Enhancing Subsalt Resolution with Elastic Multi-Parameter FWI: a Gulf of America case study

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Summary

The integration of sparse Ocean Bottom Node (OBN) acquisition with Elastic Full-Waveform Inversion (EFWI) has remarkably improved subsalt imaging in the Gulf of America. We present a case study of applying the Elastic Multi-Parameter Full Waveform Inversion (E-MPFWI) to a sparse OBN data in one of the Amendment surveys in Mississippi Canyon. Through proper kernel separation, E-MPFWI jointly inverts a low frequency background velocity that accounts for the kinematic effect and a high-resolution reflectivity of the subsurface, which, even compared to the FWI derived reflectivity (FDR) in single parameter FWI, has improved SNR with better illumination, leading to sharper interfaces in the challenging subsalt area.

Introduction

Full Waveform Inversion (FWI) has evolved to a robust and reliable technique to build accurate velocity models for depth imaging, which has been routinely applied in seismic processing for both land and marine surveys, especially the sparse Ocean Bottom Node (OBN) acquisition with blended sources has greatly promoted the success of FWI in geologically challenging area like Gulf of America and Brazil basins within operational budgets. This configuration is specifically allowed to record low-frequency signals that can be as low as sub hertz which has favored the high-end FWI and stable kinematic model building. The integration of sparse OBN acquisition with the latest Elastic Dynamic Matching FWI (E-DMFWI) has demonstrated clear advantages in inverting high quality velocity model with enhanced illumination, accurate salt geometry inversion, and detailed mapping of sediment truncations against salt feeder zones.

Traditional single parameter elastic FWI mostly focuses on inverting a P-wave velocity, while shear velocity and density are passively updated following some analytical relation with Vp derived with well constraints. Though this has been proven robust and effective, in complex geological setting, a single function may not represent the whole model properly.

Furthermore, the combination of node sparsity and blended sources poses large limitations for traditional depth imaging methods like Reverse Time Migration (RTM), especially for high resolution imaging. Least-Squares Reverse Time Migration (LSRTM) has become the industry benchmark for high-resolution seismic imaging, specifically for its power to compensate for irregular illumination and sharpen structural interfaces. LSRTM effectively suppresses migration artifacts and balances amplitudes in poorly illuminated areas, such as beneath the complex salt bodies in the Gulf of America. FWI derived reflectivity (FDR), which is equivalent to a nonlinear version of data-domain least squares RTM, has proven to be an effective algorithm to produce a high-resolution seismic image as a natural product of high frequency FWI, especially the one derived from elastic FWI.

Multi-Parameter Full Waveform Inversion (MP-FWI) inverts velocity and reflectivity at the same time, where the velocity represents the low-resolution background model that accounts for the kinematics while the reflectivity is derived from the high-resolution impedance (Huang *et al*., 2025, Macesanu *et al*., 2026). This has been implemented in both acoustic (Yang *et al*., 2021) and elastic media (Huang *et al*., 2025) and have been applied in both land (Sheng *et al*., 2026) and marine surveys (Huang *et al.*, 2026). By using a full elastic wave equation, Elastic Multi-Parameter Full Waveform Inversion (E-MPFWI) not only inverts for reflections but also takes advantage of the contribution of the entire wavefield including mode converted waves and transmissions. A key advantage of this approach is the least-squares effect, which suppresses incoherent noise and focuses energy in poorly illuminated zones. Starting with a smoothed version of a 12Hz E-DMFWI model as initial, we demonstrate the kinematic background velocity is optimized and allow the E-MPFWI to resolve high-resolution reflectivity that is both structurally accurate and dynamically consistent with the true elastic properties of the subsurface.

Examples

The test data was acquired using sparse ocean bottom nodes from the Amendment phase 4 survey in Gulf of America (Figure 1). The node data was acquired with 1.2 km x 1.2 km staggered node spacing, a 75 m × 75 m source grid, and the minimum max offset is larger than 30 km. The dual vessel utilized the extended low frequency Gemini sources, where the lowest usable frequency can be pushed down to 0.6 Hz (Xing *et al*., 2026). This enhanced low-frequency source is a single-chamber design and thus can be treated as a point source with no angular or azimuthal variation. This can particularly benefit the numerical simulation in FWI as the directional effects inherent in air gun arrays are often complex to be modeled accurately.

The combined contribution of E-DMFWI and sparse OBN data is well demonstrated in Figure 2. Compared to the RTM image using a legacy model as the initial (Figure 2a), a model from 12 Hz E-DMFWI results in a significant uplift in the salt geometry and subsalt image in the RTM result (Figure 2b). The corresponding FDR further demonstrates the enhanced illumination and resolution in the subsalt area (Figure 2c).

