Using full waveform inversion to update supra-salt velocity models: a case study in the Gulf of Mexico
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Summary
In the Gulf of Mexico (GOM) salt province we often find sediment carapace on top of shallow salt structures or in the basins around the salt. Conventional reflection tomography has difficulty giving any reliable updates for this layer due to the lack of reflection events in the geo-bodies. We applied Full Waveform Inversion (FWI) to a geologically challenging area where shallow geo-bodies, fractures, and carapaces co-exist with shallow salt. The high resolution of the FWI updated velocity provides a better image of the supra-salt, salt boundary and subsalt.

Introduction
Wave-equation based FWI, pioneered by Lailly (1983) and Tarantola (1984), updates a velocity model by minimizing the mismatch between the observed and modeled seismic data. Studies have proven that FWI can provide detailed and interpretable models, especially in the presence of shallow channel features and gas pockets (Sirgue et al., 2009; Jones et al., 2013; Ratcliffe et al., 2013; Mothi et al., 2013). In this study we applied FWI to resolve complex overburden velocities in a geologically challenging area where shallow geo-bodies, fractures and carapaces co-exist with shallow salt. An interpretation driven workflow is commonly used to adequately estimate velocity models in these complex regions (Ritter, 2010). However, this workflow is often expensive. It involves geological interpretation and requires several processing steps including interpretation of geo-bodies/carapaces, interval velocity scans and constrained reflection tomography. Reflection tomography is often challenging due to the lack of reflectivity; however FWI can use transmitted arrivals as an advantage to better update velocity models.

Methodology
FWI applications around salt bodies remain challenging mainly due to the sharp velocity contrast at the salt flanks and the lack of transmitted arrivals penetrating through the salt. The sharp velocity change at the top of salt (TOS) generates refractions or head waves that can interfere at far offsets with the diving waves used for the FWI update. If the salt geometry is already well defined, this is not a problem. However, this is unlikely to be the case when the supra-salt velocity is not correct. Also, updating for this sharp velocity contrast at the TOS requires running FWI at extremely high frequencies, which would make the cost unreasonable and increase the chances of cycle skipping problems (Shah et al., 2012). This means that the only way the salt geometry can be updated is with lower frequency FWI and a smoothed velocity model, which limits the accuracy of the sediment update right above the salt.

In order to avoid FWI issues with salt and to apply proper constraints to the inversion, we use a top down approach and apply FWI in two separate passes. The legacy VTI sediment-only model is used as the initial model for a first pass FWI to update supra-salt sediment velocities. FWI uses transmitted arrivals to reduce velocity uncertainties of the complex overburden, and therefore generates a better positioned TOS. After refining the TOS, we then conduct the salt flood migration for base of salt (BOS) adjustment. Once the salt geometry has been better defined, we apply a second pass FWI on this improved salt model with an update mask targeting only in the carapace and geo-body regions right above the salt. We then refine the salt geometry again and examine the potential benefits and impact of FWI on subsalt imaging using deep-water GOM field data.

Study area
The study area is located in the Alaminos Canyon protraction of the GOM and features a water depth of approximately 2000 m – 2700 m. A wide azimuth (WAZ) survey was acquired in a northeast-southwest orientation with a nominal fold of 189, an 8100 m maximum inline offset, and a ±4000 m maximum crossline offset. We use the legacy VTI model from reflection tomography as the baseline to study the benefits of FWI. Although tilted transverse isotropic FWI can be more beneficial in this area, we conducted a VTI FWI to have a fair comparison with the conventional VTI model building results.

Figure 1 shows the typical geology setting in this area: there is an allochthonous salt system, with the supra-salt sediment being mainly divided into two layers, namely a compartmentalized sediment layer and a thick carapace layer capping the salt.

Challenges of reflection tomography
We can see from the controlled beam migration (CBM) common image gathers (CIGs), shown in Figure 1d, that the conventional reflection tomography gives a velocity that flattens the shallow events relatively well. However, the resolution of the tomographic model is limited and is inadequate for resolving the fault partitions. Also, unsurprisingly, the reflection tomography fails to update the velocity model where little reflectivity and reliable
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moveout is available. For example, this is seen in the carapace geo-bodies and also in the very thin sediment layer just above the TOS.

