HIGH-RESOLUTION FULL-WAVEFORM INVERSION FOR STRUCTURAL IMPROVEMENT AND PROSPECTS DELINEATION: A CASE STUDY AT HAUGALAND HIGH

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Summary

The Haugaland High, in the Norwegian North Sea, consists of a layered overburden of sub-horizontal sediments almost 2km thick that sits on the chalk basement. The background velocity regime of these top layers has a low vertical gradient down to the chalk interface. This velocity behavior is particularly poorly suited for diving wave FWI, and the strong multiple content present in the data does not allow for an efficient tomographic update. Using all reflections and diving waves recorded, Time-Lag FWI can provide a high-resolution velocity field that explains the complex velocity variation present in the overburden and simplifies the reservoir structure. With the use of narrow-azimuth towed-streamer data covering 2000km2, the velocity was updated up to 40Hz, both helping structural imaging and bringing additional information to better understand the rock properties of the basement over the entire region.

High-resolution full-waveform inversion for structural improvement and prospect delineation: A case study at Haugaland High

Introduction

The Haugaland High, in the Norwegian North Sea, consists of a layered overburden of sub-horizontal sediments almost 2 km thick, sitting on the chalk basement. The background velocity regime of these top layers is very simple, with a low vertical gradient in the top half of the overburden, which then decreases to zero or even negative in places, down to the chalk interface. With such a low velocity gradient, diving wave analysis showed that an offset of at least 8 km is needed to record diving waves from the entire overburden thickness (Ramirez et al., 2020). Additionally, the hard and shallow water-bottom results in heavy contamination from multiple energy throughout the section. This means that tomographic velocity update methods are less reliable unless a thorough demultiple step is applied beforehand, which has the potential to damage primary energy. In addition to the above-mentioned challenges, the region also contains complex geological features such as shallow channels and sand injectites. These localized geobodies strongly contrast with the surrounding layer, causing distortion of the underlying migrated image if they are not correctly resolved in the velocity model.
Recent developments in Full-Waveform Inversion (FWI), and notably Time-Lag FWI (TLFWI) (Zhang et al., 2018), have proven effective for inverting models with strong velocity contrasts (as in the case of salt). In addition, they provide the benefit of using the full wavefield, including all reflection information, rather than limiting the FWI update to diving wave energy only. This progress allows for enhanced velocity resolution and the ability to capture thin geobodies with a high velocity contrast. This paper shows how TLFWI was used with data from various acquisition configurations (narrow azimuth (NAZ), split-spread, ocean bottom cable (OBC)) to retrieve the Haugaland High velocity and solve the basement structural distortion.

TLFWI application over the Haugaland High area

In the Haugaland High area, the Edvard Grieg field is currently the most developed field in terms of hydrocarbon production. This field is covered by many wells and has been imaged using various seismic acquisition designs (Lie and Nilsen, 2016), yet no previous seismic images correlate with the available well information. Measurements collected during drilling of horizontal wells indicate a flattish character for the top of chalk layer, while the seismic images show a more rugose reflector. To better understand the velocity variations present in the overburden that cause this image distortion, TLFWI was performed using an OBC dataset. With its better handling of noise and amplitude mismatch, TLFWI is able to make use of the reflection energy on top of the diving waves, thus providing higher resolution to the velocity field. We performed the inversion up to 65 Hz to better capture the velocity variation associated with the overburden geological details (Figures 1a, b). This largely reduced the wobbling imaging artifact at the reservoir level. Furthermore, it also captured the velocity inversion due to the presence of a hydrocarbon reservoir, even though this reservoir target is located below a strong velocity contrast layer. After Kirchhoff pre-stack depth migration (K-PSDM) (Figures 1c, d), the resulting image showed a very simplified reservoir structure that matches with the numerous horizontal wells present in the field. Considering the complexity of monitoring a field in production, this new result is a dramatic change, considerably easing future analyses.
With successful application on a 50 km^2 OBC dataset, we extended the use of TLFWI to a 2000 km^2 narrow-azimuth streamer dataset covering both Edvard Grieg and Solveig prospects. The Solveig field has similar geological properties as Edvard Grieg, with a reservoir located below the top of chalk seal. This field is, however, more expanded and spread over four compartments (Figure 2a). With only 6 km maximum offset for the NAZ data, the amount of available diving waves was limited and TLFWI had to rely mostly on reflection waves. Without the full recorded direct arrival and water bottom information contained in the OBC data, one difficulty in this case was to explain the water-layer velocity variation and the water-bottom contrast to accurately model all the multiple energy, constituting most of the data in this shallow water survey. This was achieved by including all the primary and multiple energy in the inversion and letting FWI update the water layer without any constraints. Focusing on the Solveig field, the obtained velocity captured the low velocity kick at the reservoir (Figures 2b, d), with the overburden details matching the well information and flattening the chalk event (Figure 2c). The fast-velocity

contrast of the sand injectites was also resolved by TLFWI to yield images with simplified basement structure (Figures 2e, f, g, h).

