FWI for the complex Walker Ridge salt province using streamer data

Dorothy Ren, Xin He, Siyun Xu, Fei Gao, Feng Lin, Jiawei Mei (CGG)*

Summary

Monument field is located in the northwest part of Walker Ridge in the Gulf of Mexico, with a Paleogene sandstone reservoir ~9 km below sea surface. The complicated overburden of low reflectivity shale bodies and complex salt geometries with steep salt flanks, multi-level weld systems, and large overhangs poses tremendous challenges to subsalt imaging, especially when the input data is suboptimal. Legacy images of streamer data from conventional velocity model building (VMB) driven primarily by manual salt interpretation, which could not systematically address the complicated overburden, show broken and distorted subsalt structures and thus render large uncertainties for further reservoir characterization. The well-proven Time-lag FWI (TLFWI) provides a leap in resolving the complex salt model and brings a step change to subsalt imaging. FWI Imaging leads to another step change in subsalt imaging by maximizing the illumination power of existing data through least-squares fitting of the full-wavefield data. Reprocessing using an iterative TLFWI and FWI-guided scenario VMB workflow and FWI Imaging technology makes the most out of the existing streamer data and obtains a step-change improvement in the subsalt image in this area. However, limited constraints from input streamer data can still bring challenges and uncertainties to the current results. This is especially true in deep sections beyond diving wave penetration depth, which require better input data with long offset, full azimuth, and good low frequency, such as Ocean Bottom Node (OBN), for the next level of subsalt imaging. Meanwhile, the strong elastic effects at the salt boundaries degrade the current velocity model obtained from TLFWI using only acoustic modeling. Therefore, we apply the recently developed elastic Time-lag FWI (E-TLFWI) to this streamer data, which gives a further improved velocity model with sharper salt boundaries and higher S/N, and better reverse time migration (RTM) image and FWI Image, especially around the complex salt boundary.

Introduction

Sitting on the outer basin of the central Gulf of Mexico (GOM), the Monument area in Walker Ridge is amongst several giant salt feeders and salt walls, with a subsalt Paleogene sandstone reservoir ~9 km below the sea surface. Salt bodies from different sources, along with the mobile shales, come together, resulting in complex salt flanks and overhangs, many sutures and inclusions, and multi-level weld systems. Adding to the complexity, salt sheets at their advancing toes easily form tiny salt fingers. All of these are difficult to interpret manually. The mixture of salt, shale, and sediments further complicates the interpretation, making it extremely challenging for conventional top-down VMB flows driven by manual salt interpretation.

Besides the geologic challenges, the existing streamer data also brings challenges to the deep subsalt imaging because of its limited maximum offset, limited azimuthal coverage, and poor low-frequency S/N. Two streamer surveys (Figure 1), one staggered acquisition, full-azimuth (FAZ) (2013) and one exploration wide-azimuth (WAZ) (2007), were acquired near Monument field. The most complex salt and shale bodies at the Monument field are concentrated in the south and west part of the area, which is primarily covered by the WAZ data with shorter offsets, ~8 km for the inline-offset and ~2 km for the crossline-offset (Figure 1d).

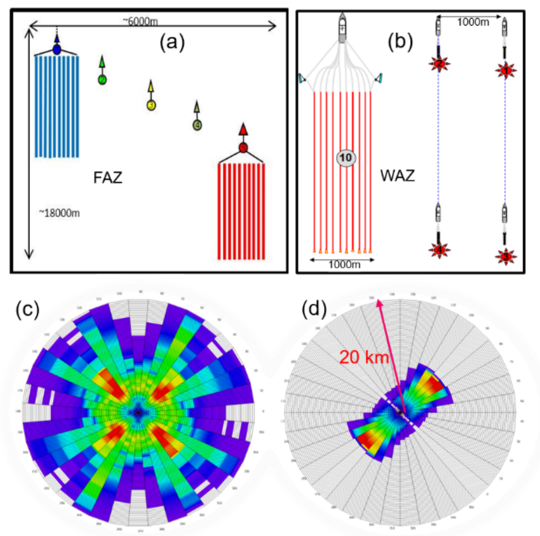

Figure 1: Survey information: (a, b) Acquisition configurations for the FAZ and WAZ surveys, respectively; (c, d) Rose diagrams for the FAZ and WAZ surveys, respectively.

The legacy velocity model from the conventional top-down salt model building flow with manual interpretation was able to define relatively simple salt bodies but failed to delineate complex salt flanks, overhangs, inclusions, multi-level weld systems and shale bodies. As a result, the legacy image shows broken and undulated events with strong swing noise at the reservoir level (Figures 2a and 2d).

