Updating salt model using FWI on WAZ data in the Perdido area: Benefits and challenges

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Summary

The deepwater Gulf of Mexico (GOM) is characterized by complex salt structures, and a major portion of velocity model building is often devoted to obtaining accurate salt geometries and intra-salt velocities. Traditionally, a top-down flow including overburden sediment updates, manual salt interpretation, salt shape scenarios, and subsalt updates has been employed. Salt model building can be highly interpretive and subjective. We show a successful application of full-waveform inversion (FWI) with wide-azimuth (WAZ) data to update salt in the Perdido area. We also discuss limitations of WAZ data when using this data-driven approach to update the salt model.

Introduction

In the last decade, there has been a collective attempt to reduce the dependence on salt scenarios and navigate towards FWI for salt model building. Shen et al. (2017) show a successful application of FWI to correct the salt model at Atlantis for an ocean bottom node (OBN) data set that contains rich low frequencies, full azimuth, and long offsets. Commenting on the results, Michell et al. (2017) state that “successful full-waveform inversion requires three fundamental ingredients: appropriate data, a good starting model, and an appropriate workflow/algorithm.” In the absence of one or more of these fundamental ingredients, one can only expect a sub-optimal model from FWI.

In this case study, we discuss the impact of using a not-so-appropriate WAZ data set, which lacks good usable low frequencies, long offsets, and full-azimuth coverage for FWI-based model building. We used time-lag FWI (TLFWI), which Zhang et al. (2018) demonstrates to be an appropriate algorithm for salt model updates. We observed significant uplift in the shallow velocity model and salt overhang definitions at most locations. We will discuss the limitations of using WAZ data for FWI and the additional effort required to obtain better starting models to overcome the lack of sufficient diving-wave energy and low-frequency signal (< 3 Hz). We will also briefly discuss the uncertainties in the inverted models, especially beyond the penetration depth of transmission waves.

Geologic background

The Perdido fold belt area of the Mexican GOM exhibits complex geology that poses great challenges for salt velocity model updates. It is characterized by several key features that separate the survey into distinctly different geologic regions. Moving from west to east is the shelf edge with prograding sediment wedges and extensional features, followed eastward by the Bravo Trough and an NE-SW trending basement high, popularly known as the Baha High (Dooley et al., 2018) (Figure 1). The Baha High acts as a giant step that prevents translation into the basin, which results in the expansive Perdido fold belt. Much of the Mesozoic section that was once deposited on the Bravo diaper may have since rafted on top of the salt nappes and flowed eastward. Above salt, there are numerous transported mini-basins, some of which are rafted carbonate. The extent of carbonate rafting also affects salt interpretation, as many times there is no clearly defined top of salt (TOS) reflector due to a weak impedance contrast between carbonates and salt. The complexity of the TOS reflector can also be extreme in some areas due to shortening as the nappe tries to advance eastward but is slowed by bulldozed sediment wedges and the Perdido fold belt. This can create a rugose TOS geometry with many small overhangs. The complexity in salt geometry has prevented adequate velocity updates for sediments around salt, which in turn has further impeded salt interpretation in this area.

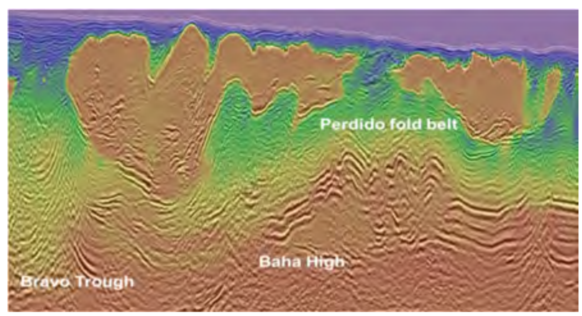

Figure 1: The major geologic components of the Perdido area are displayed. The Bravo Trough on the west side is the source of the allochthonous salt nappes. The Baha High is a basement high on top of which sits the Perdido fold belt.

