Paradigm shift: Recent advances in model building and imaging at Shenzi

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Summary

After many years of processing seismic streamer data acquired over the Shenzi field in deep-water Gulf of Mexico (GOM) with the best available technology, the workflows have remained highly interpretive, far from robust, often time-consuming, and ultimately proved inadequate for resolving the complexity of the salt and subsalt velocity models. Recent advances in full-waveform inversion (FWI) algorithms combined with a newly acquired, ocean bottom node (OBN) data set have ushered in a fundamental shift in velocity model building and imaging at Shenzi as we move away from mostly interpretation-driven to more data-driven processes.

While the velocity model obtained from Time-lag FWI (TLFWI) using the legacy rich-azimuth (RAZ) streamer data provided significant imaging uplift over the best previous processing, an additional step-change improvement in image quality was achieved by running TLFWI with the OBN data. The OBN TLFWI model combined with the long offsets of the OBN data allowed steeply dipping events along the salt feeder to be seen for the first time on the reverse time migration (RTM) image. However, despite these large improvements, the image still suffers in areas of low illumination. Least-squares RTM (LSRTM) showed some good improvement over the RTM but proved less effective where the starting image was too poor. By running TLFWI to a maximum frequency comparable to the RTM, we were able to generate an FWI Image, an estimation of the reflectivity obtained directly from the FWI velocity model, with good S/N, more balanced amplitudes, and improved steep-dip and fault imaging, making it a direct rival to the RTM and LSRTM images.

Introduction

The Shenzi field, located in deep-water GOM, consists of a set of Miocene reservoirs flanking a steep and complex salt feeder, all lying beneath a thick salt canopy. Exploration using 2D narrow-azimuth streamer data began in the 1990s with production commencing in 2009. In 2005, a high-fold, RAZ streamer survey with 8.5 km maximum offset was acquired to provide better illumination over this geologically complex area (Howard, 2007).

Despite several reprocessings of the RAZ data with the most advanced imaging and model building techniques available, imaging issues persisted. At the subsalt level, noise interference, lack of resolution, and zones of weak amplitude all complicated the interpretation. Synthetic studies indicated that these problems were predominantly due to an inaccurate velocity model. Additionally, the steep dips along the salt feeder had yet to be imaged with the RAZ data set.

Each previous RAZ processing project followed a conventional top-down model building flow. Salt geometries were first updated through manual interpretation and many salt scenario tests. Subsalt velocities were updated by propagating local velocity information from well data throughout the project area. Then subsalt velocity tomography based upon RTM surface offset gathers (SOGs) was applied to flatten the gathers (Yang et al., 2015). This traditional flow is highly interpretive, fails to capture the subsurface complexity, and often operates poorly in areas of complex geology.

To address the velocity model and imaging issues, a more powerful approach is needed. Advances in FWI algorithms are transforming our ability to update salt and subsalt velocities. We have seen recent successes applying FWI with OBN data to update salt velocities (Michell et al., 2017; Shen et al., 2017; Shen et al., 2018; Zhang et al., 2018; Nolte et al., 2019). Our method follows a similar strategy, leveraging improvements from TLFWI (Zhang et al., 2018; Wang et al., 2019) with more appropriate data from a long-offset OBN acquisition to update the velocity model. In this workflow, the entire velocity model is updated in a data-driven means with minimal human intervention. Equipped with a better velocity model, the contribution of the OBN data to the subsalt image is examined, including full-wavefield imaging through FWI.

Impact on model building

While the OBN data were being acquired, TLFWI using the RAZ data was run to improve the starting model for the OBN velocity update. Three rounds of TLFWI up to 6 Hz were carried out, with the first round starting from a smoothed version of the legacy model. In between the rounds, edits were made to the initial model based upon either well information, updates from RTM SOG subsalt tomography, or modifications to the salt geometry based upon indications from the previous round of TLFWI (Kumar et al., 2019). The result was consistent image improvement throughout the project area.

