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Novel Variable Streamer Length Acquisition Tailored to Full Waveform Inversion and High Resolution Imaging

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Summary

The South-Western Barents Sea is characterized by a complex geology with a heterogeneous overburden. Different target depths add a further level of complexity to the design of the appropriate acquisition and imaging configuration that is required to image the subsurface accurately. Refraction based Full Waveform Inversion (FWI) has been widely used to create detailed velocity models in the Barents Sea. The maximum model depth that can be updated by using refracted energy is limited by recorded offsets. In this case study we show the advantage of a novel acquisition solution that combines a triple-source with a high density multisensor streamer spread and a variable cable length. We evaluate the effect of long offset data on FWI, show how the updates can be extended to greater depths, and demonstrate the high-density acquisition for high-resolution imaging.

Introduction

Within the survey location in the Norwegian Barents Sea, two stratigraphic units have been identified as the key target areas for hydrocarbon plays. The shallow Jurrasic/Triassic sandstones and deeper, potentially karstified, carbonates in the Late Permian (Sakariassen et al., 2018). Each target has its own specific requirement towards a seismic survey in order to optimally image the subsurface for reliable interpretation and prospect analysis. A key requirement is to record a dense dataset, with a sufficient amount of near offsets, in order to preserve the high frequencies needed to resolve thin sedimentary beds. Targets around the Permian level on the other hand require long offsets for both, imaging and accurate velocity analysis.

Seismic surveys are often designed for optimum imaging of a certain stratigraphic unit accepting a slight degradation of the data elsewhere. In this case study we demonstrate how an intelligent acquisition solution coupled with high-end imaging technology allows us to create a dataset that meets all requirements for both, shallow and deep targets. The survey presented in this case study is located in the Hammerfest Basin in the Barents Sea. A triple-source combined with a high-density streamer spread provided an efficient way of collecting seismic data. Compared to legacy data in the area the bin size was reduced and highest frequencies are better preserved.

In the Barents Sea, the combination of relatively shallow water depths and a hard, rugose sea floor creates a tremendous amount of noise, which complicate the use of reflections in FWI for velocity updates. On the other hand, this geological setting generates particularly strong and stable refractions (diving waves). Previous studies have showed that refraction-based FWI provides an excellent tool for high resolution velocity model building in the area (Korsmo et al., 2016). FWI not only provides accurate imaging velocity models, but can also be incorporated in a quantitative interpretation (QI) workflow. In the absence of any well information the detailed FWI velocity model can be utilized as a low frequency model within a seismic acoustic inversion scheme (Feuilleaubois et al., 2017). Furthermore, the velocities derived from FWI can provide an indication of reservoir porosity. The maximum depth that can be updated by refractions FWI is limited by the deepest turning point of the diving waves. Modeling studies showed that long offset data (>7 km) are required in order to utilize refraction FWI at the Permian level.

Survey Planning and Seismic Acquisition

Recent Barents Sea case studies have shown that seismic images of shallow plays can have a spectral content in the 2-200 Hz range. Preservation of the recorded spectral bandwidth throughout a 3D imaging workflow requires denser crossline sampling compared to what usually is acquired. The survey design for the Hammerfest basin exploration survey followed the principles and concepts outlined in Widmaier et al. (2017). In order to preserve the high-frequency content, a high-density 16 x 56.25 m multisensor streamer spread was combined with a triple-source configuration (Figure 1) resulting in a nominal acquisition bin size of 6.25 m x 9.375 m. The pop interval for the triple-source was 12.5 m with dithering in order to provide good shot point sampling, high fold, and enable advanced deblending in the processing stage. The multisensor streamers were towed at 25 m depth to provide broadband receiver-ghost free data with a high signal-to-noise ratio of the low frequencies for FWI and QI work. To enable optimal imaging of both shallow and deeper targets and to provide long offset for FWI, a unique streamer configuration with a variable cable length was deployed. While the dense cable separation of 56.25 m was configured up to 7 km offset, three out of the 16 cables were deployed with 10 km cable length (i.e., a high-density spread with sparser long offset tails) (Figure 1). The dense streamer separation (56.25 m) is also beneficial for imaging of the shallow overburden by utilising migration of multiples as demonstrated in recent Barents Sea case studies (Rønholt et al., 2015). On the near offset end, the inline offsets were reduced to 88 m and further optimized by a U-shaped staggering of the streamer front ends. The survey (ca 4100 km^2) was acquired by the PGS Ramform Atlas during summer 2018 and is unique with respect to spatial sampling, streamer spread design and offset ranges provided for large scale exploration surveys.

