4D FWI – evolution of learnings from a 4D OBN application

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Summary

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 this is a fairly simple process as the image is merely a directional derivative of a velocity model, the resolution of which is largely controlled by the maximum frequency of the FWI and of course the subsurface properties.

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

In this paper we extend FWI imaging into 4D, we review a pilot study of several approaches for 4D FWI on a dense OBN survey in the North Sea. We then show the full field application of the preferred solution, which we compare to conventional Kirchhoff migrated 4D products.

Introduction

FWI was first proposed by *Tarantola (1984)*, but 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, to provide a significant uplift in imaging underneath a gas cloud. For many years FWI was run to 7Hz or 10Hz. *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. The industry started to accept the validity of the amplitude information from such publications and has led to FWI imaging as either an alternative view or in some cases the prime product for imaging the subsurface.

Method

The datasets used in our study are from dense OBN 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 the same data, but we will focus on two:

- Parallel 4D FWI
- Joint Inversion 4D FWI

The Parallel 4D FWI scheme is simply running 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, with only nodes that exist in both datasets used for the inversion. We also found marginal benefit in applying a delta-source threshold (15m). We migrated the baseline and monitor surveys to allow us to validate our thresholds via inspection of the 4D reflectivity differences.

Results

The evaluation of various FWI techniques was performed on a narrow swath of 5 receiver lines. We found our various approaches to be very similar in terms of 4D anomaly location and noise content. Despite the Joint approach having a fewer number of iterations, no adverse impact on data quality was observed (*Davies et al 2024*).

Figure 1 shows the RTM stack of the baseline data, overlaid in colour with the 4D velocity difference. The changes in velocity appears to be correlated to wells within the study area.

Following the analysis of the trial results, the full areal extent, which consists of approximately 15,000 nodes per survey, was taken through the Joint inversion approach. The 4D FWI difference was converted to a 3D FWI image and compared to a 4D difference derived from a reflectivity product (from another vendor), and show a great deal of agreement. The 4D FWI image has slightly more 4D leakage in the overburden, but at the reservoir, the 4D FWI imaging provides a cleaner 4D difference, believed to be due to the least squares nature of the 4D FWI process. At this time, the operator is still evaluating this data in order to understand the changes between the conventional and FWI 4D differences.

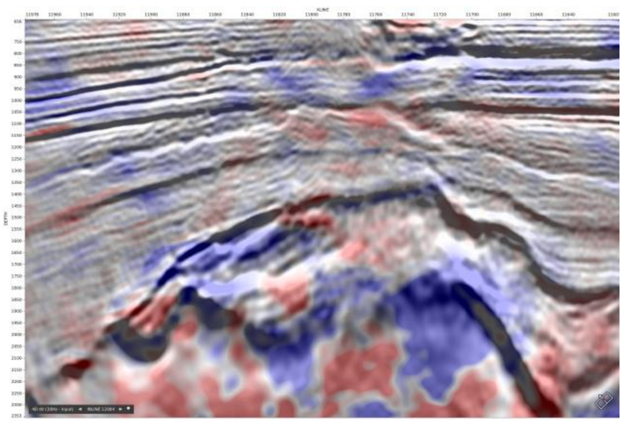

Figure 1: An inline from a 3D PreSDM (grey scale) overlain with the 4D FWI change in velocity (red-blue).

Conclusions

The results of the testing gave us confidence to proceed with the full scale 4D FWI deployment. Whilst there is a good degree of similarity of results, there are also some significant differences that are still being evaluated.

Key words

FWI imaging
4D FWI
OBN

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