Experimental laboratory study on the acoustic response during injection of supercritical CO2 into brine saturated sandstones

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SUMMARY

Quantitative knowledge of the acoustic response of rock from an injection site on supercritical CO2 saturation is crucial for understanding the feasibility of time-lapse seismic monitoring of CO2 plume migration. A suite of sandstones with similar composition but different petrophysical properties has been tested to reveal the effects on acoustic responses of supercritical CO2 injection into brine saturated sandstones. CO2 is first injected into dry samples, flushed out with brine and then injected again into brine saturated samples. Such experimental protocol allows us to obtain acoustic velocities of the samples for the wide range of CO2 saturations from 0 to 100%. On injection of supercritical CO2 (scCO2) into brine-saturated samples, some of samples exhibit observable perturbation of ~10% of compressional velocities with the increase of CO2 saturation form 0% to maximum (~50%). However for some sample effect of scCO2 injection on acoustic properties is negligible.

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Key words: geological sequestration, rock physics, supercritical CO2

INTRODUCTION

Geologic sequestration can be considered as one of the most favourable mitigation strategies against the negative effects of atmospheric greenhouse gases, in particular carbon dioxide (Schrag, 2007). Industrial –scale projects across Australia such as Otway project (Otway basin, Victoria), South West Hub (Harwey, WA), CTSCo (Surat basin, Queensland), CarbonNet (Victoria) are required a comprehensive assessment of storage capacity as well as public awareness. 4D monitoring of plume migration is a key component for these subjects. Seismic methods are the most effective methods for monitoring as they can provide numerical characteristics of plume, such as CO2 saturation and size of the plume. However the effect of scCO2 on mechanical properties of reservoir rocks is not known in details. Quantitative understanding of the acoustic response of sandstones from the injection site on complete or partial saturation with scCO2 is crucial for time-lapse seismic imaging of CO2 plume migration.

Wang and Nur (1989) pioneered laboratory experiments on CO2 injection. They injected CO2 in hexadecane-saturated sandstones and measured their elastic responses. Xue and Ohsumi (2004) studied CO2 injection effects on the P-wave velocity and deformation of water-saturated Tako sandstone. Shi et al. (2007) used acoustic P-wave tomography for monitoring and quantification of supercritical CO2 saturation during injection into brine-saturated Tako sandstone. Lei and Xue (2009) injected gaseous and scCO2 into water-saturated sandstone under controlled pressure and temperature conditions and monitored the dependency of P-wave velocity and attenuation on saturation. Shi et al. (2011) conducted a comprehensive study of scCO2 injection into brine-saturated sandstone using computer tomography methods. Long term effect of brine/scCO2 on the mechanical properties of sandstones was studied by K. Zemke et al. (2010). Siggins et al. (2010) performed the first measurements on samples from the CRC-1 well in the Otway Basin, Australia. The acoustic responses were measured during gaseous and liquid CO2 injection into dry samples. Recently Lebedev et al (2013) reported results of scCO2 injection into brine saturated sandstones from CRC-2 well (Otway project).

In this work, we investigate effects of scCO2 on the acoustic properties of four sandstone samples extracted from different locations, such samples exhibit variety of petrophysical properties typical for different injection interval. This study is designed to answer two main questions: (1) What are the elastic properties of the host sandstone and can standard technique of Gassmann's fluid substitution be applied to calculate the elastic properties of saturated sandstone using standard laboratory measurements on the dry sample; (2) How will CO2 injection change acoustic velocities. CO2 is injected into either dry or brine saturated samples, which allowed us to obtain the acoustic velocities of the samples at reservoir conditions for the whole range of CO2 saturations from 0 to 100%.

METHOD AND RESULTS

Four 38.5 mm in diameter cylindrical samples with similar composition, but different porosity / permeability were selected for this study. The helium porosities and permeabilities of the samples were measured by an Automated Porosimeter and Permeameter (AP-608 ,Coretest Co.) and are shown in Table I along with other petrophysical properties. The porosities vary from 14% to 23% and the permeabilities widely scatter from 4 mD to 2.7 D. Samples were cut perpendicular to bedding plane.

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Table I: Petrophysical properties of the samples

Sample	A	B	C	D
Density (dry), kg/m^3	2200	2280	2090	1950
Porosity, %	17	14	21	23
Permeability, mD	4	27	450	2700
Cutting direction	v	v	v	v

Samples were measured using tri-axial rig incorporated with core flooding equipment. P- and S- wave velocities of the samples were measured in axial direction using ultrasonic transducers at 1 MHz central frequency. Samples were flooded by brine using a liquid pump LC-20A (Shimazu, Ltd). Supercritical CO2 was injected into brine saturated sample using syringe pump D260 (Teledyne – Isco, Co). All components of the rig were heated and maintained at 45°C.

