THE VALUE OF DUAL-AZIMUTH ACQUISITION: IMAGING, INVERSION AND DEVELOPMENT OVER THE DUGONG AREA

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Summary

The Dugong area in the Norwegian North Sea was surveyed by North-South (N-S) orientated, variable depth streamer data, and recently, East-West (E-W) orientated triple source multi-sensor data. By reprocessing the original N-S data in combination with the E-W, we found that a combined dual-azimuth (DAZ) volume can provide significant imaging improvements supporting the de-risking of nearfield exploration targets. The uplift came in the form of enhanced structural imaging, resolution, signal-to-noise ratio and amplitude reliability. These were due to the complimentary illumination, sampling, and cable-varying characteristics of the two surveys, combined with advanced DAZ velocity model building and reprocessing methods. The benefits were found to directly aid in development decisions. Firstly, an inversion study utilizing both azimuths in a joint manner yielded more reliable probabilistic estimates of reservoir-level oil sands when compared to a single azimuth inversion due to the richer illumination and hence amplitude fidelity. Secondly, DAZ full-waveform inversion (FWI) imaging facilitated a substantial improvement to near-surface resolution with the potential for shallow hazard identification.

The value of dual-azimuth acquisition: imaging, inversion, and development over the Dugong area

Introduction

The Dugong area is situated within the Northern Viking Graben (NVG) region of the Norwegian North Sea, and was surveyed by a contiguous 44,000 km^2, North-South (N-S) orientated, variable-depth streamer dataset. These data were most recently processed in 2018 using attenuation-compensating Kirchhoff pre-stack depth migration (Q-KPSDM). A complementary 14,000 km^2, East-West (E-W) orientated triple-source multi-sensor dataset was acquired during 2020 and 2021. The aim was to improve subsurface imaging to de-risk near-field exploration targets. By reprocessing the original N-S data in combination with the new E-W data, a dual-azimuth (DAZ) volume was generated over the Dugong area, striving for improvements in resolution, structural imaging, spectral content, signal-to-noise ratio and amplitude reliability for inversion. In this paper, we show that, when compared to single-azimuth data, the DAZ product achieved these goals, providing significant uplift due to reprocessing with the latest technologies, as well as the enhanced illumination and subsurface sampling provided by the second azimuth. In addition, the benefits of the supplementary E-W azimuth were found to directly aid in development decisions. Firstly, a DAZ inversion study revealed that, by utilising the E-W azimuth, a more reliable probabilistic estimate of reservoir-level oil sands is achievable. Secondly, DAZ full-waveform inversion (FWI) imaging was possible, providing a substantial improvement to shallow imaging resolution with the potential for hazard identification.

Acquisition, Processing and Imaging

The two surveys were acquired with cable profiles and sensor-varying properties that were complementary beyond their direct sampling and illumination differences. The E-W multi-sensor data relied on receiver ghost notch compensation through constructive ghost notch interference from the accelerometers. While this provided enhanced signal recovery within the receiver notch bandwidths, the 18 m flat-tow profile meant that low-frequency signal-to-noise would be worse than that of the N-S orientated, variable-depth streamer data (maximum 50 m depth). The N-S data recorded up to 6 dB more signal below 7 Hz (see Figure 1), while utilizing notch diversity to yield a broadband spectrum. This influenced FWI, where the enhanced lowest frequencies (below 4 Hz) from the N-S data alone chiefly drove the inversion. Another difference was that the N-S data used dual-source (nominal 18.75 m cross-cable bin spacing), while the E-W used triple-source (12.5 m spacing), improving the spatial sampling.

