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Deep Updates - Challenges and Solutions for FWI

N. Chemingui[1], A. Valenciano[1], T. Martin[1]*

[1]PGS

Summary

Conventional velocity model building (VMB) in complex regimes, such as intra and subsalt data, requires time-consuming manual intervention. It is a process that can produce unreliable models, leading to an increase in uncertainty for subsalt lead evaluation. We demonstrate an application of Full Waveform Inversion (FWI) to refine legacy velocity models generated by conventional VMB. We present our solution on a simultaneous long-offsets (SLO) dataset from the Gulf of Mexico, acquired with dual-sensor streamers, which provided low-frequency rich data. The SLO configuration recorded data with 16 km of offset, enabling both refractions and reflections to update the deeper parts of the velocity model. We employ an FWI velocity gradient that eliminates the migration isochrones. This provides support for the intra and subsalt model updates by removing the reflectivity imprint from the updated models. The FWI application successfully refined the geometry of the salt bodies including the base salt and the intrasalt enclosures. RTM images show a marked uplift, particularly for both the salt flanks and subsalt reflectors.

Introduction
Full waveform inversion (FWI) builds high-resolution velocity models. It involves nonlinear minimization of the misfit between recorded and modeled seismic data, while iteratively updating the subsurface model. FWI's success depends on recovering the short- and long-wavelength features missing in the starting model, without which, the use of seismic images can lead to a level of uncertainty in evaluating leads and prospects. Most FWI applications target shallow water data where transmission waves are recorded, enabling the inversion to resolve small-scale features up to the deepest turning point (e.g. Sirgue et al., 2009). Successful applications in deeper water data, where refracted and diving waves are often missing due to limited towed-streamer cable lengths, are now being published. Consequently, there has been a growing demand for acquiring better data for FWI, e.g., long offsets from ocean bottom seismic (Shen et al., 2017) and high signal-to-noise low frequencies (Dellinger et al., 2016). FWI developments have focused on better inversion solutions that reduce the data requirements, producing deep model updates. These efforts combine modified gradients, robust norms for measuring the data misfit, and *a priori* model constraints which permit all wave modes in the data (reflections, refractions, and diving waves) to be used. Here, we combine an acquisition strategy employing simultaneous long offsets (SLO) and a robust FWI solution, inverting both reflections and transmitted arrivals. Our inversion automatically simulates the blended data as acquired in the field with the SLO acquisition. We demonstrate this robust application for accurately updating models in complex intra and subsalt regimes, reducing ambiguity in the final RTM images.

Methodology
The SLO survey acquired high-fold, long offset, and full-azimuth (FAZ) data in the Central and Western planning areas in the Gulf of Mexico (Long et al., 2014), in water varying from 1200 m to 1400 m. Five randomly delayed sources provided offsets in excess of 16 km. The dual-sensor streamers were towed at 20 m obtaining a good signal-to-noise ratio at the low end of the frequency spectrum. The data contained low frequencies, wide azimuths, and long offsets; all useful for FWI.

The inversion scheme uses time-domain wave propagation and a normalized form of the Born scattering kernel to compute the FWI gradient (Tarantola, 1984), solving the two-way anisotropic wave equation using the pseudo analytic (PA) method (Ramos-Martinez et al., 2011). For matching high-contrast interfaces, we use a variable-density implementation for better matching of the relative amplitudes. We use a robust velocity gradient derived from Inverse Scattering theory and impedance-velocity parameterization of FWI (Ramos-Martinez et al., 2016), eliminating the migration isochrones that dominate conventional cross-correlation FWI gradients. The modeling kernel was adapted to automatically accommodate data from simultaneous shooting the SLO data. Figure 1a shows a blended shot gather from two of the sources. The horizontal axis extends 8.1 km and contains data from near and far sources; offset varying from 125 m to 16 km. Figure 1b shows synthetic data from the near source only, while Figure 1c shows data from the blended near and far sources. The difference between panel b and c represents the long offset recordings from the far source.

