OPTIMIZING OF A DAS VSP IMAGE FOR 4D ASSESSMENT AT THE CULZEAN FIELD

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Summary

We discuss the processing and imaging solutions designed to assess 4D signal in a monitor Vertical Seismic Profiling (VSP) survey acquired with Distributed Acoustic Sensing (DAS) over the Culzean field, Central North Sea. With a baseline DAS VSP survey acquired during a pilot programme in 2019, a monitor survey acquired in 2021 aimed to provide the means to assess reservoir and overburden time shifts in the Culzean field ahead of full field 4D seismic acquisition. We show how a 4D compliant processing workflow effectively tackled non-repeatability aspects of the monitor survey including significantly increased background noise levels compared to the baseline and variation in the source signatures and the recorded data. An improved de-multiple workflow utilizing Wave Equation Deconvolution Imaging and final imaging with Reverse Time Migration, achieved a high quality image in the overburden and at the key reservoir section for analysis of 4D time shift signal.

Optimizing of a DAS VSP image for 4D assessment at the Culzean field

Introduction

Located in Block 22/25a of the East Central Graben area of the UK Central North Sea, the Culzean field is situated 230 km off the coast of Aberdeen at a water depth of 90m. Discovered in 2008, the field went into production in 2019 under operation by TotalEnergies E&P UK (TEPUK) with six wells currently targeting gas condensates at a depth of 4,300m below sea level in High Pressure, High Temperature (HPHT) Mid Jurassic and Triassic reservoirs. As described by Merry et al. (2020) and Moore et al. (2021), a 3D DAS VSP survey was acquired in the spring of 2019 as part of a wider VSP acquisition programme and subsequently processed in 2021. Achieving a high quality 3D image of the reservoir interval, the results of this data acquisition and processing instigated the acquisition of a DAS monitor survey in June 2021 (Figure 1) with the primary objective of assessing reservoir and overburden 4D time shifts in the Culzean field. The results of this 4D survey would act as a feasibility for future full field 4D seismic surveys.

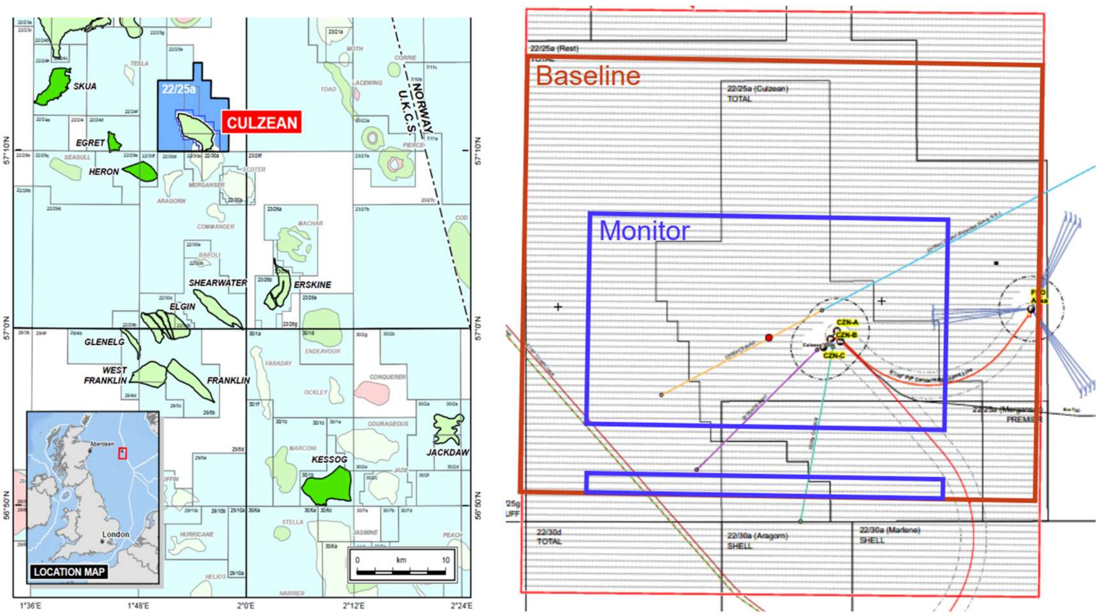

__Figure 1__ Culzean field location and survey programme area for both the Baseline and Monitor surveys with the C2 well highlighted in orange. Note the smaller shot carpet of the Monitor survey.

