Application of simultaneous inversion (FWI and nonlinear LS-RTM) for improved imaging.

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Summary

Imaging of complex faulted structures requires the most advanced imaging algorithm that handles multi-pathing, an accurate background velocity model for correct structural positioning and an element of least-squares migration to mitigate limitations of the imaging system (migration and acquisition process). In this paper, we address all these challenges with a single data-driven inversion process that updates both the background velocity model and the reflectivity model simultaneously.

With a seismic data example from the Outer Vøring basin in the Norwegian sea, we demonstrate how the inversion heals the fault shadow zone, improves the structural imaging compared to the underlying Kirchhoff pre-stack depth and reverse time migration results. The inversion provides a better well to seismic tie compared to the alternatives and the de-coupled parameters (velocity and reflectivity) can be used to directly derive reservoir property attributes such as relative density. The seismic data example shows low-density sand layers at the target that correlate with the measured properties at the well. The applied methodology has the potential for both turnaround reduction, quality improvements and prospect de-risking by combining velocity estimation, imaging, and reservoir property estimations into a pure data-driven inversion process.

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Introduction

Depth imaging in heavily faulted regions with large-scale lateral velocity variations is a notorious challenge. The complex wavefield propagation in such areas, requires an imaging algorithm that can handle multi-pathing in addition to a detailed velocity model with large contrasts. Furthermore, it requires that an accurate estimation of the velocity model can be performed, enabling the migration algorithm to map all acquired energy to the right subsurface position. Even in this ideal case, limitations with the imaging system (acquisition and migration) will impact the results, leading to erroneous amplitudes and limited resolution. These shortcomings will still be present for a reverse time migration (RTM) that utilizes the true earth model. A well-known solution to mitigate these illumination and resolution effects is least-squares reverse time migration (LS-RTM), commonly implemented in the image space based on de-blurring operators (point-spread functions, PSF's).

In this paper, we present a case study from a fault shadow zone in the Vøring basin, Norwegian Sea. We have utilized a new simultaneous seismic inversion process built on the full waveform inversion (FWI) framework. The two products from this inversion are an accurate imaging and reflectivity model (FWI velocities and nonlinear LS-RTM). The two earth properties are inverted iteratively and simultaneously in the data-space.

The new imaging results show a significant uplift in focusing and resolution and heals the fault shadow zone compared to the underlying RTM image. More specifically, the LS-RTM corrects for the low amplitude response near the major fault structure, which could be misinterpreted as rock property effects on the conventional imaging providing a significantly improved structural image. The inversion also gives direct access to other attributes, such as the relative density, and we show the agreement with the measured response at the target well.

Geology and imaging challenges

The Ivory gas discovery is located in PL528, offshore Norway, about 20 km NE of the producing Aasta Hansteen gas field. The discovery well 6707/10-3 S was drilled in 2014 in 1420 m water depth. The Ivory structure forms a three-way dip closure along a basin bounding fault that stretches from the Luva Discovery (in Aasta Hansteen) in the south to the Nyk High proper to the north (figure 1). The gas bearing reservoir in Ivory is the Upper Cretaceous Kvitnos Formation which constitutes approximately 200 m thick turbiditic sandstones deposited in a basin floor setting. The throw of the main fault to the north ranges from 300 m in the east and up to 1 km in the west and creates a poor seismic image in the fault shadow.

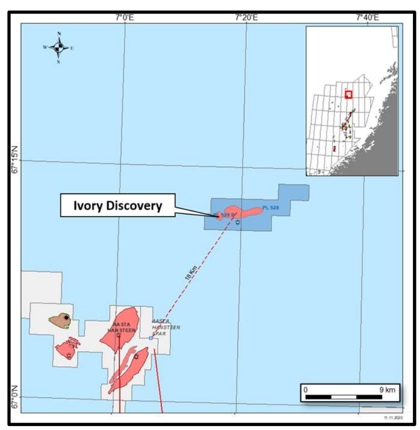

***Figure 1** Study location*

A full Pre-Stack Depth Migration reprocessing of GeoStreamer seismic data including FWI was performed in 2020. Although the inclusion of FWI velocities for the overburden section in the final velocity model improved the Kirchhoff imaging of the Kvitnos target compared to the legacy data there was still clear remnant fault shadow up-dip of the discovery well. Based on this result an RTM was performed and this further improved the reflector continuity in the footwall block but was unable to heal the fault shadow effect completely (figure 2).

