High frequency FWI on Clair OBN dataset -challenges and successes

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Summary

Nowadays, high frequency full waveform inversion is routinely applied for building high resolution velocity model from which high-fidelity reflectivity image, FWI Imaging, is derived. It can be used as a complementary or even as an alternative product to Kirchhoff, RTM or LSM images (Jones et al., 2023).

In 2022 we completed a project that re-built the p-wave velocity model over the Clair field applying high frequency (50Hz) Dynamic Matching Full Waveform Inversion – DM FWI (Mao, et al., 2020) utilizing legacy and recently re-processed ultra-high density node data.

The objectives of this paper are to discuss the successes and challenges of applying high frequency DM FWI to OBN data and the alternative QC methods required as the industry moves towards higher frequencies and resolution with FWI.

Introduction

In 2017, bp acquired the densest OBN survey in UKCS to establish a suitable baseline for 4D time lapse monitoring of PP and PS images over the Clair field. The 4D signal at Clair is modelled to approximately 1% acoustic impedance change, but despite the small signal, Davies et al (2011) have shown that reliable 4D signals have been observed at Clair on both PP and PS data using the permanent array that was installed in 2006.

Tillotson (2019) and Smith (2019) have both shown the value of this dense acquisition on 3D static images of both PP and PS data, both in terms of full stack response and PP and PS AVO responses. The success in 3D has further increased the confidence in detecting relatively small 4D signal.

Given that 4D signals are weak at Clair, other reservoir properties are of interest if they can provide insight. The expected change in velocity is around 2%, which is larger than the expected acoustic impedance change and thus 4D FWI is of interest should reliable 3D updates to the model be obtained within the reservoir.

An FWI pilot study was perfromed on a subset of the data in 2020 and the results have been published elsewhere (eg., Wang et al,2021; and Korsmo et al, 2021). Following the initial pilot study, the learnings were applied to the full 2017 dataset. The objectives of this paper are to discuss the results amd importance of data pre-processing and alternative QC methods for evaluating higher frequency FWI model building.

Phase 1 – pilot study

As with most implementations of FWI, DM FWI begins with the low frequencies. This OBN data is rich in low frequencies which enables a starting frequency of around 2 Hz. The legacy velocity model, generated in 2018 with FWI (9 Hz peak frequency) and tomography, was used as the initial model. To avoid the risk of updates becoming trapped in local minima, this model was smoothed prior to FWI. FWI was run on raw hydrophone field data for the first four frequency bands (3 Hz, 5 Hz, 6 Hz and 8 Hz) with multiple iterations per band.

As we moved outside of the traditional frequency ranges used for FWI it became apparent that multiple contamination was impacting the results. Below 10 Hz the impact was minor, however, at 10 Hz and higher there was a clear imprint from multiples in the velocity model. To mitigate this effect, starting at 10 Hz and above, we used pre-processed data. We steadily increased the maximum frequency (start of slope) of the updates from 20 Hz to 50 Hz in 10 Hz increments.

The resultant velocity model is clearly an improvement over the legacy model (Figures 1a and 1b) with significant differences at reservoir level. The estimated velocity produced an excellent tie with well sonics.

The associated RTM images (Figures 1c and 1d) clearly show that the image using the updated model has fewer imaging artefacts in the overburden along with subtle improvements in both resolution and fault imaging positioning. The gas-oil contact is significantly clearer and has a far simpler and geologically reasonable appearance.

Phase 2 – full dataset processing

The scope of the full field study was to apply the same technology as used on the pilot area to the full area. During the pilot study a number of learnings, both in terms of code and approach were noted and these were incorporated into the full field application.

