Early warning ultra-light marine seismic 4D time-lapse detection system

Introduction

The Edvard Grieg field is located 180km offshore the west coast of Norway. The field was discovered back in 2007 and production came on stream in 2015. Oil production is around 90 to 100.000 bbl per day through 13 horizontal production wells. Reservoir pressure support is maintained from 4 active injection wells. Regular full-field 4D OBC seismic campaigns have been repeated four times to monitor fluid flow and production effects in the reservoir. The extensive amount of high-quality seismic data has provided a precise understanding of the dynamics of the reservoir and has so far supported two drilling infill campaigns on the field.

Edvard Grieg is now a mature field and supporting frequent full field 4D seismic campaigns could become less economically viable. An innovative light and focused 4D seismic monitoring approach was thus introduced and tested. It consists of detecting changes in a specific area of the subsurface using a few optimally placed source and receiver pairs. 4D seismic changes in the reservoir can be tracked in the non-migrated domain by comparing the resulting processed traces acquired at different times.

This method has already been developed and demonstrated onshore for SAGD & CCS, and the main objective of this study was to adapt it to offshore challenges and show its robustness by detecting the water-front sweep in the reservoir. The end goal is to offer an affordable solution to complement and help trigger or space out larger 4D campaigns over a dynamically changing reservoir.

Ultra-light 4D monitoring system

Performing a full-field 4D time-lapse survey is a time-consuming and often quite costly operation. Following several repeat surveys (usually 3 to 4) and with a good simulation model, it is possible to predict the behaviour of fluid movement in the reservoir.
Using this knowledge, one could set up a much smaller and lighter monitoring system with trigger points, where specific locations in the reservoir are monitored for change, but preferably more often than just the typical 2- or 3-year interval for time-lapse 4D surveys.
The idea would be to select "spots" in and around the reservoir zone, which can act as early warning signs of certain wanted or unwanted fluid movements. Based on analysis of a limited number of locations, a more costly full-field or larger time-lapse study could be activated. Figure 1 illustrates how such an ultra-light monitoring system can be set up in an offshore environment with a lighter vessel, a small source (~500 in^3) and a handful of receivers. Selected target spots can then be monitored frequently at a fraction of the cost compared to a full-field time-lapse survey implementation.

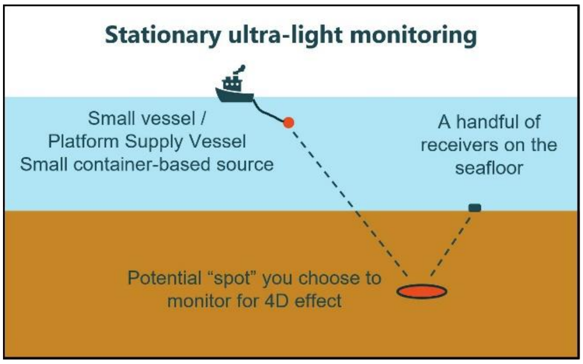

Figure 1 *Illustration of how the ultra-light monitoring system can be set up in an offshore environment.*

The Edvard Grieg case

For the Edvard Grieg field, four full-field time-lapse OBS surveys have been performed in 2016, 2018, 2020 and 2022. They have all been actively used to update and build a very detailed simulation model for proper history matching and forward modelling of field performance. Figure 2 shows the 4D response (NRMS difference) between various years in the reservoir. From the cumulative 2022-2016 difference (Figure 1c) it is clear that larger parts of the reservoir are now waterflooded by injection and as such, continuing to perform full-field 4D surveys may not be as useful as before. They could probably be made smaller or as we are proposing in this case, substituted with several key "spots" to monitor.

Looking at the 6-year cumulative difference, it is clear that certain small areas could be used as activation points for a new survey, by selecting a limited number of detection points that would require further investigation if the detected 4D effect was differing from the model. 6 such “trigger-spots” are proposed in Figure 1c, marked as blue stars.

To assess the feasibility of the focused seismic methods, this paper will focus on two initial “validation spots”, one in a zone affected by 4D changes and one in a zone that didn’t change between 2016 and 2018. These are marked as red stars in Figure 2b and will be used to validate the results.