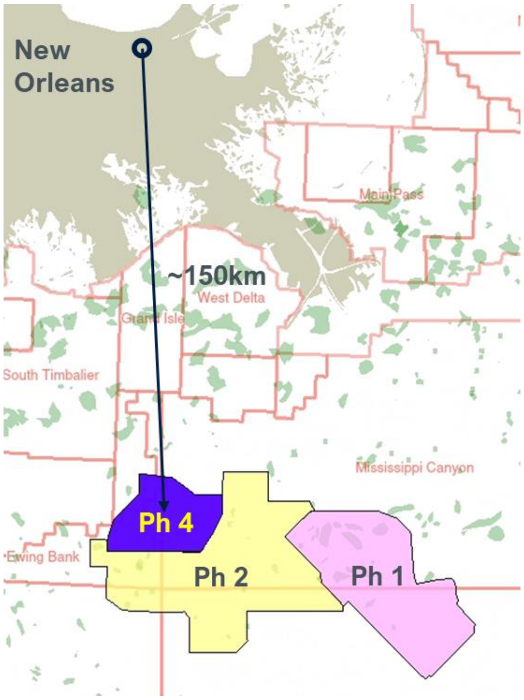

Figure 1 Map of the Amendment 4 survey area.

E-MPFWI was applied to this sparse node data, where the starting velocity model is a low pass filtered 12 Hz E-DMFWI model, as shown in Figure 3a and the corresponding FDR in Figure 3b, to remove the high-resolution component while preserving the kinematics. The E MP FWI resulted model is shown in Figure 3c and a 15Hz RTM image of the OBN data using this model is shown in Figure 3d. Even with deblending properly applied, the RTM result still shows quite amount of swing noise in the subsalt basin and suffers more from illumination effects compared to the FDR. Figure 3e and 3f show, respectively, the inverted velocity and reflectivity after 15 Hz E-MPFWI. As expected, the E-MPFWI inverted velocity does not seem being updated significantly, which attributes to two facts: 1) the E-MPFWI started with a smoothed version of a 12 Hz EFWI model, which has been converged well and kinematically accurate, and 2) the velocity update in E-MPFWI is the low frequency component accounting for kinematic improvement, which is minimum in this case. However, the inverted reflectivity in Figure 3f is significantly superior to the RTM image, and it even has higher resolution than the FDR image in Figure 3b, this is also attributed to the proper scale separation in multi-parameter FWI.

A closer comparison of the zoomed sections on the right side of each image in Figure 3 reveals clear uplifts in the inverted reflectivity, with much better resolved reflectors near the base of salt and more balanced amplitude while preserving the amplitude variation as pointed by the arrows compared to other two images. The depth slices in Figure 4 further demonstrate the clear improvement of the inverted reflectivity in the resolution.

Conclusions

We successfully applied the Elastic Multi-Parameter FWI to a sparse OBN data from the Amendment phase 4 survey in the Gulf of America. By initializing the process with a smoothed version of 12 Hz E-DMFWI model, E-MPFWI provides a robust and efficient path toward high-fidelity reflectivity inversion. Due to the scale separation associated with E-MPFWI framework, the resulted reflectivity shows improved continuity and resolution in the complex subsalt area even compared to the FDR of single parameter FWI. The multi-parameter approach is critical for resolving the complex subsalt architectures, delivering a product that is not just an image, but a physically consistent elastic model.

