Introduction

Safe CO_2 storage requires short and long term monitoring of the CO_2 fate in the reservoir and early detection of potential leakages towards the surface (Pawar et al., 2015). Seismic methods often constitute the cornerstone of geophysical monitoring, although other techniques (electromagnetic, gravimetry) can also be used. Conformance monitoring requires verifying that the CO_2 behaviour inside the reservoir is consistent with reservoir-based model forecasts. In this context, pore pressure management can play a critical role. Indeed, while one can think that storage capacity is driving large-scale (gigatons) CO_2 storage, the initial state of reservoir pore pressure and the resulting build-up caused by injection might be the main limiting factors (Ringrose and Meckel, 2019).

Tracking pore pressure changes in the reservoir is therefore crucial for both efficient (maximizing storage capacity) and safe (mitigating pressure build-up early enough) CO_2 storage. Nevertheless, the link between time-lapse changes observed in geophysical data and pore pressure changes is far from being trivial. For example, P-wave velocity changes due to CO_2 injection depend on many parameters, and are not limited to pore pressure changes (Landrø, 2001; Hansen et al., 2011; Verdon et al., 2013).

In this paper, we propose to study these dependencies for a selection of relevant rock physics models. We analyse the link between pore pressure changes, saturation, and other rock physics properties that might be affected by the CO_2 injection (porosity, fluid mixing). We qualitatively categorize these effects and evaluate their link to common properties (seismic velocities, attenuations, density and resistivity) that can be derived from geophysical data.

Rock physics models

We consider three types of geophysical data: seismic, gravimetry and electromagnetic or electrical data. We assume that geophysical inversion is carried out and provides spatial distributions of selected geophysical properties. For example, with FWI (Full Waveform Inversion) or AVO (Amplitude Versus Offset) inversion, one can get maps of P-wave velocity or P- and S-impedances respectively. In the same way, CSEM (Controlled Source ElectroMagnetics) or ERT (Electrical Resistivity Tomography) data provide resistivity estimates while gravimetry data can map density changes. From these properties, a second inversion step can be applied to estimate selected rock physics properties. Such two-step inversion strategy is described by Yan et al. (2019) and applied at Sleipner with seismic FWI.

It is observed (Landrø, 2001; Hansen et al., 2011; Rubino et al., 2011; Park et al., 2013) that CO_2 injection will usually cause a decrease of P- and S-wave velocities (V_P and V_S), a decrease of P-wave quality factor Q_P (increase of attenuation), a decrease of bulk density ρ and an increase of bulk resistivity R_t. These dependencies are related to a change in the rock frame and the pore fluid compressibilities as well as the porosity and fluid saturation changes. Such property changes can be derived from the first (geophysical inversion) step and constitute the observed data for the second (rock physics inversion) step where an inverse problem must be solved to quantify the rock physics properties affected by the injection (see Figure 1). These properties are commonly limited to saturation and pore pressure, but other quantities should not be neglected such as porosity and patchiness distribution of fluids. The forward modelling operator, describing the link between rock physics and geophysical properties is a combination of rock physics models.

In a first order approach, where pore pressure effects are neglected (like in Sleipner), conventionnal (Biot-)Gassmann rock physics models (Gassmann, 1951; Biot, 1956) are shown to be good enough to describe observed changes in seismic data due to saturation (Dupuy et al., 2017). In this case, in addition to CO_2 saturation, the main controlling parameter is the fluid mixing, i.e., if fluid phases (brine and supercritical CO_2) are heterogeneously (patchy) or uniformly mixed in the pore space. An effective fluid phase is usually considered and equation such as Brie et al. (1995) used to define a patchiness exponent e that is spanning the different mixing between uniform and patchy mixing (see more details in Dupuy et al. (2017)).

