Time-Lapse FWI for North Sea deep Culzean reservoir monitoring

I. ESPIN[1], N. SALAUN[1], A. PINTUS[1], A. WRIGHT[1]

[1] CGG

Summary

The Culzean field, in the North Sea, has been producing since 2019 gas condensate from fluvial sandstones located within dipping rotated fault blocks at approximately 4km of depth. Two surveys have been acquired with ocean bottom sensors to image and then monitor the evolution of the reservoir during production. In addition to classical time-lapse seismic processing, a time-lapse FWI has been performed to estimate the velocity variation over the production time. Due to the thick chalk layer located just above the target structure and the dipping nature of the reservoir, 4D FWI is the ideal tool compared to more conventional 1D approach based on time-shift estimations. This fast velocity layer represents a challenge for velocity model building and processing in general as it prevents the penetration of diving waves even with 7km of offset and also generates strong multiple curtains covering the reservoir interval. Despite the shallow water environment and complex geology, the 4D FWI implemented in this project was able to recover velocity variations as weak as 1% after only 3 years of production, providing crucial information that can help reservoir evolution assessment.

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Introduction

Time-lapse seismic is an essential tool to monitor and optimize reservoir production or control gas storage. Through this methodology, several 4D attributes can be extracted to identify and characterize property changes in the reservoir (Lumley, 2001) and to improve the resource recovery while mitigating possible risks related to hydrocarbon extraction. Among these parameters, the velocity variation (*dv*) indicates the change with time of the wave propagation velocity inside the medium. This information is critical to estimate fluid changes or compaction/extension effects inside the reservoir and in its surroundings (Ribeiro and MacBeth, 2006). The *dv* parameter can be retrieved by inversion using the time-shift (*dt*) between two seismic datasets. To obtain *dt*, the cross-correlation is the most common method. However, not only does the extraction of these timeshifts contain uncertainties based on the size of the cross-correlation window (Ji et al., 2021), but it also has the disadvantage of being a one-dimensional variable, which is a simplified approximation in cases of complex geology.
While the development of full waveform inversion (FWI) is used to update the propagation velocity of the seismic wave, time-lapse or 4D FWI was introduced to recover *dv* (Routh et al., 2012; Hicks et al., 2016). By using data with limited preprocessing and considering the full wavefield, time lapse or 4D FWI is an ideal tool to derive velocity variations with monitoring time. It enables direct measurement of the variations of physical properties, with a shorter timeline than conventional 4D-processing, offering earlier information on reservoir evolution. FWI challenges, such as cycle skipping or multi-parameter crosstalk, are similar to the 3D case, but inaccuracy in source wavelet estimation or acquisition device positioning has a crucial impact on time-lapse FWI. Recent advances in FWI (Zhang et al., 2018) has allowed taking advantage of the reflected waves, enabling velocity model update beyond the maximum illumination depth of the diving waves, hence opening the way for 4D FWI to be used for deep reservoirs (Li et al., 2021), particularly in complex geological settings (Bortoni et al., 2021). In this paper, we describe how we implemented 4D FWI to recover velocity variations as weak as 1% after 3 years of production. The target is a dipping reservoir located below a thick chalk layer where only reflection energy is available to update the velocity model.

Field overview

The Culzean field is located in Block 22/25a in the East Central Graben of the UK Central North Sea (Figure 1a) and it represents one of the largest UKCS hydrocarbon discoveries in the last 15 years.

