Improving mini-basin and subsalt imaging with reflection full waveform inversion

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Summary

Reflection-based full waveform inversion (RFWI) is increasingly used to recover long wavelengths of the background velocity model and provide updates that extend beyond the reach of diving waves. In our case study, we use an RFWI method that first updates the density using the high-wavenumber components of the decomposed full waveform inversion (FWI) gradient and then updates the velocity using the low-wavenumber components. We show on a deep water example from the Mexican side of the Perdido fold belt that RFWI improves the velocity inside sediment mini-basins and thus the interpretability of the underlying salt. We also apply this method for the intra-salt and subsalt velocity updates and show how it can improve imaging of the deep targets.

Introduction

Subsalt imaging is strongly affected by the velocity model of the overburden. Both a proper suprasalt velocity and a precise salt interpretation are required to define an accurate salt geometry. Additionally, velocity errors related to sediment inclusions and sutures within the salt, so called 'dirty salt', as well as subsalt velocity, can have a large influence on the imaging of targets under the salt. Different methods are already available to help solve for all these components of the velocity model, but they each have their own limitations.

Ray-based tomography is a default tool for updating both suprasalt and subsalt velocities. However, when the shallow sediment geology is complex, tomography can fail to provide a velocity model that is accurate enough for correct top-down salt geometry modeling. Ray-based tomography also has limited success in dirty salt and subsalt applications in the Gulf of Mexico (GOM), even when reverse time migration (RTM) angle gathers (Xu at al., 2011; Li et al., 2011) or surface offset gathers (SOGs) (Yang at al., 2015) are used. Due to a narrow range of incident angles at subsalt events, ultra-long offset data is essential for improving subsalt velocity tomography updates with either type of RTM gathers.

FWI that primarily uses diving waves can refine the velocity model beyond the capabilities of tomography and has become a standard tool used to improve the imaging of the shallow overburden (Sirgue et al., 2010; Ratcliffe et al., 2014). However, when applied on data acquired with traditional narrow or wide azimuth (WAZ) geometry, FWI has difficulty properly updating deeper strata due to the lack of diving wave penetration. To reduce the need for long offset acquisition and reliance on the refraction energy in data, reflection-based FWI methods that utilize the low-wavenumber component of the FWI gradient (Mora, 1989) are increasingly used to update deeper parts of the model (Ramos-Martinez et al., 2016; Sun et al., 2016). The low-wavenumber component is generated along the reflection wavepath when transmission energy is reflected back to the surface from deeper reflectors. Methods like explicit model separation (Xu et al., 2012) or wavefield decomposition (Liu et al., 2011; Tang et al., 2013; Irabor and Warner, 2016) have been proposed to separate low-wavenumber from the dominant high-wavenumber components.

In our case study, we use the RFWI approach described by Chazalnoel et al. (2017). Following the separation of the FWI gradient based on the propagation direction of the wavefields, high-wavenumber and low-wavenumber terms are obtained alternately to update density and velocity, respectively. The high-wavenumber density update introduces the deep reflectors needed for the next iteration of low-wavenumber velocity updates. Our results show that this method is able to improve the velocity of the sediment mini-basins where both ray-based tomography and FWI had limited success. We also demonstrate how application of RFWI results in a better salt geometry interpretation. Finally, we show that RFWI can refine dirty salt velocity and update subsalt velocity to improve subsalt imaging.

Study area

Our study area is situated in the western GOM, on the Mexican side of the prolific Perdido fold belt. The water depth ranges from 1500 m to 3500 m. Large deposits of salt and shale are influenced by a regional compressional system. Advancement of the salt nappes is hindered by the Perdido folds, resulting in salt autosutures and a rugose top of salt (TOS). Shallow overburden is severely deformed due to the shortening, while large folds and thrusts form the subsalt Lower Tertiary targets.

Data used in the study was acquired using a WAZ acquisition geometry. Maximum inline and crossline offsets were $\pm$ 8100 m and $\pm$ 4200 m, with a nominal fold of 189 and record length of 14 s. Data pre-processing steps included denoise, source and receiver deghosting, designature, and 3D surface-related multiple elimination.

