AVO analysis and seismic reservoir characterization in a deepwater reservoir in KG Basin: An integrated approach

Som Subhra Banerjee[1], Shrijib Patra[1], and Kondal Reddy[1]

ABSTRACT

An integrated geophysical study was conducted to characterize a deep-water reservoir cluster located offshore in the Krishna-Godavari (KG) Basin, along the east coast of India. The seismic dataset underwent advanced reprocessing followed by targeted in-house conditioning to enhance data quality for Amplitude Versus Offset (AVO) analysis. Leveraging offset well information, the conditioned data was analyzed using rock physics and AVO techniques to identify classical anomalies indicative of hydrocarbon-bearing sands within a Pliocene-Miocene slope fan complex. AVO cross-plot analysis revealed deviations of gas sands from the wet sand/shale trend, although reliability diminished when anomalies aligned with background trends. Fluid substitution modelling and elastic property analysis further supported the identification of prospective hydrocarbon zones. To refine reservoir characterization, simultaneous angle-dependent seismic inversion was performed using four partial angle stacks, resulting in volumes of P-impedance, V_P/V_S, and density. These inverted attributes provided enhanced insights into reservoir geometry, fluid content, and lithological variations, contributing to reduced exploration risk and improved delineation of future drilling prospects.

KEYWORDS

AVO, fluid factor, seismic data conditioning, simultaneous inversion, reservoir characterization

INTRODUCTION

The Krishna-Godavari (KG) Basin, located along India's eastern offshore margin, was formed on a rifted passive margin during the continental breakup from Antarctica and is recognized as a prolific hydrocarbon province (Bastia et al., 2006). Pliocene-age sands were deposited through slope channels, leveed channels, distributary systems, and lobes, with seismic imaging and drilling confirming sand dispersal via slope and fan complexes. Exploration efforts in the basin primarily target high-amplitude seismic anomalies associated with structural features such as anticlines, fault closures, rollovers, and toe thrusts. Rapid sedimentation during the Miocene period contributed to the development of growth faults and rollover anticlines, which serve as effective hydrocarbon traps.

In deep-water settings, seismic amplitude anomalies are commonly used to identify gas sands, however, their reliability diminishes when these anomalies converge with background trends in AVO crossplot space. This study focuses on a deep-water reservoir cluster identified through seismic character and offset well data (Figure 1). The objective is to enhance reservoir characterization by integrating seismic data conditioning, rock physics modelling and AVO analysis. Subsequent seismic inversion studies further revealed the geomorphological features and depositional architecture of the reservoir system and facilitated the quantification the seismic amplitudes in relation to lithology and hydrocarbon content.

GEOLOGICAL SETTING

The study area lies within the KG-Offshore block, encompassing roughly 1,200 km^2 along the eastern coast of India, offshore the Krishna and Godavari River systems. The region spans a bathymetric range of 500 to 2,000 meters. The Krishna-Godavari Basin is a classic example of a passive rift margin basin, shaped by a complex polycyclic geological evolution. Its first marine transgression occurred during the Albian-Aptian period, marking the onset of significant sedimentary processes. A south-eastward tilt of the basin from the Late Cretaceous to the Paleocene facilitated further marine transgression and the development of extensive fluvial systems by the Krishna and Godavari rivers. These systems contributed to the formation of the present-day deltas during the early Miocene (Gupta, 2006). Shelfal reservoirs in the basin consist of mid to late Miocene coastal plain to shoreface sands, while the slope domain features Plio-Pleistocene slope-derived channel deposits and incised slope channel sands.

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Exploration targets primarily include Miocene to Plio-Pleistocene submarine fan systems and channel-levee complexes, with reservoirs characterized by turbidite channel and fan architecture. The hydrocarbon-bearing intervals are interbedded with shales, and the structural setting is dominated by rollover anticlines associated with growth faults, offering promising trap configurations for hydrocarbon accumulation (Figure 2).

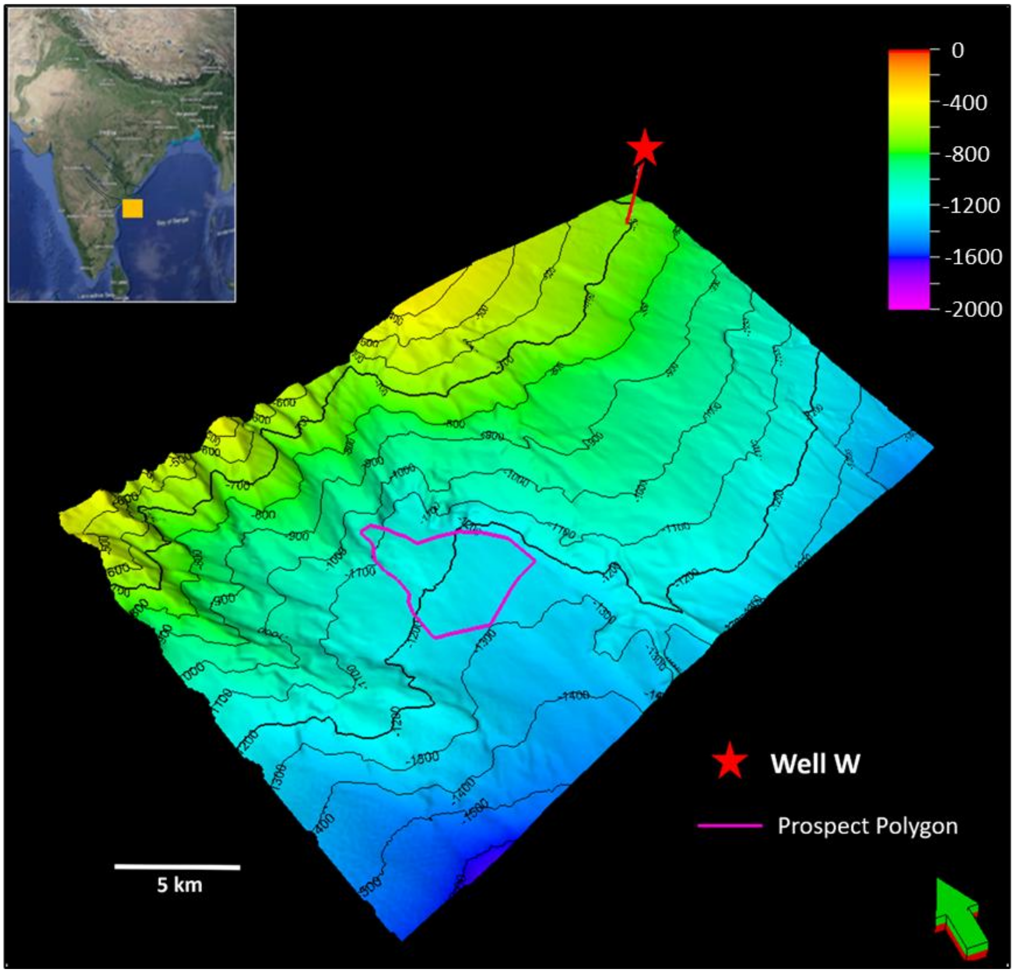

Figure 1: Block location along with seismic data conditioning area, the offset well and prospect polygon.

METHODOLOGY

The current study employs a four-stage methodology involving rock physics modelling, seismic data conditioning, AVO analysis and seismic inversion. The workflow adopted is tabulated below (Figure 3).

WELL-BASED ROCK PHYSICS ANALYSIS

The study area includes an offset well W, that penetrates both Pliocene and Miocene reservoir intervals. Detailed analysis of the well data, including lithology, petrophysical properties, and fluid indicator was conducted to gain insights into reservoir characteristics.

Offset well W was analysed to understand the elastic behaviour of gas sands. The well penetrated hydrocarbon reservoir in the Pliocene and Miocene intervals. The elastic logs show a distinct decrease in P-impedance and V_P/V_S at the top of the gas sand, indicating a gas effect (Figure 4).

