# Land seismic multi-parameter FWI imaging

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## Summary

Multi-parameter full-waveform inversion (MP-FWI) imaging uses minimally processed field data to simultaneously estimate a subsurface velocity model and a high-resolution reflectivity image using the full wavefield, including multiple reflections. This eliminates the need for complex modeling and adaptive subtraction workflows required to remove multiples before migration. Furthermore, multiple reflections can better illuminate near-surface reflectivity that is difficult to image with primary reflections due to limited near-offset trace density, especially in areas with surface obstructions or complex geologic structures. In this paper, we present a successful application of MP-FWI imaging to seismic data acquired in a desert environment with significant geological complexity in the near-surface and at target depths. We show that the MP-FWI reflectivity image and velocity model estimated using the full wavefield are superior to results produced using a more conventional processing and imaging workflow.

## Introduction

Conventional 3D land seismic data processing and imaging workflows consist of many cascaded operations, including noise removal, surface-consistent corrections, demultiple, 5D common-offset vector (COV) interpolation, model-building, and migration. Each of the preprocessing steps is designed to satisfy the assumptions of conventional imaging algorithms, which typically only use primary reflections to estimate a subsurface reflectivity image. The parameter space for each processing step must be fully explored to ensure the highest-quality results are realized, which can be time-consuming and subjective. Due to the low signal-to-noise ratio of most land seismic data, processing results can be difficult to evaluate. This is particularly true in desert environments where the primary reflections are often severely contaminated with cultural noise, air waves, surface waves, guided waves, a wide variety of multiples, and complex distortions of each of these modes associated with near-surface scattering.

MP-FWI imaging offers an alternative approach to the conventional processing and imaging workflow. This implementation of FWI separates the kinematic and dynamic aspects of the wavefield to robustly perform a simultaneous inversion such that reflectivity, velocity, and other Earth parameters can be determined. The derived velocity model is suitable for conventional imaging, should it be required, and the reflectivity image is suitable for both structural interpretation and quantitative analysis (McLeman et al., 2022). Multi-parameter inversion challenges, such as crosstalk and relative scaling differences, are addressed through the use of a novel second-order quasi-Newton method (McLeman et al., 2021). This MP-FWI imaging technique does not use ray-based, single-arrival, or Born approximations that might typically be employed in conventional imaging algorithms, facilitating the use of the full wavefield—including all orders of multiples—when estimating the subsurface models. The inclusion of multi-scattering events, together with the least-squares imaging approach, provides improved illumination and amplitude reconstruction, especially in areas with complex geology (Rayment et al., 2023).

In this paper, we demonstrate the successful application of the MP-FWI imaging approach outlined by McLeman et al. (2023) in a land setting for the first time, using a dataset acquired in a desert environment.

## Method

In this case study, we consider a merge of two 3D land seismic surveys acquired in a challenging desert environment. The subsurface in this area is generally characterized by alternating carbonate and clastic sequences with significant regional dip, punctuated by many complex unconformities and faults. Both surveys were acquired using vibratory sources and geophone arrays arranged in an orthogonal cross-spread pattern. The acquisition geometry is mostly regular, with some irregularity in the vicinity of dunes, sabkhas, cliffs, jebels, and wadis.

The conventional seismic data processing workflow included cultural noise removal (adaptive notch filtering), despiking, refraction static corrections, linear noise removal, random noise removal, surface-consistent deconvolution, demultiple, and 5D COV interpolation. Several passes of surface-consistent scaling and residual statics corrections were applied throughout the workflow.

In parallel with the preprocessing, an initial velocity model was built using refraction tomography in the near-surface and smoothed depth-converted stacking velocities in the deep. The raw field data was used for first-break picking and partially stacked super gathers were used for velocity analysis. Diving wave FWI was then used to update the near-surface model, starting at 5 Hz and progressing up to 12 Hz in five frequency steps. Elementary processing was applied to the field data for diving wave FWI to reduce linear noise in the near offsets and low-frequency incoherent noise. Then, the deep velocities were updated with three passes of reflection tomography. Residual depth errors were then measured at several well locations to calibrate the velocity and anisotropy models. Structural interpretation along eight key horizons guided the anisotropy calibration and constrained each reflection tomography update. To conclude the conventional processing and imaging workflow, we migrated the fully processed seismic data using both COV Kirchhoff prestack depth migration (KDM) and reverse-time migration (RTM).