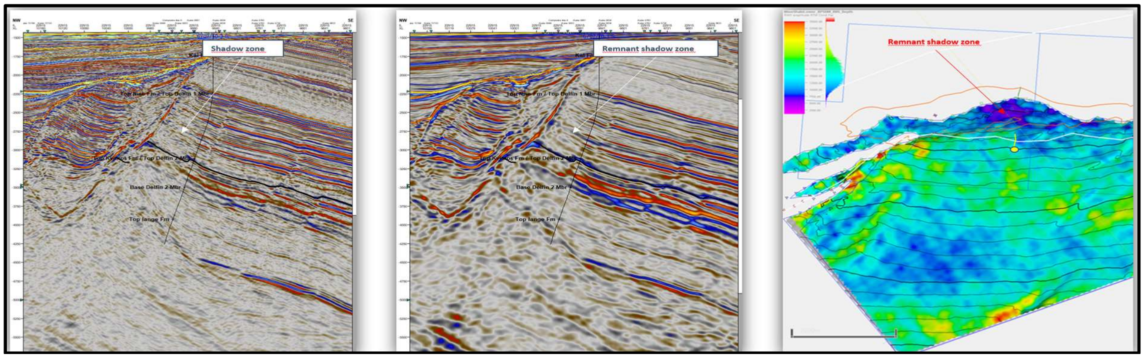

Figure 2 *The prospect imaged with Kirchhoff PSDM (left) and RTM (middle) with well trajectory overlayed. RMS amplitude map extraction in a window from Top Kvitnos to 250ms above extracted from RTM image (right). Amplitude dimming near the major fault structure annotated.*

Solution based on simultaneous inversion

To overcome the imaging challenges in this complex area, it was clear that both the velocity model and the algorithm that remaps the recorded seismic amplitudes had to be revisited. Our preference was a pure data-driven seismic inversion process that simultaneously invert for both these two earth properties (Yang et al., 2021).

This inversion process is based on the FWI framework, where an iterative process seeks the velocity and the reflectivity model that explains the observed data. The modelling engine is an alternative formulation of the two-way wave equation, parametrized as velocity and vector reflectivity (Whitmore et al., 2020). This enables us to model the full acoustic wavefield with a single modelling engine, not limited by first order scattering terms (Born approximation) and without the requirement of building a detailed density model. The two parameters of the wave equation (velocity and reflectivity) are the two earth properties that we resolve in this iterative inversion process. From a single backpropagation of data-residuals, the optimization process will update both models. With a closed form solution, implemented with Inverse Scattering Imaging Condition (ISIC), the two earth properties are updated without parameter leakage. (Whitmore and Crawley 2012; Ramos-Martinez et al., 2016).

Results

The inversion utilized pre-processed data and the corresponding imaging model from 2020 as the initial velocity field. To handle the nonlinearity of this optimalization process, the simultaneous inversion was performed in frequency stages up to 28 Hz.

Figure 3 shows a comparison of the previously considered best structural image from 2020 reprocessing (RTM) compared to the new nonlinear LS-RTM. The new results show improved resolution and better amplitude balancing, especially up-dip towards the main fault compared to the RTM results. The increased resolution can also be confirmed with the FK- and amplitude spectra in 2c-e. The RTM image suffers from the shadow zone near the major fault structure, leading to amplitude dimming (annotated white dotted box), that could be misinterpreted as a rock property effect. The LS-RTM image heals these amplitudes and reduces the uncertainties related to these lateral amplitude variations. Furthermore, the increased resolution, event continuity and amplitude fidelity achieved with the LS-RTM image enables confident structural interpretation.