ROCK PHYSICS AND FLUID SUBSTITUTION

Rock physics templates were constructed using elastic properties derived from well logs. Given the presence of

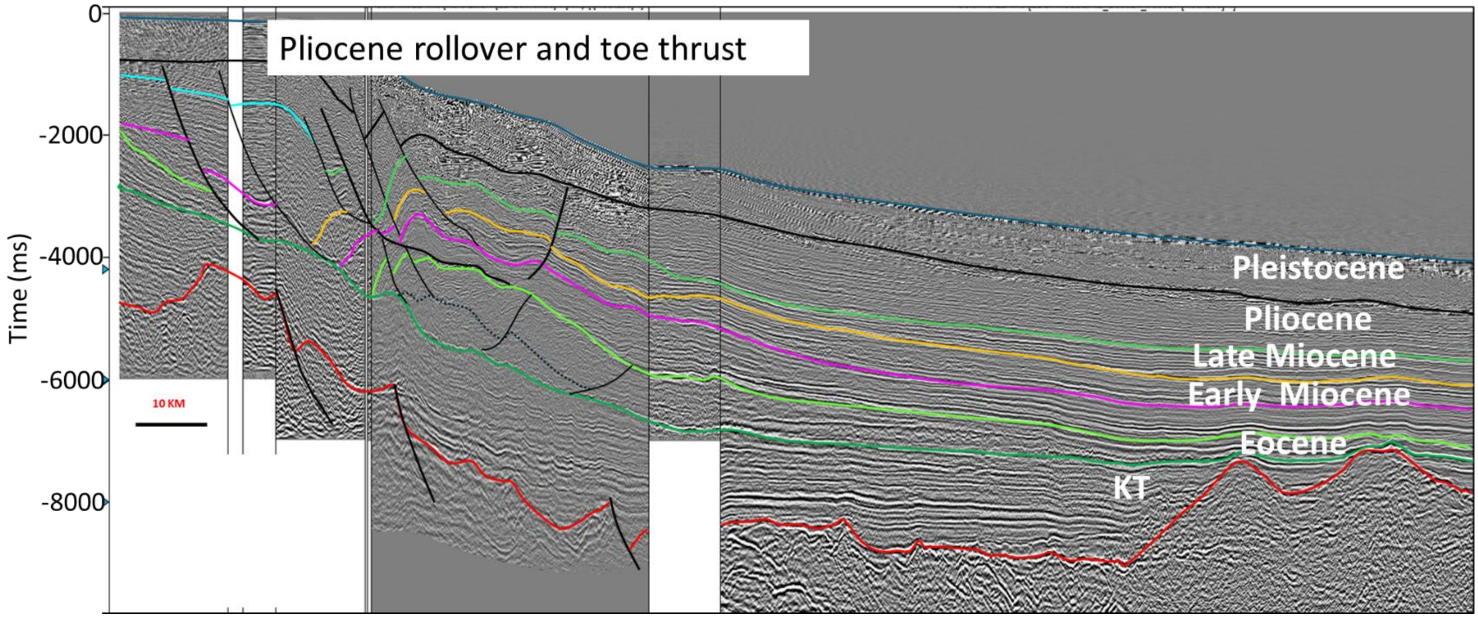

***Figure** 2: Seismic transect showing the depositional features in the block area including Pliocene rollover and toe thrust*