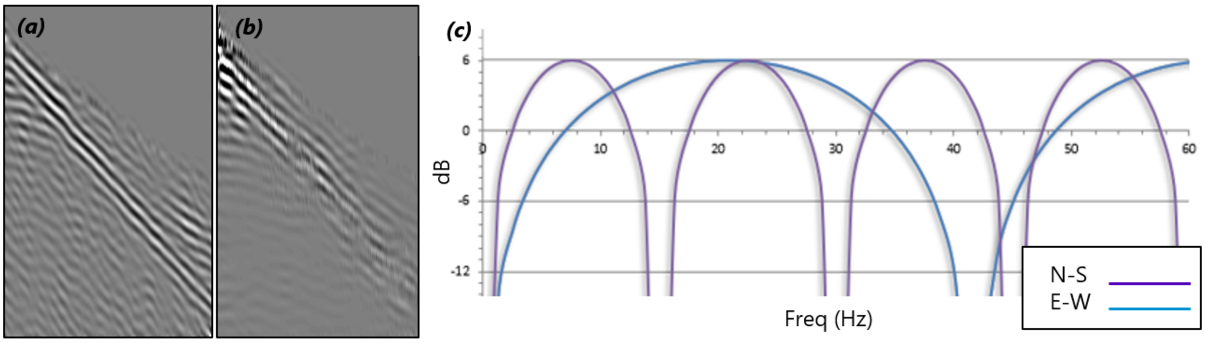

Figure 1 *(a) N-S and (b) E-W co-located shot gathers (below 4 Hz) with (c) Idealised power spectra*

Consistent and modern processing was undertaken on both datasets. This included 3D multi-channel deconvolution imaging and wavefield extrapolation based demultiple (Poole, 2019) to address complex multiples that originated from various near-surface features such as shallow gas. Furthermore, 3D joint source and receiver deghosting was performed, extended for the multi-sensor data to include data domain sparseness weights for increased signal recovery from the accelerometer (Poole and Cooper, 2018). Co-operative denoise was also performed between the surveys, extending the DAZ benefits beyond conventional illumination enhancements and arithmetic noise suppression. Co-operative denoise was particularly effective at removing coherent wavefront noise along the Base Cretaceous Unconformity (BCU), which can otherwise hinder fault interpretation (Figure 3c). DAZ combination processing also included interleaved static corrections and octave-split DAZ stacking, aided by cross-correlation weights (Hung and Yin, 2012) to ensure illumination differences were optimally leveraged.

Both azimuths were used to improve upon the single-azimuth 2018 Q-FWI velocity, anisotropy and attenuation models (Xiao et al., 2018) utilized for Q-KPSDM. This took the form of DAZ multi-layer tomography and, more critically, Time-Lag FWI (TLFWI; Zhang et al., 2018), using both azimuths simultaneously to invert for the full wavefield, including reflections. This also drove a DAZ TLFWI-guided Q-tomography in an extension of the work by Zhou et al. (2014) to resolve deep Q bodies. Furthermore, over a targeted area, FWI Imaging (Zhang et al., 2020) was performed to compute a direct estimate of reflectivity using DAZ TLFWI up to 65 Hz. Although most previous FWI Imaging studies used data acquired with richer azimuthal coverage, such as node or source-over-spread data (Kerrison et al., 2021), combining the triple-source E-W survey with the N-S was nevertheless expected to provide an imaging uplift through improved sampling and illumination.

Results

The final 2021 DAZ product compares favourably to the 2018 N-S Q-KPSDM across many aspects, see the full-angle stacks shown in Figure 2. A profound improvement to structural imaging was realized from a combination of illumination enhancement from the second azimuth, as well as enhanced spectral content from the reprocessing with 3D directional ghost compensation. This improvement brought about greater reliability in the interpretations of both shallow targets, such as remobilized injectites (Figure 2d), and fault blocks below the BCU. The improved fault imaging on the 2021 DAZ volume was validated by the results of a machine learning-based fault picking with improved continuity and considerably less false positives (Figures 2c and 2f).

