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What does Rock Physics tell us about detectability of fluid changes in underground reservoirs? Practical applications for seismic monitoring of CO_2 storage in saline aquifers.

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Summary

Seismic detectability of fluid changes in underground pore space depends on various factors including subsurface geology, changes of fluid saturation, pressure and temperature as well as repeatability of geophysical measurements. In this presentation, forward modeling, including the use of rock physics models, is performed to assess the impact of these factors on the detectability threshold on seismic data of fluid changes within an underground porous reservoir. Field data from Canada and the North Sea are used to illustrate how various seismic repeatability scenarios and fluid substitution models can impact decisions for long-term monitoring of CO_2 storage in saline aquifers.

Key factors that impact seismic detectability of fluid changes in underground pore space

Seismic detectability of fluid changes in underground reservoirs is governed by three main factors highlighted in Figure 1. First, the subsurface geology, and more specifically what type of rock hosts the fluid. The mineral composition, porosity and pore space stiffness are the key parameters in play in this first piece of the puzzle that is mostly static in a time-lapse sense (with the notable exception of carbonate rock dissolution) and out of our control. The second piece of the puzzle is the fluid change that is induced by field operations. Unlike the host rock, operators have (almost) full control over the amount, composition, pressure and temperature of the fluid that is injected and/or the amount of fluid that is extracted from the pore space. The last key factor is the geophysical monitoring setup. This piece of the puzzle is also somewhat controlled by the operator in charge of picking a setup that provides sufficient repeatability within a given budget. In practice, this task is a lot easier in oil and gas operations than carbon sequestration.

Seismic modelling can be performed to analyze the impact these key factors and their various parameters have on the detectability of fluid changes on time-lapse seismic data. Figure 2 shows the three main steps involved in this forward modeling exercise. Elastic modeling using rock physics models is the first step that translates changes of fluids (composition, pressure, temperature) into changes of elastic properties (P-wave velocity, S-wave velocity and density). Seismic modeling (ranging from a simple convolution with a 1D wavelet to complex 3D full-waveform algorithms) is then employed to generate synthetic seismic data. Noise modeling is the last step in the workflow and determines whether fluid changes trigger a time-lapse change (amplitude and/or time shift) that is detectable over a given level of noise in the seismic data.

