Unlocking the potential of WAZ data for subsalt imaging using FWI: A case study in the Perdido area

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Summary

Full-waveform inversion (FWI) has become the norm in velocity model building for different surveys from land to marine, and from streamers to ocean bottom nodes. FWI using wide-azimuth (WAZ) streamer data in areas with complex geologic settings can fall short of resolving the complexity when starting from a poor initial velocity model. Previous studies have shown that iterating salt scenarios and Time-lag FWI (TLFWI), an effective and stable FWI algorithm for salt, can lead to a better initial model for the next round of FWI and eventually result in a step-change in the salt model and the subsalt image, even when only using WAZ streamer data. However, this approach relies on RTM images for the evaluation of model updates, which are highly susceptible to illumination issues. The recently developed FWI Imaging algorithm can bolster the approach by reducing the impact of poor illumination for subsalt imaging, easing model evaluation. In our case study in the Perdido area, we employ TLFWI and FWI Imaging to maximize the value of WAZ data for velocity model building and subsalt imaging.

Introduction

A full-waveform inversion (FWI) approach works best when supported by suitable data and a good starting model (Michell et al., 2017). Wide-azimuth (WAZ) data acquisition does not fall into the 'suitable data' category due to the short maximum offsets, limited azimuthal coverage, and poor signal-to-noise ratio (S/N) at the low frequencies.

The Time-lag FWI (TLFWI) algorithm proposed by Zhang et al. (2018) has proven effective for updating salt and subsalt velocities in varying geologic scenarios (Wang et al., 2019; Wray et al., 2021; Liu et al., 2021) and for different acquisition types, including WAZ. Furthermore, Kumar et al. (2019) show that the initial model for FWI plays a crucial role in obtaining good output from FWI, particularly when using suboptimal streamer data. The subjective nature of the manual interpretation process during the salt velocity model building can be reduced by using indications from the TLFWI model to guide the update of the initial model for the subsequent iteration of FWI. On the other hand, the evaluation of a model is still based on an RTM image that often suffers from illumination issues and migration swings, making it difficult to use for model assessment, especially for areas with complex overburden where we most need to resolve velocity errors.

Recent advances allow TLFWI to simultaneously generate a velocity model and a reflectivity, termed FWI Image (Zhang et al., 2020; Huang et al., 2021). Consequently, the benefits of using full-wavefield data and least-squares fitting inherent in TLFWI translate to the FWI Image, making it a better option than RTM for both imaging and model evaluation.

The study area is on the Mexican side of the Gulf of Mexico and has complex geology consisting of intricate salt structures, steep salt feeders, plus rafted and thrust carbonate sections. The input data is from a flat-cable WAZ acquisition with diving waves barely penetrating the shallow top of the salt. We apply both TLFWI and FWI Imaging on this WAZ data set to maximize its value in solving the subsalt imaging challenges in this complex area.

TLFWI for updating velocities

The legacy model built using overburden FWI with a least-squares cost function, tomography, top-down salt interpretation, and Reflection FWI (Chazalnoel et al., 2017) suffers from algorithmic and data limitations. As a result, the subsalt image is inadequate for well planning, with most of the Lower Eocene and Mesozoic sections appearing as migration swings, indicating significant velocity errors (Figure 1A).

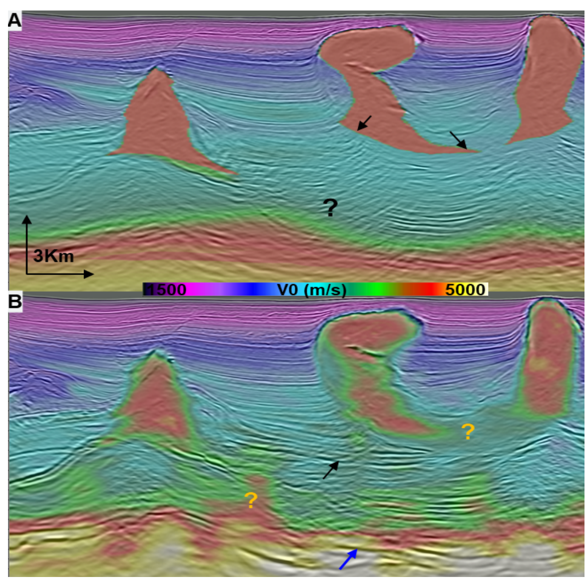

Figure 1: RTM image from the legacy model (A) shows significant uncertainty in the salt geometry (black arrows) and subsalt image (black question mark). RTM image from the FWI model (B) shows uplift in the salt flanks and Mesozoic section compared to (A).

