Advanced Q-FWI-Driven Imaging and Reprocessing in the Sarawak Basin, Offshore Malaysia

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Summary

The Sarawak Basin, located offshore East Malaysia, is a mature and highly prolific hydrocarbon province that continues to attract exploration and redevelopment interest. Despite decades of seismic acquisition and processing, persistent imaging challenges remain due to the shallow-marine environment, strong multiple contamination, complex structural styles, and laterally variable, highly attenuative overburden associated with shallow gas accumulations. These factors introduce significant uncertainty in reservoir delineation, fault interpretation, and amplitude reliability, ultimately increasing exploration and development risk.

This abstract presents a comprehensive reprocessing and imaging case study from the Sarawak 3D multiclient program, integrating newly acquired multi-streamer seismic data with adjacent legacy surveys. An advanced processing and velocity model building workflow was implemented, combining broadband data conditioning, state-of-the-art demultiple techniques, high-resolution full-waveform inversion (FWI), reflection tomography, and Q tomography. Particular emphasis is placed on the role of Q-FWI in refining velocity and attenuation models, enabling more accurate wavefield propagation in the presence of strong absorption and scattering effects.

The resulting velocity and Q models significantly improve seismic events focusing, faults continuity, and amplitude fidelity across the study area. Depth-migrated images show enhanced illumination beneath gas-affected zones, reduced structural ambiguity, and improved gather flatness compared with constant-Q imaging. The results demonstrate that the integration of high-frequency FWI and variable-Q depth migration provides a robust and scalable solution for addressing long-standing imaging challenges in shallow-water, structurally complex basins such as Sarawak. The workflow establishes a solid foundation for quantitative interpretation and supports future exploration and production optimization in the region.

Introduction

The offshore Sarawak Basin hosts numerous producing fields within Tertiary clastic and carbonate reservoirs. While exploration success has historically been high, the basin presents a set of persistent geophysical challenges that complicate seismic imaging and interpretation. These challenges are primarily driven by shallow-water acquisition conditions, strong free-surface-related multiples, complex faulted structural geometries, and heterogeneous near-surface conditions dominated by shallow gas and highly attenuative sediments.

Water depths across the study area range from approximately 80 to 160 m, placing the surveys firmly within a regime where multiples are particularly strong, thus challenging. In addition, the presence of shallow gas pockets introduces severe velocity distortions and absorption effects, leading to amplitude dimming, phase instability, and shadow zones in conventional seismic images. Legacy datasets processed with standard workflows often exhibit poor fault definition, residual moveout in depth gathers, and limited illumination beneath gas-charged zones.

To address these issues, a new Sarawak Phase 3 multiclient project was initiated, integrating modern acquisition technologies with advanced processing and imaging workflows. The primary objective of this study is to demonstrate how a fully integrated earth model building strategy, centered on high-resolution FWI and variable-Q imaging, can significantly reduce subsurface uncertainty and unlock additional geological insight from both new and legacy seismic data.

Acquisition

The study area covers approximately 2,812 km² of multisensor 3D seismic data acquired during two separate acquisition campaigns. The first survey, acquired in 2017, employed Compressive Seismic Imaging (CSI) acquisition configuration designed to enhance near-offset sampling and signal fidelity. The second survey, completed in 2023, utilized a triple-source acquisition geometry, providing improved azimuthal coverage and enhanced illumination of complex structures.

Both datasets were recorded using collocated hydrophone and particle-velocity sensors, enabling greater signal bandwidth and improved signal-to-noise. Given the different acquisition vintages and geometries, careful attention was paid to data regularization, amplitude balancing, and phase consistency to ensure seamless integration of the two surveys. An additional nearby dataset, processed with a comparable high-end workflow, was incorporated as migration aperture data to improve illumination near survey boundaries and to ensure amplitude consistency for subsequent quantitative interpretation.

Processing Workflow

Prior to imaging, all datasets underwent a comprehensive broadband processing sequence. Full deghosting was applied to remove receiver and source ghost effects, significantly extending the usable bandwidth at both low and high frequencies. This was followed by 3D designature to standardize the source wavelet across surveys and acquisition campaigns. The resulting broadband datasets provided an improved starting point for both demultiple processing and waveform inversion, particularly in the low-frequency range critical for FWI convergence.

