Revealing Complex Structures in Shallow Waters of the Gulf of Mexico Using FWI

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Summary

The shallow water region of the Gulf of Mexico is known to present significant petroleum prospects due to dynamic tectonic activities during the late Cretaceous to early Tertiary. Previous imaging in this region using sparse ocean bottom cable (OBC) surveys was poor, mainly due to unresolved overburden velocity in the Mesozoic section. We implemented a velocity model building (VMB) approach driven by Time-lag full-waveform inversion (TLFWI) to resolve the complex velocity features in this area. This approach improved imaging of complex geological structures, such as faulted sediment basins, allochthonous salt formations, and carbonate blocks, which were previously unclear in legacy images. The TLFWI-driven velocity model building, in combination with the advanced imaging technique FWI Imaging, revealed the Mesozoic and other structures at the deep section, allowing us to obtain a better geological interpretation of the basin.

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Introduction

The shallow water region of the Gulf of Mexico, with depths ranging from a few meters to about 80 m, is a promising region for petroleum exploration. Complex geological structures characterize this area, including Tertiary sand/shale sediments and Mesozoic to Cretaceous-Jurassic salt and carbonates. These formations, shaped by dynamic tectonic activities from the late Cretaceous to the early Tertiary, feature extensive fault systems and allochthonous salt bodies, which present substantial challenges for seismic imaging and heightened exploratory risks.

The latest OBC survey in the region, conducted in 2017, utilized a sparse shot and receiver arrangement of 25 m × 450 m. This setup offered full-azimuth coverage within 8-10 km offsets and a maximum offset of ~20 km in the North-South direction. However, a recent legacy project (2020-2021), using this dataset, failed to adequately resolve the Mesozoic geological complexity, as evidenced in Figure 1. The resulting seismic images, shown in Figures 1c and 1d, did not reveal subsalt mini-basins or carbonate blocks at the deeper section.

Our reimaging effort with the same OBC dataset focuses on improving our understanding of the Mesozoic structure. We employed a velocity model building (VMB) strategy driven by TLFWI (Zhang et al., 2018) to address the significant velocity complexities in this area.

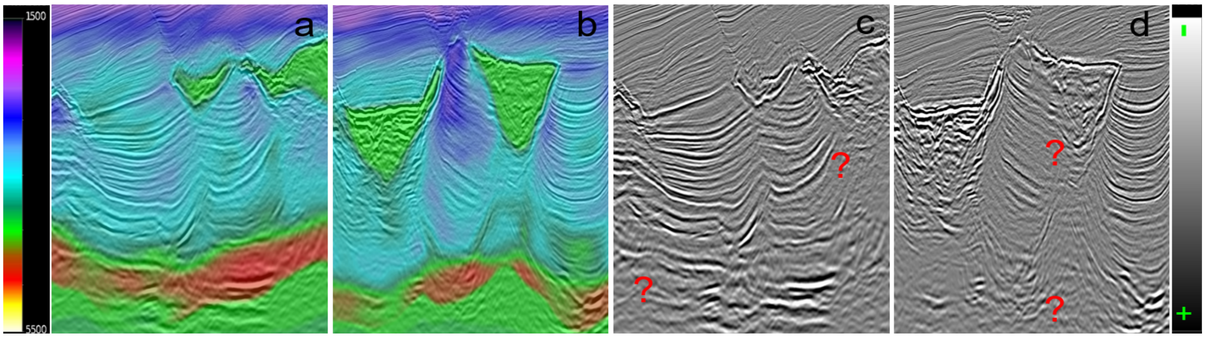

Figure 1 *a) and b) Legacy velocity model and c) and d) legacy RTM stack at two cross sections. Red question marks highlight areas with significant structural uncertainty.*

TLFWI-Driven Velocity Model Building

In this reimaging effort, the standard VMB approach of using a smoothed legacy velocity model as a starting point did not work well, because the legacy model had significant errors, such as misplaced salt and Mesozoic sections. Given the sparse OBC data's limited offset range and less-optimal low-frequency signals, mislocated deep salt or carbonate bodies could lead to cycle-skipping and incorrect updates in FWI. As a result, our initial model was a broadly smoothed sediment velocity model, stripped of interpreted salt and carbonate bodies from the legacy model. We then employed an iterative TLFWI process (Vandrasi et al., 2022) to correct the significant errors in the starting model. Allochthonous salt canopies, salt feeders, and autochthonous salts, identified from TLFWI velocity model clues and FWI Images, were progressively added to the initial model for subsequent TLFWI iterations. Before the final 11 Hz TLFWI, we updated background anisotropy models based on well ties and set them to zero within the inverted salt and carbonate bodies.