The TLFWI algorithm was first applied to the smoothed legacy model in the study area. The resulting FWI model resolved much of the shallow overburden and improved the salt geometry and subsalt image, as shown in Figure 1B. Salt flanks became more focused, and the Cretaceous event (blue arrow in Figure 1B) was more continuous and coherent, aiding interpretation of subsalt events. However, significant uncertainty (represented by orange question marks in Figure 1B) remained in the complex subsalt region, indicating that a better initial model might be needed for FWI to further improve the image using this WAZ data set.

TLFWI output used to improve the initial model

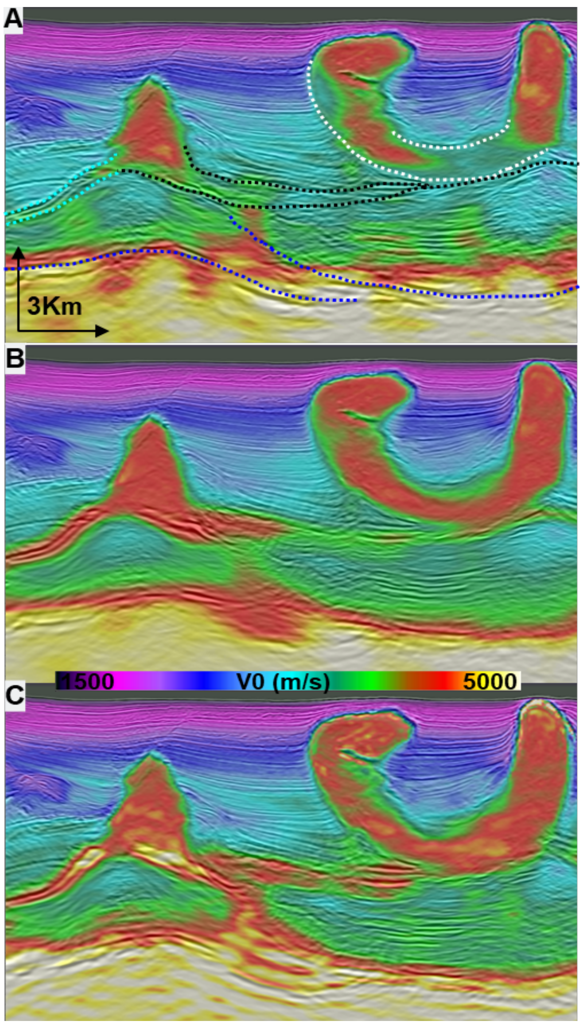

Figure 2: FWI model (A) revealed indications for model adjustments required to build the updated initial model (B). FWI (C) on the updated initial model is more geological, has better definition of salt boundaries and subsalt velocities, and improved the subsalt image.

While some unresolved areas did remain after TLFWI, the FWI model provided several indications for further model updates, as shown in Figure 2. The salt bodies to the right appear to be connected (white dotted line) per the faster velocities shown by FWI. In addition, it showed indications for a faster carbonate section (cyan dotted line) and a potential salt wing (black dotted line) in the image. Better imaging of the Cretaceous event (blue dotted line) indicated the need for a velocity re-trend in the deep section. These changes were incorporated to build a better initial model (Figure 2B) for the next FWI.

The FWI output (Figure 2C) based on the updated initial model showed geologically conformal velocities and gave significant improvements to the RTM image, including more focused salt flanks and subsalt events. However, Figure 3A shows that some locations still have an unclear structure in the RTM image (blue arrows).

