Time-lapse FWI to improve understanding of superimposed reservoirs in deep offshore

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Summary

Superimposed reservoirs are common in oil and gas production, but they are challenging to monitor with time-lapse seismic imaging. A common seismic attribute used for assessing reservoir evolution during production is the time-shift measurement which is obtained comparing two 3D seismic images. In the case of superimposed reservoirs, computing these time-shifts becomes challenging due to the change at the top reservoir that affects measurements at the lower one. Directly computing the wave propagation velocity variation between the time-lapse seismic data is an alternative solution. These obtained velocities need to reach a sufficiently high frequency to ensure a vertical resolution to correctly separate the reservoirs.

On two offshore West-African case-studies, we illustrate how 4D FWI workflow can finely separate superimposed reservoirs, by providing high resolution velocity variations along the monitoring time. The first case study consists of short offset towed streamer acquisition where the challenge of missing low frequency and diving wave penetration is undertaken by a combination of 4D tomography and 4D FWI. For the second case study, long offset node records mean that only the 4D FWI is needed. This time saving allows for prompt delivery of the velocity variation with time without requiring a complex time-lapse processing beforehand.

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Introduction

In offshore West Africa, it is common to find complex geological structures where one producing reservoir is situated above another. To improve production and mitigate risks, field operators monitor these reservoirs with various methods, most notably the use of 4D seismic surveys. By acquiring and imaging 3D seismic data at two different time periods, it is possible to assess how fluids are evolving inside the reservoir. Conventional 4D seismic approaches rely on jointly processing the base and monitor data using a similar processing sequence and computing a difference between the obtained images (Nguyen et al., 2015). This difference allows capturing subsurface property changes between these two periods, such as pressure and saturation. However, these changes are not directly retrieved. Indeed, the variations in amplitude and in depth between these two images can be used as proxies of change in the physical properties of the strata and hence further inversions are necessary to recover the property changes. In this standard workflow, the time shift (*dt*) between two surveys is the proxy for estimating the small change in velocity of the seismic wave propagation (*dv*). This conversion between *dt* and *dv* becomes difficult in the case of superimposed reservoirs as the time-shifts generated by the top reservoir might have an imprint on the one below. With standard *dt* measurement methods based on cross-correlation, the window of this correlation should be small enough to capture the 4D effects of each individual reservoir, while also large enough to provide a stable measurement. Different methods of *dt* computation have been developed to overcome this issue (MacBeth et al., 2020) but they mostly rely on a 1D assumption which could be too simple in case of complex structured geology.

Directly computing the velocity variation between the surveys is an alternative solution, but it needs to ensure that the resolution of the obtained independent velocity models is high enough to accurately separate the superimposed reservoirs. With the advancements in hardware and inversion algorithms, full waveform inversion (FWI) can now reach a spatial resolution of the velocity model close to the temporal resolution limit of the recorded seismic data (Wei et al., 2021), hence FWI could be a viable solution to solve this problem. Various successful FWI based approaches have been proposed (e.g., Hicks et al., 2016) but so far few showed a resolution high enough to properly distinguish superimposed reservoirs.

The objective of this study is to take advantage of the high resolution of the FWI for a better vertical separation of superimposed reservoirs and to eliminate the imprint of the upper reservoir on the lower one. In this paper, we demonstrate how FWI at 50Hz on towed streamer data and at 40Hz on ocean-bottom-nodes (OBN) data is a practical solution to directly recover the *dv* from the raw seismic data.

Data preparation for time-lapse FWI

Using time-lapse FWI to recover velocity for both base and monitor data has the advantage of starting from the raw recorded data, avoiding any possible bias introduced by seismic processing. By starting at an early stage, time-lapse FWI can provide velocity variations at the same time as conventional fast-track products. Despite starting from raw data, the recorded seismic still needs to be corrected from environmental (water layer) and acquisition changes in order to reduce the discrepancy between the two surveys. First, we addressed the source and receiver positioning differences since any positioning difference could be interpreted as a velocity variation between base and monitor. We applied the water layer inversion (Dega et al., 2021) to correct for shot positioning and water column variations in velocity and height. Once base and monitor are at the common reference, we corrected errors in receiver positions by minimizing the difference between the theoretical and measured direct arrival time. The second type of corrections deals with the emitted source wavelet variation. Even if gun arrays are designed to give a very high repeatability, minor changes lead to frequency and phase distortions or bubble alteration. To compensate for this uncertainty in the signature, we extracted a signature for each dataset using a data-driven inversion approach. We finally applied a 4D static binning to harmonize offset distribution and fold between the surveys. While the application of a matching filter is common in conventional 4D time processing, we did not apply any matching between base and monitor nor include extra constraint in the cost function.