Addressing repeatability challenges

A key processing challenge known from the outset of the project was the non-repeatability elements of the monitor survey. With the baseline survey acquired prior to production initialisation of the well, differences in the background noise levels of the survey were expected to be large, with the DAS fibre response also altering due to this varying well condition. Whilst source positions were highly repeatable, with an average mean error less than 2m, sub-optimal source signature variations were observed between the near field hydrophone data of each survey. Although the processing workflow optimized during the baseline survey (Moore et al. 2021) was to be used as a starting point, major modifications had to be implemented to address these challenges in a 4D compliant manner.

Even if the monitor survey was acquired in the shut-in well, the background noise level of the monitor survey (Figure 2b) was expected to be significantly higher than the baseline survey (Figure 2a). In reality this difference exceeded 30dB in amplitude across the full frequency range with additional high amplitude noise bursts present. An extensive de-noise workflow had to be designed to suppress this noise and reveal both the up-going and down-going signal. Key to this were co-operative based de-noise techniques utilizing the cleaned baseline data (Gao et al. 2021) and a Deep Convolutional Neural Network trained to suppress noise patterns present in the monitor data. Utilizing phase and amplitude discrimination in both 3D curvelet and F-Kx-Ky domain, this multi-step de-noise workflow was highly effective in suppressing the vast majority of noise in the monitor survey and allowing us to achieve a monitor signal to noise ratio comparable with the baseline survey (Figure 2c and Figure 2d).

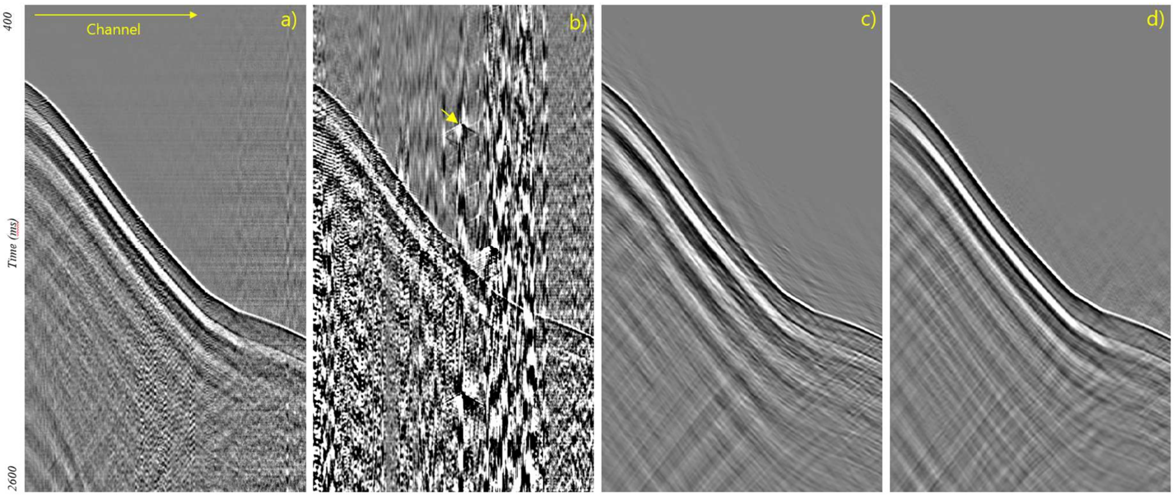

***Figure 2** A shot gather of the raw baseline data (a) and the monitor data (b) showing a significant increase in the background noise levels and noticeable amplitude bursts in the monitor data. The same monitor survey shot gather is shown after the extensive de-noise workflow (c) including multi-pass co-operative de-noise and DNN based de-noise. A comparison with the baseline data at a corresponding stage (d) shows the signal to noise level is now comparable with key up-going events now identifiable.*

With the noise differences addressed between the two surveys, the next major challenge was to address the differences in the source signature and DAS cable response. A shot-to-shot de-signature workflow, originally designed during the baseline processing, was implemented and proved effective in addressing the majority of differences in the source signatures within each survey. It also allowed to accurately de-bubble each dataset taking into account differences in the bubble periodicity observed especially on the monitor data (Figure 3). The final step of the de-signature workflow involved shaping the data to a target signature common between the two surveys.