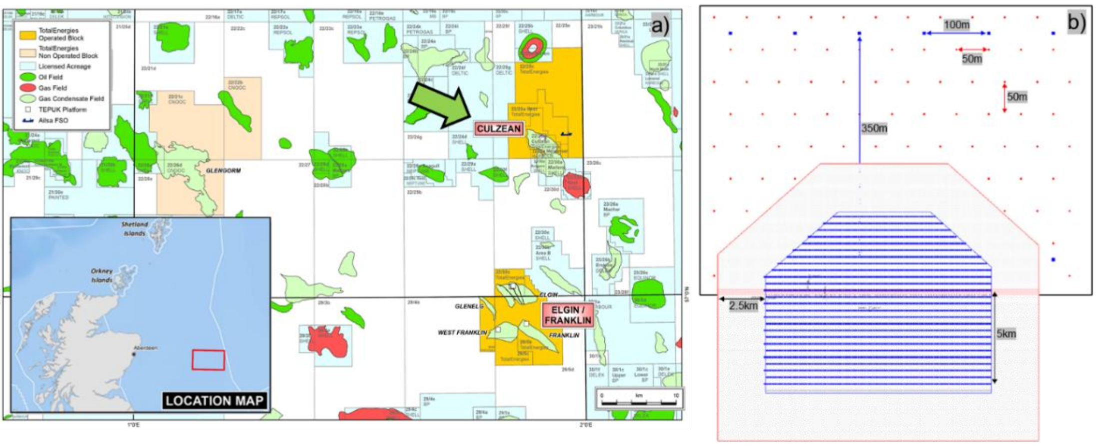

Figure 1: *Culzean field location (a) and acquisition layout of the monitor 2022 data (b), where red and blue points represent shot (50m x 50m grid) and receiver locations (100m x 350m grid), respectively.*

This field, discovered in 2008, has produced gas condensate from high pressure, high temperature reservoirs since 2019. These reservoirs correspond to fluvial sandstones of Triassic and Jurassic age located within easterly dipping rotated fault blocks at approximately 4km depth. The sub-chalk setting of this field is the main challenge for the seismic imaging and therefore for the monitoring of these reservoirs. To properly image this field, an ocean bottom cable (OBC) survey was acquired in 2010 and then completed with a second acquisition in 2011. This acquisition used a cable separation of 350m, a receiver spacing of 25m and carpet shot grid of 50m. To monitor the 4D response of the reservoir and overburden caused by the production of the reservoir, an ocean bottom node (OBN) acquisition was performed in 2022. This acquisition has 100m in-line receiver spacing, receiver line spacing of 350m and a shot carpet of 50m x 50m source spacing (Figure 1b).

Time-Lapse FWI

Due to the strongly dipping nature of the reservoir, in addition to a conventional 4D processing, a time-lapse FWI was applied to identify and quantify the evolution of the reservoir. First, a 3D FWI was run starting from a smoothed version of diving-wave FWI legacy model (Figure 2a) with the aim of creating an initial model for the 4D FWI. Inversion was run down to a depth of 10km using the baseline OBC dataset after minimal preprocessing. Even including the full-offset range of 7km in the inversion, the diving wave penetration is limited to 3km of depth. This limit corresponds to the top of the chalk level, which exhibits a strong velocity contrast compared to the sediment layers above and below it, trapping the diving waves. The deeper update, which includes the reservoir, can therefore only rely on reflection energy (primary and multiple). The high impedance contrast at the top and base chalk generates a strong multiple curtain which is one of the challenges for the conventional 4D processing sequence. However, by properly modelling the water layer velocity (Dega et al., 2021) and the contrast at the water bottom, FWI can model the multiples and benefit from extra illumination and information at the reservoir. Figure 2b illustrates the resulting velocity field, showing homogeneity along the chalk layer, and catching well the strong velocity increase at the top and velocity inversion at the base (Figure 2c). Analyzing in detail the reservoir level (Figure 2d), local slowdowns of velocity could be related to fluids trapped at the upper part of the reservoir. This result confirms the effectiveness of our implementation of FWI even in such a complex geological setting.

