Seismic-driven Reservoir Characterization

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Summary

Reservoir characterization is a critical process in the exploration and development of hydrocarbon resources. As fields mature and exploration targets become more complex, the challenges in accurately delineating reservoirs have intensified. This paper presents a comprehensive framework for seismic-driven reservoir characterization, focusing on the integration of advanced geophysical technologies to address key challenges such as subtle fault detection, thin reservoir prediction, heterogeneous carbonate characterization, and remaining oil identification. Central to this approach are innovative techniques developed on the GeoEast Reservoir Characterization Platform, including AI-assisted subtle fault prediction, integrated seismic facies analysis, full-band frequency seismic inversion, integrated remaining oil detection, and seismic-driven reservoir modeling. The efficacy of these methods is demonstrated through two detailed case studies: a giant heterogeneous carbonate oilfield in the Middle East and a complex structural reservoir in the South Caspian Basin. The results show significant improvements in interpretation accuracy, modeling efficiency, and drilling success rates, leading to new discoveries in mature fields. This paper concludes that the synergistic application of these advanced seismic-driven technologies provides a robust foundation for enhancing recovery and optimizing development strategies in challenging reservoir environments..

Introduction

The global energy landscape is increasingly defined by the exploitation of complex and mature hydrocarbon reservoirs. As exploration gradually shifts to development, particularly in brownfields and challenging geological settings, reservoir characterization is facing unprecedented challenges. Accurate subsurface models are paramount for optimizing drilling campaigns, improving recovery factors, and maximizing the economic life of assets. Seismic data, providing unparalleled lateral continuity, remains the backbone of reservoir characterization. However, traditional seismic interpretation and inversion techniques often fall short in addressing the subtleties and complexities of modern reservoirs. This paper delineates three primary challenges and introduces a suite of integrated, seismic-driven technologies designed to overcome them.

Challenge 1: Subtle Fault and Thin Reservoir Prediction

The first significant challenge lies in the identification of subtle structural discontinuities and the prediction of thin-bed reservoirs. Small-scale faults, with throws often below the seismic resolution, can compartmentalize a reservoir, significantly impacting fluid flow and well placement. Similarly, thin reservoirs, such as channel or carbonate layers, are difficult to resolve using conventional seismic data due to the tuning effects and limited bandwidth. While improvements in seismic acquisition and processing (e.g., high-density surveys, pre-stack depth migration) have enhanced data quality, extracting reliable information on subtle faults and thin beds requires specialized, high-resolution interpretation and inversion techniques (Fig.01). Failure to accurately characterize these elements can lead to erroneous reservoir models and suboptimal development decisions.

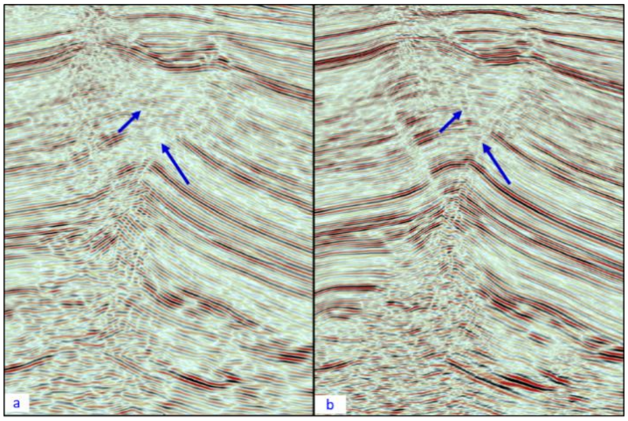

Fig.01 Subtle faults prediction in Middle Asia, a-Legacy seismic section-OBC, b-NEW seismic section-OBN

Challenge 2: Remaining Oil Prediction

The second major challenge is the prediction of remaining oil distribution in mature fields. After years of production, reservoir heterogeneity and uneven sweep efficiency lead to complex, bypassed oil distributions. These remaining oil saturations are controlled by a combination of geological factors (e.g., stratigraphic complexity, fault sealing) and dynamic production history. Using seismic data to directly predict the spatial distribution of remaining oil is notoriously difficult, as the seismic response is influenced by multiple rock and fluid properties. The challenge is to integrate seismic attributes with production data and geological understanding to delineate untapped compartments and optimize infill drilling and enhanced oil recovery (EOR) strategies.

