Applications of multi-parameter FWI in complex geological settings in the North Sea.

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Summary

We have applied a multi-parameter inversion process based on the Full Waveform Inversion framework (FWI) to estimate the velocities, the attenuation factor (Q) and the reflectivity on two challenging datasets from the North Sea. The geological complexity includes shallow gas anomalies, high-velocity cemented structures and salt domes. The velocity and the reflectivity (derived from least-squares reverse time migration, LS-RTM) are resolved with minimum leakage, where the kinematic effects are explained by the background velocity model and the dynamic effects with the LS-RTM image. We further extend the multi-parameter inversion scope to incorporate Q-model estimations with a new dispersion kernel in FWI. The results from the field-data examples demonstrate the power of the multi-parameter inversion, leading to superior images over conventional migration methods.

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Introduction

Conventional imaging algorithms, both ray- and wave-equation based, have their limitations when geological complexity increases. Firstly, they all utilize a predefined velocity model that could either be a good or less good representation of true earth model. Secondly, the migration process does not correct for the limitations of the imaging system, which may lead to false amplitude variations and blurring effects.

As an alternative to migration, imaging can be posed as an inversion process, where we update and refine the image and the propagation model in an iterative joint inversion. This essentially performs velocity estimations with Full Wavefield Inversion (FWI) and least-squares reverse time migration (LS-RTM) in one process. The advantages with this approach relate to the utilization of the full wavefield for velocity predictions (reflections and refractions) and the continuous velocity refinements and stabilization of the LS-RTM process that correct for illuminations and de-blurring effect.

In this paper, we demonstrate how such an approach can resolve the velocity model and the reflectivity model and be further extended to incorporate the estimation of the attenuation (Q-model). We demonstrate the technology on different complex geology, including heterogenous overburdens, gas pockets, chimneys, large velocity contrasts e.g. salt from different areas in the North Sea.

Methodology

Full Waveform Inversion (FWI) has proven to be a robust and efficient data-driven technology to resolve complex velocity models. The inverted model is then used in the migration process to provide an estimate of the subsurface reflectivity. In highly complex areas, this may not be sufficient. A better solution would be to invert for reflectivity with a least-squares migration (LSM). This process corrects for propagation effects that may lead to false amplitude variations and limited resolution in conventional imaging (Korsmo et al., 2019).

An alternative to a cascaded FWI and LSM process, is to perform multi-parameter inversion which performs velocity and reflectivity estimations simultaneously (Yang et al., 2021). Key elements in this technology are a full wavefield modeling engine implemented with vector reflectivity wave-equation and parameter de-coupling based on inverse scattering theory (Whitmore et al., 2020; Whitmore and Crawley 2012; Ramos-Martinez et al., 2016). This methodology enables the utilization of the full wavefield, where the kinematic effects from reflections (in addition to refractions) contribute to the velocity estimations. The dynamic effects (amplitudes) are being explained by the reflectivity parameter, inferred through least-squares reverse-time migration (LS-RTM).

Another earth parameter that highly influence the image quality is the ability to correct for attenuation. Huang et al., (2023) have implemented a dispersion sensitivity kernel in FWI to invert for the attenuation factor (Q-model). This dispersion kernel is derived from a new visco-acoustic wave equation which fully separates the acoustic, dispersion and amplitude effects. Prioritising the dispersion over the amplitude-loss effects during the inversion, reduces the dependency on a good amplitude match between the recorded and modeled amplitudes for a successful estimation of Q.

In this paper we make use of the multi-parameter inversion to simultaneously update the velocity and reflectivity model in complex geological settings with field data examples from the North Sea, including shallow gas anomalies, cemented sands, and a salt dome. We further extend the multi-parameter inversion scope to incorporate Q-model estimations.

Field data examples

The first field data example is from the southern North Sea, over a salt dome with a complex overburden, consisting of low-velocity anomalies caused by leaked gas in the first few hundred meter below the seafloor.

Figure 1a shows the vintage velocity model overlayed on the corresponding Kirchhoff PSDM image. A zoomed section of the shallow seismic anomaly can be found in the bottom right of the picture, indicating a structural sag which suggest a non-resolved slow-velocity anomaly. The new multi-parameter inversion detects the low-velocity anomaly (annotated with the white ellipse) in Figure 1b and resolves the structural sag, see the zoomed display (bottom left in Figure 1b). Notice how the base event in black (impedance kick) now aligns with the white dashed line, representing a possible gas-water- contact. Figure 1c shows the inverted Q-model overlayed on the Q-Kirchhoff PSDM results. The high attenuation area (low Q-values) could indicate accumulation of gas, which is also supported by the strong seismic response. The background Q-model was set to 150, which also formed as the initial Q-model for Q-inversion. The low Q-values in the inverted model goes down to 40 over the gas anomaly. Notice as well how the multi-parameter inversion has modified the velocity model significantly in the deeper section, around and below the chalk and salt dome. This has been achieved without any reflection tomography; however, two passes of interpretation and flooding were required around the salt dome to bring the velocity model closer to what fits the observed data before FWI where able to adjust the model further. These deep velocity updates have been achieved by utilizing the reflection part of the data as described in the methodology section.