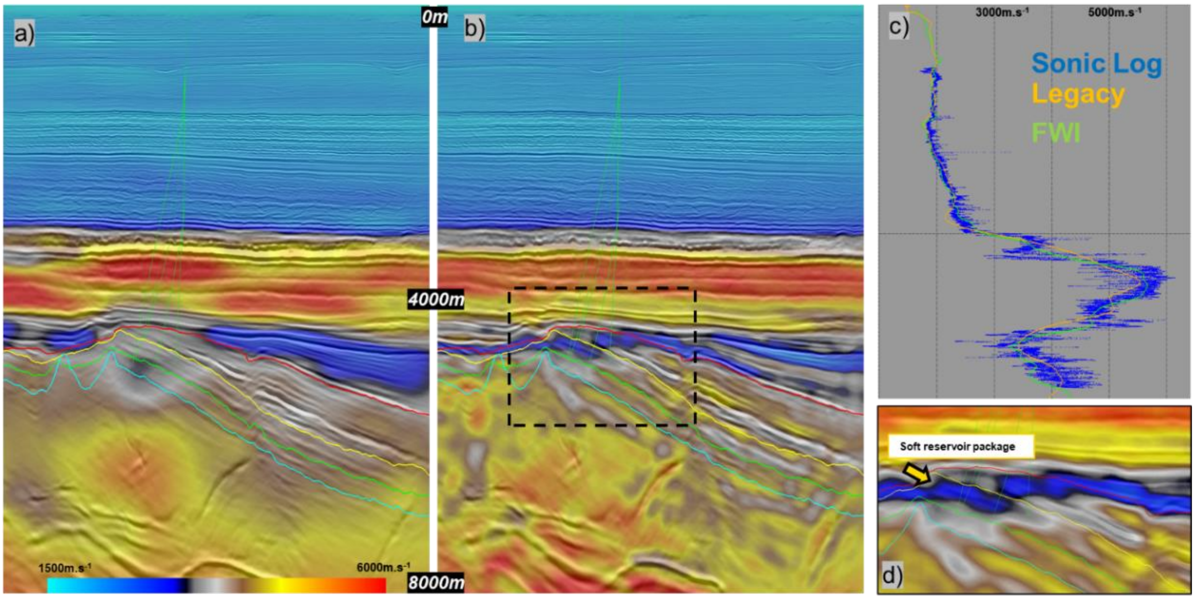

Figure 2: 3D FWI velocity update. Legacy model (a), 3D FWI result (initial model for 4D FWI) (b), comparison of Vp profiles vs sonic well log (c), 3D FWI zoom at the reservoir (d).

The initial model of 4D FWI was a smoothed version of this model. The time-lapse FWI flow consisted of running two independent FWI, one for the base and one for the monitor, both with the same parameterization. Subsidence at the sea floor has been well documented at the neighbouring Elgin field, and even after only 3 years of production, it was of interest to obtain dv in the full section to check for effects in the overburden. Thus, 4D FWI was run without any mask or 4D constraints.

For 3D FWI, minimum pre-processing was applied to the data to avoid any discrepancy linked to the denoising steps. However, two steps are critical to ensure time-lapse FWI success. The first one is to correct for the source and receiver device locations. Mild uncertainty on these parameters will result in velocity artefacts between the base and the monitor. Water layer inversion was used to rectify the shot locations and mitigate the uncertainties associated with the source barycentre. This method also allows the correction of variation in the water column velocity and height, enabling a common reference between the two surveys for the water layer. The direct arrival cone was used to reposition the receiver devices. The second key parameter is the variation of the source signature between the two surveys. Even if the source is designed to be repeatable, small changes in gun volume, position and parametrization inside the array will change the frequency content, phase, and bubble of the source signature. To correct for these variations, wavelets were extracted through inversion for each dataset. This method was selected over the use of near-field hydrophones (NFH) to estimate the far-field, as no reliable record of NFH was available for the 2010 data. In addition to these corrections, a 4D static binning was applied to guarantee an equal offset range and fold between the two datasets. These corrections are purely deterministic, no matching filters were necessary and the time-lapse FWI was started a few days after receiving the last shot point of the monitor survey.

Results

With the two intermediate velocity fields obtained in the same time frame as the ultra-fast-track processing, the *dv* at 10Hz from 4D FWI can be computed by a straight subtraction. The normalized delta velocity (*dv/v)* is calculated as $dv/v = (v_{P,monitor} - v_{P,base})/v_{P,base}$ and shows the percentage of velocity variation with time. Figures 3a and 3b show results along a section through the reservoir structure. Even at 10Hz, the *dv/v* (Figure 3b) is well delineated between the various reservoirs horizons and shows compaction (blue) and extension (yellow) of the reservoir as consequence of production. The clear decompression, represented by a negative value of about 3% of *dv/v*, is observed at the Joanne top reservoir level (yellow line), as expected by the reservoir engineer. Extension between the Juddy and Smith horizons is also observed (black arrow).

As a QC of the obtained velocities, 4D seismic difference were computed after 4D binning and RTM stack migration, without any post-processing, using decimated node data after ultra-fast-track processing. These results, shown in Figure 3c and 3d, illustrate how the 4D signal associated with timeshifts (not amplitude variations) is reduced when using different velocities for base and monitor (3d) rather than using a unique velocity for the two migrations (3c). This confirms the quality of the obtained 4D velocities and enables better separation of 4D information coming from amplitude variations than the ones coming from *dv* and *dz*.

