Elastic Dynamic Matching FWI robustness against initial model errors using ultra-long offset OBN and Gemini Source Data

Khaled Abdelaziz, Hao Xing, Zhuoquan Yuan, Faqi Liu, Carsten Udengaard, Richard Haung, Aurora R. Castelan, Mohamed Hegazy

Abstract

Full Waveform Inversion (FWI) has revolutionized model building but remains limited by dependence on accurate starting models, low-frequency availability, and complete illumination. When observed and modeled data are misaligned by more than half a wavelength, conventional FWI easily becomes trapped in local minima due to cycle skipping. This study demonstrates that Elastic Dynamic Matching FWI (E-DMFWI), applied to a full azimuth, ultra-long-offset of ~60 km (~30 km minimum maximum offset) OBN survey using the Gemini extended frequency source, can help overcome such limitations. Through a controlled test in which a salt wing was intentionally removed from the initial model, E-DMFWI successfully rebuilt the missing structure and achieved convergence toward the same velocity and elastic fields as the production model. This result confirms the method's robustness against significant initial-model errors and underscores the synergy between broad-band acquisition design and cycle-skipping-resistant inversion.

Introduction

The convergence behavior of FWI is mainly governed by four interrelated factors: (1) Illumination, which defines the angular and spatial sampling of the subsurface; (2) The objective-function and its sensitivity to cycle skipping, which controls the algorithm's resilience to kinematic misalignment; (3) Low-frequency content, which enables recovery of long-wavelength components of the velocity field, and (4) the underlying physical assumptions such as modeling engine, anisotropy definitions, and rock physics relationships.

These factors do not operate in isolation. Low frequencies can stabilize a conventional least-squares misfit, while their absence demands a more robust objective formulation. On the other hand, low frequencies can rescue a convergence if and only if physics is modeled correctly. Similarly, improved illumination only translates into better inversion results when the objective function can correctly handle complex, multi-arrival wavefields.

Dynamic Matching FWI (DM FWI) addresses these challenges by introducing a dynamic event-matching operator that allows the inversion operator focusing on correcting the kinematic misalignment (Mao *et. al*., 2020, Huang, *et. al*. 2020, Xing *et. al*., 2020). This event-based alignment relaxes the classical half-wavelength condition, mitigates cycle skipping, and expands the basin of convergence. By maintaining coherence across all waveforms: P, converted-S-wave, surface and interbed multiple arrivals, E-DMFWI ensures more stable updates even from geologically biased or incomplete initial models (Macesanu *et. al*., 2024, Liu *et. al*., 2025).

Method

To evaluate the robustness of elastic Dynamic Matching FWI, we conducted a controlled experiment within a complex salt province. The initial FWI model (model A hereafter) was built through years of tomography, iterative top-down salt-modeling approach, and acoustic FWI using legacy streamer data (Figure 1). A second initial model (model B hereafter) was created by deliberately removing a questionable salt feeder from the main salt body. This modification introduced a substantial structural error while keeping sediment velocities otherwise unchanged.

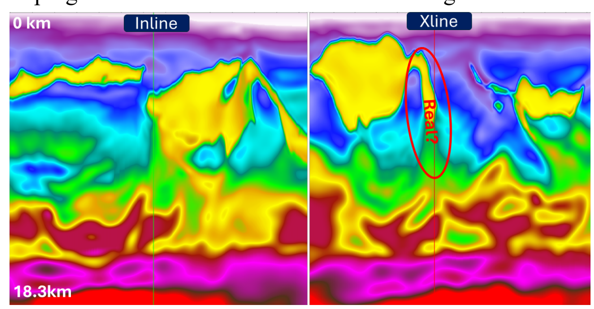

Figure 1: Initial model inline and xline showing the questionable salt feeder that was removed in the experiment.

Both models A & B were used as initial models, and two parallel inversions were executed using E-DMFWI with a frequency progression from 1.6 Hz to 4.4 Hz. The inversions followed a standard multiscale strategy where lower frequencies guided large-scale kinematic updates and higher frequencies refined elastic detail. The pressure field with minimal processing was used as input, and synthetic data was simulated through an elastic finite-difference modeling framework. The shear velocity is updated through a rock physics linear relationship with the compressional velocity.

Acquisition Geometry and Source Design: The survey configuration features ultra-long offsets (~60 km) and full-azimuth node coverage, providing exceptional subsalt and salt-flank illumination. The Gemini source contributed extended low-frequency content and a near-point-source radiation pattern (figure 2), improving bandwidth and directional uniformity. It delivers enhanced energy down to 1.0 Hz, as shown in phase ring QC plots drawn from raw data even before deblending (figure 3).

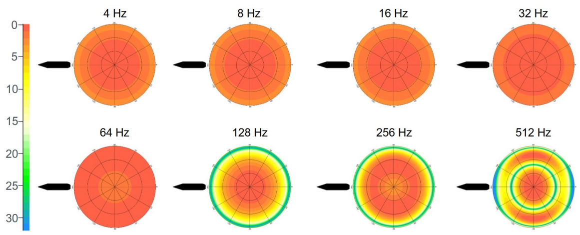

Figure 2: Source directionality QC which shows that Gemini source can be considered omni-directional up to 128Hz.

