# Opportunistic 4D using a regional non-repeated 4D monitor, an Ærfugl case study

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## Introduction

It is not common practice to use multi-client datasets for a 4D monitoring project, as the 4D adage of 'repeating the acquisition geometry' is generally not satisfied.

Standard 4D time-lapse acquisitions require extra planning, specialised navigation equipment and strict repeatability constraints for sources and receivers. Multi-client surveys on the other hand are configured to cover extensive areas efficiently with relaxed positioning requirements. Combining both types of seismic surveys for a 4D project constitutes a technical challenge associated with uncertainties related to non-repeatability of the source and receiver positions.

In this case study, a multi-client dataset has been used opportunistically for monitoring the production of a gas field in the Norwegian Sea.

The Ærfugl field is approximately 60 km long and 2-3 km wide, with a stratigraphic pinch-out to the east (Figure 1). The field comprises a Cretaceous Lysing Formation reservoir of a partly confined turbidite system (Fugelli and Olsen, 2005; Hansen et al. 2021). A test producer P1 drilled in 2013 proved the presence of gas before the start-up of the first regular producer in 2020. In total, six wells were set on production in the period between 2019 to 2021. Prior to the 2022 multi-client survey, two conventional 4D surveys were acquired, in 2005 and 2017 respectively. Only minor water flooding effects were interpreted on the 2017 data. However, as most of the production started after 2017, more 4D effects were expected by using the multi-client 2022 dataset as monitor two.

Despite the different geophysical objectives, the planned timing of the multi-client 2022 data acquisition was optimal for being integrated into this 4D reservoir production monitoring program where major production variabilities have been observed at the various wells after 2020. While the legacy 4D surveys (2005-2017) were optimised in terms of dual source and streamer geometry repeatability, the '4D opportunistic' multi-client dataset was acquired with larger sail-line spacing and wide-tow triple source. The sail-line azimuth of the multi-client dataset was the only navigation feature in common with the baseline surveys, but no effort was made to match the shooting direction.

To understand and mitigate the risks related to such a non-repeated datasets, the project was executed in three phases, each dependent on the success of the previous stage:

1. Analysis of geometrical repeatability and 4D imaging risk assessment.
2. Multi-vintage 4D imaging on a subset of the full area, shared by the three datasets.
3. Extension of the area of interest covering the two last surveys (2017 and 2022).

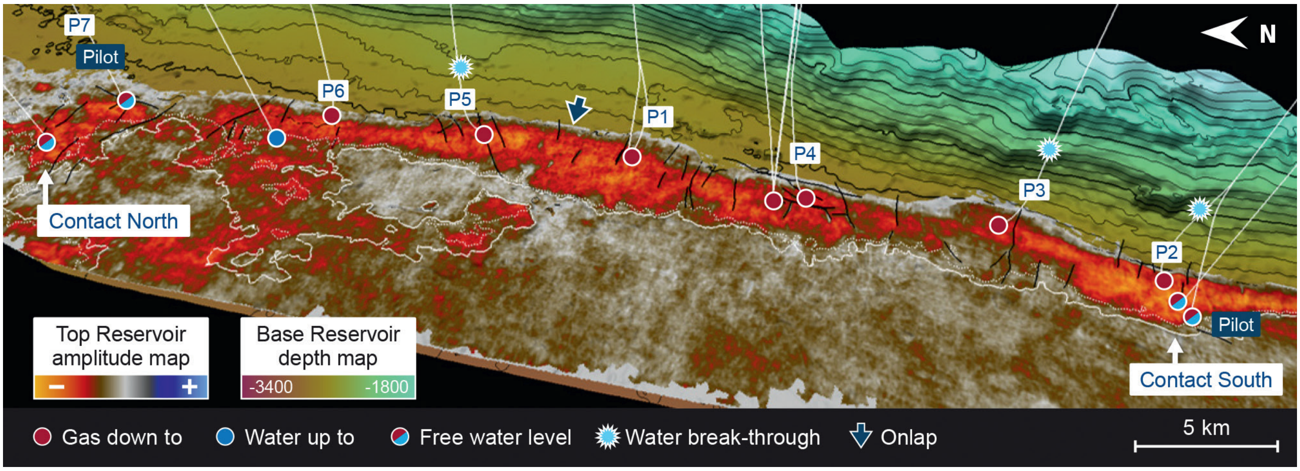

**Figure 1** Top Lysing depth map onlapping the base reservoir depth surface. The attribute map is minimum amplitude extracted from an AVO fluid volume where warm colours indicate gas presence. Wells are shown in white, annotated with fluid contact information. (Hjellbakk et al. 2023).

