The road to 200Hz FWI using hybrid streamer and node acquisition over Nordkapp

G. Henin[1], L. Janot[1], H. Jiang[1], S. Masclet[1], N. Salaun[1], J.E. Lie[2], V. Danielsen[2], P.E. Dhelie[2]

[1] CGG; [2] AKER BP

Summary

The Nordkapp Basin is a large under-explored salt basin of the Barents Sea. Despite several exploration campaigns over the past decades, no successful drilling was achieved. A new hybrid survey combining streamers and nodes was acquired in 2021 to unlock this new play. Sparse nodes recording continuously during a 3 months period, with a nominal spacing of 1200m in both inline and crossline directions, supplemented a natively dense source over streamer data acquired with 7 simultaneous sources and 18 cables. We present here a fully data-driven FWI flow designed to exploit and combine the different types of data recorded by this survey to obtain optimal velocity model. The flow combines the ultra-low frequencies diving waves obtained from node interferometry and the ultra-wide offsets of node active seismic gathers to obtain a background velocity model for accurately imaging salt flanks. For higher frequency FWI, the streamers dataset with its dense spatial sampling including more near offsets traces complemented the sparse OBN data. The final 200Hz FWI product allows to directly distinguish in the velocity model the Carnian sands target and reveals details in shallow as small as 3 to 4m, which opens up new possibilities for hydrocarbon and shallow hazard detections.

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Introduction

The Nordkapp Basin, located in the south-western part of the Barents Sea, is a large, under-explored salt basin with a proven petroleum system containing mature Triassic source rocks. Despite several exploration campaigns carried out over the past decades, no successful drilling has been achieved in this very complex area. To overcome these challenges and unlock this new play, a new seismic acquisition design was proposed by Dhelie et al. (2021). This survey was first assessed through a comprehensive survey design (Lie et al., 2021), with the goal to combine both high-resolution streamer imaging to delineate thin sand layers and wide-azimuth records to correctly image sharp salt boundaries. A hybrid design with streamer and ocean bottom nodes (OBN) was then retained. The source-over-streamer spread data is natively dense with good near-offset coverage, thus offering good conditions for imaging, while the OBN data provides full-azimuth coverage and long-offset data for deeper diving-wave penetration and velocity updates (Dellinger et al., 2017). In this paper, we present a method designed to exploit and combine the different types of recorded data to obtain an optimal velocity model. It involved solving salt diapir imaging challenges and recovering high-frequency details within the sediment layer variation to finally provide very high-resolution Full-waveform Inversion (FWI) Imaging.

FWI using node data

The proposed acquisition design combines 18-cable streamer data with sources located in front of and above the streamers, and a sparse OBN carpet with 1200 m node spacing (Figure 1a). The OBN data is natively heavily blended due to the hexa-source (TopSource - TS) and front-source (FS) setup. The source firing sequence was selected to simplify streamer deblending; however, the 300ms dithering was not sufficient to optimally randomize signal in the low frequencies, leading to significant amounts of residual noise in this frequency range after deblending (Figure 1b, orange arrows). The seismic below 3 Hz could therefore not be used for initial FWI updates. Conventional velocity model building flows try to overcome this lack of low frequencies with elaborate initial velocity models incorporating manual salt interpretation. But with such complex geology, FWI would have to start from a higher frequency with a conventional approach. This would make it prone to cycle-skipping due to the potentially inaccurate information incorporated in the initial model, relying heavily on early interpretation.

The continuous records from nodes, deployed before the start of the streamer acquisition, offered an alternative to conventional active source data, thanks to a recording period of 3 months. The interferometry method uses continuously recorded seismic data to reconstruct virtual source data at the receiver locations, granted that a sufficiently long continuous record is available (Schuster, 2009). Successful experiments with Middle East land datasets (Le Meur et al., 2020) have shown its applications for velocity model building. Cross-correlations combined with temporal stacking provide virtual source gathers exploiting both active sources and environmental noise contributions. Sparse ultra-long offset gathers with 1200 m between traces in both directions could then be generated by interferometry, properly reconstructing surface and diving waves down to 1 Hz (Figure 1b). Interferometry provided a solution to recover low-frequency signal, which could not be obtained by straight denoising of the active source data.