Figures 1a-b show the RAZ legacy model and RAZ TLFWI model overlaid on their respective 15 Hz RAZ RTM images. The salt feeder was reshaped by RAZ TLFWI, and the inversions started to detect the faster Mesozoic velocities that extend from the bottom of the subsalt basin along the feeder flanks. The basement image remains broken but

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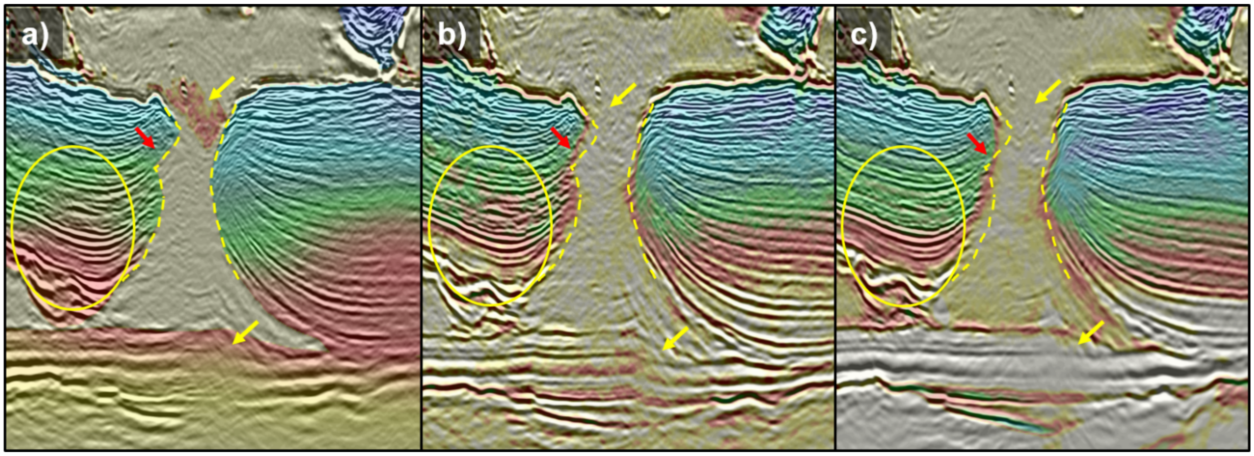

Figure 1: a) Legacy model, b) 6 Hz RAZ TLFWI model, and c) 11 Hz OBN TLFWI model overlaid on top of their 15 Hz RAZ RTM images. The dashed line indicates the salt geometry of the legacy model. The salt wing (red arrow) is completely removed in the OBN TLFWI model.

becomes more coherent and continuous overall. Figures 2a-b show the 15 Hz RTM images of the RAZ data migrated with the legacy and RAZ TLFWI models on another line cutting through the feeder. Here the crest is weak and broken on the legacy image, while the amplitudes become stronger and more coherent with the RAZ TLFWI model.

Even though the application of TLFWI with the RAZ data alone provides substantial improvement in image quality, event breaks or remaining undulations indicate that the velocity model, the input data, or both are not good enough. To make better use of the improved algorithm, we combined it with the long-offset, full-azimuth coverage of the OBN data. The OBN survey consisted of a dense core of nodes surrounded by a halo of sparse nodes. Maximum offsets are in the range of 20 – 45 km. Good S/N and the TLFWI algorithm allowed the OBN inversion to start at 1.6 Hz, reducing the chances of cycle-skipping. The OBN TLFWI was run to a maximum frequency of 11 Hz, but most of the kinematic errors were corrected by < 6-7 Hz.

Figure 1c shows the OBN TLFWI velocity model overlaid on its 15 Hz RAZ RTM image. The salt wing that was present in the legacy model and partially present in the RAZ TLFWI model has been completely removed, and the amount of salt in the feeder has increased substantially. We note that the basin velocities have slowed in the Miocene/ Oligocene interval, allowing this expansion to take place. The Mesozoic velocities first detected by RAZ TLFWI have been further refined, with the velocity model becoming more structurally conformal to these packages. Basement and autochthonous base of salt (BOS) events are much better focused and aligned, an indication of more accurate velocities above. In Figure 2c, the structure is further improved everywhere with less crossing of events.

