Navigating full-waveform inversion success in Mexico with complex geology: shallow-water and land case studies

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Summary

We present practical full-waveform inversion (FWI) workflows for shallow-water and land cases in the presence of complex salt and carbonate geology in Mexico. The major challenge of applying FWI in the southern Gulf of Mexico shallow-water area comes from the short offset and partial azimuth of the existing data when the exploration targets are beyond refraction penetration depth and present sharp velocity contrasts. To overcome this difficulty, we propose to iterate between FWI and interpretation to obtain a more accurate input model, as the compensation for inadequate acquisition to facilitate deep reflections to converge. Land FWI in this area suffers from excessive noise, lack of low frequency signal etc., in addition to the short offset and complex geology as in marine cases. We summarize the key factors of implementing land FWI in this area and propose corresponding practical solutions to common land issues. Particularly, we discuss the FWI workflow to utilize shallow refractions and the deep reflections with absence of low frequency. Contrary to the marine case, Born-modelling-based reflection FWI was employed in land scenario to generate a deep background update prior to the conventional full-record FWI. In both cases, FWI converged to a model that significantly improved the subsalt and Mesozoic image, aiding in subsurface characterization and prospect identification.

Introduction

In the Campeche shallow-water area of Gulf of Mexico, the offshore geology is highly complex and varies across different locations and depths. Salt diapirs and canopies can create complex geometries and Cretaceous carbonate formations are deformed. These variations can cause significant changes in seismic velocities and result in complex reflection patterns, making the convergence of FWI extremely challenging. An effective solution to resolve this issue is to take advantage of the less severe non-linearity of the diving waves by extending the offset. In recent years, the combination of FWI and long-offset ocean-bottom node (OBN) data has already achieved a step-change uplift in subsalt imaging for exploration purposes in the northern Gulf of Mexico (GoM) (Vigh et al., 2023). However, the existing data of both towed-streamers or ocean-bottom cables (OBC) do not contain the offset length required to penetrate the deep targets with diving waves. Additionally, the lowest frequency in the reflection data only allows small interpretation error of the salt or carbonate bodies.

The land imaging cases share the same issue as the marine case in this region due to the continuation of complex salt and carbonate geology, but with shorter offset and limited frequency content in the data. Moreover, we also need to deal with the common land seismic problems, such as excessive noise, topography, and irregular surveys. These difficulties make the model building and imaging with land data more challenging. In this abstract, we discuss some effective measures to address these practical issues. And for both shallow-water and land scenarios, we designed a workflow that gradually optimized the input model to improve the convergence of deep reflections, to resolve the complexity of the model for the targets.

Strategy of FWI in shallow-water

In this study, the processing area is mainly covered by two wide-azimuth (WAZ) towed-streamer surveys and one OBC survey with a max offset of 9 km and lowest frequency of approximately 2.5 Hz. Due to the limited offset and lowest frequency available, we need to compensate by using a better input model to assist FWI in achieving better convergence. The workflow generally consists of two parts: conventional layer-based model building and FWI-interpretation loops. The layer-based model building still updated each zone separately including supra-salt sediment update, salt modelling, subsalt sediment updates as well as carbonate and autochthonous salt interpretation. Then this model was fed into FWI to get the low-wavenumber update, i.e., salt reshaping, velocity trend adjustment etc. Due to inaccurate input model with respect to the given lowest frequency, normally FWI gives the hint of potential interpretation error but is not able to converge to the correct model without interference. With the help of FWI-derived reflectivity (Bai et al., 2022) as well as the updated image and velocity, the interpretation for salt and carbonate are modified to represent the indicative update from FWI. Then the next loop of FWI will further improve the salt and carbonate structure, along with the better convergence in the inversion.