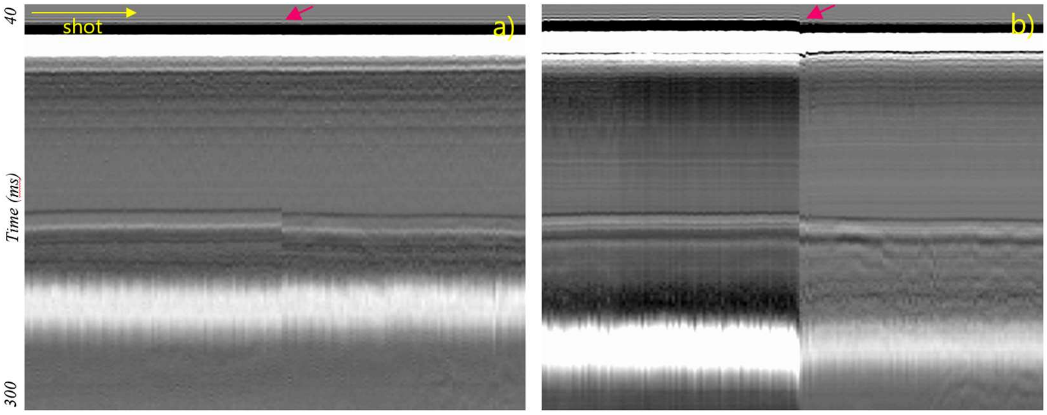

***Figure 3** A selection of Near Field Hydrophones from the baseline survey (a) and the monitor survey (b) for two saillines. The sailline change is shown by the red arrow. The monitor has anomalous hydrophone responses in both timing and amplitude on one of the saillines due to the hydrophone becoming tangled. The variation in the bubble periodicity between the two surveys can also be observed.*

However, the de-signature process was complicated due to issues with the recorded near field hydrophones during the monitor survey acquisition. Acquisition challenges meant that, whilst nominally expected to be 4m below the source gun, the hydrophones occasionally became tangled in the suspending cables leading to a variation in the true depth of up to 4m, not recorded in the trace headers. To ensure this error was not subsequently introduced into the data, careful analysis of the near field hydrophones was conducted via time shift and amplitude comparisons with both the corresponding baseline NFH and an additional set of monitor NFH positioned on the gun frame. Those of high quality were used for the shot-by-shot de-signature whilst those of low quality were either dropped and interpolated or replaced by an average line by line operator.

A time and phase analysis around the direct arrival shows that this de-signature approach corrects for these source side differences between the two surveys; we then apply a shot by shot amplitude matching to tackle residual small-scale differences. With source side differences now accounted for, residual global amplitude miss-matches between the baseline and monitor survey are attributed to receiver side differences, likely arising due to the highly differing conditions in the well between the two surveys (such as the impact of temperature differences on recorded strain, Sidenko et al., 2021). Receiver by receiver spectral matching was therefore applied in a global window correcting for these differences, which are most noticeable at the lower frequencies.

Whilst a detailed processing workflow had been designed for the baseline data, further technical improvements were thought to be necessary in a time-lapse imaging context, to increase confidence in the observed 4D signal. Most notable of these was the use of two multiple models. Whereas the original baseline processing used only a 3D model-based water layer de-multiple (MWD) technique (Wang et al., 2014), the 4D processing additionally applied a Wave Equation Deconvolution (WEDECON) imaging technique (Poole, 2019). While MWD predicts surface related multiples originating only from the water bottom reflection, the WEDECON method generates a near surface reflectivity directly from the DAS VSP data, allowing for multiple modelling from additional near surface generators, as shown in Figure 4. Utilizing a simultaneous adaptive subtraction of the models in the 3D complex wavelet domain, WEDECON and 3D MWD provided an improved solution for de-multiple in this area.

