Low frequency laboratory measurements of the elastic and anelastic properties of the sandstone flooded with supercritical \( \text{CO}_2 \)

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SUMMARY

The results of the first low frequency experiments conducted on a sandstone sample (Donnybrook, Western Australia) flooded with supercritical \( \text{CO}_2 \) (sc\( \text{CO}_2 \)) are presented. The aim of the experiments was to investigate the effects of sc\( \text{CO}_2 \) injection on the elastic and anelastic properties of the rock. The sandstone sample (porosity – \( \sim 11.4\% \), permeability – \( 0.28 \ \text{mD} \)) was cut in the direction orthogonal to a formation bedding plane and tested in a Hoek’s triaxial pressure cell equipped with the means for independent control of pore and confining pressures. The pore and confining pressures were set up at 10 and 31 MPa correspondingly. The low-frequency system and the pump comprising sc\( \text{CO}_2 \) were held at a temperature of \( 42^\circ \text{C} \). Supercritical \( \text{CO}_2 \) was injected into the sample preliminary saturated with distilled water. The elastic parameters obtained for the sample with sc\( \text{CO}_2 \) at frequencies from 0.1 to 100 Hz are very close to those for the dry sample. Some discrepancy in calculated acoustic velocities can result from the difference in water and sc\( \text{CO}_2 \) densities. The increase of the extensional attenuation after sc\( \text{CO}_2 \) injection into water saturated sandstone was insignificant. The applicability of Gassmann’s fluid substitution theory for the interpretation of obtained results was also tested during the experiments.

Key words: elastic properties, extensional attenuation, supercritical \( \text{CO}_2 \), sandstone, seismic frequencies

INTRODUCTION

Laboratory studies of the \( \text{CO}_2 \) effects on the elastic and anelastic properties of sedimentary rocks are important for interpreting seismic data obtained during monitoring the processes caused by sc\( \text{CO}_2 \) injected into depleted natural gas reservoirs. Supercritical \( \text{CO}_2 \)-rock interactions can lead to the dissolution and precipitation of minerals with reduction of pore space (Zemke et al., 2010), and also to drying and disintegration of clay minerals (Foster et al., 2006). These processes may result in changes of the petrophysical and fluid transport properties of rocks and significantly affect their elastic properties (Rochelle et al., 2004). All effects caused by \( \text{CO}_2 \) are required quantifications in both field and laboratory scales.

There are few papers devoted to laboratory measurements of acoustic properties of water/brine saturated sandstones flooded with sc\( \text{CO}_2 \). Xue and Ohsumi (2004) studied the influence of sc\( \text{CO}_2 \) injection on the \( P \)-wave velocity in water saturated sandstone where they observed a decrease of 10\%. Shi et al. (2007) performed an integrated laboratory and numerical study of ultrasonic \( P \)-wave velocity response to sc\( \text{CO}_2 \) displacement of pore water in Tako sandstone. Using acoustic tomography they observed significant variations in the \( P \)-wave velocity reduction across the sandstone sample. They also stated that Gassmann’s theory can be applied to predict the \( P \)-wave velocities in sandstones flooded with sc\( \text{CO}_2 \) if the fluids are mixed at a scale below the critical diffusion length. The laboratory measurements with sc\( \text{CO}_2 \) injected into water saturated sandstone were also undertaken by Lei and Xue (2009). They showed a decrease in \( P \)-wave velocity by \( \sim 14.5\% \) and growth of attenuation by a factor of 3.7. Lebedev et al. (2013) carried out a laboratory investigation of acoustic properties of sandstone samples extracted in the Otway basin, South Australia. They found a \( P \)-velocity decrease of 7\% with sc\( \text{CO}_2 \) injection into brine saturated sandstone.

In this paper we present the results of the first low frequency experiments conducted on a sandstone sample (Donnybrook, Western Australia) flooded with sc\( \text{CO}_2 \). The aim of the experiments was to investigate the effects of sc\( \text{CO}_2 \) injection on the elastic and anelastic properties of sandstone. We also compare the bulk modulus measured for the sandstone saturated with water–sc\( \text{CO}_2 \) mixture to the bulk modulus predicted by Gassmann’s theory.

EXPERIMENTAL SET-UP

The low frequency laboratory system used in our experiments with sc\( \text{CO}_2 \) is shown in Figure 1. The system is comprised of a \( \text{CO}_2 \) cylinder, a \( \text{CO}_2 \) syringe pump and a low-frequency apparatus designed for measurements of complex Young’s moduli and extensional attenuation of rocks at seismic (1–100 Hz) and teleseismic (\( \lesssim 1 \)Hz) wave frequencies (Mikhaltsevitch et al., 2011). A rock sample to be tested is placed inside a sleeve, which is mounted within the triaxial core holder. The fluid passages in the steel plugs attached to the sample enable the flow of fluids through the sample and provide the means for pore pressure control (Figure 2). The core holder and the hydraulic actuator are connected via fluid lines with two hydraulic pumps providing radial (\( P_{\text{rad}} \)) and axial (\( P_{\text{ax}} \)) static pressures applied to the rock.

The electrical schematics of the apparatus is presented in Figure 3. The multilayer piezoelectric adaptor transforms the
periodic voltage, applied by an oscillator, into mechanical stress, which causes displacements in the aluminium standard.

Figure 1. Laboratory testing system: 1 - CO₂ cylinder, 2 - CO₂ syringe pump, 3 - low-frequency apparatus for complex Young’s modulus measurements.

