

Investigations of Seismic Signatures of CO₂ Saturation as Part of a Geological Storage Project

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Summary

The current study provides an extensive series of measurements that aims at predicting the seismic behaviour of CO₂-saturated rocks. This has implications on monitoring CO₂ geological storage using seismic methods. The ultrasonic pulse transmission technique is the underlying methodology used in this work. Unlike previous rock physics studies involving CO₂ as pore fluid, care is taken to separate pore fluid effects from pore pressure build-up effects during the experiments. This allows for the sampling of the effects of the CO₂'s varying phase states (gas – liquid - supercritical fluid) on the overall rock seismic response. Measurements were done on core samples from the Weyburn oilfield, Saskatchewan. Of the observations arising from the measurements done in this study, there are two that are of particular note. First, both the P- and S-wave speeds decrease substantially as the CO₂ transforms from gas to either liquid or supercritical phase. This observation is consistent with the increase of CO₂ fluid density across these phase boundaries. Second, across the gas-liquid phase transition both wave speeds drop abruptly as would be expected for the change in the physical properties of the CO₂ across this first order phase boundary. In contrast, across the gas-supercritical phase boundary the velocities change more gradually. This suggests that it may be difficult to distinguish the gas-supercritical boundary using seismic reflection techniques.

Keywords: CO₂ sequestration; seismic monitoring; rock physics; ultrasonic velocity; Weyburn reservoir.

1. Introduction

As is well known, societal acceptance of CO₂ geological sequestration depends critically on the ability to monitor movement of CO₂ in the subsurface. Geophysical remote sensing techniques, particularly the use of 4-D reflection seismology, will be a key component in monitoring motions of CO₂ underground (e.g., Carcione et al., 2006; Ivanova et al., 2012). As such, there is a great need for a good understanding of how CO₂ will influence the seismic properties of rocks. This is doubly interesting in that free CO₂ at depths intended for CO₂ sequestration can be in gas, liquid or supercritical phase states. However, to our knowledge, there is a general lack of experimental tests of such effects. Here we propose a laboratory protocol for the measurement of P- and S-wave speeds and attenuations through natural rocks saturated with CO₂. This protocol was developed on the basis of experiences gained during an extensive series of laboratory

measurements of P- and S-wave velocities of carbonate reservoir and cap-rock core samples from the Weyburn, Saskatchewan, project and some test sandstones.

2. Experimental Protocol

The protocol includes two important components. First, the samples chosen undergo a rigorous material characterization that includes He and Hg porosimetry, XRF whole rock chemistry, thin sectioning, SEM scanning, and micro-CT imagery. This allows for an understanding of the mineralogy, the porosity, and the architecture of the pore space within the rock. The more crucial set of tests, however, are those in which the rock sample is subject to a large variety of confining and pore pressures, saturation states, and temperatures. A given test begins with coring of a cylinder of the given sample. The ends of this cylinder are ground as parallel to one another as possible and the sample is then dried under vacuum at modest temperatures (~70 °C). The sample is then prepared for the high-pressure measurement suite by attaching a set of specially constructed ultrasonic transducers to its ends and then hermetically sealing this. This assembly is placed in a pressure vessel. The P- and S-wave measurement protocol then follows by

i) Obtaining the P- and S-waveforms under a series of increasing confining pressures but with the pore space subject to vacuum to provide the 'dry' properties, this is carried out at different temperatures to evaluate the effect of temperature on the rock frame.

ii) Repeating these measurements with the pore space saturated with inert nitrogen gas. An additional suite here tests carried out at constant differential pressure (difference between the confining and the pore pressure) allows for assessment of any potential effective stress variations that could occur in the sample. This is critical because the rock elastic properties themselves depend nonlinearly on confining pressure.

iii) Repeating these measurements with full CO₂ gas saturation under a variety of pore pressure and temperature in order to sample the full range of CO₂ phase states. These measurements are all carried out at constant differential pressure. This involves at least 5 different suites of measurements carried out under conditions of constant temperature or constant pore pressure (Fig. 1).

iv) Repeating the 'dry' measurements once the suite of CO₂ tests are completed, and

v) Finally carrying out the measurements under full saturation with liquid water.