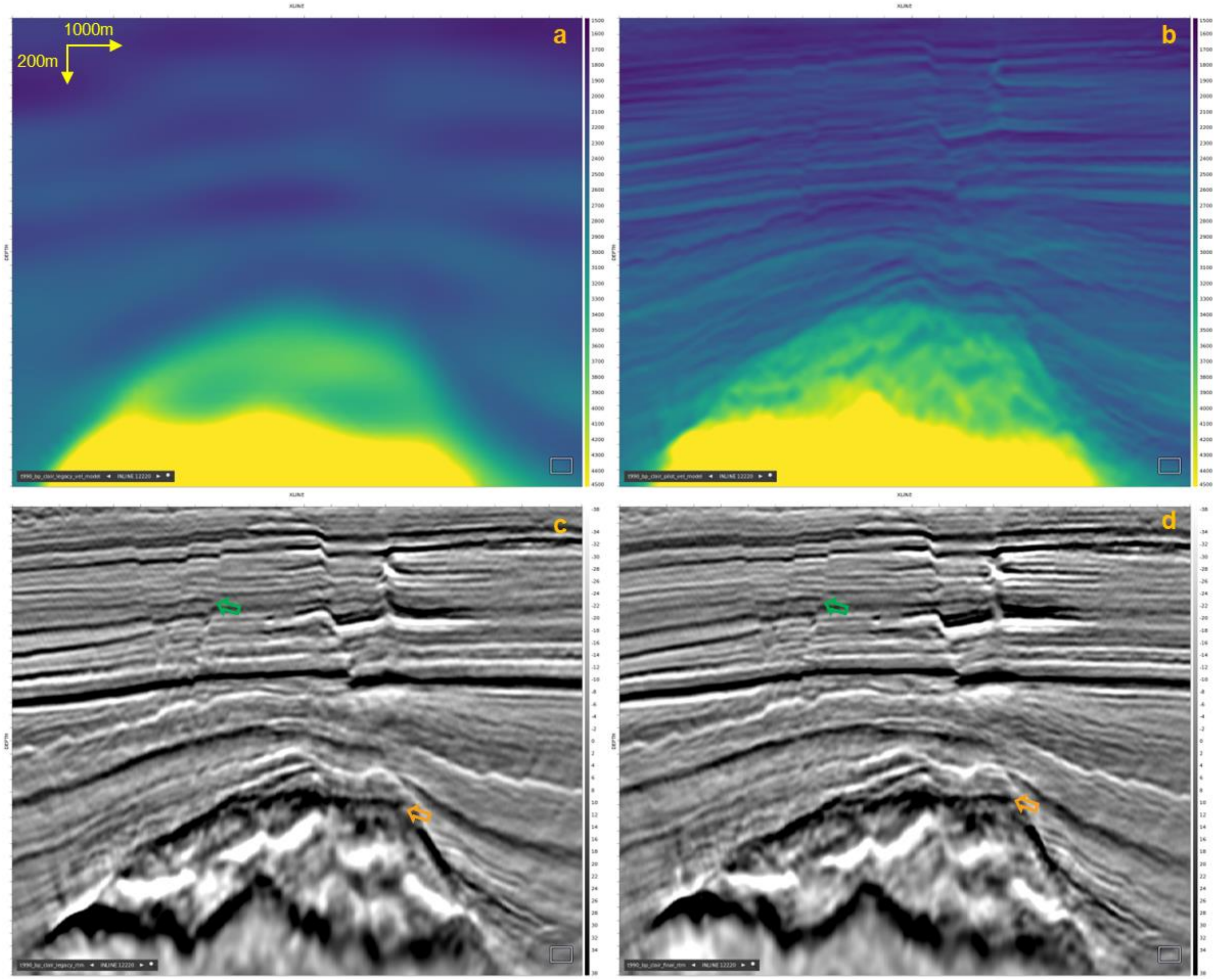

Figure 1: Legacy velocity model (a), pilot FWI velocity model (b), RTM with legacy velocity model (c), RTM with pilot FWI velocity model (d). Orange arrows show an improvement in Oil- Gaz contact, green arrows show an improvement in faults focusing.

Diving wave analysis showed that very little diving wave energy was returning from the reservoir and the updates in the reservoir section were being driven primarily by the reflection only DM FWI passes.

Following thorough analysis of the benchmark data it was determined that the multiples within the data that impacted the high frequency FWI updates were interbed rather than free surface multiples. For this project the availability of a newly re-processed dataset with improved de-ghosting, zero phasing and de-multiple proved beneficial in generating a model. The resulting FWI Imaging yields improved bandwidth and has a more broad-band appearance with less side lobes and less multiple contamination than previous velocity models generated over the Clair field (Fig. 2).

The final velocity model shows significant uplift over legacy and pilot velocity models. It conforms better with geological structures, has improved matching with sonic logs and check shots, produces flatter gathers and improved focusing in migrated images with simpler geological structures.

The DM FWI velocity model generated a high frequency FWI Imaging with improved overburden and reservoir when compared to equivalent Kirchhoff or RTM images (Figures 3a and 3b). It has better resolution and signal to noise ratio and reveals more detail in the reservoir section.

The least squares nature of this image also leads to improved imaging beneath a hole in the receiver patch due to the presence of a platform. The FWI Imaging was used as the primary QC for the higher frequency passes of DM FWI.

As the model building moved to frequencies above 20 Hz, it was observed that the conventional QCs were less conclusive in demonstrating when the FWI updates were converging or improvements in the model in terms of gather flatness. This was because the kinematics of the model were accurate, but the higher frequencies were adding more detail into the model without changing the overall kinematics.

To determine when the high frequency DM FWI passes were converging and to demonstrate improvements in the model alternative QC tools were employed – We took advantage of the RTM stacks being insensitive to the changes above 30Hz by measuring the NRMS (Kragh et al, 2002) and amplitude envelope difference between the RTM and FWI Imaging after each iteration. The measure is sensitive to both timing and amplitude changes and are a good indicator of when the updates start to be over-fitted (Fig. 3c and 3d).

