Improving images under complex salt with ocean bottom node data

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Summary

Subsalt imaging at the Stampede field in the Gulf of Mexico (GoM) has remained challenging for decades due to the existence of a large and complex sediment inclusion inside a thick tabular salt. Recently, appropriate full-waveform inversion (FWI) algorithms have been developed for automatic salt model updating (Shen et al., 2017; Zhang et al., 2018). By applying this technology to newly acquired ocean bottom node (OBN) data with good low-frequency content and ultra-long offsets, we are able to invert both the shape and velocity of this complex sediment inclusion at Stampede and provide significant improvement to the subsalt image. A good starting model for FWI is still needed in this workflow, but detailed interpretation efforts may not be necessary. Moreover, we expect further improvements to the subsalt imaging if data with even longer offsets becomes available.

Introduction

Subsalt imaging is challenging in the GoM for many reasons, one of which being the existence of sediment inclusions inside salt bodies. These inclusions critically impact subsalt imaging, but it is often difficult to accurately define their shape and velocity (Ji et al., 2011; Li et al., 2011; Huang et al., 2012; Helgesen et al., 2013).

Stampede is a producing oil field in the deepwater GoM. Discovered in 2005, Stampede is located 115 miles south of Fourchon, Louisiana in ~3,400 ft water depth. Imaging at the Stampede field is complicated by the presence of up to 15,000 ft of salt in the overlying sedimentary column. This salt body includes overhangs, inclusions, sutures, steeply dipping flanks, and a rugose base of salt (BOS). All of these detailed structures are challenging for conventional top-down model building flows to capture. After years of processing effort using available streamer data, the overall imaging has improved dramatically over the Stampede field, but the subsalt images still carry large uncertainty underneath the most difficult part—a large and complex sediment inclusion inside thick tabular salt (Mohapatra et al., 2013).

FWI has long been considered the most promising data-driven tool for velocity model updates. However, until recently, successful applications of FWI to update salt structures have almost only been seen on synthetic data. Recent breakthroughs on real data sets have been demonstrated by Shen et al. (2017) and Zhang et al. (2018), where FWI successfully corrects salt misinterpretations and achieves better subsalt images. These studies all stressed the importance of low-frequency, full-azimuth, and long-offset OBN data to update complex salt geometries and correct velocity errors. Encouraged by these FWI advances and OBN successes for subsalt imaging, Hess acquired OBN data over the Stampede field in 2018.

FWI using OBN data greatly reduced velocity error

The OBN data set was acquired in the north-south direction. The nominal node spacing is 350 m by 350 m, while the nominal shot spacing is 50 m by 50 m. A phase QC shows the data has good S/N at low frequencies, usable down to 1.6 Hz. It also has ultra-long offset coverage: the center nodes have full-azimuth shot coverage with offsets up to 18~20 km; the boundary nodes have full-azimuth shot coverage with offsets up to ~8 km and limited azimuth shot coverage with offsets up to ~30 km (Figure 1).

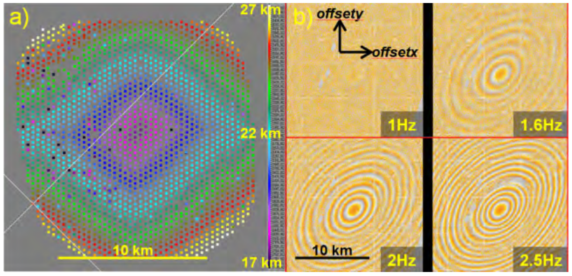

Figure 1: Stampde OBN data overview: a) maximum offset for each node; b) phase QC for all shots from one node at different frequencies.