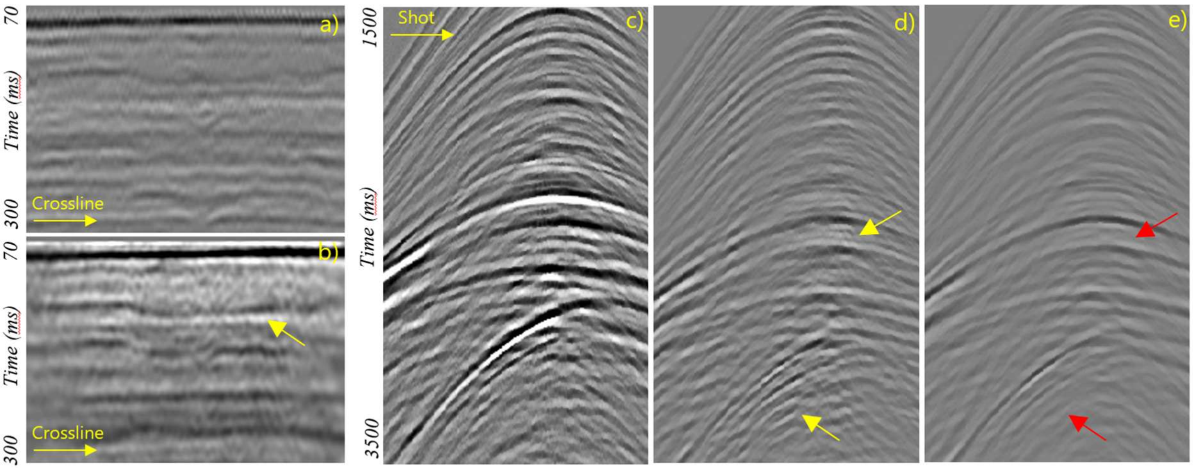

Figure 4 *A comparison between the near surface reflectivity as observed from the legacy Kirchhoff OBC down-going stack a) and from the WEDECON imaging (b). The WEDECON utilizes the dense shot spacing to give a detailed model of the near surface multiple generators within the area of available shots. Comparing to input data (c), subsequent multiple modelling (d) has a good correlation between modelled and observed multiples in timing and amplitude. A comparison to the 3DMWD model (e) highlights the improved higher frequency response of the WEDECON model and the modelling of non-water bottom related surface multiples from near surface generators.*

Up-going wavefield imaging and 4D analysis

Being able to provide a high-resolution image of the reservoir package with low noise levels for both surveys was key to assess the 4D response in the area. Following final pre-processing steps including DAS fibre directivity compensation in the sparse tau-p domain and up-going wavefield separation, a 50 Hz Reverse Time Migration was conducted for all available channels (approximately 8 m sampling) to a total depth of 6 km. A post-migration processing flow provided further improvements to the signal-to-noise ratio and frequency content of the final 3D results. NRMS, QI and Time Shift metrics were all frequently investigated as a means of assessing the potential 4D signal. Pre-survey modelling based on available geo-mechanical information suggested a potential time shift of 0.5ms at top reservoir due to pressure depletion in the reservoir and subsequent compaction effects. The notable time shift response is observed at the top of the reservoir (Figure 5) in agreement with 4D feasibility results.

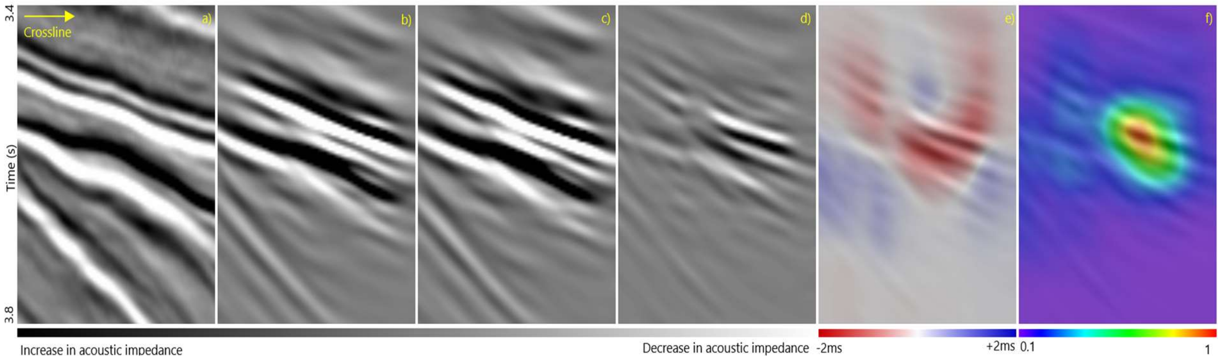

Figure 5 *Crossline comparison: a) legacy Kirchhoff OBC surface seismic, 50HZ RTM final stack of the DAS VSP b) baseline survey and c) monitor survey and d) 4D difference. A windowed time shift analysis e) highlights the 4D response at the top of the reservoir package whilst a NRMS analysis (f) highlights the good level of repeatability outside of the area of 4D effects.*

Conclusions

To achieve the objectives of assessing reservoir time shifts in the Culzean field with 4D DAS VSP, we optimized an existing baseline processing and imaging workflow to tackle the non-repeatability challenges arising in the monitor survey. An extensive de-noise workflow was designed to attenuate the significantly increased background noise on the monitor data. Source signature and receiver response differences were addressed by a robust shot-to-shot de-signature and targeted 4D compliant matching. In addition, a combined MWD and WEDECON workflow effectively modelled and attenuated surface related multiples from the water bottom and near surface generators. High frequency imaging of both the monitor and baseline up-going wavefields with Reverse Time Migration identified a notable 4D response at the top reservoir with a time shift comparable to that theorized by 4D feasibility studies. This feasibility study has highlighted the potential of DAS VSP as a tool for 4D reservoir monitoring with the results de-risking full field 4D Seismic surveys at the Culzean field in the near and far future.

Acknowledgments

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