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Modelling ultrasonic laboratory measurements of the saturation dependence of elastic modulus: New insights and implications for wave propagation mechanisms

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ABSTRACT

Seismic time-lapse techniques are a valuable tool used to estimate the mobilization and distribution of stored CO_2 in depleted reservoirs. The success of these techniques depends on knowing the seismic properties of partially saturated rocks with accuracy. It is commonplace to use controlled laboratory-scale experiments to determine how the fluid content impacts on their properties. In this work, we measure the ultrasonic P- and S-wave velocities of a set of synthetic sandstones of about 30% porosity. Using an accurate method, we span the entire saturation range of an air-water system. We show that the rocks' elastic behaviour is consistent with patchy saturation and squirt flow models but observe a discontinuity at around 90% gas saturation which can be interpreted in two very different ways. In one interpretation, the responsible mechanism is frequency-dependent squirt-flow that occurs in narrow pores that are preferentially saturated. An equally plausible mechanism is the change of the mobile fluid in the pores once they are wetted. Extrapolated to seismic frequencies, our results imply that the seismic properties of rocks may be affected by the wetting effect with an impact on the interpretation of field data but would potentially be unaffected by the squirt flow effect. This provides strong motivation to conduct laboratory-scale experiments with partially saturated samples at lower frequency or, ideally, a range of frequencies in the seismo-acoustic range.

1. Introduction

Effective remote seismic monitoring of geological CO_2 storage reservoirs for carbon capture and storage (CCS) projects depends on a thorough understanding of the physics associated with wave propagation in rocks saturated with multiple fluids. Model-based approaches help ensure the injected CO_2 is accurately interpreted as being trapped within the reservoir, and could also help optimise injection locations, rates and therefore storage. It has been noted that CO_2 distribution in the pore space plays an important role in the monitoring process (Eid et al., 2015) and more generally, the contrast between the acoustic properties and densities of oil, brine and CO_2 is exploited in monitoring applications of seismic data (Arts et al., 2004; Chadwick et al., 2010; Ghosh et al., 2015; Toms et al., 2007). However, flow in porous media is controlled by wettability and pore-scale capillary pressure effects (Krevor et al., 2015; Zhang et al., 2016) but these concepts are often neglected in most wave propagation theories used in interpretation of CO_2 reservoir time-lapse data.

Models based on physical properties that can relate seismic attributes to CO_2 saturation are valuable because they provide a generally applicable framework rather than having to resort to empirical relations. This creates a need for experimental data that can be used to calibrate/validate these models. In general, seismic wave velocity and attenuation are properties that are known to be sensitive to fluid in the pores and this fact has been used to determine and quantify the fluid content in reservoirs (Domenico, 1976; Murphy, 1982, 1984; Winkler and Nur, 1982; Winkler and Murphy, 1995). Furthermore, fluid-saturated rocks exhibit frequency-dependent behaviour due to wave-induced fluid flow (Biot, 1956; Chapman et al., 2002; Guéguen and Sarout, 2011;

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Murphy, 1982; White, 1975). The dispersion arises from unrelaxed wave-induced fluid pressures and is accompanied by seismic attenuation.

Measurements of elastic properties of rocks span a wide range of frequencies, as such; extrapolation of results from one frequency range to another requires an understanding of the mechanisms responsible (Paffenholz and Burkhardt, 1989). Also, the associated frequency-dependence could further be exploited for better saturation estimation either through direct analysis of frequency-dependent effects (Castagna et al., 2003; Wu et al., 2014), or reconciling laboratory measurements to calibrate theoretical models for seismic data interpretation (Gist, 1994; Lei and Xue, 2009). Different physical mechanisms with different characteristic frequencies have been proposed to account for this but there is still no general consensus as to which mechanisms dominate (Müller et al., 2010; Murphy et al., 1986; Sarout, 2012). Controlled laboratory-scale experiments are helpful in understanding the mechanisms associated with multiphase saturation effects on seismic properties and can serve as key calibration tools for the theoretical models (Lei and Xue, 2009; Nakagawa et al., 2013).