Main steps of experimental procedure are the following:
(1) Ultrasonic compressional and shear velocities of a dry sample are measured at room temperature at confining stresses of up to 60 MPa in steps of 4 MPa;
(2) The experimental system is heated up to 45 °C and the ultrasonic measurements of P- and S-wave velocities on the dry sample are repeated;
(3) Then confining pressure of 12 MPa is applied to the sample and it is flooded with brine (NaCl, salinity 3500 ppm) with an injection pressure of 6 and 9 MPa. The ultrasonic velocities are measured again on the fully saturated sample at confining pressures from 10 MPa to 70 MPa in steps of 4 MPa..
(4) CO2 is continuously injected into the sample until pore pressure reaches a critical point of 9.3 MPa at which CO2 become a supercritical fluid. The ultrasonic velocities are then measured again at confining pressures from 15 MPa to 70 MPa in steps 4 MPa.
(5) CO2 is released from the sample by reducing pore pressure to 0 MPa but keeping the confining pressure at a constant level of 12 MPa. The sample is flooded with the brine at an injection pressure of 9 MPa. Then the ultrasonic velocities are measured again at confining pressures from 15 MPa to 70 MPa in steps of 4 MPa.
(6) The confining pressure is fixed as 30 MPa and scCO2 (temperature 45°C, pressure 9.3 MPa) is injected into brine-saturated sample with injection rate of 1 mL/min. Ultrasonic velocity measurements are taken during scCO2 flooding.
(7) Brine, with the same concentration of salts, is flooded into the sample at a injection rate of 1 mL/min and the ultrasonic velocities are measured during the process of the CO2 replacement.
(8) Residual scCO2 saturation in the sample is estimated by measuring the amount of brine volume removed (and collected) from the sample. The total amount of CO2 stored in the sample (the volume of scCO2 and amount of CO2 dissolved in the brine) is estimated by weighing the sample after the CO2 injection and at the end of the experiment when the pore pressure reduced and the CO2 released from the sample.

More details of experimental equipment can be found in Lebedev et.al. (2013).

Figure 1. shows stress dependency of sample A for dry, 100% brine saturated as well as fluid substitution using Gassmann's procedure. P and S wave velocities are plotted against effective pore pressure (Peff)

$$Peff = Pconf - \alpha Ppore$$

Where, Pconf is confining pressure, Ppore is pore pressure, and α is an effective stress coefficient, which in this study we assume to be equal to unity.

Brine saturated sample has small stress dependency for effective pressures over 20 MPa. This fact is important for analysis of the reasons caused changes of velosities during scCO2 flooding into brine saturated samples. Other samples exhibit similar stress dependency. Experimentally measured velocities are in a good agreement with velocities calculated from dry velocities using Gassmann's relations for all four samples.

Ultrasonic velocities measured during the injection of scCO2 into a brine saturated sample at confining stress of 30 MPa and pore pressure of 9.3 MPa are shown in Figures 2-5 for each sample. Figures 2 shows gradually decreasing of P-wave velocity with increasing of scCO2 injection for sample A with "low" permeability of 4 mD. At the maximum saturation of ~50% reachable at this experiments, P-wave velocity still exceeds P-wave velocity at 100% scCO2 saturated sample on about 100 m/s. Velocity for sample B decreased at the beginning of scCO2 flooding and then gradually increases (Fig. 3). Residual CO2 saturation of 50% was achieved for that sample as well. Sample C shows no measurable changes in velocity (Fig. 4). Finally for sample D with highest permeability of 2.7 D gradual decreasing of P-wave velocity is observed, however even residual saturation of scCO2 was about 50%, P wave velocity at this state is not different from that for 100% scCO2 saturated samples.

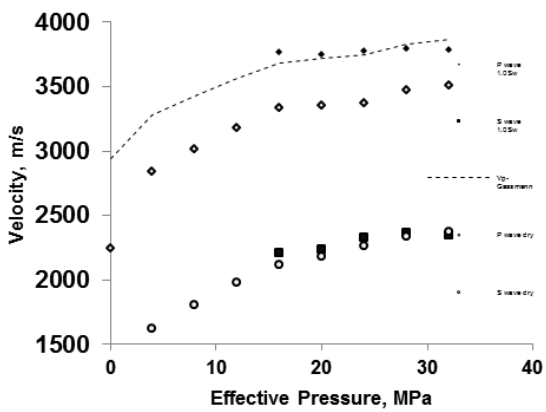

Figure 1. Velocity vs. effective pressure dependence for sample A: dry, 100% brine saturated. Pore pressure 9 MPa.Temperature 45°C.

