High resolution quad source acquisition and processing for improved imaging around the Wisting field, Barents Sea

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Summary

This paper presents a novel acquisition design and image processing using the latest Multi-Parameter Full Waveform Inversion technology (MP-FWI). The acquisition was optimized to capture the required wavefield sampling, in terms of primaries, ghosts, multiples and diving-wave refracted energy. A key point was to design a densely and well sampled acquisition that indeed captured all of the wavefields and as much reflected energy as possible in all azimuths with both short- and long-offsets. The final setup involved four sources towed inside a 12-streamer dense setup with negative -250m offset. This design is capable of delivering an almost even sampled shot-carpet as well as provide full azimuth zero -offset coverage. As the streamers were 4km long, offsets of up to 3750m was captures which are important for AVO work in this area of the Barents Sea. MP-FWI imaging has been used to simultaneously determine velocity and a variety of subsurface attributes, such as anisotropy, relative density, reflectivity and even angle-dependant reflectivity for AVA analysis.

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Introduction

Designing and implementing an efficient but at the same time high quality seismic acquisition setup, has been a key driver in the exploration business for ages. More streamers, wider tows, higher speeds, efficient sources, higher fold, smaller bins and longer offsets are some of the parameters that are juggled to balance the cost vs. benefit in terms of first order quality of the recorded seismic data. Once recorded, the raw bits and bytes need to go through an extensive processing and imaging flow before the final image and geological benefits can be realized. This process of making tangible and costly changes in the acquisition setup to increase the ultimate quality of the final seismic image is not necessarily straightforward to illustrate. One example could be that reducing the streamer separation from 75 down to 37.5 m would make the number of sail-lines double, and the cost increase similarly. However, it is not trivial to claim that the seismic data is twice as good. Recent developments in image processing make use of Full Waveform Inversion technology, to image and generate a detailed subsurface model directly from the raw recorded wavefields. This method make use of all the recorded data, being primaries, ghosts, multiples and diving-wave refracted energy. A key point is to design a densely and well sampled acquisition that indeed captures all of the wavefields and as much reflected energy as possible in all azimuths with both short- and long-offsets.

The Barents Sea Wisting challenge

Compared to numerous more conventional hydrocarbon plays, the Barents Sea and more specifically the Wisting area has some challenges that require a slight bit of re-thinking in terms of designing the acquisition setup such that high quality seismic images can be used to characterize the subsurface and the oil proven reservoir targets with great accuracy. Firstly, the primary targets lie very shallow. The water depth is around 400m and the reservoirs themselves are located at only 600-800m total depth, so the overburden constitutes only ~200m of sediments. The second key issue is related to the huge geological uplift (1.5 to 2km) that has occurred in this area, which has brought very high velocity sediment-layers into the shallow strata, making amongst other issues, the water-bottom into a very hard and strong reflector. The third and maybe less well-known issue in this area, is related to how hydrocarbons and oil-filled reservoirs stand out compared to waterfilled areas. The Wisting field itself was discovered in 2013 through well 7324/8-1, which discovered an oil leg of ~50m in the Realgrunnen Subgroup formations, Stø, Fruholmen and Snadd of Jurassic age. Later exploration wells targeting the same formations within 5-6km distance, 7324/8-2 and 7324/7-1 were both found to be waterfilled or dry with minor oil-shows, illustrating that drilling a fault bound closure in this area needed a more concise method to separate oil-, gas- and water-bearing reservoirs from each other. Figure 1 shows a cross-section from the area through most of the key structures. The green arrow points to prospectivity in the Stø formation.