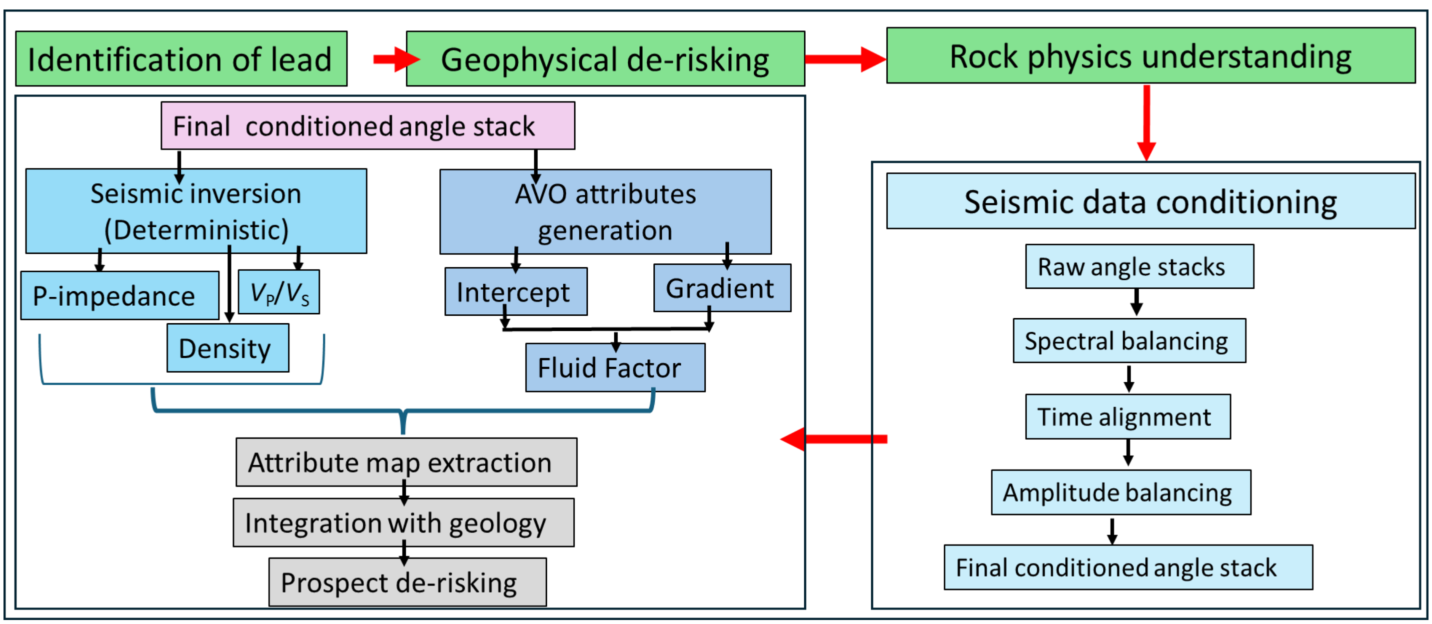

***Figure 3:** Adopted workflow for the study.*

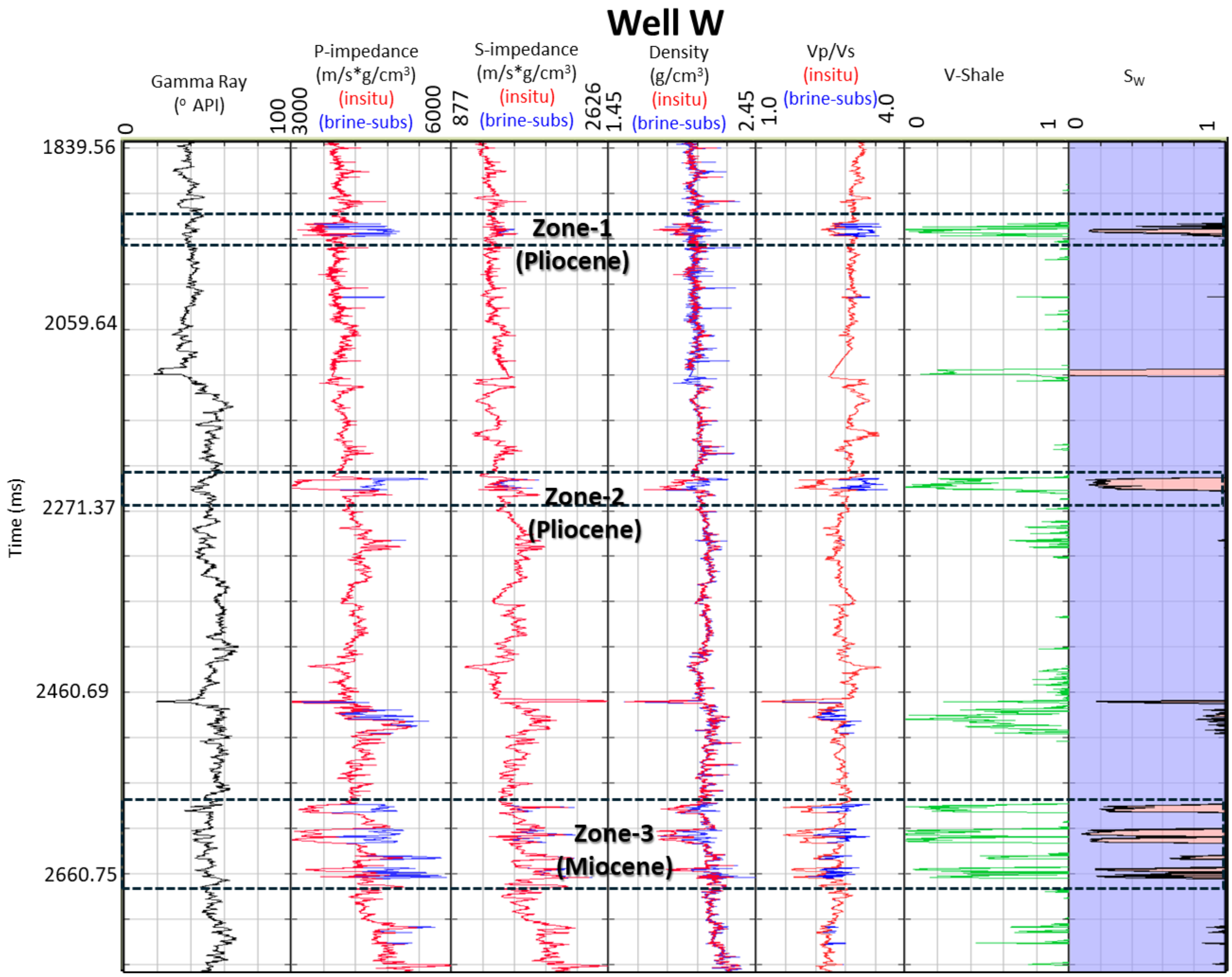

Figure 4: *Log behaviour across gas sands*

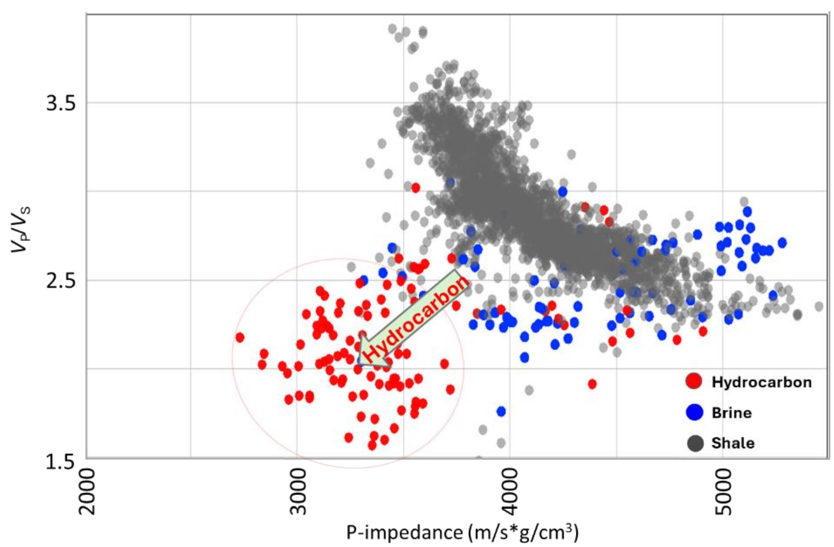

Figure 5: *Cross-plot of P-Impedance versus V_P/V_S, colour-coded by lithology showing separation of gas sands from background.*

thin brine sand layers in the well, fluid substitution modelling was carried out using Biot-Gassmann theory (Biot, 1956) to simulate various fluid saturation scenarios. This approach enabled a clearer understanding of the AVO response differences between gas sands, brine sands and shales.

To visualize these effects, cross-plots of P-impedance (Ip) versus V_P/V_S ratio were generated and color-coded by lithology (Figure 5). The plots revealed that gas sands form a distinct cluster, deviating from the background trend due to their lower density and compressional velocity characteristics. In contrast, brine sands showed significant overlap with the shale trend, resulting a clear discrimination of hydrocarbons against background shales and brine reservoirs.

Additionally, detailed AVO analysis was conducted at well W to evaluate the seismic responses of both gas-bearing and brine-substituted reservoirs. This investigation offered valuable insights into the distinct AVO behaviours exhibited by different reservoir types across the Pliocene and Miocene intervals. Gas sands displayed characteristic AVO anomalies, typically Class III responses in the Pliocene and Class II in the Miocene, indicating strong amplitude variations with offset, which are diagnostic of hydrocarbon presence.

In contrast, brine-substituted sands exhibited more subdued AVO signatures, often aligning closely with background trends and lacking the pronounced offset-dependent amplitude changes observed in gas-bearing intervals. These differences in AVO behaviour were instrumental in refining reservoir interpretation and improving the predictive accuracy of hydrocarbon indicators in the seismic data.

Once the rock physics and AVO modelling study yielded encouraging results of lithology and fluid discrimination at well log scale, the next step involved the conditioning of seismic data and assessing lithology and fluid discrimination in seismic scale. Comprehensive seismic data quality control and conditioning were performed to ensure the dataset was suitable for AVO analysis and subsequent reservoir characterization.

SEISMIC DATA QC AND CONDITIONING

The legacy seismic dataset was reprocessed using Pre-Stack Depth Migration (PSDM) employing an advanced and updated reprocessing workflow. Following this, in-house seismic conditioning was applied to further enhance the quality of the data. Key conditioning steps included spectral enhancement, time alignment, and amplitude balancing, each aimed at optimizing the dataset for AVO analysis and detailed seismic reservoir characterization.

Spectral balancing was the initial step to equalize the frequency and phase content across angle stacks. As this step may slightly alter the timing of seismic events, requiring subsequent time alignment of angle stacks. The time alignment step ensured consistent event positioning across all angle stacks (near, 5 to15 deg, mid,15_to 25 deg, far, 25_to 35 deg and ultra-far, 35_to 45 deg). Finally, amplitude normalization was applied to correct for offset-related amplitude variations and acquisition imprints. These enhancements ensured that the seismic data was suitable for identifying subtle stratigraphic features, evaluating fluid content, and improving the accuracy of reservoir property predictions (Kemper et al., 2010).

To clearly demonstrate the benefits, a comparative approach was adopted, contrasting unconditioned and conditioned datasets. The unconditioned stacks showed a noticeable reduction in background amplitudes with increasing offset, which can obscure true AVO responses and lead to misinterpretation of reservoir properties (Figure 6).

The conditioning workflow successfully corrected offset-dependent amplitude decay while preserving true amplitude variations. This significantly improved the dataset's reliability for AVO analysis, fluid discrimination and lithology prediction (Figure 7). A comparison of the frequency spectra between the unconditioned and conditioned seismic datasets demonstrates a marked improvement in spectral alignment following conditioning. The unconditioned data shows spectral irregularities, particularly with significant attenuation of higher frequencies in the amplitude spectrum (Figure 8). Such spectral misalignment can compromise resolution and introduce interpretational uncertainties. In contrast, the conditioned dataset exhibits a more consistent and