Acknowledgements

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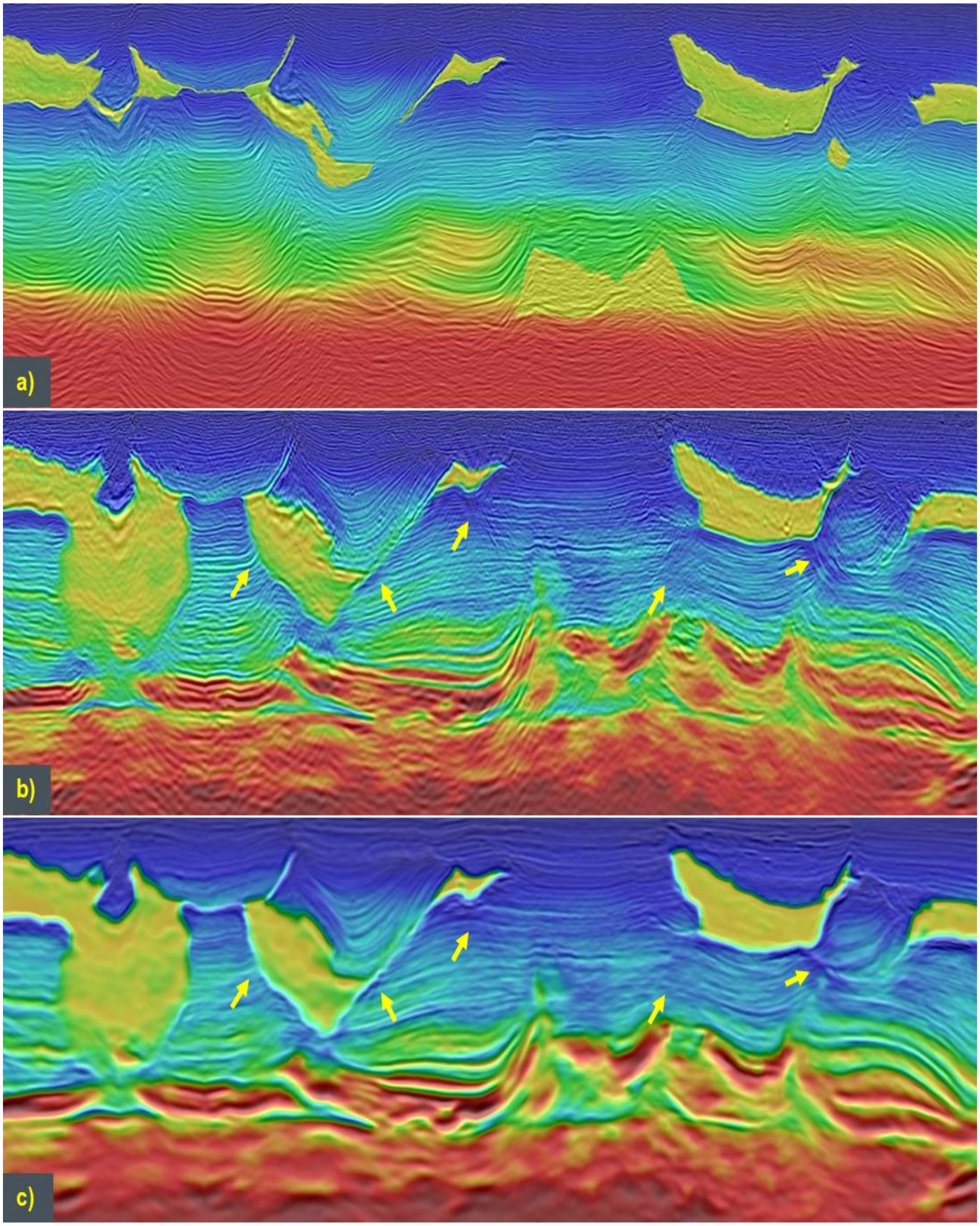

Figure 2): A sparse node example from the Gulf of America: a) RTM image using the legacy model overlaying with it; b) RTM image using 12 Hz E-DMFWI model overlaying the model and c) FDR after 12 Hz E-DMFWI overlaying the model.