With 991 nodes and virtual shots located at actual node positions, interferometry-based virtual gathers had up to 50 km of offsets available, allowing an update down to 6 km of depth. FWI with passive node data was run up to 3 Hz, as the spatial sparseness of the data appeared to affect the higher frequency model updates. Interferometry ensured convergence of the FWI starting from 1 Hz with a smooth initial velocity model, even in the case of salt walls with several kilometres of height (Figure 1c). As the interferometry uses the raw recorded data, such an update can be obtained at the very beginning of the velocity model building workflow. Following this first step, active seismic nodes were then used for FWI updates above 3 Hz. After deblending, reflections and diving waves could be properly retrieved above 3 Hz, even for up to 40 km of offset and 20 s of record length (Figure 2a). The use of active seismic wide-azimuth gathers exhibiting usable diving waves up to very large offsets allowed for stabilization of the FWI results. Node data conveniently supplemented the streamer data, which are dense but limited in offset and hence in diving-wave depth penetration.

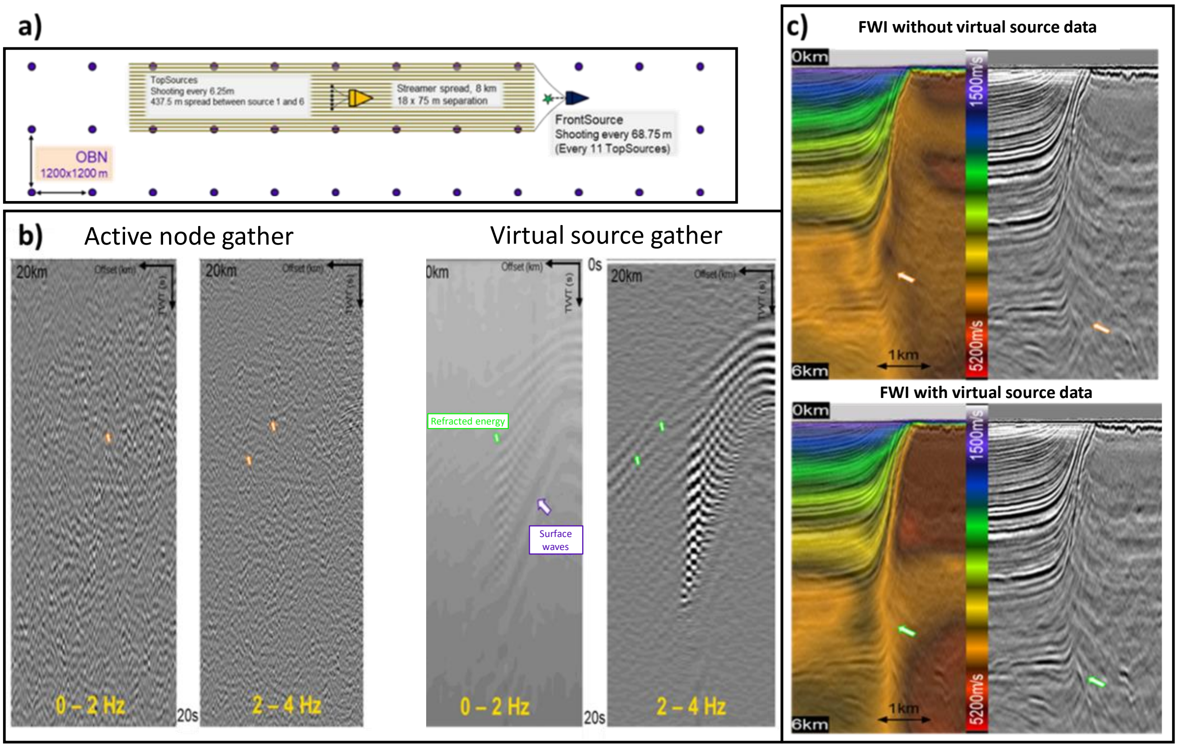

***Figure 1**: Node Interferometry; a) Hybrid acquisition design; b) Comparison of active seismic and virtual source gathers; c) FWI with and without interferometry gather contribution.*

