Acquisition-Imaging Confluence: Sub-Hertz Elastic FWI for Improving Subsalt Imaging

Introduction

Full-Waveform Inversion (FWI) is a fully data-driven seismic inversion algorithm designed to produce subsurface velocity models with high-accuracy and high-resolution by iteratively matching the synthetic with observed data. The primary challenge in FWI is cycle skipping: when the phase or timing difference between synthetic and observed seismic data exceeds half of a wavelength at a giving frequency, the inversion tends to converge to a local minimum. In general, four factors control FWI quality: the source wavelet, the accuracy of the initial velocity model, the richness of low-frequency content in the seismic data and the robustness of the FWI algorithm.

The source wavelet is dependent on the gun signature during acquisition. A proper wavelet can be derived from the input data, though it can be part of the inversion. When a properly derived wavelet, synthetic data under acquisition geometry can be fully simulated with the matched phase and spectrum to that of the observed data. This factor ensures that no human-induced cycle skipping is introduced in the preprocessing.

The accuracy of the initial velocity model and low-frequency content of the input data are inextricably linked. Low frequency data can tolerate less accurate initial models while a more accurate initial model can allow FWI started at higher frequency. Deriving of an accurate initial model is not always straightforward especially in the area with complex geologies. For example, in the Central US Gulf of America, complex salt geometries often obscure underlying reservoirs. Most of the existing velocity models were built from legacy streamer data using a conventional top-down workflow: sediment tomography (sometimes combined with diving wave FWI), followed by top-of-salt and base-of-salt interpretation with sediment flood and salt flood migration, and finally, tomography for subsalt area using surface offset gathers. This process is not only time-consuming, but it can often result in significant errors regarding salt geometry and subsalt velocity due to limited illumination and imaging angle.

Recently, significant progresses have been made on the acquisition side which benefit FWI convergency: 1) Sparse nodes with ultra-long offsets and 2) the ultra-low frequency data below 1 Hertz. Several Amendment surveys in the Gulf of America were designed with primary focuses on velocity model building and imaging using FWI. Amendment Phase 1 and Phase 2 surveys utilized conventional air gun arrays. Due to the absence of the receiver side ghost and sensors on the quieter water bottom, FWI could provide stable updates starting from 1.6 Hz. The latest Phase 4 survey utilized Gemini source, where the lowest usable frequency can be push down to 0.6 Hz. Figure 1a compares the amplitude spectra of a conventional air gun and a Gemini source, showing an approximate 15 db gain at 1 Hz for the Gemini source. Figure 1b shows the phase ring at various frequencies, where coherent events are visible down to 0.6 Hz. This enhanced low-frequency source is a single-chamber source and thus can be treated as a point source with no angular or azimuthal variation. This can also benefit the numerical simulation in FWI as the directional impact from air gun arrays is hard to simulate.

FWI algorithms are differentiated with different definition of matching represented in the objective functions. Conventional least-squares based FWI attempts to globally minimize the L2 norm of the difference between the input and synthetic data, where it is often found challenging to invert velocity models containing high-gradient boundaries, such as salt or carbonate interfaces. Dynamic Matching FWI (DM FWI) overcomes these challenges by introducing a local dynamic event-matching operator in both time and space allowing the inversion operator to focus on correcting the kinematic misalignment (Mao, et. al., 2020). This approach has demonstrated the robustness to resolve large velocity errors and provides a significant uplift in subsalt image (Huang, et. al. 2020, Xing, et. al., 2020). By maintaining coherency across all waveforms: P wave, S-wave, surface and interbed multiples, Elastic Dynamic Matching FWI (E-DMFWI) ensures more stable updates even from geologically biased or incomplete initial models (Macesanu, et. al., 2024, Liu, et. al., 2025).

In this paper, we demonstrate the benefits of ultra-low frequency data and the power of applying dynamic matching FWI to the ultra-low frequency OBN data acquired using Gemini source with an initial model having significant error.

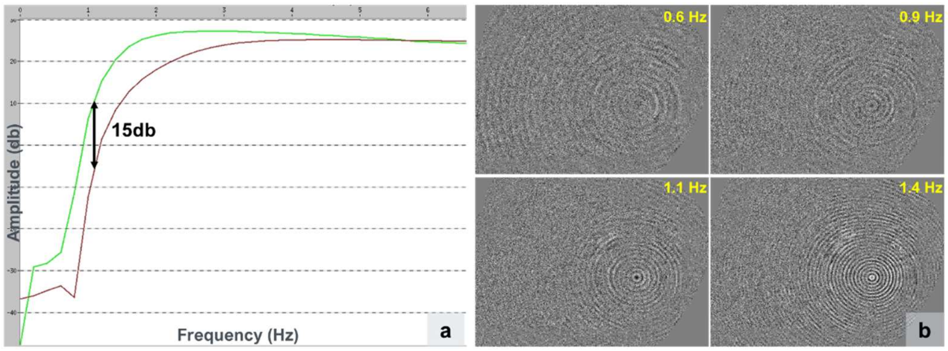

Figure 1 *(a) Spectrum comparison of Gemini source (green) with conventional air gun (red), and (b) phase rings at different frequencies of a Gemini node gather.*

Ultra-Low Frequency Data Increases Initial Velocity Tolerance

To evaluate the tolerance of DMFWI to error in the initial velocity model, we introduced top-down constant 4% slowdown velocity error to the initial model, which should cover most potential simple initial model errors, either convert from time RMS or 1D well velocity extrapolation.

