4D FWI – learnings from a North Sea OBN case study

Daniel Davies, David Cavalin[1], Fuchun Gao[1], Lee Saxton[1], Matvey Romanenko[1], Phil Tillotson[2], Lifeng Wang[2]*
1 TGS
2 bp

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 the FWI and of course the subsurface properties.

As 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 area obtained from conventional 4D imaging. Finally, FWI imaging has also enabled turnaround time for projects to be significantly reduced.

Initially there was some skepticism about the amplitude fidelity of such volumes, but through a series of examples, the industry has accepted the technique as either an alternative solution, or in some cases as the primary interpretative product.

In this paper we extend FWI imaging into 4D, outline several approaches for 4D FWI, discuss the pro's & con's of each and demonstrate these by applying each approach to a dense OBN survey in the North Sea. We will compare the reflectivity and FWI derived differences from the various approaches and discuss how this technology may evolve in the future.

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.

Despite the progress made, there are still very few published examples of using FWI imaging in 4D. In this paper we show the application of several implementations of 4D FWI to a shallow water OBN survey from the North Sea.

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 in 3D (*Romanenko et al, 2023*), we have run several versions of 4D FWI, but we will focus on two versions:

- Parallel 4D FWI
- Joint Inversion 4D FWI

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, 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 we used.. We found marginal benefit in applying a delta-source threshold (15m). To validate this, we migrated the baseline with the monitor geometry, inspection of the full stack image relative to the correct geometry led us to believe that our selection criteria was acceptable. In addition to the checking of the geometries, prior to 4D FWI, we looked at the time shift between migrated volumes to ensure we could observe the predicted time-strains in the reservoir. The was performed in order to understand the likely chance of success and whilst not necessary for future projects, it was important as we embarked on our first field wide application of 4D FWI.

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For both 4D FWI schemes, for each frequency band, we generate 3D FWI images and the associated 4D FWI image to compare with conventionally derived 4D reflectivity images. Again, this is not strictly necessary on future projects, but was vital for us to gain confidence in moving forward through to the higher frequency bands.

The use of a Joint inversion approach is advantageous, as not only does it use the 4D difference within the inversion process thus making it a true 4D inversion, it serendipitously results in far faster convergence. We discovered that we were able to converge in around half the number of iterations of the parallel flow. This then allows the user to run more iterations if 4D noise is of a concern, as whilst it is not visible in 3D results, some noise is visible on the higher frequency bands on a 4D FWI image without these extra iterations.

Results

We have found our approaches to be robust and the reduction in overall number of iterations using the Joint approach has no adverse impact on data quality, in fact, the use of the 4D difference within the inversion leads to improved 4D images, both in terms of velocity comparison and relative to the conventional processing flow. Figure 1 shows the RTM stack of the baseline data, overlaid in colour with the velocity change. The increase in velocity is constrained by a known fault and is a result of injection. Similarly, the slowdowns in blue identify known areas of production.

Conclusions

The results give us confidence that 4D FWI will be used more widely and as confidence grows in the technique, application at scale will occur. Not only will quality improve, projects will be delivered in far timeframes as a result of being able to work the baseline data in advance and allowing 4D FWI products to be delivered within weeks of acquisition completion.

Key words

FWI imaging
4D FWI
OBN

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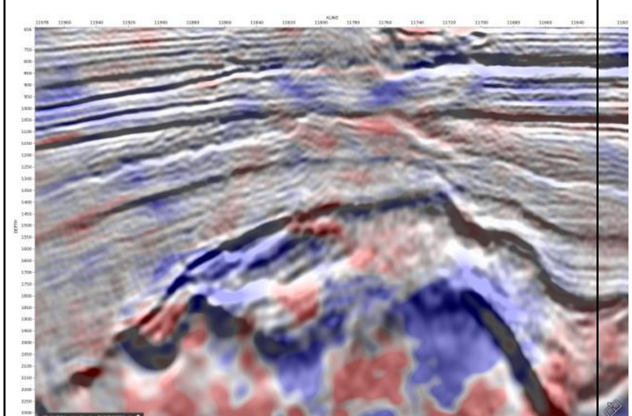

Figure 1: An inline from a 3D PreSDM with a 4D FWI