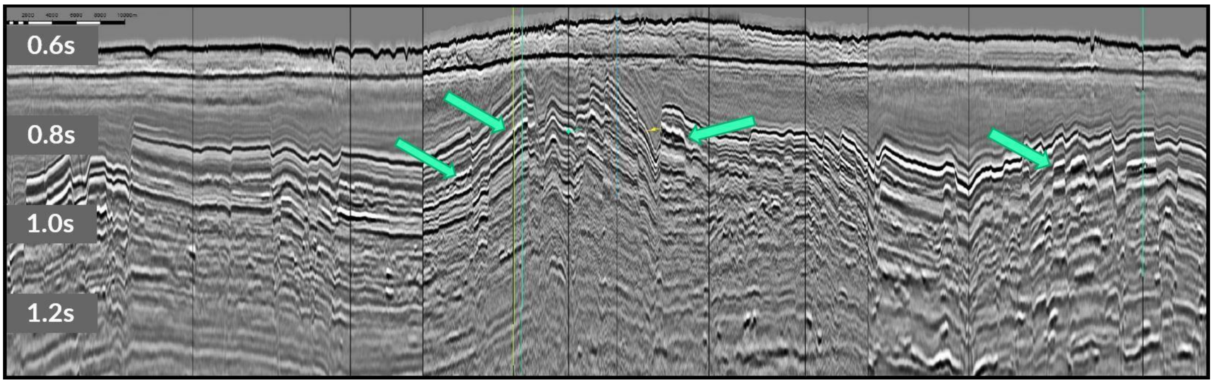

Figure 1 *Seismic cross-section over the area of interest. The green arrows point to interesting prospects in the Stø formation.*

As the targets in the area are very shallow, high resolution seismic imaging has been a go-to method. In 2016 the p-cable method was used to acquire a very detailed high resolution 3D seismic dataset. A disadvantage of this setup is the lack of offsets (100m max) as well as the very small line-spacing, which reduces the efficiency to around 1/10 of what a conventional seismic acquisition normally achieves. With the above in mind and also the success of using an advanced acquisition setup for exploration in nearby licenses back in 2019 (Dhelie et al., 2020), we slightly modified this setup to still use a single vessel but dropping the four sources even further back, successfully achieving a -250m negative nominal near-offset. Full azimuth zero-offset coverage was achieved while also including 3750m long offsets for proper AVO work, as this has proven to give reliable separation of the fluid components of the reservoirs. Efficiency is maintained by using many streamers and four sources deployed wide to get an almost equal shot density in both inline and crossline direction. The final acquisition setup is illustrated in Figure 2.

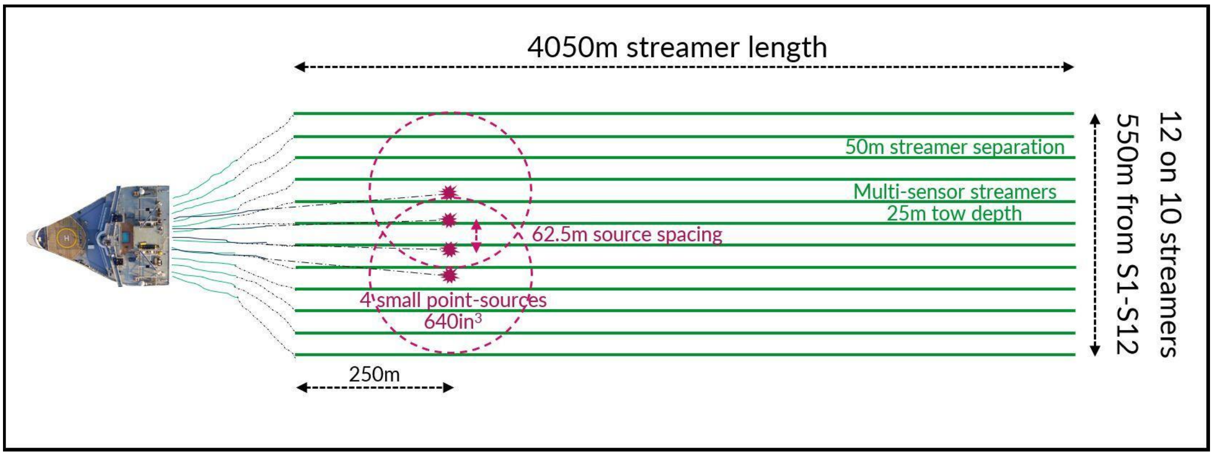

Figure 2 *The acquisition layout used for the two surveys. Note the 250m negative source offsets that improves the important near offset coverage.*