Mini-basin velocity update with RFWI

In our application of RFWI, we started with a velocity model that went through several iterations of tomography and FWI updates. These updates were able to improve the

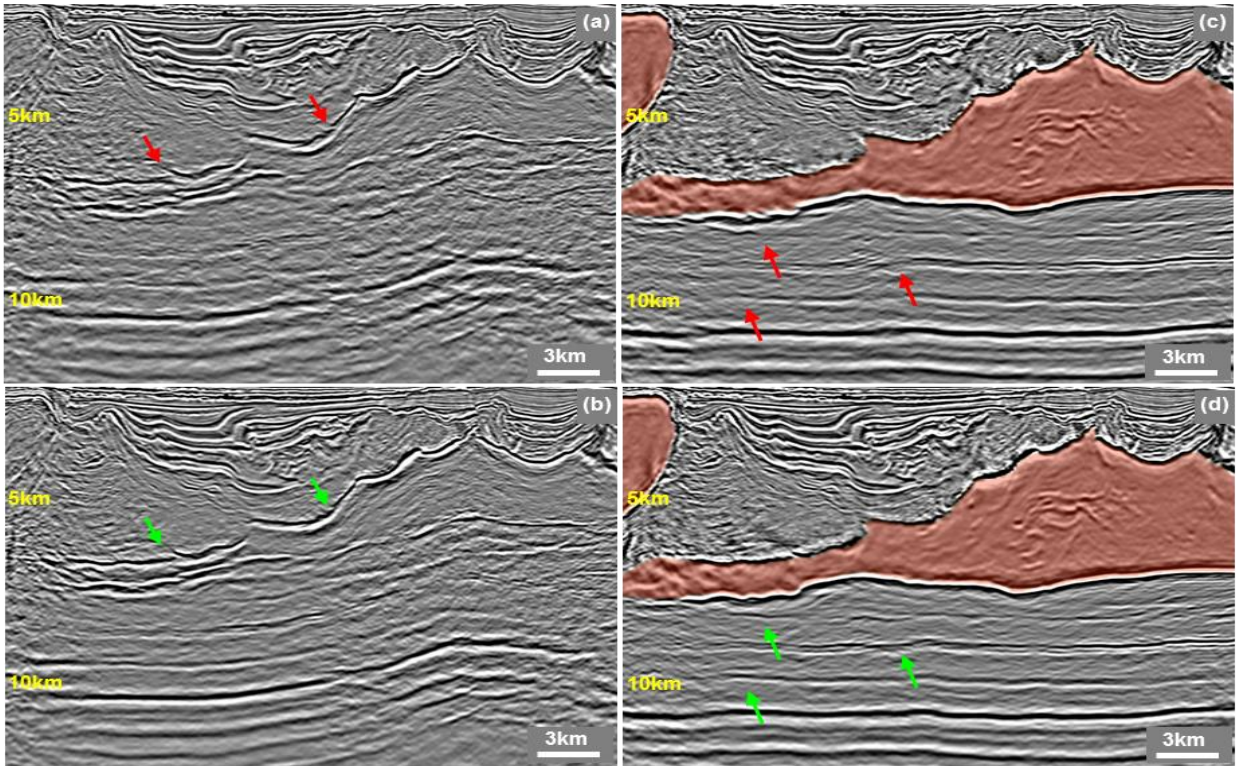

Figure 1: Sediment flood RTM shows TOS before (a) and after (b) suprasalt RFWI. Salt body RTM image before update (c). Suprasalt RFWI and re-interpretation improved focusing of BOS and continuity of subsalt (d).

velocity of the shallow folds but failed to properly update the shale velocity at the bottom of the mini-basin due to the close proximity of salt, the absence of reflectivity inside the shale, and the shale depth. The sediment flood RTM shows that the underlying rugose TOS was poorly imaged, without sufficient focusing needed for a precise horizon interpretation (Figure 1a).

