Dynamic matching multiparameter FWI of velocity and reflectivity for land seismic data

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Summary

Velocity model building (VMB) and seismic imaging in land environments present additional challenges compared to marine settings. We describe a multiparameter full-waveform inversion (MP-FWI) approach that jointly estimates velocity and reflectivity, adapted for land scenarios. The scale-separation strategy applied in MP-FWI improves background velocity estimation from reflected energy beyond the penetration depth achievable with refracted and diving waves. We employ the dynamic matching (DM) objective function, which enhances velocity estimation at low frequencies under strong noise conditions. Additionally, iterative reflectivity inversion within FWI improves shallow subsurface illumination, where conventional imaging often performs poorly. The reflectivity kernel in MP-FWI boosts high-wavenumber content, improving coherence and resolution. We illustrate the method using a dataset acquired in the Midland Basin, onshore U.S.

Introduction

Applying FWI in land settings to improve model accuracy and image resolution is challenging due to factors such as poor signal-to-noise ratio (S/N) at low frequencies, uncertainty in source wavelet estimation, and surface topography effects, issues less severe in marine environments (e.g., Vigh *et al*., 2018).

For shallow imaging, limited near-offset coverage and complex near-surface geology often obscure primary reflections required by conventional imaging algorithms (Reta-Tang *et al*., 2023). Leveraging additional energy beyond primary reflections can improve illumination. While refracted energy provides valuable information for velocity estimation, its penetration depth depends on maximum offset and the rate of change of velocity with depth. Beyond this depth, FWI relies on reflected signals with predominantly vertical wavepaths, where short-wavelength velocity features dominate updates.

In this work, we jointly estimate velocity and reflectivity using an MP-FWI formulation introduced by Yang *et al*. (2021) and recently extended to the elastic case by Huang *et al*. (2025). Here, we use the acoustic implementation combined with the DM objective function (Huang et al., 2021). We first describe the method, then present an application to a Midland Basin land dataset.

Method

Our MP-FWI approach for estimating velocity and reflectivity includes two key components: *i*) wave-equation parameterization in terms of P-wave velocity and *ii*) scale separation to reduce parameter crosstalk.

Using reflectivity in the wave-equation parameterization avoids the need for a density model to synthesize reflected events for velocity inversion. Unlike Born modeling, reflectivity modeling produces a full acoustic wavefield including multi-scattering, free-surface effects, and refracted energy in a single simulation (Whitmore *et al*., 2020).

Scale separation in the FWI gradient yields two components:

- A long-wavelength gradient for velocity estimation (Ramos-Martinez *et al*., 2016).
- A high-wavenumber gradient for reflectivity updates (Whitmore and Crawley, 2012).

Legacy land surveys typically have shorter maximum offsets compared to ocean-bottom node (OBN) marine acquisitions, limiting refracted energy penetration depth. Consequently, the velocity kernel emphasizes background velocity updates from reflected events beyond this depth. For shallow targets, it mitigates high-wavenumber leakage in velocity updates caused by reflection interference.

The DM objective function improves low-frequency velocity estimation by maximizing phase alignment between observed and synthetic data via multidimensional cross-correlation. This reduces sensitivity to amplitude mismatch and noise, critical for land FWI applications (Reta-Tang *et al*., 2023; Krishnasamy *et al*., 2023).

For reflectivity inversion, the full wavefield enhances shallow subsurface illumination beyond what primary reflections provide. The reflectivity kernel amplifies high-wavenumber content, and iterative updates reconstruct relative amplitudes, improving resolution and coherence.

Field Data Example

We applied MP-FWI to a Midland Basin dataset. The 3D survey spans ~267 square miles and targets formations such as the Barnett Shale and Mississippi Limes. Data were acquired with vibrator sources, with nominal maximum inline and crossline offsets of 24,000 ft. Pre-processing included de-spiking and removal of coherent events (e.g., ground roll, converted waves) not modeled by the acoustic engine. The initial velocity model was built using refraction tomography and with the application of DM FWI on first arrivals, followed by reflection tomography (Figure 1a). We then refined the model using DM MP-FWI with the full acoustic wavefield after coherent energy removal. Figures 1b and 1c illustrate the scale separation: velocity updates from the velocity kernel versus the conventional single parameter DM FWI gradients. Conventional FWI gradient exhibits high-wavenumber features produced by specular reflections, an order of magnitude larger than tomographic updates. In a conventional workflow, these velocity updates are further conditioned, and reflection tomography is applied to improve the background velocity. In contrast, the velocity kernel enhances the low-wavenumber updates, improving the convergence in the background velocity estimation within the same FWI framework. To demonstrate reflectivity inversion benefits, we compare crossline sections from MP-FWI and legacy single-parameter FWI. MP-FWI delivers superior focusing and resolution, as confirmed by depth slices (Figure 3). Channel definition in MP-FWI images is markedly improved over single-parameter results.

