Reservoir Characterization Using Multi-Parameter FWI with Robust Angle Gathers

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Summary

Seismic inversion for reservoir characterization requires a multi-parameter approach to accurately estimate subsurface properties. However, multi-parameter Full Waveform Inversion (FWI) faces challenges due to cross-talk between earth properties, each influencing seismic data differently.

To address this, we propose an inversion strategy that resolves P-wave velocity (Vp) and angle-dependent reflectivity—both essential for petrophysical inversion and rock property extraction. This approach separates the parameters within the acoustic approximation, where Vp is mainly driven by phase, and reflectivity (impedance gradient) by amplitude variations.

The inversion efficiently leverages the 5D pre-stack domain to generate angle-domain common-image gathers (ADCIGs) for robust amplitude variation with angle (AVA) extraction, enabling the recovery of elastic properties of the subsurface.

The method is demonstrated on wide-azimuth towed streamer data over a complex subsalt field, with well control validating the extracted AVO response. The workflow offers a robust and efficient framework for estimating subsurface properties while minimizing parameter trade-offs—proving highly effective for prospectivity assessment.

Introduction

Over the past decade, successful applications of Full Waveform Inversion (FWI) have demonstrated its potential to bridge the gap between seismic imaging and reservoir engineering, providing detailed subsurface models that enhance reservoir insights. However, its computational intensity and sensitivity to assumptions about the earth model have traditionally constrained its routine application to single-parameter inversions. Multi-parameter FWI extends conventional approaches by simultaneously estimating multiple subsurface properties, e.g., P-wave velocity (Vp), S-wave velocity (Vs), density (ρ), anisotropy, and attenuation. This comprehensive framework potentially improves lithology discrimination, fluid identification, and reservoir property estimation, offering a more complete characterization of the subsurface.

However, despite these advantages, multi-parameter FWI presents several challenges. Parameter cross-talk remains a significant issue, where trade-offs between Vp, Vs, and density can lead to ambiguity and errors in the inversion results. The sensitivity of seismic data to different parameters varies, with velocity exerting a strong influence on seismic waveforms, while other properties may produce more subtle effects on phase or amplitude, particularly within bandwidth limited data. Furthermore, data acquisition limitations and unmodeled physics, can hinder convergence and introduce artifacts. Computationally, the increased model space dimensionality associated with multi-parameter inversion significantly amplifies processing costs, making large-scale applications challenging. These parameter trade-offs, sensitivity imbalances, computational demands, and data constraints, collectively make multi-parameter FWI a highly non-linear and ill-posed inverse problem that requires careful strategy to achieve reliable results.

To address these challenges, various strategies have been proposed. Improved parameterization of the modeling relations helps mitigate cross-talk in multi-parameter FWI by enhancing the decoupling of different properties. For example, impedance or reflectivity formulations help reduce trade-offs between velocities and density (e.g., Yang et al, 2022). Regularization techniques that incorporate geological priors from well logs or rock physics and enforce physically consistent updates further suppress artifacts (e.g., Asnaashari et al, 2013, Wang et al, 2024). Data-driven approaches, including adaptive weighting (e.g., Warner and Guasch, 2016) and machine learning-assisted model preconditioning (e.g., Wang et al, 2024; Alfarhan et al, 2023), also enhance inversion stability and robustness. Additionally, advanced optimization methods, such as Hessian-based preconditioning (e.g., Pratt et al, 1998, Metivier et al, 2012, 2013, Biondi et al, 2017) improve both quality and computational efficiency for large-scale applications.

In this study, we present a hybrid approach for estimating elastic earth properties through a multi-parameter FWI framework and a robust rock physics inversion workflow. The multi-parameter FWI is formulated to jointly invert for Vp and angle-dependent reflectivity (Yang *et al*, 2022). This approach produces high-resolution velocity and reflectivity models while leveraging angle-domain common-image gathers to extract amplitude variation with angle (Chemingui *et al*, 2023, 2024; Reiser et al, 2024). By moving beyond the acoustic assumption, the rock physics inversion enables the recovery of elastic properties critical for reservoir characterization.

We validate the effectiveness of our methodology through an exploration survey in a complex subsalt setting, where well control confirms the accuracy of the extracted AVO response at the reservoir level.