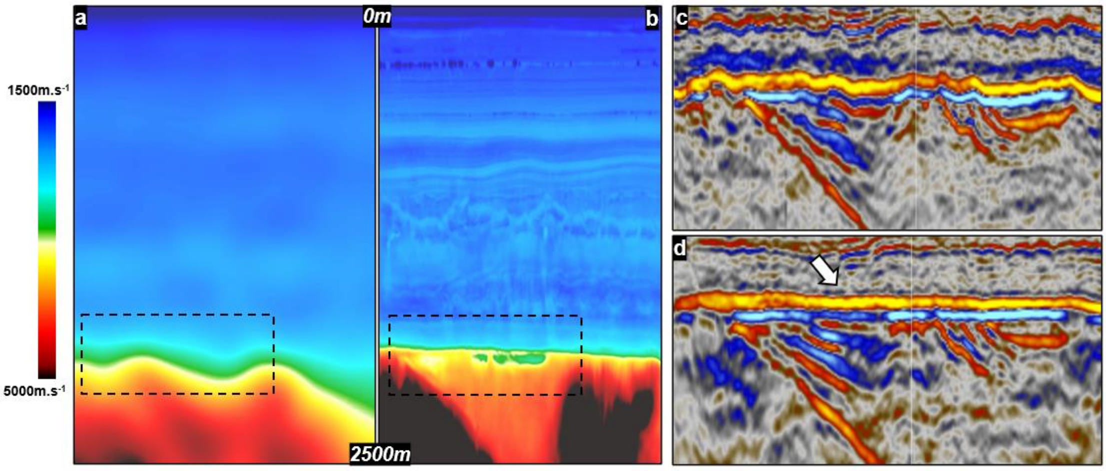

Figure 1: *On the OBC survey over the Edvard Grieg field, when using the legacy velocity (a), the resulting K-PSDM image (c) shows a strong wobbling at the chalk level (yellow event) and on the reservoir located just below (light blue event). After TLFWI, the velocity included many details in the overburden (b), simplifying the chalk basement structure (white arrow) on the image (d). This result better matches the trajectory of horizontal wells present in the field.*

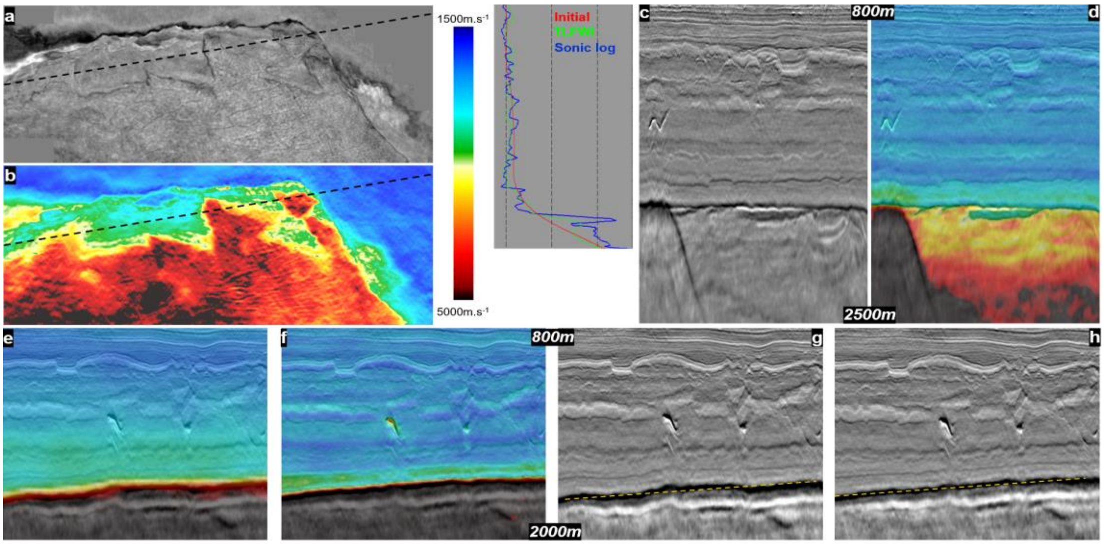

Figure 2: *The Solveig field is composed of various compartments that were captured by TLFWI using NAZ data (a, b). On a random line (dashed line), the velocity obtained shows many details in the overburden, confirmed by well logs, thus improving the imaging of the chalk and sub-chalk levels. The details in the velocity also captured the velocity inversion visible at the reservoir location (c. d). When compared to the legacy velocity (e), TLFWI modelled the injectite fast velocity contrast despite its limited size (f). The updated velocity provided a more continuous chalk event (g, h).*

