Noise strikes, but signal wins in Full Waveform Inversion

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Summary

Due to inherent benefits such as ultra-long offset, full-azimuth (FAZ) illumination and low-frequency availability, a large multi-client sparse-node survey was acquired in the Gulf of Mexico aimed at Full Waveform Inversion (FWI) oriented model improvements. A six-source simultaneous shooting acquisition was used to reduce survey time and increase source density. The heavy blending noise resulting from this acquisition configuration brings challenges for proper FWI performance. We applied a Dynamic Matching FWI (DMFWI) algorithm that concentrates on inverting the kinematic difference and suppressing the noise impact, which was applied to the acquired raw sparse node data without conducting any pre-processing. Our success in achieving a complete upgrade for both sediment and salt confirms the effectiveness of this approach in solving velocity issues under challenging signal-to-noise ratio conditions.

Introduction

Ocean bottom node (OBN) seismic data with ultra-long offsets, full azimuths, and low frequencies, which are critical for FWI, can expand the illumination limits and more effectively solve both imaging and model building uncertainties. Driven by factors such as cost, efficiency, and the proven capability of FWI, pioneer geophysicists have suggested sparse OBN data with long offsets and suitable low-frequency sources for future salt model building (Michell et al. 2017). With typical node spacing of approximately one kilometer, this new concept acquisition is fit-for-purpose for a vast area velocity survey. Combining FWI models derived from the new sparse OBN survey with existing steamer data is an effective solution to upgrade existing subsalt images.

FWI, as a non-linear inversion algorithm, seeks to find optimized models that provide the best global correspondence matching between the generated synthetic data and the observed field data. Its success highly depends on how the misfit between the two datasets is represented. Conventional Least-Squares FWI (Lailly 1983; Tarantola 1984) employs an objective function that measures the Summed Square Difference (SSD) of the two, which considers both the amplitude and phase information. The amplitude misfit can be easily dominated by noise contamination in the observed seismic data, which is irrelevant to the kinematic velocity error. The issue is especially severe for data acquired by simultaneous shooting, which is becoming the standard seismic shooting approach nowadays. The additional challenge from the added blending noise is it contains the same wavelet character as the signal. With heavy blending noise, the FWI's performance can be adversely affected, and, as a result, issues can be caused in real model building applications. Additionally, there are elastic effects not properly simulated by the acoustic wave equation, which is a common issue in most of the practical FWI practices.

To boost FWI performance with minimum or even no time processing effort, we tuned our FWI to focus on inverting the kinematic difference through promoting the high-fidelity information. Instead of minimizing the SSD, our objective function seeks to maximize the normalized local cross-correlation, which measures the time and model dependent relevance in the local windows. This local window dynamic matching scheme mitigates the amplitude impact on FWI by downplaying the large amplitude events and amplifying the contribution from weaker events, which is critical to allow the signal rather than the noise to win in the misfit computation. The detailed implementation is summarized in Mao et al. (2020).

Here, we demonstrate the effectiveness of our DMFWI approach in correcting model errors under challenging signal-to-noise ratio conditions. Our case study demonstrates its capability to achieve a complete salt geometry update from shallow to deep and drastically improve the whole migration image.

Input data analysis

In summer 2019, a large multi-client blended OBN survey was completed in the Gulf of Mexico. Presurvey acquisition studies, which were driven by FWI requirements, indicated survey design with nominal node spacing 1000m by 1000m (except a dense infill area) and source spacing 50m by 100m. A minimum 40km offset for each node location was acquired to honor enough deep penetration for FWI subsalt update. The reliability of 18km depth penetration is verified by an RTM based diving wave illumination study. Aiming to acquire all shots within the battery life of the node to reduce the operational cost, the survey was acquired in a blended style with three dual-source vessels. The two sources on each vessel were fired within plus-minus one second time dither from the pre-plot source location. Detailed information about the data and the challenges in preparing the data can be found in Roende, et. al, (2020).