Multi-parameter Full Waveform Inversion Imaging

Using the high-resolution acquisition design described above, two overlapping surveys were efficiently acquired orthogonal to each other covering the Wisting field and the surrounding prospective area. The objective was to discover the extent and location of available hydrocarbons in the survey area in order to optimise field development. For imaging, we used a sophisticated multi-scattering least-squares approach to maximise the utility of the newly acquired high-resolution data. Recent advances in full-waveform inversion (FWI) have transformed this industry standard tool from being a method that provides a limited bandwidth velocity model update, using only the diving waves, to becoming a broad bandwidth imaging tool using both reflection and transmission arrivals along with their ghosts and multiples. Multi-Parameter FWI (MP-FWI) imaging has demonstrated the capability to make use of minimally processed input data to simultaneously determine velocity and a variety of subsurface attributes, such as anisotropy, relative density, reflectivity and even angle-dependent reflectivity for AVA analysis (McLeman et al., 2023). In the following, we use the MP-FWI imaging approach as described by Rayment et al. (2021) to simultaneously determine velocity and reflectivity models directly from the raw data.

Traditionally, processing and imaging a new acquisition involves a time-consuming pre-processing sequence run in a sequential fashion, including noise attenuation, deghosting, designature, demultiple, regularisation, followed by model building and imaging. Performing stages such as demultiple in the Barents Sea is non-trivial due to the relatively shallow, hard, rugose seafloor. Despite the improvements of this acquisition design (particularly the inclusion of data around zero offset), a conventional workflow would still be time-consuming. The need to perform such extensive pre-imaging data processing stems from the inability of legacy migration technology, such as Kirchhoff and reverse-time migration (RTM), to correctly map all multi-scattering arrivals back to their generators due to the use of the Born approximation. MP-FWI imaging, on the other hand, makes no such assumption and uses all reflection and transmission arrivals, including their ghosts and multiples, during the inversion to provide improved subsurface illumination, resolution, and amplitude fidelity. Since data pre-processing is not required, there is no risk of primary attenuation from common conventional processing techniques such as adaptive subtraction.

A smooth initial velocity model was built from the available well logs and extrapolated along regional horizons. The associated anisotropy model was built using regional knowledge. Diving wave FWI was then performed using a frequency continuation approach of 5 Hz, 9 Hz and 12 Hz. Visco-acoustic MP-FWI imaging was then commenced with an initial maximum frequency of 16 Hz and a frequency continuation approach of 21 Hz, 28 Hz and 40 Hz. Given the complex near-surface, hard sea floor, and that the target reservoirs sit within the first 1 km, a top-down approach was used. An inversion to 1km was run first followed by a second pass to the desired maximum output depth of 3 km. The second pass provided further refinement to the imaging within the first 1 km.
In Figure 3, the initial model and MP-FWI imaging derived velocity are overlaid on their respective Kirchhoff preSDMs, which both used pre-processed data as input. It is clear that the MP-FWI imaging adds considerable detail to the velocity model, resolving the velocity contrasts across the tilted fault blocks and the varying layers within the fault blocks. In addition, there is considerable lateral and vertical velocity variation and strong contrasts directly below the seafloor, which are being resolved by MP-FWI imaging. The underlying preSDM image and well-tie both demonstrate significant improvement.

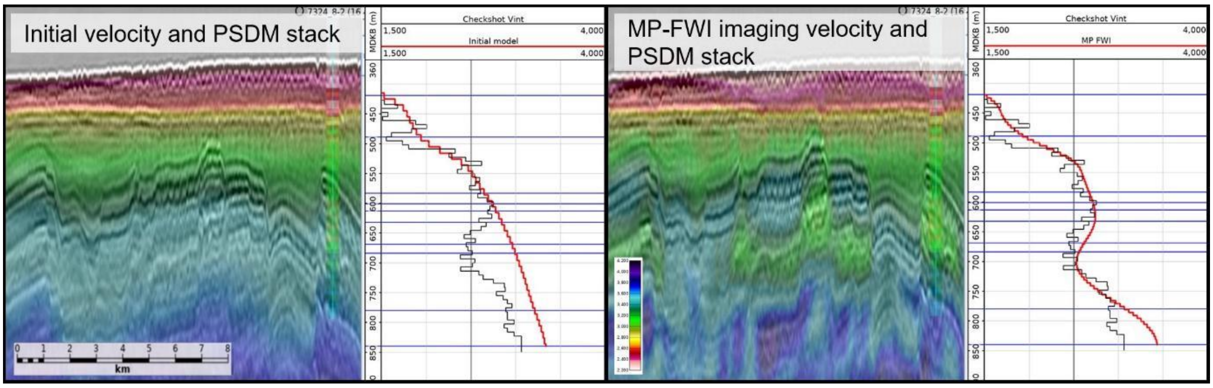

Figure 3 *Cross section comparison between the initial velocity and a 40Hz MP-FWI imaging derived velocity model, overlaid on the PSDM stack. The initial and updated well-tie is also shown.*

Figure 4 shows depth slices at 850 m of the same velocity fields overlaid with the 40 Hz MP-FWI imaging reflectivity. There is excellent geological conformance of the velocity to the fault blocks, which are clearly imaged in the reflectivity.