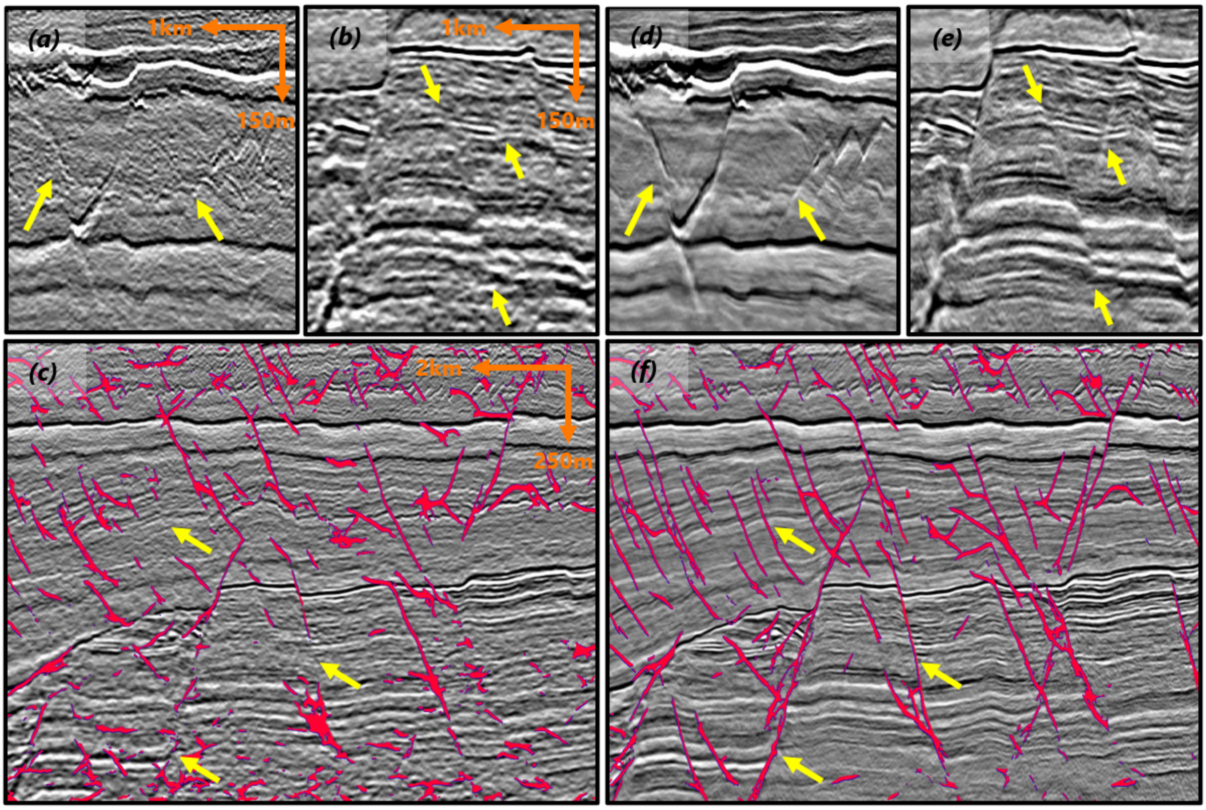

***Figure 2** (a)-(c): 2018 N-S Q-KPSDM final stack. (d)-(f) 2021 DAZ final stack. Images (c) and (f) have been co-rendered with machine learning-based fault picking (in red), derived from their respective data. Yellow arrows highlight clear areas of improved fault or injectite definition.*

Figures 3a and 3b demonstrate the uplift achieved initially by the 2021 reprocessing of the N-S data alone. Note however both azimuths contributed to the improved velocity model used to produce the image in Figure 3b. To achieve another step change in illumination, fault imaging and noise suppression sub-BCU, the E-W azimuth was essential. Figure 3c shows even greater reflector coherency and continuity resulting from the increased recording aperture afforded by the E-W azimuth and the ability to co-denoise and combine the datasets through cross-correlation weighting.

