The power of elastic FWI with sparse ocean-bottom node acquisition for complex subsalt imaging

Hao Xing, Richard Huang, Yining Li, Cosmin Macesanu, Faqi Liu, Mohammed Hegazy, TGS*

Summary

This study demonstrates the power of Elastic Dynamic Matching Full-Waveform Inversion (E-DMFWI) applied to data from sparse ocean-bottom node (OBN) acquisition to enhance subsalt imaging in the Gulf of America. By utilizing ultra-long offset, full-azimuth and low frequency data from the Amendment Phase 2 (PH2) and Phase 1 (PH1) surveys, E-DMFWI effectively delineates salt feeder, carbonate and deep Luanne salt. It refines salt geometry under complex shallow salt bodies which successfully images continuous events in the poor illumination zone that was impossible to achieve before. Our findings confirm that this integrated approach offers superior imaging capabilities in such geologically challenging settings and has the potential to significantly improve project efficiency as well.

Introduction

The central US Gulf of America has become a highly prospective area for hydrocarbon exploration. However, subsalt exploration in this area is challenging due to the complex salt geometries that obscure underlying reservoirs. There is a continuous demand for advanced data acquisition and processing techniques to support the exploration and processing techniques to support the exploration and drilling activities.

Full waveform inversion (FWI), especially the elastic version, has become a core technology facilitating the successful processing of seismic data in such challenging areas. This surely reflects the advancement of the FWI (both acoustic and elastic) algorithms themself, but it certainly also benefits from the improvement in data acquisition technology. Wide-azimuth (WAZ) data has proven its advantage over conventional narrow azimuth data with improved subsurface illumination, fold coverage and multiple attenuation. The legacy project utilized multi-WAZ data, and it adapted conventional diving wave FWI updates in the overburden, followed by interpretation driven salt model building (Dhananjay, et al., 2018). While the project was very successful with the results showing big improvement, however, it still has a lot of uncertainty, especially in the subsalt, and the whole process was time consuming and labor intensive.

Since 2019, multiple sparse ocean bottom node (OBN) surveys with ultra-long offsets have been designed and acquired to facilitate employing the power of FWI for better velocity model building and subsalt imaging (Huang et al, 2020). These include the Amendment surveys in the Mississippi Canyon, Gulf of America. Until now, the Amendment surveys have been conducted in two phases (Figure 1): Phase 1 has nominal node spacing of 1000m by 1000m; and phase 2 has node spacing of 1200m by 1200m. Both surveys have source spacing of 50m by 100m and a minimum offset of 40km for each node to ensure enough deep penetration of diving waves for FWI updating down to the basement. Low-frequency sources were employed to enhance signal below 2Hz, which is crucial for accurate subsalt velocity updates.

The application of acoustic dynamic matching FWI (A-DMFWI) to the Amendment project has demonstrated its capability to improve subsalt imaging through advanced velocity model building using ultra-long offset, full-azimuth and low-frequency-rich sparse OBN data (Mao et al, 2020; Xing et al, 2020). However, A-DMFWI only considers the pressure wave (P-wave) signal in the acoustic approximation, neglecting elastic effects, which leads to a phase mismatch in far-angle wavefields bouncing from high contrast media, making it less effective in resolving sharp boundaries. As a result, the A-DMFWI derived model exhibited salt halo artifacts, velocity leakage into sediment, inaccurately positioned top of salt compared to well markers, and blurred subsalt geo-body and carbonate boundary.

By employing the full elastic wave equations for wavefield propagation, elastic dynamic matching FWI (E-DMFWI) incorporates shear waves and density impact in P-wave propagation, resulting in more accurate simulation of seismic wave in the areas of the earth with strong heterogeneity. E-DMFWI was applied to the Amendment data including all phase 2 nodes and the northern half of phase 1 nodes. The E-DMFWI result has demonstrated clear advantages over the conventional top-down model building workflow and A-DMFWI, by fully unlocking the power of ultra-long offset, full-azimuth and low-frequency sparse OBN acquisition to derive high resolution velocity models and improve subsalt imaging. The E-DMFWI updated velocity model and its FWI derived reflectivity (FDR) exhibits robustness across all the target areas, requiring little interpretation involvement which significantly speeds up the project progress (Wang, et al, 2021)

Method

The Amendment E-DMFWI project started with legacy 12Hz A-DMFWI velocity model. Depth variant smoothing was applied to remove details from shallow sediment and deep carbonate and Luanne features. To assess the capability of E-DMFWI, one substantial portion of salt under the secondary salt, previously from interpretation, was removed on purpose from the initial model. The input to the E-DMFWI is the raw hydrophone data with minimal preprocessing, including deblending, debubble and basic denoise.