Challenge 3: Integrated Reservoir Modelling

The third challenge involves the construction of integrated reservoir models that honor multi-scale and multi-disciplinary data. The most effective reservoir models integrate data from cores, well logs, production history, and seismic. However, fundamental differences in scale, resolution, and physical measurement between these datasets create significant integration hurdles. For instance, well data offers high vertical resolution but is spatially sparse, while seismic data provides dense spatial coverage but with limited vertical resolution. Reconciling these differences to create a geologically consistent and dynamically calibrated model is a non-trivial task. Traditional two-step modeling approaches, where the structural and property models are built sequentially with limited seismic constraint, often fail to capture the true reservoir complexity.

This paper is structured to address these challenges systematically.

Methods

To enhance the accuracy and efficiency of reservoir characterization, a suite of innovative methods has been developed based on the GeoEast Reservoir Characterization Platform. These techniques are designed to work synergistically, transforming seismic data into high-fidelity geological models.

2.1 AI-Assisted Subtle Fault Prediction

After a decade of intensive research and development, BGP has successfully transitioned from manual fault interpretation to AI-powered automated fault interpretation, marking a paradigm shift in structural geology. This transition has yielded dramatic improvements in both efficiency and interpretation objectivity. The current AI fault prediction system incorporates three key advancements over conventional methods [1]:

Neural Network Upgrade: The architecture has evolved from traditional Convolutional Neural Networks (CNNs) like U-Net to the more powerful Transformer architecture. Transformers, with their self-attention mechanisms, are better suited for capturing long-range dependencies in seismic data, leading to superior performance in identifying low-contrast, discontinuous features indicative of subtle faults. This upgrade enhances the signal-to-noise ratio of fault probability volumes, making faint faults more discernible.

Fault-Preserved Filtering Techniques: A novel seismic data conditioning technique has been developed to enhance the fault signal while suppressing noise. Unlike conventional filters that may smear discontinuities, this method selectively attenuates noise without compromising the sharpness of fault edges. By applying this filter as a pre-processing step, the input data quality for AI prediction is significantly improved, leading to more reliable results (Fig.02).

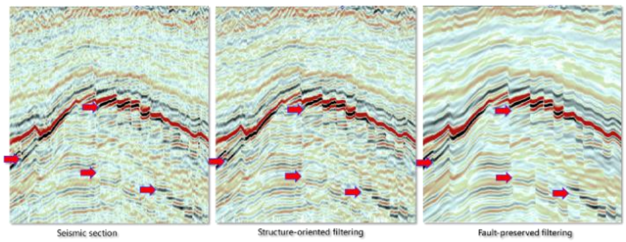

Fig.02 Fault-preserved filtering improve subtle fault prediction

Basin-Scale Applications and Efficiency: The scalability of this technology has been demonstrated in large-scale projects. A notable example from the Songliao Basin involved processing 11,000 km² of 3D seismic data. The AI system completed the fault interpretation task in just 27 hours, a task that would have taken interpreters months using manual methods. This not only accelerates project timelines but also ensures a consistent and exhaustive fault interpretation across the entire survey.

2.2 Integrated Seismic Facies Analysis

Seismic facies analysis is crucial for understanding depositional environments and reservoir heterogeneity. However, conventional seismic attributes are often contaminated by the effects of faults, leading to ambiguous facies interpretations. To address this, an integrated technique has been developed that leverages the results from AI fault prediction.

The process involves using the AI-derived fault volume as a mask to guide a seismic data conditioning workflow [2-3]. This workflow selectively reduces the amplitude expression of faults in the seismic data, thereby enhancing the continuous stratigraphic and depositional signals, such as those from channels and deltas. A comparison of seismic attributes before and after conditioning reveals a dramatic clarification of depositional systems. For instance, channel margins and internal architectures become much clearer, significantly improving the accuracy of seismic facies classification and the subsequent geological interpretation.