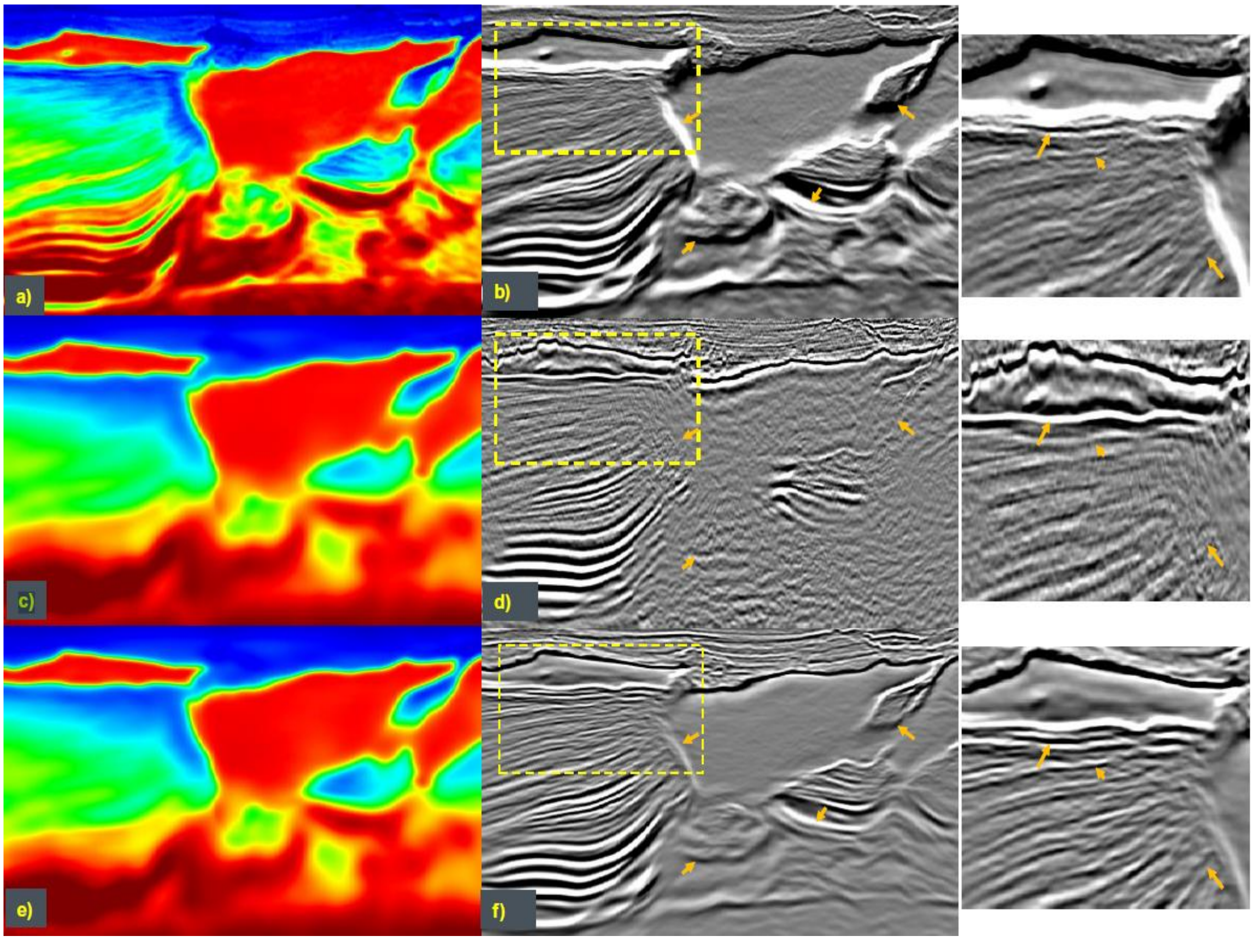

Figure 3: One-inline section of a) 12 Hz E-DMFWI velocity and b) the corresponding FDR; c) the E-MPFWI initial velocity and d) 15 Hz OBN data RTM image using the initial model; e) the E-MPFWI inverted velocity f) and inverted 15Hz E-MPFWI reflectivity.

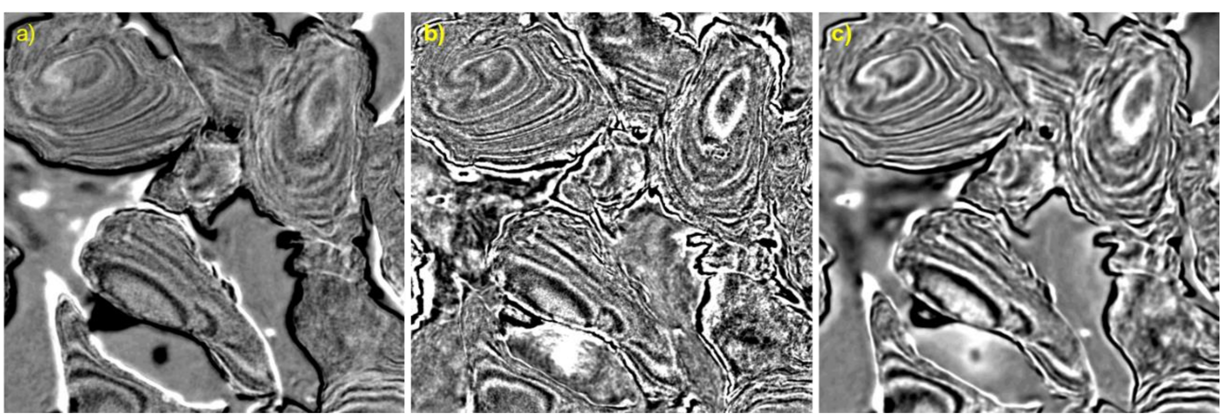

Figure 4: a) depth slice of FDR after E-DMFWI; b) 15 Hz RTM image of WAZ streamer data using initial model of E-MPFWI; and c) Reflectivity inverted using E-MPFWI.