RFWI was then applied from 4 Hz to 7 Hz using a wavelet extracted from the data. High-wavenumbers of the density were updated down to TOS to drive the low-wavenumber velocity update above it. Figure 1b shows the sediment flood RTM image after RFWI update. We can see improvements in the imaging of TOS: a strong peak event has fewer swings and is now more coherent. The initial velocity model is shown in Figure 2a and perturbation in Figure 2b. Sediment flood RTM SOGs showed a more distinct TOS event following RFWI application (Figures 2c and 2d). Although data QC indicated that the imaging was improved, the perturbation showed the somewhat vertical nature of our RFWI update. Due to poor reflectivity of the shale, this deeper part of the perturbation was dominated by the contribution of low-wavenumber energy backscattered from the stronger TOS event. Separating the update down to the TOS, and then subsequently down to the Mesozoic, was one way to mitigate the vertical resolution limitation in our RFWI method (A. Gomes and N. Chazalnoel, personal communication, 2017).

The suprasalt RFWI updated velocity model was used to re-run sediment and salt floods, which were then used to re-interpret the TOS and base of salt (BOS), respectively. Improved images of both the BOS and subsalt show the direct impact of the suprasalt velocity accuracy on salt interpretation (Figures 1c and 1d).

Subsalt velocity update with RFWI

Following the shallow sediment update and salt geometry refinement, we applied a second iteration of RFWI. We allowed updates in sediment inclusions within the salt and in the subsalt, but maintained the precise salt boundaries necessary for high-definition imaging. The parameters used were similar to those in the suprasalt RFWI application. The key difference was allowing the high-wavenumber density update to extend to 14 km. We show an example from a location where large sediment inclusions and sutures influence the imaging under a salt nappe (Figure 3a). Improvement in the intra-salt velocity provided more correct BOS positioning and reduced pullup in the subsalt (Figure 3b). RTM SOGs after RFWI showed flatter gathers both within and below the salt (Figures 3c and 3d).

Our final example shows the application of RFWI in an area of highly deformed Perdido folds. Lines across the dip (Figure 4a) and strike (Figure 4b) directions of a subsalt

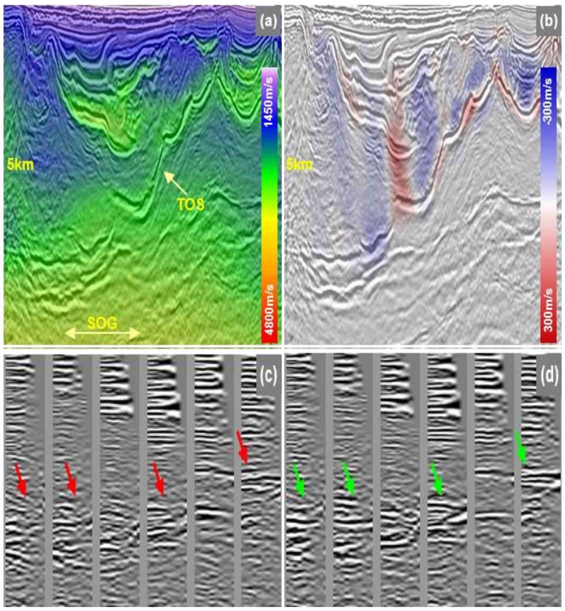

Figure 2: Initial velocity model (a) with TOS and SOG locations. Mini-basin RFWI perturbation (b). Sediment flood RTM SOGs zoomed on TOS before (c) and after RFWI (d).

fold show that the RFWI update improved the structural continuity of the Lower Tertiary and Mesozoic sections (Figures 4c and 4d). The initial, relatively smooth, subsalt velocity is shown in Figure 5a. Low vertical resolution of the perturbation (Figure 5b) again showed that backscattered energy was dominated by events generated from the strongest reflectors. Even with this current limitation in our RFWI, RTM SOGs (Figure 5c) were overall better defined and flatter (Figure 5d). Gather improvements, along with better stack continuity, indicated that the update was moving in the right direction.

Conclusions and discussions

RFWI was able to improve the hard-to-determine suprasalt mobile shale velocity within a mini-basin. The result of the image uplift was a less ambiguous salt interpretation. More coherent and flatter gathers, as well as improved structural continuity, show that RFWI provided improvements to both intra-salt and subsalt velocities. Good results were likely due to the presence of favorable strong events below our target zones that generated the reflected energy necessary for the low-wavenumber update. However, RFWI still depended on a good starting velocity model and relatively correct depth positioning of the necessary deep reflectors. To mitigate the lack of vertical resolution of the current method, a top-down approach of the update was performed. This increased the benefit from the RWFI application by improving the imaging of both shallow and deep strata in a geologically complex salt province.