To address the challenges of complex geology and limited data constraints at the Monument area, we adopted the FWI-driven VMB workflow (Ravi et al., 2019) of iterative TLFWI (Zhang et al., 2018; Wang et al., 2019) and FWI-guided scenario tests. The first round of TLFWI reasonably determined the shallow velocities within the diving wave penetration depth and provided hints for potential scenario edits at places, mainly in the deep section, where the initial

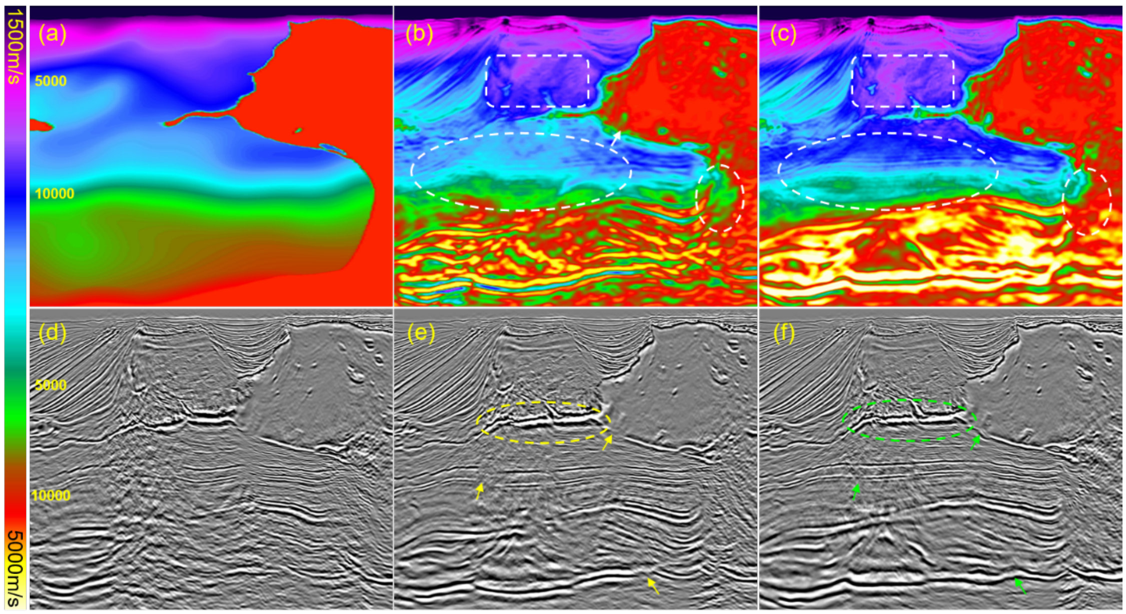

Figure 2: Velocity model and 15 Hz RTM image improvements by iterative TLFWI and FWI-guided scenarios. (a) Merged legacy velocity model and (d) remigration image. (b) First round TLFWI 8 Hz velocity model and (e) RTM image. (c) Final round TLFWI 8 Hz velocity model and (f) RTM image.

model errors are large and TLFWI's update power from the tomography term of reflection energy is limited. With a closer input model from the scenario work guided by the previous round of TLFWI, the subsequent TLFWI further improved the velocity by correcting small-scale manual interpretation errors and adding high-wavenumber details. Iteratively, the improvements accumulated, and a step change in the velocity model and corresponding RTM image was achieved in the end.

However, even with a greatly improved velocity model, RTM still failed to image the structure beneath complex salt bodies due to the limited illumination from primary reflections. Therefore, FWI Imaging (Zhang et al., 2020; Huang et al., 2021; Wei et al., 2021) was implemented to maximize the illumination power of the existing data through iterative least-squares fitting of the full-wavefield data. The resulting FWI Image shows improved event continuity and higher S/N compared to its RTM image.

TLFWI-driven VMB workflow

The four-way closure target at a depth of ~9 km lies beneath a ~5 km thick salt sheet and a slow shale body, with a complex salt weld and overhang structure in between (in the middle of Figure 2). The legacy velocity model (Figure 2a) built through manual interpretation followed by many scenarios failed to define the complex salt geometry, dirty salt velocity, and shale bodies, which led to severe subsalt structural distortion and discontinuity, as shown in the legacy RTM image (Figure 2d).

