Processing and imaging an ultra-dense OBN survey: A case study from the North Sea

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Summary

We describe the processing and imaging of a multi-petabyte blended OBN survey from the central North Sea. The primary target was at the Base Cretaceous Unconformity level with numerous processing and imaging challenges such as shallow channels, gas and injectites with complex geometries and varying velocities as well as lateral variations below the high-velocity chalk layer due to thickness variations and faults. In addition, there are substantial peg-leg multiples and very strong seismic interference.

A state-of-the-art deblending algorithm not only enabled the efficient and cost-effective acquisition of high-density OBN data but additionally allowed us to successfully separate the strong seismic interference. This, in turn, provided a data set suitable for the application of U/D and D/D deconvolution (Hampson and Szumski, 2020) that resulted in images free from multiple contamination. High fold, rich-azimuthal coverage and high-quality low-frequency information provided a clearer image of various targets than had previously been achieved. These attributes also allowed FWI to resolve the complex shallow channels systems that resulted in improved deeper imaging.

These results highlight the importance of a tailored, efficient, geophysical approach to data analysis and processing. The results of this multi-petabyte OBN survey provide a high-fidelity, high-resolution image of the subsurface that will help reduce the risk of structural complexity at target level.

Introduction

The benefits of ocean-bottom node (OBN) seismic over, or in addition to, broadband surface streamer seismic for exploration purposes in the North Sea have been proven through a number of case studies. Significantly better imaging (with respect to both structural definition and amplitude fidelity) results from the increased signal to noise ratio and improved illumination of the subsurface. This is a result of the multi-azimuth and long offset coverage of OBN datasets combined with a carefully designed processing and imaging workflow taking full advantage of the recorded information.

Drawing from these experiences and with an exploration focus, a large multi-client OBN survey has been acquired in the central North Sea, covering 1500 km^2 (full fold), in order to de-risk the structural complexity in the area. With primary targets at the level of the Base Cretaceous Unconformity, the imaging challenges are numerous, including the presence of shallow channels, gas, sand injectites with complex geometries and varying velocities as well as lateral variations below the high-velocity chalk layer due to thickness variations and faults. The acquisition configuration, processing and imaging approaches were designed to address these geophysical challenges and provide a reliable, high fidelity image of the subsurface.

Acquisition configuration

The survey location and initial acquisition configuration are illustrated in Figure 1. The data were acquired simultaneously by initially two, and later three, source vessels, each employing a triple-source configuration. The nominal geometry of 67 node locations and 800 shots per km^2 led to an extremely dense survey with over 1200 fold on a 12.5 x 25 m grid. The three-boat configuration along with the fact that all nodes on a receiver line were live throughout deployment resulted in a 4 component total of 130 billion traces being recorded. This data volume would be equivalent to a 520,000 km^2 conventional marine seismic survey at 80-fold.

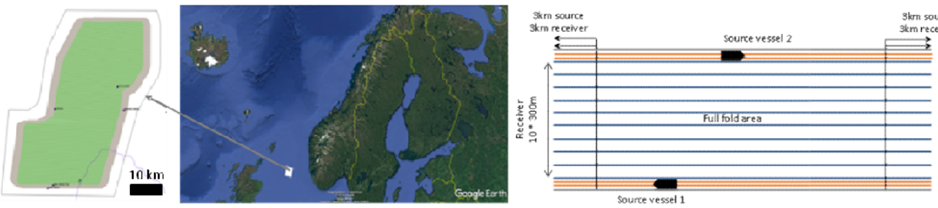

Figure 1 (top left) survey location and outline; (top right) initial two-vessel parallel acquisition pattern with receiver lines (blue) and source lines (orange). (Map courtesy of AGS)

Processing and imaging considerations

Throughout the acquisition campaign, the recorded data were transferred on-shore for processing with regular shipments allowing for continuous quality control. One of the first steps was to check, and correct if required, the orientation of the nodes to ensure an accurate rotation as well as the fidelity of the recorded amplitudes to ensure consistency between all components. Subsequent processing steps, including up/down (U/D) deconvolution, rely on the pressure and vertical component being compatible and containing only body waves. A data-driven method was developed by using the first break picks from the hydrophone and three geophone components for all traces within a small radius around the receiver station. The method is able to simultaneously solve for a number of parameters including vector fidelity, receiver position and shot shift. Comparisons are made to the field information in the trace headers and statistical analyses performed to automatically highlight and resolve outliers. This automated OBN orientation QC method proved instrumental in performing an efficient and reliable QC over such a large data set.

