Estimating Subsurface Properties with Angle-Domain Multi-parameter FWI

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Summary

We present a multi-parameter Full Waveform Inversion (MP-FWI) strategy designed to enhance reservoir characterization by jointly inverting for P-wave velocity and angle-dependent reflectivity. The formulation exploits the distinct sensitivities of seismic traveltimes and amplitudes to decouple low- and high-wavenumber components of the model, improving the recovery of subsurface properties critical to prospect evaluation.

Implemented in a full 5D pre-stack framework, the method produces angle-domain gathers suitable for amplitude variation with angle (AVA) analysis, and therefore provides a practical path to elastic property estimation beyond acoustic assumptions. We demonstrate the approach on wide-azimuth towed streamer data from the U.S. Outer Continental Shelf, where the inverted reflectivity volumes and AVA responses show strong agreement with well data. The method proves effective in mitigating parameter trade-offs inherent to multi-parameter inversion, while the iterative optimization approach compensates for limitations of conventional migration-based imaging, particularly with streamer acquisitions. The workflow delivers high-resolution subsurface models that potentially enable rock property estimation in complex geological settings.

Introduction

Full Waveform Inversion (FWI) has become a powerful tool for constructing high-resolution velocity models, bridging the gap between seismic imaging and reservoir characterization. Traditional FWI applications, however, have primarily focused on single-parameter inversion, typically P-wave velocity, due to the complexity and ill-posed nature of jointly inverting multiple earth properties.

Multi-parameter FWI extends this capability by simultaneously estimating a range of complementary subsurface properties, such as velocity, density, impedance, anisotropy, and attenuation, providing a more complete physical representation of the earth. However, this added complexity introduces significant challenges, including parameter cross-talk, varying sensitivities among parameters, and higher computational costs. The combined effects of parameter trade-offs, sensitivity imbalances, computational demands, and acquisition limitations render multi-parameter FWI a highly non-linear and ill-conditioned inverse problem that requires a carefully designed strategy to achieve reliable and geologically meaningful results.

In this work, we propose a hybrid inversion framework that targets P-wave velocity and angle-dependent reflectivity as distinct model components (Yang et al, 2022; Chemingui *et al*, 2023). This formulation, based on acoustic principles, leverages the natural decoupling between phase- and amplitude-sensitive components of the seismic response. By integrating inversion directly with angle-domain imaging and using a 5D pre-stack formulation, we generate common-image gathers that preserve amplitude variation with angle (AVA), which is a key input for elastic property and rock physics interpretation (Chemingui *et al*, 2024; Reiser et al, 2024).

We apply this workflow to a wide-azimuth towed streamer dataset from the U.S. Outer Continental Shelf, demonstrating how the joint inversion produces reliable reflectivity estimates that align well with well control and enhance subsalt reservoir imaging. The approach offers a practical solution for elastic property estimation in complex environments.

Methodology

The proposed inversion strategy jointly estimates P-wave velocity and angle-dependent reflectivity using a wave equation formulation tailored to decouple long-wavelength kinematic structures from fine-scale amplitude variations. Instead of relying on conventional parameter sets, e.g., density and P-wave velocity, we adopt a representation in which velocity governs wavefield propagation, while reflectivity, expressed as the gradient of acoustic impedance, controls the back-scattered wavefield.

This formulation eliminates the need for an explicit density model and simplifies the inversion by leveraging a velocity-reflectivity parameterization (Whitmore et al, 2021). The reflectivity component is established through inverse scattering theory, which allows sensitivity kernels to be computed separately for velocity and reflectivity updates (Whitmore and Crawley, 2012; Ramos et al, 2016). Scale separation ensures that velocity updates capture low-wavenumber background structures, while reflectivity updates refine high-resolution features tied to impedance contrasts.

A key aspect of our approach is the integration of angle-domain common-image gathers (ADCIGs) into the inversion loop, reconstructed in a full 5D pre-stack domain with binning in azimuth, and reflection angle (Chemingui *et al*, 2023). This framework enables accurate modeling of AVA effects while enhancing illumination balance through iterative data matching and back-projection of 5D pre-stack reflectivity. The inversion process progressively refines both velocity and reflectivity models, with regularization ensuring stability across poorly illuminated regions.