Given the shallow-water setting, multiple attenuation was a critical component of the workflow. An advanced demultiple strategy was implemented, explicitly separating short- and long-period multiples and applying dedicated modeling and subtraction approaches for each component.

Short-period multiple prediction was performed using a SWIM-based approach (Lu *et al*., 2011; Oukili *et al*., 2015). In this method, deghosted seismic data were migrated to generate a detailed near-surface reflectivity model, which was then used to model the multiple energy that closely matches the kinematics and dynamics of the recorded multiples. This approach allowed the use of relatively mild subtraction parameters, reducing the risk of damaging primary reflections.

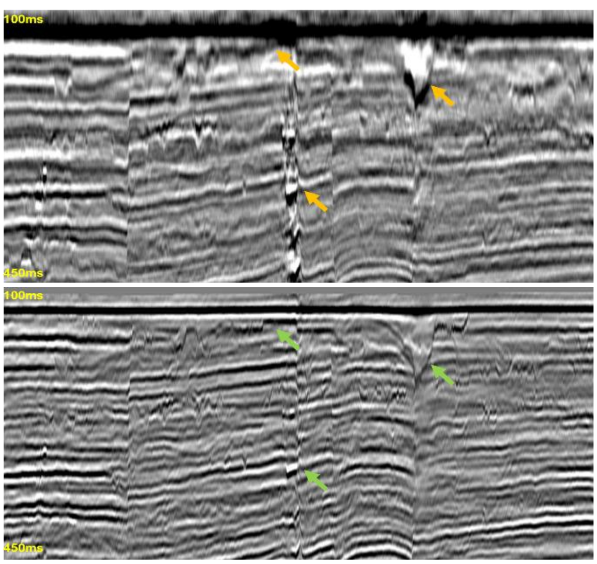

Figure 1: Near surface reflectivity cube generated through traditional Kirchhoff migration (top) and SWIM (bottom). SWIM clearly imaged shallow overburden significantly better (green arrows) as compared to traditional Kirchoff (orange arrows).

Figure 1 compares the reflectivity model generated using SWIM (bottom) with that obtained from a traditional imaging algorithm such as Kirchhoff (top). By leveraging the recorded multiple energy in the dataset, SWIM clearly provides a more detailed and higher-resolution image of the shallow events, as highlighted by the green arrows, compared with the Kirchhoff result (orange arrow). Some of these events act as multiple generators; therefore, their accurate representation within the reflectivity cube is critical for reliable multiple modelling.

Both short- and long-period multiple models were subsequently adaptively subtracted using a multi-model curvelet-domain approach with primary-preservation masking (Perrier *et al*., 2017). This strategy proved particularly effective in preserving complex primary energy associated with faulted and folded structures, while significantly reducing multiple-related noise.

Velocity Model Building and Full-Waveform Inversion

The initial velocity model was built from a smooth Dix interval velocity field (Dix, 1955) derived from a pre-stack time-migrated (PSTM) velocity analysis. This model provided a kinematically reasonable starting point but lacked the resolution required to accurately describe the complex overburden and shallow gas effects present in the area.

Full-waveform inversion was the primary driver for velocity model refinement. The inversion strategy followed a multi-scale, frequency-progressive approach, starting at 4 Hz and extending up to 24 Hz. The workflow was executed in two main stages.

In the first stage, both refracted and reflected energy were utilized over the full offset range under a constant-Q assumption. The objective of this stage was to establish a stable, low-wavenumber background velocity model capable of accurately predicting wavefield kinematics.

The second stage focused exclusively on reflected energy, with offsets limited to 5,000 m. At this stage, a spatially variable Q model was introduced, informed by intermediate velocity updates and geobody interpretation. This Q-FWI approach allowed simultaneous refinement of velocity and attenuation, leading to a more realistic representation of wave propagation in strongly absorptive zones.

Following FWI, both the velocity and Q models were further refined through a final pass of reflection tomography. This step ensured optimal gather flatness and consistency with the observed reflection data prior to final depth migration.