In the Nordkapp basin, Mesozoic salt mobilization forms wall-like salt diapirs accompanied by high seismic velocities in the surrounding sediments due to the tertiary uplift. This makes it difficult to distinguish salt velocities close to 4500 m/s from those of the sediments at around 4200 m/s. Compared to the FWI result using only streamer data, the proposed FWI flow using active and passive node data improves the definition of crucial salt contours from the very first low-frequency updates (Figure 2b) without the need for manual salt body interpretation. It is an alternative to conventional ray-based tomography methods and also mitigates cycle-skipping risks by lowering the starting frequency down to 1 Hz.

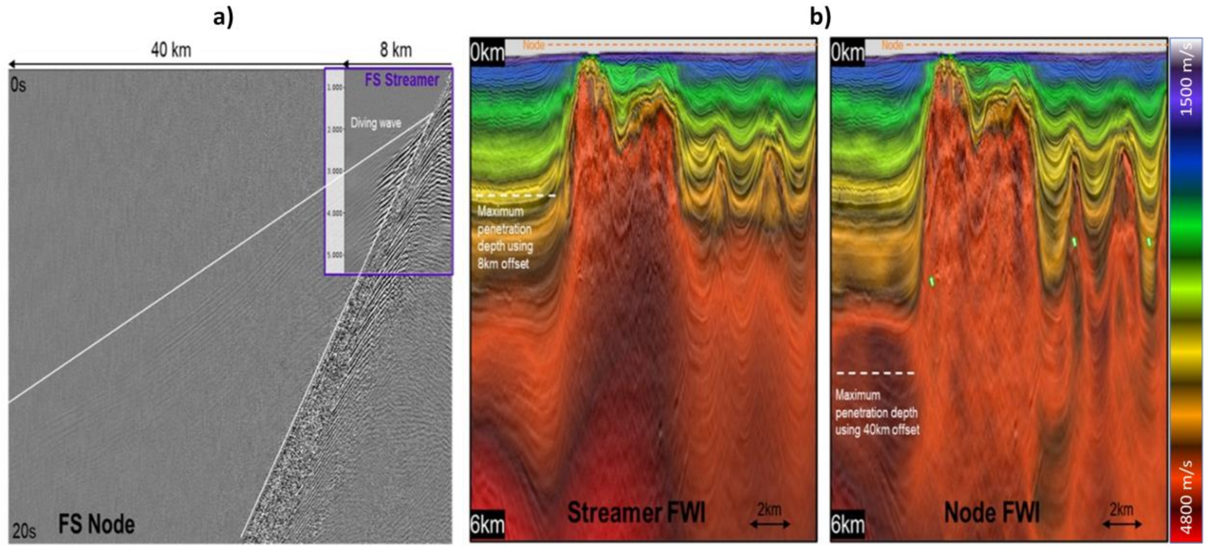

***Figure 2**: Uplift from node FWI over streamer FWI: a) Nordkapp ultra-long offset OBN gather after deblending; b) Comparison of streamer and node FWI – migrated seismic overlaid with velocity models; Orange dotted line shows the extent of the node carpet, deployed to cover the salt diaper area.*

Moving to high-resolution FWI

With the latest FWI developments (Zhang et al., 2018), effective use of the full wavefield in the inversions is now achievable. Primary reflections, multiples and ghosts are especially valuable in high-frequency updates and contribute to details in the velocity model. When the inversion frequency is increased, the velocity model can reveal reservoir details not observed with conventional seismic reflection imaging workflows. The highest resolution of FWI is obtained through the exploitation of all types of waves in the records to better balance illumination, which also avoids migration artifacts and spatial sampling issues. Thanks to the use of node gathers, the long wavelength trend of the velocity model was accurately estimated. However, the lack of near offsets related to the sparse node grid for the recorded primaries and multiples prevented FWI updates above 10 Hz for the node data.