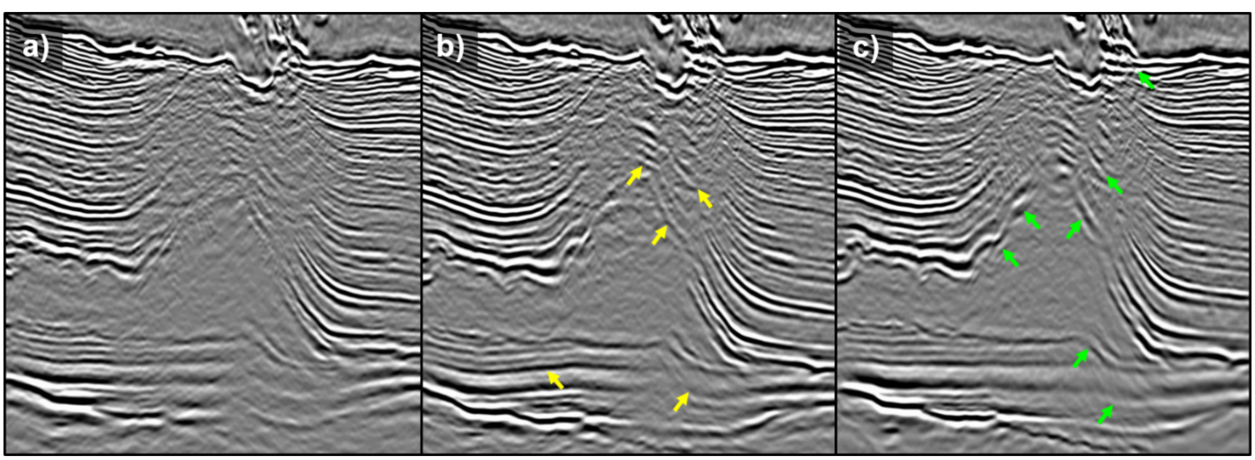

Figure 2: 15 Hz RTM images using a) legacy model, b) 6 Hz RAZ TLFWI model, and c) 11 Hz OBN TLFWI model.

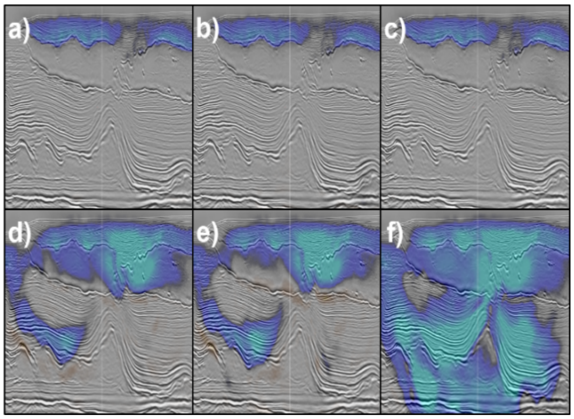

Figure 3: Illumination maps for RAZ data using a) legacy model, b) RAZ TLFWI model, and c) OBN TLFWI model. The same maps are shown for OBN in d), e), and f).

Amplitudes of events climbing over the salt are stronger on the RTM image from the OBN TLFWI model. The basement has healed almost completely and is now much more simplified.

To study the model accuracy, we examined the illumination maps generated from large scattering angle RTM images (Ahmed, 2018). The maps give a qualitative picture of the model accuracy and diving wave illumination to the extent where the model is sufficiently accurate. We generated them for three different models (legacy, RAZ TLFWI, OBN TLFWI) using RAZ (Figures 3a-c) and OBN data (Figures 3d-e). Due to the limited offsets available in the RAZ data, the illumination maps change very little for the three different models, and the diving wave penetration is limited to above the salt (Figures 3a-c). On the other hand, the impact of the longer offsets of the OBN data can already be seen on the legacy and RAZ TLFWI maps through increased illumination in the subsalt (Figures 3d and 3e). However, because the maps were generated from the crosscorrelation of forward- and back-propagated wavefields, they are affected by the accuracy of the model used to generate them. Hence the extended illumination in Figure 3f shows that the OBN TLFWI model is of much better quality than the RAZ TLFWI model. It also demonstrates that the diving waves penetrate down to the basement in the OBN data.