The resulting velocity model and image improvement validated the workflow of FWI-interpretation loops. In Figure 1, comparing to one loop of FWI, further interpretation changes with additional FWI greatly improved the complex structures such as salt feeder, Cretaceous carbonate as well as autochthonous salt. The better characterization of the Cretaceous carbonate directly impacted the drilling success rate as shown in Figure 2. In the circled area, the Mesozoic structure presents a potential trap on the legacy image, but the updated image reveals more reliable carbonate along with autochthonous salt. This approach was implemented in the entire project covering over 8000 km^2, and the regional image improvement provided more insight into the subsalt and Mesozoic stratigraphy and a more reliable interpretation for exploration (Figure 6).

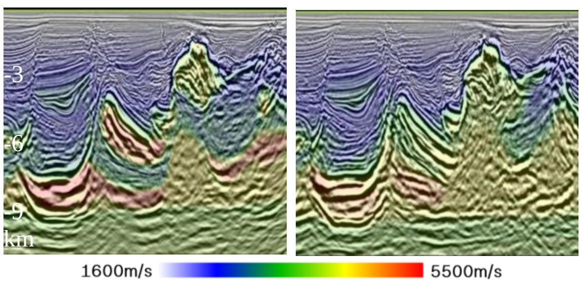

Figure 1: Comparison between single FWI (left) and three FWI-interpretation loops (right), with presence of complex salt and deep carbonate.

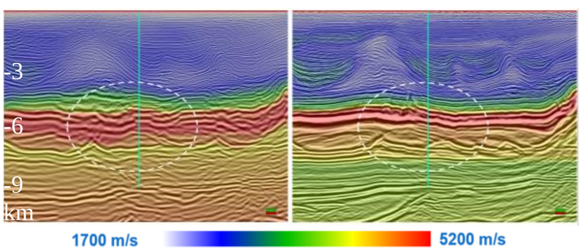

Figure 2: Impact of the proposed FWI-interpretation strategy on exploration targets: legacy (left) and FWI updated (right) model with image overlay. The FWI loops generated more reliable Mesozoic structures and mitigated exploration risks.

Key factors for land FWI

Land FWI in Mexico shares common challenges with other regions, including a low signal-to-noise ratio, rugged topography, and irregular acquisitions. Moreover, it faces additional hurdles posed by complex allochthonous salt and highly deformed Cretaceous carbonate formations that extend continuously from the offshore areas of the Gulf of Mexico. The complex geology combined with the shorter offset (4 to 6 km) and absence of low frequency (<5 Hz) in the acquisition will make the convergence more challenging than marine FWI, especially when the exploration targets are in the deep subsalt or Mesozoic sections.

Firstly, a stable and representative wavelet is critical to wavefield simulation and the convergence of FWI. Due to the source effect and near-surface conditions, the wavelet extracted from different areas or offset ranges normally show different phase or time shifts. Figure 3 demonstrates the wavelets derived from different offset groups and their impact on the velocity update. As can be seen from the comparison, the mid-range offset (1500 to 3000 m) generated a more stable and geological update, which indicated better convergence in the inversion. To further increase the stability of the data, surface-consistent deconvolution is optional and subject to test. Additionally, to handle the elevation variation of the topography in the forward modelling, we adopted the curvilinear grid in the finite-difference method to simulate the wave propagation without involving the air layer (Dai et al.,2019).

Secondly, the excessive noise in the land data is another hurdle to utilize the advantage of FWI for model building. The ground roll normally contaminates the near-offset reflections, and the entire shot record suffers from the scattering at near-surface or environmental noise. In this case, high-resolution radon preconditioning (Cheng et al., 2016) was chosen to further improve the signal-to-noise ratio at low frequency after eliminating the surface waves with surface wave modeling and inversion (SWAMI) (Strobbia et al., 2014).