Another useful QC attribute for high frequency FWI is a cross correlation map between RTM and FWI Imaging. Figure 4 shows this QC through different FWI stages from 10hz to 50hz along BCU horizon. As we move to higher frequency RTM and FWI Imaging look more similar to each other and therefore the cross correlation approaches a value of 1. Lower correlation shows areas where FWI Imaging doesn't look similar to RTM – it can highlight areas where we see value of FWI Imaging comparing with RTM or it can indicate some potential problematic areas where FWI was struggling to converge on an optimum solution.

These extra attributes proved very helpful when making decisions with regards to FWI parameter testing.

Conclusions

FWI imaging is a rapidly evolving technology. Our DM FWI implementation has clearly shown uplift beyond the depths which would be updated via a traditional diving wave approach and that reflections positively contribute to the result.

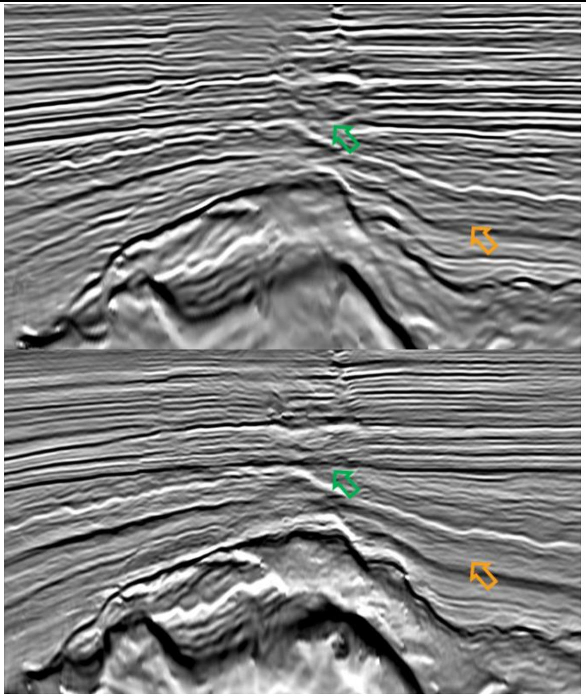

Figure 2: Comparison of the FWI Imaging of the pilot result (top) and latest full field application (bottom). Orange arrows show an area with reduced interbed multiple footprint, green arrows show better continuity of the horizon.

We have shown value in using pre-processed data rather than raw field data can be beneficial when running high frequency FWI and can result in cleaner and more detailed FWI velocity model and associated FWI Imaging.

When moving to high frequency FWI, traditional QCs such as RTM QC and Kirchhoff migration QC as well as misfit curves are less informative and additional QC products are required. Attributes typically employed in 4D processing - NRMS and amplitude envelope difference, alongside cross correlation maps between FWI Imaging and RTM stacks- are helpful QCs for monitoring progress of high frequency FWI updating and indicating areas where FWI Imaging quality exceeds RTM QC.

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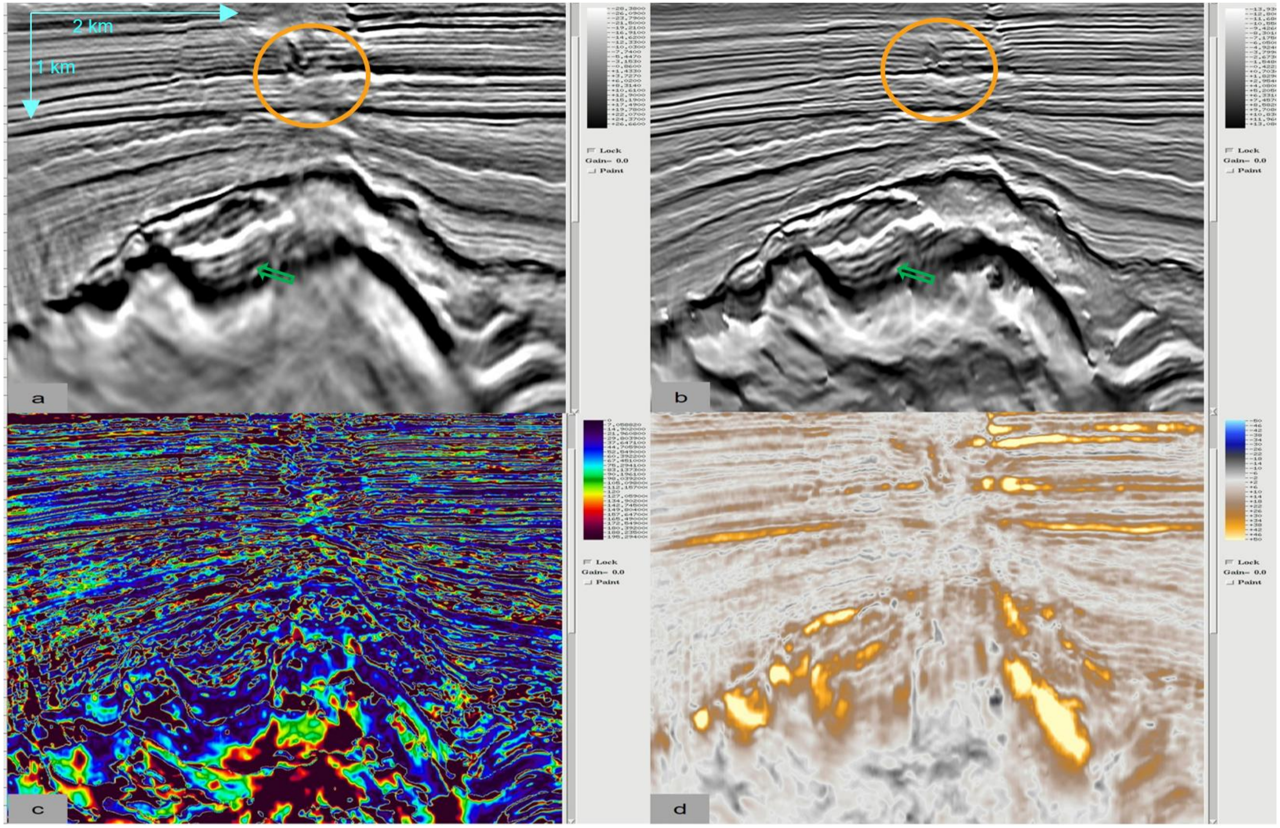