Methodology

Our method employs a simultaneous inversion strategy for velocity and angle-dependent reflectivity, using a wave equation parameterized in terms of velocity and reflectivity (Whitmore et al, 2021). This formulation eliminates the need for an explicit density model, simplifying the inversion process while preserving accuracy. The governing wave equation is expressed as:

$$\frac{\partial^2 P}{\partial t^2} - V\nabla\cdot(V\nabla P) + 2V^2(\boldsymbol{R}\cdot\nabla P) = S(x,t) \qquad (1)$$

where P represents the pressure wavefield, V is velocity, S(x,t) is the seismic source term, and R (vector reflectivity) is linked to the acoustic impedance Z(x) through:

$$\boldsymbol{R}(\boldsymbol{x}) = \frac{1}{2}\frac{\nabla Z(\boldsymbol{x})}{Z(\boldsymbol{x})} \qquad (2)$$

The implementation of the multi-parameter inversion integrates sensitivity kernels from inverse scattering theory, effectively decoupling velocity and reflectivity updates (Whitmore and Crawley, 2012; Ramos et al, 2016). By leveraging scale separation, the method isolates long-wavelength velocity components from high-frequency reflectivity variations, reducing parameter cross-talk.

A key advancement in this approach is the direct incorporation of angle-domain information into the inversion process to enable full 5D inversion. The vector-reflectivity wave equation inherently encodes the geometric properties required for precise extraction of the scattering angle at every image location (Chemingui *et al*, 2023). The reflection angle θ is computed as:

$$\theta = \arccos\left(\frac{\boldsymbol{R}\cdot\nabla P}{\|\boldsymbol{R}\|\cdot\|\nabla P\|}\right) \qquad (3)$$

The iterative generation and updating of angle gathers (ADCIGs) play a dual role in the workflow. First, they provide pre-stack reflectivity data crucial for refining velocity models. Second, they enable detailed amplitude versus angle (AVA) analyses. The pre-stack gathers enhance the inversion process by ensuring alignment between observed and modeled seismic data across both the time-space and angle domains.

The generation of synthetic data leverages azimuth and angle binned image gathers to construct comprehensive 5D datasets, fully capturing azimuthal and angular variations. By iteratively back-projecting pre-stack reflectivity data, the approach corrects for acquisition gaps and uneven illumination, thereby enhancing the amplitude fidelity of the image gathers. The integration of scale separation principles ensures that velocity updates predominantly affect large-scale structures, while reflectivity refinements enhance fine-scale reservoir features. This progressive refinement strategy, coupled with full data modeling and iterative 5D pre-stack updates, significantly improves the resolution and reliability of the derived subsurface models.

Field data applications

Our 3D field data example comes from a wide-azimuth towed streamer survey acquired in the Mississippi Canyon protraction of the U.S. Outer Continental Shelf, an area well known for its complex salt tectonics and challenging imaging environment. The background velocity model was built with elastic FWI using a sparse node, long offset dataset, while a denser but limited-offset streamer dataset was used for the MP-Inversion to estimate angle-dependent reflectivity. Figure 1a presents a depth profile of the velocity model, while Figure 1b displays an 8Hz FWI-derived reflectivity (FDR) section. The subsurface structure is highly complex, featuring significant velocity contrasts and strong lateral variations, owing to the elaborate salt geometry and associated deformation.

