Leveraging Angle Gathers for Refining Subsurface Models in Multi-Parameter FWI

S. Crawley[1], N. Chemingui[1], R. Abdul Alim[1]

[1] TGS

Summary

We discuss the use of angle gathers in updating subsurface models within multi-parameter Full Waveform Inversion (FWI). The framework utilizes binned image gathers for modeling full pre-stack data during simultaneous inversion of velocity and angle-dependent reflectivity. Tested on field data, the method demonstrated significant improvements in imaging, producing an accurate high-resolution subsurface model. Angle gathers are instrumental in both refining the velocity model and enabling analysis of amplitude variation with angle.

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Introduction

Full Waveform Inversion (FWI) has transformed seismic imaging by enabling the creation of high-resolution subsurface models through iterative matching of synthetic seismic data with field observations. However, traditional FWI approaches often focus on single-parameter inversions, typically limited to P-wave velocity (Vp). While effective in many geological scenarios, these methods may face limitations in complex environments where multiple earth parameters play a significant role in shaping seismic responses.

To address some of these limitations, we adopt a multi-parameter inversion approach that simultaneously estimates velocity and angle-dependent reflectivity (Yang *et al.*, 2022). By coupling FWI with a non-linear data-domain least-squares reverse time migration (LS-RTM), we directly invert for angle gathers, providing robust tools for velocity model building. This innovative framework integrates the modeling of 5D reflection data using binned image gathers, ensuring comprehensive use of azimuthal and angular information during inversion.

The inclusion of angle gathers augments the FWI process by enabling detailed analysis of amplitude variation with angle (AVA) (Chemingui *et al*, 2023, 2024; Reiser et al, 2024) and refining velocity models in a manner that aligns closely with the observed seismic data. By directly modeling (or demigrating) angle gathers, the framework achieves a seamless integration of imaging and velocity updating, overcoming challenges posed by incomplete data acquisition and illumination variations. This approach offers a robust solution for building accurate subsurface models while providing high-resolution insights into reflectivity properties.

Methodology

Our approach utilizes simultaneous inversion of velocity and angle-dependent reflectivity using a vector-reflectivity-based wave equation (Whitmore *et al.*, 2021). By parameterizing the wave equation with velocity and reflectivity as direct model parameters, this method eliminates the need for explicit density models. The wave equation is expressed as:

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

where P represents the pressure wavefield, V is the velocity, S is the source term, and R (vector reflectivity) relates to acoustic impedance (Z) as:

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

This formulation integrates sensitivity kernels derived from inverse scattering theory, effectively decoupling updates to velocity and reflectivity. The scale separation inherent in this approach isolates long-wavelength velocity components from high-frequency reflectivity features, minimizing parameter cross-talk and enhancing the reliability of model updates.
A key innovation is the incorporation of angle gathers directly into the inversion process. Geometric information embedded in the wave equation enables the direct computation of incidence and reflection angles during inversion (Chemingui *et al*, 2023). The reflection angle (θ) is derived from the gradient of the forward-propagated wavefield (∇P) and vector reflectivity (R):

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

The iterative generation and updating of angle gathers 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 angle gathers augment the data-matching process of FWI by aligning modeled data with field recordings in both the time-space and angle domains.
The modeling of synthetic data leverages binned image gathers for comprehensive 5D reflection data modeling, ensuring that all azimuthal and angular information is fully utilized. These gathers serve as inputs for velocity updates, enabling simultaneous improvement of the subsurface model and the reflection image. Through back-projection of pre-stack reflectivity information, the process iteratively updates the gathers, compensating for incomplete acquisitions and uneven illumination.
Moreover, scale separation (Whitmore and Crawley, 2012; Ramos-Martinez *et al*., 2016) ensures that long-wavelength velocity updates are separated from high-frequency reflectivity changes, allowing the progressive refinement of subsurface models from coarse background structures to detailed reservoir attributes. By combining full data modeling, pre-stack information, and iterative updates, the workflow significantly improves the accuracy and resolution of FWI models.

Applications and Results

The workflow was tested on 3D field data from the Norwegian Sea over the Outer Vøring basin. We built initial models from smoothed tomographic velocity models using machine learning, and simultaneous inversion was performed using raw field data, employing frequencies up to 15 Hz. Figure 1 presents an inline slice from the initial and inverted reflectivity models, displaying significant improvements in illumination, focusing, and coherence after several iterations. Arrows highlight areas with particularly notable enhancements.