E-DMFWI utilizes elastic wavefield propagation and focuses on the P-wave inversion. Other elastic parameters including S-wave velocity and density are updated passively following empirical relations derived from well constraints (Liu, et al, 2025).

Field Results

Figures 2A and 2D present a velocity model derived from conventional top-down velocity model building workflows and the corresponding Wide-Azimuth Reverse-Time Migration (WAZ RTM) images. Due to poor illumination and limited imaging angles beneath the secondary salt body, the legacy velocity model failed to capture parts of the salt body, including all high-dipping salt feeders and small geologic inclusions. The WAZ RTM image (Figure 2D) struggled to delineate subsalt basins, yielding interpretations that closely matched salt feeders, thereby increasing the interpretative uncertainty.

Using the legacy model (Figure 2A) as the initial model, application of the data-driven A-DMFWI addressed many salt tectonic challenges. Improvements in imaging salt feeders and the Luanne basement have enhanced confidence in this model (Figure 2B). The FDR (Figure 2E) from the velocity model indicates improvements in areas with poor illumination. However, due to simplified physics causing phase mismatches from distinct salt boundaries, A-DMFWI still exhibits significant salt velocity leakage into sediments and smeared sediment truncation to salt feeders, especially beneath rugose salt bodies.

Figures 2C and 2F display a velocity model and its corresponding FDR from the purely data-driven E-DMFWI. Compared to A-DMFWI, E-DMFWI more accurately simulates the phase and amplitude of the wavefield, clearly delineates reduced salt halo artifacts, sharper salt boundaries, salt feeders, carbonates, reasonable salt exit velocities, and well-defined geological inclusions. Notably, the FDR corresponding to the E-DMFWI model is a non-linear inversion-based variant of data domain Least Square RTM, which offers significant imaging improvements in areas with poor illumination from primary reflections, owing to additional illumination from the full wavefield, particularly diving waves and multiples.

During the A-DMFWI phase, a substantial section of the deep salt body was inserted by interpreter's insights with the guidance of A-DMFWI hints (Figure 3A and 3D), which was not in the initial legacy model. To assess E-DMFWI's capabilities, this entire salt body was removed purposely in the E-DMFWI initial model (Figures 3B), and WAZ RTM image (Figure 3E) indicates a clear degradation from the A-DMFWI RTM. Figure 3C demonstrates that the fully inverted salt body via E-DMFWI results in a much clearer definition of salt boundaries and more coherent Luanne salt in the FDR (Figure 3F). This test boosts confidence that E-DMFWI can tackle complex geological challenges and significantly enhance project efficiency.

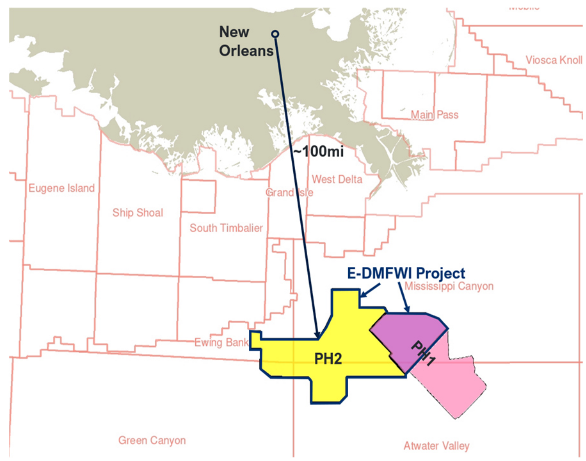

Figure 1: Amendment surveys in GOA. The dark blue polygon defines the E-DMFWI project area.

Conclusions

The integration of sparse Ocean Bottom Node (OBN) acquisition with Elastic Full-Waveform Inversion (EFWI) markedly improves subsalt imaging in the Gulf of America. This combined approach offers accurate salt geometry inversion, detailed mapping of sediment truncation to salt feeder zones, enhanced illumination, providing valuable insights for subsalt exploration and development. The Amendment Phase 1 and Phase 2 surveys exemplify how advanced acquisition and processing techniques can overcome challenges posed by complex subsalt geology and significantly reduce project turnaround time.

