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The effect of CO_2 partial saturation on seismic and ultrasonic velocities in Castlegate sandstone

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Introduction

Time-lapse seismic is one of the most powerful tools for monitoring CO_2 storage in subsurface reservoirs as well as detection of CO_2 leakage into the overburden. Interpretation of time-lapse seismic data requires rock physics models that describe the dependence of seismic velocities on CO_2 saturation. Validation of rock physics models by laboratory experiments is difficult since velocities of rocks for partial gas saturation exhibit dispersion (velocities are frequency dependent), and in the lab, direct velocity measurements can only be carried out at sonic/ultrasonic velocities. It is, however, possible to measure the dynamic stiffness of a rock at seismic frequencies, from which seismic velocities can be calculated under the assumption of a homogeneous rock mass and the absence of macroscopic dispersion effects (Spencer, 1981). In this work, seismic velocities were obtained from dynamic-stiffness measurements with Castlegate sandstone with partial CO_2 saturation, and compared to ultrasonic velocities.

Methods

Measurements were done in a specially designed compaction cell, allowing for simultaneous measurements of quasi-static rock deformation, P- and S-wave ultrasonic velocities in axial direction, and dynamic stiffness (Young's modulus and Poisson's ratio) at seismic frequencies from which seismic velocities can be calculated (Szewczyk, et al., 2016). Castlegate sandstone was used to study the effect of CO_2 on seismic and ultrasonic velocities. In order to generate a homogeneous CO_2 saturation, the samples were saturated with CO_2-saturated water at a pressure of 7.5 MPa. Subsequently, the pore pressure was reduced to 5.5 MPa, 5 MPa, and 4.3 MPa, resulting in CO_2 gas coming out of solution. The amount of CO_2 coming out of solution can be calculated, and under the assumption that the CO_2 gas (gas saturation $\leq 10\%$) is immobile and does not leave the sample, the pressure-dependent gas saturation can be estimated. The confining stress is reduced by the same amount as the pore pressure in order to keep the effective stress constant (reference measurements were done with pure water at the same stress and pore pressure states).

Results and discussion

The results are presented in Figure 1. They show that for a liquid-saturated sample (no free CO_2); the P-wave velocity varies from 2.85 km/s at low frequency to about 3 km/s at ultrasonic frequency. This slight increase may be due to dispersion, or an experiment error. For the same sample with free CO_2 in the pore space, the velocity dispersion is strongly enhanced. For 10% CO_2 saturation, the P-wave velocity increases from 2.5 km/s at 1 Hz to about 2.95 km/s at 5×10^5 Hz (increase in velocities by 18%). The seismic velocities are in good agreement with the Biot-Gassmann theory (solid lines in Figure 1). Ultrasonic velocities, on the other hand, exhibit a relatively small dependence on gas saturation and cannot be described by the Biot-Gassmann theory. The results of Gregory (1976) on Bandera sandstone as well as those of Murphy III (1984) on Cotton Valley sandstone also show a strong dependence of the velocity dispersion in gas saturation in partially saturated samples. According to their results, the velocity dispersion of P-wave increases with the increase of gas saturation up to 10% (Gregory, 1976; Murphy III, 1984). This is similar to our results.

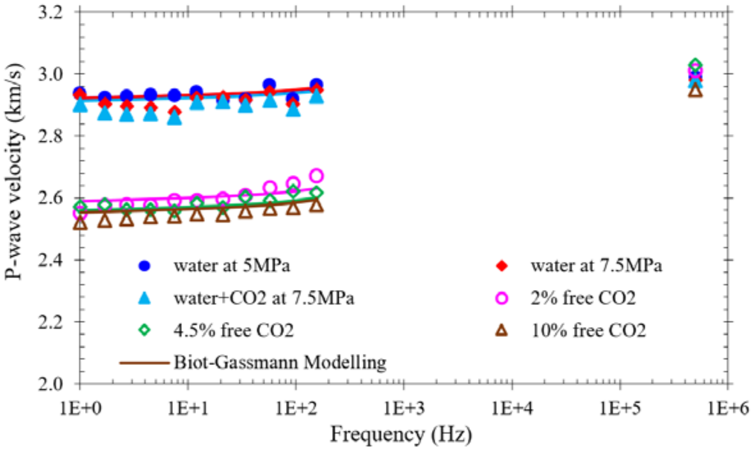

Figure 1: P-wave velocity for different pore fluids and as a function of frequency

Conclusions

The results revealed that for Castlegate sandstone at seismic frequencies, P- and S-wave velocities can be described to good approximation by the Biot-Gassmann model. Already a small CO_2-gas saturation results in a significant velocity reduction. On other hand, ultrasonic velocities exhibit only a small sensitivity to CO_2 gas. Velocity dispersion as well as wave attenuation can consistently be simulated with the Cole-Cole model. A transition frequency of around 200 kHz was found. By applying the White's patchy saturation model, a typical patch size of about 1 mm was obtained.

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