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## Geometrical repeatability assessment

A repeatability study was carried out using only shot/receiver coordinates. Different 4D binning strategies were evaluated by analysing attribute maps. The most useful attributes for understanding geometrical differences were the sum of the source and receiver distances (dSdR) and the fold of coverage. Despite having the same acquisition azimuth for the three surveys involved, the 2022 survey was unfortunately acquired in the opposite direction for most of the area. Only a very small part was covered with data where the baseline and both monitor surveys were acquired in the same direction. This required that all the following 4D binning work utilised reciprocity of source and receivers. Although dSdR values were unconventionally high, up to 500 m for near offsets, it was decided to proceed with phase 2 and process a small area through a full 4D sequence.

## Acquisition geometries of the three vintages

The baseline dataset was acquired in 2005. Conventional shallow hydrophone streamers were used for this acquisition. The first monitor survey was acquired in 2017, using deep towed multisensor streamers. That survey was designed as a dedicated 4D acquisition aiming to repeat the baseline shot/receiver coordinates and using the identical dual source specifications.

In the summer of 2022, PGS acquired a multi-client program in the Norwegian Sea. The project was extended to the North-East to cover the Ærfugl field and to use the new dataset for 4D time-lapse purposes. The acquisition azimuth was altered by six degrees compared to the optimal 3D survey design to match the azimuth of the baseline survey. All other parameters were kept the same as for the multi-client acquisition. The 2022 acquisition is very different from the other two surveys as it features wide-tow triple source, deep-towed multi-sensor streamer technology, denser trace coverage, a larger streamer spread and shorter inline near offsets. Figure 2 describes the different acquisition designs involved. Figure 3 shows how well repeated the shot and receiver locations were in 2017. In this example two additional outer cables offer increased redundancy because the inner cables from the monitor dataset overlay the baseline exactly. On the other hand, it's very difficult to find anything in common between 2005 and 2022 shot/receiver positions.

