High-resolution FWI Through Dual Azimuth Seismic Data Integration In Halten Dønna Terraces Area: A Comparative Study

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Summary

This study presents a pioneering investigation into the advancements in seismic velocity model building through the integration of dual azimuth seismic datasets in the challenging geological setting of the Norwegian Sea. Leveraging a legacy dataset and a newly acquired seismic with long streamer-tails and high-frequency Full Waveform Inversion (FWI) up to 24 Hz, our study aims to provide a comparative analysis between the traditional single azimuth approach and the innovative dual azimuth methodology. The geological complexity of the Norwegian Sea, marked by high impedance contrast, rough surfaces, and intricate anisotropy, adds further significance to this study. Through meticulous processing of legacy and new datasets, our results showcase a superior and high-resolution velocity model. The dual azimuth strategy not only enhances subsurface illumination but can also contributes to improved reservoir predictions. This study marks a milestone, setting the stage for future seismic studies, underlining the importance of multi-azimuth acquisition strategies for elevated subsurface imaging in challenging geological environments.

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Introduction

Seismic velocity model building plays a pivotal role in understanding subsurface structures, aiding in hydrocarbon exploration and reservoir characterization. This study focuses on advancements in velocity model building through the integration of dual azimuth seismic datasets acquired in the Norwegian Sea. Building upon a legacy study that employed a single azimuth dataset, our study leverages the synergy between a historical dataset and a newly acquired one, featuring extended cable lengths and higher frequency FWI.

The Norwegian Sea area has several interesting features and complex geology. The overburden is characterized by high impedance contrast, rough surfaces, and complex velocities and anisotropy due to periods of subsidence, uplifting and erosion. There is also shallow glacial morphology which generates strong noise and multiples. Deeper below the overburden there are tilted fault blocks possibly containing Jurassic sandstone reservoirs in structural traps. In the Cretaceous section there are clastic systems and stratigraphic traps (Faleide et al., 2015). The area of study is highlighted in Figure 1.a.

In this study, our primary focus is to compare the efficacy of legacy velocity model building using a single azimuth dataset against a more advanced velocity model building (VMB) methodology employing a dual azimuth dataset. The new model building methodology takes advantage of two long streamer-tails spanning 10 kilometres each. Additionally, Full Waveform Inversion (FWI) has been executed with an increased frequency range, reaching up to 24 Hz. This comparative analysis aims to shed light on the improved insights gained through the integration of dual azimuth datasets in the challenging geological conditions of the Norwegian Sea.

Dataset Overview

The legacy single-azimuth dataset, denoted as HVG 11, was acquired in 2011. This survey encompassed 173 lines oriented with a line direction of 117/297°, covering an area of approximately 3598 km^2. The HVG 11 dataset comprises double-source gun array, with ten 7,050m long cables at a separation of 100 m.

In 2022, PGS undertook a significant advancement with the acquisition of a new azimuth of multi-sensor streamer data, designated as GSX 22 (perpendicular to HVG 11). This was conducted over existing datasets in the Norwegian Sea. The new azimuth configuration featured a wide-tow triple source setup and longer streamer-tails, resulting in data with denser crossline sampling, improved near-offset distribution, and extended offsets tailored for FWI. The dataset comprises triple-source, 14 streamer cables with a 75 m separation and cable lengths of 7,000 m and 10,000 m (for the longer tails).

Figure 1.b provides a visual representation of the acquisition configurations, illustrating the contrast between the legacy dual-source dataset and the newly acquired azimuth.

VMB workflow

We employed Full Waveform Inversion (FWI) (Virieux and Operto, 2009) as the primary tool for velocity model building. FWI is well-suited for handling the complexities of dual azimuth datasets, allowing us to iteratively improve our subsurface velocity model by minimizing the misfit between observed and modelled seismic data. The integration of the two datasets provides additional constraints, enabling a more accurate and detailed representation of the subsurface geology.

The legacy VMB heavily relied on reflection tomography updates with minimal FWI passes, whereas the recent VMB was predominantly driven by FWI with limited interaction with reflection tomography.

In the challenging geology beneath the Base Cretaceous Unconformity (BCU), obtaining reasonable velocity updates from reflection tomography proves to be a formidable task.