For higher frequency FWI, the streamer dataset with its dense spatial sampling and more near-offset data is better suited than the sparse OBN data because it avoids the spatial aliasing issues for the high frequencies. For these model updates, the whole records were used, without any muting. The inversion exploited primaries and multiples to add details to the velocity model obtained via node-based FWI. For conventional imaging production, the 40 Hz FWI update was retained as the migration velocity model. This mid-frequency result already includes clear details of the Carnian sand target (Figure 3c, black arrows) in the velocity model. This model was used for streamer RTM production, combined with an advanced pre-imaging de-multiple, to obtain consistent target events without distortion from near to ultra-far stacks (Figures 3a and 3b).

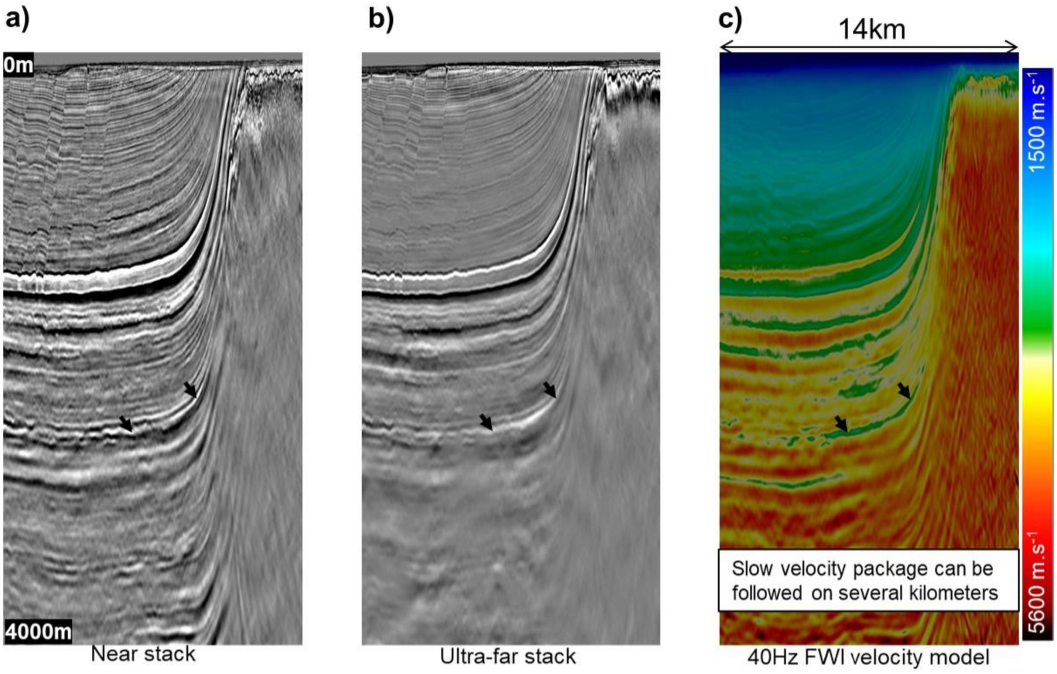

***Figure 3**: 40 Hz FWI: reverse-time migration (RTM) results for a) near stack and b) ultra-far stack. c) 40 Hz FWI velocity model used as final migration model.*

In addition to this 40 Hz FWI product, a shallow resolution assessment was performed prior to potential drilling (Espin et al., 2022). While source-over-spread data is designed to properly sample the near surface (Figure 4a), the use of FWI, when pushed up to 200 Hz, can lead to an ultra-high-resolution image. The 200 Hz FWI velocity and derived FWI Image (Figures 4c and 4b, respectively) is clearly outpacing the resolution of the Kirchhoff pre-stack depth migration (K-PSDM), revealing details as small as 3 to 4 m. The extra illumination from the full wavefield allows for increased spatial resolution, revealing highly dipping thin geological structures. In the very shallow part of the data, immediately below the water bottom, small gas pockets and pockmarks hardly visible in the conventional high-resolution volume are clearly delineated thanks to FWI Imaging. High-resolution velocity information in addition to reflectivity opens up new possibilities for advanced drilling hazard detection.

