4D FWM for deep water OBN monitoring

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Summary

This paper presents a dedicated 4D formulation of Full Wavefield Migration (FWM). The method, which makes use of both primary reflections and multiples for imaging, is applied and validated for Ocean Bottom Node (OBN) monitoring surveys.
The aim of this 4D imaging study is to significantly reduce processing/imaging runtime without compromising the 4D image quality. A pilot test, using deepwater West Africa OBN dataset, demonstrates that effective 4D imaging can be achieved with fewer nodes and a shorter turnaround.

Introduction

Exploration and production in deepwater hydrocarbon reservoirs pose major technical challenges because of large water depth, complex seabed conditions, and heterogeneous subsurface geology. Ocean Bottom Nodes (OBNs), which use multicomponent sensors placed on the sea-floor, have become an effective solution for imaging these reservoirs. These autonomous systems can operate in ultra-deep water and record wide-azimuth data from surface seismic sources.
Time-lapse 4D OBN surveys enable monitoring of reservoir changes during production, providing key insights into fluid movement, pressure variation, and recovery efficiency. Recent advances in OBN acquisition systems have lowered operating costs while improving the repeatability that is critical for 4D seismic monitoring.
OBN acquisition benefits from the separation of seismic sources and receivers, enabling dense shooting, wide-azimuth illumination, and long offsets. In this paper, we investigate whether acquisition can be optimized by reducing the number of deployed OBNs and shortening delivery time for the first 4D images through fast-track imaging, without compromising interpretability of the 4D signal.
Reducing the number of nodes can directly lower the cost of an OBN survey. However, enough sensors are still required to maintain adequate seismic reflection fold. In deep water, standard practice is to use the down-going wavefield recorded by thousands of OBNs, typically spaced about 350 m apart.
This study evaluates whether Full Wavefield Migration (FWM) can relax constraints on the density, geometry, and layout of seabed sensors. Using real 4D datasets from a deepwater OBN survey offshore West Africa, we simulate alternative OBN layouts and assess their impact on 4D signal resolution.
The second objective is to reduce as much as possible the first delivery time of an interpretable 4D image. The proposed 4D FWM imaging concept allows us to reduce significantly the number the processing sequences and to provide a 4D image with enough resolution to interpret the 4D signal in term of production changes in the reservoir.

4D FWM: imaging with multiples concept

The imaging methodology, called Full Wavefield Migration (FWM) (Lu et al., 2018), uses both primary reflections and multiples to image geological structures. In this multi-wavefield approach, a source wavefield built from the recorded data is forward propagated, while a receiver wavefield built from the same data is backward propagated. The image is then formed using a deconvolution imaging condition applied to the two wavefields.
FWM uses primaries together with all recorded orders of sea-surface multiples. Applied to OBN data, the method effectively turns each shot pair into a virtual sea-surface source–receiver system. As a result, the illuminated area is mainly controlled by source location and the highest recorded multiple order. FWM has demonstrated the ability to produce high-quality images with very sparse seabed sensor layouts. Previous studies have shown the illumination benefits of incorporating recorded sea-surface multiples in both 3D and 4D imaging workflows (Lecerf et al., 2015, 2020; Lu et al., 2015).
The 3D FWM framework was reformulated for 4D imaging. A single source wavefield is computed, and the base and monitor receiver wavefields are calibrated so that the deconvolution imaging condition is better suited to time-lapse analysis and less sensitive to 4D noise. Using the same denominator and regularization terms in the spectral division suppresses non-repeatable artefacts and cancels out the crosstalk. In addition, the first source term in the numerator is identical for both vintages, so the 4D signal is controlled only by the calibrated back-propagated wavefields. Compared with a 2×3D workflow, this formulation improves the image repeatability and reduces 4D noise in the seismic difference volumes.

This OBN-on-OBN time-lapse study evaluates the potential of 4D FWM to deliver an interpretable 4D image with minimal turnaround, referred to here as an ultra-fast-track 4D product (4D UFT). In monitoring studies, reducing the OBN pre-imaging workflow is challenging because non-repeatable effects can degrade the 4D image. However, by using hydrophone-only datasets for the back-propagated wavefield, the proposed 4D FWM formulation helps to

reduce pre-processing requirements. In this case study, we estimate that 3–5 weeks may be sufficient to deliver a reliable ultra-fast-track 4D product.