Conclusions

We demonstrated the application of acoustic multiparameter FWI (MP-FWI) for jointly estimating velocity and reflectivity in land seismic data. The integration of the dynamic matching (DM) objective function significantly enhances velocity estimation at low frequencies, where land data typically suffer from poor signal-to-noise ratios. The velocity kernel derived from scale separation enables more reliable updates at depths where only reflected energy is available, improving background velocity convergence. Similarly, the reflectivity kernel facilitates iterative image reconstruction, delivering higher resolution and continuity compared to conventional imaging approaches.

Key words

Land data, multiparameter FWI, velocity, reflectivity

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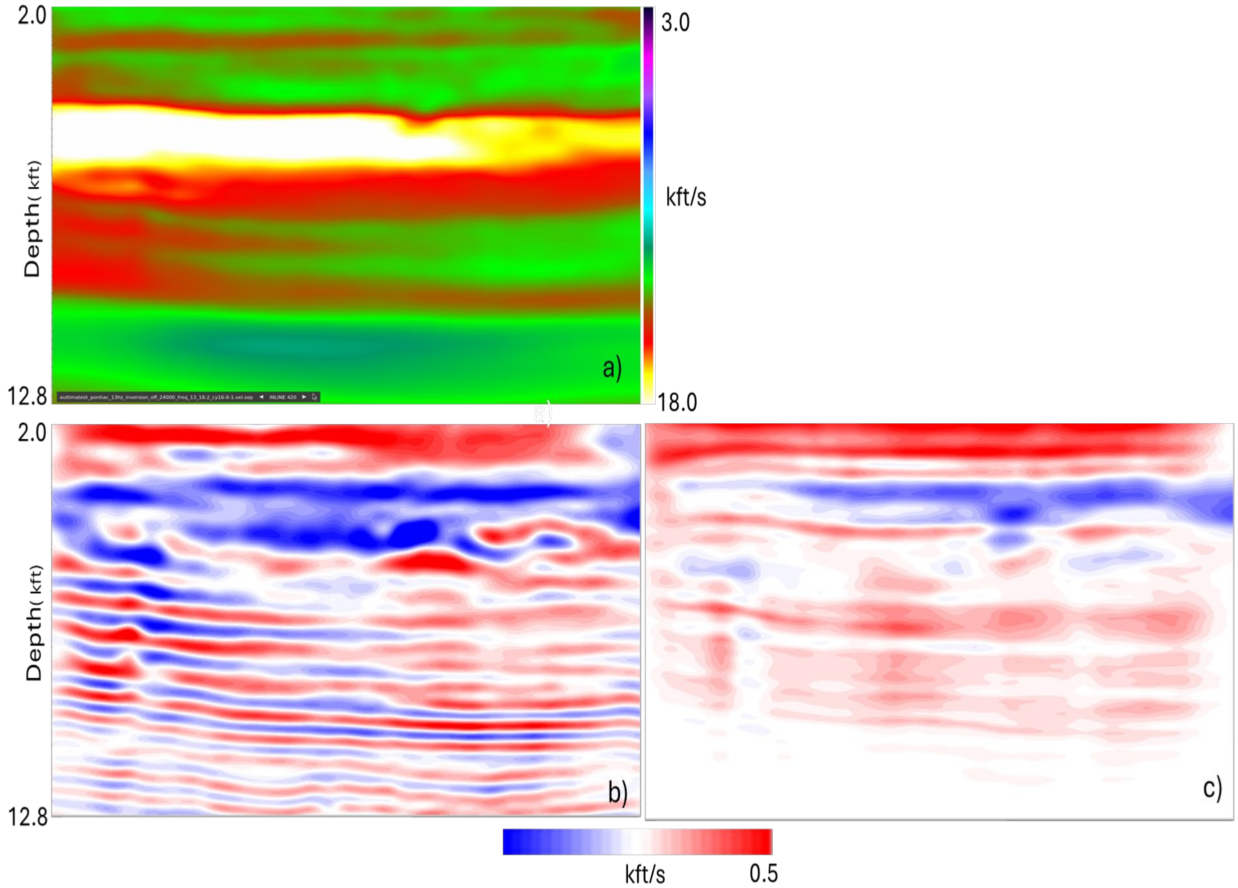

Figure 1. Midland Basin example. a) Initial velocity model. Velocity updates using b) the conventional FWI gradient and c) the MP-FWI velocity kernel.