For years, geophysicists and geologists relied on numerous salt scenarios, which tend to be time-consuming and often indecisive. Inspired by Shen et al. (2017) and Zhang et al. (2018), we decided to apply the TLFWI algorithm discussed by Zhang et al. (2018) for velocity model building in this area. The TLFWI was carried out up to 6.5 Hz, which was enough for correcting the kinematic errors.

Input data

There are two WAZ surveys in the study area shot along EW and NS directions, respectively. The EW WAZ survey is a conventional WAZ acquisition with 4 source vessels

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and 2 streamer vessels with a streamer length of 8 km. The orthogonal NS WAZ has a similar acquisition system with an additional leading source about 4.5 km in front of the other source vessels, providing up to 14 km offset coverage in the NS direction within a narrow azimuth range. Compared to OBN data, WAZ data suffers due to lack of usable low frequencies below 3 Hz and poor offset coverage.

To demonstrate the importance of low frequencies for FWI, we applied FWI using two data sets with different low-frequency content. The starting model was built using a traditional top-down approach with an additional 200 m smoothing (Figure 2a). As shown in Figure 2b, the TLFWI with WAZ data containing usable data from 3 Hz can update the overhang sediment velocity and carbonate above TOS, providing an improved subsalt image. However, when using WAZ data with all low-frequency signals below 4 Hz attenuated, the carbonate and overhang velocity cannot be fully updated by FWI because it is trapped in a local minimum due to missing low-frequency information (Figure 2c).

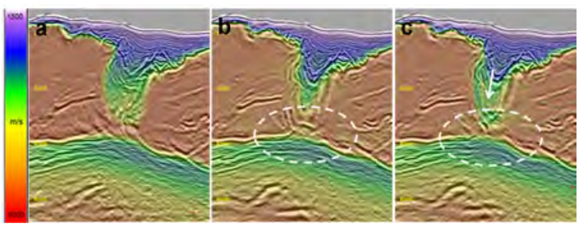

Figure 2: (a) initial model from top-down salt interpretation approach with 200m smoothing, (b) FWI model starting from 3 Hz, (c) FWI model starting from 4 Hz.

Additionally, lack of long offsets limits the diving energy penetration depth, which can also degrade FWI results. Diving wave penetration QC (Ahmed, 2018) shows that WAZ data with 8 km offsets clearly has less coverage compared to WAZ data with 14 km offsets (Figures 3a and 3b). The inclusion marked by a white arrow in Figure 3 is shown to be better covered by WAZ data with 14 km offsets.

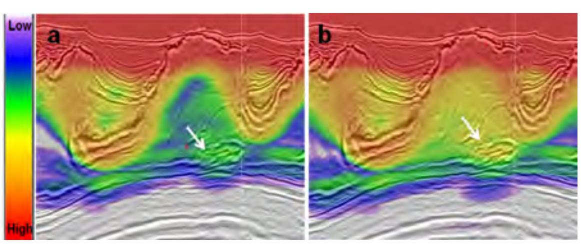

Figure 3: Diving wave penetration depth for (a) 8 km offset and (b) 14 km offset WAZ data are shown. The inclusion marked by the white arrow is better covered by diving waves from the 14 km offset survey.

TLFWI successfully updates allochthonous salt bodies

Although WAZ data is not ideally suited for FWI, we still see tremendous value in using an appropriate FWI algorithm to build salt models. At places where the initial model is good, TLFWI can directly update the salt geometry and velocity. The real benefit of FWI over interpretation-based approaches is the ability to simultaneously invert for overburden sediments, salt geometry, intra-salt, salt overhang, carbonate, and subsalt velocities. In an interpretation-based model building approach, we often fix either the salt shape or sediment velocities and therefore cannot update both simultaneously.