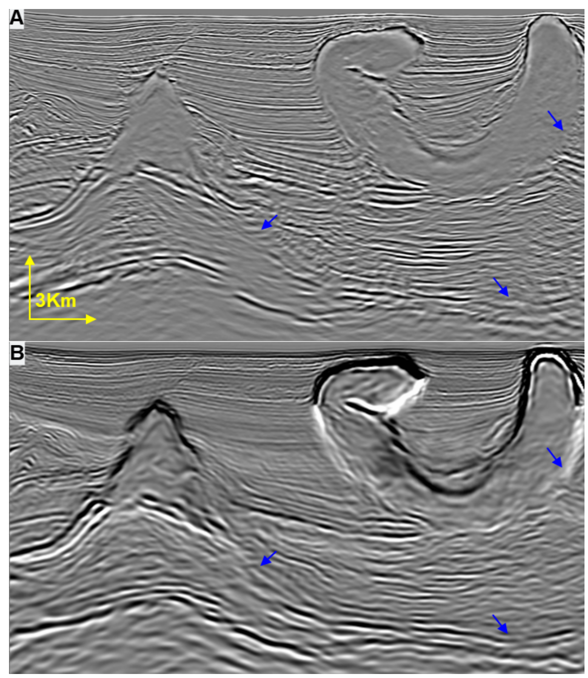

Figure 3: RTM image (A) using the FWI model from Figure 2C shows some uncertainties (blue arrows). In comparison, the FWI Image (B) has better illumination and S/N. These figures and the subsequent ones show RTM images and FWI Images with maximum frequencies of 15 Hz and 8 Hz, respectively.

FWI Imaging and its benefits over RTM imaging

FWI Imaging, which applies least-squares fitting to the recorded full-wavefield data to generate an image along with a velocity model, can take advantage of the additional illumination from the energy beyond primary reflections, such as diving wave energy and multiples. Due to these advantages, the FWI Image (Figure 3B) from the same model showed better coherency of the subsalt structures and imaged some portions of the salt flanks and Cretaceous that were not clear in the RTM image. In addition, the illumination compensation results in more uniform amplitudes compared to the RTM.

Using FWI Image to maximize the velocity update

For the location shown in Figure 4, after the model updates driven by iterative TLFWI and salt scenarios, the velocities and image were substantially improved over the starting model. In particular, the base of salt for the shallow salt body, the bottom of the Oligocene basin (blue arrow in Figure 4B), and the top of the Cretaceous were better imaged after FWI.

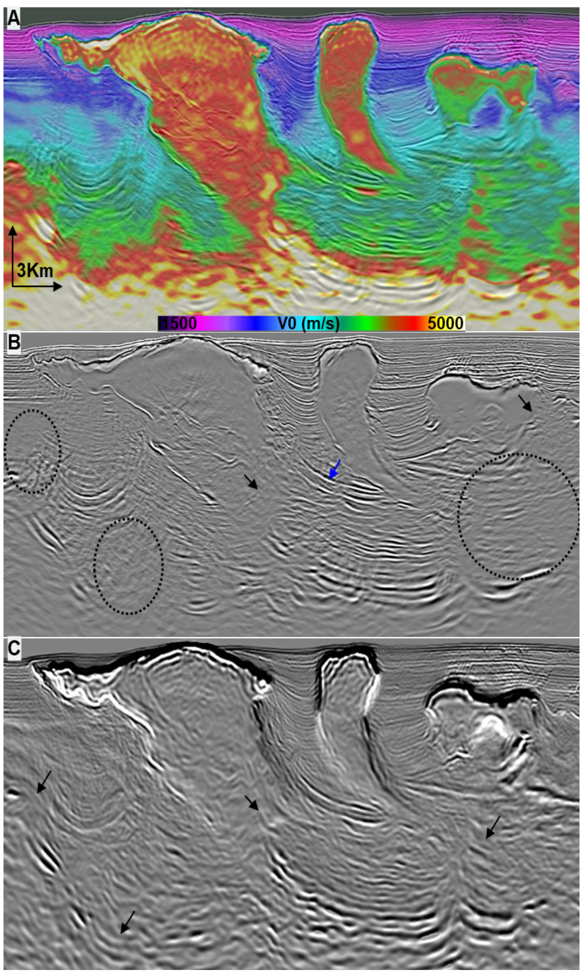

Figure 4: FWI model (A) improved the velocities and image but showed unresolved areas in the corresponding RTM image (B). FWI Image (C) has better illumination, S/N, and resolution of the structure.