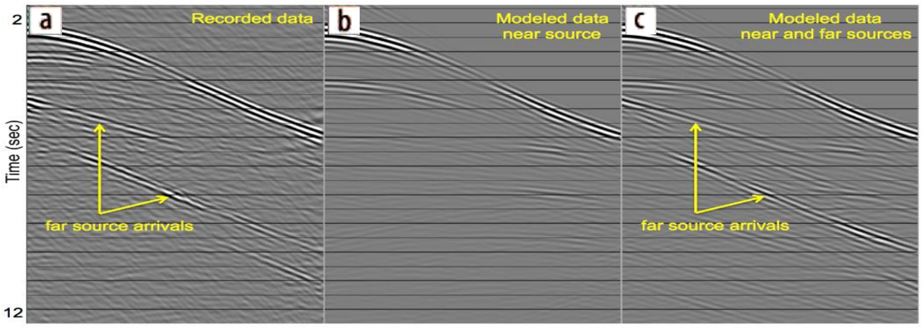

***Figure 1** Shot records: (a) field data, (b) modeled data from near source, and (c) modeled blended data from simultaneous near and far sources.*

Example
To minimize the likelihood of cycle skipping, we performed a multi-stage FWI. The SLO data had coherent signal in the 2-4 Hz frequency band, which was used for the initial pass of model building. The initial velocity model was generated using an interpretive VMB workflow including wavelet-shift tomography and salt interpretation following a top-down strategy. Figure 2 shows a comparison of the updates using only refractions (left) and a combination of refractions and reflections (right) for the

SLO data. The refracted modes produce reliable velocity updates up to 6 km depth. In contrast, our robust FWI velocity gradient uses the reflections to update the velocity model beyond the penetration depth of diving waves. Figure 3 shows a comparison of the RTM images from the initial (left) and the FWI (right) velocity models. The FWI velocity model improves the image of the salt boundaries (top, bottom, and flanks) as well as the sediment truncations against the salt. Similarly, the deeper reflectors display improved continuity after FWI.

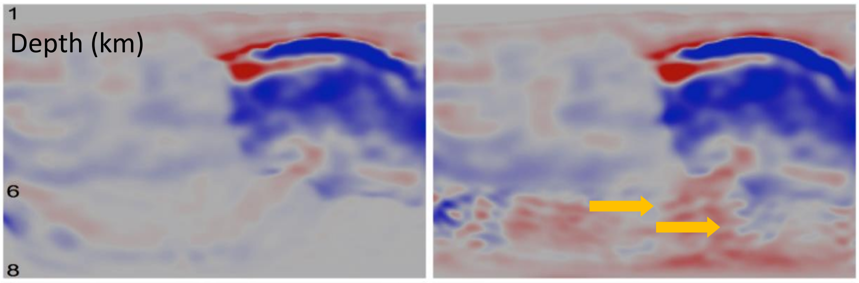

Figure 1 *FWI comparisons: refractions (left), vs. refractions and reflections (right). Reflections update the long wavelength components of the model beyond the penetration depth of diving waves (orange arrows).*

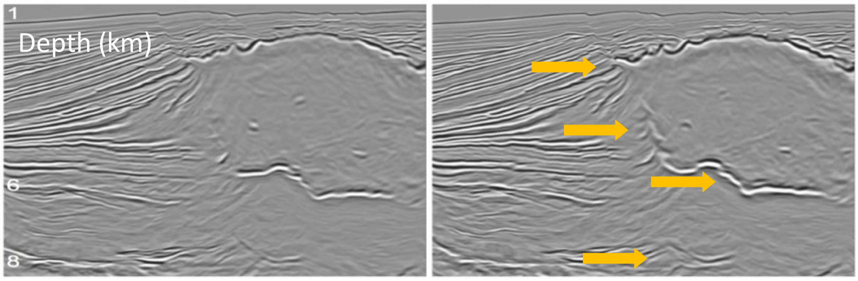

Figure 2 *RTM images comparison: initial (left), vs. FWI (right). Note how the FWI model improves the imaging of the salt boundaries and the sediment truncations (orange arrows).*

Conclusions

We discussed an automated workflow for refining velocity models in complex regimes using data from SLO recordings, using a robust FWI gradient that incorporates reflection data for deep model updating. Our scheme automatically simulates the blended data as acquired in the field without source separation. Applications to both data sets demonstrated that FWI is able to refine the sediment velocities and repair the geometry of the salt including the intra-salt enclosures, improving the RTM image at the salt flanks and the subsalt reflectors, and reducing uncertainty in the final images.

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