

Estimating Vp/Vs in Middle East Carbonates: Insights from Rock Physics and Joint PP-PS Inversion

Introduction

Reliable Vp/Vs prediction is fundamental to fluid saturation mapping and oil–water contact delineation in carbonate reservoirs. Yet in offshore Abu Dhabi, complex pore geometries, diagenetic overprinting, and variable fluid distributions make Vp/Vs estimation from seismic data particularly challenging. The well dataset available for this study is representative of mature offshore carbonate fields: density logs are degraded by borehole washout and rugosity, sonic coverage is sparse or unreliable, and empirical log reconstruction alone proved insufficient to establish a physically consistent elastic framework. Rock-physics modelling was therefore adopted as the primary means of building a reliable log set for inversion calibration.

Conventional PP-wave AVO inversion has long been the default tool for seismic reservoir characterisation in the region. However, in carbonate settings, PP data alone often struggle to yield reliable Vp/Vs estimates: the AVO gradient is typically subtle, and the separation between P-impedance and Vp/Vs in the inversion is weak. The result is a Vp/Vs volume dominated by the prior model and carrying high uncertainty, which is insufficient for confident fluid discrimination. This study presents a workflow applied to a multicomponent Ocean Bottom Node (OBN) dataset acquired over an offshore Abu Dhabi carbonate field and demonstrates how rock-physics analysis combined with native-domain joint PP-PS inversion can directly address these limitations.

Rock Physics Analysis

The rock-physics study served two principal objectives: to build a physically consistent set of modelled elastic logs for inversion calibration, given the limited and uneven quality of the measured well data, and to define physically grounded Vp/Vs trends that account for both pore geometry and fluid content to constrain the inversion and guide interpretation.

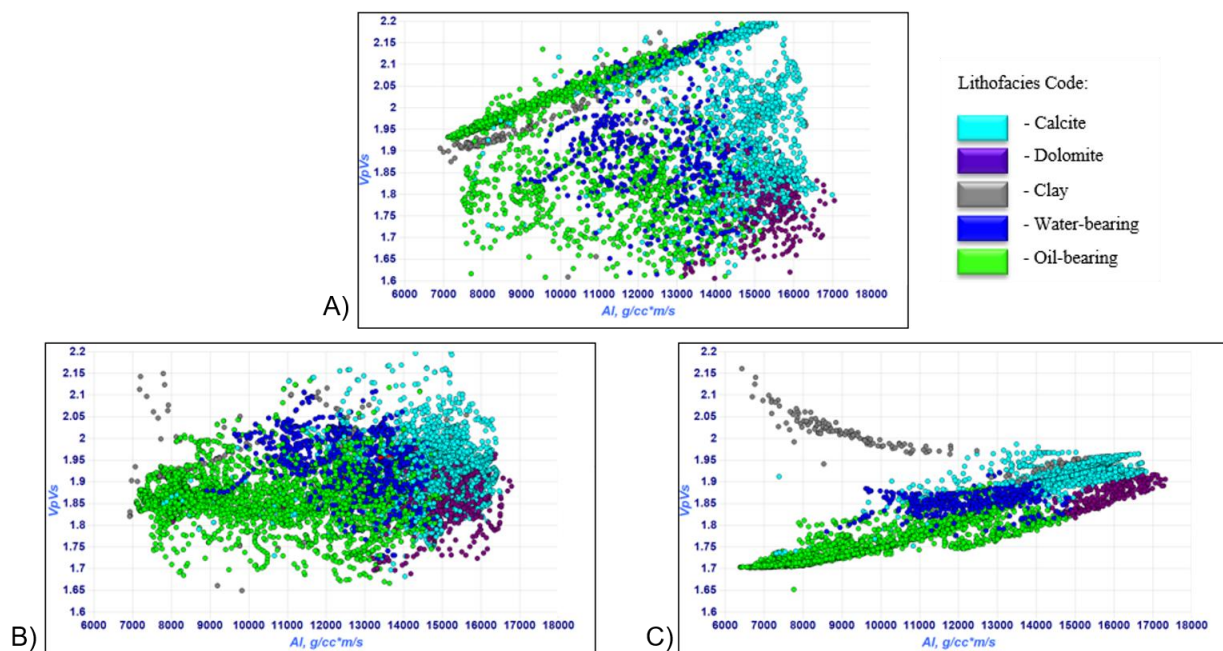


Figure 1 Vp/Vs versus acoustic impedance cross-plots with measured (A), corrected (B) and modelled (C) logs

Gassmann fluid substitution was applied under brine- and oil-saturated scenarios using petrophysical inputs from available wells. The Xu-Payne pore-type model was employed to represent the co-existence of stiff interparticle pores, compliant micro-fractures, and vuggy porosity characteristic of Abu Dhabi carbonates. These pore types exert contrasting influences on the bulk and shear moduli and cannot be adequately captured by generic empirical trends or elastic-derived relationships.