Acknowledgements

We thank TGS and its partner SLB for their permission to publish these results and TGS multiclient for allowing us to use the Amendment data.

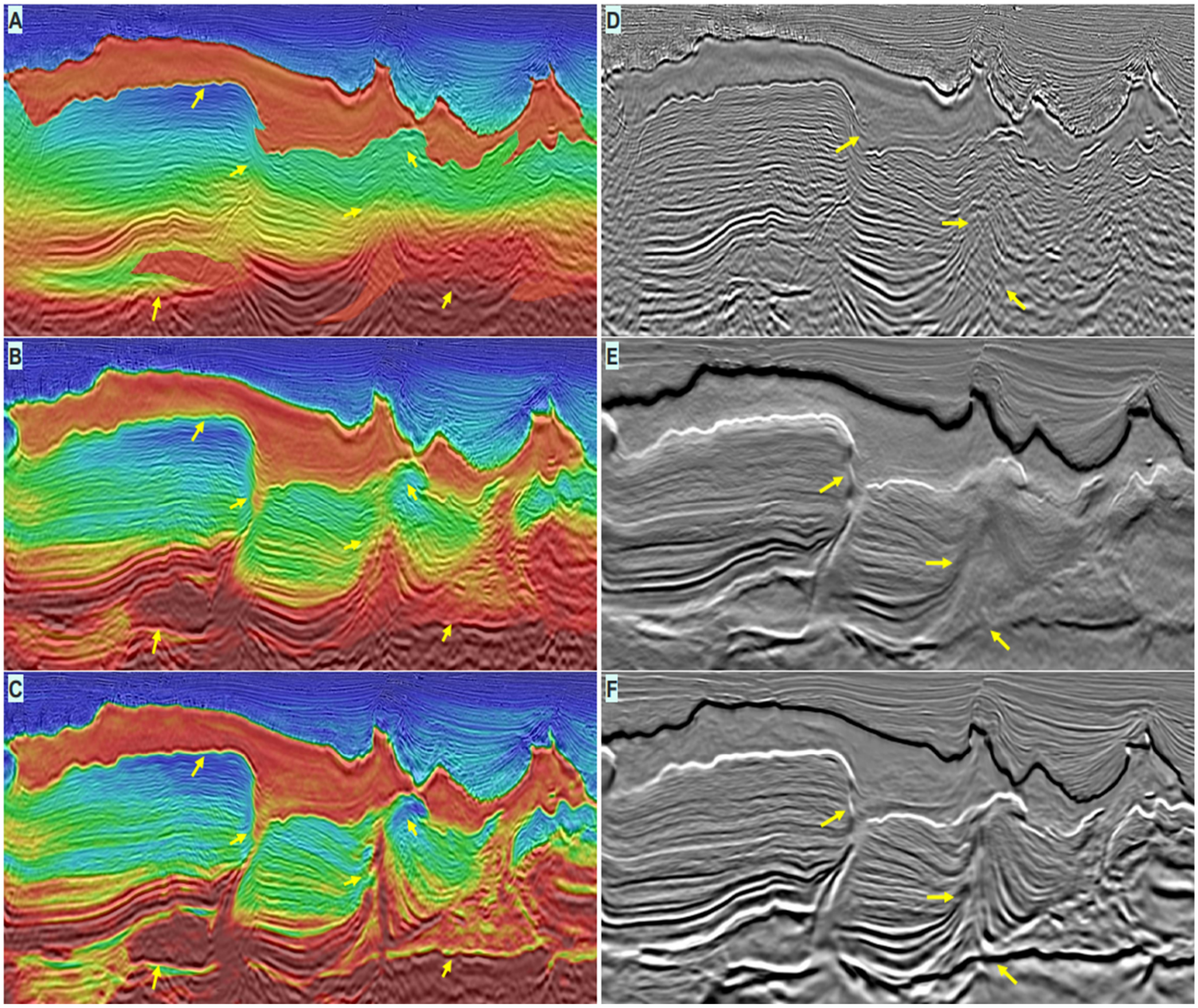

Figure 2: A). The legacy velocitymodel. B). Velocity model from 12Hz A-DMFWI C). Velocity model from 12Hz E-DMFWI. D). The legacy RTM image. E). FDR from 12Hz A-DMFWI. F). FDR from 12Hz E-DMFWI. The arrows highlight significant improvements from conventional top-down model building flow to A-DMFWI model building and to current E-DMFWI model building.