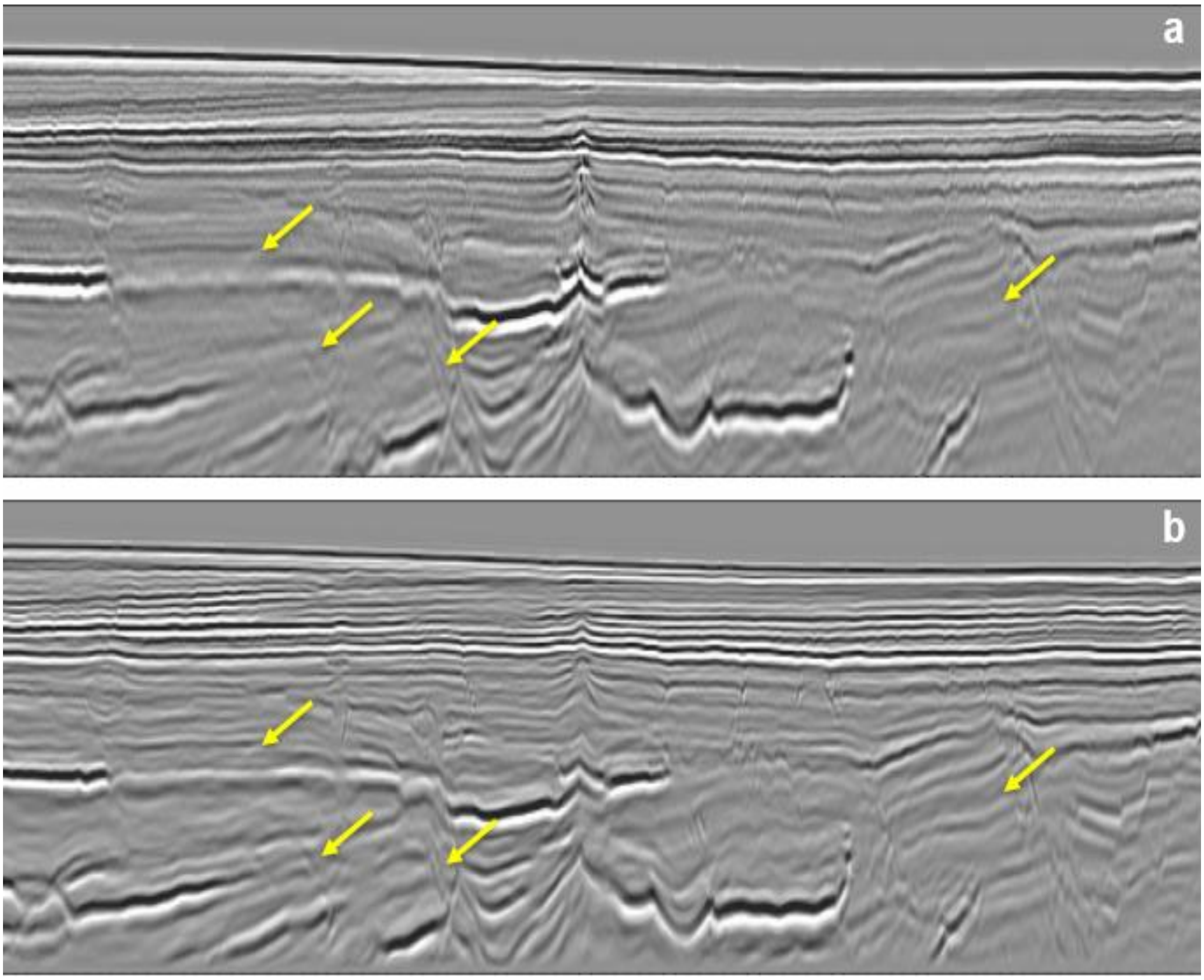

Figure 1: *Initial (a) and inverted (b) reflectivity models. Areas of poor illumination and focusing are improved throughout the image.*

Figure 2 displays selected angle gathers from a section of the same line, located beneath a complex overburden formed by volcanic sills. The gathers span 0-60 degrees, showing the initial results (a) and those after several iterations (b). Decomposing the initial reflectivity image into angle gathers reveals artifacts that stack into the post-stack image. Through iterative angle-dependent modelling, the pre-stack reflectivity is constrained to better explain the data, resulting in cleaner inverted gathers with more balanced and even illumination.