In addition, the irregular acquisition geometry and the combination of many small surveys will raise a practical problem in balancing the gradient and the resulting convergence. This issue worsens when the gradient or the inversion is dominated by deep reflections due to its poor performance in convergence. This FWI work consists of 15 irregular surveys with various acquisition parameters over a period of years. Hence, the seismic data were regularized with matching-pursuit Fourier interpolation (Schonewille et al., 2013) in five dimensions (5D MPFI), considering both the offset and azimuth in shot domain. This interpolated dataset was used specifically for updating the subsalt and Mesozoic, which is beyond the maximum penetration depth of refractions with given acquisition geometry.

Finally, a logical strategy of combining various types of FWI could facilitate the convergence with this legacy dataset. Within the penetration depth of refractions (<3 km), the inversion showed relatively easier convergence as refractions exhibit a more linear relationship with model perturbations. The subsalt area and Mesozoic carbonate beyond the refraction penetration depth were controlled by only reflections with an absence of low frequency (receiver roll-off frequency). Reflection-based FWI (RFWI) (Sun et al., 2018) was run for deep background model update prior to the conventional FWI with full shot record. The RFWI adopted Born modelling and was able to form the low-wavenumber gradient to facilitate the convergence of the full-record conventional FWI, which mostly provided the high-wavenumber update due to the feature of this dataset. Following the same strategy of marine cases, tomography and interpretation of salt and carbonate were interleaved with reflection-based FWI to improve the starting model fed into the inversion.

Figure 4 shows the velocity update dominated by refractions, as well as the FWI derived reflectivity (FDR), also referred to as an FWI image (up to 9 Hz). For the deep update below the salt and in the Mesozoic formations, RFWI was used to refine the background model and improve the focusing and continuity of the subsalt events on the image, which can be validated by RTM angle-gathers as shown in Figure 5. The proposed approach was implemented across the entire project spanning over 5000 km^2 and improved the regional image, particularly at the challenging areas such as salt flank and Mesozoic structures (Figure 7). This enhancement essentially contributed to identifying potential prospects and mitigating exploration risks.

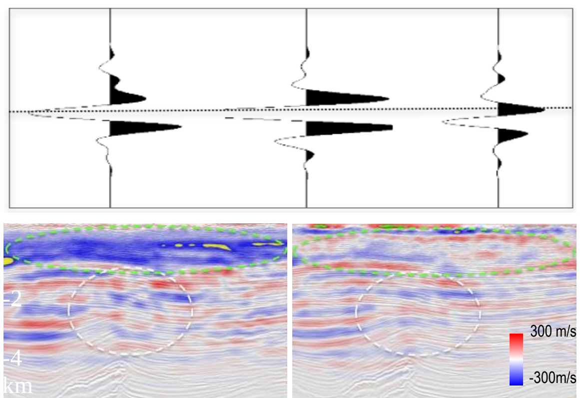

Figure 3: Impact of the wavelet extraction in land FWI. Top: wavelet extracted using offset of 0 to 3000 m (left), 0 to –1500 m (middle) and 1500 to3000 m (right). Bottom: velocity update (DV) using the wavelet of 0 to 3000m (left) and 1500 to –3000 m (right). The update is very sensitive to the wavelet, which can be verified by the shallow anomalous slow-down and the non-geological update in the circle.

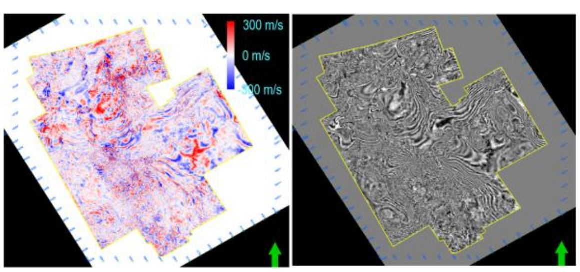

Figure 4: Velocity update and FWI-derived reflectivity (FDR) at depth slice of 2400 m.