Figure 3: DM FWI Final results, RTM QC (a), FWI Imaging (b), NRMS (c) and amplitude envelope difference (d). Orange circles show an improvement in imaging around the platform, green arrows show a resolution improvement in the reservoir.

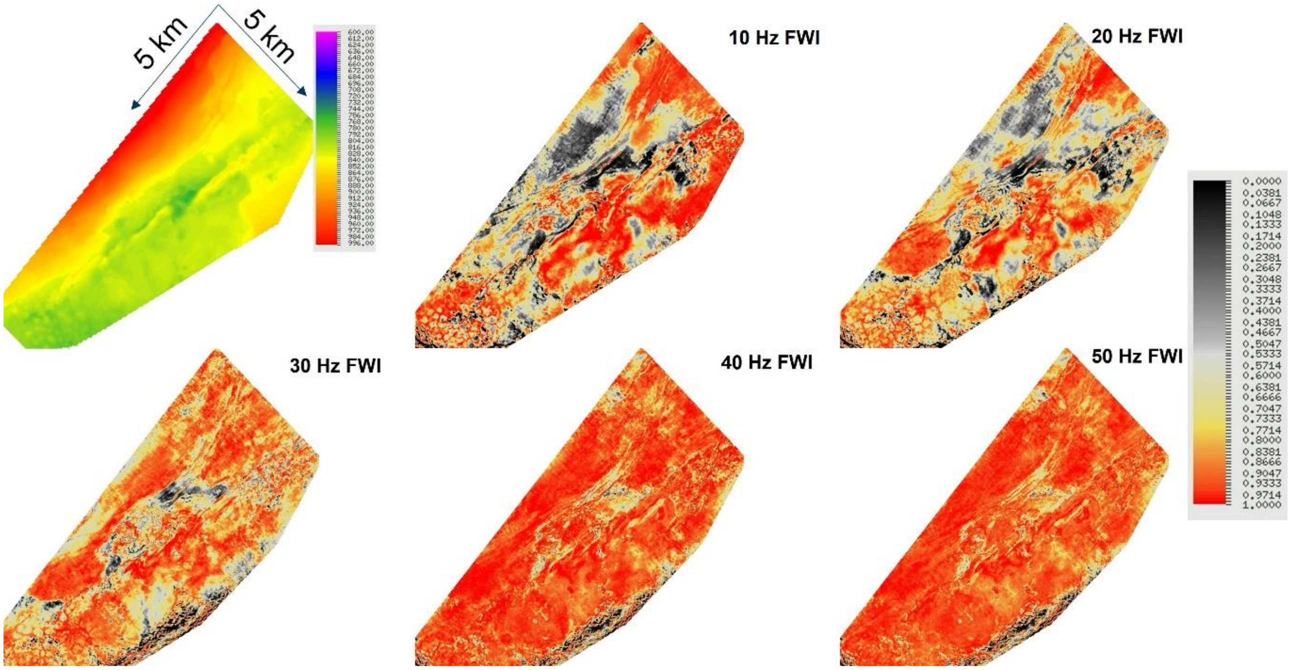

Figure 4: RTM-FWI Imaging Cross correlation maps throughout high frequency FWI.