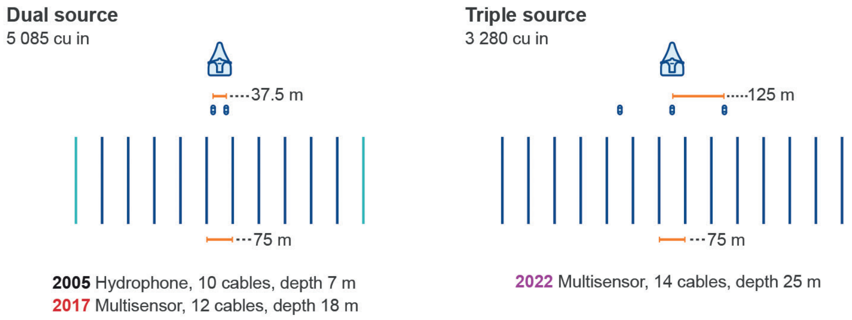

**Figure 2** Acquisition survey design scheme for the three surveys

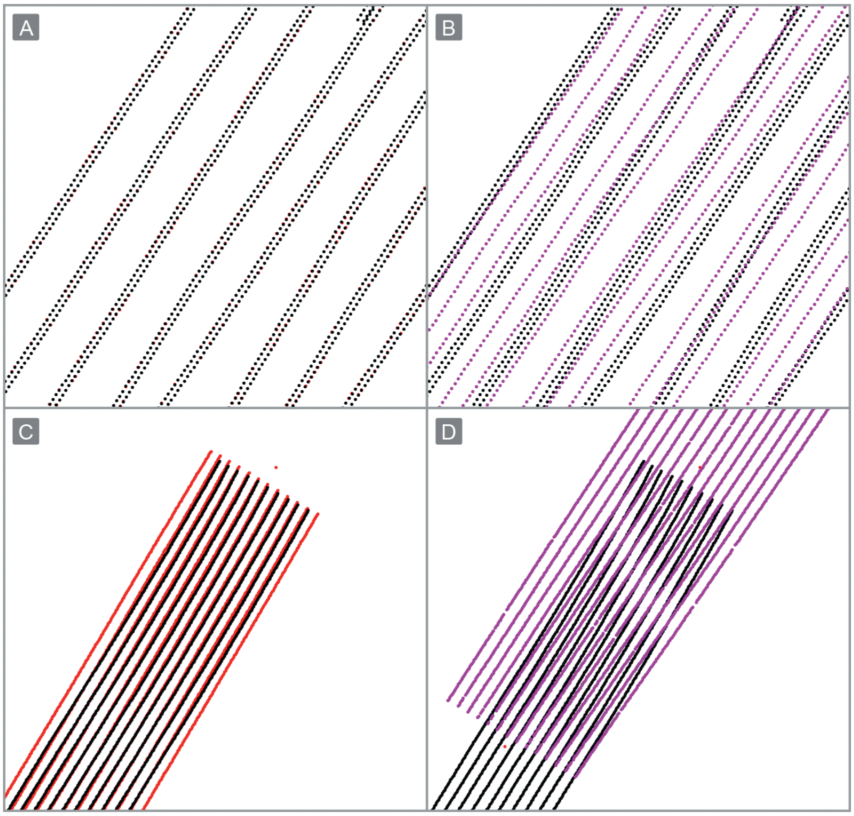

**Figure 3** Source and receiver positions. 2005 (black) vs 2017 (red) repeated dual sources (A), dual sources 2005 (black) vs wide-towed triple sources 2022 (purple), non-repeated (B). (C) and (D) display the repeatability of the streamer geometry. The 2022 multi-client dataset was acquired mostly in the opposite direction.

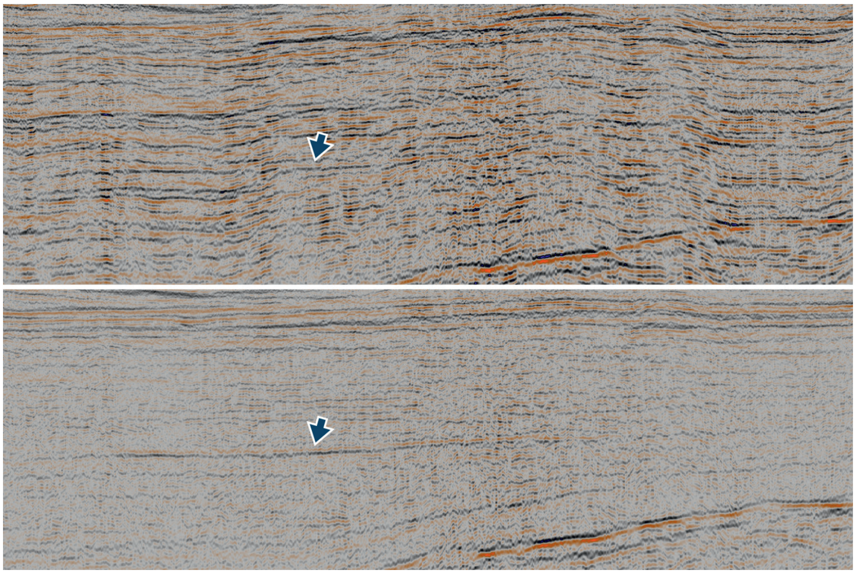

**Figure 4** 3D QC full angle stack. Monitor dataset 2022. Before demultiple (top), after demultiple (bottom). An arrow indicates a reservoir reflection.

Seismic sources for the 2005 and 2017 acquisitions were the same: two sources, 5085 cu.in. each, 6 m depth with 37.5 m source separation. The 2022 survey was, however, acquired with three sources, with a volume of 3280 cu.in. each, 7 m depth and source separation of 125 m (250 m total). The source set-up discrepancy was one of the 4D challenges for this reservoir monitoring project.