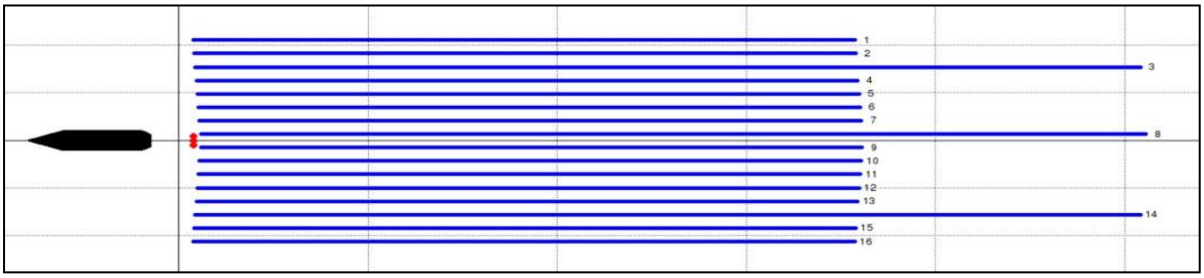

Figure 1. *Combination of a high density 16 x 56.25 m streamer spread with a triple-source. Three out of the 16 cables were deployed with 10 km cable length providing long offset tails for FWI.*

Methodology

In order to produce an accurate image of the subsurface and fully extract the potential of the densely acquired data a high-resolution imaging velocity model is required. Therefore FWI was used to capture small-scale velocity variations caused by geological heterogeneities (e.g. gas pockets, rotated fault blocks or channels). The aim of FWI is to create a velocity model which describes the entire recorded wavefield. This is done by minimizing the residuals between the recorded and modeled shot gathers. Differences are minimized iteratively until a convergence criterion is met. Our modeling engine is based on an efficient pseudo-analytic extrapolator that ensures modeling of accurate waveforms free of numerical dispersion (Crawley et al., 2010).

Modeling studies showed that diving waves recorded at 7 km offset provide velocity updates to a maximum depth of approximately 2.5 km. For deeper updates, longer offsets are required in order to record a sufficient amount of diving waves from deeper geological layers. In pre-survey studies different cable configurations were tested in order to analyse the effect of various streamer separations on the inversion results. The tests showed that a dense streamer spacing is not required to obtain stable FWI updates. Therefore only three out of the 16 streamer were extended to an offset of 10 km. Once the data was recorded, several inversion tests were performed to understand the additional depth that can be gained by using offsets between 7 km and 10 km. The results show that refraction-based FWI provides updates to approximately 5 km depth (Figure 2) when using offsets up to 10 km.

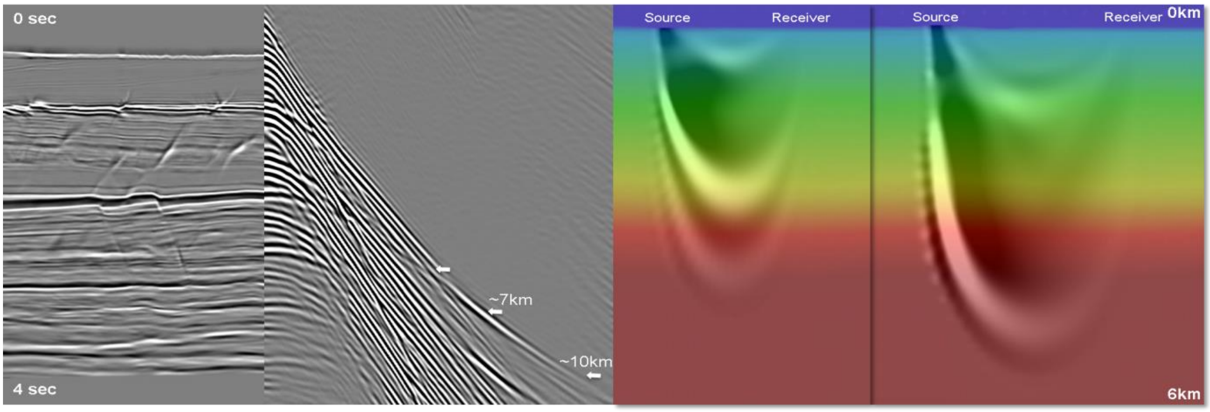

Figure 2. *Seismic stack with shot record overlay that illustrates individual refractions recorded at different offsets (a), sensitivity kernel for an offset of 7 km (b) and 10 km (c).*