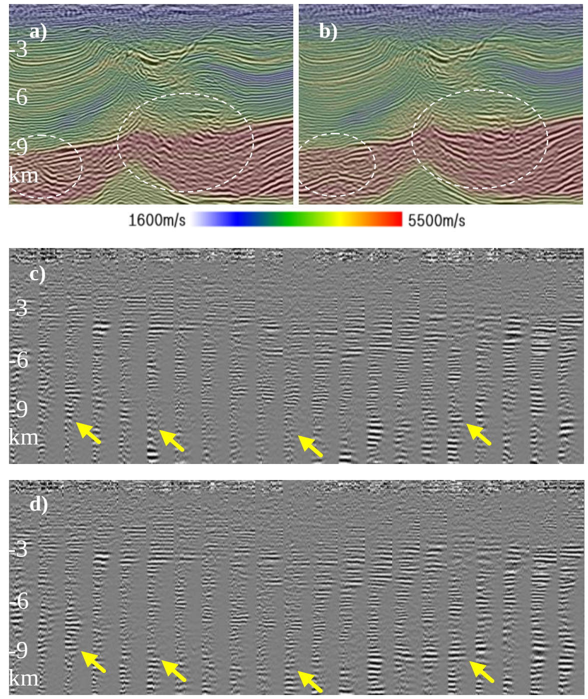

Figure 5: Reflection-based FWI improved the model kinematics below the allochthonous salt and modelled the velocity variation inside Cretaceous carbonate layer: a) velocity model and RTM image (15 Hz) of input; b) output from FWI; c) RTM angle-gathers of the input model; d) RTM angle-gathes of the updated model.

Conclusions

We presented shallow-water offshore and onshore case studies to demonstrate the strategies of applying full-waveform inversions in Mexico with presence of complex geology. For both cases, the fundamental problem is still the inadequate acquisition in offset and azimuth, which could not provide sufficient refractions or diving wave for good FWI convergence. In order to make deep reflections converge with the given lowest frequency, we proposed to loop between FWI and interpretation change based on FWI's indicative update to provide more accurate input model as compensation. In terms of low frequency, the land data has severe issues due to the limiting specifications of the receivers used. Reflection-based FWI was employed to build the deep background model before introducing details from conventional FWI with the entire shot record. In addition, the land FWI was subject to the known issues of topography, excessive noise and irregular surveys. We discussed the possible solutions and demonstrated their effectiveness. Although this work was performed subject to the challenges of land seismic data, the updated RTM image provided more insight in the subsalt area that assisted in interpreting the exploration targets and identifying potential prospects.

Acknowledgments

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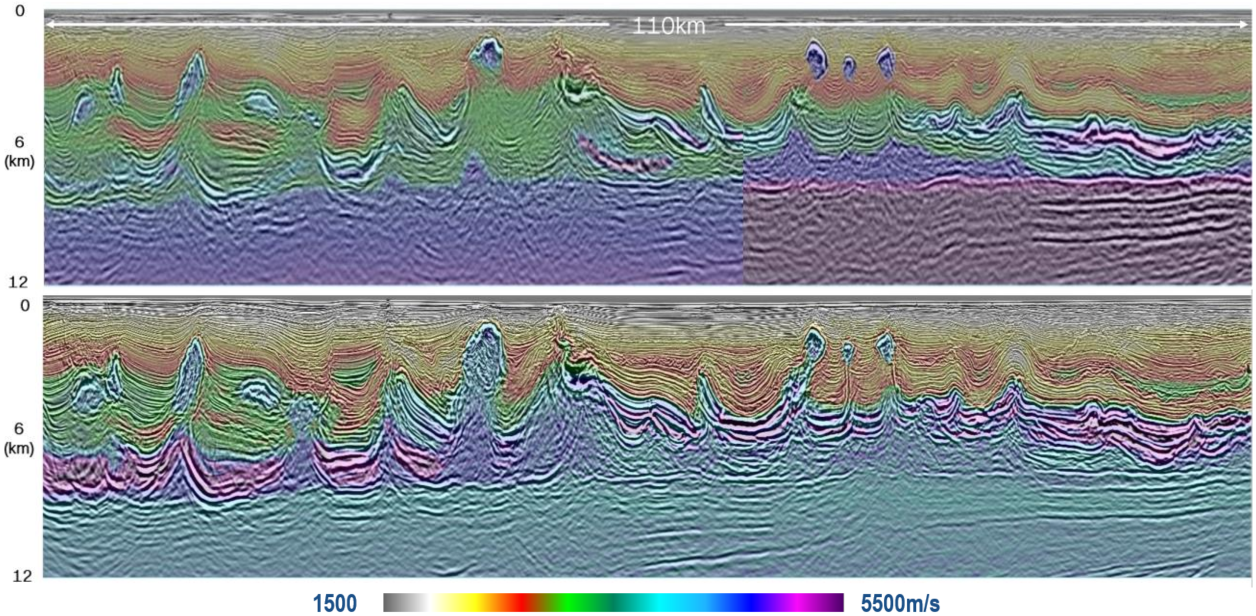