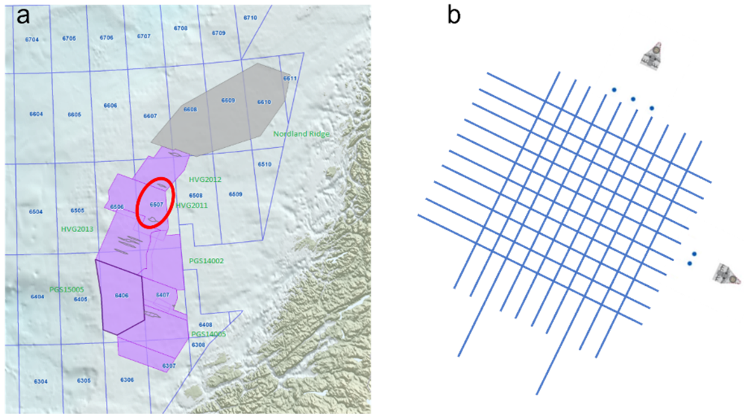

Figure 1 *a) The area of study highlighted, b) the legacy dual-source acquisition versus new acquired azimuth with wide-tow triple-source configuration. Notably, the new azimuth features longer streamer-tails designed for deeper FWI updates.*

Throughout all VMB stages, the dual azimuth dataset played a pivotal role. The key VMB stages include:

- Reflection tomography to prepare the starting model for FWI
- Refraction based FWI using Dynamic Time Warping technique (Huang et al., 2021) up to 12 Hz
- Reflection and refraction based FWI up to 24 Hz

In the initial phase, updates were made to the background velocity model and low-wavenumber components. A highly restrictive mute, around the first arrival, was applied to isolate refractions. The entire length of the cable was utilized, featuring a long streamer-tail (10 km) that effectively sampled the deep section, particularly underneath the BCU and Base Evaporite.

During the subsequent stage, the inversion process minimized the entire dataset (including both reflection and refraction) to update the model, starting at low frequencies before progressively increased. These FWI passes ranged from 6 Hz to 24 Hz. The updates were made to the mid and high wavenumber components of the velocity model.

Throughout the various stages of FWI, adjustments were made to account for anisotropy, and minimal reflection tomography was performed. The updated model underwent evaluation in both the shot domain (shot modeling) and the image domain.

Anisotropic Effects

Through an assessment of the well-to-seismic tie, shot modeling, and examination of migrated gathers in the image domain, it was observed that anisotropy in the extremely shallow section beneath the water bottom necessitates the incorporation of negative delta and epsilon values to enhance the shot matching and mitigate mis-ties at shallow markers such as Kai and URU. The unconsolidated nature of sediment in this layer renders the introduction of negative anisotropy geologically justifiable. The VMB procedure involved multiple evaluations and revisions of the anisotropy volume, particularly focusing on epsilon.

Results

The final model and the associated dual azimuth migration stack have been compared with legacy processing (Figure 2). The Kirchhoff pre-stack depth migration (KPSDM) full stack for the legacy processing is single azimuth (HVG 11) while Figure 2.b shows the multi-azimuth KPSDM full stack for the reprocessed one. In the mid and deeper sections, substantial improvements in subsurface imaging are evident, attributed to an enhanced and high-resolution model, better data processing and lastly the combination of dual azimuth data.

Figure 2.d provides a visual representation of the final velocity model post 24 Hz FWI. This highly detailed velocity model captures small-scale features and small wavelength velocity perturbations, simplifying the interpretation of deeper structures and elevating the quality of imaging. Examining the well profiles of two representative wells in the survey, as illustrated in Figure 3, reveals that the new velocity model closely aligns with the sonic log trend. The high-resolution velocity model successfully captures the details of the sonic log, underscoring its precision and fidelity.

The combination of legacy and new datasets plays a pivotal role in significantly enhancing constraints on the velocity model. The use of longer cable lengths, coupled with the dual azimuth approach, result in a more robust and high-resolution velocity model compared to the previous single azimuth study. The high resolution FWI at 24 Hz enhances the fidelity of the seismic imaging and capturing finer details which can be used for quantitative interpretation.

The enhanced velocity model resulting from the dual azimuth dataset has direct implications for hydrocarbon exploration in the Norwegian Sea. Improved subsurface imaging increases the accuracy of seismic interpretation, aiding in the identification of potential reservoirs and reducing exploration risks. The detailed velocity model also provides valuable insights into structural complexities, facilitating better reservoir characterization and development strategies.

Conclusion

In conclusion, this study showcases the significant advancements achieved in velocity model building through the integration of dual azimuth seismic datasets in the Norwegian Sea. The combination of a legacy dataset and a newly acquired one, featuring 10 km streamer-tails and several passes of high-resolution FWI up to 24 Hz, has resulted in a more robust and accurate subsurface representation. The dual azimuth approach enhances our ability to better illuminate the subsurface and improve the imaging which will contribute to improved reservoir predictions. The detailed velocity model also provides valuable insights into structural complexities, facilitating better reservoir characterization and development strategies. This study sets a precedent for future seismic studies, emphasizing the importance of multi-azimuth acquisition strategies for achieving enhanced subsurface imaging in challenging geological environments.

