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Low frequency laboratory measurements of the elastic and anelastic properties of the sandstone flooded with supercritical 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 CO_2 ($scCO_2$) are presented. The aim of the experiments was to investigate the effects of $scCO_2$ injection on the elastic and anelastic properties of the rock. The sandstone sample (porosity – 11.4%, permeability – 0.28 mD) was cut in the drection ortogonal 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 $scCO_2$ were held at a temperature of 42º C. Supercritical CO_2 was injected into the sample preliminary saturated with distilled water. The elastic parameters obtained for the sample with $scCO_2$ 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 $scCO_2$ densities. The increase of the extensional attenuation after $scCO_2$ 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 CO_2, sandstone, seismic frequencies

INTRODUCTION

Laboratory studies of the 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 $scCO_2$ injected into depleted natural gas reservoirs. Supercritical 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 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 $scCO_2$. Xue and Ohsumi (2004) studied the influence of $scCO_2$ 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 $scCO_2$ 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 $scCO_2$ if the fluids are mixed at a scale below the critical diffusion length. The laboratory measurements with $scCO_2$ injected into water saturated sandstone were also undertaken by Lei and Xue (2009). They showed a decrease in P-wave velocity by ~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 scCO2 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 $scCO_2$. The aim of the experiments was to investigate the effects of $scCO_2$ injection on the elastic and anelastic properties of sandstone. We also compare the bulk modulus measured for the sandstone saturated with water–$scCO_2$ mixture to the bulk modulus predicted by Gassmann's theory.

EXPERIMENTAL SET-UP

The low frequency laboratory system used in our experiments with $scCO_2$ is shown in Figure 1. The system is comprised of a CO_2 cylinder, a 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 (≤1Hz) 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_{conf}) and axial (P_{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

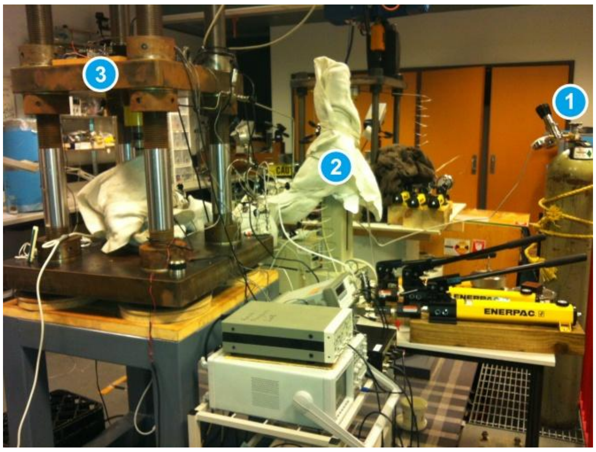

Figure 1. Laboratory testing system: 1- CO_2 cylinder, 2 - CO_2 syringe pump, 3 – low-frequency apparatus for complex Young's modulus measurements.

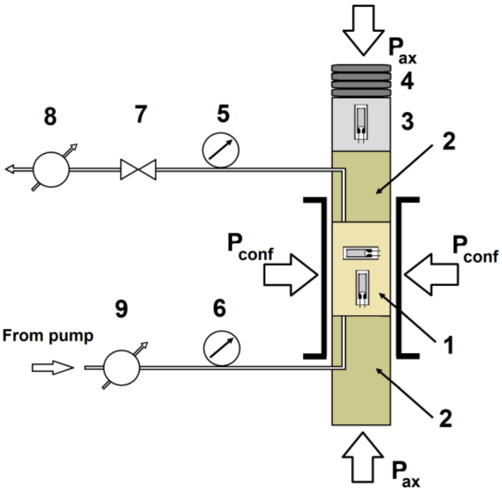

Figure 2. The diagram of fluid passages: 1 – sample with two orthogonal strain gauges, 2 –two steel plugs with fluid passages, 3 – aluminium standard with a strain gauge, 4 – piezoelectric adaptor, 5 and 6 – pressure gauges, 7 – relief valve, 8 and 9 – flow meters.