The calibrated model was validated against measured logs within intervals of sufficient quality, confirming good agreement and appropriate pore-type parameterisation for the given lithologies. A rock physics template (Avseth et al., 2005) on the V_p/V_s versus acoustic impedance crossplot defined the physically plausible fluid discrimination space, serving as both a quality filter for measured data and the prior constraint for inversion. Figure 1 illustrates the gradual improvement of separation between lithofacies after corrections and modelling in the acoustic impedance versus V_p/V_s crossplot. The outcome was a mutually consistent V_p , V_s , and density log set, physically anchored to lithology and fluid distribution, which provides reliable well control for all subsequent inversion steps.

Seismic Processing and PS Data Quality Considerations

The value delivered by joint PP–PS inversion is critically dependent on the quality of the PS data used in the inversion. In the shallow-water offshore Abu Dhabi setting, the multicomponent OBN PS data presented significant processing challenges. The presence of a hard seabed leads to the generation of strong multiples, whilst shallow karst bodies produce scattering noise. Coupled with the inherent sensitivity of PS imaging to velocity errors, this complex combination of factors required a tailored workflow response. The foundation for achieving high-quality joint inversion results was laid at the acquisition stage: the survey was designed with a high-density OBN geometry (approximately ten-thousand-fold coverage) specifically to optimise PP and PS data quality as input for joint inversion.

A hard seabed combined with high-contrast sedimentary layering generates strong short-period multiples that are difficult to separate from primary PS reflections. Mud-roll and guided wave noise further contaminate PS gathers at near offsets, while limited low-frequency signal and shallow diving wave penetration make velocity model building particularly challenging, requiring a robust starting model and a carefully tailored FWI strategy (Chen et al., 2025).

Shallow karst bodies and laterally variable carbonate facies in the overburden generate strong interbed multiples and scattering noise that degrade PS wavelet consistency across the survey. PS imaging is also inherently more sensitive than PP to velocity and anisotropy errors, as the asymmetric mode-conversion ray paths can cause conversion point mispositioning and residual moveout that directly bias AVA information (Kopytov et al., 2025). Therefore, joint use of PP and PS data in velocity model building was essential with each wavefield providing complementary constraints that improved the robustness of the final models.

A dedicated processing sequence targeting free-surface multiples (Domont et al., 2025), amplitude balancing, residual moveout correction, and bandwidth extension, was applied iteratively, which achieved approximately five octaves of usable PS signal bandwidth, in a comparable range of the PP data with wavelet stability monitored through well-tie and deterministic wavelet estimation QC at each stage. Figure 2 demonstrates the evolution of the deterministic PS wavelets before and after the inversion preconditioning stage. The horizon registration derived from PP-PS time-domain alignment was used to build the initial model for the joint inversion, providing a spatially consistent V_p/V_s prior that reflects the true kinematic relationship between the two wavefields. Close integration of seismic processing and reservoir characterisation teams throughout the full workflow was instrumental in ensuring that the PS data contributed positively to the joint result. Feedback from 1D modelling QC at wells guided remaining PS processing decisions, which ensured wavelet instabilities were resolved before the full 3D inversion was run.

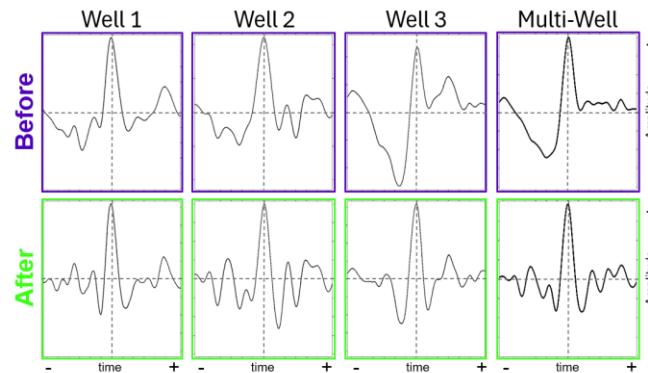


Figure 2 Comparison of deterministic PS wavelets estimated before (above) and after (below) inversion preconditioning, demonstrating improved wavelet symmetry, bandwidth, and side-lobe reduction — confirming the improvement in amplitude and phase fidelity delivered to the inversion.