Figure 6: Shallow-water regional model and image uplift over legacy processing using WAZ towed-streamer data. Top: legacy processing; bottom: reprocessing with proposed FWI-interpretation loops.

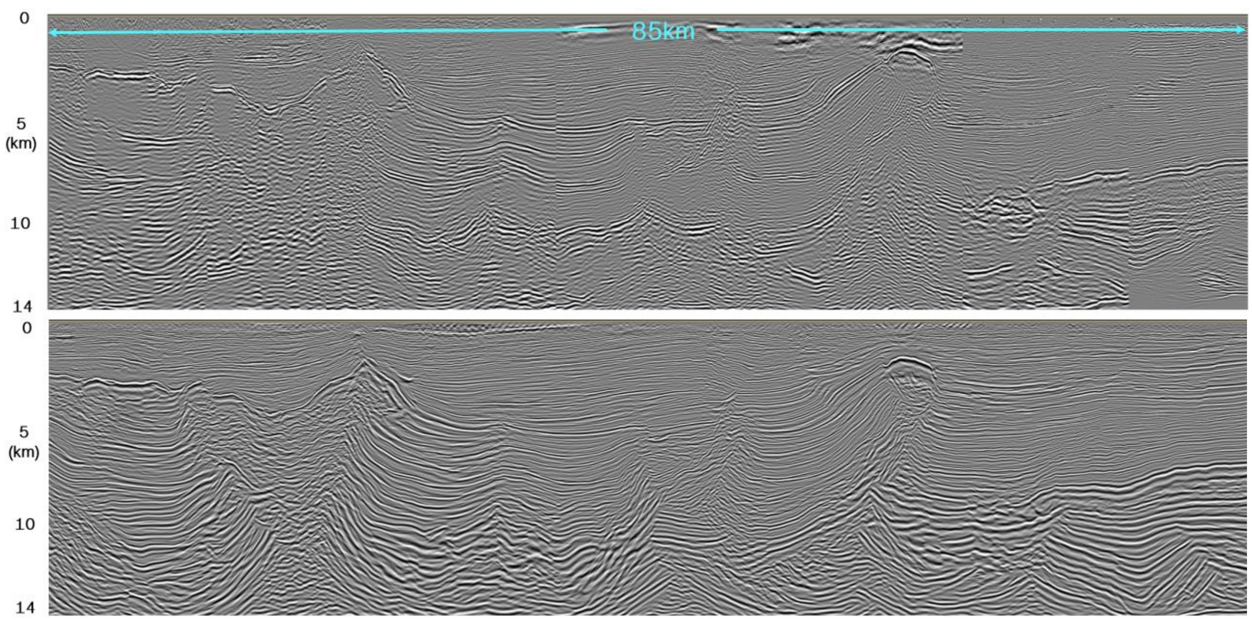

Figure 7: Onshore RTM image improvement from reprocessing with application of land FWI. Top: merged legacy processing; bottom: reprocessing. The subsalt and Mesozoic structures appear more geologically plausible amid the limitations of seismic data.