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Sensitivity analysis of 4D seismic attributes to calibrated petroelastic models under dynamic reservoir conditions

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Abstract Summary

A well-calibrated petroelastic model (PEM) is essential in 4D quantitative interpretation, translating changes in reservoir dynamic properties to 4D seismic attributes such as impedance, AVO gradient, and intercept. This study evaluates the sensitivity of these attributes to saturation and pressure changes using commonly used dry rock frame models based on empirical data, inclusion theory, contact theory, and cementation. Although all models provide a good fit to the static sonic logs, their 4D responses to dynamic properties vary significantly. For saturation-related scenarios (water displacing oil and gas displacing oil), the Critical Porosity model and the fifth percentile (P5) of the patchy cement model (PCM), sampled via probabilistic calibration produce the lowest and highest 4D responses, respectively. Cementation type and its distribution in PCM do not significantly influence the seismic response to saturation changes. In contrast, pressure-induced responses are highly sensitive to both cementation characteristics and variations in sampled hyperparameters. Furthermore, models that incorporate stress sensitivity using compliance theory generate different pressure-related 4D responses compared to those using Hertzian theory. These findings highlight the importance of selecting an appropriate dry rock frame model and accounting for model uncertainty to ensure reliable 4D interpretation in reservoir monitoring.

Introduction

Time-lapse (4D) seismic data are important for reservoir monitoring and management, as they provide valuable information about changes in reservoir pressure and fluid saturation during production and injection. Estimating of these dynamic changes from 4D seismic data involves several sources of uncertainty, one of which is the choice of PEM, which links physical properties derived from geomechanical and production data to the observed 4D seismic attributes. Gassmann's fluid substitution model is a well-established approach for estimating changes in elastic properties due to saturation changes. In this model, dry rock frame models account for the effects of lithology and stress sensitivity in estimating the elastic moduli of rock frame. Using an approximation of Gassmann's model, Han and Batzle (2004) argues that the ratio of the dry rock frame bulk modulus to the rock matrix bulk modulus controls the 4D seismic response to saturation changes. In other words, although different dry rock frame models can be calibrated to match wireline log data with reasonable accuracy, they may lead to different 4D responses to saturation changes. In this study, we assess the sensitivity of 4D seismic attributes to a range of calibrated dry rock frame models under two production scenarios. Using a qualitative Log2Seis analysis, we demonstrate how different dry rock frame models with varying parameterisations result in different 4D amplitude responses and time shifts. In addition, we examine the impact of changes in water saturation, gas saturation, and reservoir pressure on 4D AVO attributes, specifically the intercept and gradient, which are key parameters for 4D inversion to pressure and saturation changes.

Methodology

Dry rock frame models are calibrated using a grid-search optimisation method (Heidari and MacBeth, 2024) on wireline log data from a North Sea clastic reservoir. For PCM (Avseth et al., 2016), calibration becomes highly underdetermined, as the number of model parameters (e.g., mineral moduli, coordination number, cement volume fraction) exceeds the sonic measurements (DT, DTS). To address this, a probabilistic calibration is used to generate multiple parameter realisations that fit the observed logs equally well (Heidari and MacBeth, 2024), allowing uncertainty quantification and its impact on 4D seismic attributes. Stress sensitivity is accounted for using two approaches: the compliance model (MacBeth, 2004) for empirical and inclusion-based models, and Hertzian theory (Mavko, 2020) for contact-based and cementation models.