However, some uncertainties remained after this approach, especially for the areas highlighted by the black dotted ellipses and black arrows in the RTM image (Figure 4B). Based on the TLFWI output and the RTM image, it is not trivial to improve the initial model further. However, when we look at the FWI Image at the same locations, pointed out by black arrows in Figure 4C, we can better delineate different geo-bodies (Figure 5A). This information can be used to update the model (Figure 5B) for the next FWI. The FWI model and FWI Image, which form the result of the entire TLFWI and FWI Image model building sequence, are shown in Figures 6B and 6D, respectively. The improvements in final velocity and image demonstrate the value of FWI Imaging for improving the velocity model, especially in complex areas.

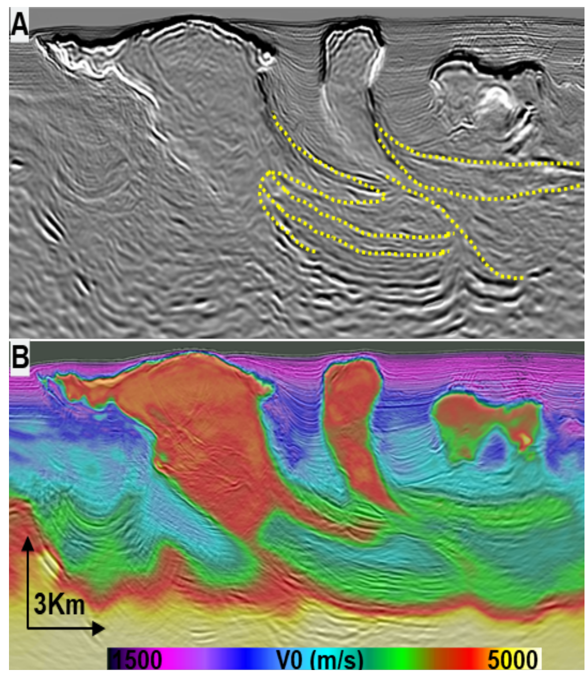

Figure 5: The interpretation (yellow dotted lines) based on the FWI Image (A) were used to update the model (B).

RTM may not be the best tool to evaluate the velocity

Most of the uncertainties in the previous section appeared to be due to imaging limitations, which suggests that RTM images may not be a reliable means for evaluating the structures and model in complex areas. A simple synthetic study was conducted to understand these limitations and the benefits of FWI Imaging over RTM imaging. The FWI Image was de-migrated to generate synthetic shot gathers based on the WAZ acquisition geometry and re-migrated using RTM (Figure 7B). At first glance, it is easy to conclude that we have a velocity issue. However, comparing Figures