## 4D processing key steps

Several case studies of opportunistic 4D projects using a non-repeated dataset can be found in the literature. These were mostly conducted for reservoirs with a strong 4D signal. For example, on the Sleipner carbon capture and storage project, eclectic acquisitions have been used for monitoring the CO2 plume (Wierzchowska et al. 2021). More challenging examples include ocean bottom node vs streamer acquisition 4D projects (Detomo et al. 2012). In the Ærfugl case the 4D signal was expected to be very weak small amplitude difference and time-shifts less than 1 ms.

For this opportunistic 4D project, special care has been taken during the processing of the signal calibration, receiver deghosting, demultiple and denoise. All three datasets were reprocessed together from raw data to ensure the best repeatability in terms of processing sequences and algorithms.

## Multiple attenuation

In addition to the 4D noise related to the acquisition geometry discrepancy, one of the 4D processing challenges was to reduce the impact of the multiples. The reservoir target reflection is practically invisible before demultiple/denoise (Figure 4) and the 4D signal was only observable post-migration (on a full stack).

Although the data are not located in very shallow water, multiples present a significant challenge. The water bottom two-way travel time is around 500 ms and the seabed is relatively hard, generating strong multiple reflections. The water bottom is highly rugose in some areas, which generates complex diffracted multiples. Various multiple models were generated for each vintage and the adaptive subtraction parametrisation was directly validated using 4D difference optimisation.

## Spatial X-shift corrections

The uncertainties of acquisition positioning were investigated to optimise the multi-vintage 4D response. The process, called 'X-shifts' correction, uses spatial warping technology for computing relative image shifting between the vintages. The procedure is performed iteratively in the pre- and post-migration domain. The application to the data is made by moving in the crossline direction source and receiver coordinates prior to 4D binning. The spatial corrections are usually relative in conventional repeated 4D acquisition and the correction is applied using a reference survey.

In our case, the system provides several collocated measurements with similar and opposite acquisition directions. Consequently, it was possible to retrieve the X-shift corrections corresponding to each individual survey, without the need of survey reference. Therefore, the applied X-shifts minimises all image differences globally. The extracted spatial correction values were in the order of metres along the sail line (crossline direction).

## 4D binning

To compensate for the lack of repeatability for the second monitor survey, a pairwise 4D binning approach was chosen to give the optimum repeatability result for this multi-vintage 4D project (Brain et al., 2013). Different grids and different 4D binning strategies were tested. An expanded binning strategy on a 18.75 x 12.5 m grid was chosen keeping multiple traces per bin. The expanded 4D binning process allows seismic traces standing in adjacent bins to be paired in a 4D context. It was essential to preserve a maximum number of traces belonging to each survey to optimise the constructive interference in the migration stack process and reduce the 4D noise. The maximum dSdR at near offsets for the repeated surveys was 100 m, whereas for the non-repeated pairs the maximum dSdR approaches 500 m, which is relatively unconstrained.

## Multi-vintage matching

The combination of dual source and triple source design, as well as various cable systems, geometries and depths provided a real challenge for calibrating the seismic signal in a 4D sense. The built-in broadband signal of both multi-sensor monitors has been preserved by using wavefield separation and a re-datuming process. A deghosting operator was applied to the baseline dataset (2005) to extend the signal bandwidth, as closely as possible, to the two monitor datasets. To optimise the 4D broadband signal calibration, a multi-vintage matching algorithm was applied using individual signal-to-noise estimation (one operator per vintage). The multi-vintage matching process allowed us to better compute the signal-to-noise for each frequency and define a common 'signal only' spectrum used as the target. The matching process was effective for attenuating the residual ghost effect on the 2005 data and optimising various 4D seismic differences.

## 4D noise removal

Due to the geological setting, the data in this area are particularly noisy at the Lysing formation. The reservoir target reflection is very weak and there is little reflectivity around it, giving a low signal-to-noise ratio. Both the 4D and 3D noise represent a significant processing challenge. Application of a harsh denoise filter at the pre-migration stage was required. Another 4D denoise technique, called co-denoise, was beneficial in this case. The procedure uses combined datasets to design and apply frequency-domain predictive filters to attenuate random noise and preserve the 4D signal. The noise, which is coherent only on one dataset, will appear randomly in the combined version and then can be attenuated by the denoise procedure. Figure 5 shows the effective 4D denoise process which allows the recovery of the 4D signal at the reservoir level. The comparison before/after images includes all denoise processes in the post-imaging sequence.