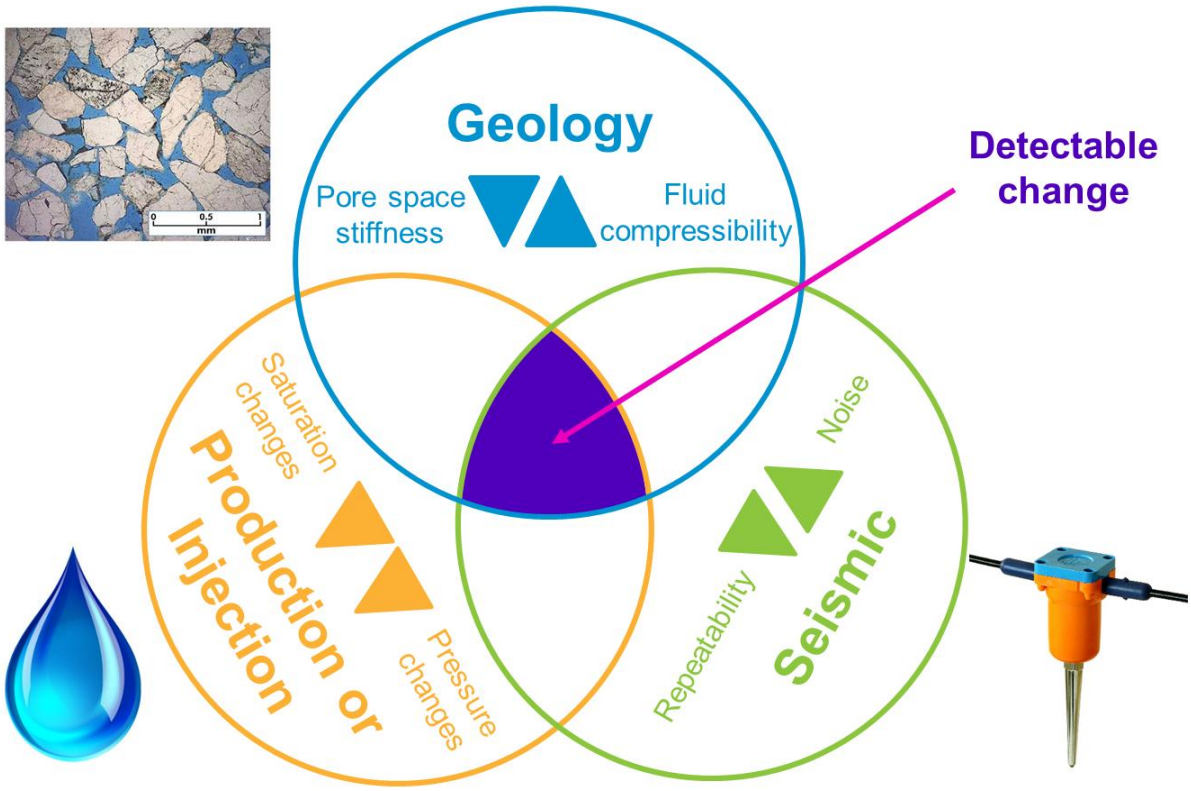


Figure 1: Key factors that impact the seismic detectability of fluid changes in underground reservoirs

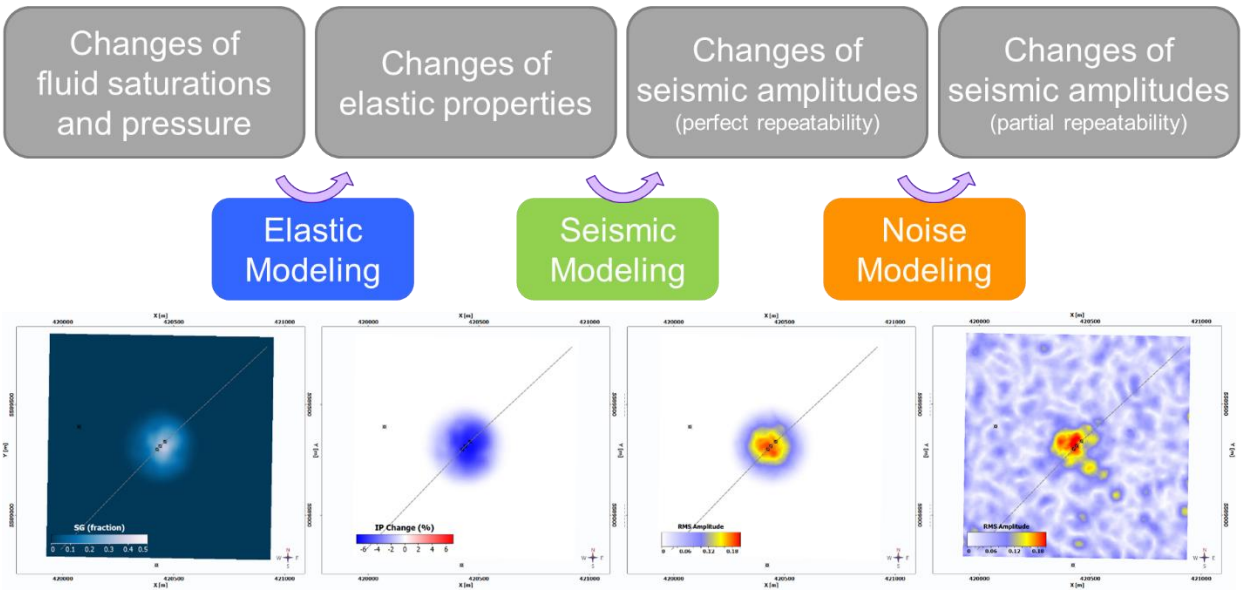


Figure 2: Main steps involved in time-lapse seismic modeling illustrated with a synthetic CO_2 injection scenario that includes changes of fluid saturation and pressure