Results

The Finnmark platform and the Hammerfest basin exhibit large lateral velocity variations. However, as a starting point for FWI we built a low wavenumber velocity model that included a smooth transition between the two geological regimes. Due to the deep tow, the recorded low frequencies showed a good signal-to noise-ratio. This allowed FWI to start at frequencies as low as 2-4 Hz and we used a maximum offset of 7 km for the first pass. Only refracted events have been selected in the inversion and once a sufficient match between recorded and modeled shots was achieved the frequency range was gradually increased to 2-15 Hz. Figure 3 shows examples from the initial and final FWI velocity models. The updated model shows the delineation of the high-velocity Finnmark platform which is further described by large velocity variations within itself. The Hammerfest Basin on the other hand is defined by a more uniform velocity distribution with some pronounced lower velocity zones and faulted structures, which are clearly visible on the depth slice (white arrows in Figure 3).

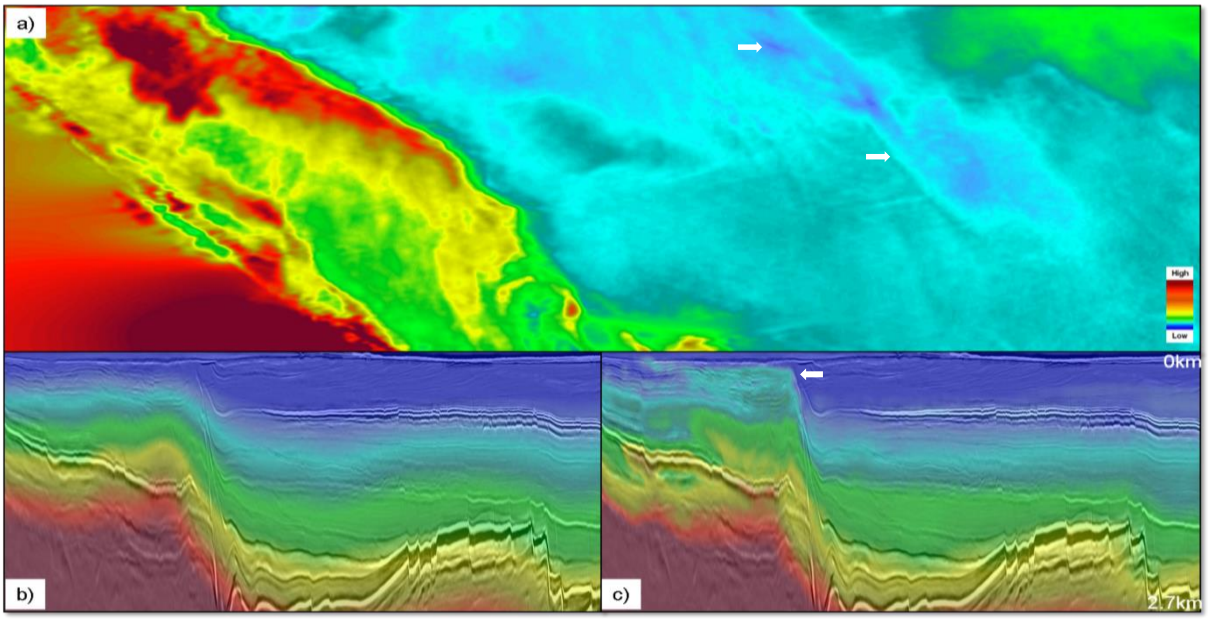

Figure 3. *Depth slice of the 15 Hz FWI velocity model (a) at a depth of 1 km. Beam migrated inline stacks with initial (b) and FWI (c) velocities overlaid show the structural consistency of the updates.*

For the shallow updates down to approximately 2.5 km depth a maximum offset of 7 km has been used. The shot display in Figure 2 highlight that offsets beyond 7 km record refracted energy from deeper geological layers. The additional recorded long offsets allowed us to build a high-resolution velocity model to ~5 km depth (Figure 4). Considering that FWI utilizes raw input data, the migration velocity model can be built at the very early stage of an imaging project. This velocity model not only helps to improve the quality of the data, but it also includes valuable information in terms of reservoir characterization. Low velocities can be an indication for porous sands, karstified carbonates, hydrocarbons or high porosity areas in general.