Furthermore, we wanted to explore the use of high-resolution velocity as a hydrocarbon indicator. The presence of hydrocarbons can strongly impact the subsurface velocity, and thus, the velocity contains valuable additional information for identifying potential prospects (Salaun et al., 2021). The Rolvsnes field, located a few kilometres west of Edvard Grieg, is a fractured porous chalk basement reservoir (Lie et al., 2016). With such geological properties, a velocity drop is expected in the weathered basement, directly indicating the existence of a porous basin. Due to the strong velocity kick at the top of chalk level, diving waves barely penetrate deeper than this event, preventing the update of the velocity underneath. For this reason, diving-wave FWI was combined with tomography to update the basement velocity in the legacy velocity model. However, below this strong velocity kick, the available traces for

RMO picking were heavily contaminated by chalk multiple, preventing a good tomography update. Therefore, the legacy velocity (Figures 3a, c) provided a relatively smooth velocity variation at the basement target level. Despite this, the use of the full wavefield in TLFWI was sufficient to offer detailed velocity information, even at the basement level. When looking at a depth slice at the basement level, slow velocity packages could be spotted, correlating well with the presence of a hydrocarbon reservoir (Figures 3b, d). The velocity depth slice also exhibited high lateral definition, highlighting the presence of large fault planes in the basement separating the various units of this complex reservoir.

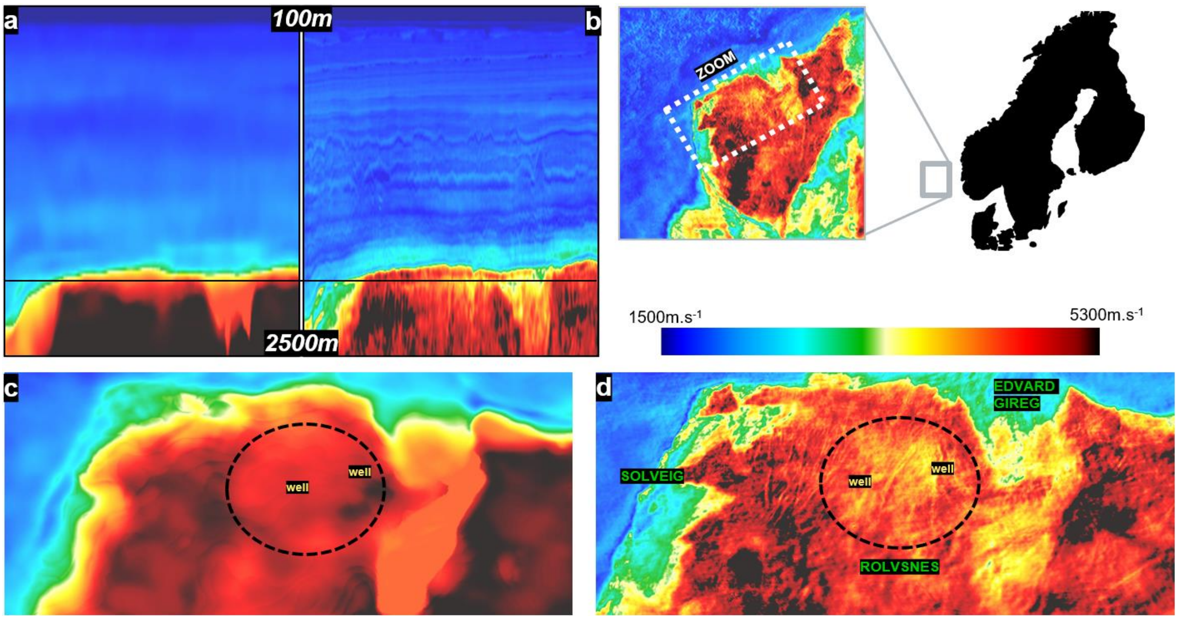

Figure 3: *NAZ data were used to perform TLFWI on a large area covering the full Haugaland High. When extracting a line crossing the three main reservoirs discovered in this area – Solveig, Rolvsnes and Edvard Grieg – velocity details were observed below the chalk layer despite the strong velocity contrast (a, b). When looking at a depth slice at the basement level (c, d), areas of slow velocity can be spotted at the Rolvsnes field location. This detailed velocity field can thus be used as an additional attribute to identify and refine future prospects.*