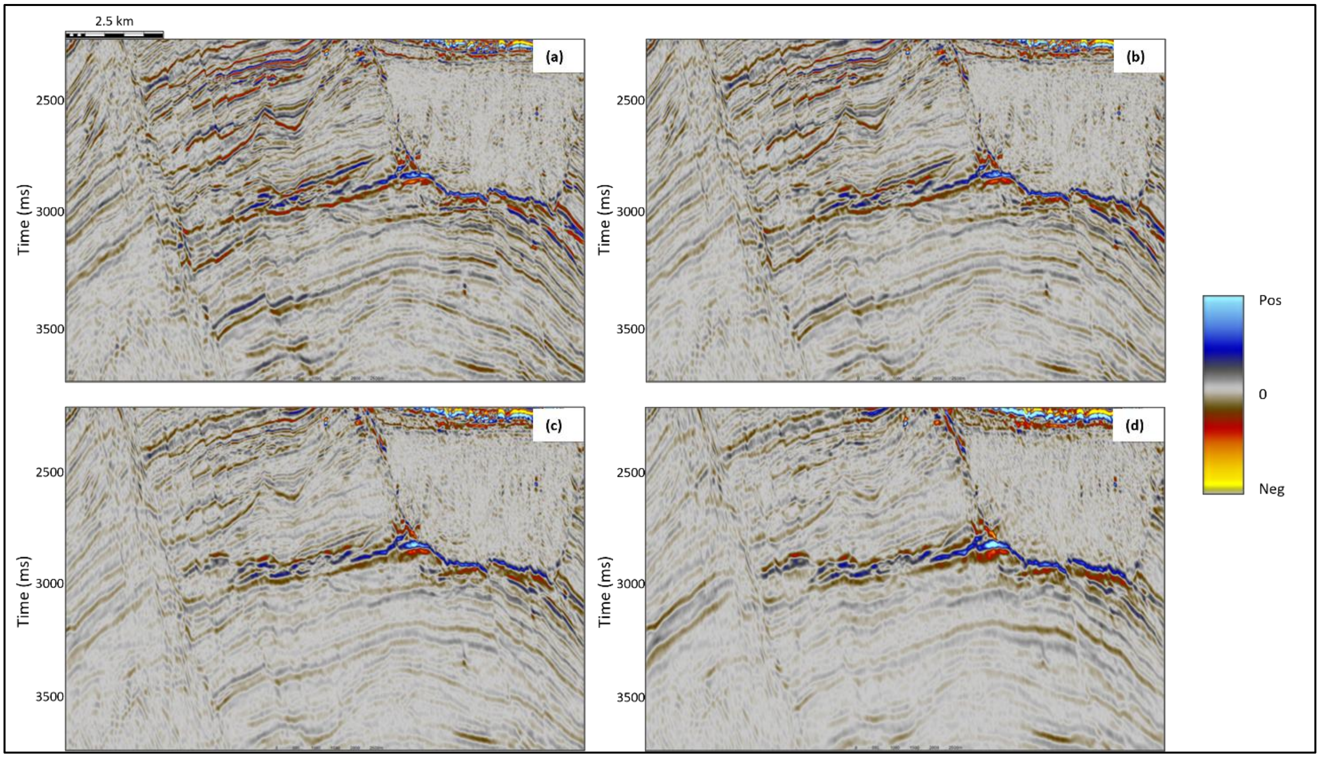

Figure 6: Segments of sections from (a) near- (5 to 15 deg), (b) mid-(15 to 25 deg), (c) far-(25 to 35 deg), and (d) ultra-far-(35 to 45 deg) unconditioned angle stacks. Background amplitudes are seen to diminish in going from near- to ultra-far angle stacks.

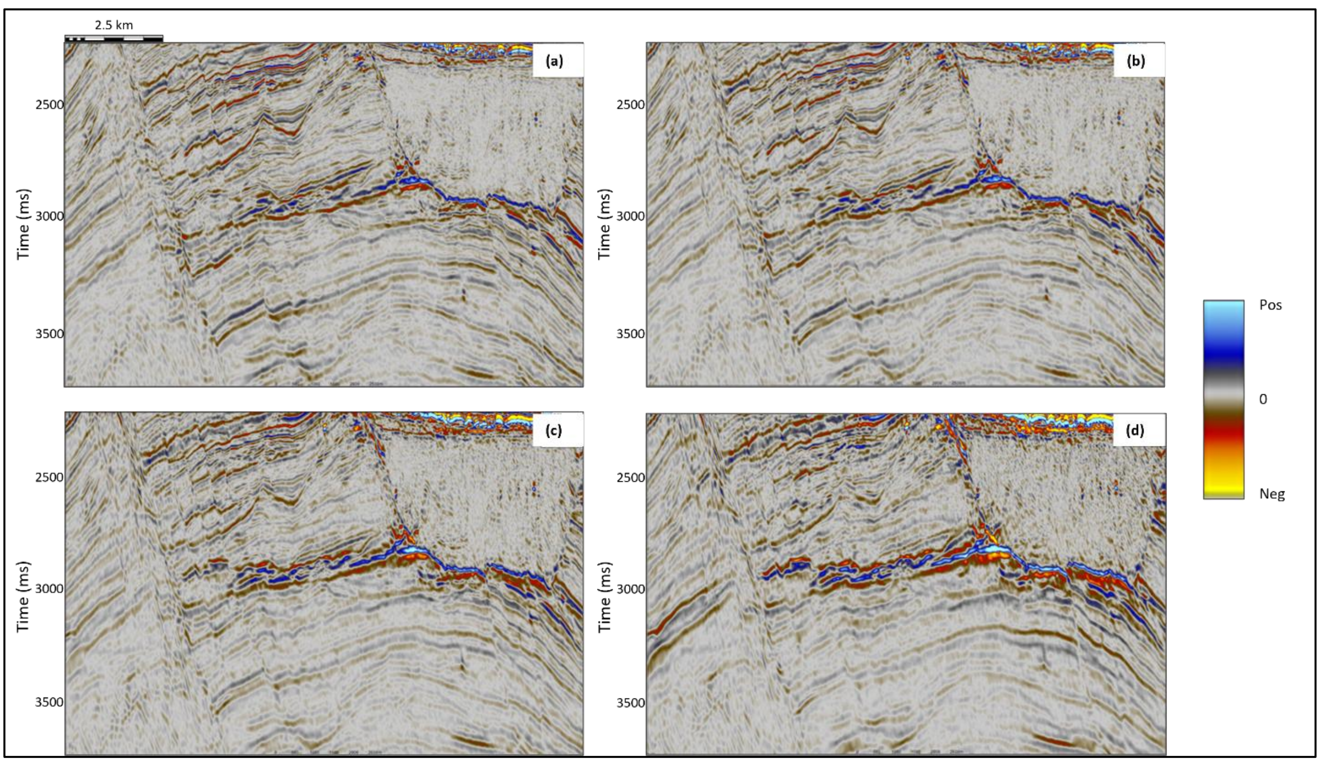

Figure 7: Segments of sections from (a) near- (5 to 15 deg), (b) mid- (15 to 25 deg), (c) far- (25 to 35 deg), and (d) ultra-far- (35 to 45 deg) unconditioned angle stacks. Background amplitudes are balanced in going from near- to ultra-far angle stacks.

balanced frequency distribution across the bandwidth, reflecting effective preservation and enhancement of key frequency components. (Figure 9). The improved spectral coherence in the conditioned data enhances the resolution and reliability of seismic attributes, making it more suitable for detailed reservoir characterization and inversion workflows.

A comparative analysis of difference volumes between near- and ultra-far angle stacks from both unconditioned and conditioned seismic datasets highlights distinct contrasts. In the unconditioned data, the difference volume is characterized by numerous seismic artifacts, including persistent background amplitudes that can obscure genuine subsurface anomalies (Figure 10). In contrast, the conditioned dataset shows effective suppression of background amplitudes, allowing true amplitude anomalies to emerge more clearly (Figure 11). This improvement enhances the visibility of potential hydrocarbon indicators and facilitates more accurate AVO analysis by isolating meaningful seismic responses from noise and background clutter (Yu et al., 2018).

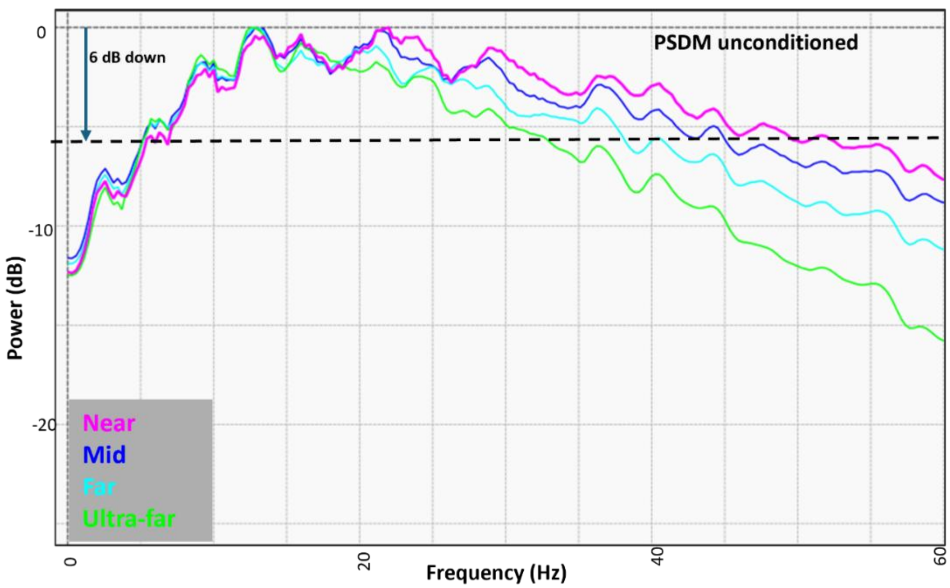

Figure 8: Frequency spectra from near to far stacks in unconditioned data showing a gradual decrease of frequency from near to far stacks.

