Effective acquisition and model building to reveal the deep structures in complex geology

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Abstract

Sparse node acquisition has become a standard approach to improve the earth model by the addition of ultra-long offsets. The new designs of node data collections coupled with simultaneous shooting can be deployed on a regional basis covering thousands of square kilometers in a cost-effective manner. In complex geological settings including irregular salt geometry, the salt interpretation has a direct impact on subsalt imaging, however salt interpretation can be quite time-intensive and challenging. Full-waveform inversion (FWI), as a data-driven optimization algorithm with full wavefield modeling, has become one of the essential tools for earth model building. However, its use in the salt tectonic contexts, especially with streamer data collection, is limited since the frequencies acquired are not sufficiently low and the offsets sufficiently long.

The recent development of robust objective functions allows the application of FWI workflow on OBN surveys in the deep-water environment in the Gulf of Mexico, to refine the salt geometry and correct the background velocity error in subsalt to uncover the structure configuration in the subsalt that has not been seen before.

Introduction

The southern extent of the Green Canyon Protraction Area in the Gulf of Mexico (GOM) retains industry interest for both hydrocarbon exploration and development of existing fields given the large infrastructure investment. However, given its complex salt tectonic history, the region's deeper structural framework below 6 km depth remains difficult to map in legacy imaging that has been mainly derived from towed-streamer input data, despite the sustained use of robust techniques like full-waveform inversion to improve the earth model accuracy for the last several years. As a well-documented, data-driven process that uses full-wavefield modelling, we now expect full-waveform inversion (FWI) to be the most effective at correcting the first order velocity errors that compromise our ability to visualize and interpret a geologically complex salt basin. Ocean bottom node (OBN) acquisition and sparse OBN techniques provide an efficient way to obtain the more suitable, long offset and low frequency input data for FWI.

The appeal of a data-driven method is that it implies positive impact on turnaround time. Repeatedly perturbing the earth model during routine seismic imaging programs to better resolve the seismic image can be necessary given the limitations of the tools at hand, whether they are due to the characteristics of the input seismic data or the applied geophysics. Field successes through FWI using diving waves within the last decade are later complemented by kinematic updates employing reflection events, expanding the depth limitation of FWI faced by seismic surveys with short offsets (Vigh et al., 2016). However, despite the availability of reflections, as well as advances that reduce constraints on the starting model for FWI (Jiao et al., 2015; Warner and Guasch, 2016; Engquist et al., 2016), the preferred driver for robust kinematic updates for recovering earth model properties remain the diving waves and early arrivals. Improvements and increased usage in OBN technology are providing more ideal input data for FWI with a wide illumination reach for the rich transmission energy recorded in these diving waves. Recent case studies show that sparse OBN and an FWI approach can produce significant interpretation uplift in subsalt for challenging basins within the northern GOM (Vigh et al., 2021).

The field data are sparse ocean-bottom node acquisition using approximately 2700 nodes with a spacing of 1.2 km. The source configuration comprised two vessels using triple sources each, spaced along 50 m inline and 100 m crossline directions, with a nominal 18-km source halo around the node boundary. A blended source acquisition was imposed for continuous recording using independent source timing between the source vessels and +/- 1 second random dithers. The acquisition parameters allowed recording of usable low-frequency signal below 2 Hz.

Methodology

The ultra-long offsets and low-frequency range acquired as part of the survey design are optimal for employing FWI to recover earth model properties at basin-scale and where the previous modelling efforts from streamer data had no accessibility. However, the starting model for FWI even in this case retains key consideration. Cycle-skipping due to exceptionally incorrect salt geometry and subsalt velocities is still possible because of acquisition recording limits on low frequency content extending below approximately 1.5 Hz. Although we expect the ultra-long offsets of 20-50 km to provide a depth penetration in the range of 10-15 km, thus returning good sampling of transmission energy in the subsalt, the errors in the overlying shallow salt geometry are the first order problem to recovering more accurately the subsalt velocity field. A key advantage of FWI as a data-fitting process is the automatic shaping and recovery of manually interpreted salt boundaries and assumed homogenous salt velocities. Recent sparse node studies with FWI have achieved salt velocity recovery and salt shaping under similar acquisition and starting model conditions with velocity changes in the 1000-2500 m/s range. For the deep record extending to the Base Louann autochthonous salt level, simulations showed the significance of having a representative velocity structure in place. For the GOM, we assume an increase in velocities related to compaction trends and lithological changes in the Lower Tertiary and Mesozoic carbonate. Without such velocity structure in place in the starting model, the predicted data will have large initial mismatch as the diving waves in the observed record will, in practice, turn or transmit earlier in response to the fast velocity trend (Vigh et al., 2021).