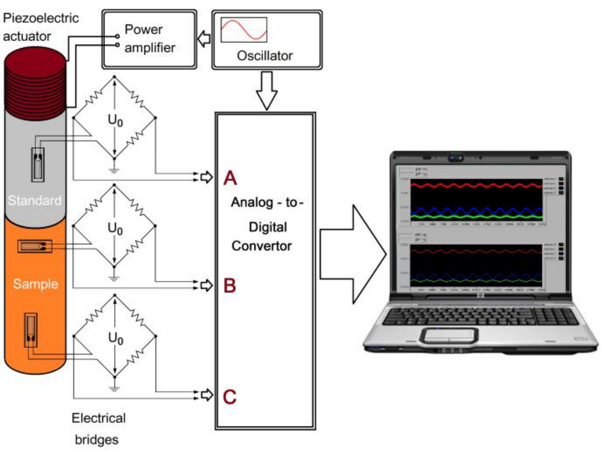

Figure 3. The electrical schematics of the low-frequency laboratory apparatus.

and rock sample mounted in series. The displacements modulate the electrical conductivity of the strain gauges coupled with the aluminium standard and rock. A set of electrical bridges transforms the modulated conductivity into electrical signals, which, after digitizing by an analogue-digital converter, are received by an acquisition computer, where the signals are averaged and processed.

EXPERIMENT

In this study we investigated the effects of supercritical CO_2 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/m^3, the density of the water saturated sample is 2509 kg/ m^3.

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 μ moduli, P-wave V_p and S-wave V_s velocities can be found using the following expressions:

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

$$V_p = \sqrt{(K + \frac{4}{3}\mu)/\rho}, \quad V_s = \sqrt{\mu/\rho},$$

where ρ is the density of the rock. The extensional attenuation Q_E^{-1} in the sample was measured as a phase shift $\Delta\varphi$ 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 computed at the frequency of the harmonic stress are used to estimate the attenuation Q_E^{-1}:

$$Q_E^{-1} = \tan(\Delta\varphi) = \mathrm{Im}(I)/\mathrm{Re}(I),$$

where $I = A_{rock}/A_{st}$, A_{st} and A_{rock} are the complex Fourier transform amplitudes of the signals obtained for the axial strain gauges coupled to the aluminum standard and sample correspondingly. The uncertainty in the measurements of Q_E^{-1} 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 during saturation did not exceed 0.2 cm^3/min. In the final stage of the measurements the low-frequency system, syringe pump (ISCO Teledyne) comprising scCO_2 and fluid lines were heated to a temperature of 40-42ºC, and scCO_2 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 scCO_2. 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 scCO_2 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 scCO_2 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 scCO_2 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 scCO_2 densities (density for scCO_2 at a temperature of 42ºC and pressure of 10 MPa is ~ 670 kg/m^3). The extensional attenuations determined in water saturated and in flooded with scCO_2 sample are practically identical within the limits of experimental error (±0.002).

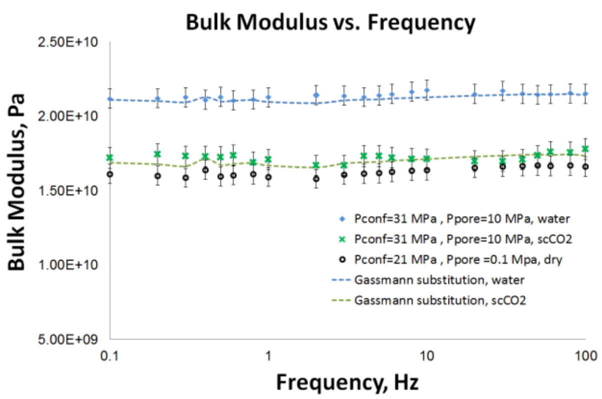

Figure 4. Sandstone bulk moduli measured when: 1) dry, 2) distilled water saturated, and 3) flooded with scCO_2. The bulk moduli calculated in accordance with Gassmann fluid substitution equations presented with dash blue (for water saturated sandstone) and dash green (for sandstone with scCO2) lines.