Laboratory-scale experimental results on CO_2 saturation effects on seismic properties have been interpreted generally using the idea of patchy saturation with a non-Reuss (e.g. Hill, 1963; Brie et al., 1995) averaged fluid moduli in Gassmann's equations (e.g., Lebedev et al., 2013; Shi et al., 2007) or White's model (e.g., Lei and Xue, 2009; Nakagawa et al., 2013). This is also the case with many partial-gas saturation laboratory experiments in the literature. These models (averaged fluid modulus in Gassmann's equation and White's model) do not always give a good fit to the data, with the moduli usually underestimated. This discrepancy is usually attributed to additional wave-induced fluid related mechanisms not accounted for in these models (e.g., Amalokwu et al., 2016; Carcione et al., 2003; Falcon-Suarez et al., 2016; Nakagawa et al., 2013). It has long been recognised and/or suggested that other mechanisms might be at play and that multiple mechanisms might be required to obtain a better fit between laboratory-scale measurements and theoretical modelling (e.g., Gist, 1994; Wulff and Burkhardt, 1997). However, the data from CO_2 experiments does not lend itself well to understanding the saturation-related mechanisms because important saturation points/intervals are missing due to experimental limitations, as many laboratory CO_2 experiments only cover ranges between 0 and 60% CO_2 saturation. The modelling is then done based on these data points, missing the effects of saturation at higher values of the gaseous phase (or CO_2) saturation even though there is evidence of multiphase saturation effects at these saturations (Goertz and Knight, 1998; Mavko and Nolen-Hoeksema, 1994; Wulff and Burkhardt, 1997). Also, the uncertainty in accurately determining the saturation state in CO_2 experiments complicates the interpretation of the experimental data as saturation has to be estimated from CT scans (e.g., Nakagawa et al., 2013) or resistivity tomography (e.g., Falcon-Suarez et al., 2016). Since in terms of the physics, the wave-induced fluid flow mechanisms in less difficult multiphase experiments are the same as in the case of CO_2/brine (neglecting chemical and wettability effects), a good compromise is to investigate these mechanisms using experiments done with air and water which have an easier control on saturation than those using CO_2-brine fluid systems.

A limited number of works have attempted to quantify these effects in order to adequately model the entire saturation dependence using theoretical models (Gist, 1994; Wulff and Burkhardt, 1997), and some have taken a more qualitative approach (e.g., Goertz and Knight, 1998; Mavko and Nolen-Hoeksema, 1994). However, these are very limited and mostly have similar interpretations of the mechanisms, namely, stiffening due to preferential stiffening of the cracks, or due to patchy saturation. Gist (1994) concluded that in order to model satisfactorily the data of Gregory (1976), both the gas-patch model of White (1975) and the squirt flow mechanism need to be considered. However, the heuristic model presented by Gist (1994) accounted for the bulk modulus dispersion due to local flow by assuming shear modulus dispersion was the same as bulk modulus dispersion, an assumption that is not necessarily valid (see Chapman et al., 2002). Aside from the fact that there is limited adequate theoretical interpretation of multiphase laboratory data, the theoretical mechanisms that have been proposed disappear at low frequencies used in seismic field surveys.

Here, we model the effects of saturation from dry to full water saturation by combining different mechanisms. The results show that the interpretation is not unique as different combinations of mechanisms can attain a fit to the experimental data. A major finding of this study is that not all the mechanisms disappear at lower frequencies and this could have important implications for fluid substitution in practice.

2. Methods

2.1. Sample description and experimental setup

The samples used in this study were synthetic silica cemented clean sandstones with a mineral composition of almost entirely quartz grains (Tillotson et al., 2014, 2012). These experiments were originally designed to study the effects of water saturation on fracture-induced anisotropy. The samples were made from a mixture of sand, kaolinite, and aqueous sodium silicate gel, using a process well documented by Tillotson et al. (2012). Results from three samples are presented in this study. There are two cylindrical samples of 5 cm diameter and approximately 2 cm thickness, one blank (non-fractured), and the other containing penny-shaped fractures aligned at 90° to the fracture normal (Fig. 1). The fractures in the 90° fractured sample are not expected to affect the results as we expect the response from the crack parallel direction to show no effects due to the fractures except for an increase in rock porosity (e.g. Chapman, 2003; Thomsen, 1995). The third sample used in this study was an octagonal-shaped prism with flat sides of approximately 25 mm made using the same method as the cylindrical samples (see Tillotson et al., 2014).

Firstly, the rocks were oven-dried at about 40 °C for about 48 h, and then placed under vacuum until a pressure 10^{-4} Pa was achieved, which ensured the rocks were completely dry. Measurements were taken for this vacuum-dried condition. Partial water saturation was then achieved using the method described by Amalokwu et al. (2014), which is summarised here. The rocks were placed in an atmosphere of known relatively humidity (RH) for about two weeks for the cylindrical samples and about 4 week for the octagonal sample, until they had reached equilibrium, which is determined by mass stabilisation (Amalokwu et al., 2014, 2015a). This method is known to give a more homogeneous distribution of water saturation compared to other methods such as drainage and imbibition, and has been used in other studies (e.g. King et al., 2000; Papamichos et al., 1997; Schmitt et al., 1994).

Controlled relative humidity (RH) was achieved using aqueous saturated salt solutions. Greenspan (1977) gave a range of salt solutions that would maintain a given RH at a particular temperature. The salts used and their approximate RH values (at 20 °C laboratory temperature) were Magnesium Nitrate (54%), Ammonium Sulphate (82%), Sodium Carbonate Decahydrate (92%), and Potassium Sulphate (98%) respectively, giving four different S_w values. The maximum water saturation achieved using this method was about 0.4 for the all three rock samples (Amalokwu et al., 2014, 2015a). The rocks were then dried and fully saturated with water using the methods described above. In order to achieve higher water saturation values, a 'modified' drainage method was used