Hybrid Streamer/Sparse node acquisition: Unlocking new targets below Base Cretaceous Unconformity with Elastic and High-Resolution FWI

S. Masclet[1], F. Wang

[1] CGG

Summary

The hunt for less obvious deeper targets below the Base Cretaceous Unconformity (BCU) within the Norwegian North Sea greatly relies on the accuracy of the velocity model as it impacts the definition of the structural traps. The presence of the limestone/carbonate sequence with high velocities overlying the targeted lower velocity mudstone units represents the main challenge in term of velocity model building and is usually out of the reach of diving waves for the full waveform inversion (FWI) application when using streamer-based data with offset limited to 8km. The recent shift of acquisition industry toward hybrid acquisition combining streamer and sparse node opens the road for deeper application of FWI and even more. In this paper, we show how this new hybrid acquisition design can help to build a reliable high-resolution velocity model down to the Brent level. Moreover, we also present how elastic FWI enables us to better explain the elastic effects induced by the large impedance contrast at BCU level.

Hybrid Streamer/Sparse node acquisition: Unlocking new targets below Base Cretaceous Unconformity with Elastic and High-Resolution FWI

Introduction

Exploration in the Northern North Sea has a long history. Nonetheless, new fairways are still being identified and exploration models developed. Recent discoveries in the upper Jurassic sands (Dugong field in 2020, Echino South field in 2019), which sit just below the Base Cretaceous Unconformity (BCU), have highlighted the need for more detailed structural mapping of the trap elements and, therefore, the need for more accurate velocity model down to the sub-BCU level. However, the presence of the limestone/carbonate sequence with high velocities overlying the targeted lower velocity mudstone units represents the main challenge in term of velocity model building and is usually out of the reach of diving waves for the full waveform inversion (FWI) application when using streamer-based data with offset limited to 8km. In response to the increased focus on near-field exploration and the hunt for less obvious deeper targets within the Northern Viking Graben (NVG) region of the Norwegian North Sea, a hybrid blended acquisition has been recently completed combining variable-depth streamers and sparse nodes (300mx300m) over west of the Fram area. This acquisition design aims at taking advantage of the full-azimuth coverage and longer offset data up to 24km to extend the application of FWI down to the sub-BCU level. In this paper, we show how this new hybrid acquisition design helps us build a reliable high-resolution velocity model down to the Brent level thanks to deeper penetration of diving waves. Moreover, we also present how elastic FWI, which was used to retrieve a long-wavelength velocity model, allows us to better explain the elastic effects induced by the large impedance contrast at BCU level before moving to high-resolution FWI.