Figure 1a shows a typical hydrophone node gather, particularly from a relative near offline offset source line. A deblending attempt was conducted and the deblended data as shown in Figure 1b was used as a reference to demonstrate the non-extreme blending noise level from this dataset. A histogram (Figure 1c) measuring the sample by sample amplitude ratio between raw and deblended data within the display window indicates an average blending ratio of six to twenty or more. The heavy blending noise brings challenges for both deblending and FWI, especially if we attempt to run FWI from raw data. Additionally, since each node gather has more than one million traces and almost three times the record length compared to marine streamer data, the processing effort for almost all steps is computationally heavy. To investigate the signal to noise ratio at ultra-low frequency bands focusing on diving waves, which is essential to FWI success, we also checked the phase ring plots (e.g. Figure 1e-1f) with ultra-long offset data included. After deblending and stacking two-by-two neighboring shots, we start to see more coherent signal rings from ultra-low frequency bands. Despite the undesirable appearance of the noise, we conducted our FWI study with raw data to explore its capability under a challenging signal to noise ratio situation. No denoise, deblending, or wavelet processing was conducted. However, deblending was applied to hydrophone data used for migration QC of the derived FWI model

Model preparation

The study area contains large-scale structures such as salt feeders, salt canopies, and small-scale structures such as rafted carbonate carapaces. It also includes features from slow velocity gas chimneys to extremely fast hard carbonates in the Jurassic Smackover. Although our Tilted Orthorhombic (TORT) legacy model set was obtained from many iterations of high-resolution tomography work and intensive human salt interpretation effort, it still struggles to reveal the accurate velocity details in such a geologically complex environment. We built our FWI initial models by converting legacy models from TORT to TTI and smoothing the salt boundary to reduce the interpretation and tomography uncertainties. The water velocity function was slightly adjusted to get a better tie. More importantly, we incorporated a faster deep velocity trend below the base of Louann salt, which was obtained from a first arrival tomography study conducted on an ultra-long offset 2D line (>80km offset) acquired during this survey. We expect this long offset line will provide deep velocity information for salt basement and presalt sediments as addressed by some earlier research studies (Harm, et. Al, 2015). An additional benefit is that with a faster velocity gradient down deep, the diving wave penetration through deep features such as salt feeders can be better illuminated. As mentioned earlier, the RTM based illumination study showed that 35km offset can provide good diving wave penetration up to 18km depth. We