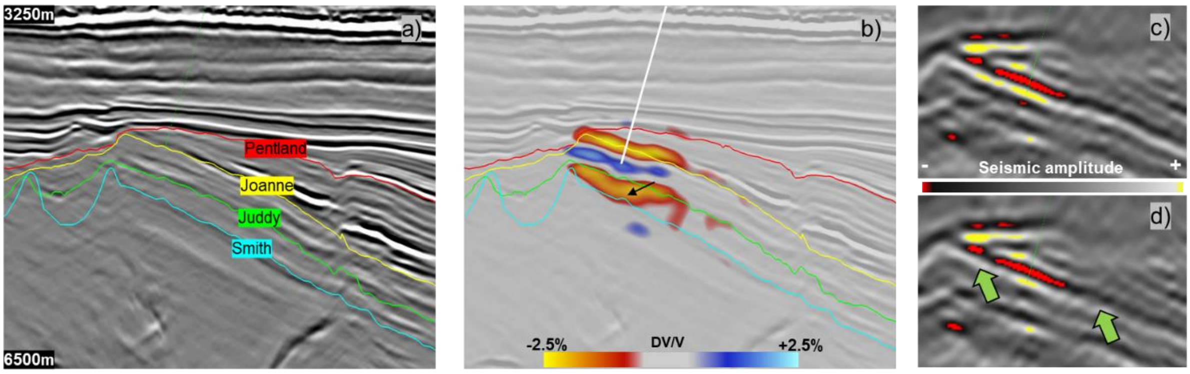

Figure 3: Section view of RTM migration with formation tops annotated (3a), *dv/v* (3b) and RTM 4D seismic difference obtained from single velocity (3c) or dual velocity (3d) overlaid with maximum amplitude display (red and yellow).

Figure 4 shows the RMS of the *dv/v* attribute at the Top Reservoir and in the Joanne reservoir interval, revealing the reservoir outline. These maps show the compartmentalization associated with well-known faulting from the relaxation of the top reservoir. Inside the reservoir, the strong compaction (positive *dv/v)* fits very well with production well data and is close to zero in the background, ensuring the good repeatability of the obtained velocity fields.

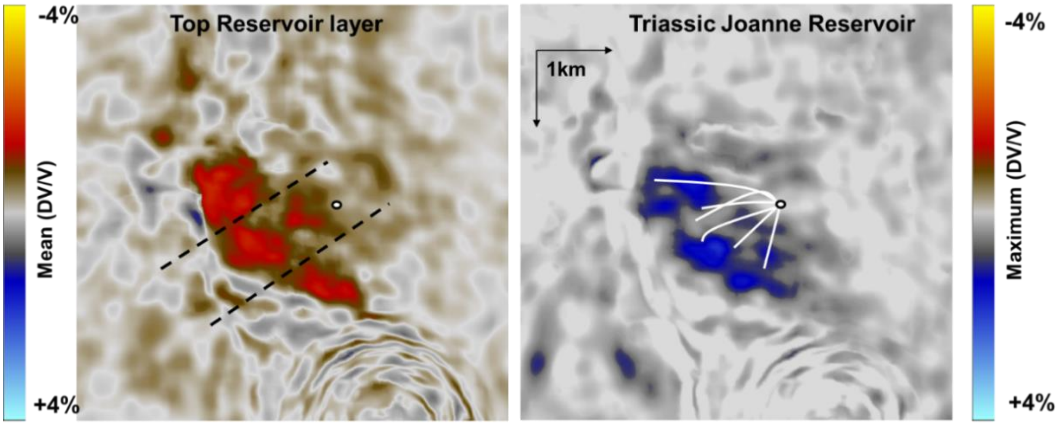

Figure 4: *Extracted average RMS of the dv/v attribute at the Top reservoir and Top Joanne. Main faults shown by black dashed lines and production well paths shown in white.*

Conclusions

Over the Culzean field, characterized by a shallow water bottom and a deep sub-chalk dipping reservoir, time-lapse FWI was able to detect velocity variations of 3%, and as small as 1%, inside the reservoir and in the over and under-burden. Observed *dv/v* exhibits the expected compaction of the reservoir and the related extension of surrounding geological layers. While conventional 4D processing would need an extensive de-multiple sequence to separate the 4D signal from the noise in the reservoir, located just below a hard chalk layer, the 4D FWI takes advantage of the full wavefield to recover the velocity variation with time. When extracting the *dv/v* at the reservoir layer, clear reservoir compartmentalization was observed in agreement with observed production data and well-known faulting. By using independent velocity fields for the base and monitor during depth migration, elastic inversion can be carried out without suffering from crosstalk between amplitude and time shifts.

The demonstrated quality of the obtained *dv* using the raw recorded full wavefield data can lead to faster and possibly more frequent reservoir monitoring using sparser receiver design. In future 4D monitoring studies, the use of elastic FWI could mitigate possible converted wave energy crosstalk at the chalk level and provide additional information about the reservoir evolution.

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