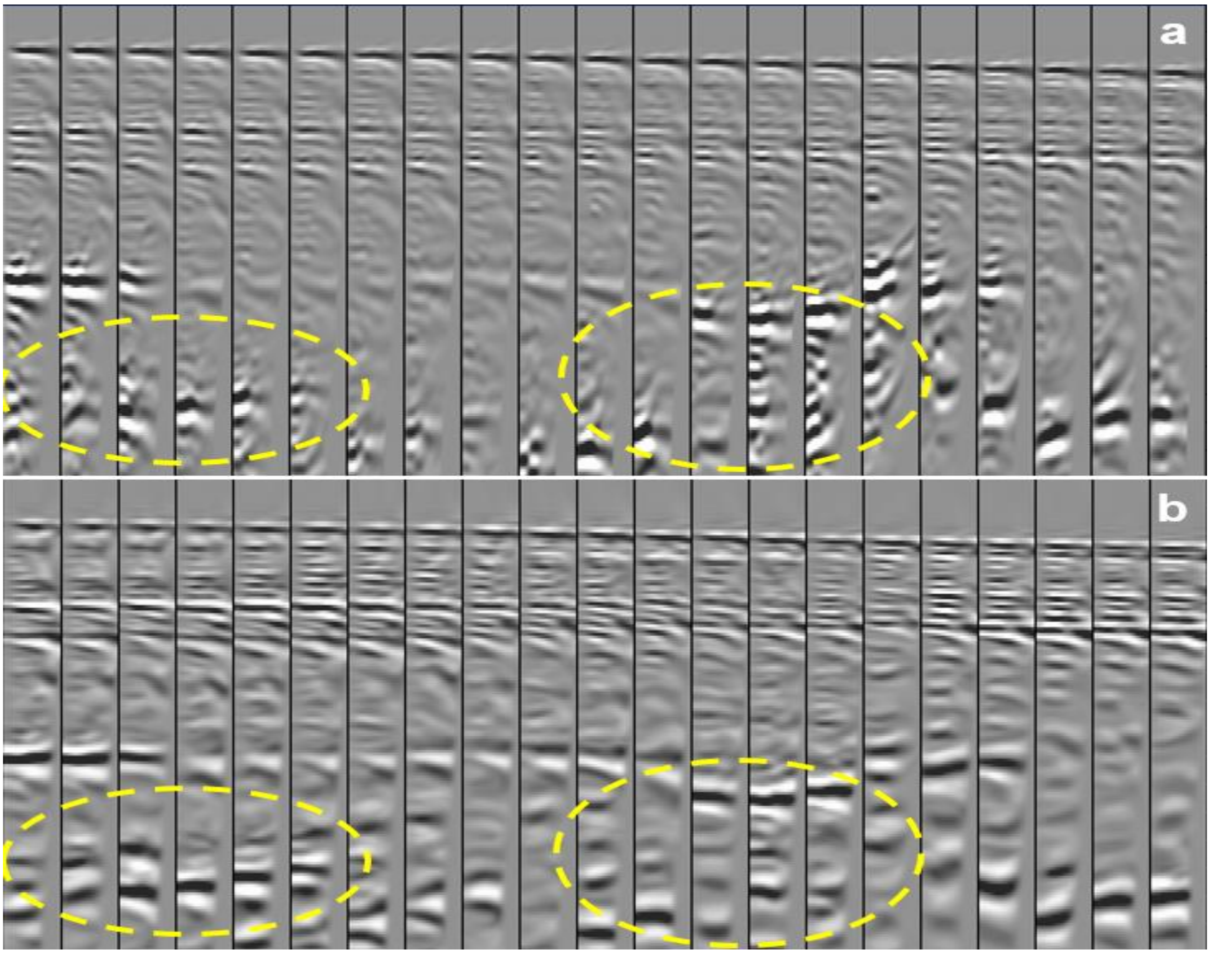

Figure 2: *Initial (a) and inverted (b) gathers. Yellow circles are areas under high velocity overburden where the iterative inversion cleans up the gathers significantly and improves the angular illumination.*

Finally, Figure 3 presents the velocity update and the final velocity model, with overlaid reflectivity. While the initial ML-generated model is already highly accurate, the inversion process introduces both high- and low-wavenumber adjustments to further refine the model and better fit the data.