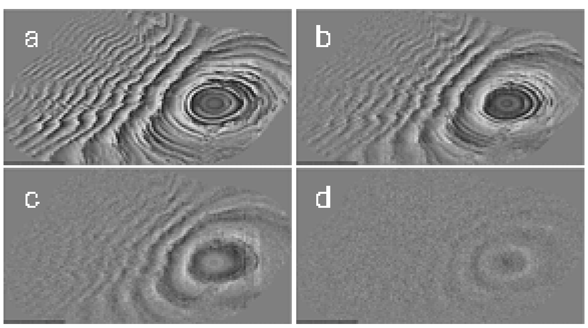

Figure 3: Phase rings QCs of the Gemini raw data right after shot slicing. Frequencies are 3.0Hz, 2.5Hz, 2.0Hz, and 1.0Hz for a, b, c, and d respectively.

Under this acquisition environment, Elastic DM-FWI leveraged the combined benefits of wide-angle coverage and low-frequency signal strength to isolate algorithmic performance from acquisition limitations. The goal was to test whether the inversion could recover the removed salt feature purely through waveform fitting, without external constraints or salt interpretation guidance.

Results and Discussion

The Elastic DM-FWI results clearly demonstrate resilience against large initial-model errors. During early iterations (1.6–2.4 Hz), the inversion reconstructed the gross geometry of the missing salt wing as a broad high-velocity anomaly consistent with observed travel times. As frequency increased toward 4.4 Hz, the algorithm refined the wing's shape and impedance boundaries, ultimately recovering a geometry (figure 4) nearly identical to that in the production model.

Equally important, sediment velocities away from the salt feature converged toward very close values achieved in the production model that started from complete salt geometry. This convergence confirms that Elastic DM-FWI not only completed the missing structure but also preserved the physical consistency of the surrounding elastic field.

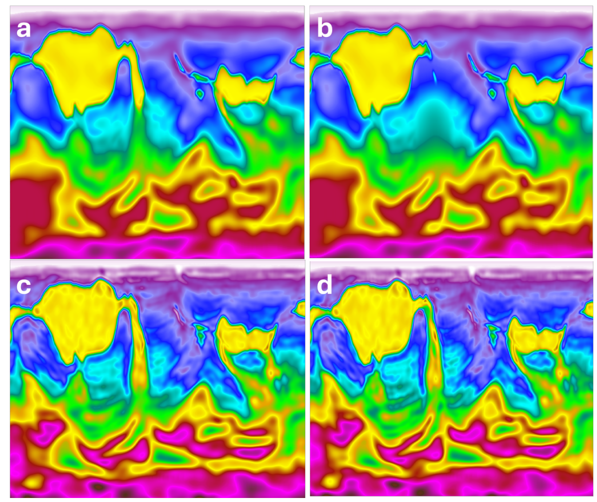

Figure 4: a) Initial model A xline showing the salt wing, b) initial model B xline showing the salt wing is removed, c) E-DMFWI model to 4.4Hz starting from model A, and d) E-DMFWI model to 4.4Hz starting from model initial model in b.

The dynamic event-matching step was instrumental: by aligning modeled and recorded total wavefield arrivals before misfit evaluation, it directed the inversion to focus on the kinematic differences and protected it from compensating for structural errors through unrealistic trade-offs among model parameters. This mechanism maintained physical realism throughout the update process.

The result also underscores the synergy between acquisition design and inversion algorithm. The ultra-long offsets provided the deep-angle coverage required to image beneath the salt, the full-azimuth geometry resolved lateral velocity contrasts, and the Gemini source ensured that usable low-frequency content was present to stabilize early iterations. Together, these factors established the optimal environment to expose and validate the intrinsic robustness of Dynamic Matching FWI.

Conclusion

This study demonstrates that Elastic Dynamic Matching FWI, when applied within a broad-band, full-azimuth OBN framework, can overcome severe deficiencies in the starting velocity model. The combination of Gemini's extended low-frequency energy, ultra-long-offset full-azimuth illumination, and dynamic matching provides a resilient foundation for model convergence.

Elastic DM FWI successfully reconstructed a missing salt feeder and produced background sediment velocities consistent with a production model derived from a more complete starting model. These results confirm that the algorithmic robustness of DM FWI extends naturally to the elastic domain, offering improved reliability in complex salt environments.

Acknowledgments

Thanks to TGS Multiclient for permission to share the results. The authors are grateful to Tara Brothers (Shell) for valuable suggestions and insightful discussions.

References

Liu, Faqi, Cosmin Macesanu, Hao Xing, Matvey Romanenko, Ge Zhan, Carlos Calderón-Macías and Bin Wang, 2025, Elastic full-waveform inversion: Enhance imaging for legacy and modern acquisition: The Leading Edge, vol 44, No. 5

Macesanu, Cosmin, Faqi Liu, Yi Huang, Hao Hu and Carlos Calderón, 2024, Implementation aspects of elastic FWI and its application to sparse OBN surveys: Extended Abstract, SEG Annual Meeting.

Mao, Jian, James Sheng, Yi Huang, Feng Hao, and Faqi Liu, 2020, Multi-channel dynamic matching full-waveform inversion, Extended Abstract, SEG Annual Meeting.

Huang, Y., Mao, J., Xing, H., & Chiang, C., 2020, Noise strikes, but signal wins in full waveform inversion. SEG Technical Program Expanded Abstracts

Xing, H., He, Y., Huang, Y., & Sheng, J. (2020). Ultralong offset OBN: Path to better subsalt image. SEG Technical Program Expanded Abstracts