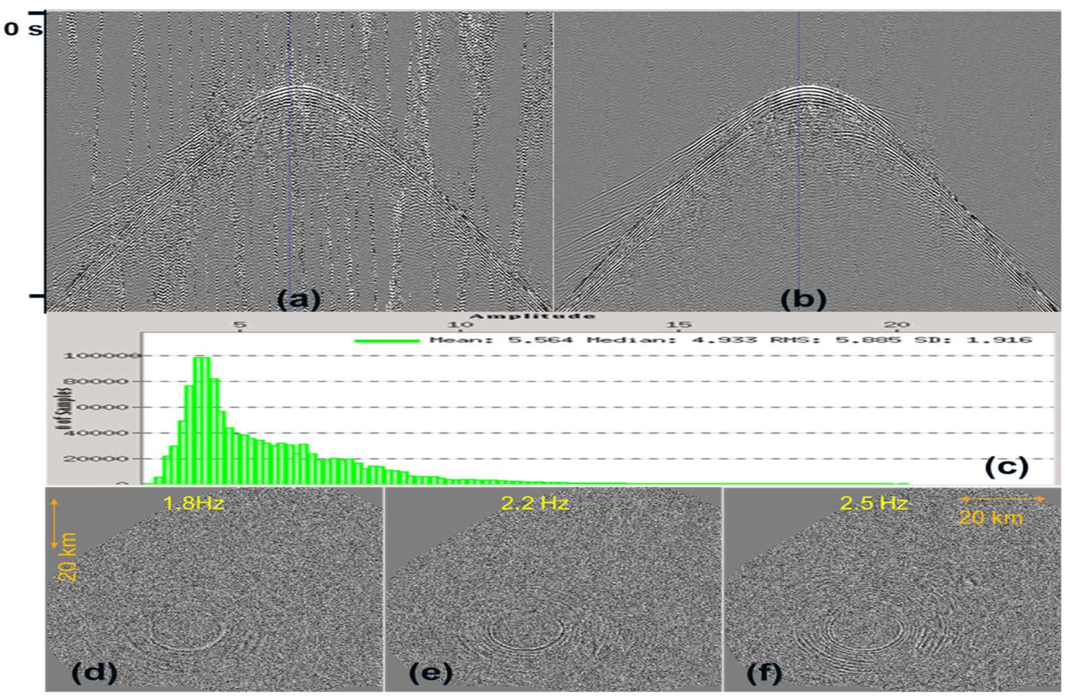

Figure 1: The data domain QC from a typical node gather. The time-domain displays show data up to 20km offset and 12 second time. (a) Raw blended hydrophone, (b) deblended hydrophone, (c) a histogram of the sample by sample amplitude ratio between a and b at the display window. Also, the low-frequency phase ring plots focusing on diving waves with ultra-long offset data included at (d) 1.8Hz, (e) 2.2Hz and (f) 2.5Hz.

are fortunate to have additional ultra-far offset information up to 60km to support an extra rich illumination.

FWI results

Our FWI study is designed to update the velocity model without any constraint in the model space to obtain a complete revision from shallow sediment to subsalt, and from salt to presalt. We used raw data from 1.6 Hz to 8 Hz and with the full offset range. Although this minimum