## 4D observations and interpretation

Attribute extractions at target horizons are useful in 4D interpretation as they exhibit higher signal-to-noise ratios and can track time-lapse seismic changes. Normalised Root-Mean-Square (NRMS) of the seismic difference between baseline and monitor surveys is commonly used to quantify repeatability quality. 4D reservoir changes were assessed using the sum of positive amplitudes (SPA) and sum of negative amplitudes (SNA) of the 4D difference to track hardening and softening respectively.

The final results from the repeated 2005 versus 2017 datasets gave NRMS values in the target interval of 10%. NRMS values for non-repeated pairs, involving 2022 dataset, were 13% for 2017 versus 2022 and 15% for 2005 versus 2022. Overall, the level of 4D noise is higher on the non-repeated datasets, which was expected as repeating the source/receiver coordinates and source set-up will always give a lower 4D noise level. The level of 4D noise on the non-repeated datasets was, however, low enough to reveal an interpretable 4D signal. Another observation is that the 2022 dataset has a two percentage points better match against the 2017 than against the 2005 dataset. This might be explained by the fact that in the 2017 acquisition, deep-tow multi-sensor streamers were utilised, as was the case for 2022. In contrast single-hydrophone shallow cables were used in 2005.

The SPA attribute represents acoustic hardening effects related to gas production. Figure 6 shows that SPA maps are consistent for different vintage pairs, which gives reasonable confidence in the quality of the signal. The hardening patches which are visible on the 2017-2005 map, are present in different areas, but adjacent on the 2022-2017 map. Meanwhile, the SPA map from 2022-2005 combines the areas of hardening from both other vintage pairs. This is a scenario which would arise from a continual production of gas.

The final 4D products show both hardening and softening effects (respectively blue and red in Figure 7). The hardening is interpreted as a combination of pressure decline and water replacing gas. This agrees with the modelled 4D response (Figure 7A), where a weak hardening effect, due to pressure decline, can be seen at the well level, combined with a stronger hardening down-flank, related to water movement. The softening effects are interpreted as an increase in gas saturation below the initial gas-water contact. The increase in gas saturation could come from gas out of solution in the aquifer or local gas expansion as the pressure in the reservoir is decreasing. The 4D effects are close to the noise level in the data, but the availability of multiple monitors enables the interpreter to link the 4D effects between the different production periods and build confidence in the visible signal.