Field Data Example

We applied our multi-parameter inversion workflow to a 3D wide-azimuth towed-streamer survey acquired in the Mississippi Canyon protraction of the U.S. Outer Continental Shelf. This region is known for its complex salt geometry, which poses significant challenges to seismic imaging and amplitude analysis. The background velocity model was generated using elastic FWI applied to a sparse node dataset with long offsets, providing robust low-wavenumber constraints.

The multi-parameter inversion was then performed using the denser but limited-offset streamer data to estimate angle-dependent reflectivity. Figure 1 shows a depth section of the inverted velocity and the corresponding low-frequency FWI-derived reflectivity (FDR) image. The complex salt overburden introduces significant illumination challenges, as evident in the seismic image.

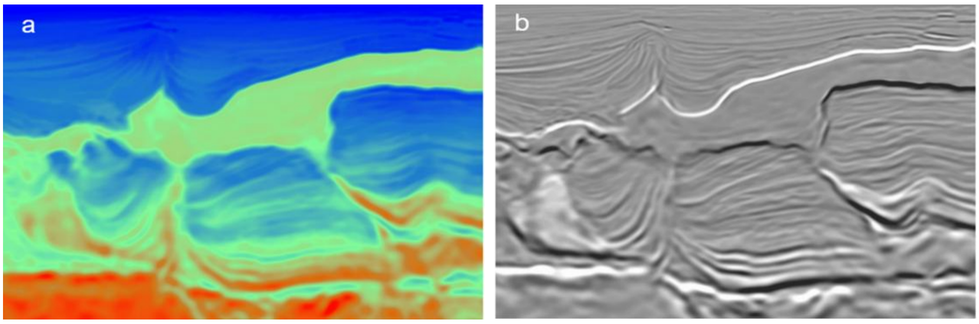

Figure 1: Depth profile of velocity model (a) and corresponding 8Hz FDR (b) showing the complex imaging challenges.

To address these limitations, we applied our inversion strategy in the angle domain to improve amplitude fidelity and compensate for illumination gaps. Leveraging full 5D pre-stack gathers, the inversion enhances both structural accuracy and the reliability of amplitude variations with angle. Figure 2 compares the RTM image with the reflectivity model derived from MP-FWI, highlighting improved resolution, continuity, and amplitude balance beneath the complex salt overburden.