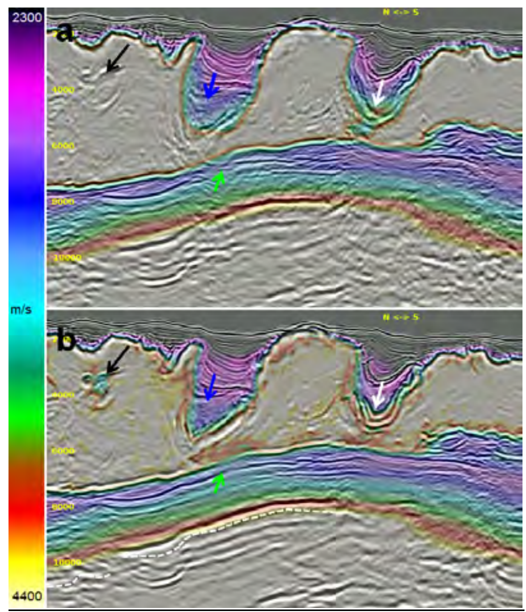

Figure 4: A successful application of TLFWI to update salt velocities: model and image (a) before TLFWI, (b) with TLFWI-updated model.

In Figure 4a, the initial model for TLFWI is a rudimentary solution from manual salt interpretation. There is significant ambiguity at the TOS, highlighted by the white arrow. This model does not contain any intra-salt velocity variation. These shortcomings in the initial model introduce kinematic errors for migration and result in a poor subsalt image after reverse time migration (RTM).

TLFWI (Figure 4b) successfully inverted the carbonate in the overhang (white arrow), identified the shale body (blue arrow), and reduced salt-related errors, including the dirty salt velocities (black arrow). As a result, the RTM showed a clear improvement in the subsalt image. Also, hints of what appears to be BOS (green arrow) were imaged in Figure 4b, which were not obvious before FWI (Figure 4a). The improvements in the overburden resulted in a significant uplift in the subsalt cretaceous section (white dashed line). This significantly reduced the cycle-time associated with running several salt scenarios/shale scans to obtain a result similar to that from TLFWI.

Improving FWI starting model to overcome limitations of WAZ data

Although we observed several areas of successful FWI application using the WAZ data when starting from a rudimentary velocity model, we were not as fortunate in all areas. Some areas with more complex salt geometry and overburden velocities did not see similar uplifts when using the top-down, interpretation-based model as the starting model. Figures 5a and 5b illustrate the input and output of TLFWI, respectively. Figure 5b shows that TLFWI was able to resolve the shallow salt sheet and carbonate highlighted by white arrows, which yielded an improved subsalt image. However, in Figure 5b, we also observed a slight pull-up highlighted by the dotted white line that indicates the overburden velocities may not be completely resolved. As discussed in Figures 2 and 3, this could be due to the lack of sufficient low frequencies and/or diving-wave energy. Hence, a better starting model may be needed.

At this location and other similar locations, we used hints provided by FWI to obtain a better initial model. The isolated faster velocity bodies (Figure 5b) could indicate the presence of more carbonate or salt in the area marked by the white circle. Based on this, a new TLFWI was performed starting with a new trial model (Figure 5c). The second TLFWI with the improved initial model better resolved the shallow salt and carbonate velocity, providing a more geological shallow model which improved subsalt structure, as shown by the dotted white lines in Figure 5d. Although we saw improvements with this new initial model, we observed that the subsalt events are still not flat in Figure 5d, and this underscores one of the major uncertainties in the velocity model obtained using WAZ data for FWI.

Occasionally, in some complex areas, using only WAZ data may result in salt shapes that are way off from the true earth model. Figure 6a shows an example of one such location where our top-down model-building approach was performed using only seismic data, with the corresponding TLFWI result shown in Figure 6b. The Mesozoic section (dashed white line) in Figure 6b indicates that we are likely way off from the true earth model. Additionally, no indications of a second salt body are visible. This shows that TLFWI using WAZ data is severely blindsided when the initial model is too far from the true model.