On top of a smoothed legacy velocity model, TLFWI with both the FAZ and WAZ data was run up to 8 Hz to update the velocity top-down using both diving wave and reflection energies (Figure 2b). In the shallow section within diving wave penetration depth, the high-resolution 8 Hz TLFWI model updated the salt model by adding inclusions, modifying the salt geometry, and thinning the weld. It also identified the slow gas hydrate near the water bottom and slow shale body above the salt weld. With this added shale body, the structure of the salt weld was simplified and the continuity was improved; although, there was still a small step (yellow circle in Figure 2e), which indicated that the shale velocity could still be too fast. Because of the better resolved overburden from TLFWI, the reservoir structure was much more geologically plausible with reduced undulations and improved focusing and continuity. However, the remaining sag and break of subsalt reflectors indicated velocity errors in the subsalt Tertiary section, which was confirmed by RTM surface offset gather (SOG) curvatures. Because of the limited useable low frequencies (~2.8 Hz) and diving wave penetration depth of the streamer data, the subsalt TLFWI update had to rely mostly on reflection energy, which is incapable of resolving large model errors and background velocity errors. Therefore, the deep background velocity trend of the legacy model was mostly preserved (white circle in Figure 2b). In addition, the up-dipping Mesozoic beddings next to the feeder suggested a possibly wider salt feeder (circle on the right of Figure 2b), and the slow-down near the salt tip together with the broken

10.1190/image2022-3744364.1

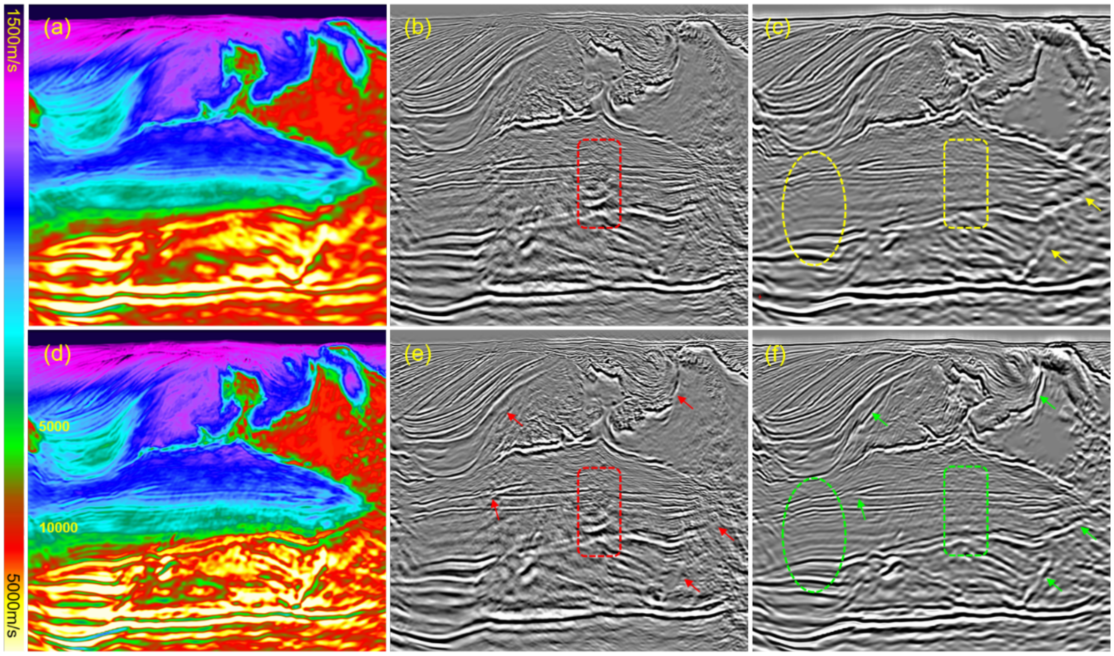

Figure 3: (a) 8 Hz TLFWI model, (b) 15 Hz RTM image from 8 Hz TLFWI model, (c) 8 Hz FWI Image; (d) 12 Hz TLFWI model, (e) 15 Hz RTM image from 12 Hz TLFWI model, (f) 12 Hz FWI Image.

base of salt (BOS) (top arrow in figure 2e) indicated a potential sediment inclusion not yet fully resolved. Lastly, the undulation of the basement event was also a good indicator of errors in the velocity trend. All these remaining velocity uncertainties were too large and/or too deep to be fully corrected by TLFWI using streamer data.