Before initiating the MP-FWI imaging workflow, we smoothed the models derived from the conventional workflow to emulate starting with less mature inputs. The maximum inversion frequency started at 15 Hz and progressed up to 25 Hz. The input to MP-FWI imaging was minimally processed relative to the input to conventional migration. The processing workflow included cultural noise attenuation (adaptive notch filtering), despiking, random noise attenuation, mild linear noise attenuation, and surface-consistent corrections. Mild linear noise attenuation is required to ensure that surface waves and guided shear waves are suppressed, but all multiples are preserved. This abbreviated processing workflow notably does not include multiple modeling with adaptive subtraction or 5D COV interpolation, which are time-consuming and challenging steps in a conventional seismic processing workflow. For the forward modeling, we used a wavelet that represents the theoretical impulse response of the acquisition system. Surface-consistent corrections are applied to the input data to compensate for complex wavelet distortions associated with heterogeneous surface and near-surface conditions.

## Results

For this application of MP-FWI imaging, two outputs were generated: a velocity model and a reflectivity model. As an external evaluation of the velocity model, the fully processed seismic data was Kirchhoff prestack depth migrated using the MP-FWI imaging velocity model. Figure 1 shows the COV KDM snail gathers migrated with the initial velocity model (refraction tomography merged with depth-converted stacking velocities), the conventionally derived velocity model (diving wave FWI followed by reflection tomography), and the MP-FWI imaging velocity model. The conventional model-building workflow significantly reduced gather curvature and azimuthal kinematic variations (“jitter”) in the gathers. This is further improved after migration with the MP-FWI imaging velocity model. This demonstrates that the MP-FWI imaging velocity model provides a clear kinematic improvement over the conventionally derived velocity model. Figure 2 shows how the imaging improvements observed on the KDM gathers translate to stacked sections. The conventional workflow significantly simplified the mid- and long-wavelength structure and increased the bandwidth of the stack due to improved gather flatness and reduction in azimuthal kinematic variations. Additional short- and mid-wavelength structural simplification is evident in the stack section migrated with the MP-FWI imaging velocity model, as highlighted by the yellow arrows. This further corroborates the kinematic accuracy of the velocity model derived using this approach.

To evaluate the quality of the MP-FWI imaging reflectivity output, we compare it to an RTM image produced using the fully processed seismic data and the model derived from the conventional workflow (Figure 3). Since MP-FWI imaging is a least-squares imaging solution that utilizes the full wavefield, the derived reflectivity has a more robust amplitude profile and better illumination compensation. Imaging of discontinuous features—such as faults, channels, and unconformities—is significantly improved, as shown by the yellow arrows. The lateral continuity of the shallow low-amplitude reflectors is also significantly improved. Refinements to the velocity model result in structural simplification in the shallow and deep high-velocity carbonate sequences. These imaging improvements are resolved directly from the partially processed field data and achieved without prior structural information from interpretation.

## Conclusions

We have demonstrated a successful application of MP-FWI imaging on land seismic data acquired in a challenging desert environment. The MP-FWI imaging reflectivity estimated directly from the minimally processed seismic data shows a significant uplift compared to an RTM using the fully processed seismic data. The improved kinematic accuracy of the MP-FWI imaging velocity model relative to the velocity model derived with the conventional model-building workflow is further substantiated by favorable KDM comparisons using the fully processed seismic data.