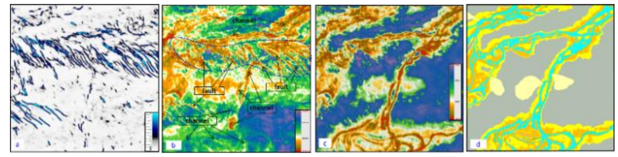

Fig.03 Integrated seismic facies analysis, a- Seismic attribute for fault prediction (AI fault prediction), b- Seismic attribute before conditioning-RMS amplitude, c- Seismic attribute after conditioning-RMS amplitude, d- Seismic facies analysis based on the new RMS amplitude.

2.3 Full-Band Frequency Seismic Inversion

Conventional seismic inversion methods often suffer from limited bandwidth, resulting in a loss of either low-frequency trends (leading to inaccurate absolute impedance values) or high-frequency details (limiting vertical resolution). The Full-Band Frequency Inversion (FFI) method is designed to overcome this limitation by integrating information across the entire frequency spectrum [4].

Key advancements in this area include:

Low-Frequency Model: The construction of an accurate low-frequency model is critical for a reliable inversion. AI algorithms are now used to condition well logs, handle missing data, and extrapolate low-frequency trends away from wells, resulting in a more geologically plausible initial model.

Full-Band Integration (Fig.04): This novel inversion scheme intelligently merges three components: 1) the low-frequency model from wells and seismic velocity, 2) the mid-to-high-frequency information derived from seismic waveform-indicated inversion, which captures the geological patterns guided by seismic data, and 3) the high-frequency details from geostatistical inversion, which honors well data statistics. The result is an impedance volume with high vertical resolution that matches well logs and maintains lateral consistency with seismic attributes.

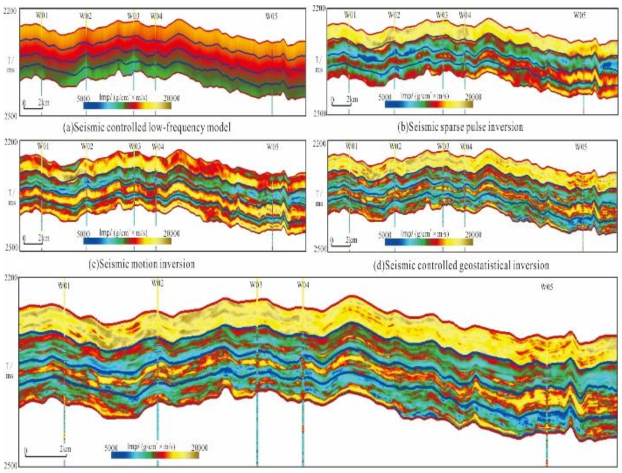

Fig.04 Full-band frequency seismic inversion

Pre-stack Full-Frequency Inversion (Pre-stack FFI) [5]: Extending the concept to pre-stack data allows for the simultaneous inversion of P-impedance, S-impedance, and density. This provides a more direct link to lithology and fluid content. Pre-stack FFI is particularly sensitive to hydrocarbon effects (e.g., changes in VP/VS ratio), enabling more reliable direct hydrocarbon detection (DHD) and quantitative interpretation (QI) (Fig.05).

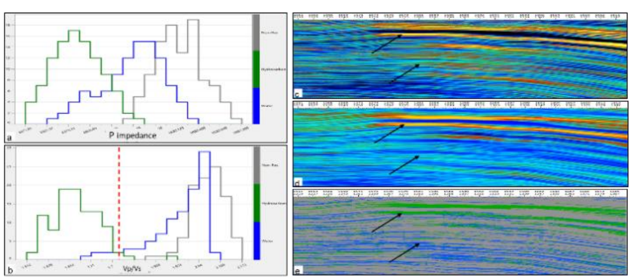

Fig.05 Pre-stack FFI (VP/VS) for Hydrocarbon detection. a-Rock physics analysis comparison(Vp), b-Rock physics analysis comparison(Vp/Vs), c-Post-stack FFI, d-Pre-stack FFI (Vp/Vs), e- Hydrocarbon detection.