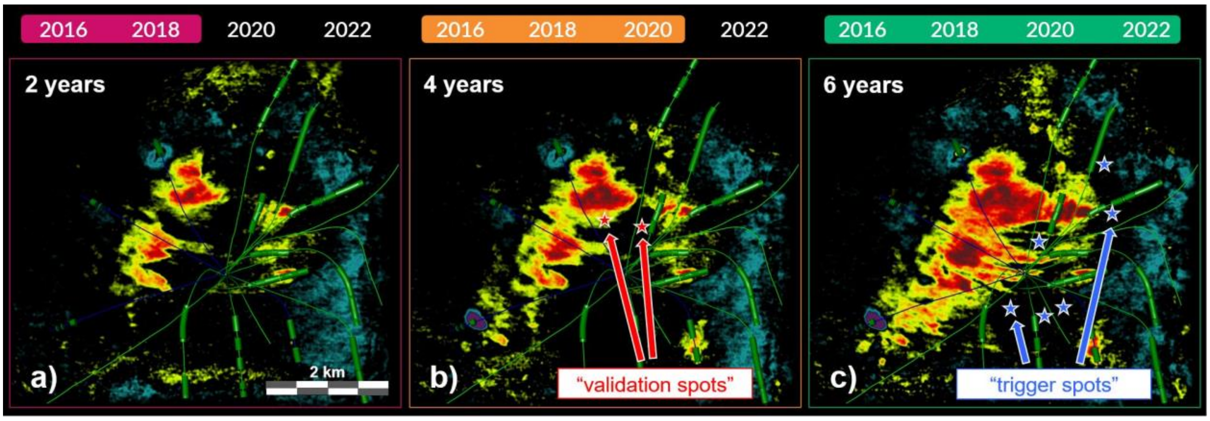

Figure 2 *4D cumulative NRMS change across the Edvard Grieg field for 2, 4 and 6 years of production and injection. Red stars mark the location for the two “spots” used to validate the method. Blue stars indicate possible future “trigger spots”.*

The regular OBS surveys done across the field are based on a source grid of 25x50m and a receiver grid of 25x200m, which provides a very dense full-azimuth coverage. An advanced survey design phase has been implemented to reduce this down to only a few receivers and a handful of source locations (see Morgan et al., 2020 and Brun et al., 2021), that could be repeated often for a fraction of the cost of a full 4D survey. In this study we have used the full legacy input data along with the velocity model to demigrate all the data. This then forms the basis to select areas with and without 4D effect to determine which source and receiver combinations can be used to detect 4D signal at the target level. This is then followed by another selection step to determine the optimum pairs for each given spot.

Processing sequence

For offshore multicomponent acquisitions (OBC in this case), the usual go-to methods to correct and attenuate most coherent noises are P-Z summation and up-down deconvolution (see, for example, Soubaras 1996). While those methods have proven their reliability, the particulars of processing very few traces for a no-imaging detection have led to preferring a hydrophone-only processing sequence to try and preserve as much as possible the optimum traces repeatability (as geophones tend to have a greater variance in signal-to-noise ratio due to coupling).

The method used is adapted from antenna processing techniques and is made possible by the optimum selection process (performed during the survey design phase) which provides among other things the reflected signal’s slopes at source- and receiver- positions for the optimal traces. When considering several adjacent receivers over a short offset range, a reflected seismic event can be approximated to a flat dipping plane (except at and around the apex of the reflexion hyperbola). By knowing the direction and incidence angle at which the signal is emitted and recorded, a 3D f-x filter can be created to filter out most of the recorded noise.
This process is comparable to a F-K filter, in that it filters out seismic noise and events based on their apparent slopes. It is however not subject to boundary effects and allows to compensate for irregularities in the acquisition positions by interpolating the traces over a regularized grid.

Unlike the F-K filter, it takes into account the real, uneven source and receiver positions for each trace and does not assume the design to be evenly spaced on an infinite grid.

This process is applied separately to the reservoir level and to a reference horizon above (after a 10Hz low-cut filter attenuating the lower frequencies of the bubble) on the base (2016) and monitor (2018) traces. No additional debubbling is performed beyond the low-cut because the antenna processing should efficiently remove its higher frequencies without harming the signal, provided the bubble effect slope is different from that of the considered event. A Wiener operator is then computed over the reference horizons of both traces to match the monitor to the base, to ensure that any difference between the traces at reservoir level is indeed a reservoir effect and not coming from the overburden.