The resulting TLFWI velocity model closely matches the geological characteristics of the region, such as faults, salt and carbonate systems, and overpressure zones near salt flanks (Figures 2a and 2e). We observed heterogeneous velocities within the salt bodies, indicating 'dirty salt' in this area. The velocity features suggest that carbonate blocks and salt feeders have been transported due to tectonic forces. The RTM stack clearly reveals that both allochthonous/autochthonous salt bodies and Cretaceous carbonate blocks (Figures 2b and 2f) are consistent with the velocity variations. The clarity of sedimentary structures in basins beneath salts or between salt bodies has substantially improved.

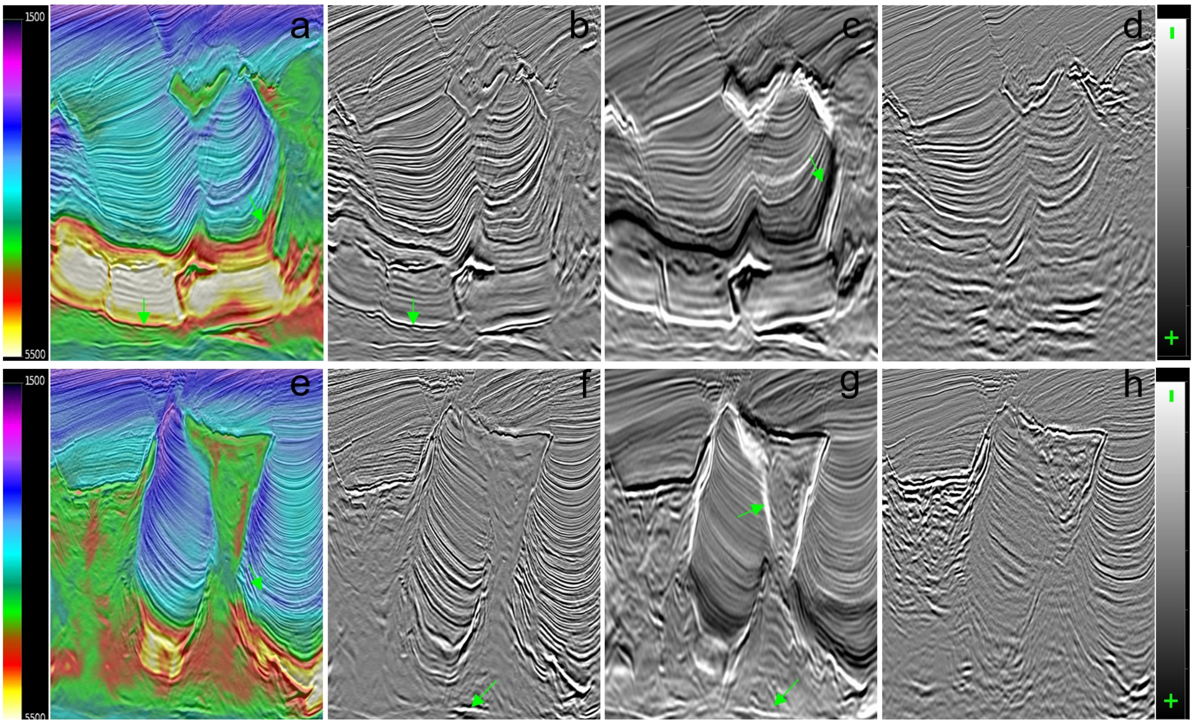

Figure 2 *Comparing the latest reimaging effort at two cross-sections. Section I comparison a) 11 Hz TLFWL velocity; b) RTM stack with TLFWI model; c) 11 Hz FWI Image; d) corresponding legacy RTM stack. Section II comparison e) 11 Hz TLFWL velocity; f) RTM stack with TLFWI model; g) 11 Hz FWI Image; h) corresponding legacy RTM stack.*