2.4 Integrated Remaining Oil Detection

This technology focuses on identifying bypassed oil resulting from two primary causes: reservoir heterogeneity and fault sealing.

Remaining Oil from Heterogeneity: High-resolution pre-stack FFI results provide detailed images of reservoir properties. AI-based geo-body extraction tools can then be used to automatically identify isolated sand bodies or porosity pods that may have been bypassed by water flooding. These "sweet spots" represent prime targets for infill drilling.

Remaining Oil from Fault Sealing [6]: This approach integrates high-confidence fault models from AI prediction with lithology models. A key enabler is an intelligent software tool called Trap-3D, which automates fault seal analysis. By calculating shale gouge ratios (SGR) or other seal potential metrics across fault planes, the software rapidly evaluates hundreds of fault blocks to identify those with high seal potential that are likely to contain trapped hydrocarbons (Fig.06). A case study from a mature field in Central Asia [7], with a water cut exceeding 97%, demonstrated the power of this method. AI fault seal analysis identified a series of previously overlooked fault blocks on the field's slope. Subsequent drilling from 2021 to 2025 resulted in seven successful wells, leading to significant new production.

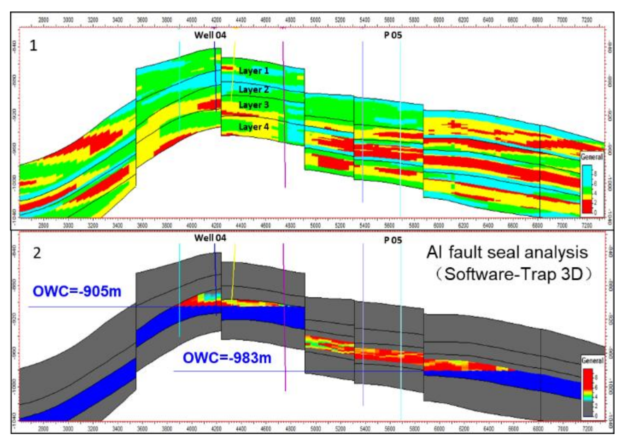

Fig.06 Automatic remaining oil prediction

2.5 Seismic-driven Reservoir Modeling

This technique closes the loop by directly using the high-resolution seismic-derived products to constrain and guide the construction of reservoir models. Three significant progressions are highlighted:

Rapid Complex Structural Modeling: By integrating drilling data (e.g., breakpoints identified from well logs) with the AI fault prediction results, a highly accurate structural framework can be built rapidly. A task that previously required over a year for complex fields can now be completed in approximately three months, drastically reducing project cycle times.

Heterogeneous Carbonate Modeling [8]: For complex carbonate reservoirs, a workflow is employed that uses the high-resolution seismic inversion results (e.g., impedance) as a soft constraint. Core and log data are used to define lithofacies, and a Bayesian discriminant method is used to populate the 3D lithofacies model, honoring the seismic trends. Subsequently, lithofacies-specific porosity-permeability transforms are applied, leading to a more accurate prediction of permeability distribution, which is critical for simulation and development planning (Fig.07).

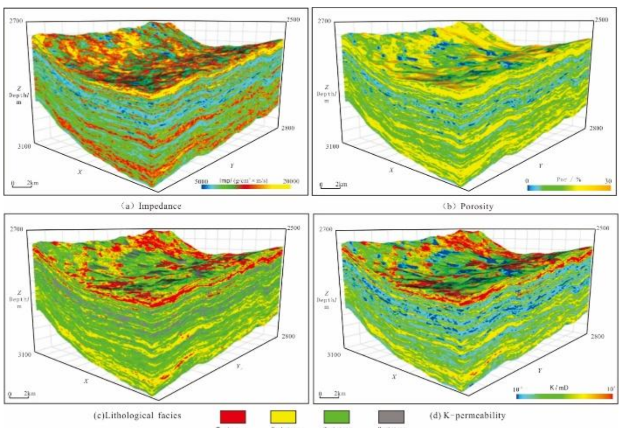

Fig.07 Seismic-driven reservoir modeling

Thin-Bed Reservoir Modeling: The use of the full-band inversion model, with its enhanced vertical resolution, as a guiding trend for geostatistical property modeling (e.g., Sequential Gaussian Simulation with Collocated Cokriging) significantly improves the inter-well prediction of thin layers. This results in a more realistic model of reservoir connectivity[10] (Fig.08).