Results and discussions

Calibrated dry rock frame models and their optimised hyperparameters are used in Gassmann's equations to estimate the maximum 4D response for a 50% change in water saturation. Capillary end-points are included in the modelling, with irreducible and residual oil saturations of 0.35 and 0.15, respectively, for a rock with 22% porosity. Figure 1 shows variations in intercept, gradient, and impedance versus water saturation changes. In PCM, cementation type and distribution around grain contacts are additional hyperparameters. We present results for both connected and disconnected cementation cases, assuming uniform cement distribution on grain surfaces. Grey curves indicate 4D responses from multiple PCM realisations generated via probabilistic calibration. Dashed green, red, and pink lines represent the 5th percentile (P5), mean, and 95th percentile (P95) responses, respectively. For small saturation changes (≤10%), all models generate similar 4D responses. Excluding Soft Sand model which is unreliable due to poor fit with static logs, the Critical Porosity model and the P5 PCM realisation produce the lowest and highest 4D responses, respectively. Responses from Critical Porosity, Keys-Xu, and Xu-White fall below P5 PCM, while Stiff Sand and Krief models are closer to the PCM mean and P95 responses. A comparison of PCM results for two cementation types shows that 4D responses are not sensitive to this diagenetic feature in unconsolidated sandstone. Figure 2 presents intercept versus gradient cross-plots illustrating the individual effects of dynamic reservoir property changes. In production or injection scenarios, multiple dynamic properties often change simultaneously, and their effects combine in the 4D seismic response. Although the 4D signal reflects all changes, it is typically dominated by one primary factor. Gradient-intercept plots are useful for identifying the dominant influence when multiple effects are superimposed.

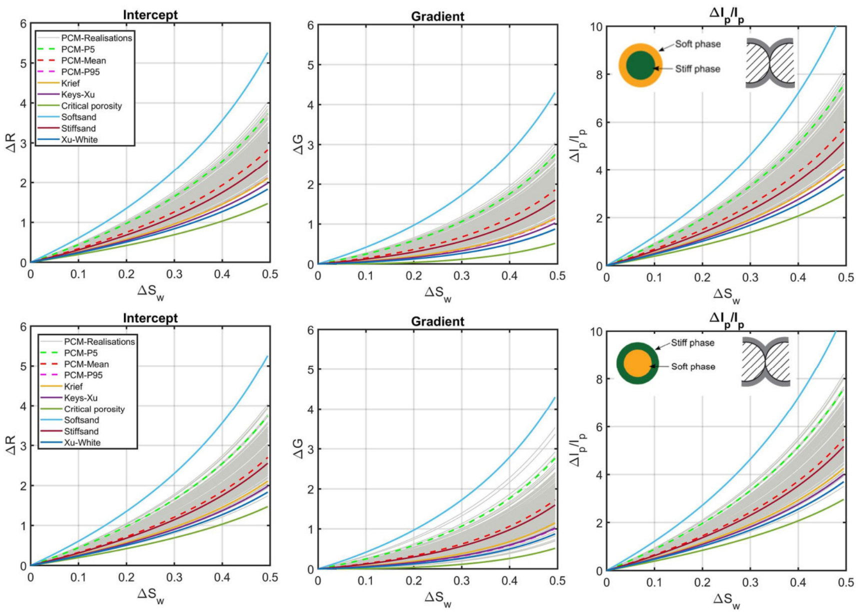
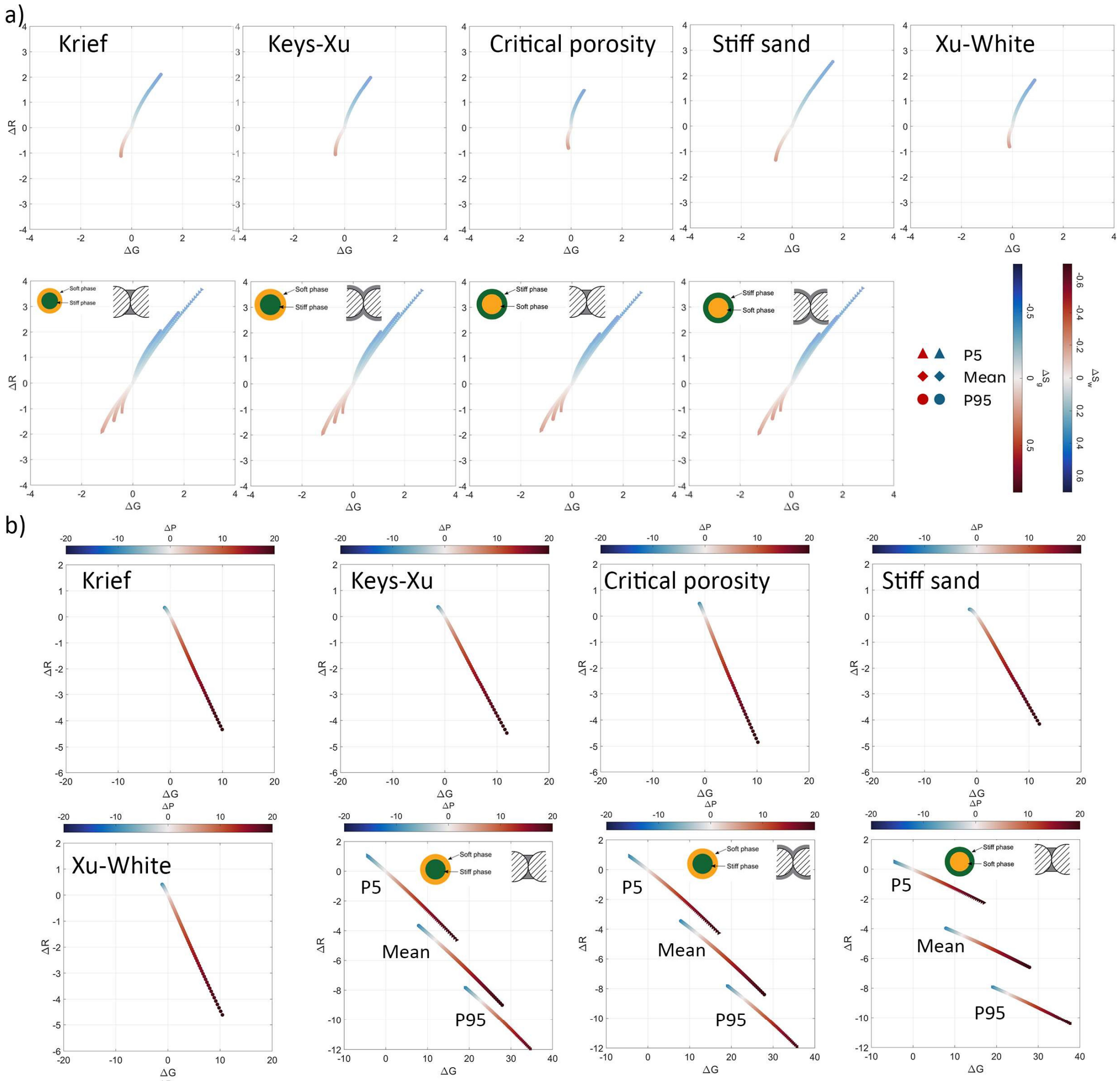