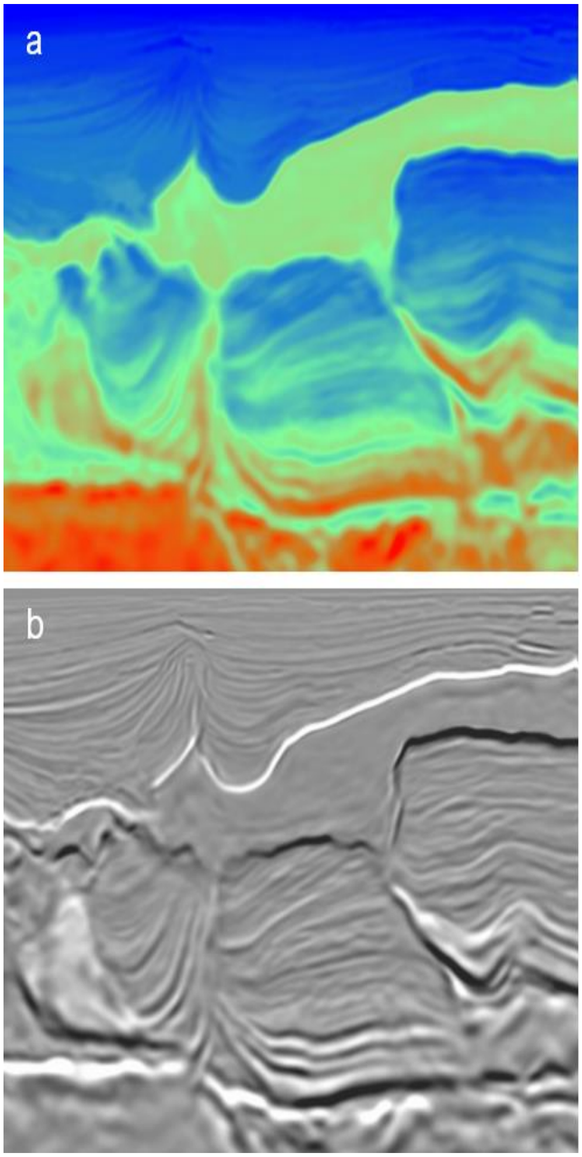

Figure 1: Depth profile of velocity model (a) and corresponding 8Hz FDR (b). The data was acquired in the Mississippi canyon area, known for complex salt tectonics. The complex shape leads to illumination challenges shown in Figure 2.

As expected, the complex overburden visible in Figure 1 leads to poor subsurface illumination in the towed streamer data, as illustrated in Figure 2a. By inverting for reflectivity, the image quality improves significantly, as shown in Figure 2b. However, the inherent limitations of the streamer acquisition—such as restricted offsets and coverage—remain noticeable in certain localized areas, where imaging artifacts or reduced resolution persist.

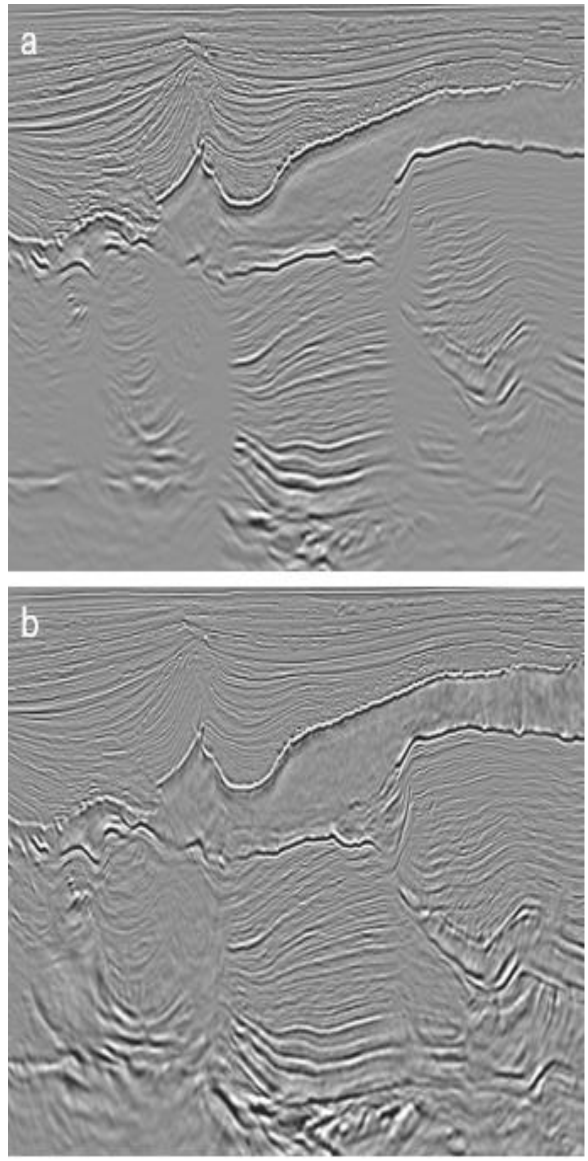

Figure 2: Raw 18Hz RTM (a) and MP-inversion for reflectivity (b) through the depth profile shown in Figure 1, using towed streamer data.

While the towed streamer data exhibits relatively uneven illumination compared to the sparse node data used for FWI, it is comparatively dense in angular information, particularly in the areas it effectively illuminates. However, the illumination gaps observed in the full stack images (Figure 2a & b) are also evident in the angle gathers.

