Application of high frequency reflection FWI in Nova Scotia: a case study

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Summary

In recent years, the industry has seen a paradigm shift with the advent of Full Waveform Inversion (FWI) technology in 3D seismic data processing projects. FWI has several potential advantages over conventional workflow, it is an iterative least squares solution of the full wavefield and thus has the ability to provide cleaner attributes because of the nature of the process. Shen *et al*. (2018) demonstrated the importance to subsalt imaging by extending beyond the traditional FWI frequencies, whilst Sheng et al (2022), Romanenko et al (2023), and Huang et al (2023) published a series of examples to demonstrate the value in 3D of extending FWI to the conventional imaging frequencies for various acquisitions.

Conventional FWI aims at inverting a volume of the velocity model, the resulting FWI imaging is incapable of accessing the attribute obtained from AVO analysis. In this paper we present a 40Hz FWI imaging product in the Orphan basin offshore Canada and demonstrate its benefit as a supplement to conventional Kirchhoff migration and outline a flow for generating FWI image gathers suitable for AVO attribute generation.

Method

The data is acquired using narrow azimuth towed streamer (NATS) with geo-streamer cables up to 8km max offset, over an area with an average water depth of 2000m.

Our objectives were to generate accelerated depth image and 40hz FWI image with improvement of Mesozoic image, structural clarity and fault definition. We use minimally processed raw hydrophone data up to 9Hz, then as we move to higher frequencies, we evaluate the use of fully processed data (SRME).

As we approach 30Hz and above, reflection FWI was applied, where kernel separation was implemented focusing on the migration kernel to enhance model resolution, since kinematics discrepancy have been largely resolved in previous FWI iterations(Ramos *et al*.,2016).

Several studies have been conducted to explore the FWI capabilities in AVA/AVO analysis. Jian et al (2023) demonstrated a method of producing pre-stack pseudo-reflectivity gathers for AVA/AVO analysis. Chemingui et al (2023) introduced an inversion workflow which updates velocity and angle & azimuth-dependent pre-stack reflectivity simultaneously, based on vector-reflectivity-based wave equation. As acoustic FWI remains the dominant approach for deriving high-frequency models. Dong et al (2024) proposed a method of decompose input data to different angle ranges then apply acoustic FWI to each of them to generate an FWI image angle gather for AVA analysis.

In this study, dynamic matching acoustic FWI was applied to field data to obtain a high-frequency FWI model. Incorporating Dong's method, we divided the input shots into discrete 10° angle bands and performed FWI on each band separately. Using the final migration model— a 25Hz FWI model in this case— as the initial input, we derived FWI images for each angle band and sorted them into angle gathers for AVA analysis.

To validate this approach, we also output Kirchhoff migrated images using the same 25Hz model, outputting CMPs, then creating angle gathers of the same fold as that of the FWI gathers. This enables a fair comparison of AVA attributes. Results will be discussed in the next section.

Results

The early frequency bands used the full raw dataset. As we looked to move away from a kinematic solution and inserting resolution into the velocity model using FWI, we found the impact of multiples to be a barrier which results in using the data after multiple attenuation as input to the FWI for the latter frequency bands. Figure 1 shows the comparison of FWI images using raw hydrophone data and de-multipled data.

Following this change of input data, we progressed up through the frequency bands. For high frequency FWI that is greater than 25Hz, kernel separation is implemented aiming at utilizing the migration kernel to boost the model resolution. The final product of a 40Hz FWI image offer significant improvements over the legacy Kirchhoff image in resolution. The velocity profile at the well location aligns more closely with the sonic velocity. Figures 2 & 3 illustrate the enhanced sediment continuity and the improved definition of velocity anomalies within the sediment basin, along with the velocity profile comparison at well location.

Figure 4 shows the comparison of legacy products with current result at the major fault plane location, At the site where events were previously disrupted by a major fault plane, significant update can be observed with refined overburden velocity model and enhanced continuity of events across the fault. Additionally, gathers that previously exhibited a wavy pattern become now significantly flatter/uniform with FWI model.

In the region with multiple faults intersecting the sediment, the latest results provide more accurately positioned faults with better focused and sharper fault planes and improved continuity for the sedimentary events between them. With reduced shallow velocity uncertainty, the BTU layer is more clearly defined, and the deep structures appear more geologically coherent. Figure 5 presents a comparison of two locations, highlighting the improvements in fault delineation and deep structural clarity.

For FWI gather, we compared the intercept-gradient product (I*G) of the FWI gather with the the Kirchhoff CMP gather of same fold. The FWI derived AVO is very similar to the Kirchhoff equivalent (Figure 6). One key observation is that the FWI derived AVO is far cleaner than the Kirchhoff data, which we believe is due to the least squares nature of FWI. (Where is the AVO you talked about here? Seem you may need to extract the amplitude curve)

One key difference between the FWI and Kirchhoff is the AVO observed at one reflector at around 3000m below mudline, where the AVO is much clearer using the FWI based AVO (Figure 7).