Figure 2. The diagram of fluid passages: 1 – sample with two orthogonal strain gauges, 2 – two steel plugs with fluid passages, 3 – aluminium standard with a strain gauge, 4 – piezoelectric adaptor, 5 and 6 – pressure gauges, 7 – relief valve, 8 and 9 – flow meters.

Figure 3. The electrical schematics of the low-frequency laboratory apparatus.

In this study we investigated the effects of supercritical CO₂ on the acoustic properties of a sandstone sample quarried in Donnybrook, Western Australia. The parameters of the sample are as follows: length – 72.3 mm, diameter – 38.0 mm, permeability – 0.28 mD, porosity – 11.54%. The density of the dry sample is 2249 kg/m³, the density of the water saturated sample is 2509 kg/m³.

The Young modulus and Poisson ratio of the sandstone are derived from the known Young’s modulus of the aluminium standard and strains detected in the standard and rock sample as it is described in more detail by Mikhaltsevitch et al. (2011).

The bulk $K$ and shear $\mu$ moduli, P-wave $V_p$ and S-wave $V_s$ velocities can be found using the following expressions:

\[
K = \frac{E}{3(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)},
\]

\[
V_p = \sqrt{\left(\frac{K + \frac{4}{3}\mu}{\rho}\right)}, \quad V_s = \sqrt{\frac{\mu}{\rho}},
\]

where $\rho$ is the density of the rock. The extensional attenuation $Q_v^e$ in the sample was measured as a phase shift $\Delta \phi$ between harmonic stress applied to the sample and resulting strain detected in that sample (O’Connell and Budiansky, 1978). The axial and radial strains in the rock are measured with two strain gauges attached to the sample. The value of stress is obtained from the strain gauge attached to the aluminium standard. The signals from the strain gauges are averaged and subjected to Fourier transform. The resulting complex Fourier transform amplitudes $A_{ax}$ computed at the frequency of the harmonic stress are used to estimate the attenuation $Q_v^e$:

\[
Q_v^e = \tan(\Delta \phi) = \frac{\text{Im}(I)}{\text{Re}(I)},
\]

where $I = A_{ax} / A_s$, $A_s$ and $A_{ax}$ are the complex Fourier transform amplitudes of the signals obtained for the axial strain gauges coupled to the aluminium standard and sample correspondingly. The uncertainty in the measurements of $Q_v^e$ is about ±0.002.

The procedure of the measurements was as follows. The elastic parameters and extensional attenuation of the vacuum-dry sample were measured at a confining pressure of 21 MPa and a pore pressure of ~0.1 MPa. Then the sample was saturated with distilled water and the same measurements were performed at confining and pore pressures of 31 MPa and 10 MPa respectively. To ensure the full saturation of the sample at least 10 pore volumes of water were pumped through the samples under a constant pressure of 10 MPa. Due to low permeability of the samples the flow rate of water...
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during saturation did not exceed 0.2 cm³/min. In the final stage of the measurements the low-frequency system, syringe pump (ISCO Teledyne) comprising scCO₂ and fluid lines were heated to a temperature of 40-42°C, and scCO₂ was injected into the sample. The injection lasted for 48 hours under a constant pressure of 15 MPa to ensure the water in the sandstone is replaced with the maximum amount of scCO₂. When the process of saturation was finished, the pore pressure was set up at ~10 MPa. The amount of the residual water in the sample after saturation with scCO₂ was estimated at ~ 40% of the pore space.

RESULTS

The results obtained for moduli, extensional attenuation, P- and S-wave velocities in the sample flooded with scCO₂ at frequency range 0.1 – 100 Hz are presented in Figures 4 – 7. For comparison the results for dry and water saturated sandstone are also presented in the figures.

The elastic parameters obtained for scCO₂ are very close to the elastic parameters measured for the dry sample. The differences in P-wave velocities can be caused by the contrast in water and scCO₂ densities (density for scCO₂ at a temperature of 42°C and pressure of 10 MPa is ~ 670 kg/m³). The extensional attenuations determined in water saturated and in flooded with scCO₂ sample are practically identical within the limits of experimental error (±0.002).

Figure 5. Shear moduli measured for dry, distilled water saturated and for flooded with scCO₂ sandstone. All pressure parameters are the same as in Figure 4.

![Figure 5](Velocity vs. Frequency)

Figure 6. P- and S-wave velocities obtained for dry, distilled water saturated and for flooded with scCO₂ sandstone. All pressure parameters are the same as in Figure 4.

![Figure 6](Pressure vs. Frequency)

Figure 7. Extensional attenuation measured for dry, distilled water saturated and for flooded with scCO₂ sandstone. The confining and pore pressures are the same as in Figure 4.

![Figure 7](Attenuation vs. Frequency)

CONCLUSIONS

We have presented the first results of the low frequency experiments conducted on a rock sample flooded with supercritical CO₂. The elastic properties and extensional attenuation for a low-permeability sandstone sample quarried in Donnybrook, Western Australia, were investigated at frequencies from 0.1 to 100 Hz. The supercritical CO₂ was injected into the sample preliminarily saturated with distilled water.

We found a reduction by less than 3 % in P-wave velocities in the sandstone flooded with scCO₂ in relation to the velocities measured in water saturated sample. We also found that the extensional attenuations measured in the sample flooded with scCO₂ and in the same sample saturated with water are practically undistinguished. This result is different to the result obtained for extensional attenuation in Tako sandstone at ultrasonic frequencies by Lei and Xue (2009).
It was also demonstrated in our measurements that Gassmann fluid substitution theory is applicable for the interpretation of the data obtained in experiments with scCO$_2$.

REFERENCES