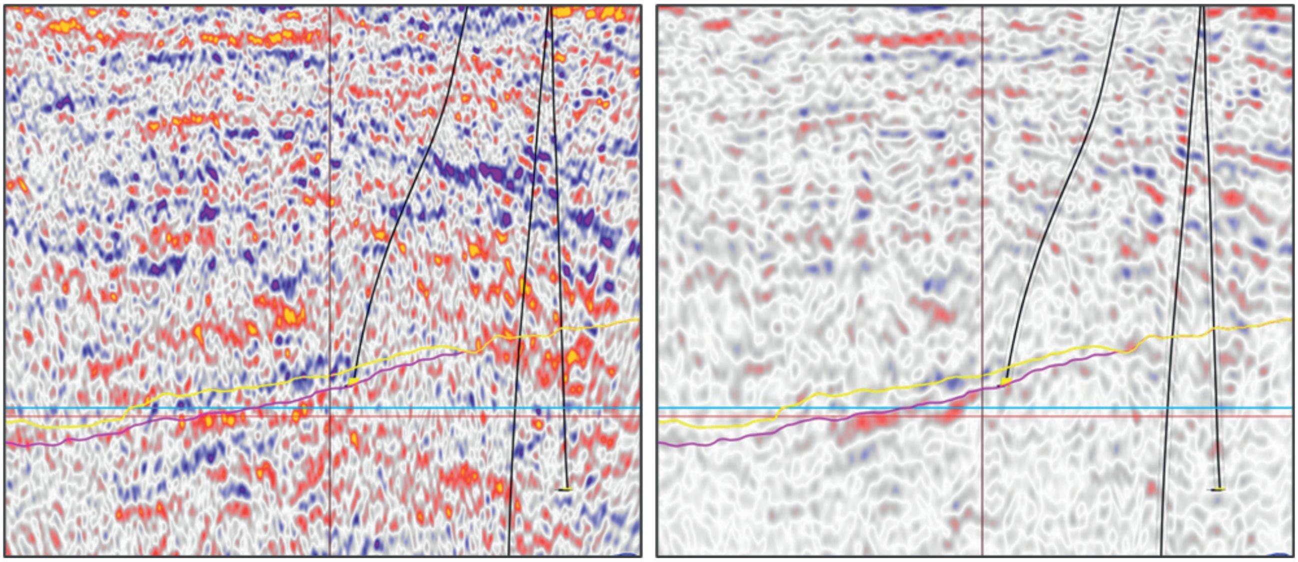

**Figure 5** Effect of the 4D denoise processes, left before and right after 4D denoise.

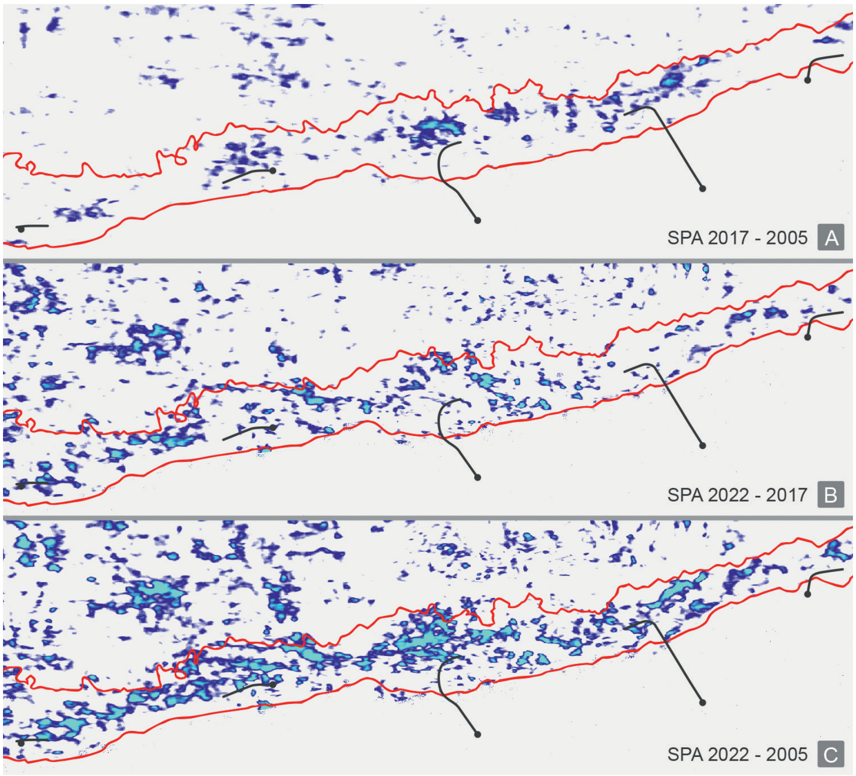

**Figure 6** 4D attribute maps of the sum of positive amplitude (SPA) of the 4D difference for different pair vintages. SPA can be interpreted as hardening effect such as water replacing gas.