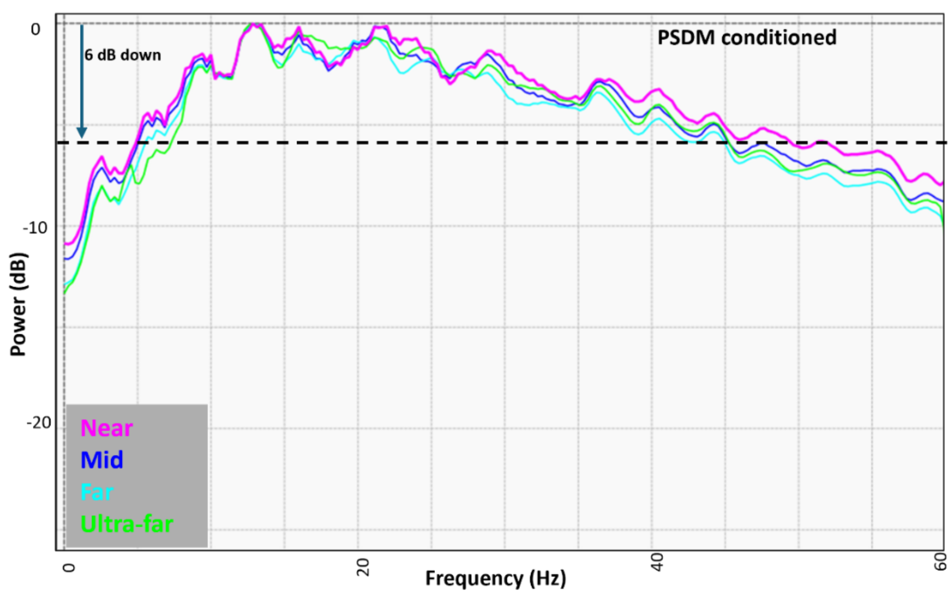

Figure 9: Frequency spectra from near to far stacks in conditioned data showing a balanced frequency distribution.

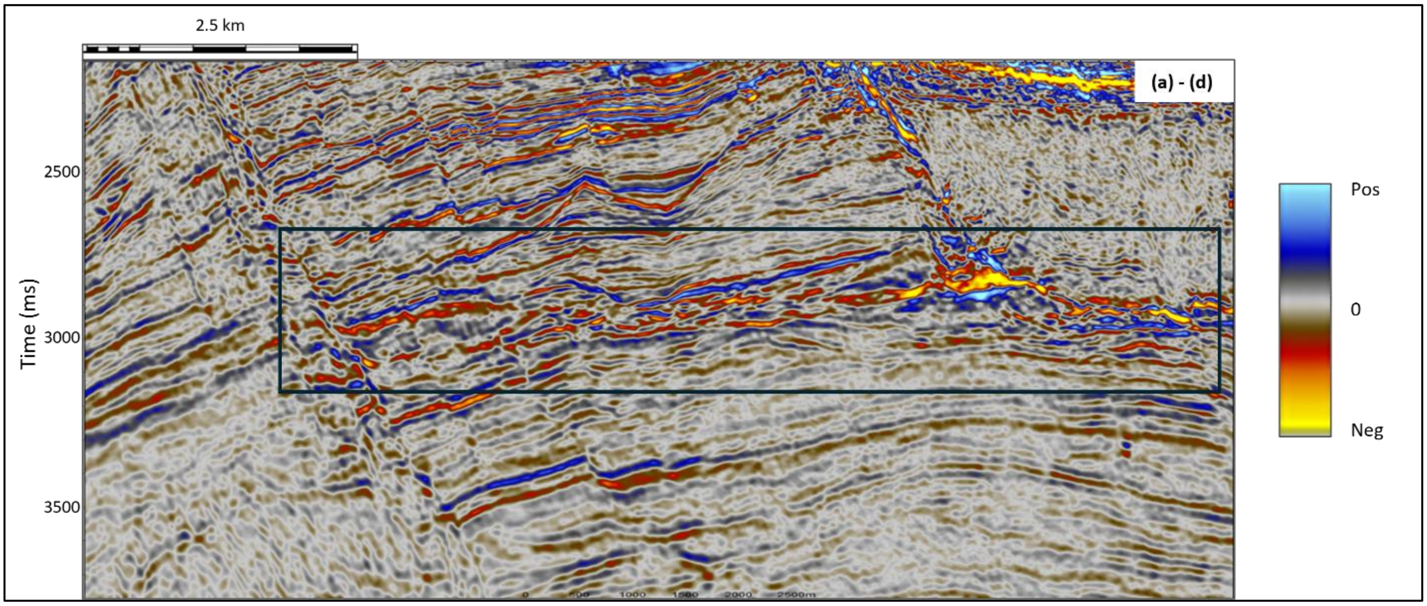

Figure 10: Difference volume between (a) near- (5 to15 deg), and (d) ultra-far-(35 to 45 deg) in unconditioned data contains numerous seismic signatures including background amplitude along with anomalies distribution.

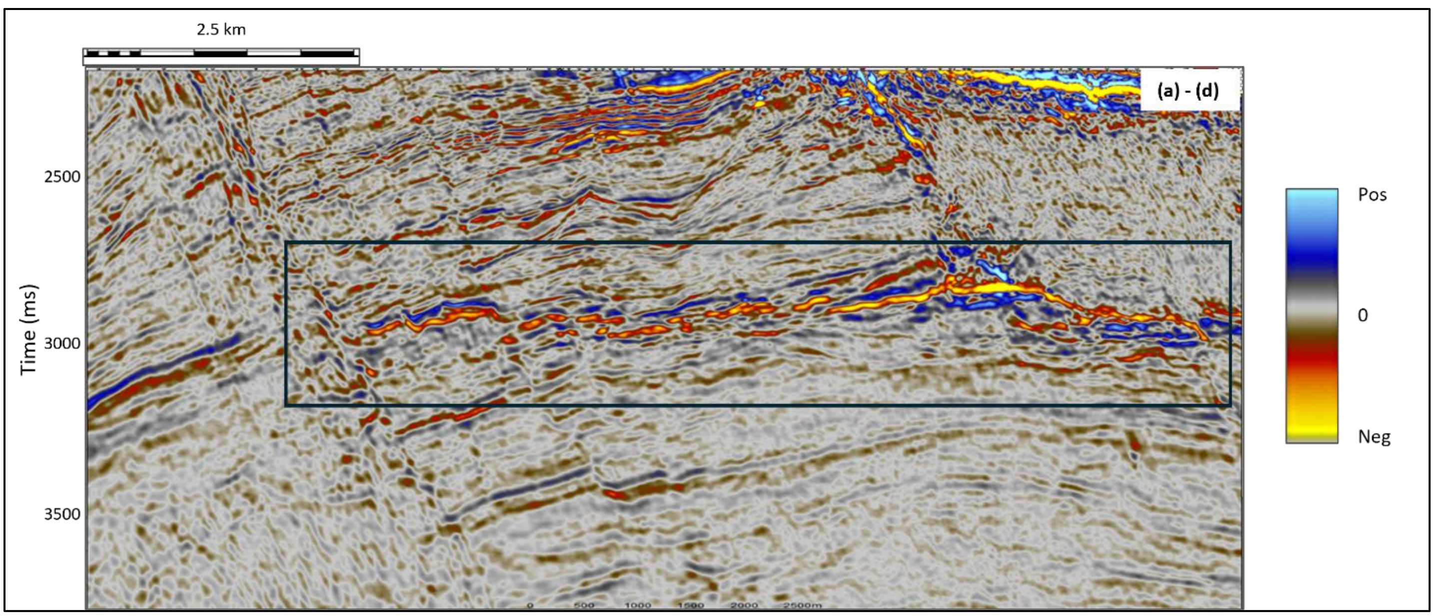

Figure 11: Difference volume between (a near- (5 to15 deg), and (d) ultra-far-(35 to 45 deg) in conditioned data showing the true amplitude anomalies to stand out more distinctly (as shown by rectangle).