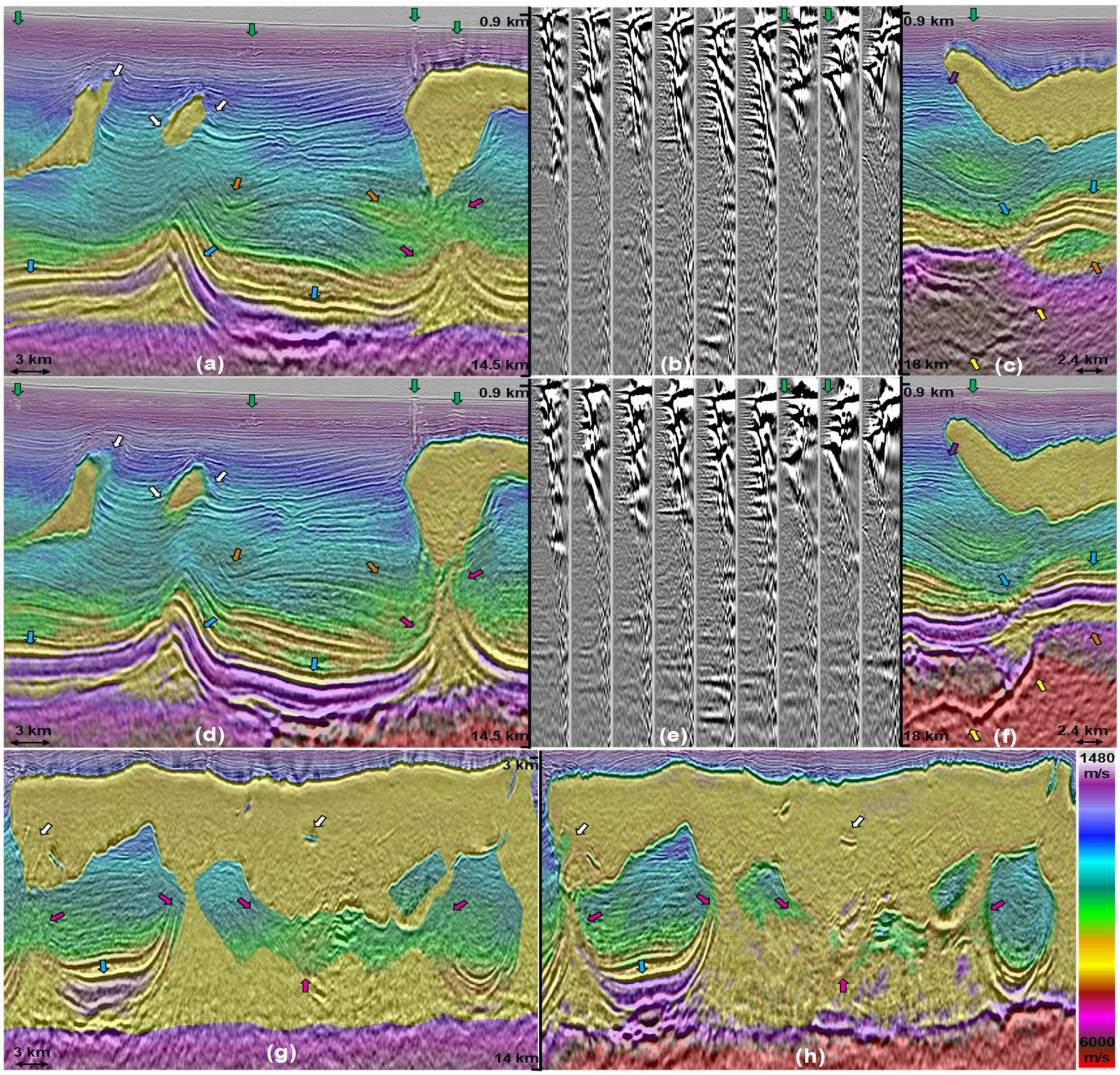

Figure 2: RTM images and gathers generated by deblended hydrophones at three QC locations. (a), (c) and (g) show the legacy velocity model overlaid on the corresponding RTM image at the first, second and third QC lines. (d), (f) and (h) show the FWI updated velocity model overlaid on the corresponding RTM image at the first, second and third QC lines. (b) and (e) show the gathers at the first QC line, from legacy model RTM and FWI updated model RTM, respectively. The green arrows highlight the gas chimney and cloud features discovered and their impact on RTM gathers. The purple arrow shows the healing of near salt sediment breaks. The orange arrows highlight the sediment velocity modifications such as removing tomography imprints. The cyan arrows capture the improved structural delineation of the fast-velocity Smackover carbonates. The white arrows highlight the salt geometry an intra-salt feature changes such as adding or removing inclusions. The pink arrows show the addition of the complex and thick salt feeders. The yellow arrows capture the emergence of some hidden presalt features. It is also obvious that the steep salt flanks and the base of Louann salt are better focused.

intervention approach seems quite ambitious, we successfully obtained a velocity model that significantly improved the RTM image and flattened RTM common imaging gathers globally. Figure 2 compares RTM result migrated with legacy models to corresponding FWI updated models, using deblended hydrophones under the same migration setting. The RTM gathers include offsets up to 20km. The corresponding velocity models are overlaid on stack images to illustrate the new features discovered by FWI. It is evident that DMFWI breaks the traditional velocity model building limits by:

- Revealing gas chimney and clouds,
- Healing near salt sediment breaks,
- Improving sediment velocity by removing problematic tomography imprints,
- Capturing and delineating the fast-velocity Smackover carbonates,
- Refining salt geometry and intra-salt features,
- Re-modeling and imaging of previously unclear salt stocks and related structures,
- Focusing the base of Louann salt,
- Accentuating presalt features.