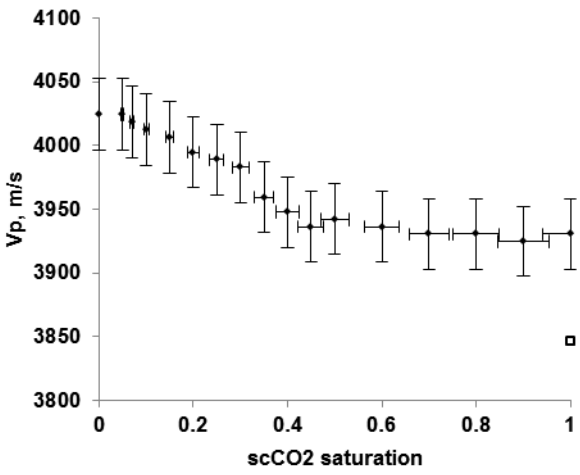

Figure 2: Ultrasonic velocities vs. scCO2 saturation for sample "A". CO2 injection into brine saturated sample. T=45°C.

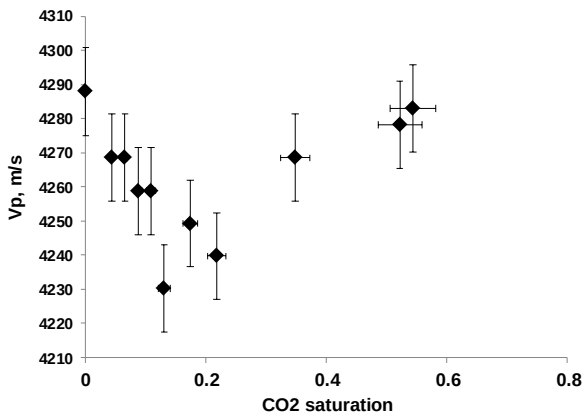

Figure 3: Ultrasonic velocities vs. scCO2 saturation for sample "B". CO2 injection into brine saturated sample. T=45°C.

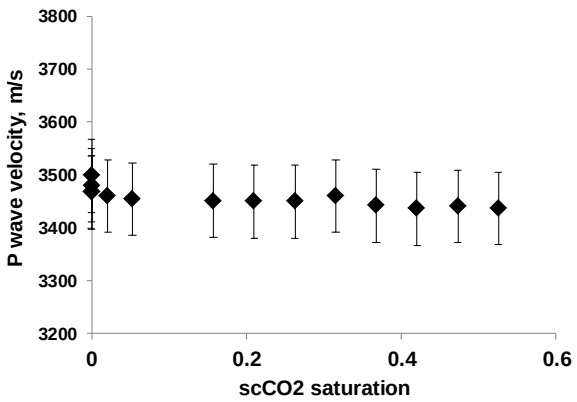

Figure 4. Ultrasonic velocities vs. scCO2 saturation for sample "C". CO2 injection into brine saturated sample. T=45°C.

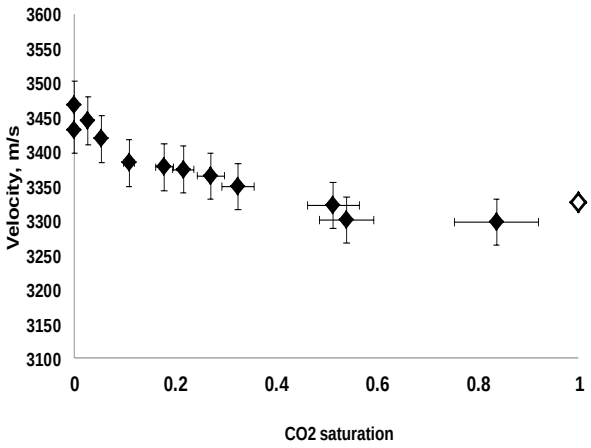

Figure 5. Ultrasonic velocities vs. scCO2 saturation for sample "D". T=45°C

CONCLUSIONS

Supercritical CO2 injection experiments are carried out a suite of sandstone specimens represented different reservoir . The experiments confirm applicability of the Gassmann's fluid substitution method to brine. On injection of scCO2 into brine-saturated samples, some of them they exhibit observable perturbation of ~10% of compressional velocities with the increase of CO2 saturation form 0% to maximum (~50%)., however one sample shows no P-wave dependence on amount of scCO2 saturation. Different samples response to scCO2 flooding shows that flooding of reactive rocks is complicated process and complex assessment should be applied to extracted samples in order to understand seismic response during CO2 geological sequestration.

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