Rethinking Statics with FWI

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Summary

Characterizing the near-surface is essential for accurately imaging deeper subsurface targets in onshore seismic exploration. Traditional model building approaches, such as reflection tomography, face challenges in updating near-surface velocities due to limited offset coverage at shallow depths. Often with traditional approaches, residual statics calculated using an NMO velocity are applied to input data for model building to overcome inadequacies in the velocity model. We have seen (Ellison et al., 2016) that statics calculated on data with an NMO approximation may not be suitable for depth imaging and can degrade the imaging result in cases that deviate from the hyperbolic assumption.

Full waveform inversion (FWI) is robust algorithm for generating velocity models with exceptional resolution and accuracy. It has been increasingly adopted in the industry with numerous successful applications to marine data, especially for surveys featuring rich azimuth, long offsets, and low-frequency recordings. However, its application to onshore data remains comparatively less common (Plessix et al., 2012; Mei et al., 2015; Lemaistre et al., 2018; Tang et al., Masclet et al., 2021; Krishnasamy et al., 2023). FWI faces several challenges in onshore applications. Seismic data acquired on uneven topography require careful handling of wavefield propagation to ensure accuracy and resource efficiency. The process is further hindered by low signal-to-noise ratios (S/N), primarily due to near-surface scattering and heterogeneity. Moreover, the low frequency signal available to start the inversion for onshore datasets is constrained by noise and acquisition parameters. These challenges facing onshore acoustic FWI have been overcome with modern workflows. Details of a modern FWI workflow with case studies are provided.

Workflow

Preprocessing the seismic data for FWI is a critical step. Key processing steps in our workflow include suppressing high-amplitude noise, attenuating ground roll, and applying inverse Q corrections. No statics are applied to the FWI input dataset. The initial near-surface velocity model is constructed using diving-wave tomography, supplemented with shallow well data when available.

For many onshore datasets, there remains a considerable risk of cycle skipping in FWI, due to the uncertainty in the initial starting model and limited low frequencies. For this reason, we employed an optimal transport cost function, utilizing the quadratic Wasserstein distance (Engquist et al., 2016; Yang et al., 2018) that uses the trace envelope to compute the travel time information for the misfit. This approach allowed us to compute more robust travel times for the misfit and reduces the likelihood of cycle skipping. Subsequently, we utilized a multi-channel dynamic matching (DM) FWI cost function (Mao et al., 2020; Sheng et al., 2020). This cost function leverages normalized local cross correlation to quantify the time-dependent disparities between observed and synthetic data. A multi-scale approach is used in the FWI updates, where the offset range and frequency bands used in the FWI updates are progressively increased. After refraction FWI an iteration of reflection tomography and anisotropy update is performed to update the deeper velocity and anisotropy models. Refinement of the velocity model is further advanced using reflection FWI (RFWI), again using the DM cost function. To generate reflection events, absent in the smooth model after diving wave FWI, density contrasts are introduced (Mao et al., 2019). This density contrast is generated by migrating the input data at each RFWI iteration. Again, a multi-scale approach is employed to further reduce the likelihood of cycle-skipping.

Case Studies

Our case study is an onshore survey in East Texas. The source and receiver spacing was 165 ft, with a source line spacing of 1320 ft, with a maximum offset of 20,000 ft. Figure 1a shows a depth slice of the diving-wave tomography, and figure 1b shows a depth slice of the FWI velocity model at 500 ft. When comparing figures 1a and 1b, we can see that FWI successfully captured shallow anomalies caused by abandoned mines in the area. The pre-stack depth migrated image derived from the FWI velocity model shows improved event continuity and a more realistic geological structure, see figure 2. Using the FWI velocity model, we recomputed both the long-wavelength and residual statics. A comparison of residual statics from refraction tomography and the FWI model revealed a clear correlation between anomalies identified by FWI and the residual statics. This suggests that these anomalies would have been missing if residual statics were applied to our input data. Furthermore, when we compare Figure 1c and 1d, we can clearly see a reduction in the residual statics post-FWI, indicating that the FWI process was able to recover some of the mid- to short-wavelength statics and transfer that to a velocity correction.