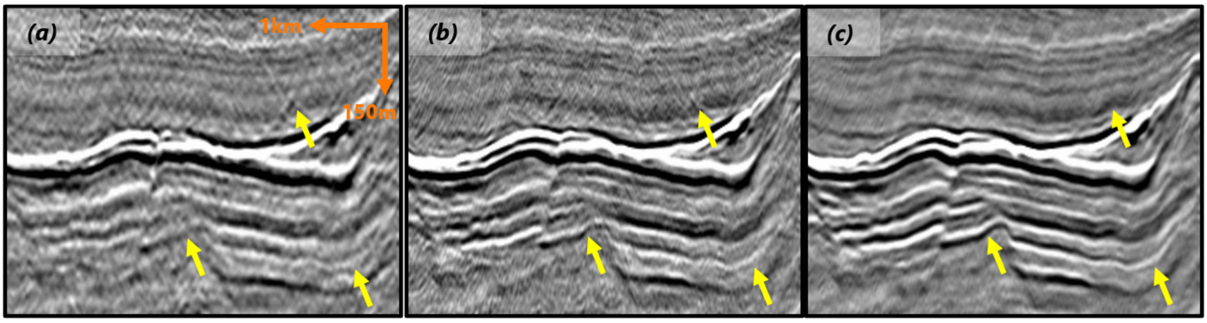

***Figure 3** (a) 2018 N-S Q-KPSDM, (b) 2021 N-S Q-KPSDM and (c) 2021 DAZ final stacks.*

The shallow overburden geology is important for well planning. The 2021 DAZ results were superior to previous vintages, improving shallow hazard identification and providing a complementary 3D dataset to conventional 2D site survey data. However, the DAZ TLFWI imaging results demonstrate an even greater advancement for shallow target identification (Figure 4). The resolution is greatly enhanced, resolving glacial scour marks and gas accumulations less than 20 m in width, due to the full-wavefield sampling (including diving waves, ghosts and multiples) of the least-squares inversion.

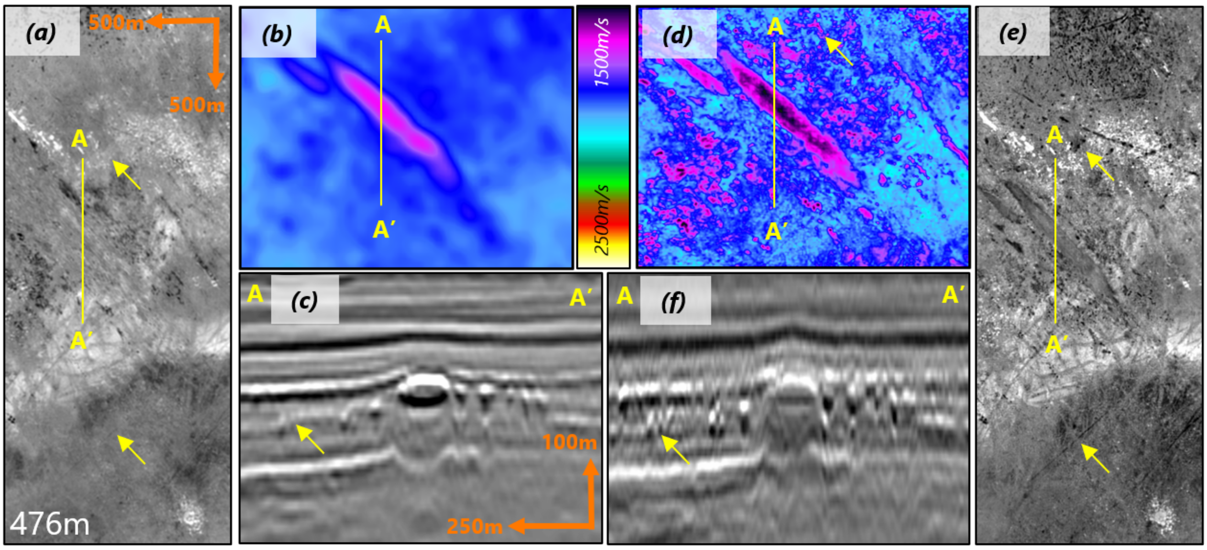

***Figure 4** 2021 DAZ Q-KPSDM (a) and (c), with 2021 14 Hz DAZ TLFWI velocity model (b) vs. 65 Hz DAZ FWI Image (e) and (f) with 65Hz DAZ TL-FWI velocity model (d)*