Impact of acquisition geometries on velocity inversion

TLFWI performed with the NAZ data as input achieved its two objectives and increased the geological understanding of the region. This showed the capacity of the inversion to take advantage of the reflections to compensate for the lack of long offsets and azimuthal diversity to invert the velocity. To better assess the impact of acquisition style on TLFWI in this region, a comparison was made over the Edvard Grieg field with three different acquisition settings. The first was the NAZ survey. The second was a source-over-streamer acquisition (Dhelie et al., 2019), having the advantage of fully recording the near incidence angle, even in such shallow water context. The third was the OBC acquisition, having a 13 km maximum offset and recording the full-azimuth wavepath. For this test, TLFWI was performed to 25 Hz starting from the same initial velocity for all three acquisition settings. Figure 4 shows the difference in obtained velocity and FWI Image (Zhang et al, 2020) between the different acquisition settings. While all three results managed to correct for false basement undulations caused by the overburden, the quality of the obtained FWI Image varied. The image obtained with NAZ data (Figure 4a) was affected by noise and lack of resolution at the reservoir level. When adding the source-over-streamer information on top of the NAZ data, more details appeared in the image both in the shallow section and in the reservoir. This showed the importance of the dense and dual-azimuth near offset to obtain a high-definition FWI Image. The tremendous wavefield sampling obtained by the OBC acquisition improved the FWI Image quality at the reservoir level, enhancing the signal-to-noise ratio (S/N) and allowing detection of thinner details. Despite the quality of the obtained streamer TLFWI, the recording of long-offset and wide-azimuth information better constrains the inversion and hence provides a clean and detailed velocity field. In the shallow part of the section, however, the split-spread data provided denser near-offset coverage and offered a superior imaging result. Considering the cost of an OBC acquisition, a combination of dense streamer and sparse node data could be a practical and cost-effective solution to enhance the velocity inversion quality over a large area of complex geology.

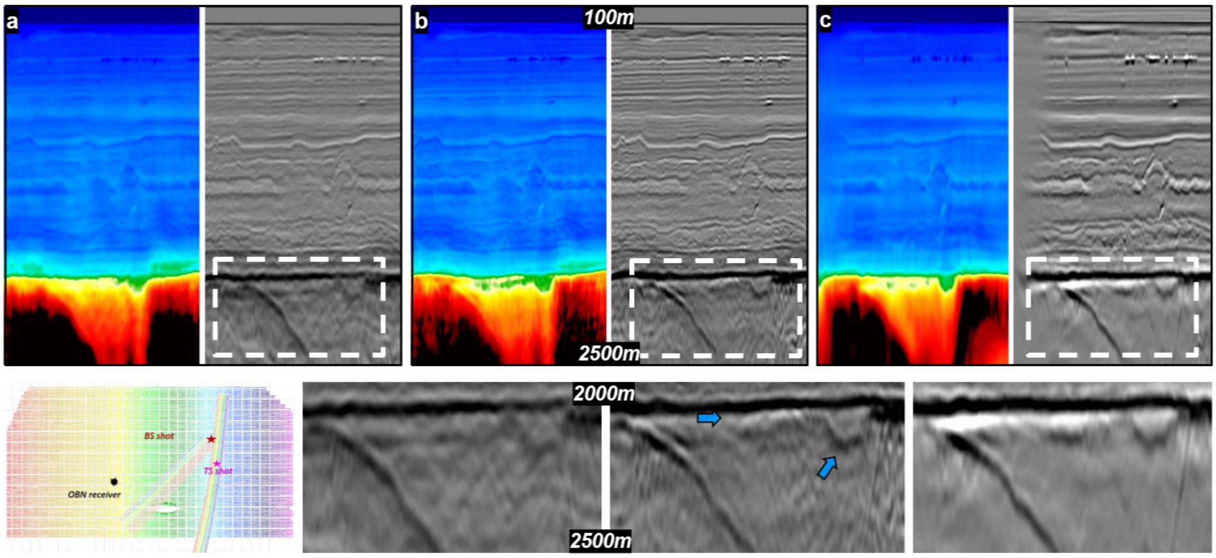

Figure 4: *Despite a good result obtained by NAZ FWI (a; left: velocity, right: FWI Image), the inherent lack of recorded data does not allow for obtaining a perfect velocity model. By using split-spread data (b), more details can be recovered (blue arrows), mainly coming from the very near offset recorded and the near offset multi-azimuth of this design. Use of OBC data, with the full-azimuth nature and long-offset record, resulted in a very detailed velocity with an increased S/N on the FWI Image.*

Conclusion

Over the Haugaland High, where no previous seismic images correlated with well information, the use of TLFWI delivered high-frequency velocity models that resolved basement undulations and offer direct information for interpretation. By using all recorded reflection and diving waves, TLFWI was effective at updating both the background velocity regime and the fine details, especially at depths where conventional FWI techniques often struggle with the lack of diving wave penetration. We also showed that more advanced acquisition designs, such as split-spread source-over-streamer or OBC, help to further improve the FWI result and the resolution of the inverted velocity.

Acknowledgements

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