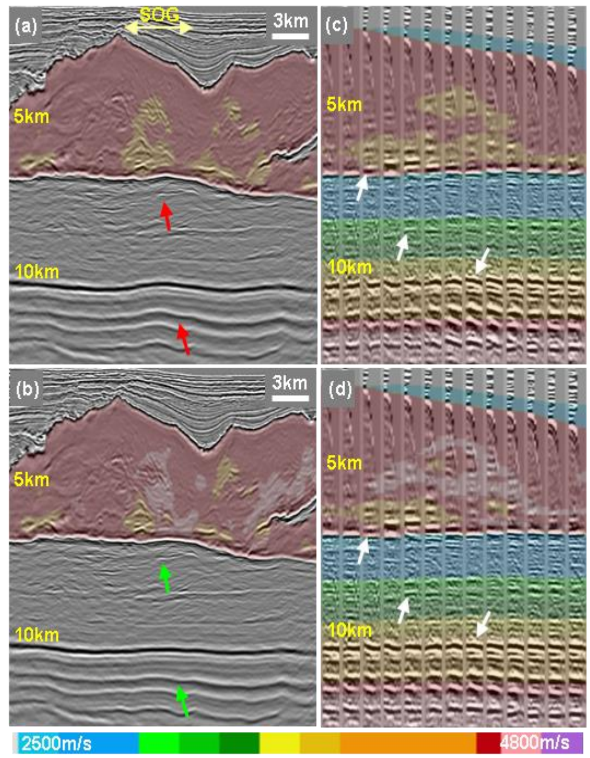

Figure 3: Salt body RTM without (a) and with (b) intra-salt and subsalt RFWI velocity update. RTM SOGs at a large sediment inclusion before (c) and after (d) RFWI.

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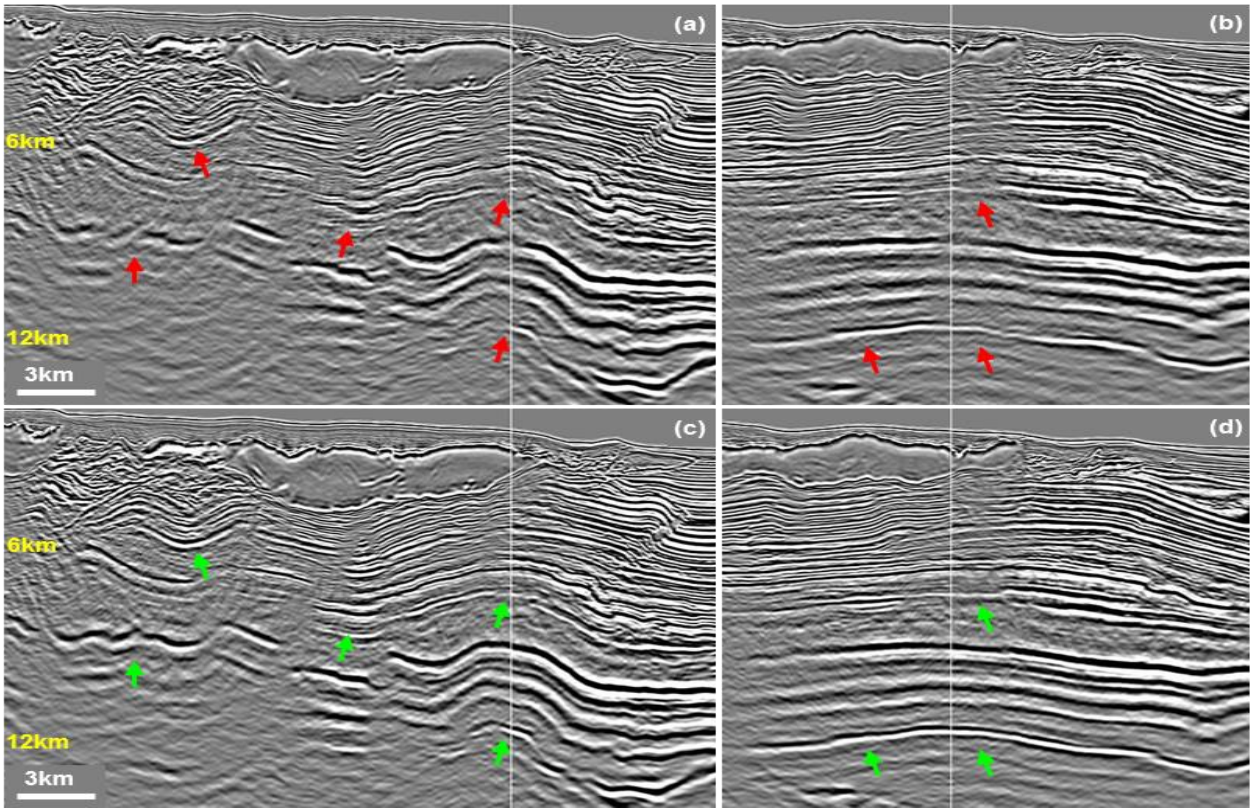