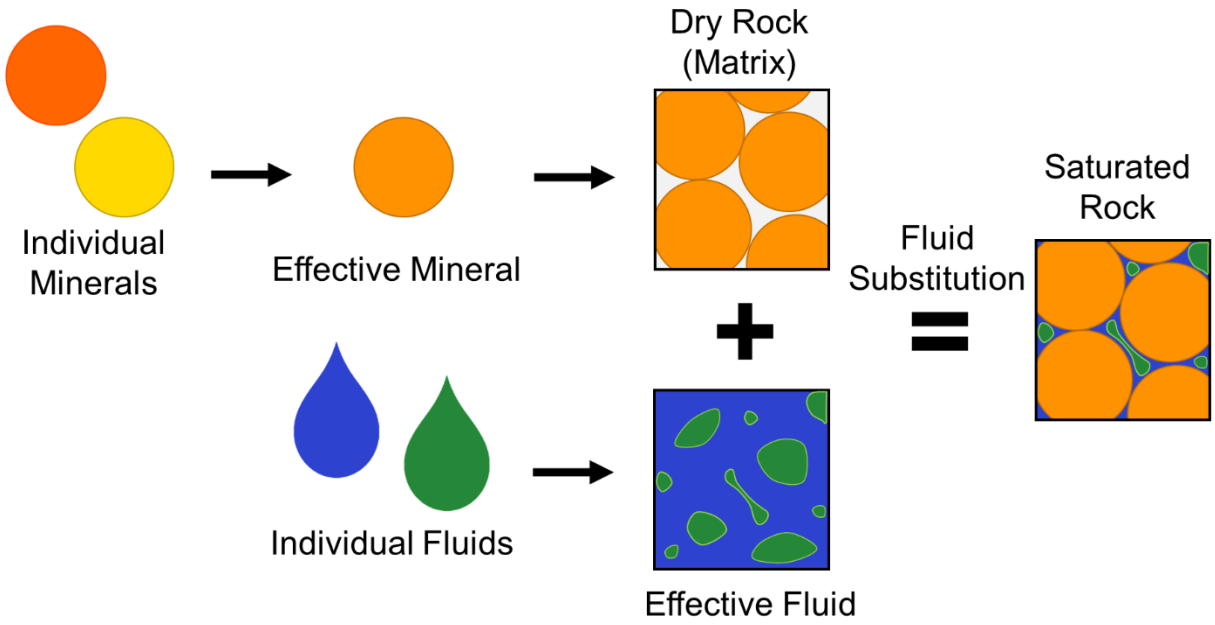


Figure 3: Main steps followed by effective medium models to predict the elastic response of a saturated rock based on its individual components

Rock Physics modeling basics

Although digital rock physics models capable of reproducing the elasticity of a rock based on their exact composition (volume of pore, fluid and mineral fractions) and texture (geometry of pore, fluid and mineral fractions) exist, they are limited to small-size samples that can be analyzed in the laboratory. Effective medium models are still relied upon for modeling at field scale due to their simplicity and power of generalization for rocks that cannot be directly observed.

Figure 3 highlights the main steps followed by effective medium models to predict the elastic properties of a saturated rock based on its composition and texture.

Individual mineral properties are usually taken from tables in reference papers that gather experimental measurements on single minerals. Apart from clay minerals, most minerals are relatively insensitive to pressure and temperature changes so their properties are assumed constant in a time-lapse sense. An empirical mixing law such as Voigt (1890), Reuss (1929) or Hill (1952) equations is then used to determine properties of a hypothetical effective mineral equivalent to a blend of the actual minerals.

Computing the elastic properties of the dry rock (namely bulk and shear moduli as density is straight forward) is the single most uncertain part of any given rock physics model. This is reflected in the multitude of available empirical and theoretical models. Grain-based and inclusion-based models are the two major families of theoretical models (and even these include some empirical parts). Most grain-based models rely on the critical porosity concept introduced by Nur (1995) and Hertz-Mindlin theory (Mindlin, 1949) that describes the elastic response of a pack of identical spheres to compression and shear stresses. On the other hand inclusion-based models such as the differential effective medium and self-consistent models based on theories from Kuster and Toksöz (1974), Mori and Tanaka (1973) and others rely on the cumulative effect of volumetric

and deviatoric strain concentration factors (often nicknamed pore shape factors) of various inclusions added to a background rock made of the effective mineral. Out of these inclusion-based models, it is worth mentioning the Vernik-Kachanov model (Vernik and Kachanov, 2010) that dissociates the contributions of pores and cracks on the compressibility of the dry rock which makes it practical to analyze the impact of pore fluid pressure on the overall compressibility of the saturated rock (Vernik, 2016).