Inversion

Owing to the potential seen in the DAZ results, a reservoir characterization study was undertaken on an early-out version of the data, aiming to improve the understanding of the Jurassic interval around an existing discovery (Prospect A) and towards a prospect to the South-West (Prospect B). Twelve wells were utilized. A selection of the wells was used for low-frequency model building, wavelet extraction, lithology classification and porosity estimation. A sparse-spike AVA simultaneous inversion was first performed on the N-S data, followed by the E-W survey to further optimize the parameters for a joint inversion. Finally, the joint inversion was run using 8 angle stacks (4 from each azimuth) simultaneously, each with their own wavelets and the optimized parameters. Lithology and fluid classifications were derived from the well logs and combined with P-impedance and V_p/V_s from the inversion. The results from the N-S, E-W and joint inversions showed good consistency at the established Prospect A, highlighted in Figure 5 by the similarly high probability of oil sands through this known hydrocarbon reservoir. However, for Prospect B, the N-S data alone (Figure 5a) indicated a high probability of oil sands, whereas the joint inversion (Figure 5b) and E-W-only results were significantly lower. The well drilled through this prospect did not encounter oil, as suggested by the E-

W/DAZ data. Due to the consistent prior processing this is suggestive of azimuthally-variant illumination affecting amplitude fidelity. This highlights the value of rich-azimuth information for AVO and reservoir characterization and to further de-risk remaining exploration opportunities.

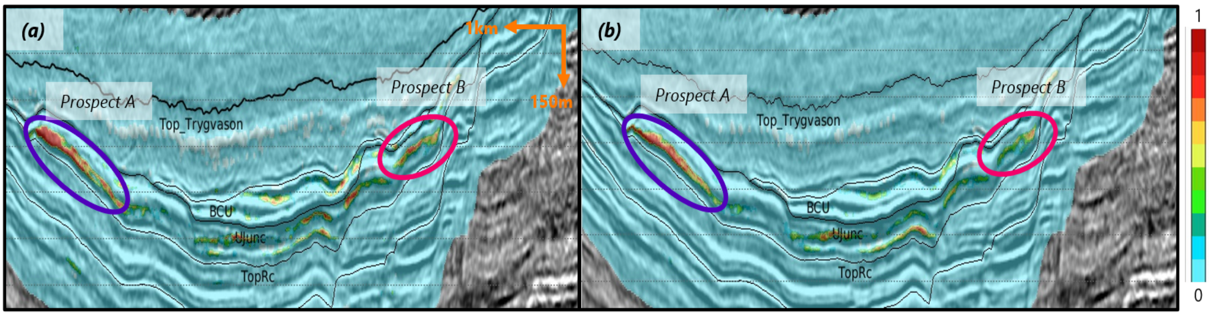

Figure 5 *Probability of oil sands from North-South only (a) and joint North-South and East-West (b) inversion, co-rendered with their respective final stacks.*

Conclusions

The 2021 DAZ results show that, despite only a short lag since prior processing of the N-S data, combining technological developments with a second perpendicular azimuth can produce a step change in imaging. This was achieved for a range of criteria including improved structural imaging and fault interpretability, enhanced spectral content and improved signal to noise ratio. These arose chiefly due to enhanced illumination, the cable-varying properties of the datasets, modern 3D deghosting, and from the ability to co-denoise and combine the surveys. Azimuthal variations extended to varying AVO responses. This had a direct impact on inversion, and hence hydrocarbon indicators within the prospects. When combining the azimuths, a joint inversion yielded greater reliability suggestive of fuller azimuthal coverage providing better illumination and improved amplitude fidelity. DAZ FWI Imaging facilitated further near-surface resolution uplift, providing another direct benefit for well planning through shallow hazard identification. Future work could include other methods for pre-stack DAZ combination.

Acknowledgements

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