The multi-parameter inversion also produced an estimate of the reflectivity, which can be seen as a nonlinear least-square reverse time migration (LS-RTM) process. Figure 2 compares the filtered Kirchhoff PSDM image using the multi-parameter inverted velocity model Figure 2a and the reflectivity inversion results in 2b. As annotated by the yellow arrows, the reflectivity inversion reveals sediments under a salt overhang and the base salt reflector with higher confidence than possible with conventional methods. The sub-salt reflectivity correlates with the new salt structures in Figure 2b and indicates potential traps below the salt overhang.

The next example is from the UK sector of the North Sea over a shallow chaotic geological structure that causes severe image distortions. Figure 3a and 3d shows the multi-parameter inversion results for velocity and reflectivity. The inversion process has detected a complex high-velocity features around 300 to 500 meters depth. A plausible explanation of these anomalies could be related to cementation processes related to methane seepage (Van Landeghem et al. 2015). The inverted Q-model shown in Figure 3b, indicates high attenuation near the cemented structures. This could be an effect of gas-leakage from a reservoir further down, being trapped and sealed by the hard-cemented shallow structures. The background Q-value is 130 and the Q-anomalies have values down to 60. Figure 3c shows the Q-Kirchhoff PSDM results using the inverted models (velocity and Q-model) which can be compared to the inverted reflectivity (LS-RTM) in Figure 3d. The yellow ellipse highlights an area where clear image improvements have been achieved with the inversion-based imaging approach over conventional methods. The inverted results have better signal-to-noise (S/N) and improved amplitude continuity through the obscured zone which can de-risk the structural interpretation.

Conclusions

Complex geological settings require non-conventional imaging. We have demonstrated how multi-parameter inversion, that utilizes the full wavefield (refractions and reflections), can solve for velocities, attenuation (Q) and reflectivity and provide superior images over traditional migration approaches. The reflectivity inversion (LS-RTM) provides a better product for structural interpretation with increases S/N compared to conventional migrations that utilize the same velocity and Q-model. This supports the inversion-based imaging approach described in this paper. The methodology has been applied on two challenging field data examples from the North Sea, containing shallow gas anomalies, high velocity cemented structures and salt domes.

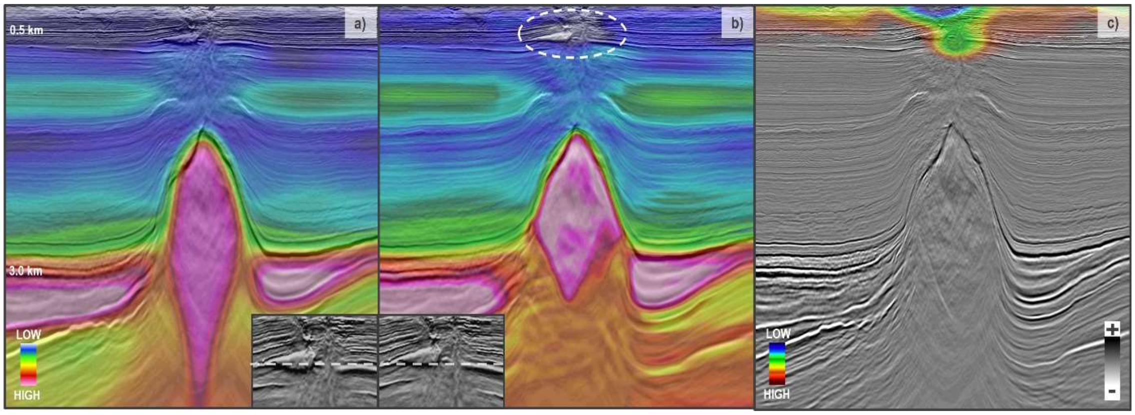

Figure 1 *Vintage velocity model and Kirchhoff PSDM image (a), new inverted velocity model and corresponding Kirchhoff PSDM image (b) and the inverted Q-model overlayed on the Q-Kirchhoff PSDM image (c). The two zoomed displays show how the shallow anomaly has been structurally resolved with the new velocity model, incorporating the shallow low-velocity anomaly (white ellipse). An area of high attenuation (low Q-values) can be seen above and near the low-velocity area in c). The application of Q-correction during the migration process improves the image resolution as demonstrated in c).*