FWI Image for Complex Geology

Despite a more accurate velocity model, RTM still encounters difficulties in providing high-quality images in certain areas, particularly beneath allochthonous salt bodies and amid complex structures like steep salt flanks/feeders. FWI Imaging, however, benefits from the least-squares data-fitting of the full-wavefield data, which enhances event continuity and coherence, especially in the low-illumination subsalt regions (Zhang et al., 2020). This improvement, as shown in Figures 2 and 3, boosts confidence in understanding complex geological features, such as sediment truncations against salt diapirs and overhangs, as well as intricate salt/carbonate/fault structures at the Mesozoic level. For instance, while the RTM stack only partially reveals the base of autochthonous salt (Figures 2f and 3b), the FWI Image offers a clearer and more accurately aligned view (Figures 2g and 3c).

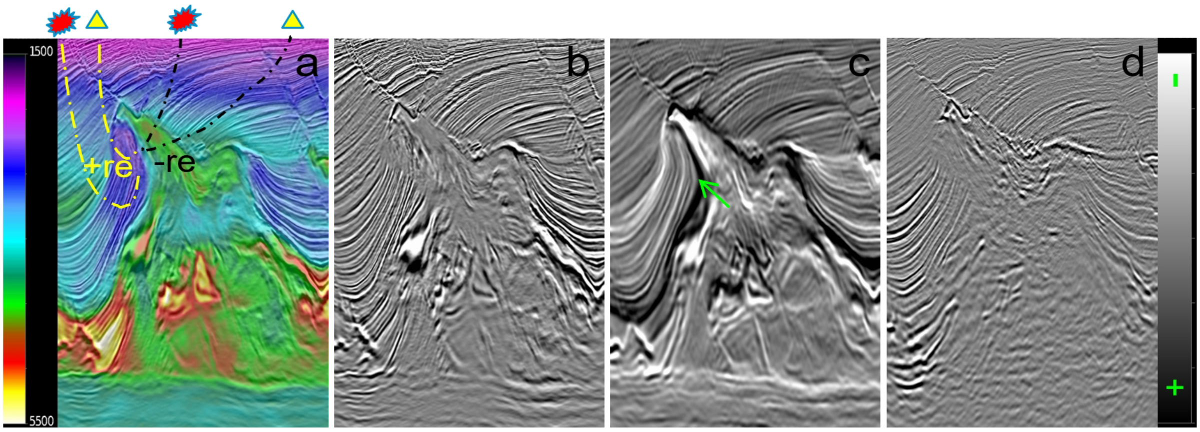

Figure 3 *Cross-section through a salt canopy: a) 11 Hz TLFWI velocity model, illustrating rays from the basin side (yellow dashed line) and salt side (black dashed line) with flipped polarity over a zone with slow velocity; b) RTM stack using the TLFWI model; c) 11 Hz FWI Image; d) legacy RTM stack.*

Furthermore, the 11 Hz FWI Image is crucial for clearly depicting high-angle structures, such as steeply dipping bases of salt canopies or tops of Cretaceous layers, often associated with the rafting of allochthonous Mesozoic sections along with salt (Figure 2c). The megaflaps experience cancellation or significant reduction of reflection energy due to imaging through faster salt and slower sediments, often leading to poorly migrated images of the overturned sedimentary layers (Figure 3a). This can result in misinterpretations of these layers as sediment truncations at the base of the salt when relying solely on RTM images (Figure 3b). FWI Images, on the other hand, provide a more accurate representation, revealing steeply dipping and overturned sediments caused by salt diapir formation (Figure 3c). Therefore, FWI Imaging significantly aids in interpreting the target Mesozoic level, resulting in a higher confidence in the interpretation (Figure 4).