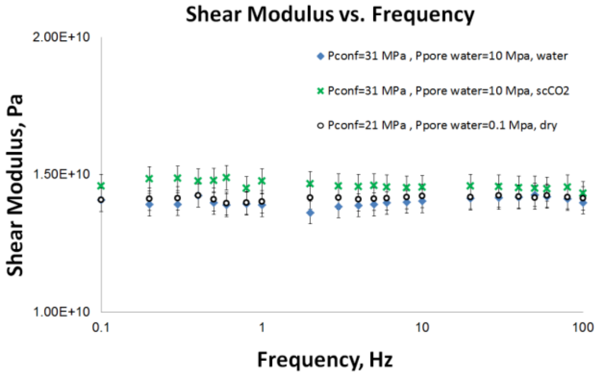

Figure 5. Shear moduli measured for dry, distilled water saturated and for flooded with scCO_2 sandstone. All pressure parameters are the same as in Figure 4.

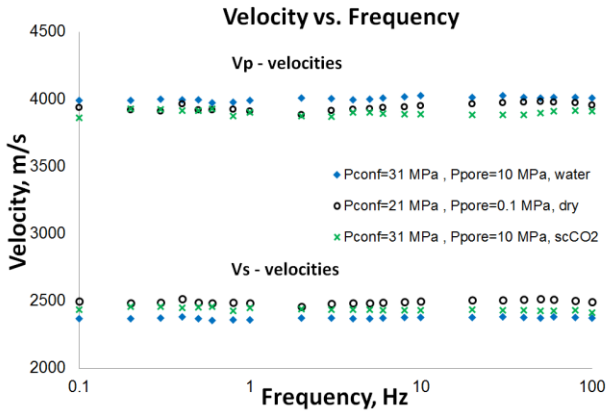

Figure 6. P- and S-wave velocities obtained for dry, distilled water saturated and for flooded with scCO_2 sandstone. All pressure parameters are the same as in Figure 4.

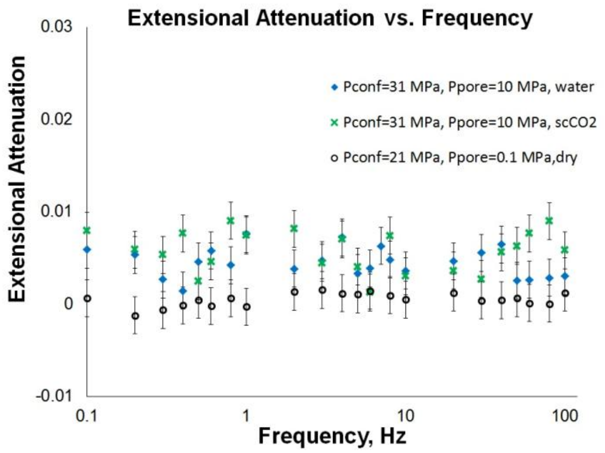

Figure 7. Extensional attenuation measured for dry, distilled water saturated and for flooded with scCO_2 sandstone. The confining and pore pressures are the same as in Figure 4.

CONCLUSIONS

We have presented the first results of the low frequency experiments conducted on a rock sample flooded with supercritical CO_2. The elastic properties and extentional attenuation for a low-permeability sandstone sample quarrried in Donnybrook, Western Australia, were investigated at frequencies from 0.1 to 100 Hz. The supercritical CO_2 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 scCO_2 in relation to the velocities measured in water saturated sample. We also found that the extensional attenuations measured in the sample flooded with scCO_2 and in the same sample saturated with water are practically undistinguished. This result is different to the result obtained for extentional 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 $scCO_2$.

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