The starting model for FWI in this study was a legacy model derived through a conventional top-down model building flow, including several iterations of ray-based tomography, diving-wave FWI, reflection FWI, top-down salt interpretations, and extensive salt scenario tests, using full-azimuth (FAZ) streamer data. To evaluate this model, we migrated it using the newly acquired OBN data. Although most surrounding areas have decent imaging quality, and despite the target sediment inclusion already including a lot of velocity details introduced by the salt scenario tests in the legacy flow, the subsalt section beneath this complex inclusion remains poorly imaged (Figures 2a and 2b). This implies that the legacy velocity model may still have large local velocity errors within the salt inclusion zone.

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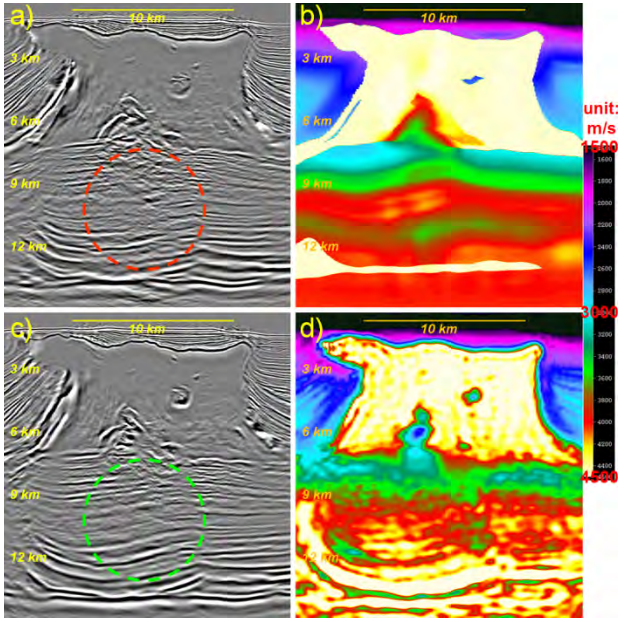

Figure 2: 15 Hz OBN RTM stack and model: a) and b) legacy model; c) and d) after OBN FWI update, 1.6~5 Hz.

Starting from the legacy velocity model mentioned above, we smoothed the velocity with a radius of 300 m to blur the sharp velocity boundaries and performed time-lag FWI (TLFWI) (Zhang et al., 2018) from 1.6 Hz to 5 Hz using the OBN data. The inverted velocity model better defined both the shape and velocity of the target inclusion zone, and brought out details that were difficult to capture through manual efforts (Figures 2c and 2d). The new model provided significant improvements to the subsalt image. The reflectors beneath this complex inclusion became more continuous and better focused with the new model.

Why is OBN data good for FWI?

Among all existing data types, OBN data is often praised for its good low-frequency S/N and ultra-long offset coverage. Dellinger et al. (2017), Michell et al. (2017), and Shen et al. (2018) all stress the importance of these features to update complex salt geometries and correct velocity errors. In order to further evaluate the benefits of OBN data for FWI at Stampede, two experiments were conducted.

First, different inversion frequencies were tested for FWI using the Stampede OBN data: 1) 1.6~5 Hz and 2) 3~5 Hz. Although the two flows only varied by the starting frequency, inversion results showed a noticeable difference. Starting from 1.6 Hz, we were able to correct the velocity errors at the target sediment inclusion zone effectively (Figures 3a and 3b). By contrast, starting from 3 Hz suffered from cycle skipping locally, and reflectors beneath this complex inclusion were still not well focused (Figures 3c and 3d). It is important to note that although FWI in the second case started at 3 Hz, all energy at lower frequencies in the data (e.g., 1.6 Hz) was still incorporated during the inversion. A worse result is expected if the same inversion frequency is performed on data with lower S/N at low frequencies.