Short offset towed streamer 4D FWI

The first case study is located in deep offshore West Africa, with a base and monitor acquired 15 years apart. To monitor the reservoir, 3D towed streamer acquisition, with relatively small maximum offset, 2.7km, was used. Unfortunately, in this scenario, diving waves could not even reach the shallowest reservoir. Moreover, because of the lack of low frequency information (lowest useful frequency is 5Hz), 3D tomography on the base data was used to obtain an initial model. When starting the 4D FWI with this common initial model, the inversion was not able to converge and strong ringing around the reservoir was observed (Figure 1B). Indeed, the monitor modelled shots were cycle skipped at the starting FWI frequency. By minimizing the offset dependent differences, seen on the PreSDM gathers, between the base and monitor migrated with the same model, the 4D tomography allowed to estimate a low-resolution *dv* (Figure 1A) which is crucial to highlight changes in the reservoir. After adding this initial *dv* into the initial velocity model of the monitor, the 4D FWI low-frequency update was stable (Figure 1C). FWI update was pushed to 50Hz, and the 4D FWI results (Figures 1F and 1G) showed a good horizontal and vertical resolution. Softening and hardening of the layers are well visible, and even if the 4D tomography *dv* used in the monitor's initial model was not well delineating the lower reservoir (Figure 1D), FWI was still able to recover the *dv* of the superimposed reservoirs (black arrows in Figure 1F).

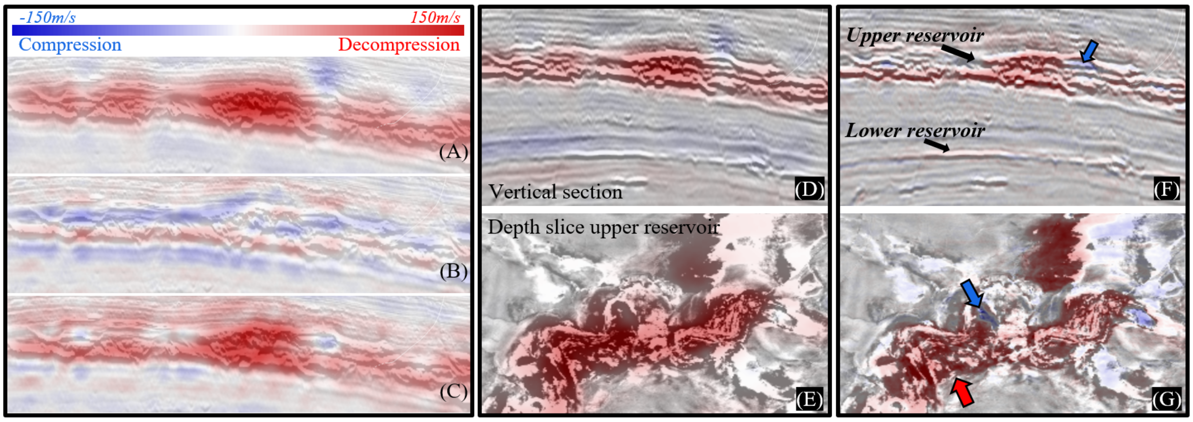

***Figure 1**: Section displays around the upper reservoir: (A) dv from 4D tomography, (B) dv from 4D FWI at 12Hz using a unique initial velocity and (C) dv from 4D FWI at 12Hz using the 4D tomography dv for the monitor initial velocity. Vertical section and depth slice of the dv from the 4D tomography (D and E) and from the 4D FWI (F and G) at 50Hz.*

Fully data driven OBN 4D FWI

The second case study consists of two OBN surveys acquired 4 years apart, over a deep offshore West Africa reservoir. Receiver lines were deployed every 300m and receiver stations every 346m on top of the reservoir (core area). For this study, five receiver lines were selected inside the core area as well as the entire shot carpet which allows a maximum offset of 15km.

When shots are modelled using the legacy velocity model obtained by diving-wave FWI (Figure 2A) and are overlaid on the observed shots, a good match of the diving-wave energy is seen but a mismatch in the reflections, indicated by red arrows, is also visible (Figure 2C). While diving-wave FWI allows to stabilize the low frequency inversion, by including the full wave-field from the beginning of the inversion leads to matching of both diving and reflection energy (Figure 2D). Having achieved a good shot matching of the base dataset at low frequency, we increased the FWI maximum frequency to 40Hz and generate the high-resolution velocity model shown in Figure 2B. This highlights the resolution obtained when using reflections and the benefits for 4D FWI especially when delineating superimposed reservoirs.