To better address the remaining velocity errors, a closer initial model is required for the next round of TLFWI. Based on the indications from previous TLFWI output, scenarios were carried out to further reduce the shale body velocity, widen the salt feeder, and add the sediment inclusion. Additionally, the subsalt velocity trend was updated based on well information followed by ray-based reflection tomography to improve the top-down background velocity prior to TLFWI. With this iterative TLFWI and FWI-guided scenario workflow, the velocity model was refined step-by-step and subsequently led to a step-change improvement in the final RTM image, as shown in Figure 2f.

FWI Imaging

Even with the significantly improved velocity model from the TLFWI-driven VMB flow described above, the RTM image still has poorly imaged areas, most notably directly below the complex salt and at the three-way truncation against the salt feeder (Figure 3b). By contrast, the 8 Hz FWI Image revealed potential steeply dipping Paleogene and Cretaceous reflectors in the three-way truncation area (yellow arrows in Figure 3c), suppressed the noise and improved the event continuity in the area directly below the complex salt (yellow rectangle box in Figure 3c), and provided more balanced amplitudes, though the resolution was still limited by the maximum inversion frequency of 8 Hz. The 12 Hz TLFWI model (Figure 3d) showed improved resolution with many more details top-down, better delineated features, and sharper salt boundaries. Although the impact of improved resolution in the velocity model is very small on the migration image (Figures 3b and 3e), as the kinematic change gets smaller from higher frequency inversion, the corresponding 12 Hz FWI Image clearly showed the benefits. We can see much better defined steeply dipping Paleogene and Cretaceous reflectors, clearer fault structure, and more interpretable reflector characteristics. Compared with the RTM image, these improvements from the FWI Image are attributed to additional illumination from the full-wavefield data and illumination compensation from the least-squares data fitting process. Due to these benefits, the FWI Image became a key product for subsurface structure and stratigraphy interpretation, even though higher frequency inversion may be needed to further improve the resolution.

Conclusions and Discussion

By applying the tailored FWI-driven VMB workflow, as well as FWI Imaging, we made the most out of the existing streamer data and obtained a step-change improvement in the velocity model and subsalt image at the challenging Monument field in Walker Ridge, GOM.

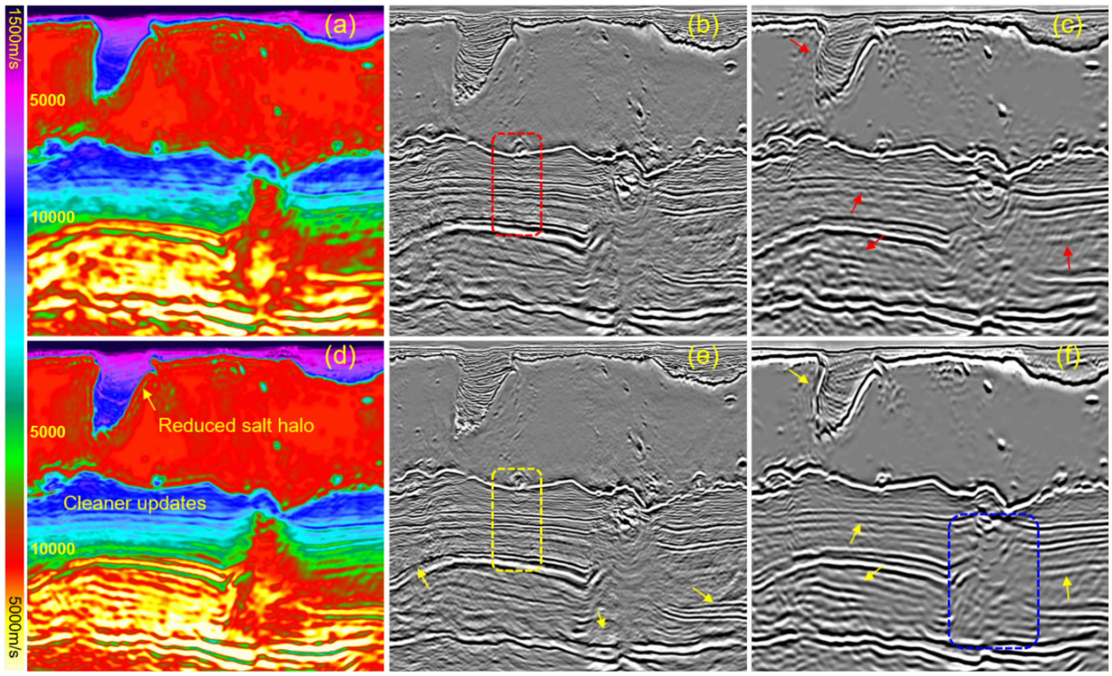

Figure 4: Velocity and imaging uplifts from E-TLFWI. (a) A-TLFWI 8 Hz velocity model, (b) 15 Hz RTM stack, and (c) 8 Hz FWI Image. (d) E-TLFWI 8 Hz velocity model, (e) 15 Hz RTM stack, and (f) 8 Hz FWI Image.