Figure 1: 4D AVO gradient, intercept, and impedance changes versus water saturation changes for different dry rock frame models. The first and second rows show PCM results in grey and dashed green, red and pink lines for disconnected and connected cementation, respectively.

The cross-plots in Figure 2a show that saturation-related effects intensify with increasing offset. This leads to positive 4D AVO gradients and intercepts for hardening signals, and negative values for softening scenarios such as gas replacing oil. The magnitude of these responses varies by dry rock frame model, with the P5 realisation of PCM showing the strongest effect. However, cementation type has little impact on the overall 4D response to saturation changes. In contrast, pressure-related effects (Figure 2b) generally weaken with offset for all models except PCM. Pressure-induced hardening yields negative gradients, while softening results in positive gradients. For PCM, both cementation type and the range of hyperparameters influence pressure-



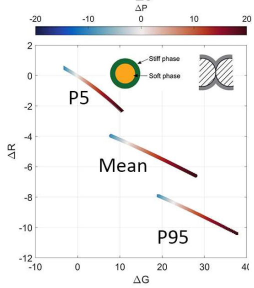


Figure 2: 4D Intercept versus Gradient cross-plots illustrating the individual effects of dynamic property changes using different dry rock frame models and parameterisations. (a) Shows changes due to water replacing oil and gas replacing oil at a constant pressure of 40 MPa. (b) Shows the impact of pressure depletion and build-up at 50% water saturation changes (no gas saturation).