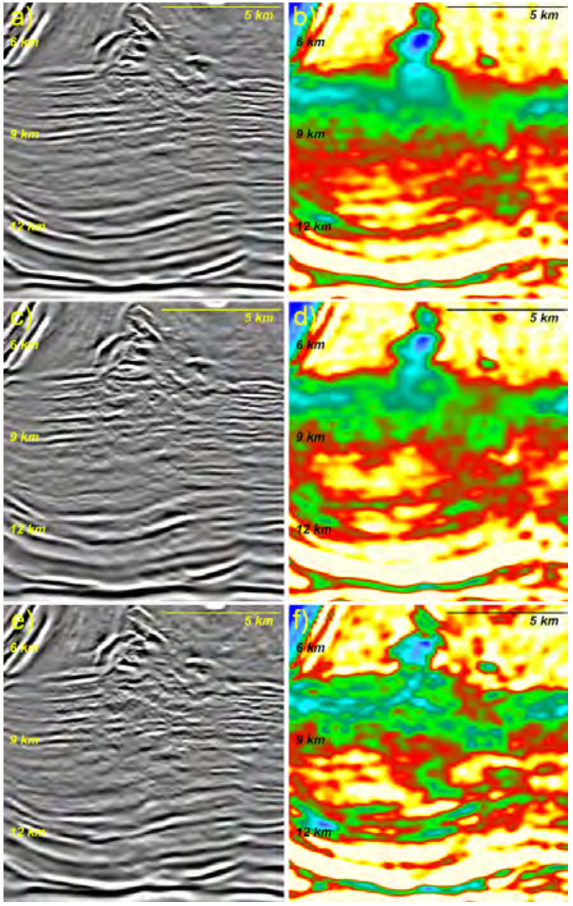

Figure 3: OBN FWI models with different inversion settings and corresponding 15 Hz RTM stacks: a) and b) 1.6~5 Hz, full OBN data; c) and d) 3~5 Hz, full OBN data; e) and f) 1.6~5 Hz, OBN data with offsets limited to 8 km in both inline and crossline directions.

Second, different offset ranges were tested for FWI with inversion frequency of 1.6~5 Hz: 1) full OBN data (same as the first case in the previous experiment) and 2) offsets limited to 8 km in both inline and crossline directions. Based on the results, although the nodes still had full-azimuth shot coverage in the second case, FWI suffered from inadequate diving wave penetration depth and was no longer able to fully resolve the target inclusion after limiting the offset range (Figures 3e and 3f). Moreover, the

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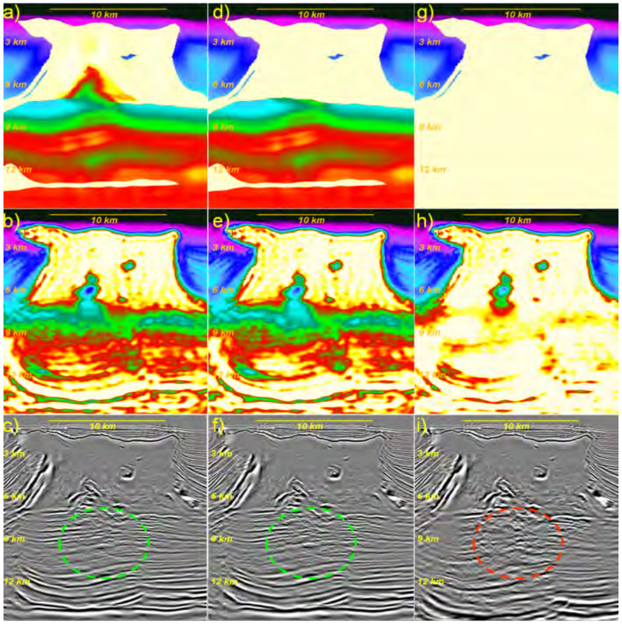

Figure 4: Different starting models and the resulting FWI models and 15 Hz RTM stacks: a) top-down model building flow and extensive scenario tests; b) and c) FWI on top of a); d) top-down model building flow with simpler clean salt; e) and f) FWI on top of d); g) salt flood model; h) and i) FWI on top of g).

velocity field from the limited offset range was noisier due to the limited angle coverage, which resulted in additional undulations in the stack.