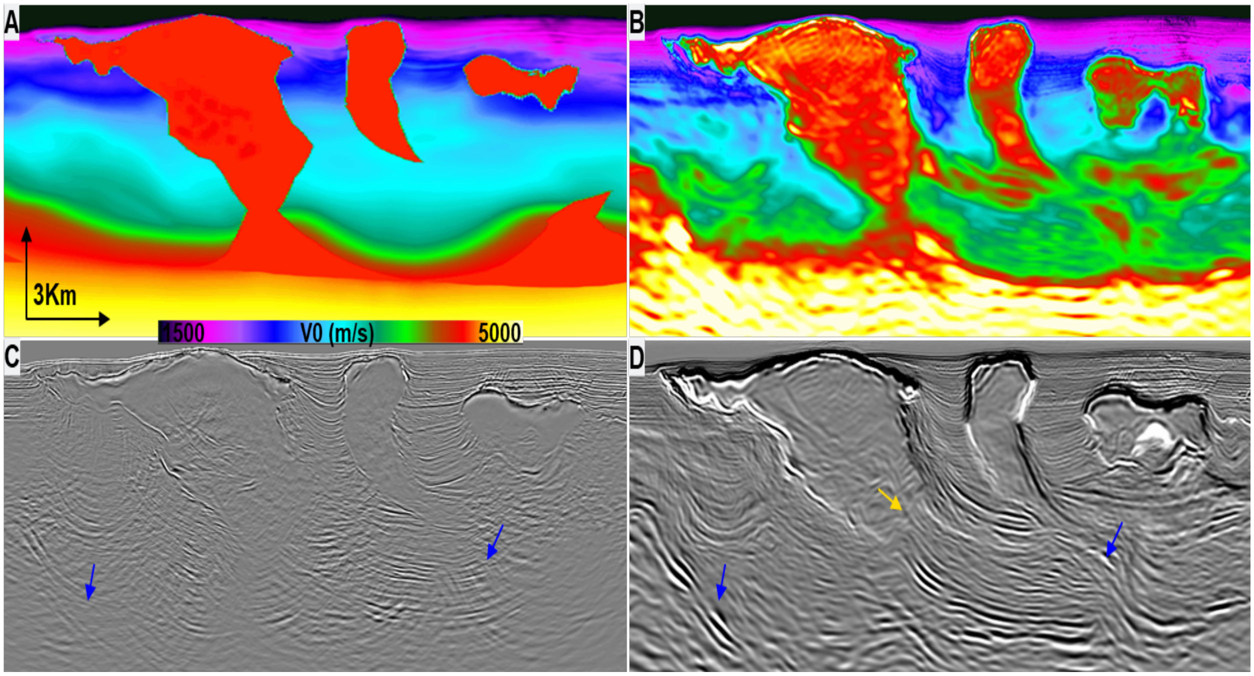

Figure 6: FWI model (B) has a better definition of salt geometry and more geologically conformal subsalt velocities than the legacy model (A). FWI Image (D) shows a dramatic uplift in the subsalt image over the legacy RTM image (C).

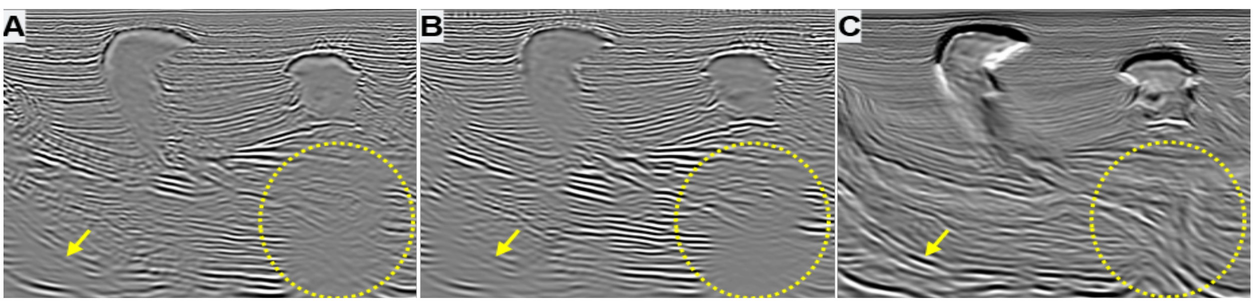

Figure 7: RTM image (A) from real data shows similar amplitude loss to that (B) from synthetic data, whereas the amplitudes are more balanced, and events have better S/N (yellow arrow and circle) in the FWI Image (C). All images are generated from the same velocity model.

7B and 7C, we observed that some events were missing in the RTM image even when the "true" velocity was used.

The key takeaway from this exercise is that adjoint imaging techniques such as RTM may not be adequate for determining if the velocity model is accurate. The limitations of RTM manifest as non-geologic events, such as broken reflectors. These features can be incorrectly interpreted as indications of velocity errors. FWI Imaging should be considered for velocity evaluation.

Conclusions and Discussions

Using a WAZ data set, we have shown the steps we took to build velocities and images with TLFWI and FWI Imaging and demonstrated the significantly improved results obtained through this workflow. Despite our best efforts, some imaging issues remain, especially for the areas beyond diving wave penetration, as marked by the orange arrow in Figure 6D. These could be further mitigated by full-azimuth, long-offset OBN data with better low frequencies, which is expected to greatly reduce the uncertainties in velocity model building and subsalt imaging.

Acknowledgments

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