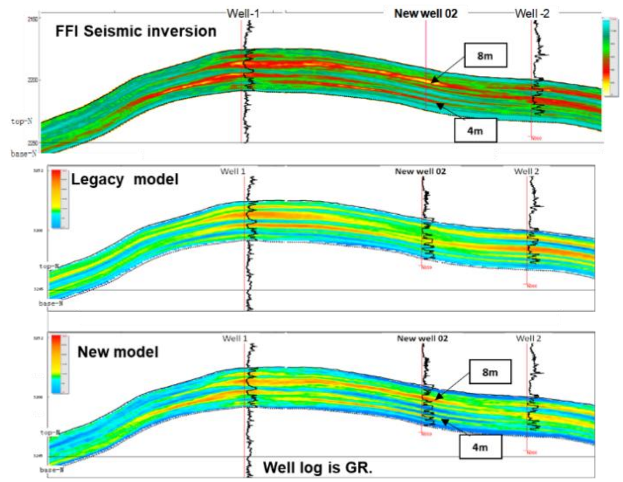

Fig.08 Seismic-driven reservoir modeling for thin bed reservoir

Examples

Case 1: Heterogeneous Carbonate Reservoir Characterization in a Giant Middle Eastern Oilfield

This case study involves a massive carbonate reservoir facing challenges related to subtle faulting and extreme heterogeneity, impacting sweep efficiency and well performance.

A comprehensive characterization workflow was executed, including seismic preconditioning, AI-based fault prediction, intelligent seismic facies analysis, full-band seismic inversion, and integrated reservoir modeling.

Key Technique 1: AI Fault Prediction with Enhancements: Three specific improvements were made: 1) Frequency optimization to select seismic attributes sensitive to subtle faults[9]. 2) Adoption of the Transformer algorithm for superior fault imaging. 3) Implementation of rigorous 3D QC using azimuth and dip attributes to validate and refine the fault network. This accurate fault model proved essential for the subsequent step.

Key Technique 2: Seismic Facies Analysis: The initial seismic attributes were heavily influenced by the now-well-defined faults and tidal channels. Applying the fault-preserved filtering and data conditioning technique dramatically enhanced the tidal channel–shoal depositional system, making the reservoir architecture interpretable (Fig.09).

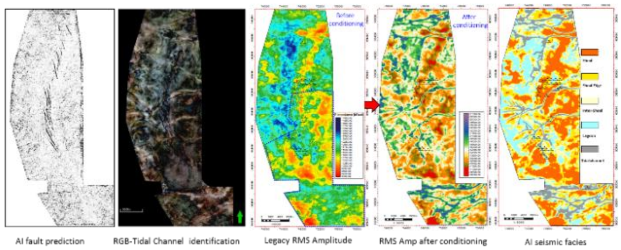

Fig.09 Seismic Facies Analysis

Key Technique 3: Full-Frequency Inversion (FFI): Leveraging the refined seismic facies for guidance, the FFI was performed. The results exhibited a 93% well-match rate and could resolve layers more than 5 meters, a significant improvement over previous inversions(Fig.10).

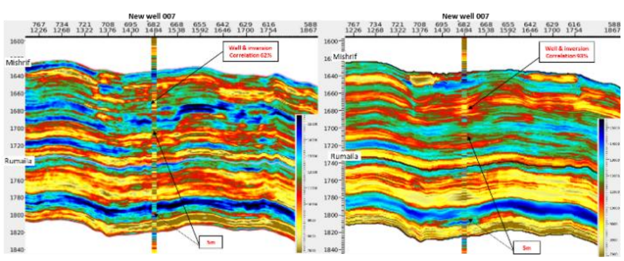

Fig.10 Full-band frequency seismic inversion, left-Legacy geostatistical inversion(2024), right- FFI seismic inversion (2025).