Combining the observations from both experiments, we consider both the low-frequency energy (1.6 Hz and below) and ultra-long offsets of OBN data crucial for resolving the target sediment inclusion and improving the subsalt image at Stampede. It would be challenging to achieve similar uplifts using any existing streamer data (narrow-azimuth / wide-azimuth / full-azimuth).

How accurate of a starting model do we need for FWI?

Based on the tests in the last section, we observed that the update power of FWI was affected by both the starting frequency of the inversion and the offset range of the data. For Stampede, the update power is limited by the lowest usable frequency (~1.6 Hz) and maximum offset coverage of the acquired OBN data. In order to further evaluate the capability of FWI at Stampede, different starting models were created with different degrees of velocity error, and the same FWI flow—1.6~5 Hz, full OBN data—was tested using each model to see how effectively large errors in the starting model could be corrected based on this OBN data.

Our first starting model experiment was to replace the legacy model with a simpler clean salt model at the target inclusion (Figure 4d). The new starting model did not include the velocity details introduced by salt scenario tests in the legacy flow, and contained larger local velocity error. However, the inversion results did not show a dramatic difference and both models resulted in similar imaging quality beneath this complex inclusion (Figures 4b, 4c, 4e and 4f).

Our second experiment was to replace the legacy model with a simple regional salt flood model (Figure 4g). This starting model did not incorporate any BOS interpretations made during the legacy top-down model building. Therefore, the starting model included very large regional velocity errors. This time, the inversion results showed a significant difference. Although FWI with the salt flood model correctly slowed down the subsalt velocities, the update power is far from enough to sufficiently correct all velocity errors (Figures 4h and 4i).

Based on these tests, we concluded that a good starting model after a conventional top-down model building flow is still needed for FWI when using OBN data, but detailed interpretation efforts can be greatly reduced as fine details of both sediment velocity and salt geometry can be detected by FWI.

How can we further improve the model?

The current velocity model still has room for improvement. One obvious issue is that the reflectors right below the target sediment inclusion are not well focused, which implies there is still some uncertainty in the velocity details, even though major kinematic errors have been greatly reduced by FWI. Another issue is that diving wave penetration is limited by the maximum offset in the input data; therefore, the velocities below the penetration depth (for example, subsalt areas) still contain relatively large uncertainty after FWI.

An intuitive attempt for the first issue is to run FWI to a higher frequency for more velocity details. Different inversion frequencies were thus tested using the Stampede OBN data: 1) 1.6~5 Hz, 2) 1.6~8 Hz, and 3) 1.6~12 Hz. We found that velocities in high contrast areas (e.g., salt-sediment interface) maintained a sharper boundary as the inversion frequency increased, and more velocity details could be inverted in the subsalt (Figures 5a, 5c, and 5e). However, migration QC showed that most of the subsalt imaging benefits came from the low-wavenumber kinematic update in the FWI model, and going beyond 8 Hz does not provide much additional imaging benefit and is not a good return on the rapidly increased computational cost (Figures 5b, 5d, and 5f). Wang et al. (2019) find

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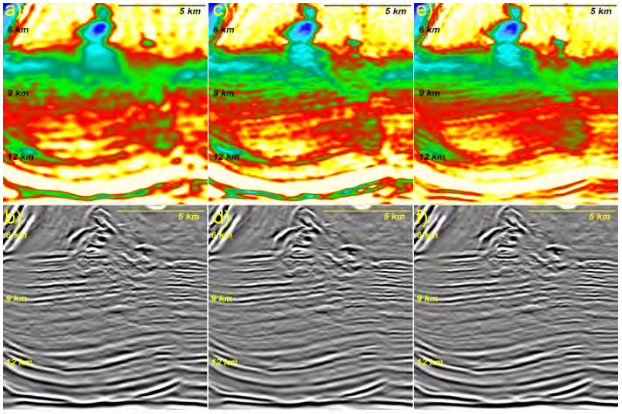

Figure 5: OBN FWI model after running to different frequencies and corresponding 15 Hz RTM stack: a) and b) FWI 1.6~5 Hz; c) and d) FWI 1.6~8 Hz; e) and f) FWI 1.6~12 Hz.