Limitations of PP-Only AVO Seismic Inversion

Pre-stack simultaneous PP AVO inversion was first performed as a baseline, using angle-stack data derived from the PP OBN. In carbonates, the PP AVO response is typically characterised by negligible amplitude gradients with low sensitivity to V_s (Li and Downton, 2000). The rock physics study confirmed that the expected V_p/V_s contrast between brine- and oil-saturated zones in this field is modest. This makes reliable V_p/V_s estimation from PP AVO alone highly unreliable in this carbonate setting.

The PP-only result illustrates the behaviour typically observed in such settings: the inverted V_p/V_s is systematically too high, spectrally unstable, and poorly correlated with the well log. This reflects a solution dominated by the low-frequency prior model rather than by data-driven shear information. Additionally, this motivates the incorporation of PS data as an independent and direct constraint on S-impedance.

Native-Domain Joint PP-PS Inversion

Unlike conventional registration-based approaches — which contaminate amplitude information through the warping process and conflate the travel-time difference between PP and PS wavefields with the inversion solution — the native-domain method preserves independent time axes for each wavefield component within the stratigraphic inversion grid (Roure et al., 2015).

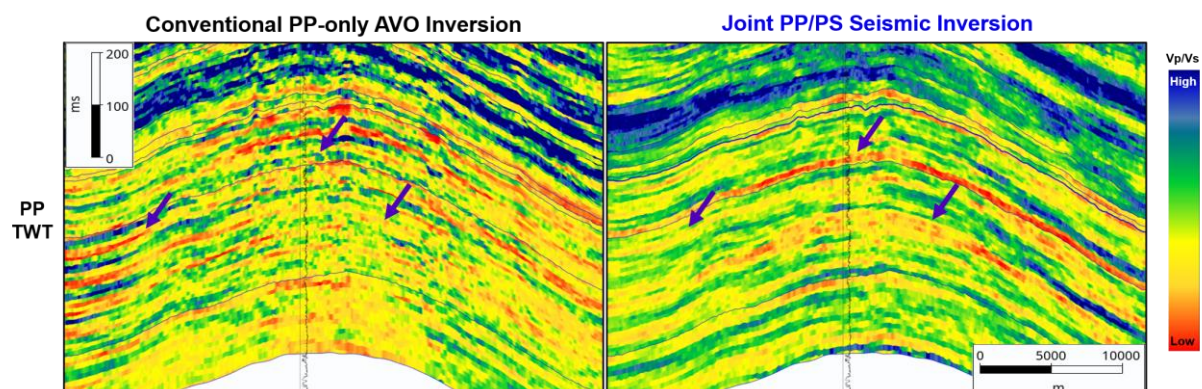


Figure 3 2D section of the inverted V_p/V_s ratio comparing conventional PP-only AVO inversion (left) versus joint PP-PS inversion (right), demonstrating higher lateral continuity, improved signal-to-noise

ratio, and more geologically consistent results in the joint inversion result. A decrease of V_p/V_s is a possible indicator of hydrocarbon presence.

In the native-domain approach, PP and PS data are inverted simultaneously in their respective natural time domains. Figure 3 illustrates the improvement in V_p/V_s recovery achieved by the joint inversion relative to the PP-only AVO reference. A joint cost function, constrained on both amplitude and travel-time components, is minimised through simulated annealing to solve simultaneously for P-velocity, S-velocity, and density. The PS data thus contribute directly to anchoring the S-impedance solution, reducing the ambiguity that limits PP-only in carbonate settings.

Conclusions

This study demonstrates that where measured elastic logs are of insufficient quality for direct use, rock-physics modelling using the Xu-Payne framework delivers a physically consistent elastic log set for reliable inversion calibration. PP-only AVO inversion is fundamentally insufficient for V_p/V_s estimation in these carbonate settings, producing biased, high-uncertainty results. The quality of the joint inversion results was made possible by the combination of purpose-designed high-density OBN acquisition and a tailored processing workflow that delivered broadband PS data — both critical requirements for reliable joint inversion. Native-domain joint PP-PS inversion on OBN data delivers substantially improved V_p/V_s recovery, better well-log fidelity, and more geologically consistent fluid discrimination, reducing subsurface uncertainty and enabling more confident reservoir characterisation in complex offshore carbonate plays.

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