These series of measurements provides a great deal of information that allows for prediction of the seismic behaviour of the given rock, but at the cost that a given run requires upwards of a week of dedicated time in the measurement system.

2.1. Ultrasonic measurements: experimental setup

The experimental setup for the ultrasonic measurements includes several functional units such as a pulse generator, a digital oscilloscope (NI USB- 5133 100 MS/s), source/receiver transducers, a cylindrical pressure vessel, fluid tanks, a thermocouple, and an electrical resistance tape (Fig. 2, see also Yam, 2011). The transducer is excited by a fast-rising, 200V square wave, sent by the pulse generator (Panametrics, model 5800 PR). The generated elastic wave after propagating through the sample is recorded by a digital oscilloscope at a sampling interval of 10 nanoseconds. The recorded waveform is the stack of at least 500 traces to reduce the noise level in the signal. The desired pore fluid is introduced into the sample via stainless steel tubing that connects the pore space of the sample to the pore fluid reservoir located outside of the vessel through the vessel lid. The confining and pore pressure systems are independent of each other such that different pressure conditions can be applied in irrespective of each other by using different pumps located outside of the pressure vessel. Both the confining pressure (pressure vessel) and the pore pressure systems are capable of reaching a maximum pressure of 70 MPa from the pumps. Higher confining pressures, up to 200 MPa, could also be achieved by using a separate air pump connected to the pressure vessel.

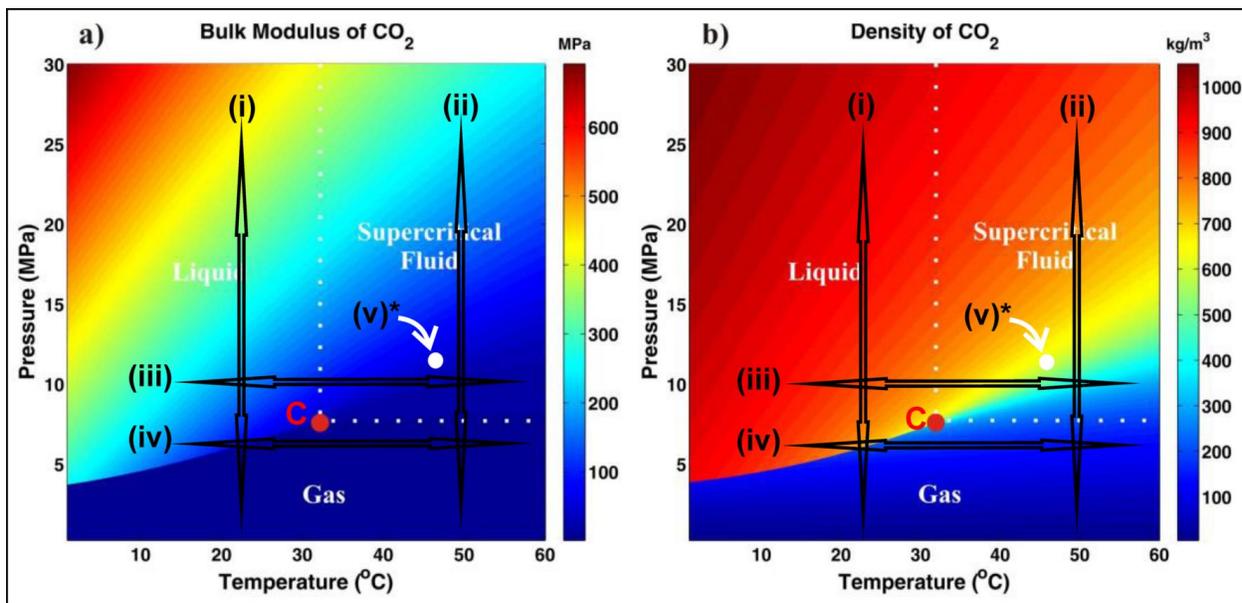


Fig. 1. CO₂ properties (bulk modulus and density) as a function of pressure and temperature based on the thermodynamic model of Span and Wagner (1996). **C** = critical point. Arrows (i), (ii), (iii), (iv), and (v) refer to the conditions under which CO₂-saturated rock velocities are measured. For (i), (ii), (iii) and (iv), measurements are done under constant temperature. (v)* refers to measurements done under constant pore pressure (about 11 MPa in this case) and T = 50 °C.