Together with the nonlinear LS-RTM process, the velocity model is updated at every iteration of the inversion. The updated velocity model and the accumulated velocity update overlayed on the inverted LS-RTM results are shown in figure 4. These updates conform with the seismic structure, and it shows how we update the layer properties instead of imposing a reflectivity imprint onto the velocity model. The de-coupling of velocity and reflectivity is achieved with ISIC.

From the derived background (Velocity) and reflectivity (LS-RTM) model, we can easily solve for the relative density since reflectivity is the directional change in impedance and impedance is the product of velocity and density. Figure 5a shows the match of relative density with the well path overlayed, figure 5b shows the well logs (gamma ray, density and velocity), the synthetic trace compared to reflectivity from Kirchhoff PSDM (KPSDM), RTM and nonlinear LS-RTM (inversion) and the corresponding cross-correlation profile (150 ms sliding window), figure 5c shows a comparison of the measured and inverted relative density, filtered to the bandwidth of the seismic inversion. The inversion results show a good well to seismic tie despite the significant uncertainties with the highly deviated well log (deviation position, check-shot calibration for a highly deviated well and dipole sonic log anisotropy correlation) and the results are improved over the Kirchhoff PSDM and RTM results in the target interval. Furthermore, the relative density variations from inversion detects the low-density sand layers measured at the well (black dotted boxes). The full 3D inverted density cube can give insight on the lithology variation and how the sand layers extend away from the measurements at the well location.

Conclusions

In this paper we have demonstrated the power of a true data-driven inversion to tackle the focusing and illumination challenges in a complex geological regime with large fault structures and lateral velocity variations. The applied methodology is a multi-parameter inversion built on the FWI framework, where we simultaneously invert for the velocity (FWI) and the reflectivity (LS-RTM) model. This nonlinear inversion has clearly improved the structural image by repositioning and simplifying the reflectivity, increasing the resolution, and healing the fault shadow zone. All these elements have been important in enabling a more confident seismic interpretation of the Ivory discovery. From the two inverted (fully de-coupled) earth properties we can directly derive other rock property attributes, such as relative density, across the full survey. The inverted results have given an improved well to seismic tie and mapped low-density sands in the target interval. The applied data-driven inversion has the potential for significant turnaround reduction compared to conventional model building, imaging, and rock physics workflows and can be used to quickly assess density variation in the data. With a conventional seismic imaging and quantitative interpretation workflow, a significant number of steps and large offset/angle would be needed for a seismic density assessment.

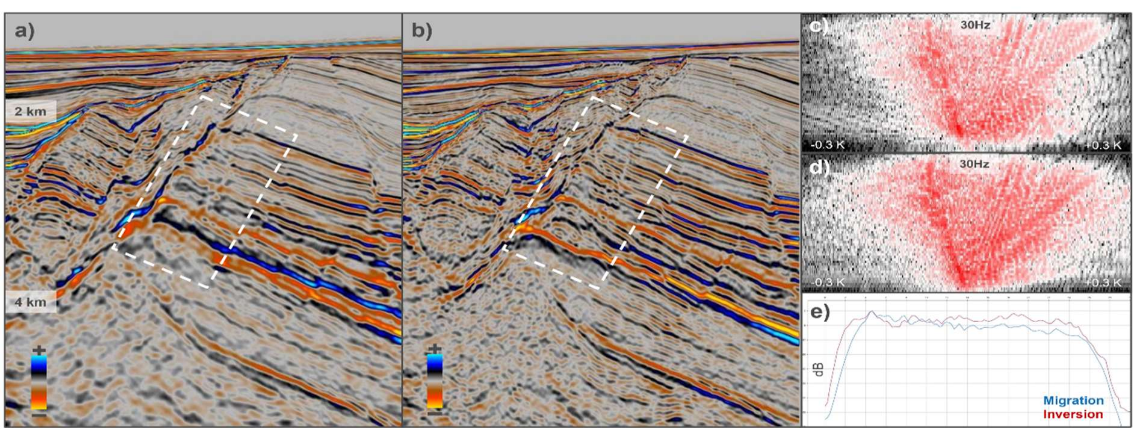

Figure 3 *RTM (a), LS-RTM (b), FK-spectra of RTM (c) and LS-RTM (d) and a comparison of the amplitude spectrums of RTM and LS-RTM (e). The LS-RTM image improves the focusing, resolution and structural imaging over RTM and heals the fault shadow zone annotated with the white dotted box.*