Proof of concept using a subset of real 4D OBN datasets

A 4D OBN survey was acquired offshore West Africa in deep water, using 1,200 receivers at a water depth of about 1,500 m. The OBN layout geometry and density were optimized for monitoring the reservoir production using the down-going wavefield with a Kirchhoff mirror migration. Two receiver grid densities were defined: above the reservoir, seabed receivers were deployed on a 300 m × 346 m hexagonal grid, surrounded by an outer ring with a sparser 600 m × 346 m grid. Source and receiver positions were repeated as closely as possible between the base and monitor surveys. For computational efficiency, this 4D FWM proof of concept uses a subset of the full dataset: five receiver lines comprising 145 OBNs, mainly in the dense grid configuration. The maximum frequency was limited to 50 Hz for this test. Legacy 100 Hz 4D Kirchhoff images generated from all OBNs (more than 1000 seabed sensors) were used to validate the resulting 4D FWM signal. The ultra-fast track 4D workflow for the base and monitor hydrophone data is summarized below.

- Clock drift, Tidal, residual x, y and z corrections
- 4D shot binning
- Hydrophone component calibration
- Shot regularisation
- 4D FWM imaging

Figure 1 shows the 50 Hz 4D UFT FWM images for the baseline and monitor surveys generated from hydrophone-only data. These images were produced using 145 OBNs distributed along five receiver lines, with sea-surface multiples providing additional target illumination. Figure 2 compares the 4D difference volumes obtained with the 2×3D FWM workflow (left) and the dedicated 4D FWM workflow (right). The specific 4D deconvolution imaging formulation significantly reduces 4D noise, particularly in the overburden, by mitigating the effects of water-column variation, environmental changes, cross-talks and source-term discrepancies. The improvement in the 4D signal is mainly driven by hydrophone calibration and by suppressing non-repeatable terms in the imaging algorithm.

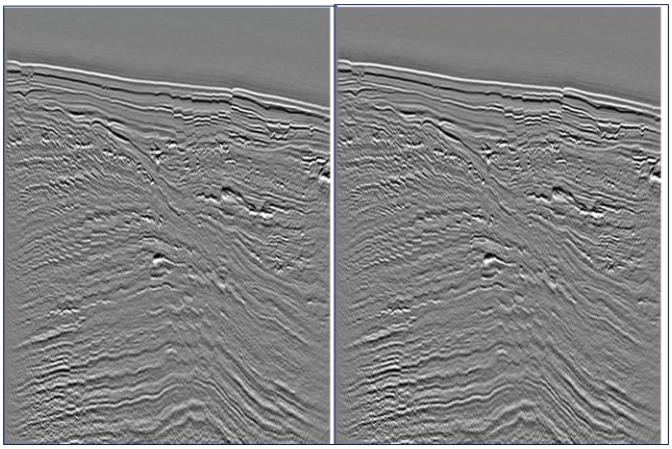


Figure 1: Base and Monitor UFT FWM images

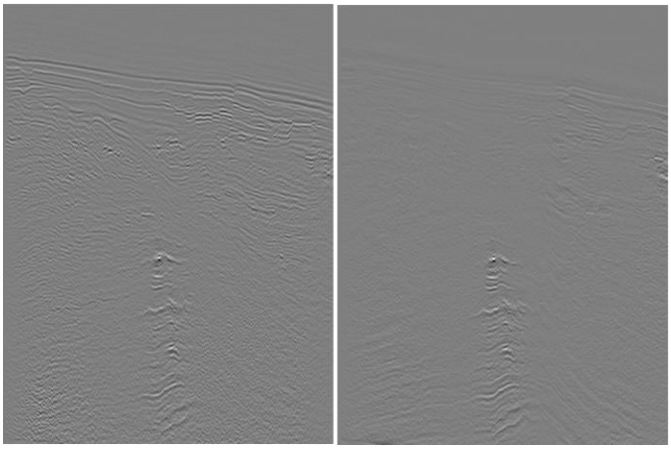


Figure 2: UFT 4D differences: 2x3D FWM (left) and 4D FWM (rigth)

OBN Decimation study

Using the ultra-fast track 4D FWM approach, we extended the analysis by further reducing the number of OBNs contributing to the 4D image. This decimation scheme uses only 45 OBNs distributed across three receiver lines, with sensor spacing increased to a sparse 600 × 692 m grid. Figure 3 compares the 4D FWM imaging results for two sensor decimation levels (45 and 145 OBNs) with the fully processed 50 Hz mirror KPSDM result.