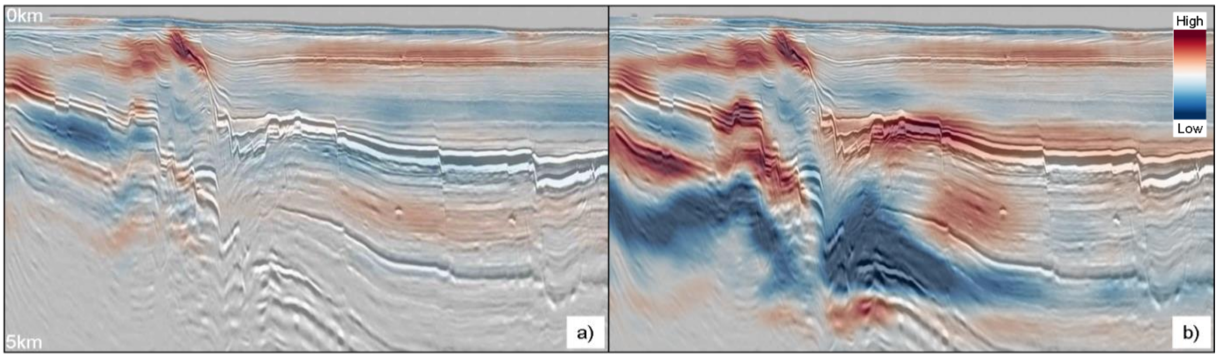

Figure 4. *FWI velocity updates overlaid a Beam depth migration stack for a maximum offset of 7 km (a) and 10 km (b.)*

An example of the high-resolution imaging achieved with this particular acquisition configuration is shown in Figure 5. Thanks to the densely recorded data and the detailed velocity model, sedimentary beds as thin as 8 m can be resolved in the Late Jurassic section. Even with a limited amount of preprocessing applied to the migration input (no multiple attenuation or regularization) frequencies as high as 200 Hz have been properly imaged.

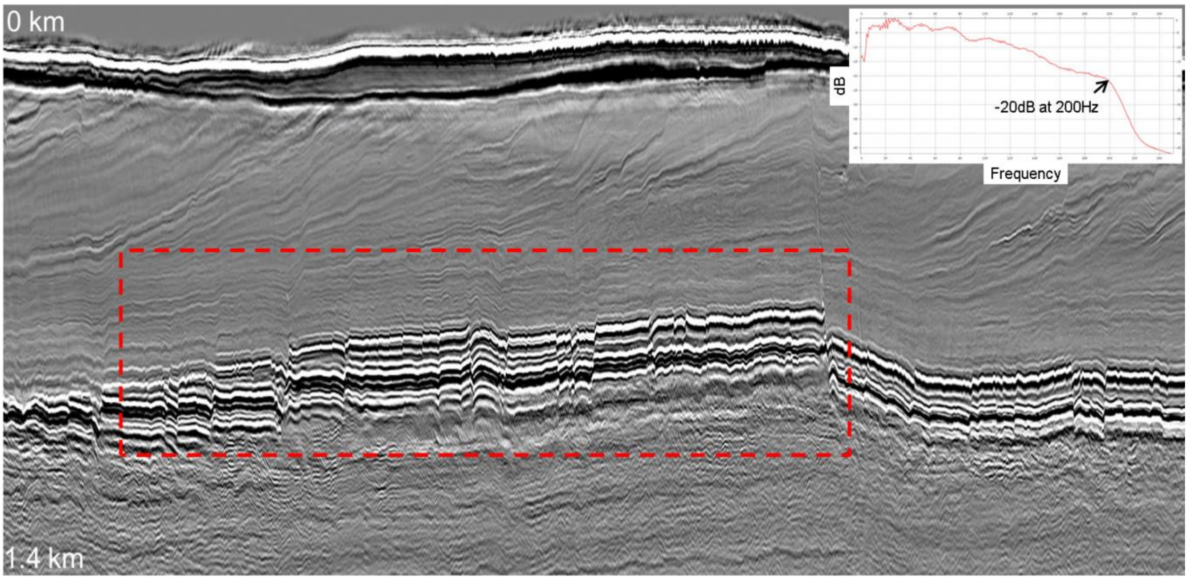

Figure 5. *Frequencies as high as 200 Hz have been properly imaged by pre-stack depth migration.*

Conclusions

In this integrated case study we present how a tailored acquisition and imaging solution provide the right seismic data in order to help unlock shallow and deep targets in the Barents Sea. A densely spaced multisensor streamer spread in combination with a triple-source shooting scheme preserves the high-frequency content that allows accurate imaging of thin sedimentary beds. We demonstrate the advantage of a variable streamer spread, including a sparse set of additional long cables. Refraction-based FWI was utilized to derive an accurate and detailed velocity model. The additional long offsets record diving waves and refractions from deeper geological layers which allowed us to build an FWI velocity model down to approximately 5 km depth. These velocities can give direct insights into potential deeper late Permian targets.

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