We built a different initial model with the aid of information from a well in the vicinity, which indicated the presence of a large allochthonous salt body. Our initial attempt to honor the information at a single well location is shown in the model in Figure 6c. The corresponding TLFWI result shown in Figure 6d is an improvement over the result in Figure 6b but is still far from the true model.

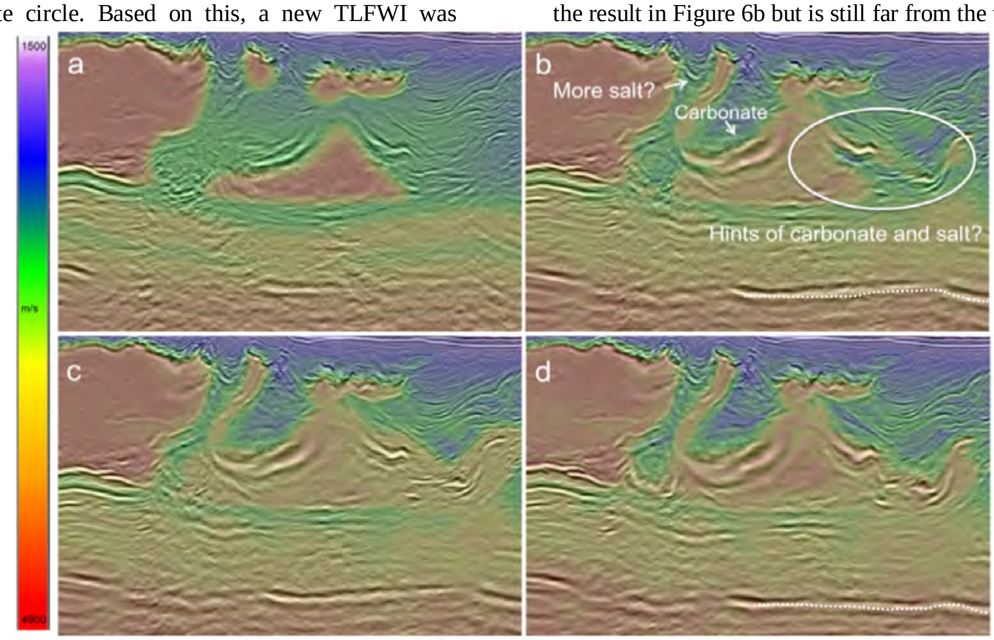

Figure 5: The starting model (a) for TLFWI is the velocity with some smoothing from conventional top-down model building approach. Velocity after initial FWI (b) shows indications for a different salt structure. An improved initial model (c) was built taking the indications from FWI into account. The final model (d) after FWI with the improved model provided the best subsalt image with a different salt structure from initial model.

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A more complex initial model was built using hints from Figure 6d and well information to obtain the model in Figure 6e. TLFWI on top of Figure 6e resulted in a better output model (Figure 6f). In the subsalt section of Figure 6f, we observed a much improved image compared to Figure 6b, underscoring the need for additional a priori information, in this case, the well information. Although we see a significant improvement, the discontinuities at the Eocene and Mesozoic levels (shown by the white arrows in Figure 6f) and the complexity of the overburden salt shape indicate that there are still severe uncertainties in the final model. Here, the well sonic log provided crucial information, but it was extremely local and did not explain the salt shape or salt velocities away from the well trajectory.

Conclusion and discussion

We demonstrated the benefits of a data-driven approach for model building using an appropriate FWI algorithm on a sub-optimal data set in the Perdido area. When starting from an initial model obtained from a top-down approach, direct application of TLFWI brought improvements at several areas with overburden complexity.

