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4D FWI on 25,000 nodes – a Clair case studybe

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Summary

This abstract covers the application of 4D full waveform inversion (FWI) on an Ultra High Density Ocean Bottom Node dataset. The node count was over 25,000 for the project, which is an incredibly high number. The work explores different methods of 4D FWI and compares their results between a test swath and full production showing how limited data in tests can lead to sub-optimal results. The paper will be able to compare the 4D FWI results to standard processed and imaged data.

Introduction

In recent years the industry has seen a paradigm shift with the advent of Full Waveform Inversion (FWI) imaging in 3D seismic data processing projects. Fundamentally, for a single parameter FWI velocity update this is merely a directional derivative of the velocity model, the resolution of which is largely controlled by the maximum frequency of the FWI and the subsurface properties.

FWI was first proposed by Tarantola (1984), due to the lack of cost-effective compute the uptake was limited. Sirgue *et al*. (2010) published an example that accelerated development when FWI was run to 7Hz. This provided a significant uplift in imaging underneath a gas cloud and for many years this frequency of FWI update was the norm. Shen *et al.* (2018) demonstrated the importance to subsalt imaging by extending beyond these traditional FWI frequencies, whilst Wei *et al.* (2023) published a series of examples to demonstrate the value in 3D of extending FWI to frequencies in excess of 100Hz. Whilst this approach has clear assumptions (e.g., that all reflectivity in the image occurs as a result of velocity changes) the quality of the resulting images has led to the adoption of FWI imaging as either an alternative view or in some cases the prime product for imaging the subsurface.

FWI has several potential advantages over conventional imaging: it is an iterative least squares solution of the full wavefield and thus has the ability to provide cleaner attributes as a result of the least squares nature of the process. As FWI uses the full wavefield (primary and multiples) it is possible to generate attributes over a larger area relative to the area obtained from conventional imaging. By using the unprocessed field data, FWI imaging has also enabled turnaround time for projects to be significantly reduced.

Despite the progress made with 3D FWI Imaging, 4D FWI imaging is still in its infancy. Davies *et al.* (2024a) have discussed the advantages and disadvantages to various methods of 4D FWI and in a further publication, Davies *et al*. (2024b) have shown an application of 4D FWI on towed streamer data.

In this paper we will review the initial tests on two Ultra High Density Ocean Bottom Node (UHDOBN) datasets as a segue into the learnings from the full field 4D application on over 25,000 node locations. We will compare the reflectivity and FWI derived differences from the various approaches and discuss how this technology may evolve in the future.

Method

The datasets used in our study are from UHDOBN surveys acquired in 2017 and 2023 (Tillotson *et al.*, 2019). Following the successful application of high frequency FWI in 3D (Romanenko *et al*., 2023), we evaluated several versions of 4D FWI on a test swath of 5 receiver lines (~450 nodes), including, but not limited to both Parallel and Joint 4D FWI approaches.

The Parallel 4D FWI scheme is simply to run identical and independent 3D FWI workflows on each dataset and obtain the 4D difference in velocity. The second 4D FWI scheme is a Joint inversion approach (Gao *et al*., 2024), which updates the baseline and monitor models in a coordinated way through the minimization of the 4D difference within the FWI update.

Despite these being well repeated acquisitions, prior to running any 4D FWI, harmonization of the nodes was required and only nodes that exist in both datasets were used. We found marginal benefit in applying a delta-source threshold (25m). To validate this, we migrated the baseline with the monitor geometry – an inspection of the full stack image relative to the correct geometry led us to believe that our selection criteria was acceptable.

Our initial results contained considerable overburden leakage of the 4D signal, however, this was hypothesized to be a result of the limited swath. In order to confirm this, after we performed RTM on both base and monitor surveys for both the full area and the test swath, it was clear that the 4D difference of the limited area was significantly noisier. This validated our assumptions and allowed us to move onto applying 4D FWI to the full 25,000 nodes of the entire dataset.

Results

A key early QC was a comparison of the test swath and the final production, this is shown in Figure 1. The reservoir softening and hardening showing a high degree of correlation, but with significantly less overburden leakage in the 4D velocity change (dV) volumes by using the full dataset.

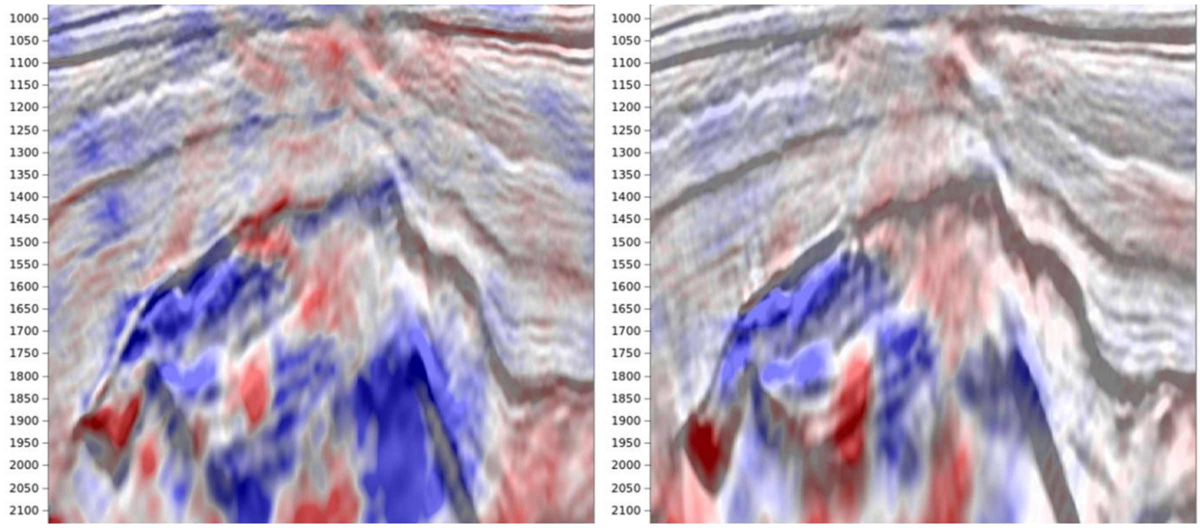

Figure 1 *3D RTM stack with 4D FWI overlay, for 5 lines swath (left) and full area (right) showing the reduction in overburden leakage as a result of imaging all the data.*