Calibration of seismic gathers using well-based synthetic gathers

Calibration of seismic gather data using well-based synthetic gathers was done to better explain the observed amplitude anomalies and enhance reservoir characterization The conditioned seismic data demonstrated an AVO response that closely aligned with the synthetic AVO model derived from well W (Figure 12). This consistency in gradient behaviour across offset angles indicates that the conditioning process effectively preserved true amplitude variations and improved data fidelity. The strong correlation between the real and synthetic AVO responses validates the reliability of the seismic dataset for reservoir characterization and confirms the presence of coherent lithological and fluid-related signatures. Such alignment is critical for building confidence in seismic interpretation and for predicting reservoir properties beyond the vicinity of well control.

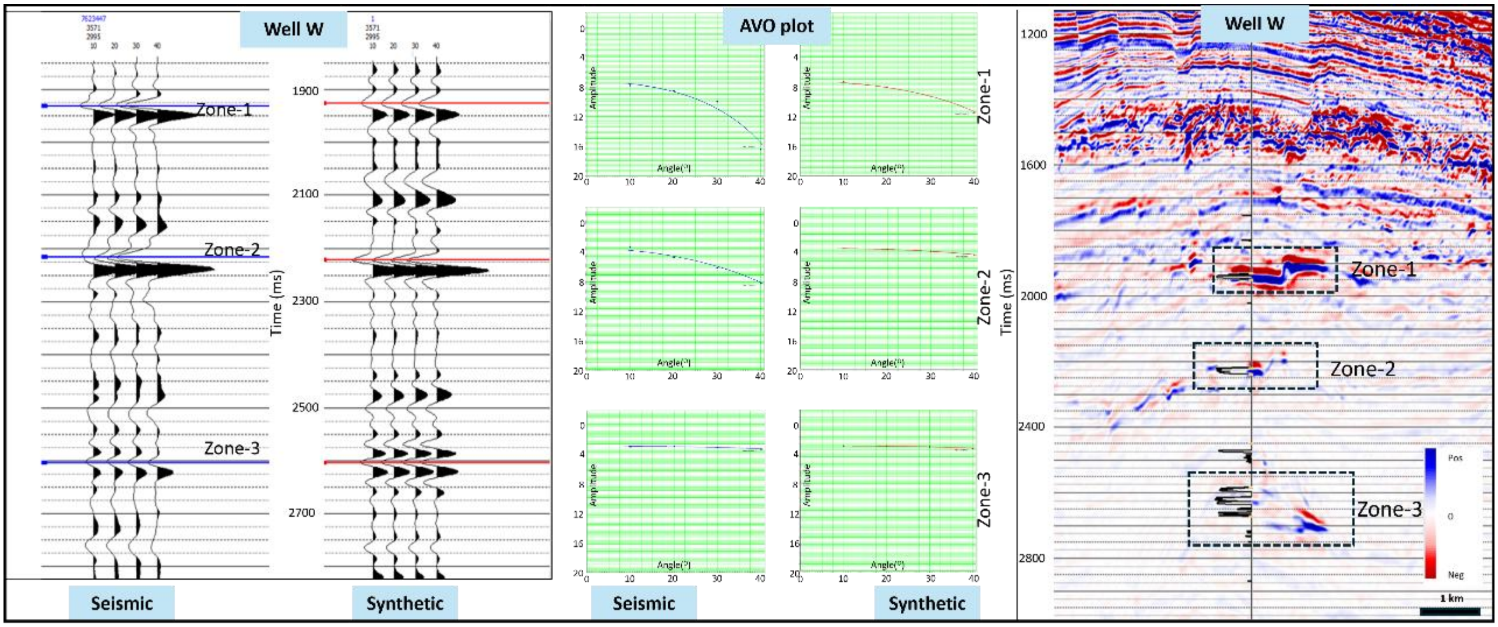

Figure 12: Conditioned seismic shows similar gradient in the AVO response to that of synthetic in the drilled well.

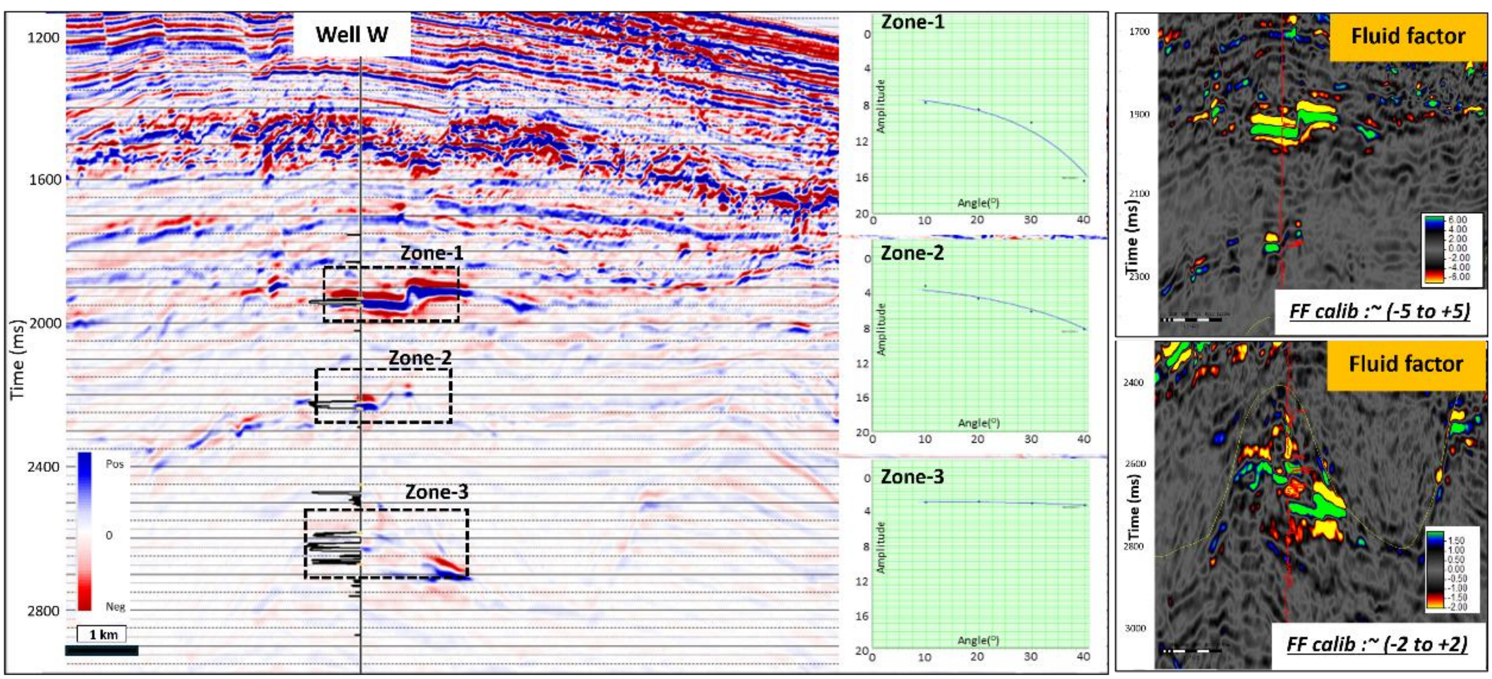

Figure 13: Gradient response diminishes from shallower to deeper reservoirs in AVO plot thereby suggesting different fluid factor calibrations.

AVO ANALYSIS AND FLUID FACTOR VOLUME

Integrating the conditioned seismic data and offset well information fluid factor volume was generated for the identified reservoir cluster. The fluid factor attribute was calibrated to well data and used to delineate hydrocarbon-bearing sands (Figure 13).

The fluid factor volume effectively highlights variations in fluid content within the reservoir, enabling the differentiation of hydrocarbon-bearing sands from water-saturated zones. This integration provided a more accurate and spatially continuous interpretation of fluid distribution, significantly enhancing confidence in identifying prospective hydrocarbon zones (Figure 14).