FWI application and quality controls

We show inversion results from eight sail-lines to demonstrate the benefits of FWI for deep water GOM data. Our approach uses the VTI anisotropy assumption and combines an FWI update of the supra-salt velocities in the 3-8 Hz frequency range and refinement of the salt geometry.

The velocity perturbation from FWI is shown in Figure 2a. FWI slows down velocities for two regions (Figure 2a, red arrows) that could consist of shale geo-bodies. Sediment layers lying directly on the TOS show a velocity increase, although a velocity inversion region was found above the salt finger. This is consistent and follows a strong continuous reflector with maximum energy at the trough (Figure 2a, yellow arrow). A filtered common shot gather is used to demonstrate the timing checks of the FWI application (Figure 2b). The events within the blue box are identified as diving wave energy from the diving wave simulation (Figure 2c). Figure 3 compares timing differences of observed and modeled data before and after FWI. The cross-correlations in Figures 3c and 3d indicate that the timing alignments between the observed and modeled wavefields are significantly improved by FWI. The shallow mid-far channel refractions/diving waves modeled by the conventional tomographic model have smaller travel times than the observed data. FWI slows down the shallow sediments and geo-bodies to correct these timing errors. After FWI, the cross-correlation between the observed and modeled wavefields has a nearly horizontal pattern, which indicates good timing alignments.

Figure 4 shows the equivalent of Figure 1 after our FWI workflow. In comparison with Figure 1, FWI slows down the velocities for the two geo-bodies (Figure 4, red arrows). These could consist of over-pressured shale. CBM CIGs from the FWI model are, in general, similar or slightly flatter than from the conventional tomographic model. The focusing of the sediment overburden is similar in both models. However, the supra-salt sediment structures were adjusted by FWI. We did not apply any reflection tomography or subsalt velocity updates after FWI, so the subsalt velocity is similar to the legacy model. The impact on the salt geometry and subsalt images from FWI was mainly observed in the complex overburden region.

Reverse Time Migration (RTM) results

Figure 5 shows an inline and a crossline section of the RTM images for the legacy and the FWI models. After FWI, the sediment velocity model follows the structures better and the geo-bodies have better delineation. Two shallow TOS regions are repositioned and become more continuous (Figure 5, red arrows). In addition, the BOS also has improved focusing and continuity. Overall, the complexity in the salt geometry is reduced with the FWI flow, suggesting that the salt geometry in the legacy model needed additional refinement due to velocity uncertainties in the complex overburden region. We also observe improvement in the subsalt regions (Figure 5, blue circles), along with better focusing and more continuous subsalt sediment structures. Both inline and crossline images show consistent improvement in the imaging quality from the FWI model, where subsalt sediments exhibit better focusing and continuity.

Conclusions

We have applied FWI to a deep water GOM field dataset. The results of this test demonstrate that FWI can be beneficial for salt interpretation and subsalt imaging. In this study FWI resolves complex overburden velocities in a geologically challenging area where shallow geo-bodies, fractures and carapaces co-exist with shallow salt. FWI gives a refined and simpler salt geometry to produce improved subsalt images. This suggests that it is beneficial to integrate FWI into the standard salt model building flow, especially for regions containing complex overburden.

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Figure 1: The legacy model overlaid on reverse time migration (RTM) images: (a) depth slice at 3450 m, (b) a crossline section, (c) an inline section, (d) controlled beam migration (CBM) common image gathers (CIGs).

Figure 2: (a) Velocity perturbation from FWI overlaid on RTM image, the red arrows highlight areas of slow-down velocity, the yellow arrow points to a velocity inversion (b) filtered observed data (3-8Hz) with shot location indicated by the star symbol, and (c) diving wave simulation using FWI model.

Figure 3: Timing differences before and after FWI: modeled data from: (a) the legacy reflection tomography model and (b) the FWI model; cross-correlation of the observed and modeled data for: (c) the legacy reflection tomography model and (d) the FWI model.
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Figure 4: The FWI model overlaid on RTM images: (a) depth slice at 3450 m, (b) a crossline section, (c) an inline section, and (d) CBM CIGs.

Figure 5: RTM images for: inline (a) and crossline (b) sections using the legacy model; inline (c) and crossline (d) sections using the FWI model.
EDITED REFERENCES
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REFERENCES


