# Full waveform inversion beyond velocity: multi-parameter earth model estimation in the angle domain

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## Abstract

Seismic inversion is fundamentally a multi-scale and multi-parameter problem. The subsurface may be viewed as a smoothly varying background model that controls wave propagation, onto which are superimposed shorter-wavelength perturbations associated with impedance contrasts and seismic scattering. In that sense, a reliable long-wavelength background model is essential for wavefield propagation, and structural positioning, while the estimation of higher-wavenumber perturbations is equally critical for recovering impedance variations, density changes, and the reservoir-scale signatures. Our previous work showed that separating these scales within the inversion is key to minimizing cross-talk between parameters and to enabling joint updates of velocity and reflectivity within a single wave-equation-based Full Waveform Inversion (FWI). In our formulation reflectivity is expressed through an impedance-gradient that describes the back-scattered energy and carries the high-wavenumber information linked to geological boundaries and reservoir heterogeneity. By using inverse-scattering-based kernels and a dedicated scale-separation strategy, the inversion can update the macro-model and the perturbation model in a more stable and geologically meaningful manner.

Our inversion strategy uses a wave equation parameterized in terms of velocity and vector reflectivity, with vector reflectivity expressed as relative seismic impedance, describing the back-scattered wavefield. This provides a practical bridge between wave-equation inversion and rock physics, while avoiding the need for an explicit density model. Density variations are especially important because many reservoir indicators are driven by amplitude behavior and angle-dependent impedance effects rather than velocity alone. Even when absolute density is difficult to recover without calibration, relative density variations derived consistently from the inverted reflectivity still provide valuable constraints for reservoir characterization.

A key differentiating aspect of our solution is the direct estimation of pre-stack reflectivity in the angle domain as part of the inversion. Conventional multi-parameter FWI does not naturally deliver pre-stack reflectivity suitable for AVA/AVO analysis, whereas our angle-domain multi-parameter FWI updates velocity and angle-dependent 5D reflectivity simultaneously throughout the inversion. The resulting angle gathers preserve amplitude variation with angle and provide a stronger basis for density-related attributes, and broader elastic-property estimation.

From an implementation standpoint, our multi-parameter FWI has benefited greatly from advances in large-scale computing. Cloud computing has been a key enabler for scalable, faster-turnaround inversion of high-dimensional wave-equation models while preserving 5D pre-stack information. Looking ahead, AI offers strong potential to further advance the multi-parameter FWI workflow, not by replacing physics-based methods, but by providing priors, constraining model space, accelerating optimization, and reducing parameter cross-talk.

In summary, we present a unified strategy that advances seismic inversion beyond velocity estimation toward full earth-model estimation. This marks a significant step forward, with background structure, impedance perturbations, density variations, and angle-domain attributes recovered within a single framework for reservoir characterization.

## References


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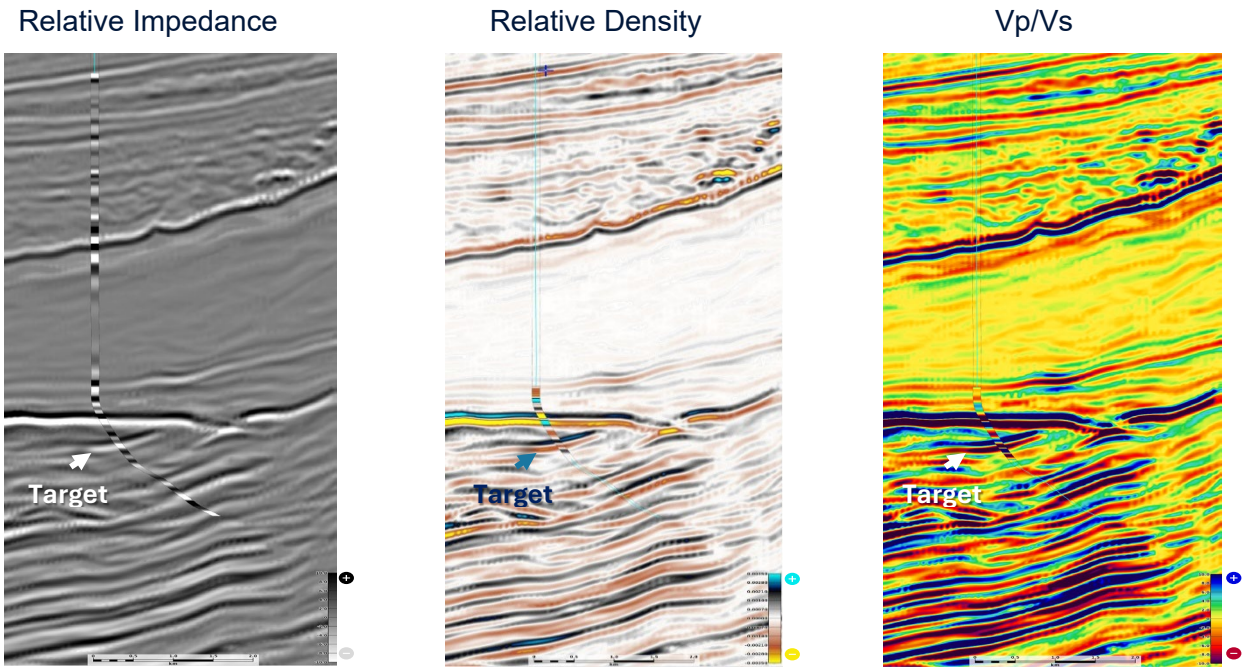


**Figure 1.** Multi-parameter FWI example showing relative impedance, relative density, and Vp/Vs derived from velocity and angle-domain reflectivity, and illustrating the value of seismic inversion beyond velocity for reservoir characterization.