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Vertical ambiguities in volumetric 4D pressure-saturation inversion resolved with time-shift assimilation

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Abstract Summary

This study focuses on demonstrating the power of joint time-shift assimilation in 4D seismic inversion to estimate pressure and saturation changes. It shows the potential of time-shift data to resolve 4D amplitude ambiguities related to the vertical distribution of reservoir property changes. We use a real case example where water saturations increase due to injection and aquifer inflow from below, while directly above this, injected gas pools at the top of the reservoir. We demonstrate how very different fluid distributions can produce the same 4D amplitude signal, but their time-shift response is quite different. Then we show how jointly inverting the observed time-shift and 4D amplitudes can resolve these ambiguities and produce a more reliable estimation of the reservoir property changes across the reservoir.

Introduction

The estimation of reservoir pressure and saturation changes from 4D seismic data faces many challenges, such as petro-elastic model uncertainty and ambiguities between the pressure and saturation signals. Those have been well addressed by the use of stochastic Bayesian inversion methods (Côrte et al., 2023). An additional challenge that is generally overlooked in 4D seismic inversions are the ambiguities related to the vertical distribution of reservoir property changes. These may arise from the presence of sidelobes, that may be treated as true signal in the inversion, or from vertically stacked reservoirs, where signals may interfere with each other vertically, or even in situations where there is complexity in the vertical distribution of fluids (e.g. water-alternating-gas injection).

In this study we use the example of a North Sea sandstone reservoir where the 4D signal contains sidelobe effects and there is uncertainty related to the vertical distribution of injected gas and inflow of aquifer water. This creates a fairly complex but manageable signal, that is a very educative example to illustrate the vertical ambiguity issue. Using a 4D seismic inversion workflow we show how the 4D amplitude signal can be produced by very different vertical distributions of property changes, some clearly not physically viable. Then we show how assimilating time-shift data in a joint inversion workflow can help resolve these ambiguities, exclude non-physical solutions and produce more reliable estimates of the pressure and saturation changes from 4D seismic data.

Method

The inversion workflow used is a direct inversion of the 4D amplitude difference volumes (three angle-stacks) to changes in pressure and saturation. It requires a petro-elastic model (PEM) which was calibrated to well log and core sample stress sensitivity data from the studied reservoir. It also requires a previous estimation of porosity for the whole seismic volume, which was done with a petro-elastic inversion of the baseline 3D seismic. To focus on the uncertainties related to the vertical distribution of fluids we use a fixed PEM for all inversions. The optimization method is a Levenberg-Marquardt non-linear least squares algorithm. We use a fixed 50 iteration stopping criteria for all inversions. The time-shift data that is assimilated is computed previously by aligning monitor to baseline seismic data through a non-linear inversion method (NLI) (MacBeth *et al.*, 2020). The time-shift and 4D amplitude stacks are assimilated jointly as separate weighted terms in the optimized objective function and no other regularization technique is used.

Example

The study is applied to real 4D seismic data from the Catcher field in the North Sea. The reservoir is a thin (10-80ft) injectite sandstone with high porosity and low shale content. Details on the reservoir can be found in Gibson *et al*. (2020). The reservoir is produced with water injection through dedicated injection wells. Additionally, some producer wells are intermittently switched to inject the produced gas back into the reservoir. This is done with the purpose of filling attic "secondary" injectite sands with gas, pushing the oil down into the producers. In some regions this process leads to gas pooling at the attic of a sand body while water flows in from below, either from the aquifer or from the water injectors. We focus on one of these regions to illustrate the vertical ambiguity issue and how time-shift data helps to resolve it. Specially for this region, but also across whole reservoir, pressures are maintained close to initial reservoir pressure. From well data and reservoir simulations we expect pressure changes below 1 MPa and there is no 4D seismic signal that indicates otherwise. A stress sensitivity study was conducted and showed that these pressure changes would produce very low 4D signals with magnitude below noise levels. For this reason, in this study we keep reservoir pressure constant between baseline and monitor, running inversions for changes in water and gas saturations only.

Figure 1 shows the 4D seismic data (amplitude and time-shift) in the first row and below the synthetic seismic data from the four different inversion results shown in Figure 2. The first thing to notice is how all four inversion results match the 4D seismic amplitude signal equally well, although their synthetic time-shifts are quite different. Inversion results 1-3 are created by 4D amplitude matching, without time-shift assimilation. To produce these different results we control the optimization step size for different properties, making the algorithm preferentially update one property over the other. Inversions 1 and 2 have parametrizations that make the algorithm update water saturation preferentially over gas saturation. Inversion 3 has a balanced updating scheme, with the same parameter values used for water and gas. Inversion 4 has the same exact parametrization as inversion 3, but it also assimilates the time-shift data in a joint inversion scheme.