A multi-scale workflow using FWI and the full trace OBN data was applied to update the conditioned starting velocity model, aiming to improve kinematics for the full depth section of 18 km. We designed an objective function including the dynamic, or amplitude, term along with the kinematic one via a weighting scheme in between these two terms called as enhanced template-matching (ETM-FWI). The FWI iterations were run in cascaded frequency bands, beginning at 1.6 Hz, and progressing gradually to maximum frequency of 14 Hz. We biased the FWI bands heavily towards low-wavenumber updates, keeping the maximum frequency < 4 Hz, until imaging improvements in comparable wavelengths stabilized so that we considered those bands exhausted before further increasing the frequency range.

Field Results

The representative data examples are reverse time migration (RTM) images which show that kinematic changes from the FWI-updated velocity model improved the interpretability of various basin structures. Given the regional scope of the program, we observed progressive changes in the long-wavelength resolution of the Base Louann salt seismic event at approximately 13-15 km depth, which anchors any basin-scale GOM interpretation. As illustrated in Figure 1, the improved continuity and visibility of this deep event compared to the starting model image is a key validation of kinematic uplift gained from frequencies < 2 Hz and suggests that the longest-wavelength updates have been reasonably achieved. Near vertical steeply dipping events of varied thickness are completely lacking from both the starting model velocity and image.

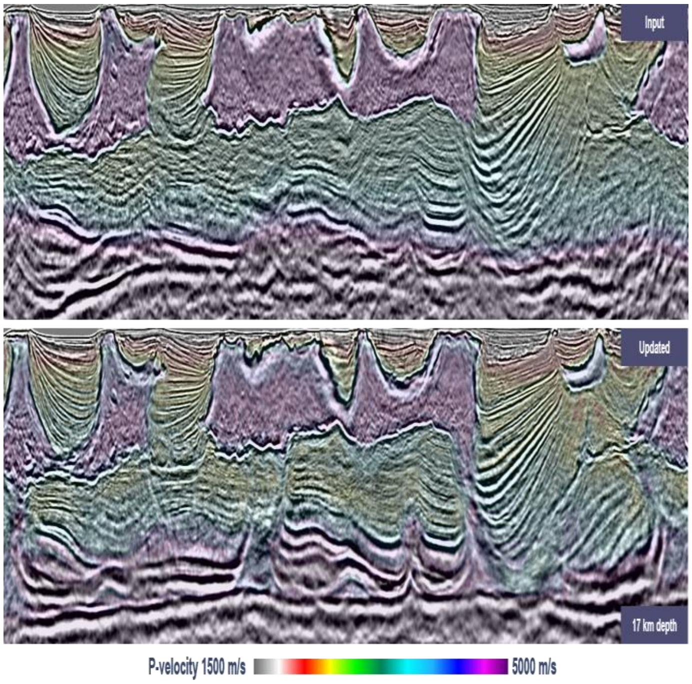

Figure 1 RTM comparison with velocity overlay showing regional impact between the starting model and corresponding OBN image (top), and the OBN FWI updated model and OBN image (bottom)

It was the aim of the FWI strategy here to automatically refine the salt boundaries and subsalt basin velocities where the complex variability would otherwise require an unrealizable number of manually- guided model perturbations. Figure 2 shows an example of the salt shaping result coming from FWI in an allochthonous body, where the rugosity of the salt body is difficult to capture in the 3D sense with the legacy interpretation.

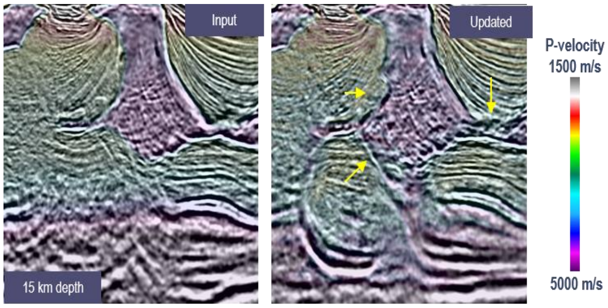

Figure 2 RTM comparison with velocity overlay showing salt shaping impact between the starting model and corresponding OBN image (left), and the OBN FWI updated model and OBN image (right)

FWI has improved velocity shaping of this body in the left flank, deeper left wing and the salt base with additions that support connection to the newly visible sub-vertical weld and salt feeder. The right wing and horizontal weld display subtle velocity adjustments that remove the kink in the input model imaging, moving the position of the fault line closer to the feeder in the stratigraphy directly below. The subsalt velocities in the two encapsulated basins are adjusted automatically along with the salt; thus, the update represents a total field perturbation that is not limited by any need to differentiate zones.

Conclusions

The results support long offset, full azimuthal sparse OBN acquisition as a viable data collection technique for regional studies, especially to derive an accurate velocity field by FWI. The FWI workflow enabled building a velocity model in this extraordinarily complex salt geology environment, and FWI showed its ability to reshape salt geometry automatically and update the deep model without requiring major human intervention. The improvement in the salt and sediment resulted in superior subsalt imaging and better understanding of the deep geologic trends.

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