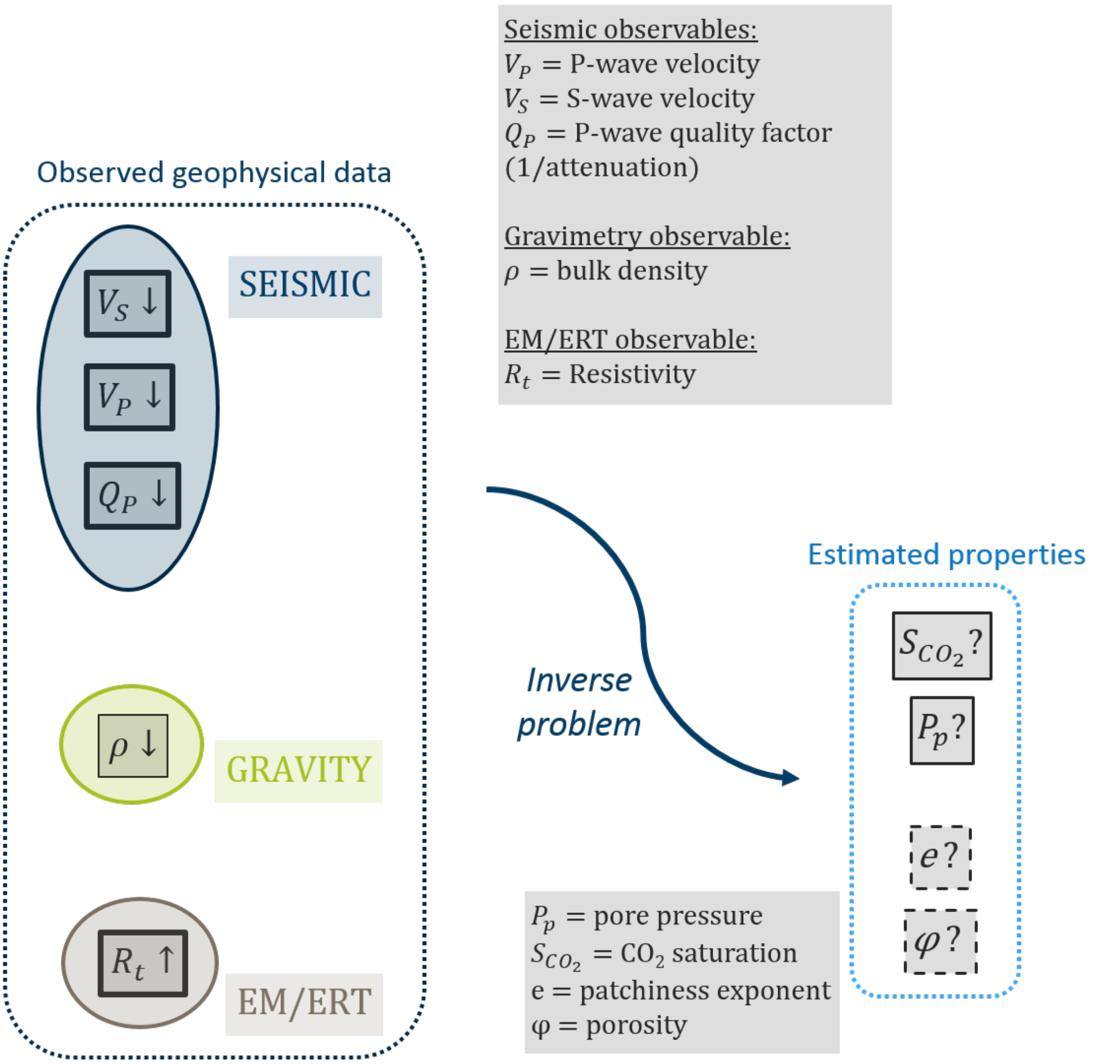

Figure 1 *Inverse problem to derive appropriate rock physics properties modified by CO_2 injection from geophysical inputs .*

If pore pressure is significantly modified by the injection, it must be taken into account into the rock physics models. First, the pore fluids properties are dependent on pore pressure (and temperature) and they can be calculated using thermodynamics models (Span and Wagner, 1996) or empirical models (Batzle and Wang, 1992). This effect is usually not the dominating one. On the other hand, the rock frame is also modified by the pore pressure changes and there is a wide range of models describing these effects (see Mavko et al. (2009) for an overview). These models must be calibrated in most cases and will provide estimations of dry rock bulk and shear moduli versus differential pressure.

Interdepencies of parameters

In Figure 2, we describe inter-dependencies of the rock physics parameters and how they are affecting common geophysical observables derived from seismic, gravimetry and EM/electrical inversions. The main effect of a pore pressure increase due to a fluid injection is a decrease of P- and S-wave velocities via the decrease of the rock frame moduli. The pore pressure change slightly affects the bulk density via changing the fluids density. It might also have an effect on the resistivity if the pore space (porosity) is impacted by the injection. On the other hand, the main effect of saturation change is towards P-wave velocity and P-wave attenuation (quality factor). The change in fluid saturation will also decreases the bulk density. Note that this density change has also a minor effect on velocities. Finally, the saturation change has a dominating effect on the bulk resistivity. In addition to these effects, the patchiness exponent can vary which might strongly affect the P-wave velocity and quality factor. Porosity can also change due to the injection and it will impact all geophysical parameters strongly.