related 4D AVO responses. Across all four cementation types, the P5 realisation produces a negative gradient and positive intercept under pressure depletion, and the reverse under pressure build-up. However, even at 10 MPa depletion, the mean and P95 realisations produce softening signals. This variability stems from differing dry rock bulk moduli produced by equally valid hyperparameter combinations that match the static logs. These findings highlights the uncertainty inherent in models like PCM, where multiple hyperparameters can generate non-unique but plausible solutions. To realistically visualize 4D seismic responses, we apply a Log2Seis workflow to generate seismic traces and corresponding time shifts resulting from saturation changes at constant reservoir pressure, using the Krief model and various PCM parameterisations. Figure 3b shows impedance changes, unwrapped 4D seismic, and estimated time shifts for the Krief

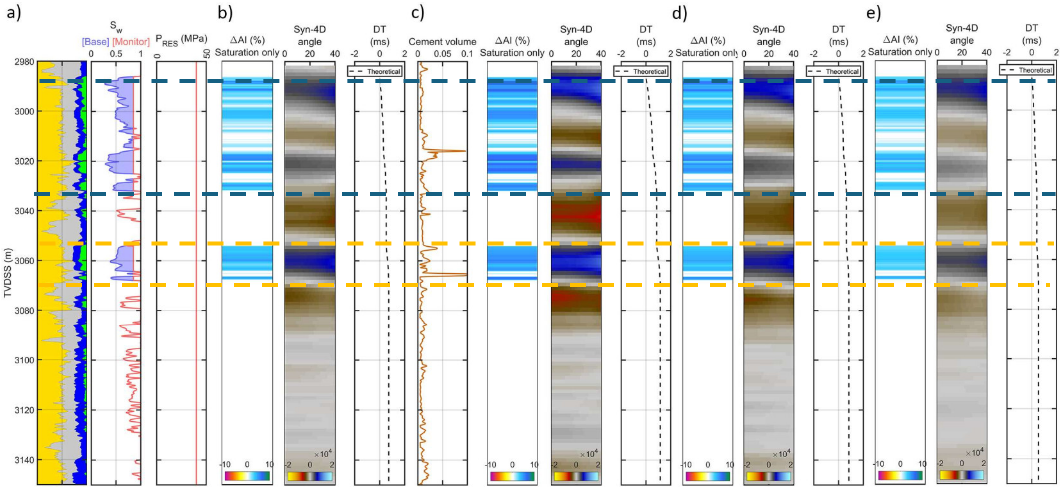


Figure 3: Log2Seis modeling of a 50% water sweep at constant reservoir pressure (40 MPa) using b) the Krief model, and c) P5, d) mean, and e) P95 parameterizations of PCM.

model. Figures 3c–e show these attributes for the P5, mean, and P95 PCM parameter sets. In the reservoir intervals, the P5 realisation yields the highest 4D amplitude and time shift, while the Krief and P95 parameterisations generates the lowest. Across all four models, 4D amplitudes increase with offset.

Conclusions

Assessment of 4D attribute sensitivity to fluid saturation changes indicates that, despite all dry rock frame models fitting the static data reasonably well, their 4D responses differ significantly. The Critical Porosity model and the P5 realisation of PCM parameters produce the lowest and highest 4D values, respectively. For the studied unconsolidated reservoir, impedance changes for Krief, Critical Porosity, Xu-White, Keys-Xu, and Stiff Sand are 4.25%, 2.96%, 3.70%, 4.00%, and 5.17%, with corresponding intercept-gradient pairs of (1.15, 2.11), (0.51, 1.47), (0.87, 1.83), (1.02, 1.98), and (1.60, 2.55), indicating substantial variability in 4D AVO responses. Cementation type in PCM has no impact on fluid substitution scenarios but affects pressure-related responses alongside hyperparameter variations. The compliance-based stress sensitivity model yields physically consistent hardening and softening signals. At 85% water saturation, only the P5 PCM realisation correctly generates hardening for pressure depletion and softening for inflation, while others incorrectly produce softening even under 10 MPa depletion, highlighting the uncertainty in PCM parameterisations under pressure-related changes.

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