As all vessels used a triple-source configuration with 8.33 m shot point interval, the shot energy heavily overlaps and so deblending was applied to the continuously recorded data. In addition to the 9 known sources from the OBN survey, very strong seismic interference was observed from other nearby vessels. Some of these even shot directly over the spread which often resulted in interference at higher amplitudes than the OBN survey's own shots. During one period 14 sources were being fired in the vicinity of the live receiver locations from 4 vessels. Therefore, this was treated as an additional deblending problem which could not be addressed using traditional seismic interference noise attenuation routines as compatibility of the pressure and geophone components could have been compromised by such aggressive denoise techniques. This challenge was addressed as a multi-vessel, multi-source deblending problem using an inversion-based deblending algorithm. We assume that the input data can be explained as a linear superposition of unblended records. The efficacy of the algorithm rests upon the manner in which the 3D frequency-domain thresholding operation is performed and the relaxation of the threshold to iteratively reconstruct the shots as if they had been acquired separately. The only information required to additionally separate the shots from the interfering shots was an accurate record of those shot times. The deblended interfering shots were discarded, although given shot locations and permission from the other operator, these shots could have been used for imaging. Figure 2 illustrates the extent of the challenge and the resulting success of the deblending step.

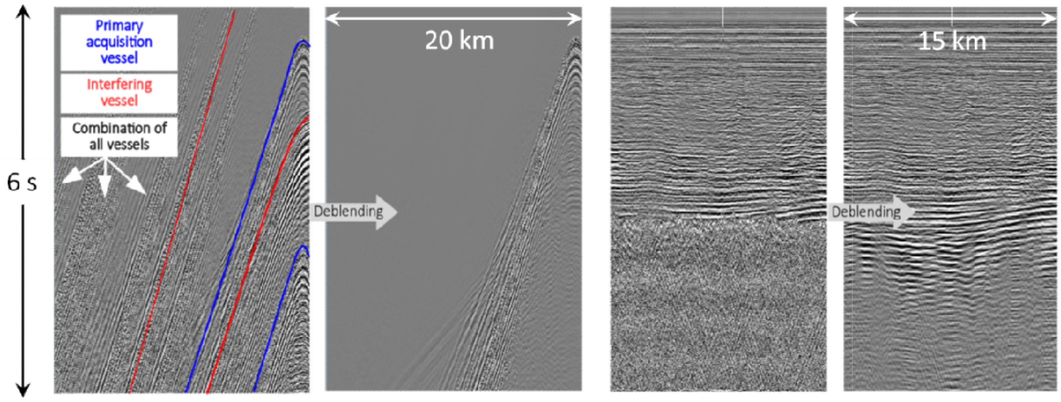

Figure 2 (left) shot gather before and after deblending. The overlapping energy from the primary acquisition vessel (shot 2 in blue) and the energy from the interfering vessel (red) have been successfully deblended. (right) Brute stack before and after deblending. The overlapping energy has been successfully deblended revealing deeper events. (Data courtesy of AGS)

One of the primary purposes of acquiring such a dense shot carpet was to use the power of U/D deconvolution (Amundsen, 2001). This is a key step to address the challenges observed in the area as it solves various problems which are typically difficult to achieve with regular processing techniques. The principle of U/D deconvolution is that the down-going wavefield contains all the energy that stimulates scattering in the Earth while the up-going wavefield is the Earth's response to that simulation. Deconvolution of the down-going from the up-going wavefield yields the Earth's response and as a result, in a single step, the process is able to attenuate both source and receiver-side free surface multiples and simultaneously apply 3D deghosting and designature. We applied a similarly powerful deconvolution technique called down/down (D/D) deconvolution to the down-going wavefield, which was described by Hampson and Szumski (2020).

These processes are applied in the 3D τ-p_x-p_y domain. Prior to the transformation, the irregular ~25 m by ~50 m shot carpet is regularised onto a common 12.5 m by 12.5 m shot grid. We performed this interpolation by exploiting irregularity and sparse representation on each 3D common receiver gather. This process properly unwraps any aliased energy while using space-varying priors estimated from lower un-aliased frequencies (see for example Herrmann et al., 2000).