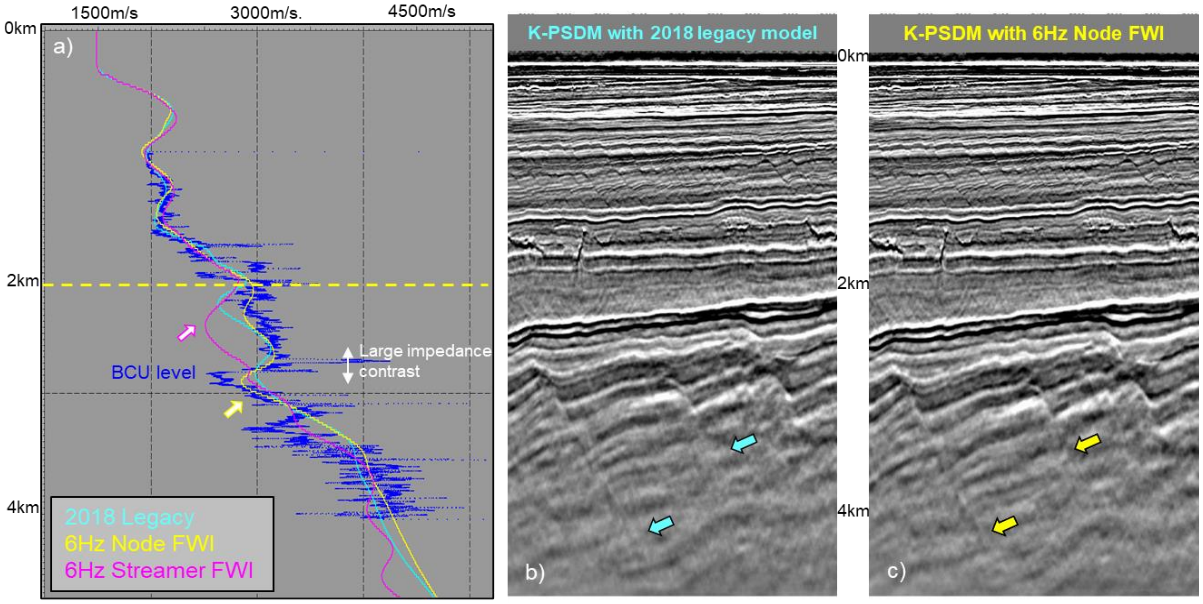

Figure 1 *a) Velocity profile at well location of sonic (dark blue), 2018 legacy model (cyan), after 6Hz acoustic FWI with streamer data (pink) and after 6Hz acoustic FWI with node data (yellow). KPSDM stack images using b) the 2018 legacy model and c) the 6Hz FWI model with node data.*

Exploiting diving waves below BCU level

The Fram area is situated within the NVG region of the Norwegian North Sea and was initially surveyed by a contiguous 44,000 km^2, north-south (N-S) orientated, 8km offset variable-depth streamer dataset. These data were processed in 2018. A velocity model was built with FWI and tomography, and the image was obtained with attenuation-compensating Kirchhoff pre-stack depth migration (Q-KPSDM). Figures 1a and 1b show respectively the legacy velocity model (Cyan velocity profile overlayed on the sonic data) and the corresponding KPSDM stack image. A complementary 14,000 km^2, East-West (E-W) orientated, triple-source multi-sensor dataset was acquired during 2020 and 2021 over the NVG region. The aim was to improve subsurface imaging to de-risk near-field exploration targets. On top of this additional streamer acquisition, it was decided to investigate the benefit of sparse node acquisition over the Fram area. The nominal spacing of nodes of this acquisition is 300m, and the receiver locations were then decimated to 900m spacing for this velocity model building exercise. The node carpet provides wide azimuths and long offsets, up to 24 km, which have demonstrated the potential for deeper FWI updates (Lie et al., 2022). Diving-wave ray analysis performed using the 2018 legacy model demonstrates that the maximum penetration depth of diving waves is increased from 2km depth to 4.5km depth when moving from 8km to 24km maximum offset. Starting from a smoothed version of the 2018 legacy velocity model, acoustic FWI (A-FWI; Zhang et al., 2018) was run using only the diving waves with the objective to obtain a reliable low-wavenumber update, crucial for higher frequency model building. We compare here the diving-wave FWI results using only streamer or only node data. In Figure 1a, the 6Hz FWI using node data manages to catch the velocity inversion below the BCU and provides a good velocity background down to 4.5km depth. In comparison with the 2018 legacy model, the 6Hz node FWI more closely follows the sonic log and, as a result, provides a superior migrated image at the target level with an improved fault imaging (Figure 1c).

Elastic effect at BCU level

It is well known that the presence of large contrast scattering bodies or sharp interfaces (e.g., salt bodies, basalt and chalk layers) induce elastic effects, causing acoustic FWI to struggle in such complex areas. Mode conversions between P- and S-waves occur at these sharp boundaries. As a result, the diving-wave cone which we usually rely on for the low-wavenumber updates is contaminated by elastic effects (Malcolm and Trampert, 2011), producing biased acoustic model updates (Masmoudi et al., 2022). In this case, the BCU with large velocity contrasts caused by the superposition of the carbonate and mudstone layers can potentially induce elastic effects (Figure 2a). The node data with recorded offsets up to 24km provide diving wave penetration below the sub-BCU level, which offers an opportunity to investigate the potential elastic effects around this velocity contrast. We run acoustic and elastic modelling using an edited 2018 legacy model in which the sharp velocity contrast at BCU was reinforced. The results displayed in Figure 2a and 2d show that initial velocity model provides a better data fit between real data and synthetics generated by elastic modelling compared to acoustic one especially for the longer offsets (over 12 km).