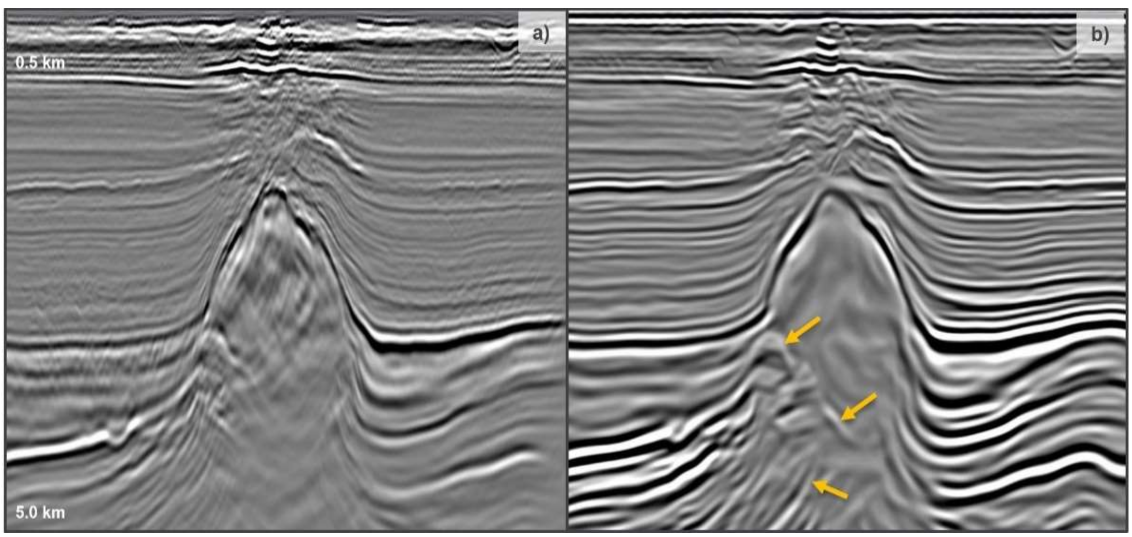

Figure 2 *Filtered version of Kirchhoff PSDM image generated with the inverted velocity model a) and the reflectivity volume from the multi-parameter inversion b). The yellow arrows indicate a possible salt overhang and associated traps, position of the base salt reflector and sub-salt sediment reflectivity that cannot be seen in the filtered Kirchoff PSDM image.*

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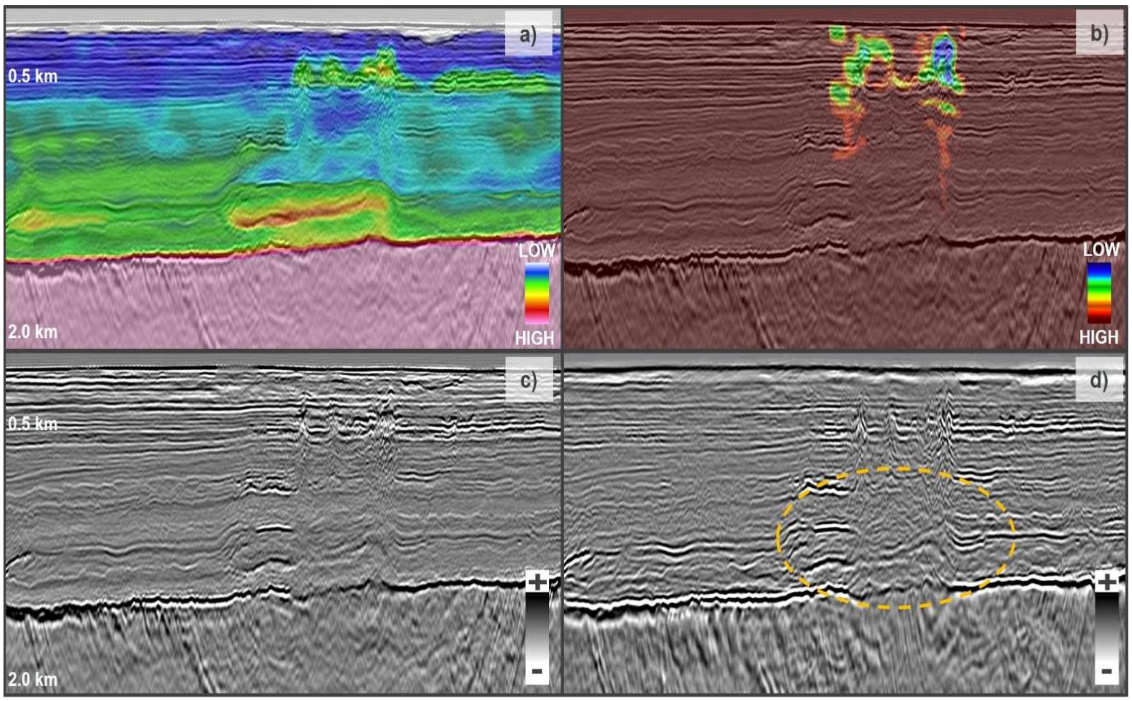

Figure 3 *Inverted velocity a) and Q-model b). Q-Kirchhoff PSDM image using the two inverted models c) and the reflectivity inversion (LS-RTM) d). Shallow high velocity cemented structures have been detected in the velocity model around 500 meters depth. The inverted Q-model shows low-Q anomalies that could indicate accumulation of gas. Improved reflectivity and S/N can be observed in the multi-parameter inversion results, highlighted with the yellow ellipse.*