Figure 4: Dip and strike RTM images across a Perdido area fold before (a) and (b), and after subsalt RFWI (c) and (d).

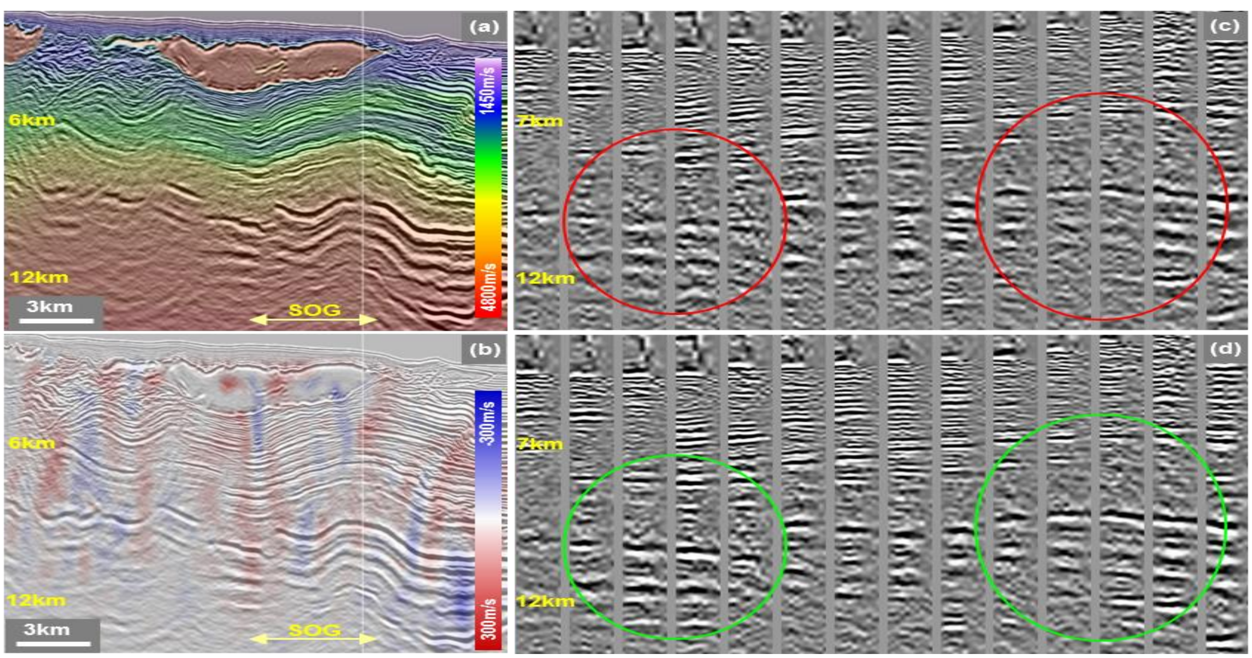

Figure 5: Initial velocity (a) and perturbation (b) from RFWI update. RTM SOGs along the same dip line before (c) and after subsalt RFWI (d).