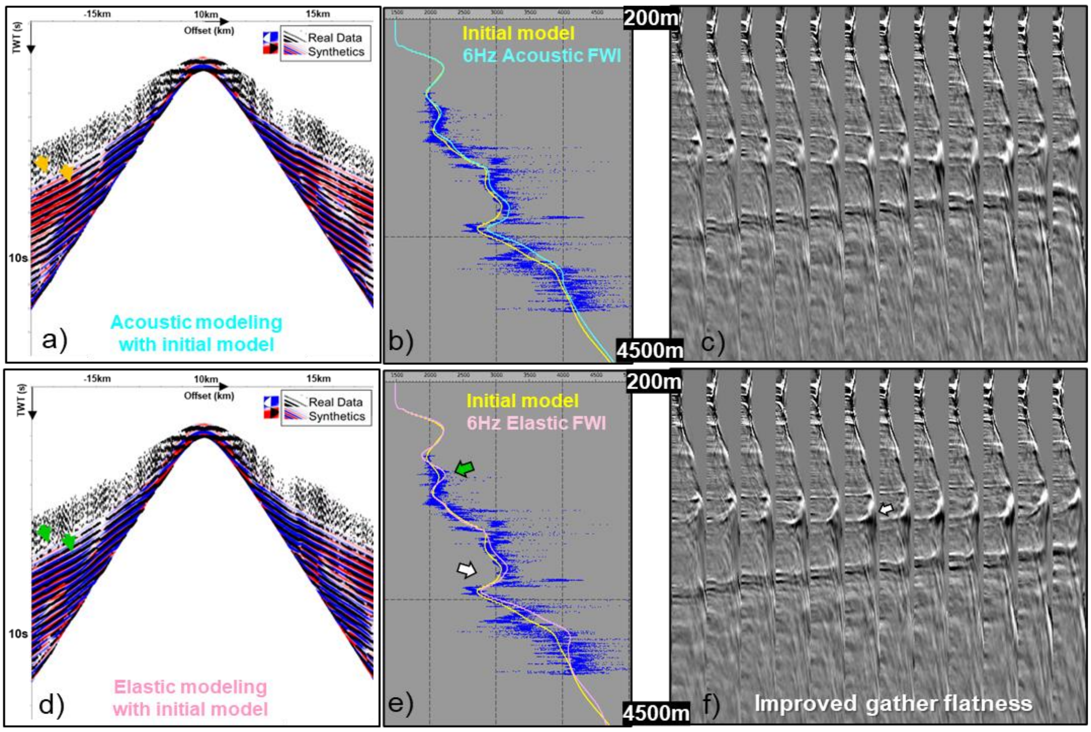

Figure 2 *Elastic effect – Comparison of a) acoustic and d) elastic modelling using the initial velocity model. Comparison of b) 6Hz acoustic FWI and e) 6Hz elastic FWI with node data, and their corresponding migrated gathers using c) acoustic model and f) elastic model*

This QC proves the benefits of using elastic FWI for the data acquired with such long offsets where elastic effects become stronger and acoustic approximation is not always valid. While allowing for better explanation of the data, elastic FWI can be more challenging due to the additional parameter needed to describe the medium, namely the shear-wave velocity (Vs). This requires some prior knowledge and/or a multi-parameter inversion. Here we inverted for Vp using hydrophone data with fixed Vp/Vs ratio coming from well logs. This was a pragmatic solution that seemed appropriate for this geological area. The results of the acoustic and elastic inversions are displayed in Figures 2b and 2e. The elastic FWI with node data improves the velocity profile by further decreasing the velocity at BCU level (Figure 2c, white arrow) and reinforcing the velocity contrast compared to the acoustic inversion. As a results, the migrated gathers using the elastic FWI (E-FWI) model exhibit an improved flatness compared to the ones migrated using the A-FWI (Figure 2c & 2f) model. We can also notice in the shallow section of Figure 2e (green arrow) the velocity increase retrieved with E-FWI, corresponding to the presence in the shallow section of injectite features.