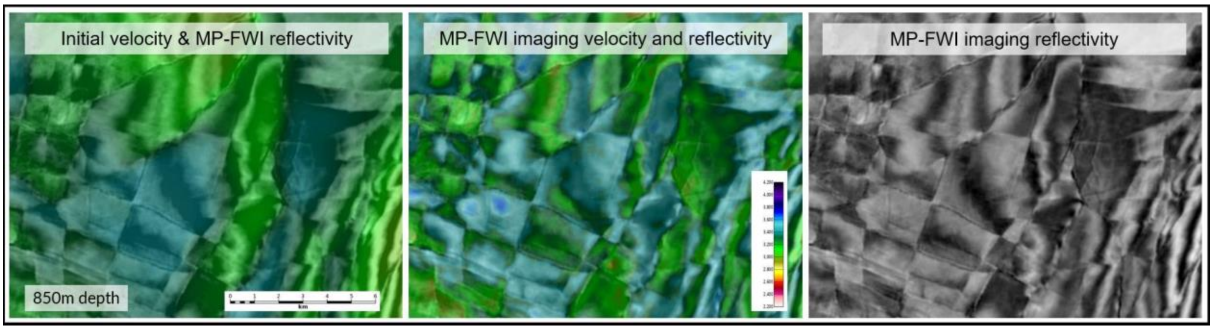

Figure 4 *Depth slice at 850m showing the initial velocity model overlaid on the MP-FWI reflectivity (left), the MP-FWI velocity overlaid with the same reflectivity (centre), and the reflectivity alone (right).*

Figure 5 compares the 40 Hz MP-FWI imaging reflectivity determined directly from the raw data from the new acquisition data against the final preSTM stack from the legacy acquisition (filtered to the same frequency and depth converted with the MP-FWI velocity field along with velocity overlays. The benefits of the improved acquisition design and sophisticated imaging technique are clear. There are significant improvements in event delineation, fault imaging and structural interpretability in the MP-FWI imaging result. There is a significant improvement of the low frequency response because the ghosts have been properly used by the inversion in the construction of the primary reflectivity.

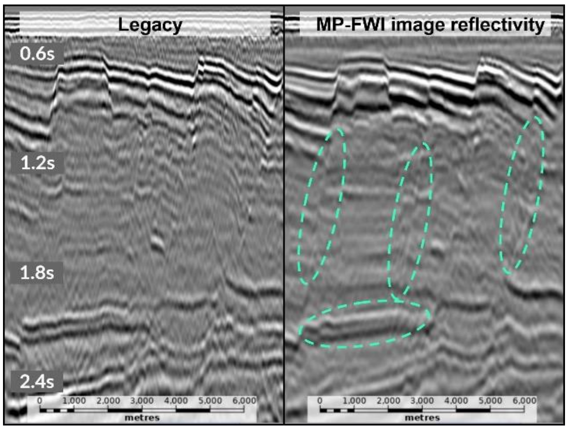

Figure 5 *Comparison between legacy seismic and MP-FWI image reflectivity. The green areas highlight clear image improvements.*

Conclusions

The Barents Sea Wisting area presents unique challenges for seismic acquisition and imaging, due to the shallow reservoirs and the high velocity sediments. An advanced high-resolution seismic survey has been developed and designed to provide negative-, zero- and long-offsets, by towing four sources inside the streamer spread with a negative nominal offset of -250m. The method delivers a combination of high density and efficiency using only a single seismic vessel. The data is imaged using the latest MP-FWI technology capable of outputting high resolution velocity, density and reflectivity parameters. The method uses the raw recorded input data, inclusive of all ghosts and all multiples to build a detailed 3D earth model. Comparisons to legacy data show improvements in event delineation, fault imaging and improved structural interpretability.

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