Individual fluid properties are computed through empirical or equation of state models. Empirical models proposed by Batzle and Wang (1992) and Han and Batzle (2000) among others have been implemented in the Fluids/DHI consortium FLAG program for example. Equation of state models have evolved from the early developments of van der Walls (1873), Redlich and Kwong (1949) and Peng and Robinson (1976) to ever more realistic models such as the one implemented by the Groupe Européen de Recherches Gazières, GERG (Kunz et al., 2007) among many options. Even these equation of state models include some empirical approximation which require careful calibration to laboratory measurements. Unlike minerals, fluids are highly sensitive to pressure and temperature that can even lead to potential phase changes. An empirical mixing law such as Wood/Reuss (1929) or Brie (1995) equations is then used to determine properties of a hypothetical effective fluid equivalent to the actual blend of fluids. Blending immiscible fluids brings an extra layer of complexity as their relative saturations can potentially vary in different parts of the pore space (homogeneous versus heterogeneous saturation models). Empirical “patchy” saturation models are used in case of heterogeneous blends.

Fluid substitution models are used to compute the bulk (and potentially shear) modulus of the saturated rock from the dry rock, effective mineral and effective fluid moduli. Gassman’s model is by far the most used due to its simplicity and relatively good accuracy. But this model is based on a number of assumptions that are sometimes violated in underground reservoirs such as a micro-homogeneity within the rock. Although alternative models such as the ones proposed by Biot (1941) and Brown and Korringa (1975) exist, they are less practical and therefore rarely used. Testing rock physics models based on different fluid substitution models is instructive as it gives an idea of the magnitude of the potential error made when using a given model for a given set of conditions.

Impact of seismic repeatability on monitoring of CO_2 storage in saline aquifer

In this first example from Allo et al. (2023), seismic forward modeling is performed based on data from the Containment and Monitoring Institute (CaMI) project in Alberta, Canada. A small amount of CO_2 injected into a shallow reservoir is used as a proxy for a leak coming from a deeper underground reservoir. Wireline well logs and multicomponent seismic data recorded at the field research station are used to characterize the subsurface before CO_2 injection. Rock physics models and 1D seismic modeling are applied to compute the expected elastic and seismic changes caused by CO_2 injection. Different levels of random noise are added to analyze the minimum time lag between seismic acquisitions necessary to detect a change in the reservoir for given seismic repeatability scenarios (Figure 4). Results indicate that surface seismic data can be used for both conformance (localization of the plume) and containment (detection of leak) monitoring. Although high repeatability between monitor surveys is critical for early detection of leaks, a slightly less repeatable set-up could be sufficient for long-term monitoring of the plume and more viable given the tight budgets of carbon sequestration projects.

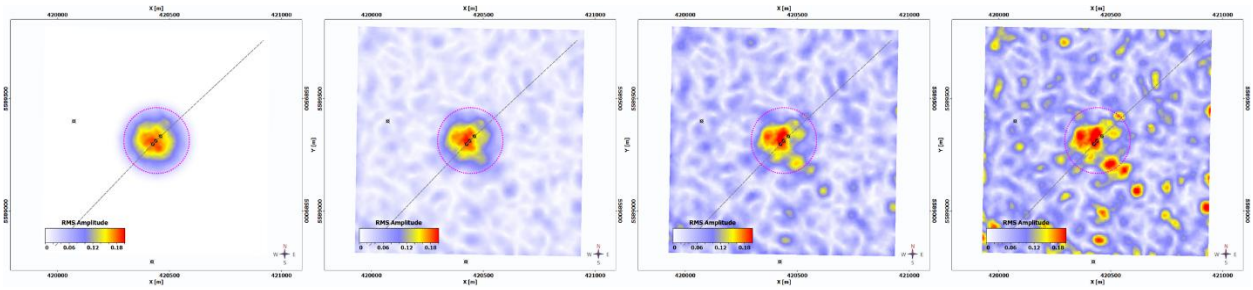


Figure 4: Simulated synthetic time-lapse RMS amplitude changes caused by the same CO_2 injection with increasing levels of added random noise (NRMS of 0, 5, 10 and 15 respectively) can help determine the detectability threshold of that specific injection scenario

Impact of fluid substitution model on monitoring of CO_2 storage in saline aquifer

Gassmann's equation (Gassmann, 1951) is routinely used for fluid substitution in elastic and seismic forward modeling applications. Although several alternatives exist, they are more complex and less practical, hence the popularity of Gassmann's equation. But this equation comes with underlying assumptions so checking that it is applicable for any given rock should always be part of the modeling workflow. In this second example from Allo et al. (2024), the saturated rock bulk moduli computed with Gassmann's equation and the more general Brown & Korringa's equation (using the practical application proposed in Allo and Vernik, 2024) are compared (Figure 5) to assess the applicability of Gassmann's equation for reservoir rocks used for CO_2 storage. The magnitude of Gassmann's inaccuracy is illustrated using data from the Northern Lights sequestration project in the North Sea.