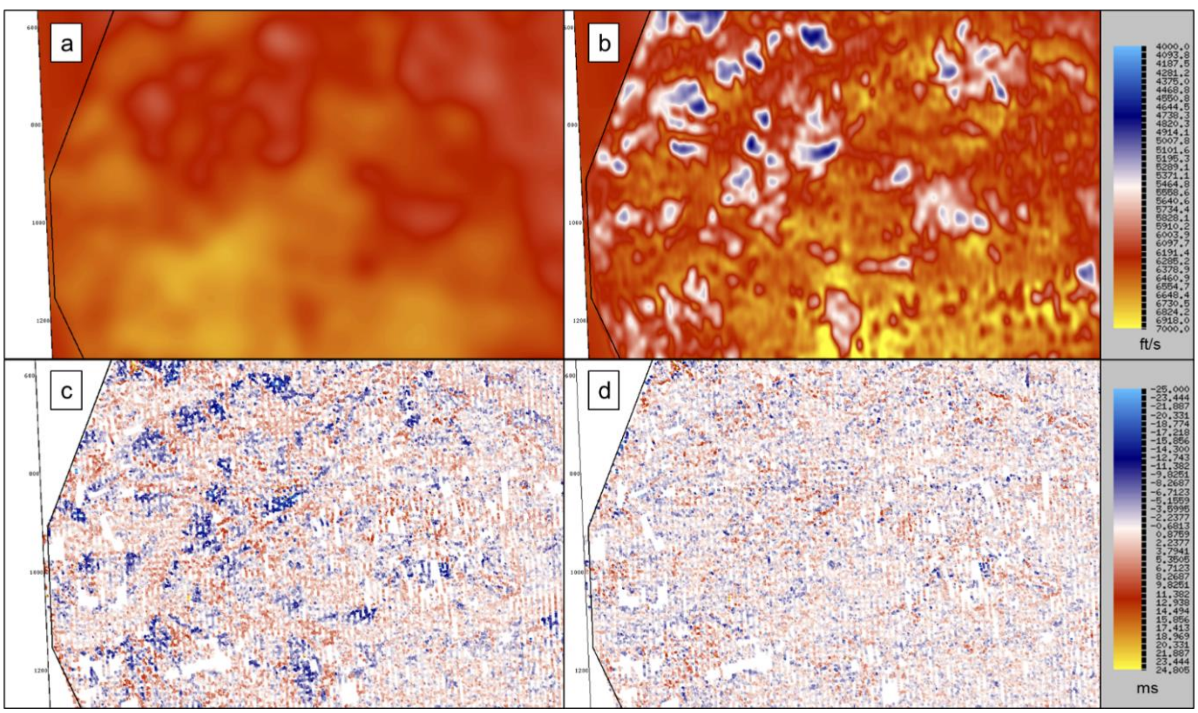

Figure 1: Depth slice at 500 ft; a) diving-wave tomography velocity model; b) diving-wave FWI velocity model; c) residual statics from diving wave tomography velocity model; d) residual statics from diving-wave FWI velocity model

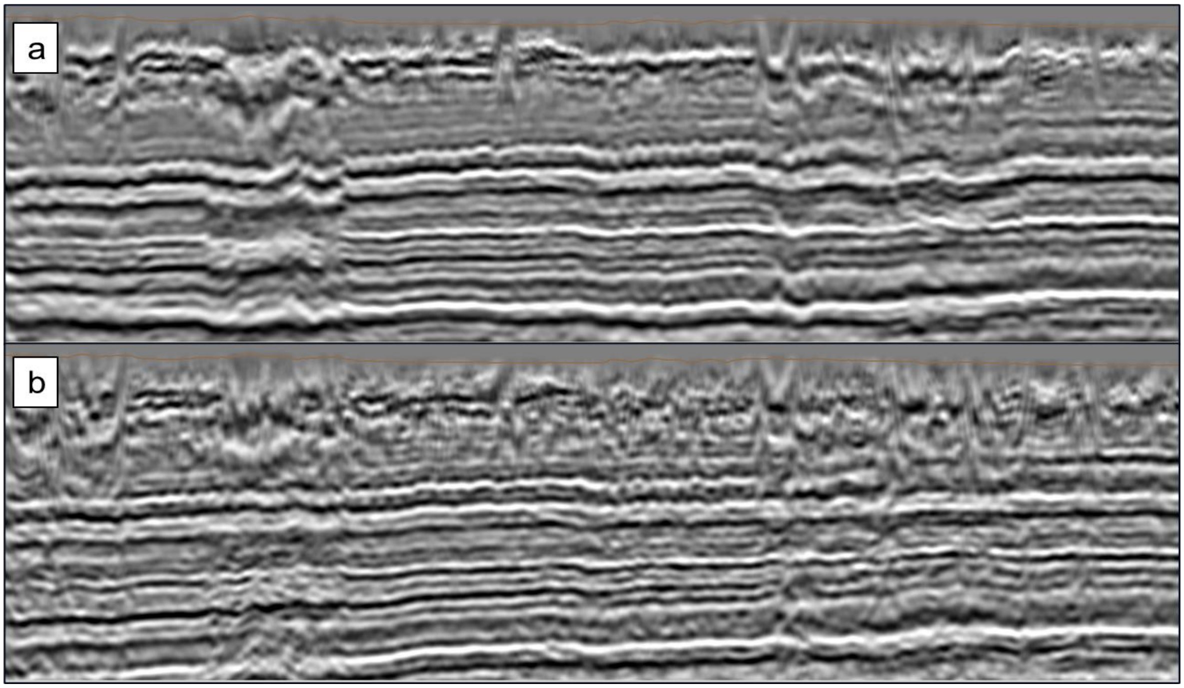

Figure 2: a) Kirchhoff PSDM with diving-wave tomography model; b) Kirchhoff PSDM with diving-wave FWI model

Conclusion

Our workflow has proven to be robust and effective for land data, consistently yielding velocity models that significantly enhance imaging quality. By incorporating FWI in an onshore model building workflow, we have demonstrated that it is possible to capture shorter wavelength corrections in onshore data, which are typically addressed by residual statics. This finding suggests that the approach of applying residual statics prior to FWI may not be the most effective strategy. Instead, allowing FWI to handle these corrections can lead to more accurate and detailed velocity models which might otherwise be obscured by the statics corrections.

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