An efficient 3D τ-p_x-p_y transform, using the chirp-z Fast Fourier Transform (Bluestein, 1970), was applied to both pressure and vertical components, followed by obliquity correction and calibration scaling applied to the vertical component to remove directivity and amplitude differences. Separation of the wavefields results in the up-going and down-going wavefields as observed just above the seabed and these are input to the U/D deconvolution process. A 3D τ-*p* mute is applied to the output prior to the inverse tau-p-q transform. Figure 3 demonstrates the result from the application of U/D deconvolution.

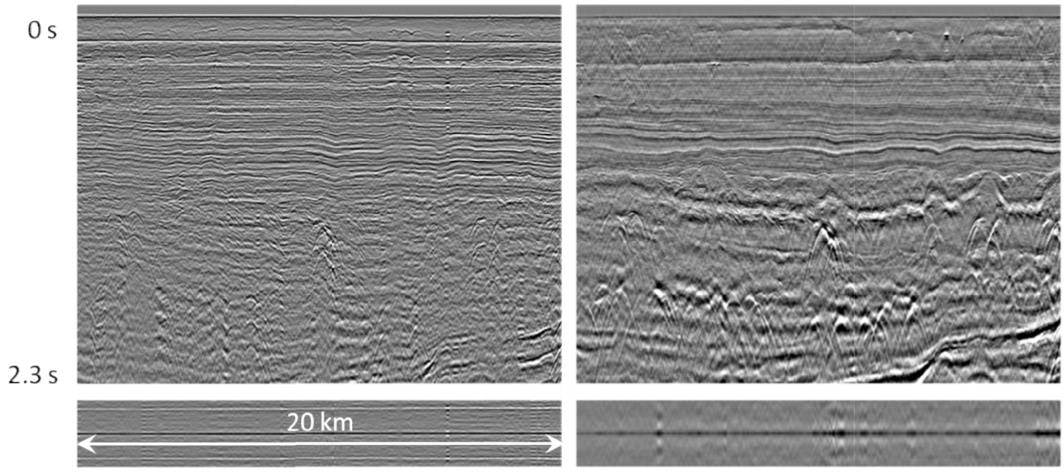

Figure 3 (left) stacked up-going wavefield with autocorrelation and (right) stacked U/D deconvolution with autocorrelation. (Data courtesy of AGS)

The down-going wavefield contains narrower illumination angles and is, therefore, able to better illuminate the near-surface. Typically a separate processing sequence is required for the down-going wavefield using adaptions of conventional algorithms such as SRME, deghosting and designature. However, Hampson and Szumski (2020) introduced down/down deconvolution which deconvolves the down-going wavefield in much the same manner as up/down deconvolution. This is considerably more effective and efficient than a sequence of lengthy customised extra steps.

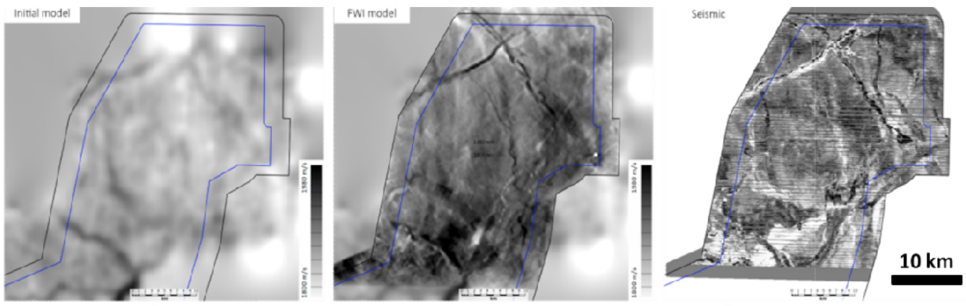

Figure 4 (left) Starting model for FWI and (middle) 5Hz FWI model. The shallow channels are resolved and match the structure on the migrated seismic stack (right). (Data courtesy of AGS)

The OBN data with long offsets, full-azimuth and good low-frequency content can be used to resolve the velocity model at different depths using a combination of full-waveform inversion (FWI) and, later, high-resolution reflection tomography. FWI is able to help resolve the velocity model at different depths, each with different challenges. In the very shallow it will help resolve the shallow channels with high accuracy and resolution which is a crucial step as these channels have a significant impact on the imaging at depth. At a deeper level, FWI can help to resolve the cemented sand injectites and finally, using the recorded long offsets, one might consider FWI to assist model building in the deeper part of the subsurface where the illumination angle of the reflection data is reduced thus restricting the sensitivity of the reflection tomography.