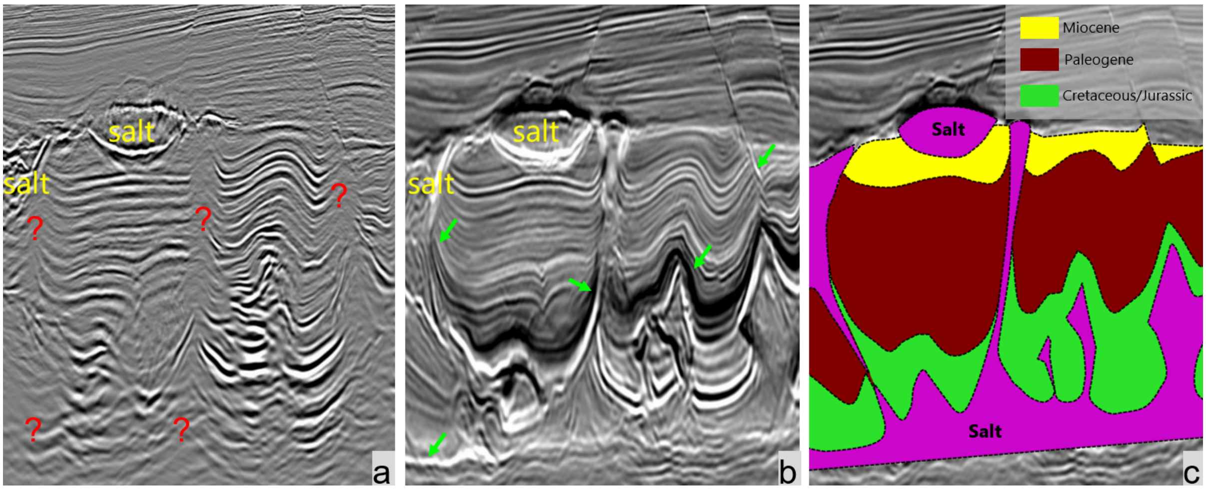

Figure 4 *Image comparison of a cross-section: a) legacy RTM stack; b) 11 Hz FWI Image; c) 2D interpretation based on the FWI Image.*

In assessing shallow hazards in this shallow water region, traditional imaging techniques like RTM and Kirchhoff struggle to accurately image the area around the water bottom and the shallow section due to missing near-angle reflections in the recorded data. Fortunately, high-frequency FWI Imaging emerges as a solution to overcome this limitation and is particularly effective for shallow imaging (Wei et al., 2023). In our study, the 20 Hz FWI Image yields a much clearer image of shallow geological events and features, including faults (Figure 5c) and gas pockets (Figure 5d), which brings significant improvement over the images produced by RTM.

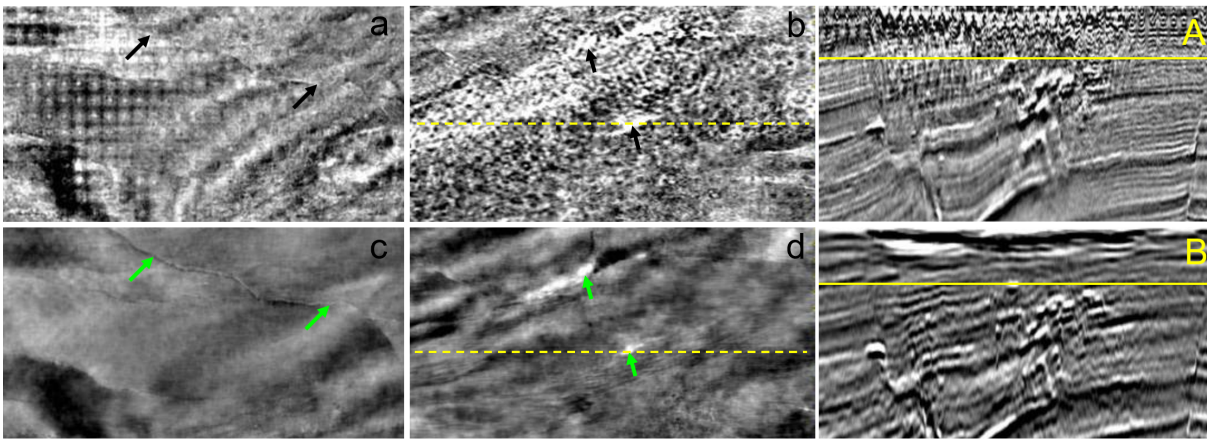

Figure 5 *Shallow images: a) and b) are RTM stacks in top view mode at the same shallow depth at two locations; c) and d) are corresponding 20 Hz FWI Images, respectively. Yellow solid lines in A) and B) indicate the depth of the top view images, while A) and B) represent the RTM stack and 20 Hz FWI Image along the same inline, respectively, marked by the dashed lines in b) and d).*