Moving to high-resolution FWI

The development of time-lag FWI (TLFWI) has enabled the use of the full wavefield in the inversion process (Salaun et al., 2022). The addition of the reflection energy in the inversion allows obtaining high-resolution velocity model. One of the main requisites to include the full wavefield in the FWI is to have an accurate and reliable long-to-mid wavelength update to which the resolution will be added. Usually, the depth of this reliable model is a function of the maximum penetration depth of the diving waves. In our case, the 6Hz diving-wave elastic TLFWI with node data provides an accurate and reliable long-to-mid wavelength update down to the Brent level. To move to the high-frequency update, it was decided to run acoustic TLFWI as reflections usually suffer less from the elastic effects compared to diving waves. With three input datasets available over the Fram area (N-S and E-W streamer datasets and full-azimuth node dataset), different combinations and workflows were tested and assessed. Finally, we decided to run a joint node and streamer acoustic TLFWI which allows to combine all benefits brought by each dataset (Lie e al, 2022): the dense lateral receiver sampling from the streamer datasets and the long offset and full azimuth information from node data. The joint node and streamer A-TLFWI was run up to 30Hz, providing a high-resolution velocity model with a very good fit with the sonic log down to Brent level (Figure 3c). The 30Hz A-TLFWI manages to detect injectite fast velocity contrasts despite its very limited size and to catch the thin limestone layer sitting on top of the target sandstone units at the BCU level (Figure 3a vs. 3c), whereas the 2018 legacy model had to rely on tomography for the deeper update and may have suffered from residual multiples. Besides, the high-resolution velocity model can also be used as an attribute for direct geological interpretation. Indeed, below the fast limestone layer at BCU level, we can clearly distinguish, within the low velocity mudstone unit, some alternating of faster and slower velocity layers corresponding, respectively, to shale and sandstone layers (Figure 3c). Figures 3b and 3d highlight the improvement on the migrated seismic from the 2018 legacy model to the 30Hz joint streamer and node TLFWI model. The migrated seismic image is simplified and exhibits less distortion at the lower cretaceous level and all sub-sequent layers down to the Brent (Figures 3b and 3d). On the tilted blocks below the BCU, the reflectors appear more continuous up to the fault planes, which is crucial to properly delineate potential prospects and can have important implications for volumetric calculations.

Discussion and Conclusion

In this paper, we demonstrate the potential of the hybrid acquisition combining streamer and sparse node. Indeed, node data provide the long offsets required to capture the sharp impedance contrast and the velocity inversion below the limestone layer. In addition, with long recorded offset, the expected elastic effects induced by the large impedance contrast at this level can be observed and inverted for using elastic TLFWI, which results in a reliable long to mid wavelength update down to about 5km depth. This update subsequently unlocks the use of full wavefield FWI at the sub-BCU level. Full wavefield from streamer and node data are then jointly inverted up to 30hz under an acoustic assumption, producing an accurate high-resolution velocity model down to sub-BCU level. Seismic imaging and, especially, fault imaging are significantly improved with more continuous events up to the fault plane. This new acquisition design opens the possibility to apply the most advanced subsurface imaging technologies, such as elastic TLFWI, down to the reservoir depth. It may therefore become part of the response to industry for the hunt of less obvious deeper targets within the Norwegian North Sea.