Conclusions

The shift from single-parameter FWI to multi-parameter inversion marks a significant step forward in seismic imaging. By simultaneously inverting velocity and angle-dependent reflectivity within a unified framework, we leverage the full potential of the seismic wavefield to produce high-resolution subsurface models and refined reflectivity attributes.
The case study results demonstrate the robustness of this approach, with significant improvements in imaging of subsurface features beneath complex overburdens. The integration of angle gathers through a non-linear data space LS-RTM process should enable amplitude variation with angle (AVA) analyses and facilitates precise velocity model updates, therefore accelerating the cycle time for model building and interpretation. Future work will focus on extending the framework to incorporate additional reflectivity attributes to further optimize reservoir characterization capabilities, enabling data-driven exploration decisions.

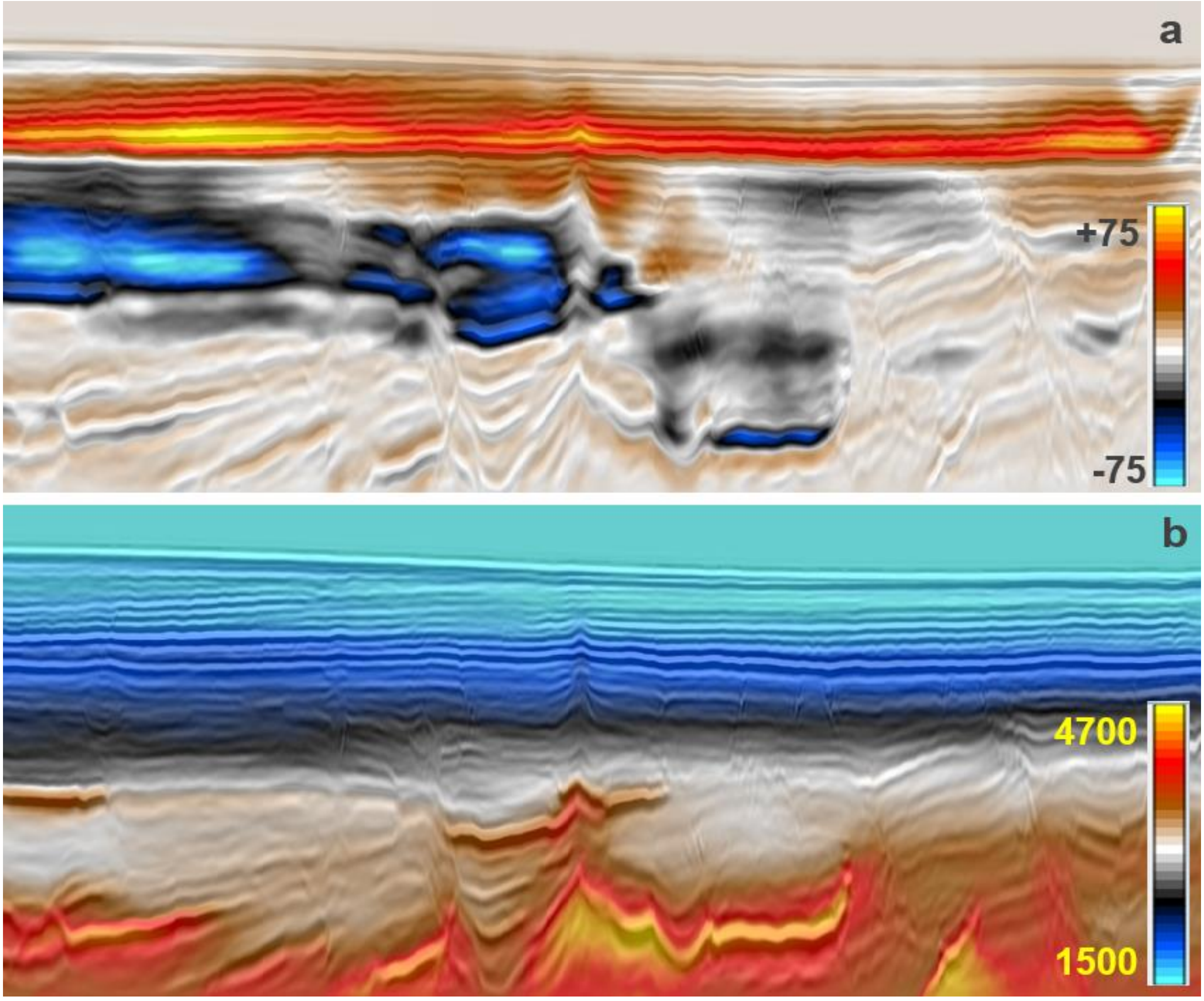

Figure 3: *Velocity update (a) and inverted velocity model (b), with reflectivity overlaid.*

Acknowledgments

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