However, this FWI-driven VMB workflow is not fully data-driven due to limited available streamer data in this area. As a result, potential large velocity uncertainties associated with scenario tests may still exist at places with complex geology, especially in the deep section beyond the diving wave penetration depth. The subsalt image of streamer data is often not very sensitive to scenario changes, which makes it difficult to justify each scenario. In addition, scenario tests are often compute- and labor-intensive, which makes it very time-consuming to exhaust different possibilities. Although well information and SOG flatness were incorporated as additional constraints to update the background subsalt velocity, background velocity errors are still present, mostly away from the well locations. On the other hand, assuming an accurate velocity model can be obtained, the existing streamer data could be insufficient to illuminate the complex subsalt structure even with FWI Imaging, such as at the boundary of the steeply dipping salt feeder and the upward-dipping reflectors truncating against salt. Therefore, better data, such as OBN data with longer offsets, wider azimuth, and lower frequencies is still needed to further improve the FWI velocity and FWI Image in this area.

Furthermore, since TLFWI is based on acoustic modeling, which cannot properly model the strong elastic effects around salt boundaries with large impedance contrasts, smearing of the salt boundary and a considerable salt halo are present in the acoustic TLFWI (A-TLFWI) results. With the application of the recently developed elastic TLFWI (E-TLFWI) (Wu et al., personal communication, 2022), significantly reduced salt halos are observed along with cleaner subsalt sediment velocity updates in comparison with the A-TLFWI model (Figure 4). E-TLFWI using an elastic modeling engine models the reflection and transmission energy at salt boundaries with better amplitudes and phases, which effectively reduces the mismatch between synthetic and recorded data in inversion, resulting in better kinematics and cleaner updates in the velocity model. As a result, improvements in the RTM image can be observed around/below salt flanks, inclusions, and other large velocity contrast locations, as shown in Figure 4e. The benefits from E-TLFWI are more obvious in the FWI Image. The E-TLFWI Image shows much sharper salt boundaries with greatly reduced halos and more balanced amplitudes, better subsalt event continuity, and higher S/N (yellow arrows in Figure 4f).

Both better input data, such as OBN, and more advanced technologies, such as E-TLFWI, are essential for the next level of subsalt imaging in the Monument area of Walker Ridge GOM.

Acknowledgments

We thank CGG for permission to publish this work.

References

Huang, R., Z. Zhang, Z. Wu, Z. Wei, J. Mei, and P. Wang, 2021, Full-waveform inversion for full-wavefield imaging: Decades in the making: The Leading Edge, **40**, 324–334, doi: https://doi.org/10.1190/tle40050324.1.

Kumar, R., H. Zhu, V. Vandrasi, D. Dobesh, and A. Vazquez, 2019, Updating salt model using FWI on WAZ data in the Perdido area: Benefits and challenges: 89th Annual International Meeting, SEG, Expanded Abstracts, 1270–1274, doi: https://doi.org/10.1190/segam2019-3216761.1.

Wang, P., Z. Zhang, J. Mei, F. Lin, and R. Huang, 2019, Full-waveform inversion for salt: A coming of age: The Leading Edge, **38**, 204–213, doi: https://doi.org/10.1190/tle38030204.1.

Wei, Z., J. Mei, Z. Wu, Z. Zhang, R. Huang, and P. Wang, 2021, FWI imaging: Revealing the unprecedented resolution of seismic data: First International Meeting for Applied Geoscience & Energy, SEG/AAPG, Expanded Abstracts, 682–686, doi: https://doi.org/10.1190/segam2021-3583772.1.

Zhang, Z., J. Mei, F. Lin, R. Huang, and P. Wang, 2018, Correcting for salt misinterpretation with full-waveform inversion: 88th Annual International Meeting, SEG, Expanded Abstracts, 1143–1147, doi: https://doi.org/10.1190/segam2018-2997711.1.

Zhang, Z., Z. Wu, Z. Wei, J. Mei, R. Huang, and P. Wang, 2020, FWI imaging: Full-wavefield imaging through full-waveform inversion: 90th Annual International Meeting, SEG, Expanded Abstracts, 656–660, doi: https://doi.org/10.1190/segam2020-3427858.1.