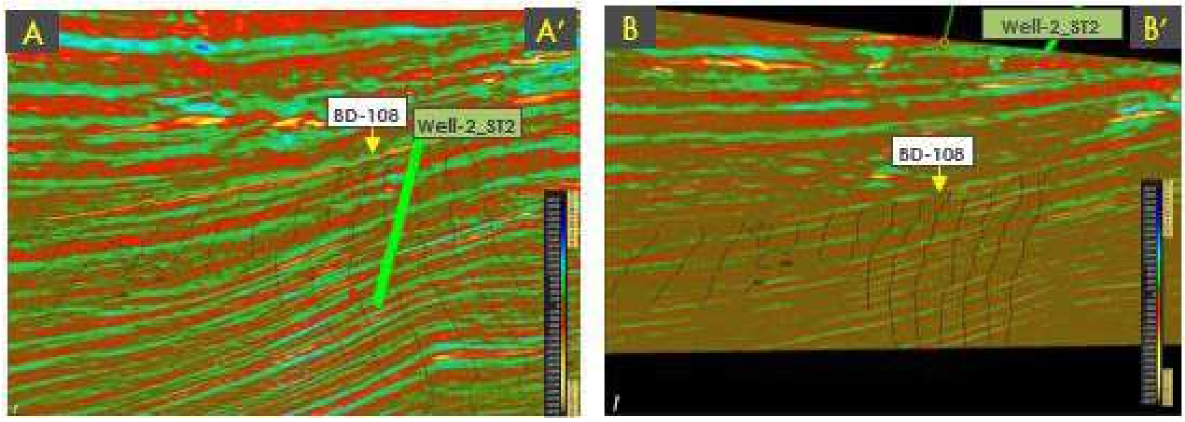

Figure 10b: Relative acoustic impedance sections across BD-108 reservoir showing the late-stage channels in section A-A' and sand continuity in section B-B'.

Development/Production Case Study: Producer Well Placement Evaluation

Well-43RD (light green well in Figures 11a, 11b, 12a & 12b) was designed to produce over 10 million barrels of oil from an existing field in the study area. Some previous wells drilled to produce from the sand unit were not optimally located, making the optimal placement of the re-drill crucial. ED, AVAEDA stratigraphic attributes, and Wide Band Spectral Decomposition were deployed in conjunction with other tools to evaluate the planned Well-43RD trajectory for sweet spots. The sub-stack (near-mid) seismic data were used to enhance stratigraphic features and minimize fluid effects. However, some prior fluid production effects on the data cannot be eliminated.

The results of the evaluation show that the sand unit has a channel-over-nose configuration, and that the depositional architecture of the sand body is a braided channel system (Figures 11a, 11b, 12a & 12b). The assessment further shows that some previous wells drilled to produce from the sand penetrated some of the late-stage channels. Additionally, it indicates that Well-48 (a water injector well) is most likely in shale-prone facies. The work validated the planned Well-43RD trajectory, showing that it is located within the sweet spot of the braided channel system. Well-43RD was successfully landed within the objective section.

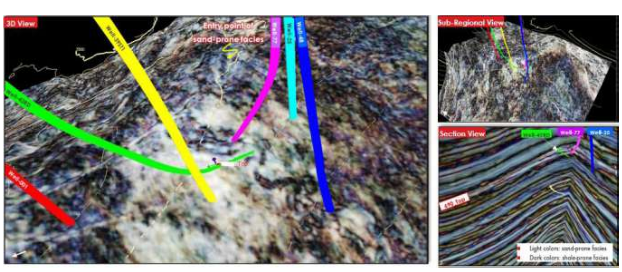

Figure 11a: Stratigraphic attribute generated for optimal placement of the producer Well-43RD. Bright smooth colors of the attribute represent sand-prone facies and dark colors represent shale-prone facies.

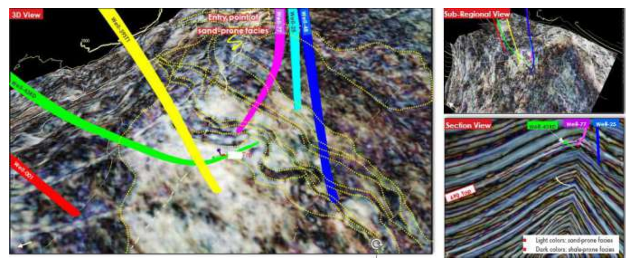

Figure 11b: Stratigraphic attribute showing sand fairways in the area. Bright smooth colors of the attribute represent sand-prone facies and dark colors represent shale-prone facies.