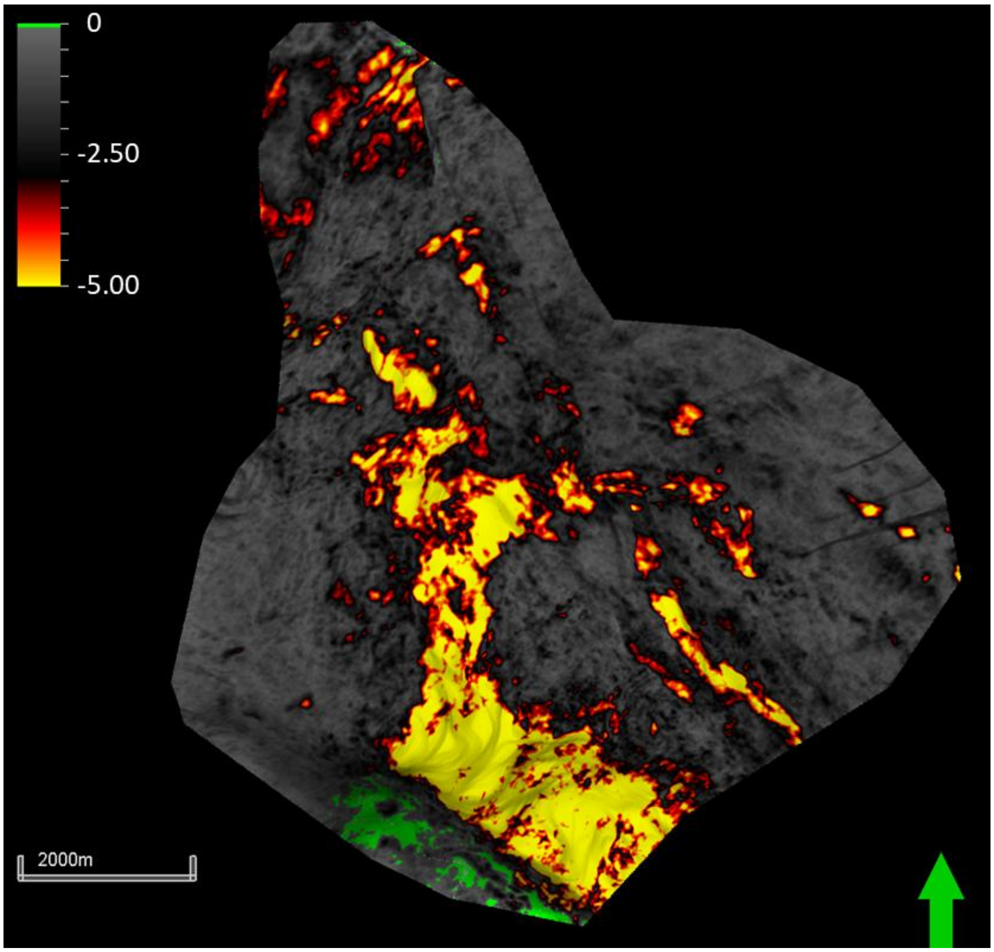

Figure 14: Hydrocarbon sand body well identified in fluid factor volume.

SEISMIC INVERSION

Building upon the AVO analysis and the generation of the Fluid Factor volume, seismic inversion was undertaken to further characterize the reservoir. A simultaneous angle-dependent inversion approach was employed to transform the conditioned seismic data into elastic property volumes that are diagnostic of the target reservoirs. Four partial angle stacks, near-(5 to15 deg), mid-(15 to 25 deg), far-(25 to 35 deg), and ultra-far- (35 to 45 deg) extracted from the PSDM-conditioned dataset were utilized in the inversion process.

Using the time-depth (TD) relationship at offset well W, angle-dependent wavelets were estimated within the zone of interest through a deterministic technique. Well log data, including P-sonic, S-sonic, and density logs, were integrated with the seismic partial angle stacks to derive wavelets for each angle stack. Wavelets were individually estimated for each stack, and their consistency in terms of frequency content and phase characteristics was thoroughly analysed.

With optimized inversion parameters and the estimated angle-dependent wavelets, all partial angle stacks were simultaneously inverted to generate volumes of P-Impedance, V_P/V_S ratio, and Density. The inversion analysis indicates that the pay sands are typically characterized by low P-Impedance (AI) and distinctly low V_P/V_S ratios, both of which are diagnostic attributes associated with hydrocarbon-bearing zones. To enhance reservoir delineation, a derived volume was computed as the product of P-Impedance and V_P/V_S ratio (AI × V_P/V_S). This composite attribute effectively accentuates the gas sand response while suppressing the background lithological variations, thereby providing improved reservoir characterization (Figure 15).

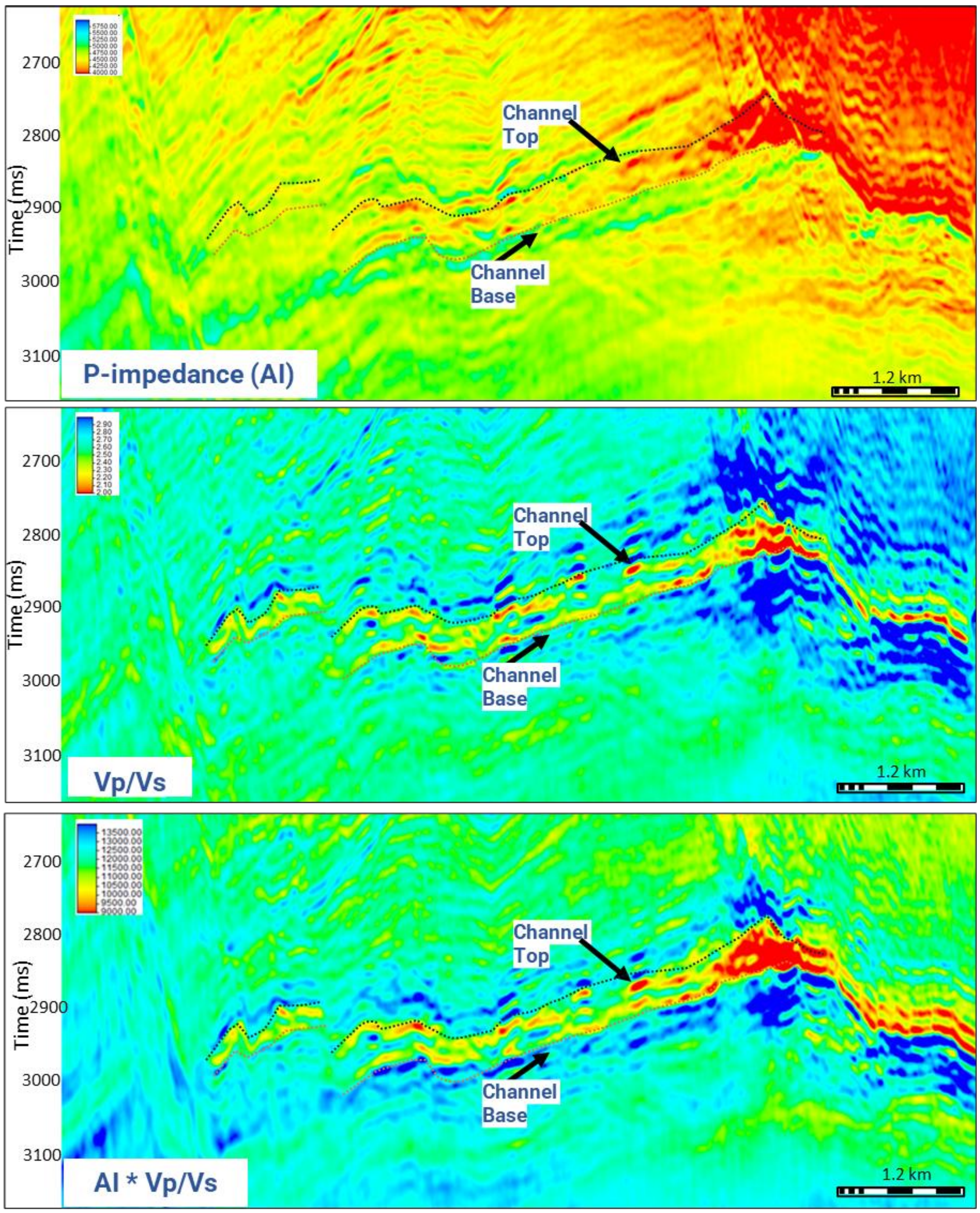

***Figure 15**: Hydrocarbon sands are characterised by low P-impedance and distinctly low V_P/V_S. Composite attribute (AI* V_P/V_S) enhances the seismic response of gas-bearing sands by amplifying reservoir-specific anomalies.*

These inverted volumes were subsequently analysed for geo-body extraction and detailed reservoir characterization, providing valuable insights into the spatial distribution and properties of the reservoir units (Figure 16). This workflow not only enhanced the interpretability of seismic data but also strengthened the predictive capability for reservoir properties away from well control.