Conclusions

We have demonstrated the value in obtaining a 40Hz FWI model using streamer data to aid exploration. The 40Hz FWI image and model reduced the uncertainty compared to legacy product, greatly improved the velocity resolution and has much improved low frequency content and signal to noise ratio.

The generation of FWI gathers has allowed us to extend FWI imaging into the pre-stack space and our work has demonstrated the robust nature of these products.

Our AVO results would be cleaner if produced from finer sampled (in angle) data and, in the future, we would look to output 5-degree angle bands.

Acknowledgements

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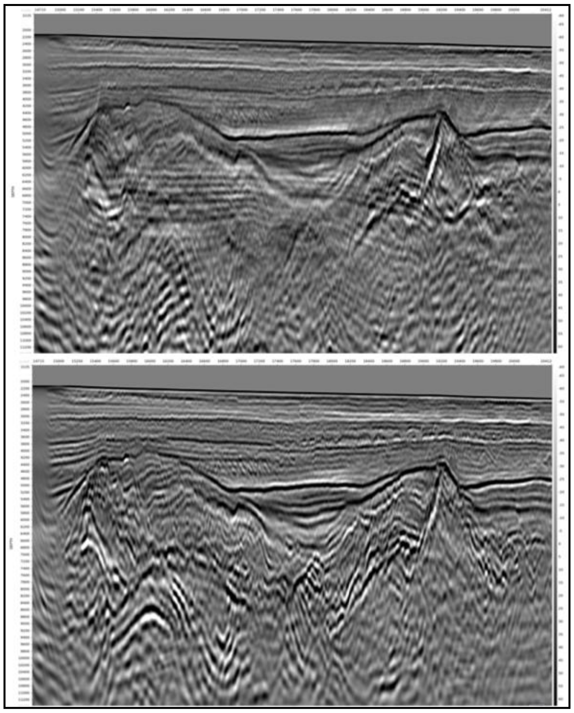

Figure 1. FWI Image(9-12Hz FWI) of using HRaw data (top) vs SRME data (bottom)

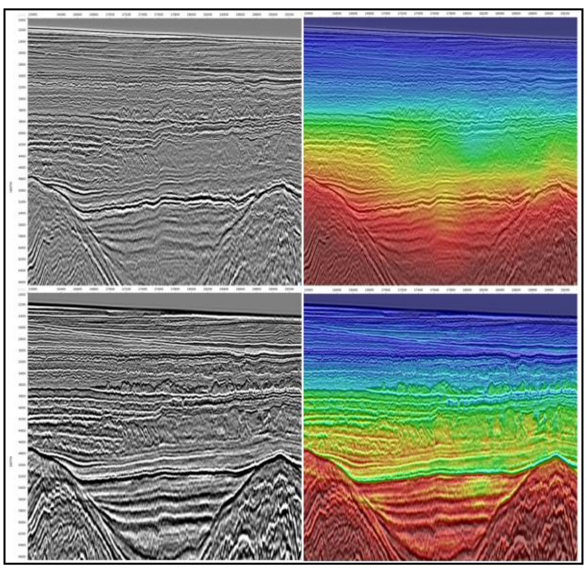

Figure 2. Comparison of Legacy Stack and Velocity Model (top) with 40Hz FDR and its Velocity Model (bottom),