Q-KPSDM

Final imaging was performed using Q-Kirchhoff Pre-Stack Depth Migration (Q-KPSDM). The use of a variable-Q model during migration proved essential for correcting both kinematic and dynamic effects associated with attenuation. Compared with constant-Q migration, the variable-Q approach resulted in improved focusing, more balanced amplitudes, and enhanced continuity of deeper reflectors beneath gas-affected zones. Figure 1 shows final full stack in the depth domain overlaid on the final velocity model.

Results

The final depth-migrated images show a strong correlation with the refined velocity as illustrated in Figure 2. The image clearly reveals a high level of structural detail and geological accuracy. Fault planes are sharply imaged, with significantly reduced shadow zones compared with legacy results. Complex fault networks that were previously ambiguous are now clearly interpretable, supporting more confident structural mapping.

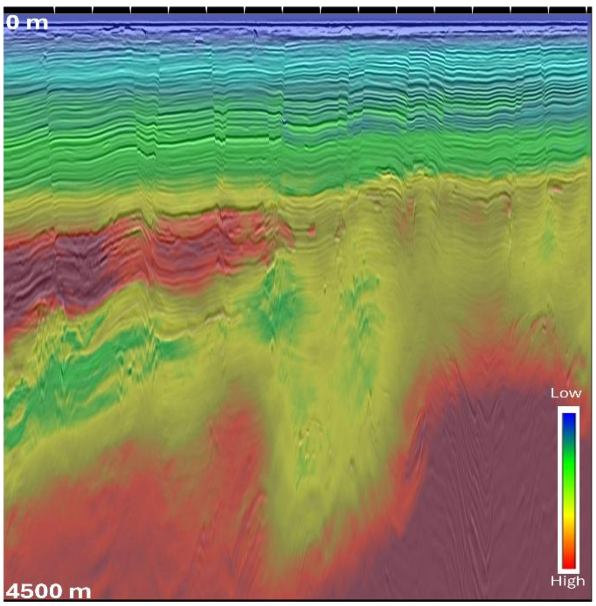

Figure 2: Final full stack in depth domain overlaid on the final velocity model. The color scale is adjusted highlight deeper structures.

A depth slice of the Q model from the shallow section is presented in Figure 3 (top), together with an RMS amplitude map computed within a 500 ms time window above the Cycle V event (Figure 3, bottom). The Q anomalies, observed in the image, vary between 20 and 45, significantly lower than the background value of approximately 125. The identified Q anomalies exhibit a strong spatial correlation with zones of low RMS amplitude observed beneath the accumulated gas anomalies

A direct comparison of migrated gathers and stacks using constant-Q and variable-Q models highlights the benefits of Q-FWI and Q-KPSDM. As shown in Figure 4, areas affected by strong shallow attenuation exhibit substantial uplift in both kinematic accuracy and amplitude consistency when the variable-Q model is applied. Notably, these improvements are achieved using the same velocity model, underscoring the critical role of attenuation compensation.

The results demonstrate that high-frequency FWI, when integrated with advanced demultiple workflows and variable-Q imaging, can effectively address many of the long-standing challenges associated with shallow-water seismic data. The improved velocity and Q models not only enhance structural imaging but also provide a more reliable basis for amplitude-sensitive applications such as AVO analysis and reservoir characterization.

The ability to update velocity and Q, using the described workflow, is particularly valuable in areas affected by shallow gas, where conventional velocity-only updates often fail to fully correct wavefield distortions. By explicitly accounting for attenuation, the proposed workflow delivers more physically consistent models and more interpretable seismic images.

Conclusions

This study demonstrates that both newly acquired and legacy seismic data in the Sarawak Basin can significantly benefit from a high-end, integrated imaging workflow centered on Q-FWI. The resulting velocity and attenuation models enable superior depth imaging, improved fault resolution, and enhanced illumination beneath gas-affected zones. The final seismic products outperform legacy results across the entire study area and provide a robust foundation for exploration and development decision-making.

Acknowledgements

The authors would like to thank TGS for their permission to present this paper.