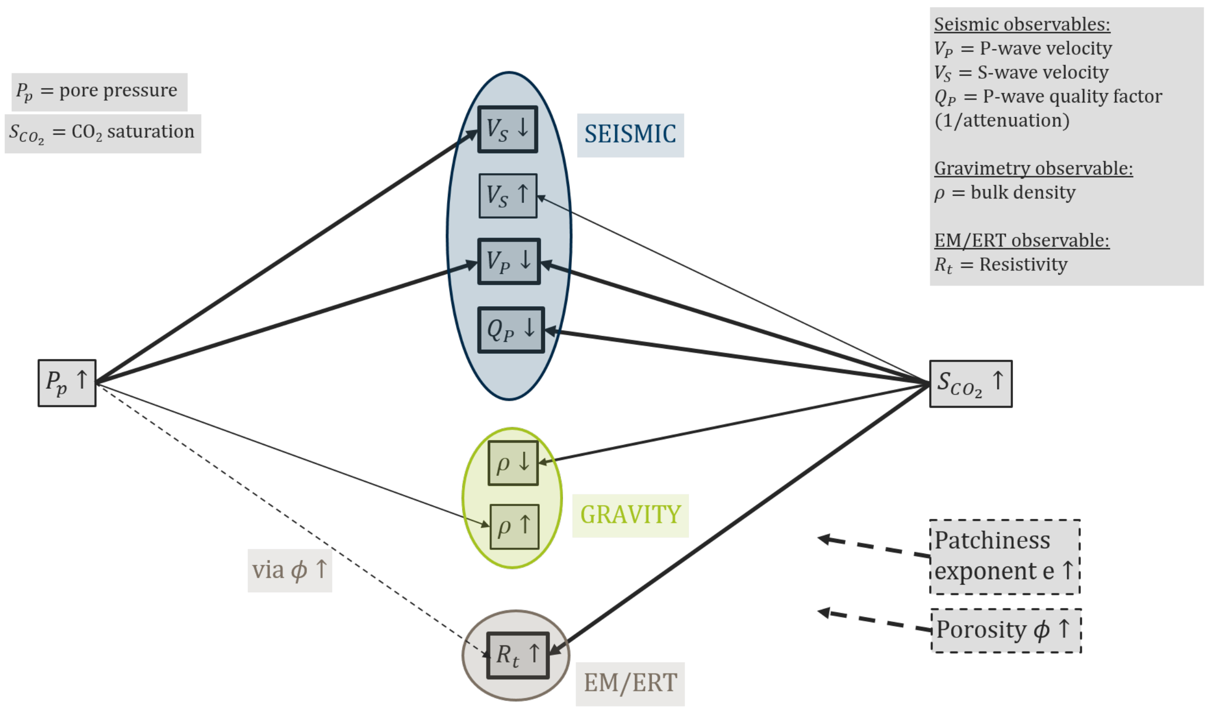

Figure 2 *Effects of pore pressure and saturation changes on geophysical observables in case of CO_2 injection.*

Example at Snøhvit

Snøhvit is a CO_2 storage site in the Barents Sea, offshore Norway, where 1600 kt of CO_2 has been injected between 2008 and 2011. The injection was stopped due to fast pressure build-up in the reservoir, observed by injection well pressure gauges and anomalous seismic signature. Hansen et al. (2011) and Grude et al. (2013) show that measurable time-shifts can be observed on the 4D seismic data. The pressure changes were estimated to be equal to 6 MPa. We show that the relative P-wave velocity change due to saturation effect is of the order of 1 to 7 % depending on the saturation and patchiness distribution. Using a calibrated pore space stiffness (Dinh and Van der Baan (2019)) model, the velocity change (decrease) due to pore pressure is of the order of 5 %. Using the Hertz-Mindlin model, Grude et al. (2014) suggested relative P-wave velocity changes (decrease) of 2.8 % due to saturation, 2.2 % due to pore pressure (decrease), and 3.3 % due to porosity change (increase). This porosity change is due to salt precipitation and is most likely localised near the well bore. Consequently, the time-shifts derived from seismic time-lapse data analysis are not straightforward to interpret. Hansen et al. (2011) suggest also to consider the effect of cooling of the rock formation on the seismic signature.

Conclusions

We show that advanced understanding of rock physics models taking into account a mix of different effects is crucial to analyse quantitatively the results of geophysical inversions. CO_2 saturation and pore pressure are both affected by CO_2 injection but additional changes might be considered such as porosity and fluid distribution changes (patchiness properties). A variational approach will be implemented to quantify all effects in detail. Pressure and saturation are also the two main outputs of reservoir flow modelling. Quantifying the expected changes in geophysical attributes is therefore possible provided that the rock physics models are properly defined and calibrated.

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