Impact of Orthorhombic Anisotropy in TTI Model Building

This case study initially utilized a Tilted Transversely Isotropic (TTI) model, yet the extensive fault system in the shallow section suggested a significant potential for azimuthal anisotropic effects. In particular, several signs of azimuthal anisotropy were observed: azimuthal-dependent gather curvatures when using the TTI model, less focused large-angle stack compared to near-angle stack, and different patterns of mismatch between synthetic and real data across azimuths using the same TTI model. Moreover, in the 20 Hz TTI TLFWI process, we observed apparent artifacts in the velocity model updates (Figure 6b). The corresponding 20 Hz FWI Image (Figure 6c) revealed undulated structural features in regions with pronounced azimuthal anisotropy effects (Figure 6a). Upon integrating Transverse Orthorhombic (TORT) anisotropy into the TLFWI updates, these distortions were effectively remedied in the FWI Image (Figure 6d). This outcome underscores the importance of accurately handling azimuthal anisotropy using TORT. Inaccurate or incomplete consideration of these effects in the TTI model can lead to artifacts, significantly impacting the fidelity of the resulting seismic images at certain locations.

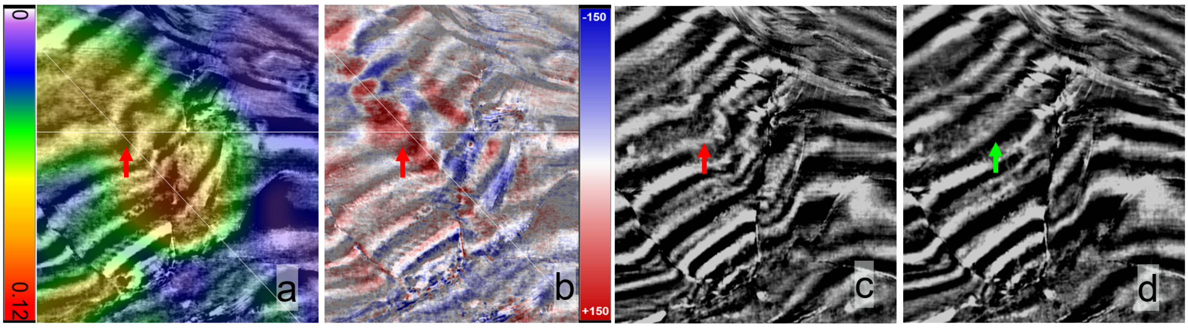

Figure 6 *Shallow depth images: a) TORT azimuthal anisotropy* $\varepsilon_{fast} - \varepsilon_{slow}$*; b) velocity perturbation in 20 Hz TTI TLFWI update; c) 20 Hz TTI FWI Image; d) 20 Hz TORT FWI Image.*

Conclusion

This case study demonstrates the efficacy of TLFWI in resolving geological complexities in a shallow water region. Despite sparse OBC data, TLFWI successfully captured velocity variations related to complex geological features, such as salt bodies and carbonate blocks. The RTM stack with a more accurate TLFWI model significantly improved the imaging of the allochthonous Mesozoic section when compared to legacy stack. The improved imaging revealed mini-basin sediments, Cretaceous carbonate blocks, and the autochthonous base of salt for the first time in this area. Additionally, given that Cretaceous layers were impacted by salt tectonics and often rafted or overturned, FWI Imaging provided a superior view of subsalt structures and carbonate configurations when compared to RTM.

Acknowledgements

We thank PEMEX and CGG for permission to publish this work.

References

Vandrasi, V., Su, Z., Huang, S., Agnihotri, Y. and Mothi, S. [2022]. Unlocking the potential of WAZ data for subsalt imaging using FWI: A case study in the Perdido area. *2nd International Meeting for Applied Geoscience & Energy*, Expanded Abstracts, 807–811.

Wei, Z., Mei, J., Wu, Z., Zhang, Z., Huang, R. and Wang, P. [2023]. Pushing seismic resolution to the limit with FWI imaging. *The Leading Edge*, 42(1), 24-32.

Zhang, Z., Mei, J., Lin, F., Huang, R. and Wang, P. [2018]. Correcting for salt misinterpretation with full-waveform inversion. *88th SEG Annual International Meeting*, Expanded Abstracts, 1143–1147.

Zhang, Z., Wu, Z., Wei, Z., Mei, J., Huang, R. and Wang, P. [2020]. FWI Imaging: Full-wavefield imaging through full-waveform inversion. *90th SEG Annual International Meeting*, Expanded Abstracts, 656-660.