The inversion results (Figure 2) from these realizations are drastically different, however, the synthetic 4D amplitudes (Figure 1) from them are nearly exactly the same, so the 4D amplitudes alone cannot differentiate between them, all could be considered viable inversion solutions. Because water saturation increase produces hardening signals with softening sidelobes, and gas saturation increase produces softening signals with hardening sidelobes, when these are stacked on top of each other, there is interference between signals and sidelobes which produces this ambiguity in the proportion between water and gas signals. The same signal can be produced by more water and less gas or more gas and less water. However, these different proportions produce very different time-shifts. Time-shifts accumulate vertically and have the advantage of being nearly free of sidelobe effects, however they lack the vertical resolution of the amplitudes. When used together in a joint inversion the time-shifts contribute to resolving the proportion between increases in gas and water saturation, while the amplitudes contribute to the vertical positioning of the property changes.

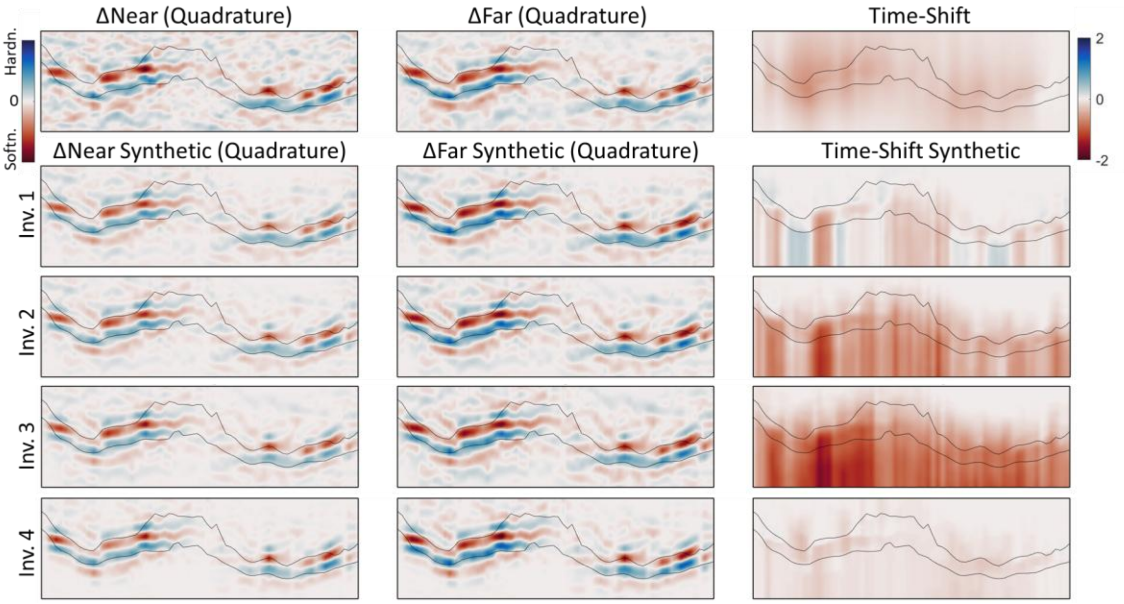

Figure 1: Observed 4D seismic amplitude and time-shift signal (Top). Synthetic 4D seismic amplitude and time-shifts produced from four different inversion results. All inversion solutions match the 4D amplitudes equally well, but only one (Inversion 4) matches the time-shifts too.

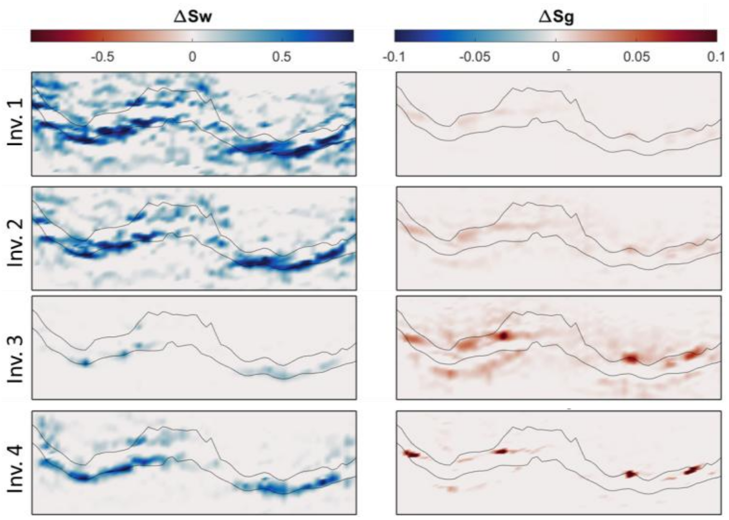

Figure 2: Water and gas saturation from four different inversion results. Inversions 1 and 2 are biased to water saturation but match the 4D amplitudes equally well. Inversions 3 and 4 have the same balanced parametrization, but inversion 4 assimilates the time-shifts jointly.

Conclusions

We demonstrate the 4D seismic amplitude ambiguities related to the vertical distribution of reservoir property changes with an example where injected gas pools at the top of the reservoir while water flows in from below. These ambiguities are related to sidelobe effects and the vertical stacking and interference of different property changes. The example shows that, very different vertical distributions of fluid change can explain the 4D amplitudes equally well, however, they cannot also explain the time-shift signal equally well. So time-shifts can act as an independent source of information and resolve ambiguities present on the 4D amplitudes. The joint inversion of 4D amplitudes and time-shifts produce solutions that are more reliable, have less physical inconsistencies and are less affected by sidelobe effects.

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