In addition to the stabilization of the overburden noise by using all the data, it is possible to further assure our results looking at crosslines and depth slices. Figure 2 shows a comparison of conventional reflectivity (top), velocity model (row 2), FWI image (row 3) and 4D dV (bottom). We observe an improvement in 3D structural imaging with FWI imaging and more importantly see significant 4D effects constrained within the reservoir.

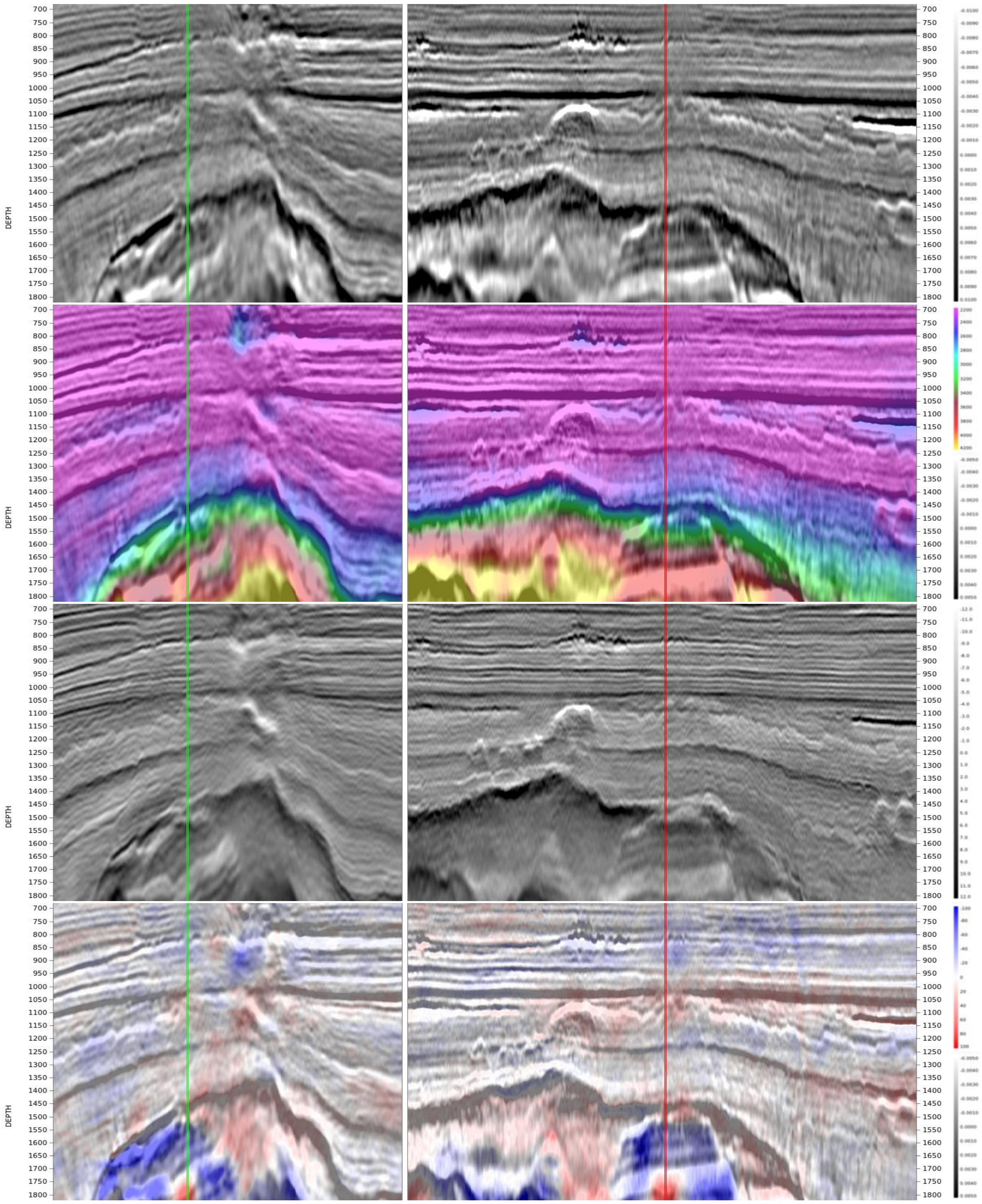

***Figure 2** Inline and Crossline for 3D RTM (top), 3D Velocity model and RTM overlay, 3D FWI image, 3D RTM with 4D FWI overlay*

Conclusions

We have found both our approaches to 4D FWI (parallel and joint) are robust. The joint approach allowed for a reduction in overall number of iterations and had no adverse impact on data quality. In fact, the use of the 4D difference as a constraint within the inversion leads to improved 4D FWI images verses the parallel method. The 4D FWI results run over the entire dataset on 25,000 nodes have been found to correlate well with conventionally processed 4D imaged data, which in turn correlates well with known geological and production related changes in the field.

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