Outcome: The high-resolution impedance volume and seismic facies were used to build a detailed lithofacies and property model using Bayesian discrimination. The resulting permeability model clearly revealed the distribution of four distinct high-permeability zones [11]. Crucially, the model identified new hydrocarbon-rich zones below the traditional oil-water contact, which were later confirmed by drilling, opening new development opportunities in this mature field (Fig. 11).

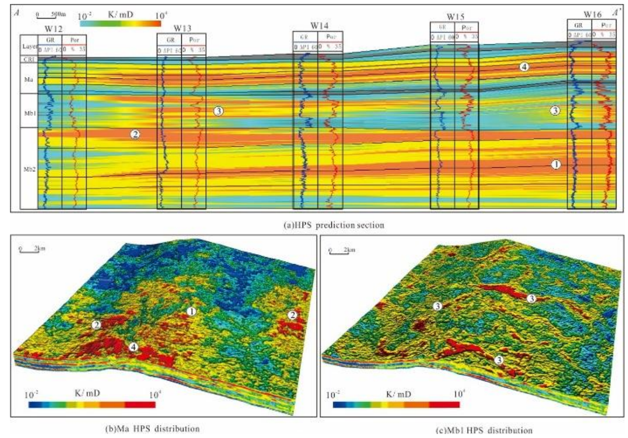

Fig.11 High quality reservoir modeling

Case 2: Complex Structure Reservoir Characterization in the South Caspian Basin

This field is characterized by extreme structural complexity with numerous small faults, posing challenges for structural modeling and remaining oil prediction.

Key Technique 1: Complex Structural Modeling with OBN Data: Ocean Bottom Node (OBN) seismic data provided superior illumination and signal-to-noise ratio compared to legacy Ocean Bottom Cable (OBC) data. AI fault prediction applied to OBN coherence volumes yielded a highly detailed fault map [12]. This allowed for the rapid construction of a complex structural model covering 780 km², incorporating 387 faults and 1,522 fault compartments, within three months (Fig. 12).

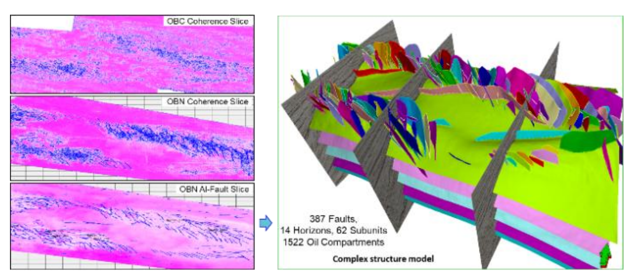

Fig.12 AI subtle fault prediction and modeling

Key Technique 2: Identification of New Prospects: The high-resolution data and accurate fault interpretation revealed a series of potential fault-bound prospects. Well-07, drilled based on this new interpretation, encountered hydrocarbons in a compartment previously considered unprospective, located below the original oil-water contact.

Key Technique 3: Seismic Facies and Pre-stack Inversion: Seismic data conditioning clarified the fluvial-deltaic depositional system, improving facies prediction. This guided a pre-stack FFI, which not only improved reservoir property prediction but also provided reliable hydrocarbon indicators. A well (Well-02) proposed based on this study achieved a field production record of 4,600 barrels per day in 2024. The overall drilling success rate increased from 50% to 100%, demonstrating the transformative impact of the integrated technology suite (Fig. 13).