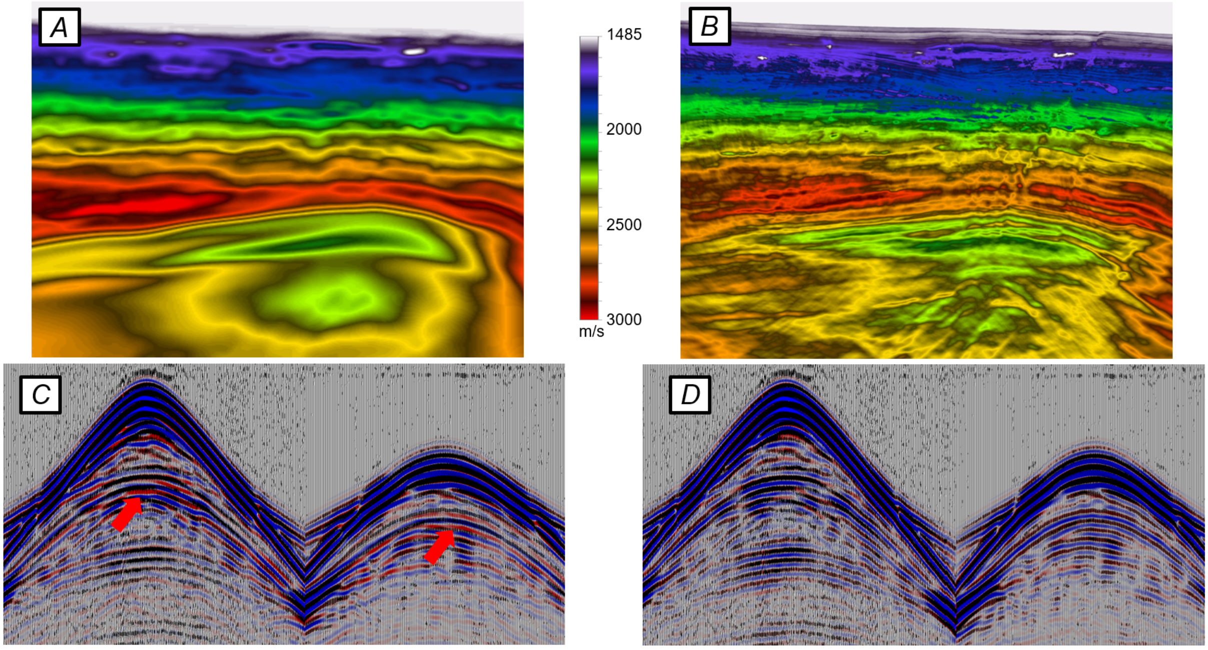

Figure 2: 3D FWI legacy velocity model (A) obtained from diving-wave FWI, and (C) the corresponding overlay between observed data (wiggle) and modelled data (red/blue): red arrows show the mismatch in the reflections. (B) Velocity model obtained using the full wavefield in the FWI, and (D) the corresponding observed/modelled data overlay, with most of the events being correctly modelled. In the overlays, blue is negative and should fit the wiggle trough, while red is positive and should match the wiggle peak.

Our 4D FWI workflow is very similar to the one described in the previous section, but for this example, we used the same initial model for both base and monitor data, without any 4D tomography update because OBN acquisitions provide inherently very low frequency signal which can better tolerate the errors in both initial models. Recording very long offsets provides a full penetration of diving waves at the reservoir level bringing additional stability to the FWI. In this case, we used a smoothed version of the legacy model as initial model of the time-lapse FWI for both the base and monitor datasets.

In parallel to the time-lapse FWI, data were also processed through a fast-track flow and imaged using reverse-time migration (RTM). The 4D difference seismic section was extracted (Figure 3A) and compared to the obtained *dv* (Figure 3B): thanks to high resolution provided by the reflections, velocity variations clearly show three superimposed reservoirs with limited 4D noise. Depth slices were extracted at the top (red, in Figure 3C) and middle (green, in Figure 3E) reservoirs. From the 4D FWI *dv* in Figures 3D and 3F, reservoirs appear spatially separated and their amplitudes correspond to changes in the reservoir: yellow for compression, which is associated with the injection phase and blue for decompression, related to production.

