5th International Workshop on Rock Physics 23 – 26 April 2019, Hong Kong SAR

Estimation of CO2 plume parameters from 4D seismic

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Introduction

4D seismic is the main tool for monitoring CO2 geosequestration. Traditionally, time-lapse signal is being interpreted qualitatively - spatial location of the main body of CO2 plume. However, storage site operators are legally bound to validate conformance of the injection to dynamic models, which requires estimates of the plume parameters: plume thickness and spatial distribution of CO2 saturation etc. Diffusion of CO2 is driven by buoyancy at relatively short distance from injection wells, so the plumes tend to form heterogeneous pack of thin low-saturated interlayers that may not be resolved accurately by surface seismic (Williams and Chadwick 2012).

Response from a thin but contrast layer is a fundamental problem for seismic monitoring, e.g., active detection of hydraulic fractures (Oelke et al. 2013). Widess (1973) developed approximate reflectivity of an isolated thin layer to answer 'how thin is a thin bed'. Here, we have to do with a similar question – what is a 'seismic CO2 plume'? Glubokovskikh et al. (2016) examined detectability of a very small CO2 leakage through a computationally expensive simulations. Extending that study, we focus on accuracy of 4D seismic estimates of the plume parameters relevant for dynamic simulations. To this end, we develop stochastic rock physics/seismic modelling workflow to estimate the sensitivity to the plume parameters and inherent accuracy limits of 4D seismic.

Modelling workflow

We focus our analysis on a typical clastic reservoir, which initially comprises of brine-saturated shale and sandstone layers. Using unconditional Markov process, we generated tens of thousands of pseudo-wells with facies, porosity, V_P, V_S and ρ assigned (see details in Table 1). After CO2 injection, some sandstone layers sealed by shales become CO2-saturated (gas saturation varies between 10% and 100%). Point-wise (0D) change of the seismic properties is computed according to the Gassmann-Wood equation. Finally, the 1D time-lapse seismic is obtained by 1.5D seismic modelling using zero-phase Ormsby wavelet (bandwidth = 90Hz, central wavelength $\lambda \sim 65$m).

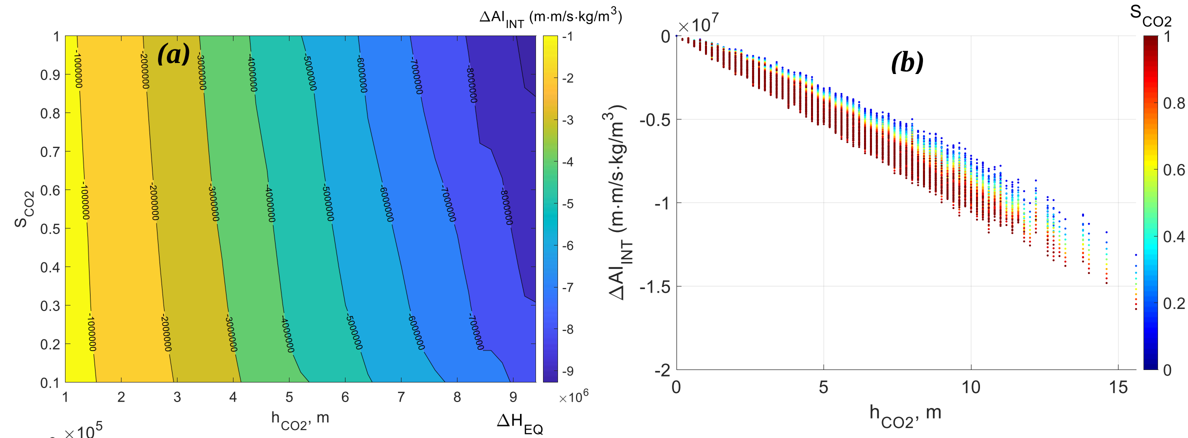
Results

The synthetic data suggests that output of 4D acoustic inversion may be modelled by sequential Backus averaging with the window $\lambda/8$. We examined the following interpretational attributes: maximum change of the 'smeared' acoustic impedance $\Delta AI_{\max}$ [$m/s{\cdot}kg/m^3$]; area under the time-lapse impedance change ΔAI_{INT} [$m{\cdot}m/s{\cdot}kg/m^3$] and its equivalent thickness $\Delta H_{\mathrm{EQ}} = \Delta AI_{\mathrm{INT}}/\,\Delta AI_{\mathrm{MAX}}$ [m].

Figure 1a, b illustrates strong dependence of ΔAI_{INT} on total gas column height h_{CO2} and lack of sensitivity saturation level in the gas-bearing sandstones – S_{CO2}. ΔH_{EQ} features similar behaviour. Another commonly-used parameter, ΔAI_{max}, may not be uniquely related to the plume parameters. In Figure 1c, neither uniform nor patchy saturation models may capture the variability of the seismic response. As the CO2 plume becomes more homogeneous, ΔAI_{max} approaches the Gassmann-Wood value. For a 'smeared' vertically plume, the Gassmann-Hill equation becomes valid. It explains popularity of the Brie's law among practitioners.

Conclusions

We studied the accuracy of 4D acoustic inversion for quantitative characterisation of CO2 storage parameters: plume thickness, mass of CO2 and vertical stratification of the plume. Using stochastic rock physics/seismic modelling workflow, we found a strong dependence of the inverted time-lapse acoustic impedance change on total gas column height, while sensitivity to saturation is negligible. Augmented by field seismic measurements of signal-to-noise levels and repeatability, these results may be used for monitoring system design, uncertainty quantification and history matching.



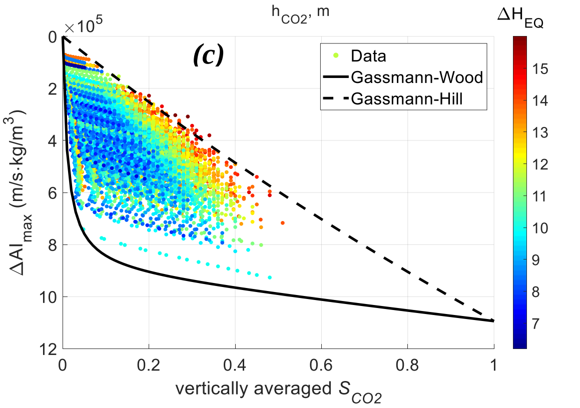


Figure 1: Sensitivity of the inverted impedance to plume parameters: (a) integral time-lapse impedance change ΔAI_{INT} versus gas column height h_{CO2} (colour corresponds to saturation level of gas-bearing sands S_{CO2}); (b) ΔAI_{INT} vs volumetric gas fraction, circles coloured by Gas saturation (c) ΔAI_{max} vs vertically averaged S_{CO2}, circles coloured by ΔH_{EQ}

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