We also migrated existing dual WAZ streamer data with the FWI updated models. The image uplifts, shown in Figure 3, validate the effectiveness of using the sparse node FWI solution to improve existing subsalt images obtained from streamer data. It is worth mentioning that the results shown here are using raw DMFWI inversion output without any post-inversion modification such as post-FWI tomography or model edits guided by interpretation. We expect that with additional effort on model regularizations or data constraints may further improve the FWI update.

Conclusions

A sparse node data has been acquired for better solving complex salt model building problems with FWI. By emphasizing the inversion on the phase and promoting signal, the overwhelming noise in the input didn't prevent DMFWI from obtaining a high-fidelity salt velocity model. Our study confirms the prevision by Michell et al. (2017) into the future subsalt imaging solution: automatic salt model building by FWI, using long offset sparse node data with rich low frequency.

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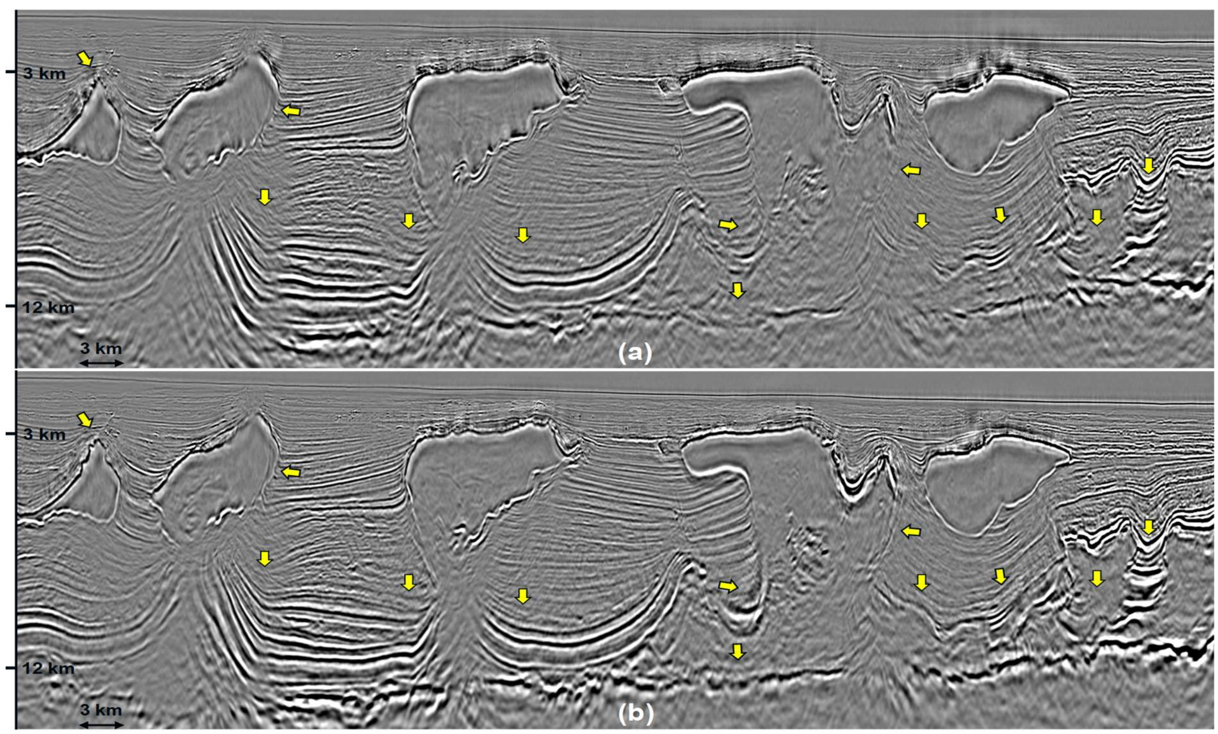

Figure 3: RTM images generated by dual WAZ data with (a) legacy models and (b) FWI updated models. The yellow arrows highlight the improvements, particularly on imaging steep to vertical salt flanks and focusing the base of Louann salt.

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