The 4D seismic image obtained using a single velocity RTM migration in Figure 4A is contaminated by kinematic noise beneath the top reservoir due to the uncounted 4D velocity change in the top reservoir. Instead, when migrating each dataset with its own velocity model (Figure 4B), the 4D leakage is reduced and the identification of the superimposed reservoirs is considerably improved. Including the estimated *dv* (Figure 4C) in the imaging allows a better separation between 4D information driven by amplitude changes rather than velocity variations.

Conclusions

Even if superimposed reservoirs are complex geological fields, time-lapse FWI was able to correctly recover the velocity variation with time both in case of short offset towed streamer and with long offset and wide azimuth OBN. The conventional 4D processing and imaging workflow only provides time shifts which cannot fully align events or focus the amplitudes correctly in the 4D image in the case of superimposed reservoirs. As demonstrated in this paper, migrating base and monitor with their own velocity models enables to reduce the crosstalk between amplitude and velocity variations: the obtained 4D difference can be directly used for elastic inversion.

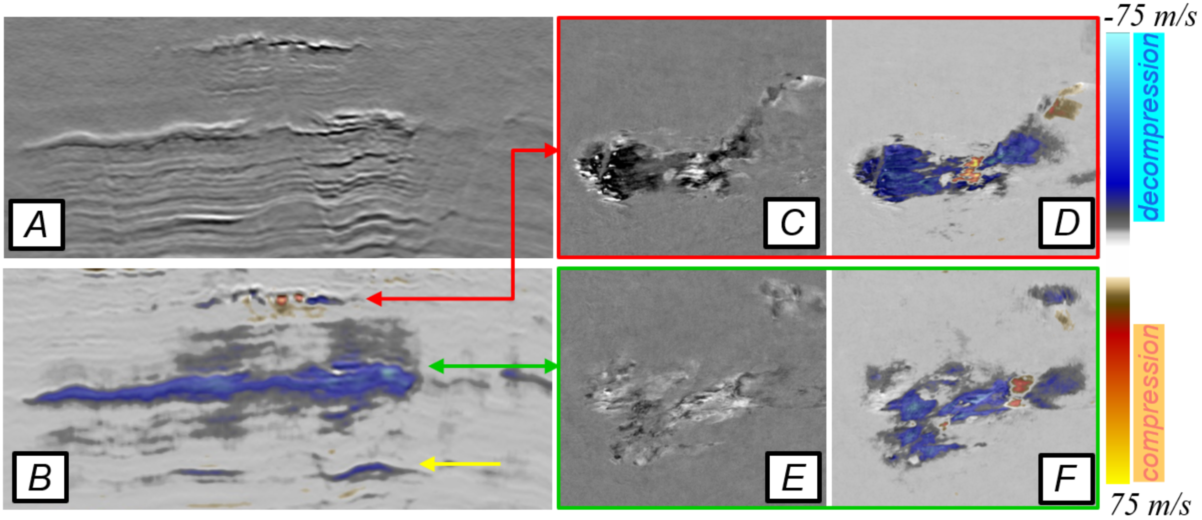

***Figure 3**: Vertical section of 4D seismic difference (A) compared with velocity variation dv (B). One depth slice extracted at the shallowest reservoir for the 4D seismic difference (C) and dv (D), and another extracted at the middle reservoir for 4D seismic difference (E) and dv (F).*

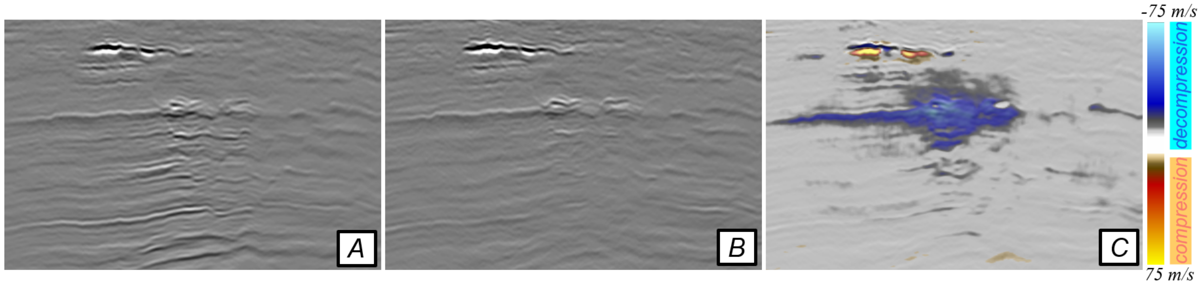

***Figure 4**: 4D seismic vertical section views of (A) RTM migrated with single velocity of the (base) and (B) RTM migrated with separate FWI velocities. (C) shows the RTM with the overlay of 4D FWI velocity difference.*

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