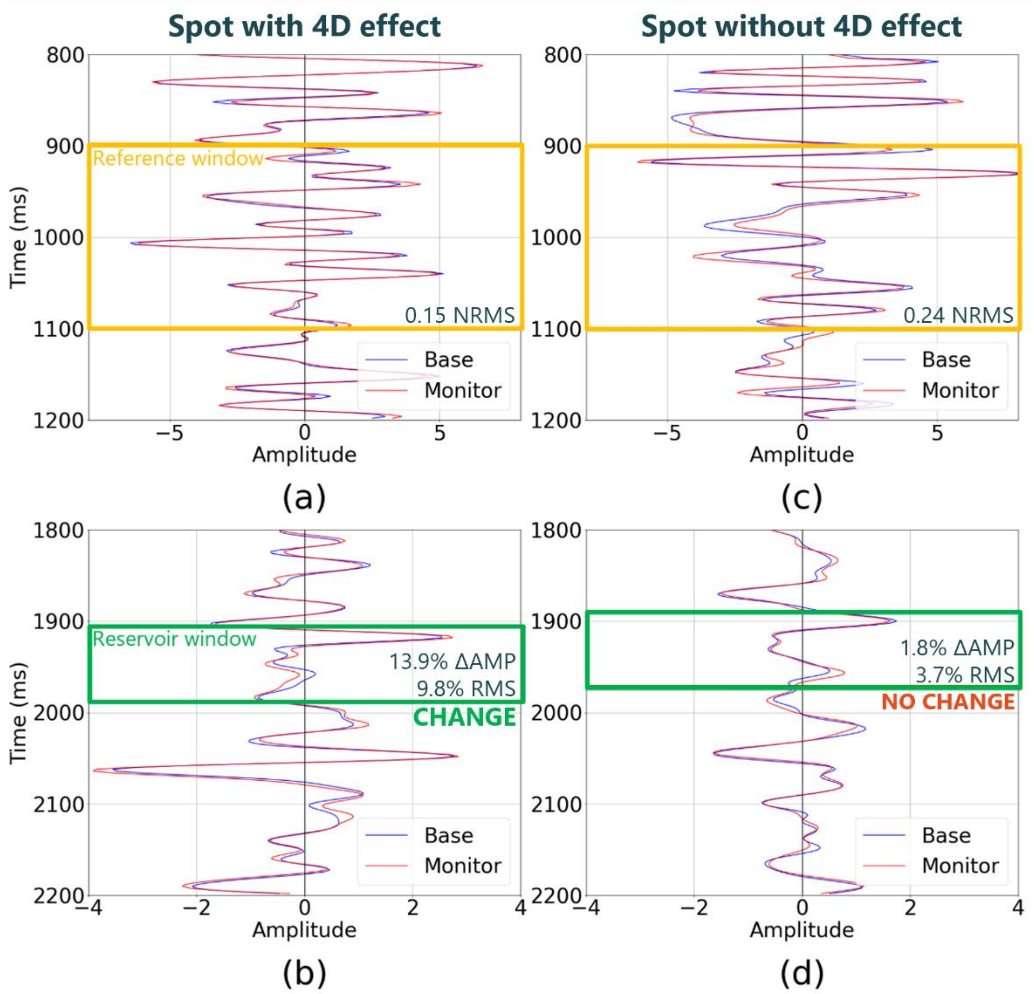

Figure 3 *Left: Overlay comparison of base and monitor corrected traces at reference (a) and reservoir (b) TWT for spot 1, in the 4D zone; the reference zone is highlighted in yellow, and the reservoir in green. Right: (c) and (d) show the same figures for spot 2, outside the 4D zone. Spot 1 shows amplitude variation at reservoir level while spot 2 does not.*

Figure 3 shows a single trace at two different intervals (reference and target) from two of the spots used to verify the method. Reference spot 1 shows good repeatability between base (2016) and monitor (2018) at 0.15 NRMS. Spot 2 is less repeatable, while still deemed acceptable when compared to typical NRMS values of offshore acquisitions (see Staples 2015), at 0.24 NRMS. This is mainly due to its longer offset, at 707m, compared to spot 1 at 257m. At reservoir level, spot 1 shows a clear change over the reservoir window, with a mean amplitude variation of 13.9% and an RMS of 9.8%. Spot 2 shows no significant change with 1.8% mean amplitude variation and 3.7% RMS.
These changes are in line with the 4D seismic results, as spot 1 is located in an area that has seen a 4D effect while spot 2 is in a zone with no measured reservoir change during the considered period.

This experience has been valuable in refining the optimum selection process, and further work on spots with lower offsets (further from the strong bubble artifacts) should yield better results. Work is also underway to include a proper debubbling step in the processing sequence for spots where no optimum fit the offset criteria and see how it affects the traces repeatability. The updated optimum selection and processing sequence will then be used for the 9 other spots.

Conclusions

In this paper we presented the results of the application of an innovative light seismic monitoring approach on the Edvard Grieg field offshore Norway. The approach aims to provide 4D information without requiring a full-field acquisition for each data point, instead using a previously acquired dataset to select optimal traces for the monitoring of specific areas in the subsurface. Those traces are then re-acquired and compared to one another to compute a localized 4D change.

In this case, the traces used for the detection were selected from 2016 and 2018 acquisitions, and two spots were chosen according to the 4D maps, one in a water flushed zone and one the water-front hasn't reached yet. After a survey design phase aiming at retrieving the most contributive ("optimal") traces for each spot and each vintage, a 3D f-x filter is applied to improve the signal-to-noise ratio over the reservoir window and a reference level above. The two traces are then matched over the reference level, to cancel out non-reservoir-induced 4D effects, and compared.

The resulting traces show a very good repeatability level and a detection in line with the 4D maps, showing that a single trace repeated two years later with the same acquisition design can indeed monitor the 4D change in the reservoir despite a perfectible survey design phase. A number of those spots could thus be regularly acquired to keep track of the water-front expansion at little cost, and help trigger 4D campaigns when they are truly needed in case unforeseen changes are detected in the reservoir.
A dedicated focused acquisition design could make use of a much lighter airgun source, repeated in a precise position to further increase the signal-to-noise ratio while being much easier to mobilize and deploy.

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