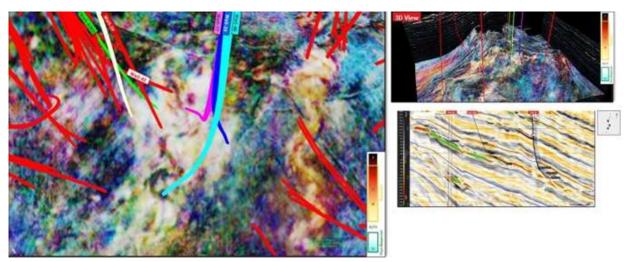

Figure 12a: AVAEDA stratigraphic attribute showing reservoir quality of the sand fairway generated for optimal placement of the producer Well-43RD. Yellowish AVAEDA attribute colors are AVO Class 3 sands & reddish colors depict AVO Class 2/2P sands. Cyan color represents non-reservoir facies.

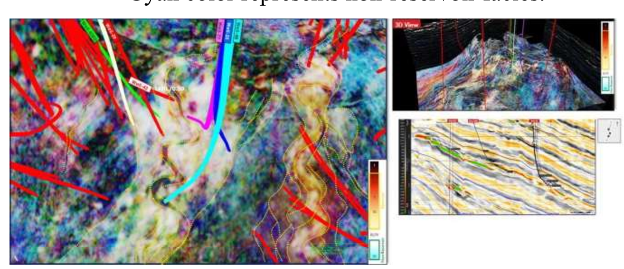

Figure 12b: Stratigraphic attribute showing braided channels in the key sand fairways targeted by the planned producer Well-43RD. Yellowish AVAEDA attribute colors are AVO Class 3 sands & reddish colors depict AVO Class 2/2P sands. Cyan color represents non-reservoir facies.

CONCLUSIONS

The comprehensive evaluation of the study area has highlighted several critical geological and structural risks, particularly related to trap configuration and lateral fault seal integrity. The prevalence of faults with relatively low throws and the presence of minor crestal faults necessitate careful consideration in prospect evaluation. The gravity-induced syn-sedimentary compressional structures have created complex mini-basins and accommodation zones, where combination traps are prevalent. The application of AI-generated fault probability cubes has significantly enhanced the resolution of structural complexities, providing a more accurate interpretation of fault interactions. This advanced interpretation has profound implications for prospect evaluation, particularly in understanding the hydrocarbon charge pathways.

The regional depositional setting, characterized by diverse sand fairways and influenced by structural highs and synclines, plays a crucial role in trap formation. The integration of stratigraphic attributes has successfully delineated key sand fairways and their relationship with structural features, offering valuable insights into sedimentation patterns and trap configurations. Field-scale reservoir assessments using AVAEDA and ED attributes have further refined the understanding of reservoir architecture and quality. The identification of channel-over-nose configurations and braided channel systems underscores the complexity of the depositional environment. The validation of well trajectories and the identification of stratigraphic traps and barriers have been instrumental in guiding successful drilling operations.

Overall, the integration of high-end technologies and advanced interpretation techniques has provided a robust framework for evaluating the hydrocarbon potential in the study area. The findings underscore the importance of a multidisciplinary approach in addressing geological uncertainties and optimizing exploration and production strategies.

BUSINESS IMPACT & RECOMMENDATIONS

The comprehensive regional and field-scale assessments of geological risks and uncertainties have proven invaluable for making informed exploration, appraisal, and development business decisions. By identifying and ranking exploration leads, the study facilitated strategic participation in bid rounds and the maturation of top-ranking Near Field Exploration leads into valuable prospects, enabling the rapid assessment of hydrocarbon volumes. The strategic placement of development and producer wells in sweet spots ensured effective connectivity between producers and injectors.

The integration of AI-driven applications with a thorough understanding of the area's geology has significantly enhanced fault interpretation and prospect evaluation. It is crucial to continually check fault interpretations for inconsistencies and revise fault probability cube models as necessary. Assessing the throw of key faults against reservoir thickness is essential to determine potential compartmentalization or self-juxtaposition of reservoirs. Proper fault seal analysis should be conducted to evaluate fault seal potential accurately.

Ground truthing and calibration of seismic attributes with well data are highly recommended to ensure the reliability of interpretations. This multidisciplinary approach, combining advanced technologies with geological expertise, provides a robust framework for optimizing exploration and production strategies, ultimately supporting successful hydrocarbon exploration and development in the study area.

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