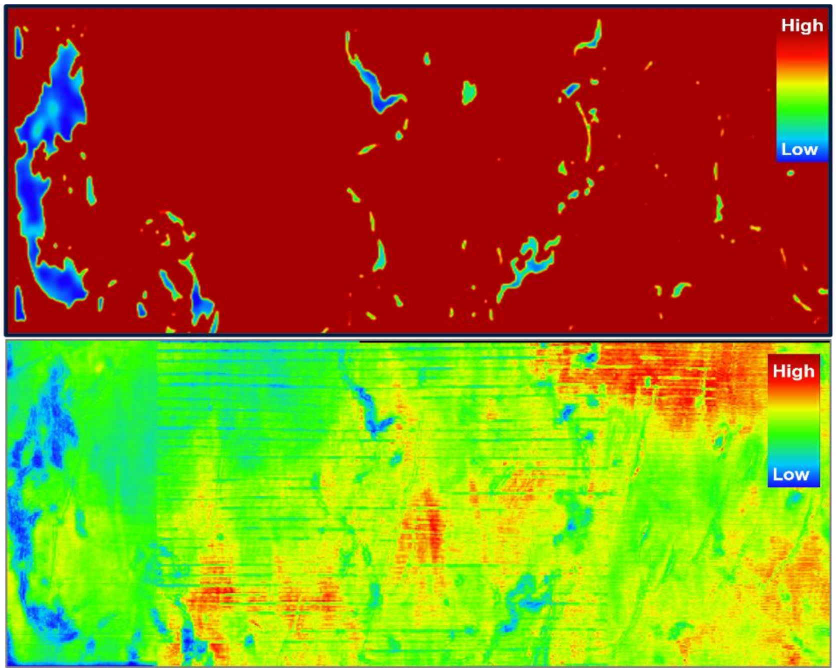

Figure 3: Depth slice of Q model (top) from the shallow section. Background Q value is 125 whereas Q anomalies vary between 20 & 45. Bottom image shows RMS amplitude calculated over 500ms window above Cycle V event.

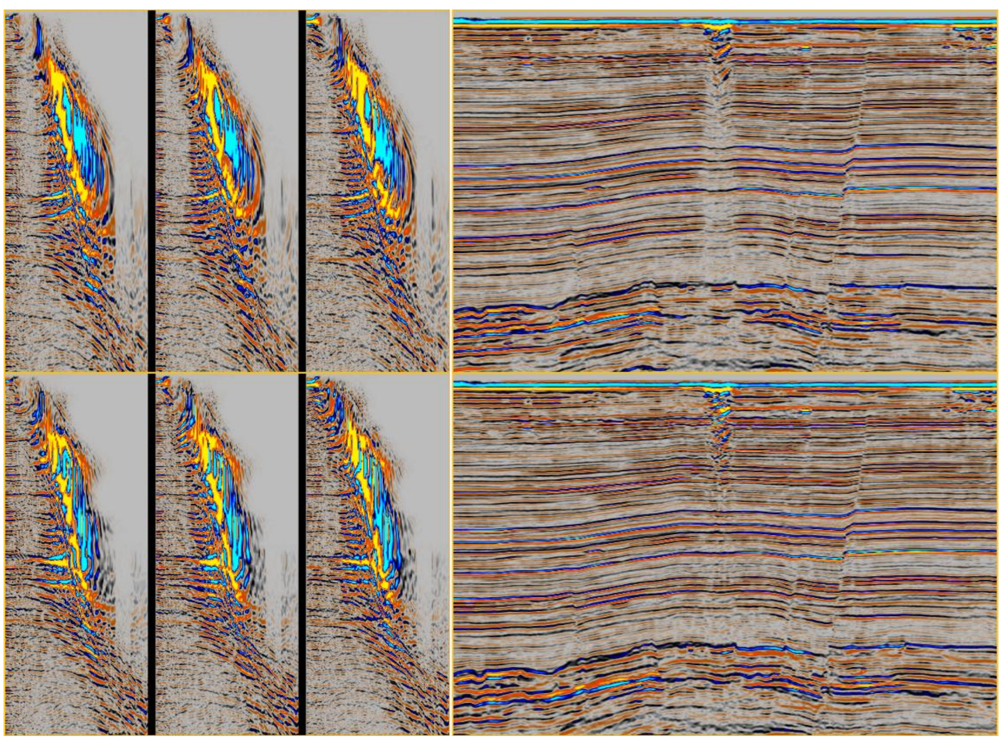

Figure 4: Migrated gathers (left) and stacks (right) with a constant Q model (top) and the final variable Q model (bottom).

References

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