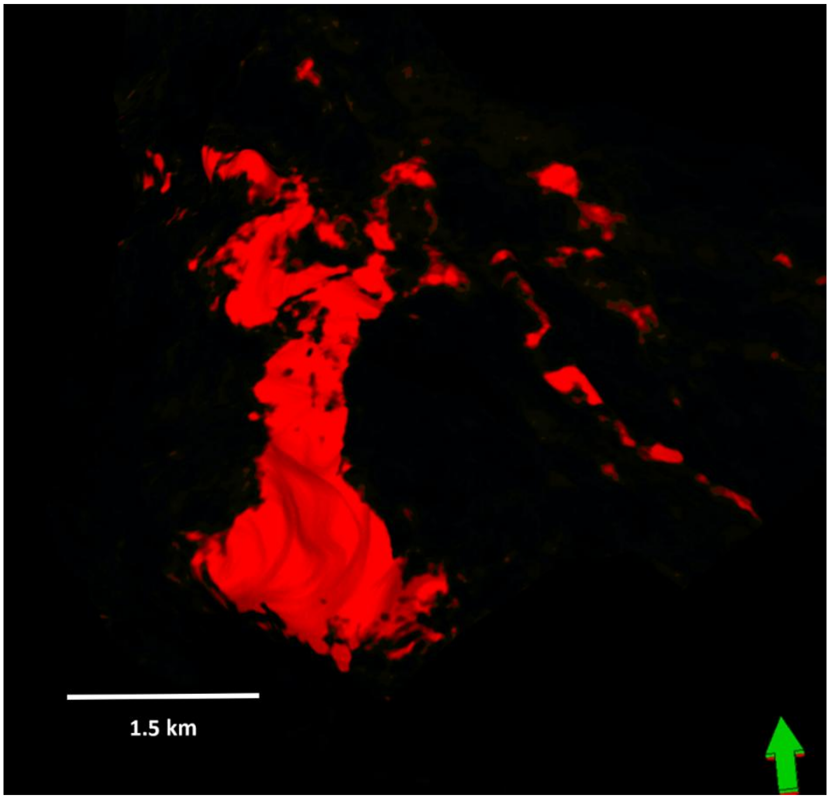

***Figure 16**: Spatial distribution of geobody from inversion attribute.*

CONCLUSIONS

This study demonstrates the effectiveness of integrating rock physics analysis, seismic conditioning, AVO attribute analysis and seismic inversion. The rock physics cross plots revealed clear discrimination of hydrocarbons sands against background shale and brine reservoirs. The cluster characterized by low P-Impedance and low V_P/V_S ratio in the cross plot revealed hydrocarbon anomalies. The conditioned seismic dataset enabled in balancing all angle stacks and generating a reliable AVO response, which, when correlated with offset well W, provided valuable insights into lithological and fluid-related variations.

The fluid factor volume, derived from the conditioned data, proved instrumental in highlighting prospective hydrocarbon zones, thereby supporting risk reduction in exploration and guiding future drilling decisions. To further refine reservoir understanding, simultaneous angle-dependent seismic inversion was performed using four partial angle stacks. This process yielded volumes of P-Impedance, V_P/V_S, and Density, which facilitated improved delineation of reservoir morphology and supported geo-body extraction.

The integrated workflow—from seismic conditioning and AVO analysis to inversion and attribute calibration, has not only sharpened geological understanding of the target zones but also established a high-confidence interpretive framework. This foundation enables more strategic exploration decisions today and paves the way for predictive reservoir modelling, optimized drilling, and future development planning with reduced subsurface risk.

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REFERENCES

Bastia, R., P. K. Nayak, 2006, Tectonostratigraphy and depositional patterns in Krishna Offshore Basin, Bay of Bengal, The Leading Edge, **25**(7), 839-845. https://doi.org/10.1190/1.2221361

Biot, M. A., 1956a, Theory of propagation of elastic waves in a fluid saturated porous solid. I-Low frequency range: J. Acoust. Soc. Am., **28**(2), 168-178. https://doi.org/10.1121/1.1908239

- 1956b, Theory of propagation of elastic waves in a fluid saturated porous solid. II-Higher frequency range: J. Acoust. Soc. Am.; **28**(2), 179-191. https://doi.org/10.1121/1.1908241

Castagna, J. P., M. L. Batzle, and R. L. Eastwood, 1985, Relationships between compressional-wave and shear-wave velocities in clastic silicate rocks, Geophysics; **50**(4), 571-581.https://doi.org/10.1190/1.1441933

Gupta, S. K., 2006, Basin architecture and petroleum system of Krishna Godavari Basin, East coast of India, The Leading Edge, **25**(7), 830-837. https://doi.org/10.1190/1.2221360

Kemper, M., E. Efthymiou, H. Morris, and J. D. Kerr, 2010, Seismic data conditioning of partial stacks for AVO – Using well offset amplitude balancing, 72nd EAGE Conference and Exhibition incorporating SPE EUROPEC 2010. https://doi.org/10.3997/2214-4609.201401188

Smith, G. C., and P. M. Gidlow, 1987, Weighted stacking for rock property estimation and detection of gas, Geophysical Prospecting, **35**(9), 993–1014. https://doi.org/10.1111/j.1365-2478.1987.tb00856.x

Yu, G., Y. Zhang, X. Wang,X. Liang, B. Liu, S. Singleton, and M. Smith, 2018, Seismic data gather conditioning for prestack seismic data inversion, International Geophysical Conference, Beijing, China, April 24–27, 2018. https://doi.org/10.1190/igc2018-118

BIOGRAPHIES

Som Subhra Banerjee is a highly experienced geophysicist with over two decades of expertise in seismic reservoir characterization and field development planning, particularly in deep-water clastic environments across India. His career spans both E&P operators and service companies, where he has consistently delivered innovative geophysical solutions to enhance hydrocarbon recovery. Currently serving as Principal Exploration Geophysicist at Cairn Oil and Gas, he is working in a multidisciplinary team focused on integrating seismic interpretation, QI studies, inversion techniques, and rock physics to generate actionable subsurface insights. He plays a key role in exploration workflows, well trajectory optimization, and input to subsurface modeling, while also contributing to seismic processing and velocity modeling. He champions the adoption of advanced seismic technologies and ensures effective knowledge transfer within the team. His collaborative approach with asset teams helps refine drilling strategies and supports decision-making at internal and JV partner forums. He is an active member of SEG.

Shrijib Patra is a geophysicist with over 20 years of experience, specializing in seismic interpretation and possessing a robust QI background. His global experience spans multiple basins, having worked with industry leaders such as Royal Dutch Shell, Schlumberger, and Cairn. He has also served as a specialist geophysicist on the central technical excellence team at BG Group, UK (now part of Royal Dutch Shell), where he gained insights into cutting-edge technologies and their practical applications.

His exploration work has taken him to basins in India, the UK, Tanzania, Mozambique, Egypt, Myanmar, Australia, and Newfoundland. Presently, he leads the Deep-Water India Exploration team at Cairn India.

Shrijib maintains active memberships with SEG, EAGE, and AAPG, and has contributed to the field of geophysics with publications in various national and international journals.

Kondal Reddy is a well-rounded geophysicist with strong skills in quantitative seismic interpretation. He is currently working as a Chief Geophysicist at Cairn Oil and Gas, Vedanta Limited, where he leads the Geophysics Function.

Kondal earned his M. Tech. in geo-exploration from Indian Institute of Technology, Bombay (IITB) and joined Cairn in 2002. He has more than 22 years of experience in geophysics domain including seismic API, field development planning and reservoir monitoring. He is also skilled in quantitative seismic interpretation including rock physics, AVO, inversion, and 4D seismic. He contributed immensely to the exploration and development of oil and gas fields in KG Basin, Cambay, Assam, and Barmer basins.

Kondal is an active member of several professional organizations, including the Society of Exploration Geophysicists (SEG) and European Association of Geoscientists and Engineers (EAGE) and published many papers and abstracts in national and international conferences and journals.

Spectacularly folded and tilted sedimentary strata exposed in the Trans-Himalayan ranges of Ladakh.

(Photo Courtesy: Santosh Kumar Chatla and Subrata Singha)