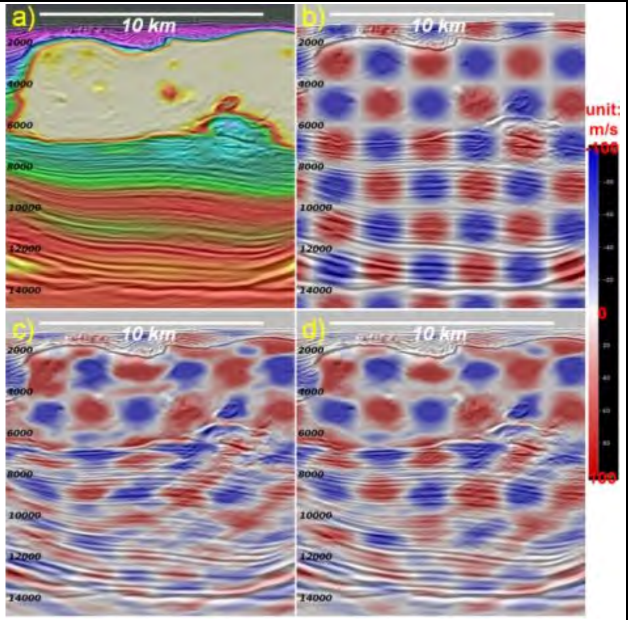

Figure 6: FWI synthetic test starting from 1.6 Hz with different offset ranges: a) starting model; b) true perturbation for modeling; c) synthetic perturbation using current OBN data; d) synthetic perturbation after extending offset range for every node by 4 km in full azimuths.

similar observations using an example with a different data type from a different area.

In order to resolve the second issue, longer offsets will be needed. For TLFWI, velocity updates below the diving wave penetration depth rely on reflection energy, and therefore may not be as reliable as those above the diving wave penetration depth. A synthetic study was performed to investigate the benefits from additional offset coverage. An initial model (Figure 6a) with an added checkerboard-type velocity perturbation (Figure 6b) was used for acoustic modeling to generate synthetic shot gathers. FWI was then tested using those shot gathers and the initial model as input to see whether the checkerboard pattern could be restored. Based on the test results, the current OBN data was able to penetrate roughly up to the BOS level but left a larger uncertainty in the subsalt region (Figure 6c). Further testing shows that if we could extend the offset range for every node by 4 km in full azimuths, then not only could the deeper sections be better inverted and subsalt velocities be better constrained, but the shallow sections could benefit from extended angle coverage and more velocity details could be captured inside the salt as well (Figure 6d).

Additionally, the current TLFWI algorithm carries its own limitations. The velocity update may still be contaminated by insufficient illumination applied or by inaccurate and/or incomplete physics modeled (e.g., density and elasticity). We expect to further improve our FWI algorithm for a more accurate model as we gain more experience in salt velocity updating with FWI.

Discussion and Conclusions

We demonstrated that FWI with OBN data was able to define both the shape and velocity of a complex sediment inclusion and provide significant subsalt imaging uplifts at the Stampede field. FWI's update power greatly depends on the offset range and S/N at low frequencies of the input data. Compared to streamer data, the better low-frequency content and longer offsets provided by OBN data enabled us to better correct velocity errors, and therefore manual interpretation efforts could be greatly reduced by a more data-driven approach.

We also recognize a few limitations of this method. First, the accuracy of the FWI model decreases with depth due to the limitation of diving wave penetration. Second, a good starting model is still needed for FWI due to the limitation of S/N at low frequencies. Lastly, the FWI velocity model can still be contaminated by inadequate physics modeled in the inversion. The combination of more suitable data and more advanced FWI algorithms should enable us to further improve the subsalt imaging.

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