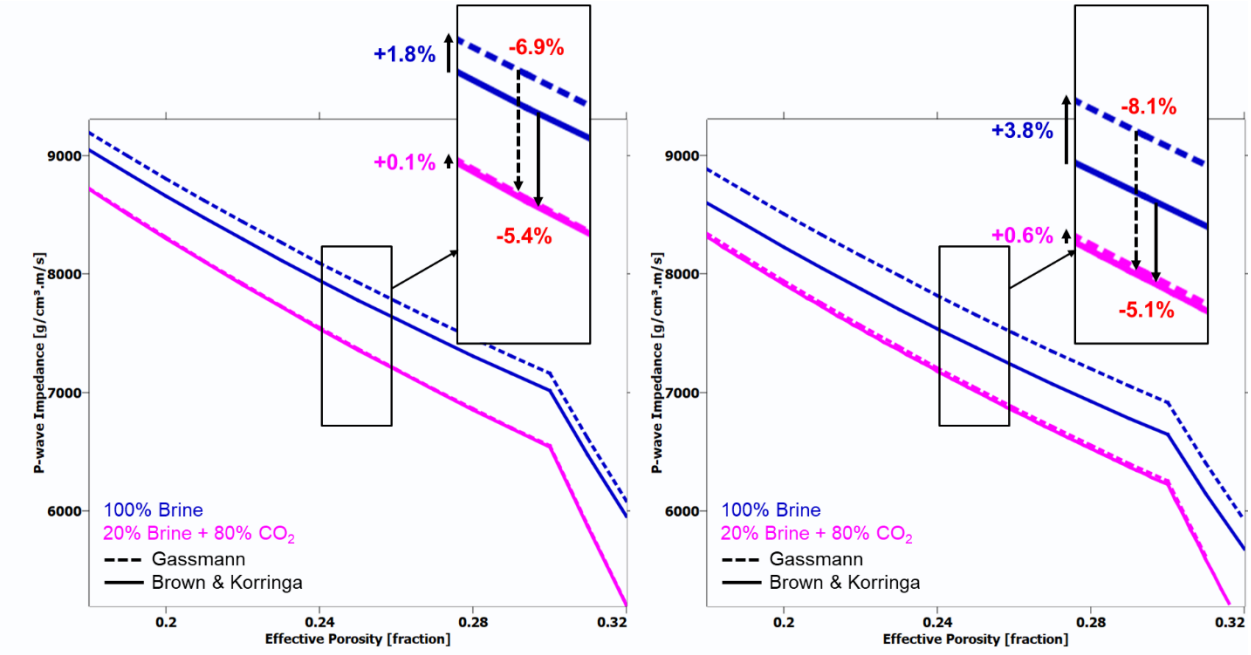


Figure 5: Difference in saturated rock P-wave impedance predicted by Gassmann (dashed lines) and B-K (solid lines) based models for brine (blue) and 80% CO_2 + 20% brine (pink) scenarios for a sandstone from the Johansen formation subjected to in-situ effective stress (left) or a hypothetical reduced effective stress caused by a pore pressure build-up

of 10 MPa due to CO_2 injection (right). Specific time-lapse changes predicted by both models for a 25% porosity sandstone are indicated in red in the zoomed insets.

Conclusions

Seismic detectability of fluid changes in underground reservoirs is governed by three main factors: the elastic stiffness of the reservoir rock pore space, the changes of saturation, pressure and temperature when fluid is replaced in this pore space and the repeatability of the seismic measurements. Rock physics and seismic modeling help understand the relative importance these factors play on the seismic detectability of fluid changes. By comparing the magnitude of the predicted time-lapse seismic response with various levels of random white noise, one can gauge the required repeatability to detect a given fluid change and orientate the choice of seismic acquisition setup accordingly leading to fit-for-purpose monitoring systems as the one described by Oggioni et al. (2025). Unfortunately, rock physics models rely on a lot of hypotheses and contain a large number of parameters that need careful calibration. Understanding the magnitude of the uncertainty caused by these parameters is crucial as illustrated by the comparison of different fluid substitution models. Choosing an inadequate model can result in a false certainty about the seismic detectability of expected fluid changes. This confidence could quickly crumble when monitoring in the field fails to detect any change and turns out to be as inadequate as the chosen rock physics model.

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