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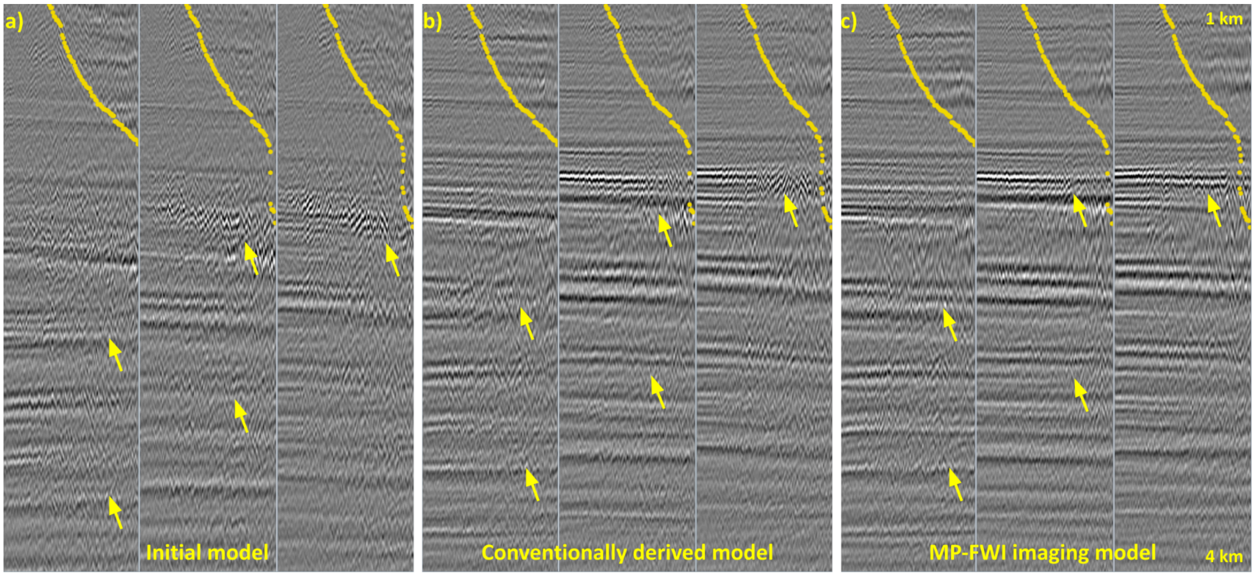

Figure 1: COV KDM snail gathers migrated with the initial velocity model (a), the velocity model derived through the conventional workflow (b) and the MP-FWI imaging velocity model (c). 50 degree angle is annotated with a thick yellow dotted line. Offsets are limited from 0 - 2.4 km.

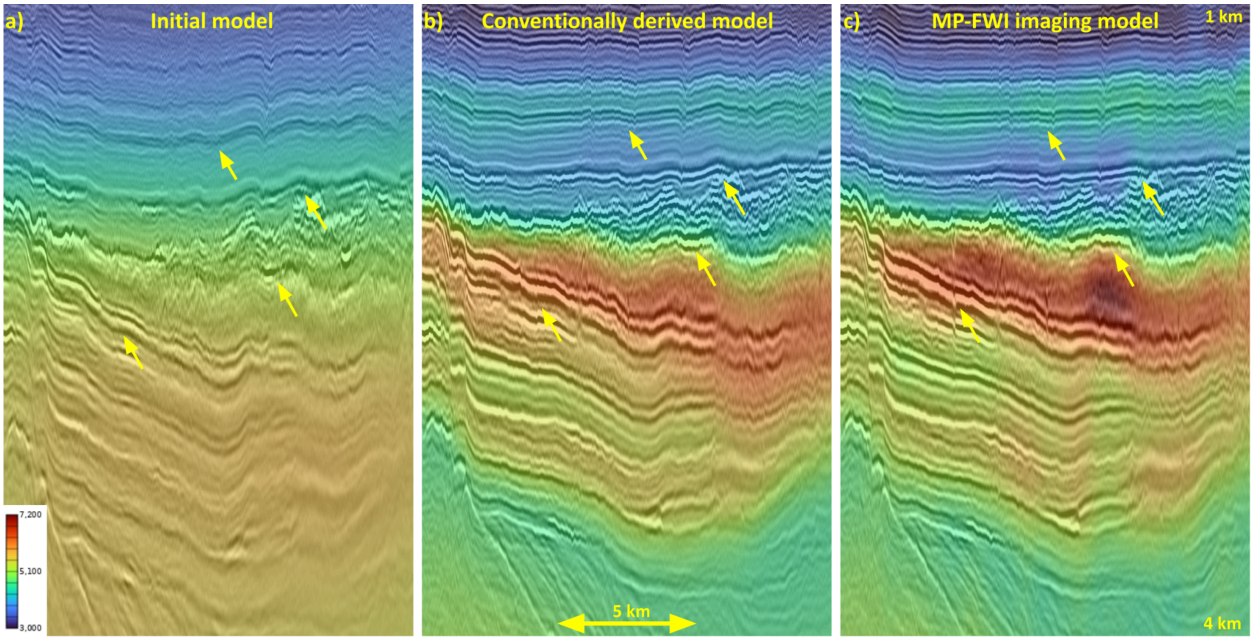

Figure 2: Velocity models co-rendered with associated KDM stacks for the initial velocity model (a), the conventionally derived velocity model (b) and the MP-FWI imaging velocity model (c).