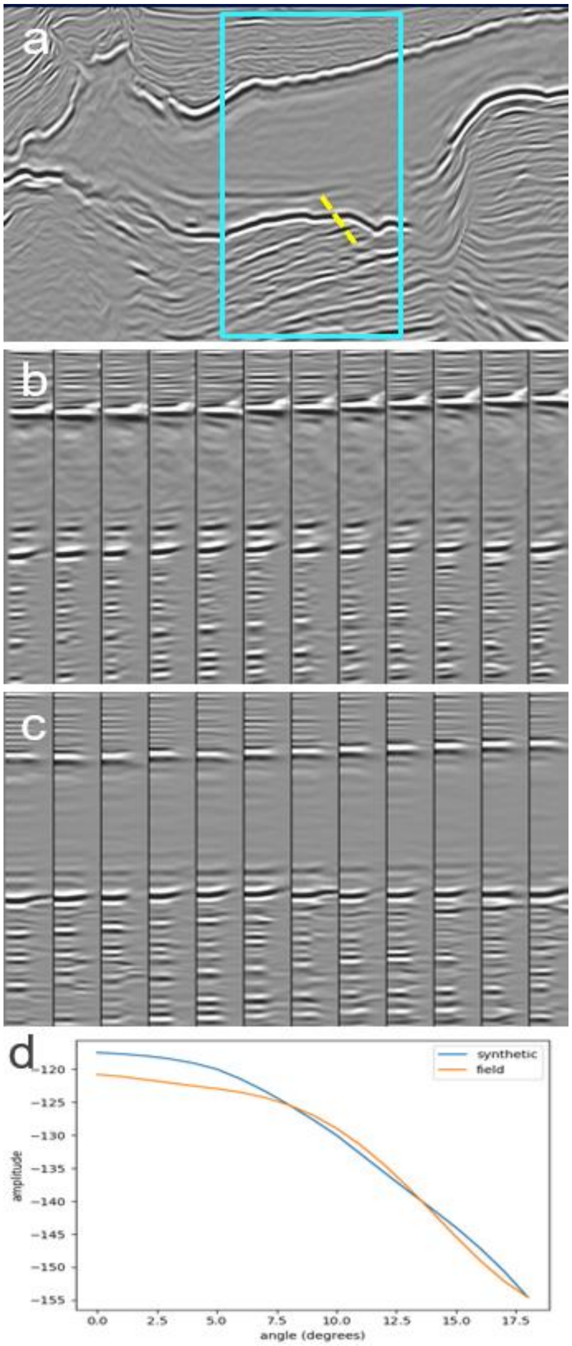

Figure 3: Image closeup showing (a) ADCIG selection range (blue box) and discovery well location (yellow dashed line), (b) RTM ADCIGs, (c) multi-parameter inverted reflectivity ADCIGs showing angular illumination compensation in the inverted gathers, and (d) amplitude vs. angle plot, with smoothed extracted amplitudes plotted against a well synthetic

Figure 3a presents a close-up of a section of the image volume near a discovery well location. The yellow dashed line marks the well position, while the blue box highlights the area where a selection of RTM ADCIGs (Figure 3b) and inverted ADCIGs (Figure 3c) were extracted. As expected, the angle range illuminated beneath the salt body is relatively narrow, with a pronounced angular fold "footprint" visible in the gathers. Regularization within the (multi-parameter) inversion framework extends the angle range in both small and large angle directions while compensating for uneven illumination across angles. Finally, Figure 3d demonstrates the agreement between the smoothed, extracted amplitudes and a well synthetic at a key horizon, where a Class III AVO anomaly is expected.

Conclusions

We presented a robust multi-parameter inversion approach that effectively mitigates cross-talk by jointly inverting for P-wave velocity and angle-dependent reflectivity within an acoustic framework. By leveraging angle-domain common-image gathers, this method enables the extraction of amplitude variation with angle, enabling the recovery of elastic properties beyond the acoustic assumption. The efficient incorporation of full 5D inversion ensures accurate angle-dependent reflectivity estimation while regularization and Hessian conditioning further enhance illumination compensation. The application to wide-azimuth towed streamer survey over a complex subsalt field demonstrates the method's effectiveness, with well control validating the extracted AVO response. The approach proves particularly valuable for reservoir characterization and prospectivity assessment, offering a reliable framework for estimating subsurface properties with reduced parameter trade-offs.

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