Acknowledgments

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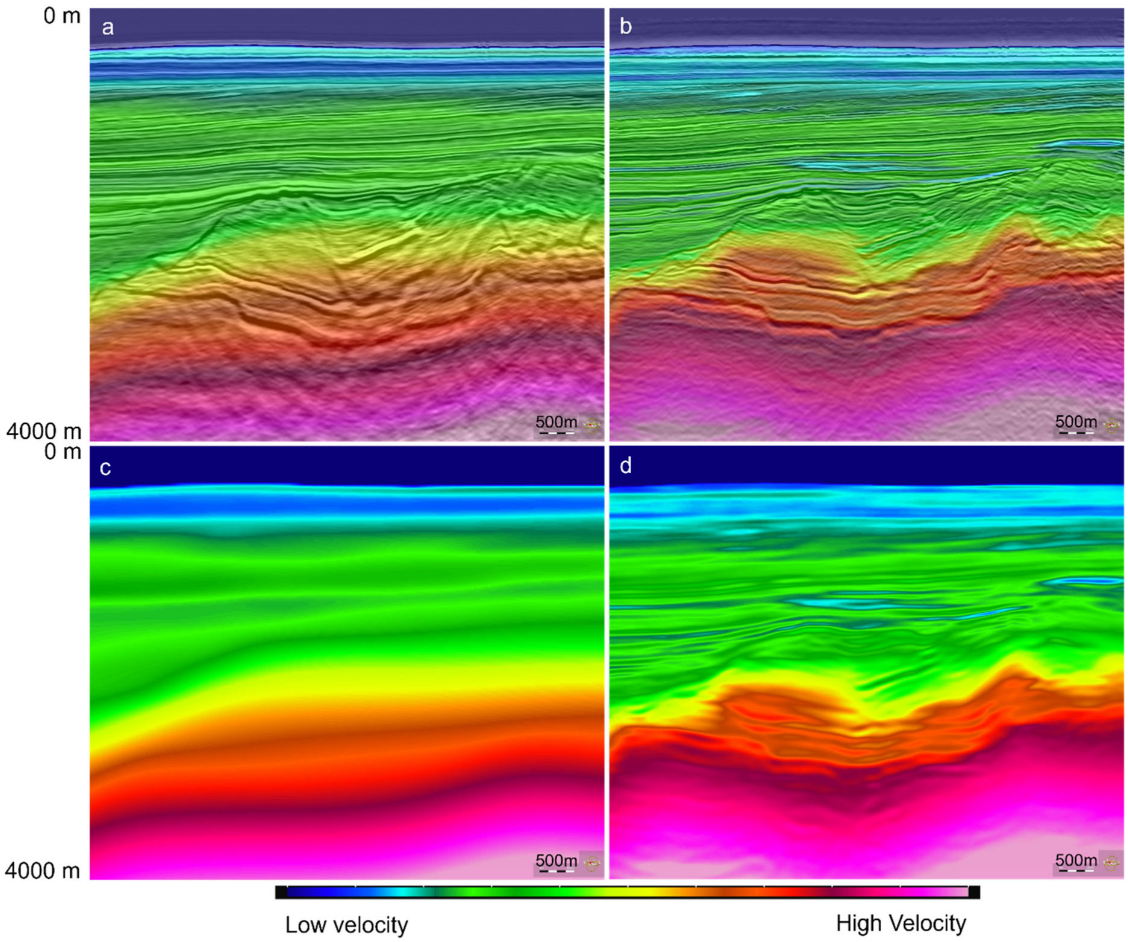

Figure 2 *a) Legacy single azimuth KPSDM stack overlaid on legacy model, b) Multi-azimuth KPSDM stack overlaid on high-resolution model, c) legacy velocity model, and d) high-resolution model.*

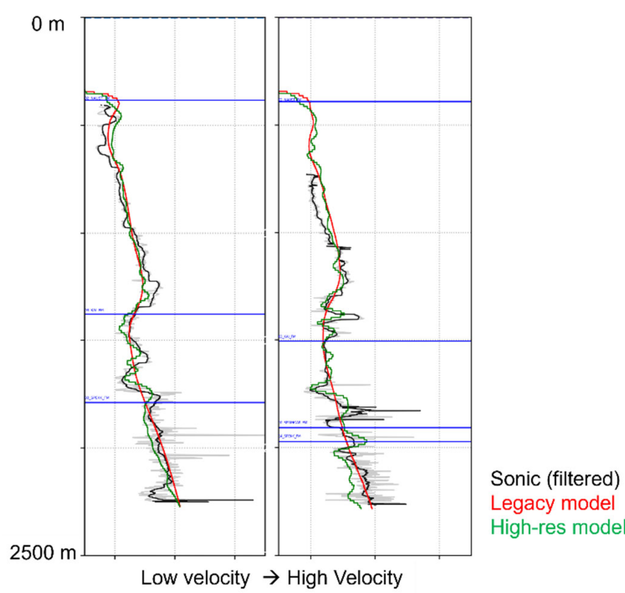

Figure 3 *Well log profiles at two representative wells in the survey.*