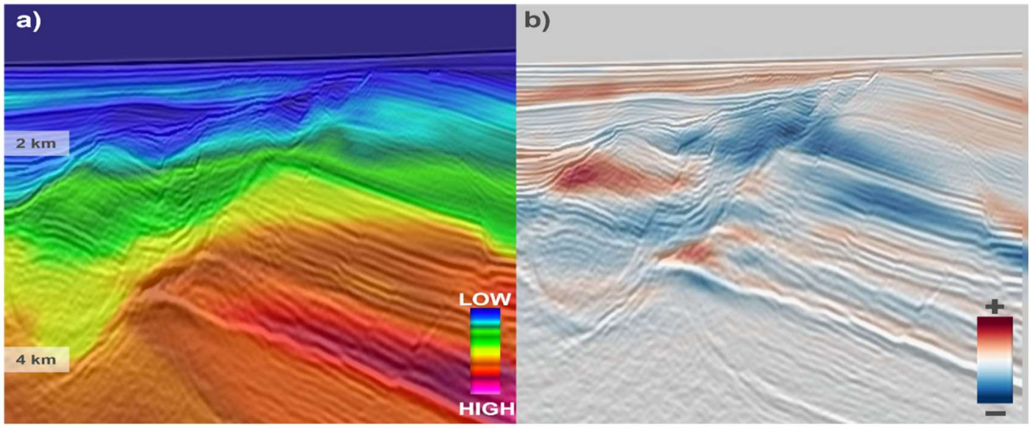

Figure 4 *Inverted velocity model (a) and the accumulated velocity update (b) overlayed on the LS-RTM image.*

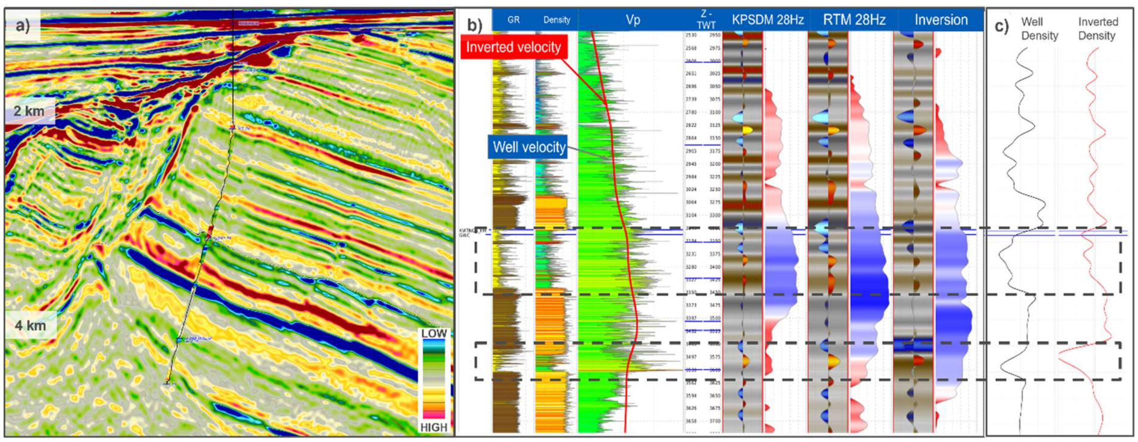

Figure 5 *Cross-section of relative density from inversion (a), well log (gamma ray, density, velocity), depth-time relation from check-shots, well to seismic tie for Kirchhoff PSDM (KPSDM), RTM and inversion with the corresponding cross-correlation profile (b) and measured versus inverted relative density filtered to the seismic bandwidth (c). The inversion shows a good well to seismic tie in the target interval and the inverted relative density picks up the two low-density sand layers detected in the well, annotated by the black dotted boxes. It should be noted that the seismic display is in depth and reasonably matches the well depth markers without the well being used as a constraint.*

Acknowledgments

The authors wish to thank Sval Energi and their license partners and PGS for permission to show the results.

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