Figure 2a shows the initial velocity model from legacy WAZ survey. A 4% slowdown in this initial model implies that the expected velocity update should be positive in most of the areas (indicated by red in the perturbation plots). Figure 2b displays the update from FWI inversion starting at 1.6 Hz (simulate the data with conventional air gun source); the result show that the FWI diverged, accumulated velocity errors cause cycle skipping at very shallow depth. Figure 2c showed the updated velocity with starting frequency at 1 Hz, which properly updated the model with some small salt bodies and reached deeper, yet cycle skipping persists under larger salt bodies and at the deeper targets. Finally, Figure 2d shows the inversion result starting at frequency of 0.6 Hz, where the inversion not only consistently corrects the background bias in the whole section, but also rebuilt the deep carbonate layer that was smoothed out in the initial model.

Ultra-Low Frequency Data Inverts Salt from Sediment Velocity

In the Gulf of America, the feasibility of inverting salt velocity models directly from sediment models has long been debated. While it has been previously demonstrated on synthetic data with starting frequency as low as 0.5 Hz, the ultra-low frequency data acquired using Gemini source allows us to attempt this test on the real field data.

Figure 3a shows one a velocity model from legacy WAZ survey. Figure 3b shows the sediment velocity model after removing the salt bodies in Figure 3a). Figure 3c display the result of E-DMFWI running from 0.6 Hz to 1.5 Hz. It is clear that the main salt bodies are rebuilt, though they are low resolution and lack fine details as expected. It is important to note that this test is computationally and resource-intensive due to large velocity errors in the initial model.

Ultra-low Frequency Stabilizes Subsalt Velocity in Real Situations

Having demonstrated the value of ultra-low frequency data acquired using Gemini source, we will address its impact on conventional projects that utilize a reasonably accurate starting velocity model with shallow salt bodies. We analyze a line passing through the node boundary of Amendment Phase 2 and Amendment Phase 4. Both datasets used initial models derived from legacy WAZ data, and they have undergone similar iterations of E-DMFWI up to 4 Hz. However, the Amendment Phase 4 data was processed starting from 0.6 Hz, while the Amendment Phase 2 data started from 1.6 Hz.

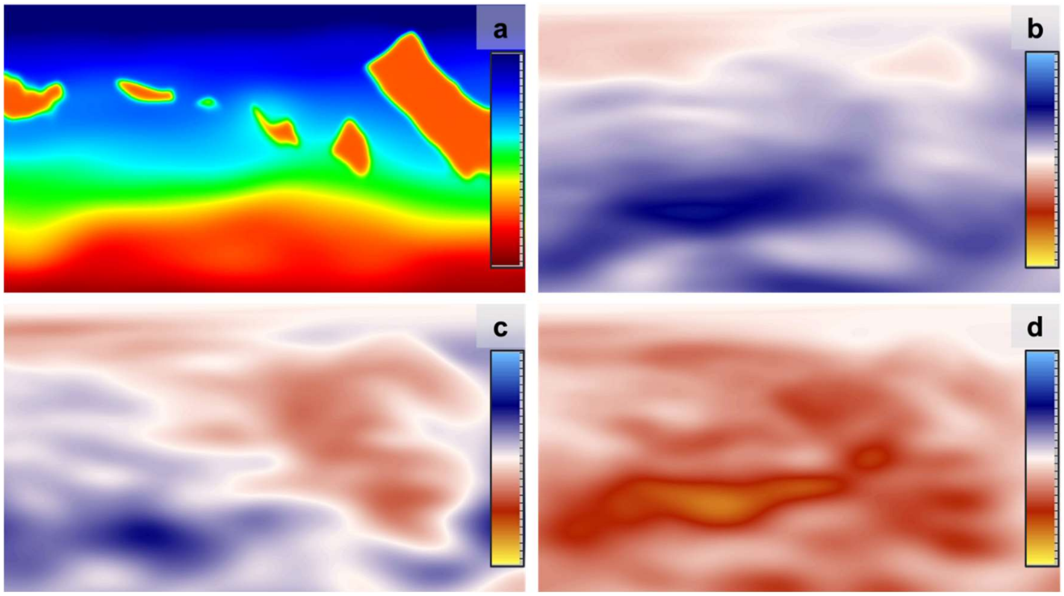

Figure 2 *Initial model tolerance test. (a) A legacy salt model which is used to build the initial model for the test by scaling it down 4%. (b) E-DMFWI update with starting frequency of 1.6 Hz; (c) E-DMFWI update with starting frequency of 1 Hz; (c) E-DMFWI update at starting frequency of 0.6 Hz, it captures the slow perturbation from top down to the carbonate fast velocity which was smoothed out in the initial model (Please add color bar to show the velocity increase/decrease)*