The primary role of FWI in this project was to capture the velocity variations in the shallow layers, including defining the shallow channels. Figure 4 shows a depth slice through the starting velocity model, the 5 Hz (defined as the filter corner point at 3 dB down) FWI model and the up-going seismic stack. This highlights the consistency between the velocity variations and the geological features.

Figure 5 shows the migrated up-going stacked results. Imaging under the sand injectites is greatly improved compared to legacy towed streamer data thanks to the increased azimuthal coverage and removal of complex diffracted multiples. The continuity of weaker reflectors above the base cretaceous unit is also much-improved and the impact of the shallow gas channels on the deeper section is resolved.

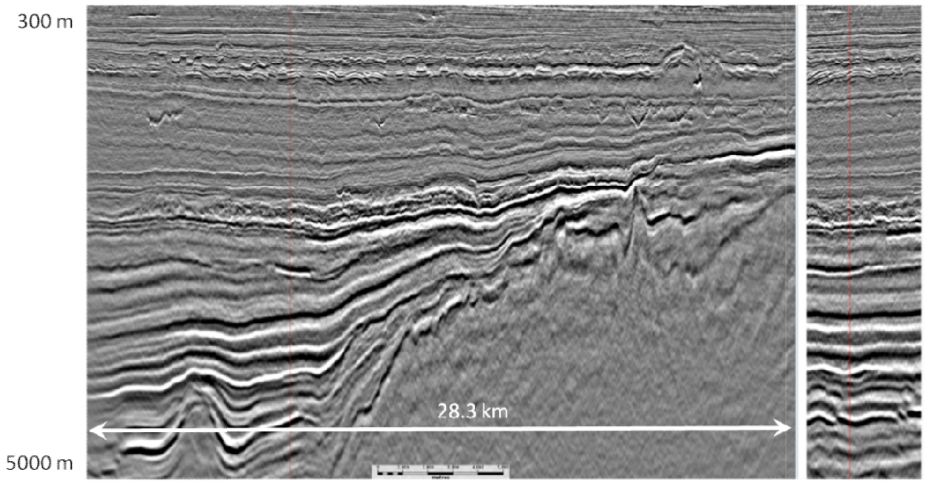

Figure 5 An inline and crossline through an up-going migrated stack volume. (Data courtesy of AGS)

Conclusions

A 1500 km^2 very dense multi-client OBN survey has been acquired in the North Sea. A state-of-the-art deblending algorithm enabled the efficient and cost-effective acquisition of high-density OBN data and the removal of strong seismic interference. This, in turn, provided a data set suitable for the application of U/D and D/D deconvolution that resulted in images free from multiple contamination. High fold, rich azimuthal coverage and high-quality low-frequency information provided a clearer image of various targets than had previously been achieved. These attributes also allowed FWI to resolve the complex shallow channels systems that resulted in improved deeper imaging.

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REFERENCES

Amundsen, L., 2001, Elimination of free-surface related multiples without need of the source wavelet: Geophysics, **66**, 327–341, doi: https://doi.org/10.1190/1.1444912.

Bluestein, L., 1970, A linear filtering approach to the computation of discrete Fourier transform: IEEE Transactions on Audio and Electroacoustics, **18**, 451–455, doi: https://doi.org/10.1109/TAU.1970.1162132.

Hampson, G., and G. Szumski, 2020, Down/down deconvolution: 82nd Annual International Conference and Exhibition, EAGE, Extended Abstracts, doi: https://doi.org/10.3997/2214-4609.202010603.

Herrmann, P., T. Mojesky, M. Magasan, and P. Hugonnet, 2000, De-aliased, high-resolution Radon transforms: 70th Annual International Meeting, SEG, Expanded Abstracts, doi: https://doi.org/10.1190/1.1815818.