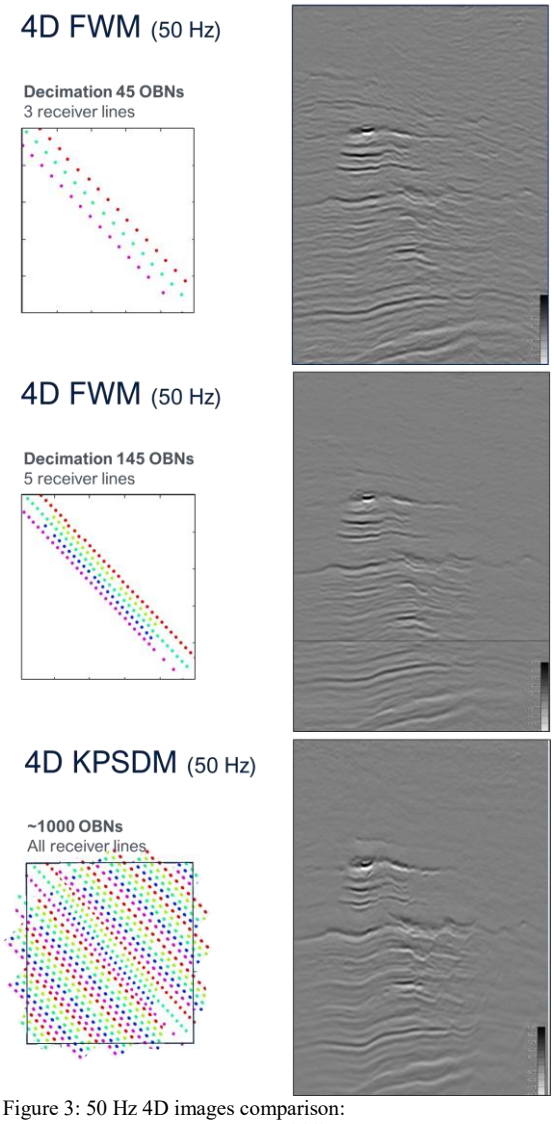


Figure 3: 50 Hz 4D images comparison:
Top, UFT 4D FWM 45 OBNs, Middle, UFT 4D FWM 145 OBNs, Bottom, Full processing mirror KPSDM ~1000 OBNs

Comparison with the fully processed 4D KPSDM result using P-down data confirms that 4D FWM can recover a valid 4D signal using only 145 hydrophone-only OBNs. However, the 45 OBNs decimation introduces too much 4D noise to yield an interpretable product. At this level of decimation, using processed P-down data as input to 4D FWM would likely help reduce P-up wavefield leakage in the 4D image.

Conclusion

We examine how Full Wavefield Migration (FWM) can be applied to a deepwater 4D OBN monitoring in deepwater reservoirs. The study investigates whether OBN acquisition can be optimized by deploying fewer nodes and shortening the turnaround for an early 4D image with an acceptable interpretability of the 4D signal. Although conventional deepwater OBN layouts use thousands of nodes spaced at about 350 m, our results show that 4D FWM can relax constraints on sensor density and support sparser geometries.
We also show that 4D FWM can reduce pre-imaging effort by using hydrophone-only data, enabling delivery of a reliable ultra-fast-track 4D product within 3–5 weeks.
We also tested a further reduction to 45 OBNs across three receiver lines with wider sensor spacing (600 × 692 m). While 145 OBNs produced suitable 4D signal, the 45 OBNs layout generated too much 4D noise to remain interpretable and extra processing steps may be recommended for such decimation.
Delivering a reliable early 4D seismic product within weeks after the final acquisition shot can add significant value to the overall 4D workflow. An early 4D result may reveal subsurface integrity issues, indicates potential infill drilling targets, or highlight unexpected production-related 4D signals. This rapid feedback can improve decision-making and strengthen subsequent 4D analysis and interpretation.

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