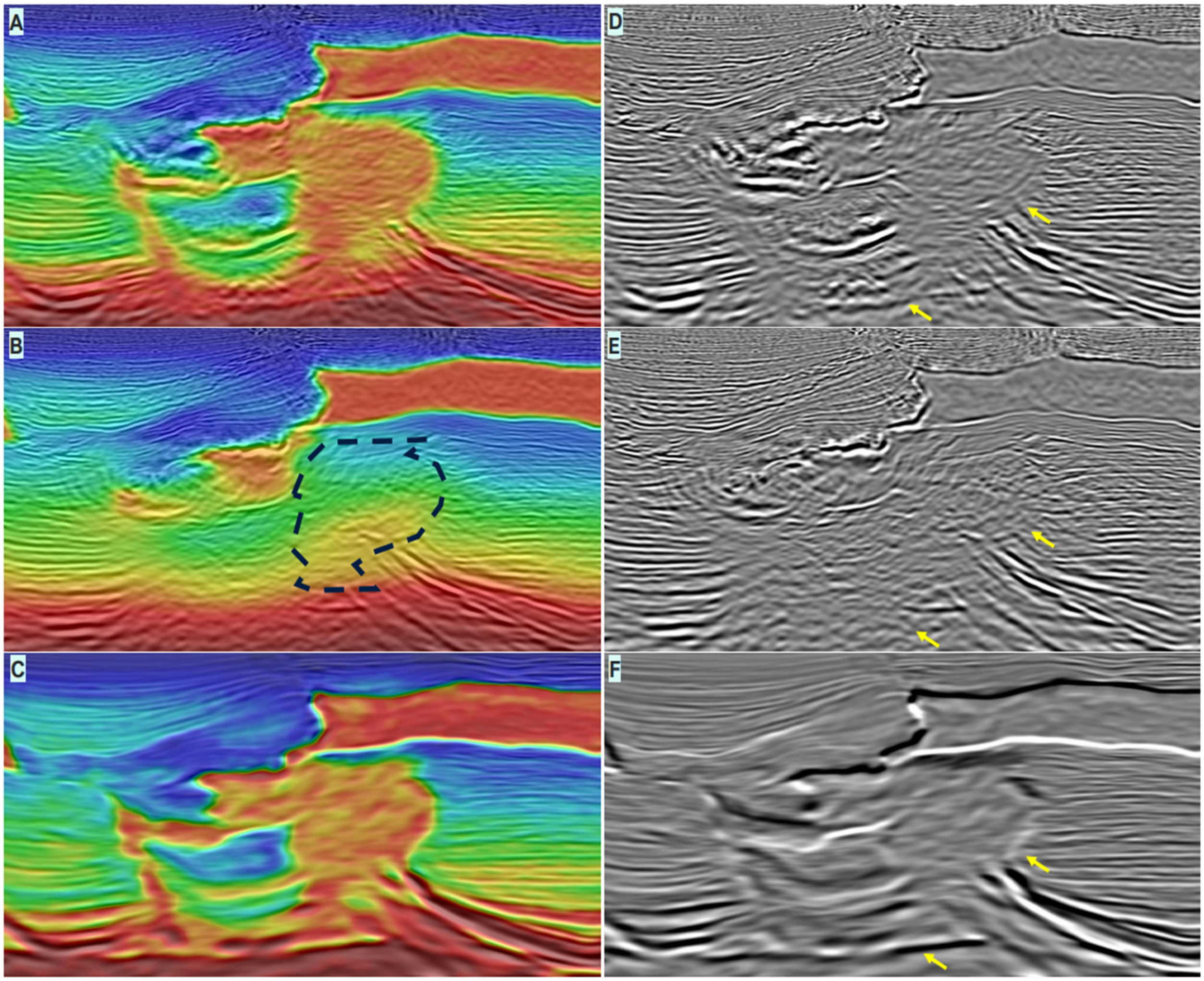

Figure 3: A) 12Hz A-DMFWI output velocity model. B) Initial velocity model of E-DMFWI. C). 12Hz E-DMFWI output velocity model. D). WAZ RTM with 12Hz A-DMFWI model. E). WAZ RTM with E-DMFWI initial model. F). FDR from 12Hz E-DMFWI model. The dash line shows the salt body was removed in the E-DMFWI initial model and inverted by data driven E-DMFWI.