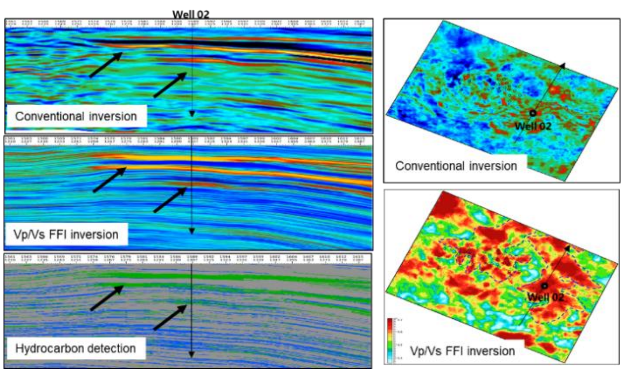

Fig.13 Pre-stack FFI inversion of Vp/Vs improves the accuracy of hydrocarbon detection

Case 3: Integrated Remaining Oil Prediction in W Block, Ordos Basin

The W Block, located within the Ordos Basin, is characterized by thin, complex reservoirs. The primary development challenge is the accurate prediction of remaining oil distribution, crucial for optimizing infill drilling and enhanced oil recovery. Traditional methods struggled to delineate thin layers (often 3-5m thick) and identify bypassed oil, leading to suboptimal field management.

Key Technique 1: High-Resolution Seismic Data Acquisition and Processing

To address these challenges, a comprehensive seismic data program was implemented. This included acquiring high-density 3D surface seismic data integrated with high-resolution uDAS (distributed acoustic sensing) 3D VSP (Vertical Seismic Profile). The uDAS-VSP provided superior vertical resolution and precise well-tie calibration. An integrated high-resolution imaging processing workflow was applied to merge these datasets, significantly enhancing the clarity and resolution of thin reservoir layers (Fig. 14).

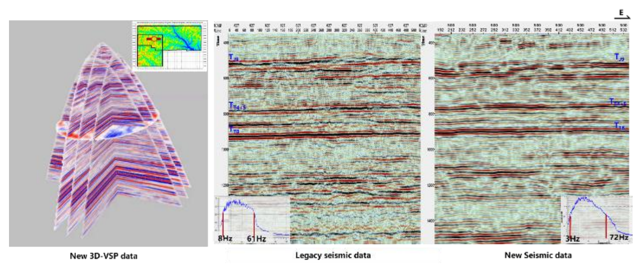

Fig.14 High density 3D seismic data & high resolution uDAS-3D VSP

Key Technique 2: Full-Band Frequency Seismic Inversion

The processed seismic data was utilized in a full-band frequency inversion to predict reservoir properties, specifically sand thickness and porosity. This advanced inversion technique successfully predicted thin reservoirs of 3-5m. The model's reliability was rigorously tested with blind wells (wells not used in the inversion process), achieving an exceptional consistency rate of over 91%. This high-confidence model proved invaluable for analyzing reservoir connectivity and optimizing water injection strategies (Fig. 15).

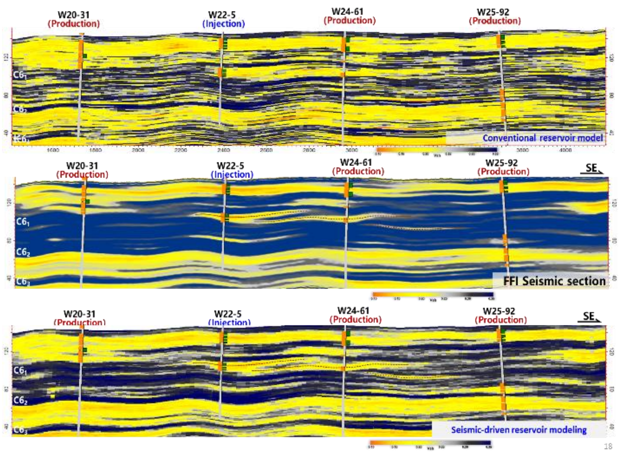

Fig.15 Full-Band Frequency Seismic Inversion and Seismic-Driven Reservoir Modeling

Key Technique 3: Seismic-Driven Reservoir Modeling and Remaining Oil Prediction

The inversion results were directly integrated into the geological modeling workflow to build a seismic-driven reservoir model. This integration dramatically improved the model's accuracy, moving away from simplistic interpolations between wells. Subsequently, this refined model was used for seismic-driven remaining oil prediction. The analysis identified two key target types: Within the Developed Area: High oil saturation zones were pinpointed in areas of poor connectivity and stratigraphic pinch-outs, representing bypassed oil. Potential Slope Areas: New potential was identified in low-relief structural traps and stratigraphic pinch-out reservoirs on the block's slopes (Fig. 16).