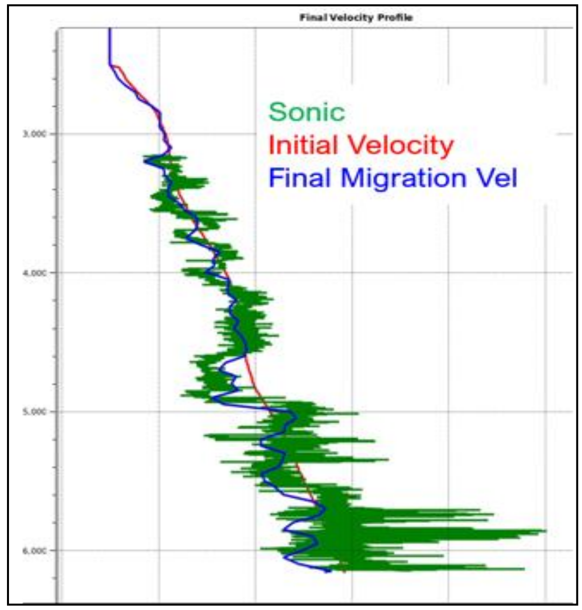

Figure 3. Velocity profile comparison at the well location

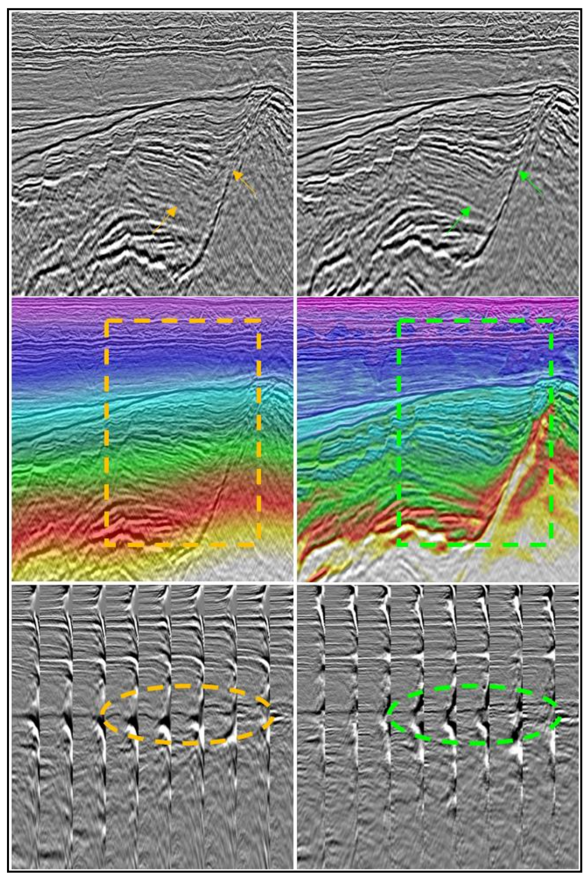

Figure 4. Comparison of Legacy (left) vs. Final (right) Stack, Velocity Model, and Gather at the location of a major fault plane.

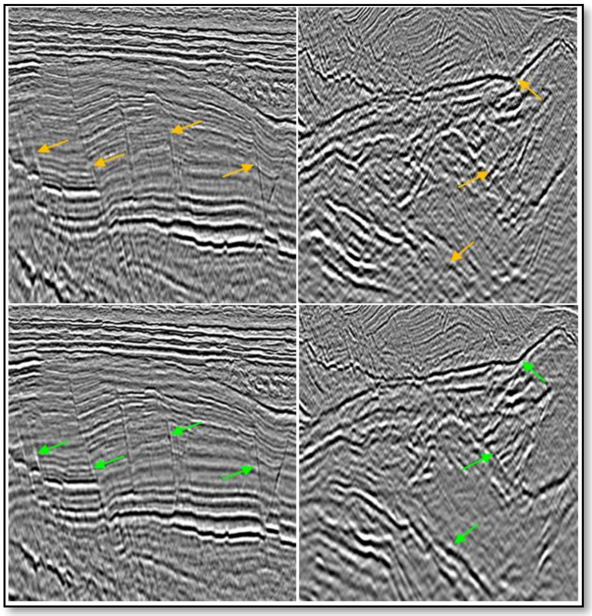

Figure 5. Legacy Stack (top) vs Final Stack(bottom) at the location where we see the fault delineation and deep structural clarity.

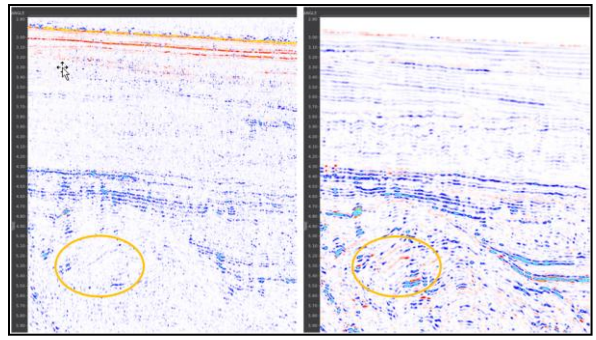

Figure 6. Intercept x Gradient for Kirchhoff gathers (left) and FWI gathers (right)

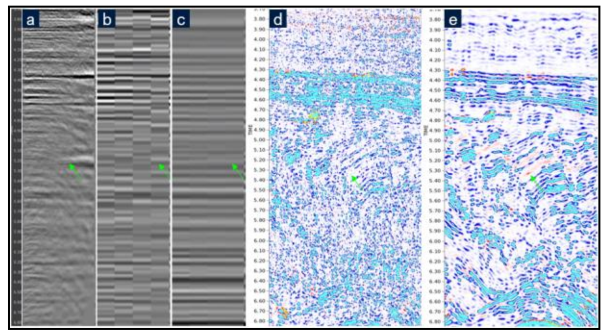

Figure 7. Kirchhoff 60 fold angle gathers (a) 4-fold Kirchhoff gathers (b), 4-fold FWI gathers (c), Intercept x Gradient from Kirchhoff gathers (d) and Intercept x Gradient from FWI gathers (e)