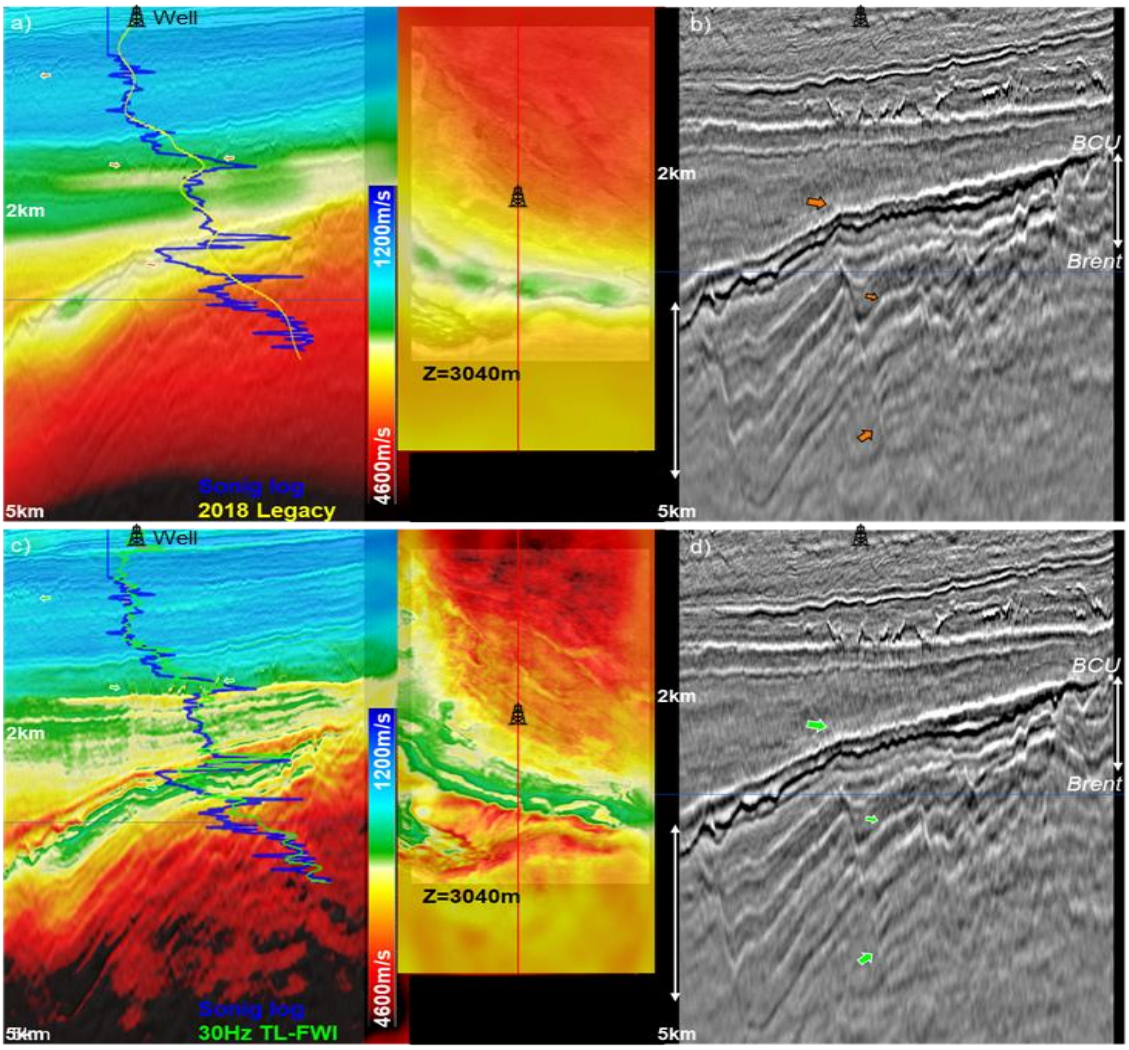

Figure 3 *High-resolution TL-FWI - Comparison of 2018 legacy model (section with velocity profile overlayed on the sonic log and depth slide view) (a) and its migrated image (, b). Equivalents for the 30Hz joint node and streamer TLFWI velocity model are shown in (c) and (d).*

Acknowledgements

We would like to thank CGG Earth data for permission to publish this work. We also thank our colleague Jaswinder Mann-Kalil for useful discussions and her geological insight.

References

Lie, J. E., Vinje V., Dhelie, P. E., Jiang H., Danielsen V., Salaun N. [2022] Nordkapp Topseis/Node Acquisition – Lessons from a Modelling Study. First Break, Volume 40, Issue 2, Feb 2022, p. 41-99.

Malcolm, A. E., and J. Trampert. [2011] Tomographic errors from wave front healing: More than just a fast bias. *Geophysical Journal International*, 185, 385-402.

Masmoudi, N., Stone, W., Ratcliffe, A., Refaat, R. and Leblanc, O. [2022] Elastic Full-Waveform Inversion for Improved Salt Model Building in the Central North Sea. *83th EAGE Conference & Exhibition*, Extended Abstracts.

Salaun, N., Wright, A., Pintus, A., Jiang, H., Janot, L., Roodaki, A., Dehlie, P.E., Lie, J.E. and Danielsen, V. [2022] High-resolution full-waveform inversion for structural improvement and prospects delineation: A case study at Haugaland high. *83th EAGE Conference & Exhibition*, Extended Abstracts.

Zhang, Z., Mei J., Lin F., Huang R., and Wang, P. [2018] Correcting for salt misinterpretation with full-waveform inversion. *88th Annual International Meeting, SEG*, Expanded Abstracts, 1143–1147.