We also presented the various shortcomings of WAZ data when the initial model is far from the true model. When using WAZ data, the initial model plays a larger role than when using data favorable for FWI, i.e., with good low-frequency content and long-offset coverage. Although we see uplifts in the model and subsalt images when using WAZ data, we have to acknowledge the presence of uncertainties in the model due to the limited penetration depth and increased dependence on reflection energy compared to more appropriate data like OBN. Although we can circumvent the limitations of WAZ data to a certain extent, long-offset, full-azimuth, rich low-frequency OBN data can provide better velocity updates when complex salt geometries are present and when the focus is on deep targets. Sharper salt model boundaries can be obtained by running FWI to higher frequencies; however, the uplift for subsalt imaging will be limited, as shown by Zhang et al. (2018).

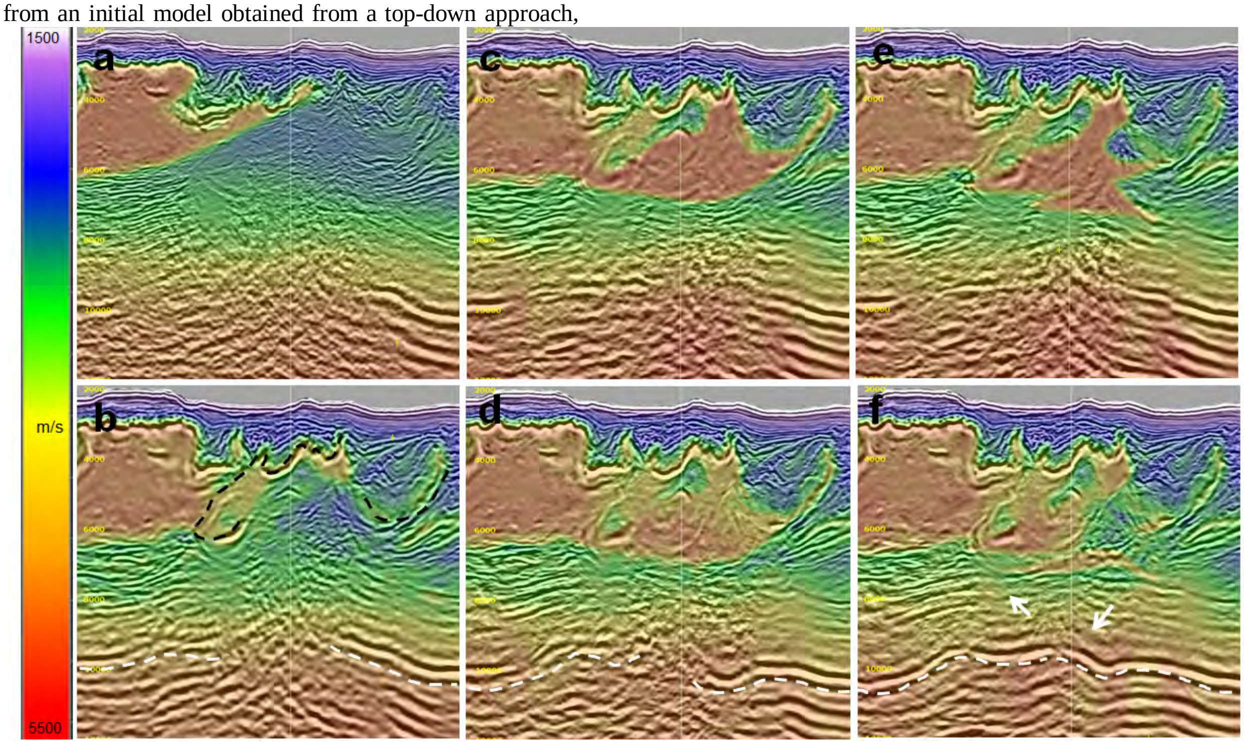

Figure 6: (a) Initial model without using well information, (b) TLFWI on top of (a), (c) first initial model incorporating well information, (d) TLFWI on top of (c), (e) improved initial model based on (c) and (d), (f) TLFWI on top of (e)

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