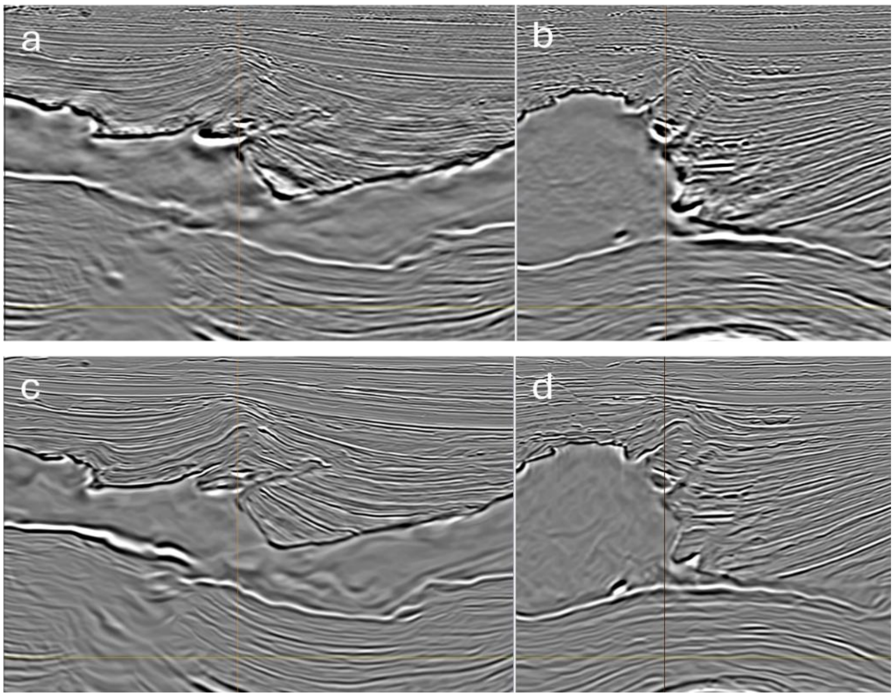

Figure 2: Comparison of RTM and MP-FWI images: (a) RTM inline; (b) RTM crossline; (c) MP-FWI reflectivity inline; (d) MP-FWI reflectivity crossline. MP-FWI improves structural continuity and amplitude fidelity beneath the salt.

Figure 3 highlights a target zone near a discovery well, where the RTM angle gathers exhibit limited angular coverage due to acquisition geometry and shadowing beneath the salt. In contrast, the multi-parameter inversion compensates for illumination gaps, extending angular coverage and enhancing the fidelity of AVA behavior. Extracted amplitudes from the inverted gathers exhibit a more coherent and geologically consistent AVA response, aligning with expectations at the prospect level and confirming the method’s robustness in complex salt environments.

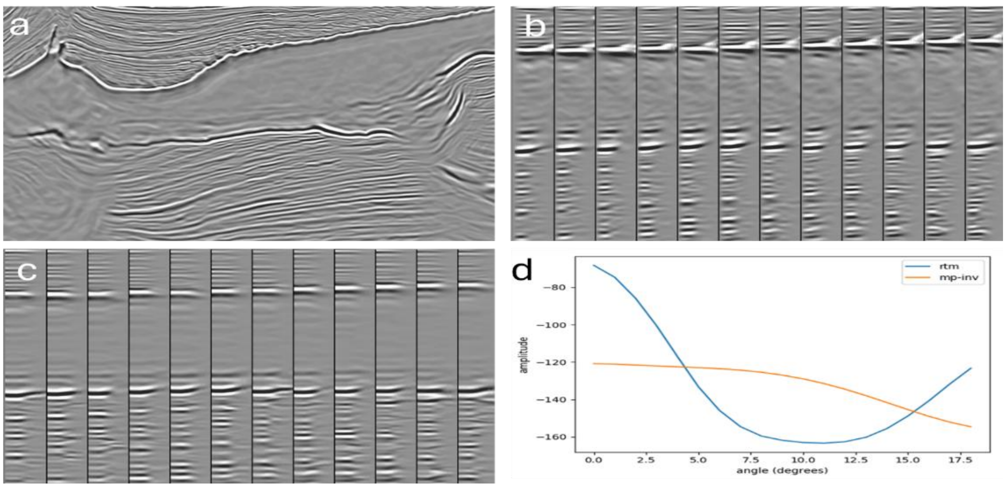

Figure 3: AVA analysis and angle-domain gather comparison. (a) Inline from target zone; (b) RTM ADCIGs with limited angular coverage; (c) MP-FWI reflectivity ADCIGs showing improved illumination; (d) Amplitude vs. angle plot comparing RTM (blue) and inversion (orange) gathers, highlighting enhanced AVA consistency.

Conclusions

We presented a robust multi-parameter inversion workflow that jointly estimates P-wave velocity and angle-dependent reflectivity within an acoustic framework. By leveraging scale separation between the low-wavenumber velocity background and high-wavenumber reflectivity components, the approach effectively mitigates parameter cross-talk while enabling direct extraction of amplitude variation with angle (AVA) for elastic interpretation.

The use of 5D angle-domain gathers within the inversion loop enhances illumination, preserves amplitude fidelity, and provides a reliable input for rock property estimation. Regularization and angle-domain conditioning further stabilize the inversion across variable acquisition geometries and complex overburden.

Application to a wide-azimuth streamer dataset from the U.S. Outer Continental Shelf demonstrated the method’s ability to recover geologically consistent and AVO-compliant reflectivity volumes validated with well control. This makes the approach particularly valuable for reservoir characterization, especially in settings where conventional AVO workflows struggle to deliver reliable elastic property estimates.

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