Impact on imaging

The OBN TLFWI gave substantial uplift on the 15 Hz RAZ RTM image, but the steep-dip imaging remains poor for this data set. Figures 4a-b compare 25 Hz RTM images generated by migrating the RAZ and OBN data with the OBN TLFWI model. The steep dips along the flanks appear on the OBN RTM image although the amplitudes remain rather weak in these areas, an indication that illumination remains poor. Least-squares processes offer a means to potentially address illumination issues. The single-iteration image domain LSRTM based upon curvelet domain matching filters applied to angle gathers shown in Figure 4c provides some amplitude compensation in these low illumination areas (Wang et al., 2016).

However, for particularly challenging areas, e.g., steep dips below BOS, the LSRTM fails to fully balance the amplitudes. We found that the image with the best illumination compensation and most balanced amplitudes is the FWI Image, an estimation of the reflectivity derived directly from the FWI velocity model (Zhang et al., 2020). The image is calculated as the derivative of the velocity model along the direction normal to the reflector dips, assuming constant density. The FWI Image coming from the 11 Hz OBN TLFWI model is shown in Figure 4d. Steep dips are better imaged, especially in complex areas, and it offers better illumination compensation than the LSRTM. The raw data input to TLFWI contains transmissions, primary reflections, and their free-surface and internal multiples. The subsurface is therefore illuminated by a greater number of modes than present in the down-going wavefield used in RTM and LSRTM that has undergone free-surface multiple attenuation. Additionally, FWI itself is a least-squares process, and the FWI Image exhibits many features of least-squares migration, including more balanced amplitudes and attenuation of migration noise.

Given the improved kinematics of the model and the benefits observed on the 11 Hz FWI Image, the maximum frequency of the inversion was pushed to 20 Hz to generate a high-frequency FWI Image that is more comparable to the 25 Hz maximum frequency of the LSRTM. Figure 5 compares the 11 Hz FWI Image, the 20 Hz FWI Image, and the 25 Hz LSRTM. The 20 Hz FWI Image shows resolution similar to the 25 Hz LSRTM image in the subsalt but with more balanced amplitudes and better event separation. The high-frequency FWI Image is particularly good for imaging steep dips and small-scale faults. The combination of high resolution, good S/N, and improved illumination make the 20 Hz FWI Image a key volume for structural interpretation and a rival to RTM and LSRTM.

Conclusions

We have shown the impact of TLFWI using OBN data on the model building and imaging at Shenzi. Through the combination of a more powerful FWI algorithm and more appropriate input data, the velocity model has been updated in a data-driven way to give significant uplift on the RTM image. The TLFWI algorithm alone was enough to produce some good improvements in image quality, but by combining TLFWI with a long-offset OBN data set, another step-change was achieved. Not only were the OBN data critical for the velocity update, they were important for the