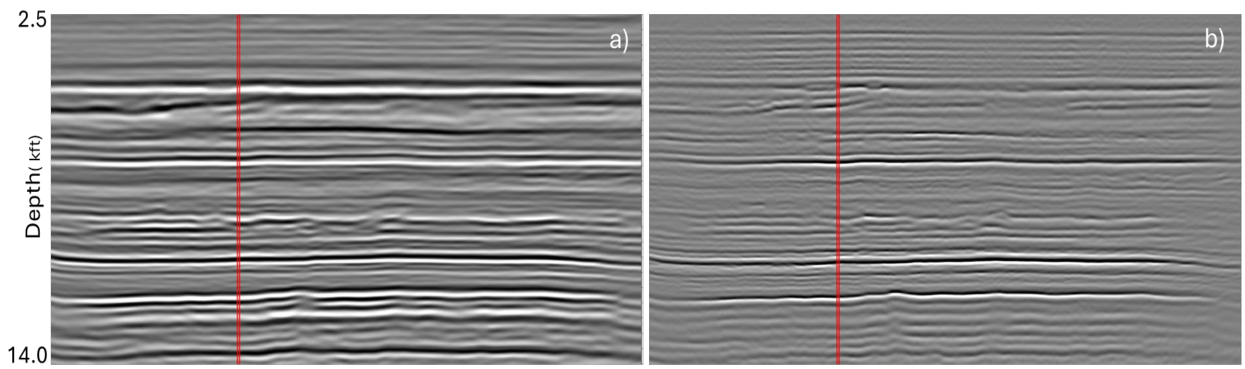

Figure 2. Midland Basin example. a) FWI image and b) MP-FWI image along the crossline direction.

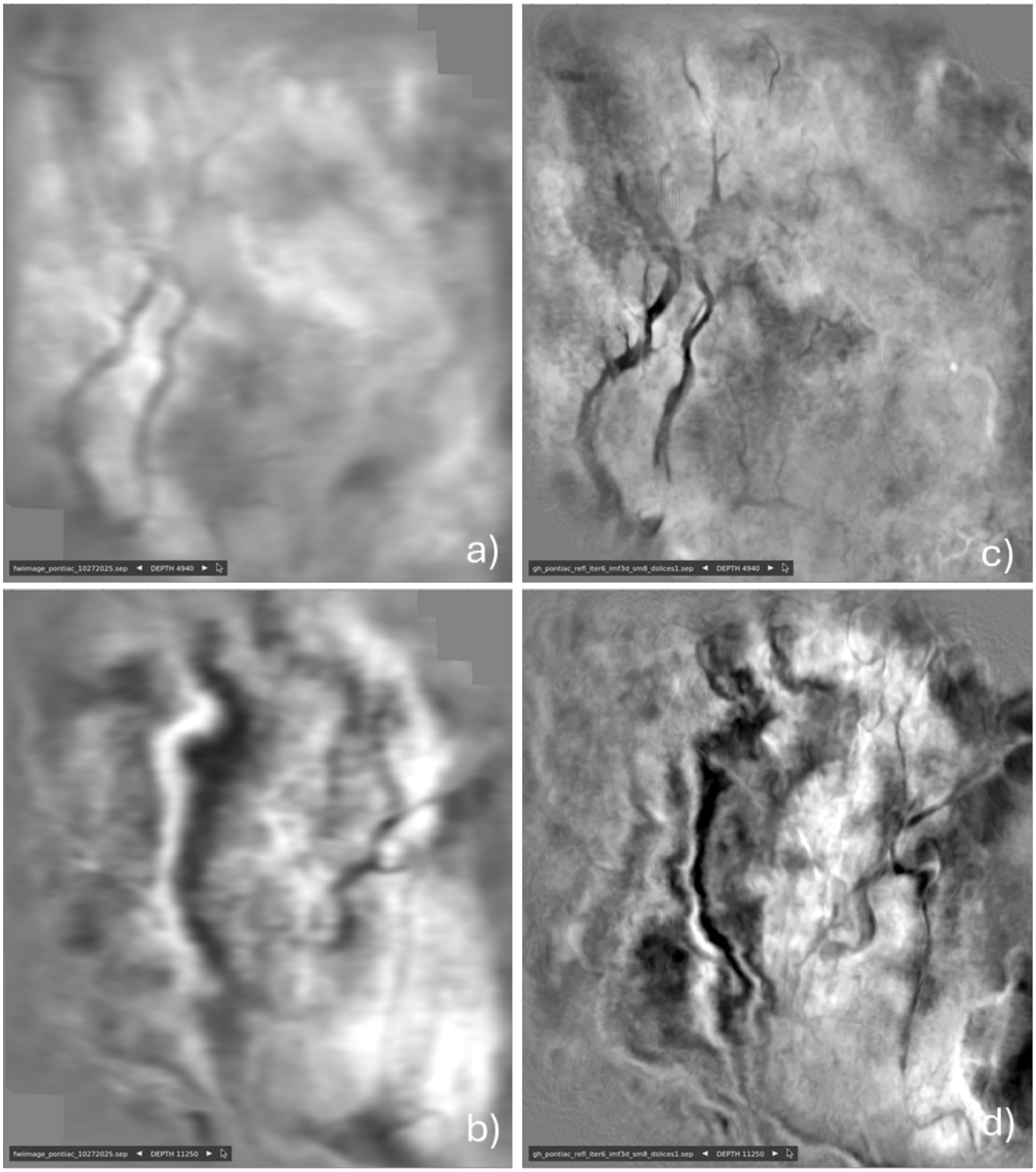

Figure 3. Midland Basin example a), b) FWI images at depths 4.9 and 11.2 kft, respectively; c), d) MP-FWI images for the same depth.