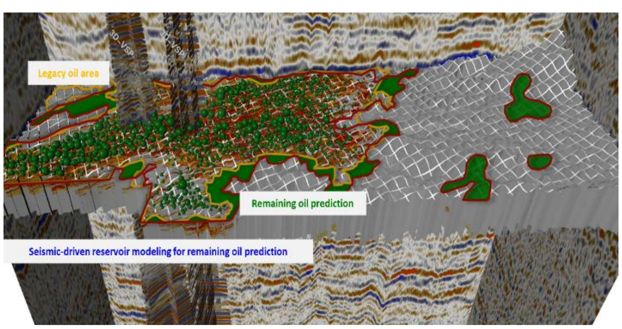

Fig.16 Remaining Oil Prediction

Key Technique 4: High-Efficiency History Matching

Finally, the accurate seismic-constrained reservoir model served as an excellent initial model for history matching. The integration of seismic data reduced uncertainty and non-uniqueness, leading to a highly efficient and accurate history matching process. This enhanced the confidence in dynamic predictions and the forecast of remaining oil distribution.

The integrated approach, combining high-resolution seismic acquisition, advanced inversion, and seismic-driven modeling, successfully addressed the challenges of the W Block. It enabled precise prediction of thin reservoirs and remaining oil, leading to optimized development plans, identification of new targets, and improved recovery factors.

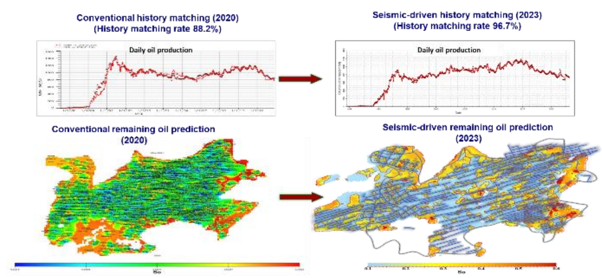

Fig.17 New model enhanced the accuracy of history matching and remaining oil prediction

Conclusions

This paper has detailed an integrated approach to seismic-driven reservoir characterization, designed to meet the growing challenges of modern hydrocarbon development. The key conclusions are as follows:

Technological Integration is Key: The synergistic application of advanced technologies—AI fault prediction, seismic facies analysis, full-band inversion, and seismic-guided modeling—creates a powerful workflow that is greater than the sum of its parts. Each step feeds valuable constraints and information into the next, leading to a more robust and reliable reservoir model.

AI is a Game-Changer: The adoption of AI, particularly advanced architectures like Transformers, has revolutionized tasks such as fault interpretation, enabling unprecedented levels of automation, accuracy, and efficiency at a basin scale.

High-Resolution Imaging is Achievable: Full-band frequency inversion techniques successfully bridge the scale gap between well logs and seismic data, providing high-resolution property volumes that are essential for characterizing thin beds and heterogeneous reservoirs.

Value in Mature Fields: The application of these technologies is particularly impactful in mature fields, where they can uncover significant new reserves by identifying subtle structural traps, heterogeneous bypassed zones, and poorly swept compartments, thereby extending field life and increasing recovery factors.

The case studies from the Middle East and the South Caspian Basin provide compelling evidence that these specialized reservoir geophysical solutions effectively address the challenges of complex structure characterization, heterogeneous reservoir prediction, thin-bed modeling, and complex remaining oil detection. It is concluded that the future of efficient and sustainable reservoir management lies in the continued development and intelligent application of such integrated, seismic-driven characterization workflows. The authors hope that these advanced solutions will contribute significantly to the exploration and development success of oilfields worldwide.

Acknowledgments

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