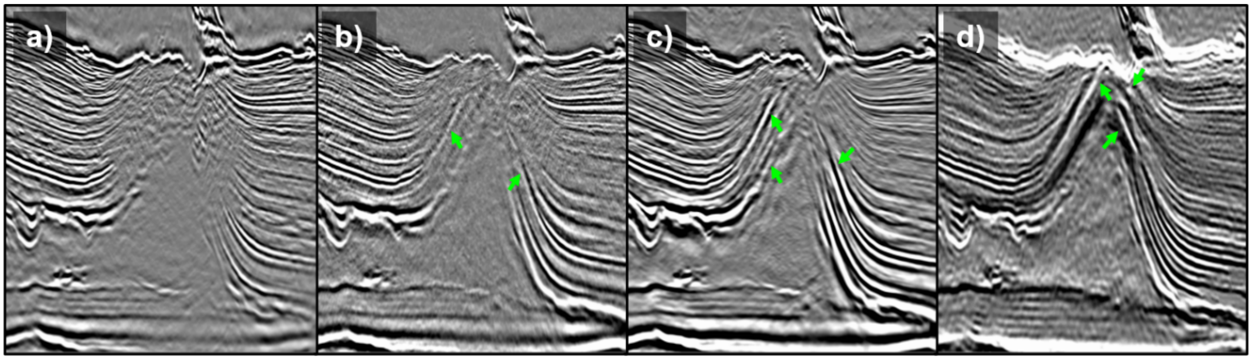

Figure 4: a) 25 Hz RAZ RTM, b) 25 Hz OBN RTM, c) 25 Hz single-iteration OBN LSRTM, and d) 11 Hz OBN FWI Image. All RTM images use the 11 Hz OBN TLFWI model.

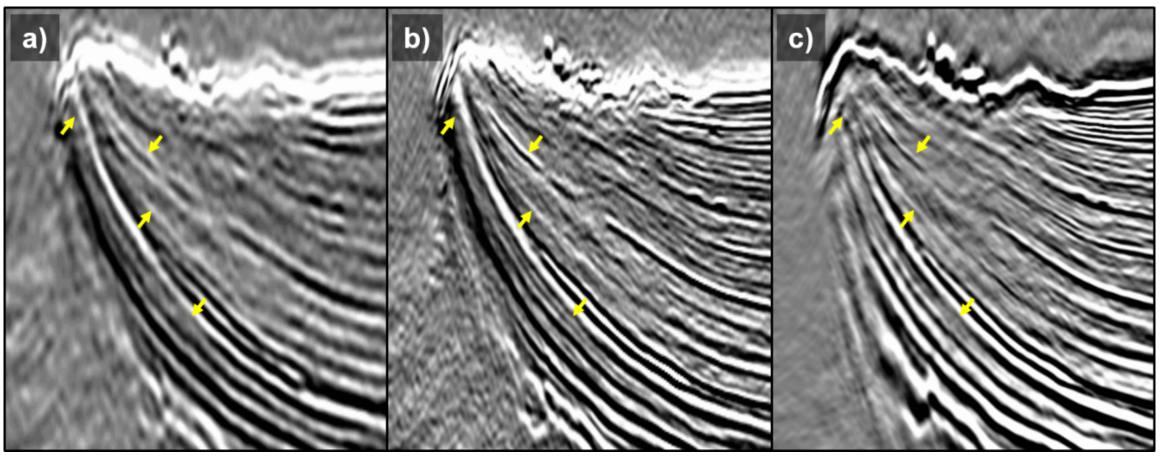

Figure 5: a) 11 Hz OBN FWI Image, b) 20 Hz OBN FWI Image, and c) 25 Hz single-iteration OBN LSRTM.

RTM images as well, particularly for steep dips along the feeder flank. Still, even with the increased illumination from the OBN data, weak zones persisted on the image. A single-iteration LSRTM was able to provide some compensation, but it appeared insufficient in places. The volume with the most balanced amplitudes is the FWI Image derived from the TLFWI velocity model itself.

Despite the improvements in image quality, several challenges remain. For instance, effects from viscosity and anisotropy continue to be an issue because of our limited ability to reliably estimate the parameter values used in the modeling. Due to the large crosstalk between these parameters and velocity, their uncertainty can significantly affect the inverted model. Synthetic studies at Shenzi have shown that the feeder flank position can shift by several hundred meters given incorrect viscosity and anisotropy parameters.

While FWI has proven to be extremely effective for updating salt and subsalt velocities, the success of its application largely depends on contribution from diving waves. In areas of Shenzi where the diving wave illumination is poorer, such as just below BOS, well information was used to guide the FWI solution. The impact of these changes on the structure proved to be minor overall, but they helped improve the well ties, illustrating that it is important to understand the limitations of the update.

To extend the FWI Image beyond a structural interpretation tool, there is a need to improve our understanding and the reliability of the FWI Image amplitudes. For instance, being able to update the density would help as currently we only invert for velocity. Including more physics in the modeling and inversion (visco-elastic effects) would also increase the amplitude fidelity of the FWI Image, but obtaining the correct additional model parameters remains a challenging area to be researched.

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