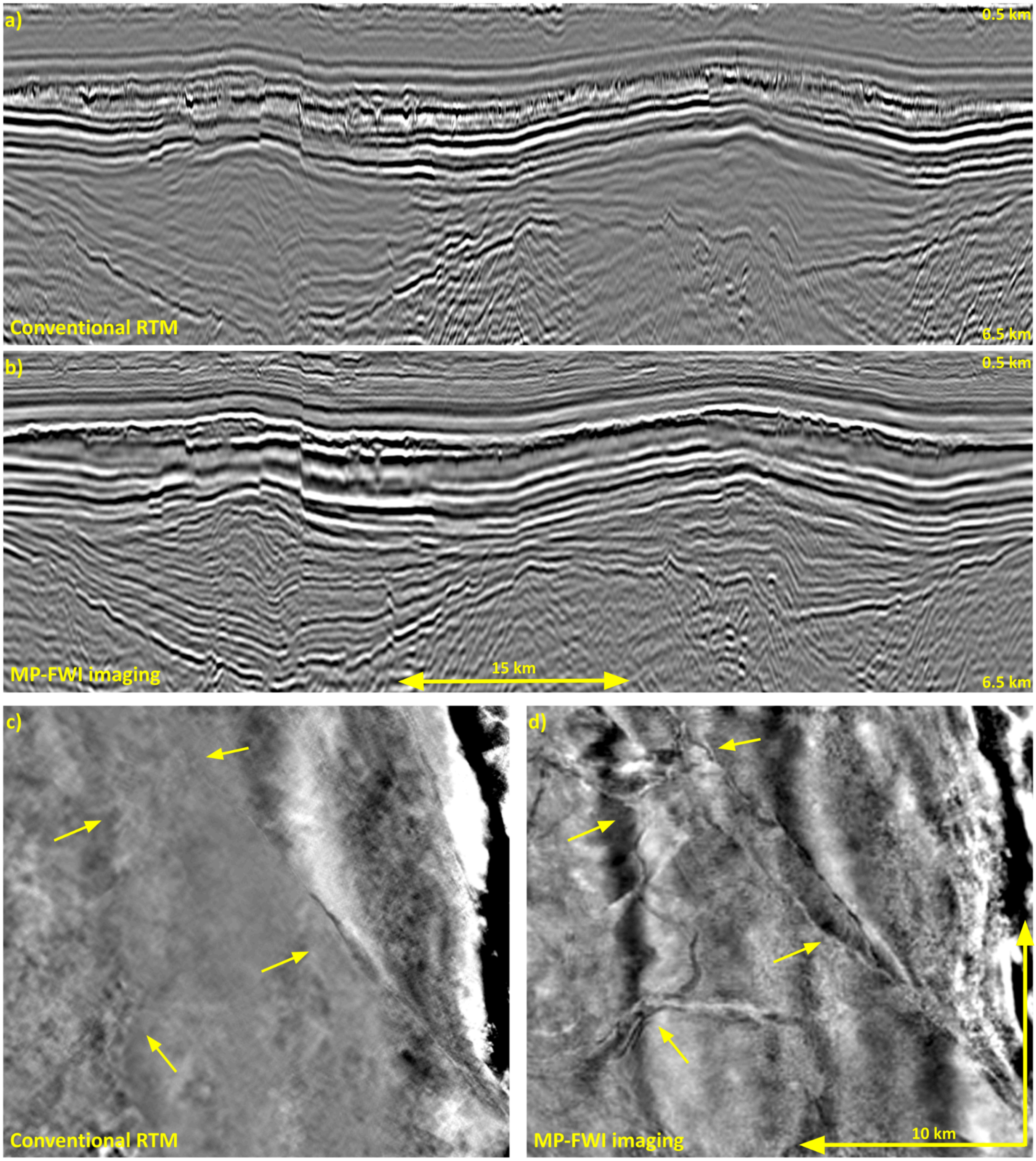

Figure 3: Vertical section through the 25 Hz RTM of the processed data using the conventionally derived velocity model (a) and the 25 Hz MP-FWI reflectivity (b). Depth slices at 780 m through the 25 Hz RTM image (c) and 25 Hz MP-FWI imaging reflectivity volume (d).