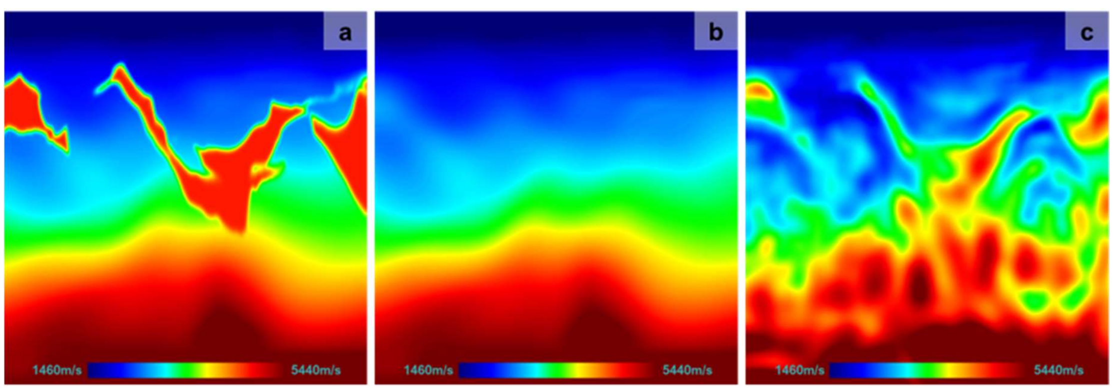

Figure 3 *A legacy velocity model (a) to be used to build the initial model by removing the shallow salt (b) and (c) is the E-DMFWI output model*

Even though the final output models are comparable (see Figure 4a and 4b), however, the velocity model from Amendment Phase 4 using Gemini source (Figure 4b) exhibits superior definition within the salt body and in the subsalt mini-basins as pointed by the yellow arrows. Consequently, it yields a more coherent RTM image in compared to that corresponds to Amendment Phase 2 in Figure 4a.

Conclusions

We have demonstrated the influence of advanced acquisition technology and robust inversion algorithms which are critical for solving complex subsalt imaging challenges in the Gulf of Mexico.

The introduction of the Gemini source, capable of delivering ultra-low frequency data down to 0.6 Hz with high signal-to-noise ratio, significantly alters the constraints of Full-Waveform Inversion.

First, starting FWI at the frequency below 1 Hz dramatically alleviates the requirement of accurate velocity model and allows the tolerance for initial velocity model errors; in addition, while computational challenges remain for large salt bodies, ultra-low frequency data help the reconstruction of salt geometries directly from sediment-flood models, reducing the dependency on manual interpretation. With the ultra-low frequency data acquired using the Gemini source, Elastic Dynamic Matching FWI (E-DMFWI) can improve the definition of intra-salt and subsalt mini-basin velocities, leading to coherent uplift in RTM imaging compared to conventional acquisition parameters. These results suggest that the integration of sub-Hertz sources with elastic inversion workflows is a viable pathway for the next generation of subsalt exploration.

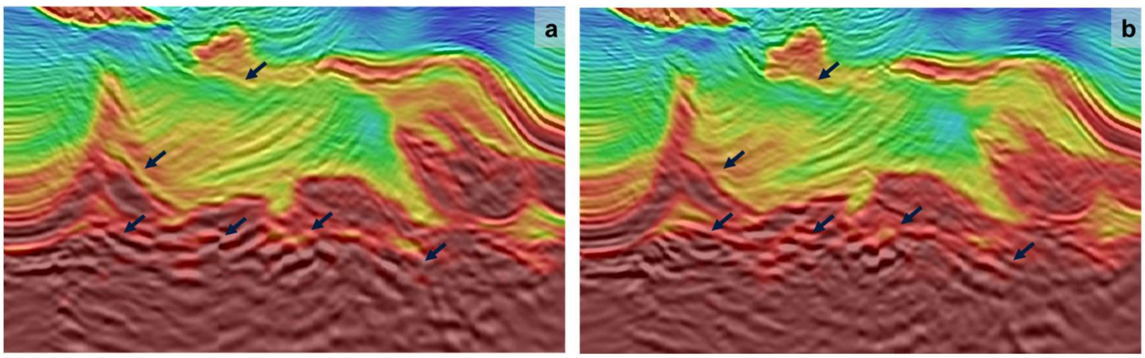

Figure 4: *(a) velocity model overlaid with 15 Hz RTM after 4 Hz E-DMFWI to Amendment Phase 2 data using conventional air gun arrays and (b) velocity model overlaid with its 15 Hz RTM after 4Hz E-DMFWI to Amendment Phase 4 data acquired using Gemini source.*

Acknowledgements

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References

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