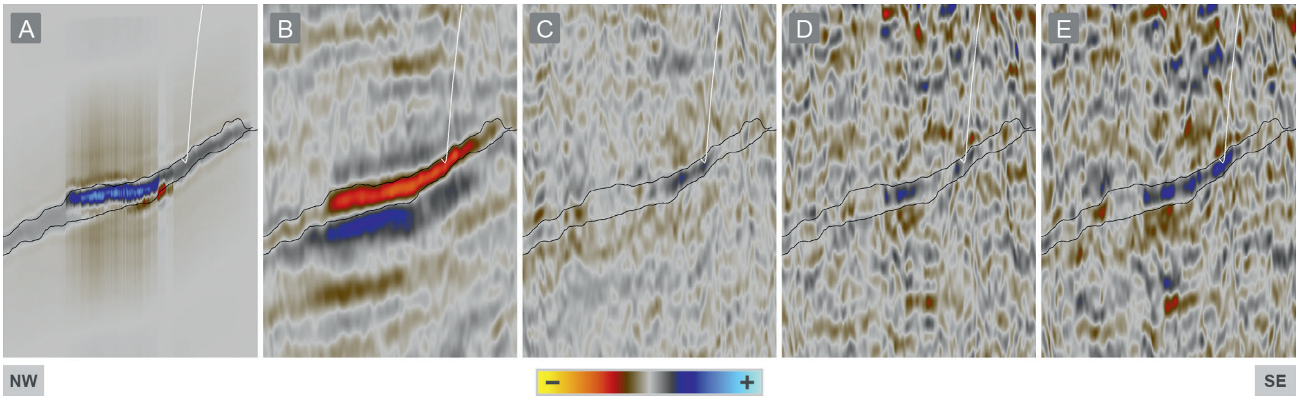

**Figure 7** Crossline section, A) the feasibility 4D model 2022-2005 B) 2005 3D stack C) 4D difference 2017-2005 D) 4D difference 2022-2017 E) 4D difference 2022-2005.

## Discussion

This project evaluates if the acquisition repeatability constraints for 4D studies can be relaxed with the use of up-to-date 4D imaging technologies. It is challenging to answer this question positively as we can observe an increase of 4D noise levels when non-repeated acquisitions are involved. However, opportunistic 4D datasets can be beneficial if the acquisition time-lapse corresponds to critical reservoir production changes. The 4D imaging workflow requires that customised processes are designed, and special care is taken. In this example, there are several factors which have contributed to the success of the 4D project.

Firstly, it is essential that the communication between geophysicists, from the imaging provider and the field operator, takes place in a continuous way during the project. 4D objectives and well production information has been shared from the beginning and no blind tests have been performed. Continued discussion, between both parties, on the interpretation of the 4D results enables the tailoring of the 4D processes throughout the sequences. For example, the level of the 4D noise to be considered during the denoise processes was constantly validated according to the remaining 4D signal understanding. Another key 4D process investigated and discussed was the final local matching for compensating the variation in acquisition geometry and source type. Such radical cross-equalisation should be avoided in a conventional 4D sequence, nevertheless the use of slowly spatially variable operator was beneficial when the 2022 multi-client dataset was involved in the final 4D difference. Again, interactions between interpreters and geophysicists were key for defining the optimum parametrisation.

Secondly, multi-vintage studies (more than two) allow us to link the 4D effects between the different production periods. Considering that the noise has no spatial consistency in the time-lapse domain, it is simpler to understand and validate complementary 4D effects using the relationship between the production periods baseline versus monitor 1 and the monitor 1 versus monitor 2. If the production starts before monitor 1, the evolution of certain 4D signals can be predicted and interpreted even if the level of 4D noise is higher in one of the survey pairs. Then the 4D denoise processes can be calibrated for a 4D signal corresponding to a late production (after monitor 1).

In summary, adding more datasets in 4D projects can be helpful for understanding the observed reservoir production even if the extra dataset is not acquired in an ideal 4D-friendly way. However, repeating the acquisition is still an important requisite for increasing the 4D signal-to-noise and the reliability of the 4D interpretation.

## Conclusions

This case study shows that multi-client datasets can be used in an opportunistic way for a better understanding of reservoir production in a time-lapse project. In this case, it was possible to retrieve an interpretable 4D signal even if the multi-client acquisition was only repeating the sail-line azimuth direction. Customised processes and special care must be considered for such projects for handling inherent discrepancy in the 4D signal-to-noise. Furthermore, continuous communication between geophysicists and 4D interpreters is key for validating every processing/imaging step. In the light of the initial 4D results of the study, it was decided to extend the area of interest from 500 km$^2$ to 1000 km$^2$ to cover the full extent of Ærfugl field.

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