Conclusions

For this Barents Sea exploration survey covering 3700 km^2, FWI with node data combining active and passive seismic helped in improving salt body delineation and overcoming streamer data shortcomings. However, the node carpet sparsity ultimately prevented their usage for direct imaging or very high-frequency FWI updates. Dense streamer data remains the dataset of choice in those cases. Both data types had to work in tandem to achieve optimal velocity model building and imaging. A fully data-driven approach combining ultra-low frequencies, ultra-wide offsets and dense near offsets led to a high-definition velocity model with accurate salt flank imaging, usable as a 3D attribute for hydrocarbon detection. This methodology, designed to get the most out of hybrid acquisitions combining streamers and sparse nodes, is consolidating a new acquisition and processing framework, assessed here for shallow water salt imaging, but now potentially reusable for many other shallow water settings.

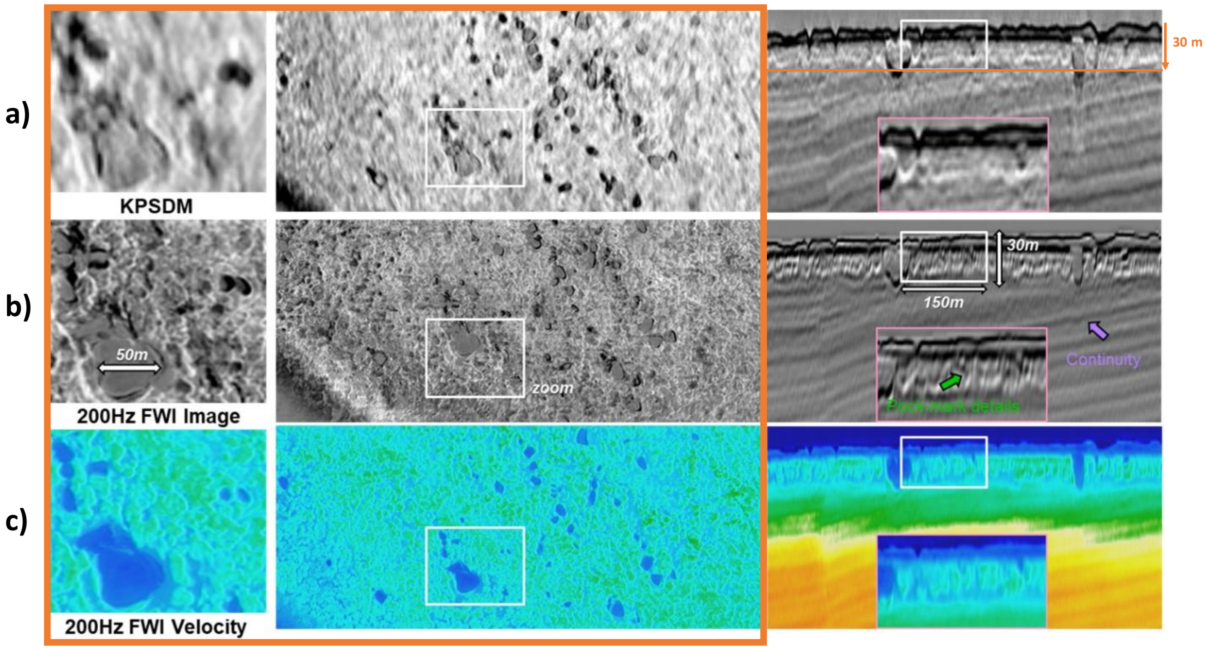

Figure 4: *Shallow imaging uplift obtained with 200 Hz FWI; a) K-PSDM result, b) 200 Hz FWI Image and c) corresponding 200 Hz FWI velocity model.*

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