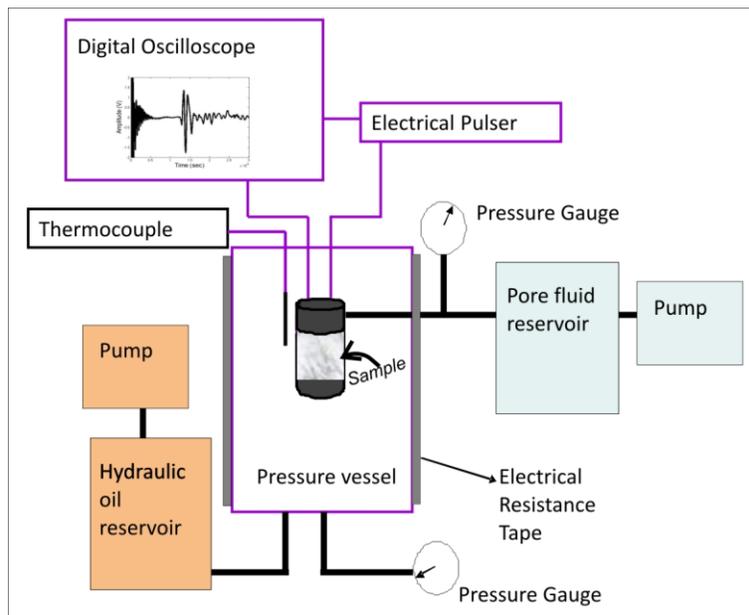


Fig. 2. The experimental setup for the ultrasonic measurement.

3. Case study

3.1. Sample description

The studied sample is a dolostone from the Weyburn area, Saskatchewan, with a (mercury injection) porosity of 14% and air permeability lower than 2 mD. The rock matrix consists of relatively loosely packed crystals (largely dolomite). Very small calcite grains and feldspar flakes are disseminated within

the matrix. Quartz is sometimes visible. The porosity is generally intercrystalline and the main pore throat size is around $0.65 \mu\text{m}$. The sample grain density is 2.83 g/cm^3 . The ultrasonic measurements were performed on a cylindrical plug, 3.81 cm in diameter and 4.8 cm long (Fig. 3).

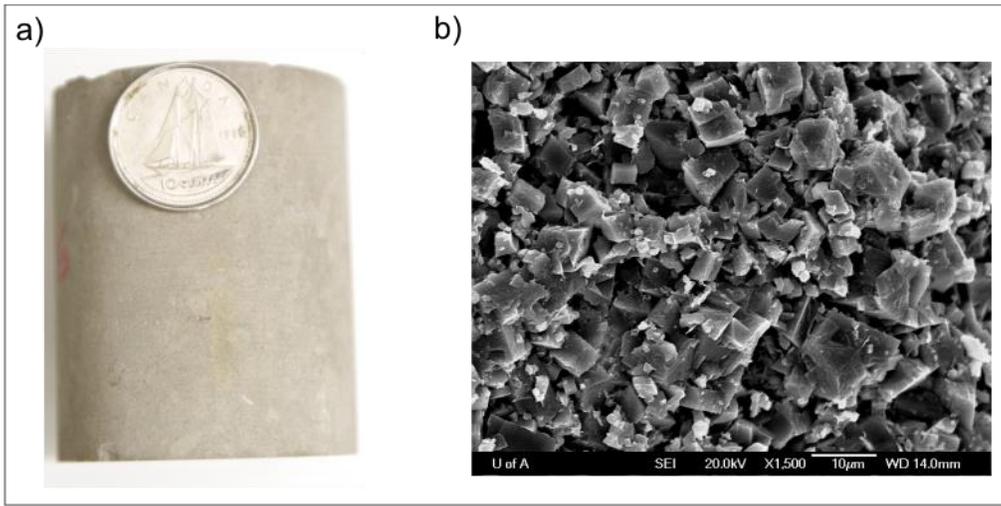


Fig. 3. (a) Photograph of the dolostone's plug and (b) a scanning electron microscope (SEM) image of the sample. Note the loosely compacted dolomite crystals in the SEM image.

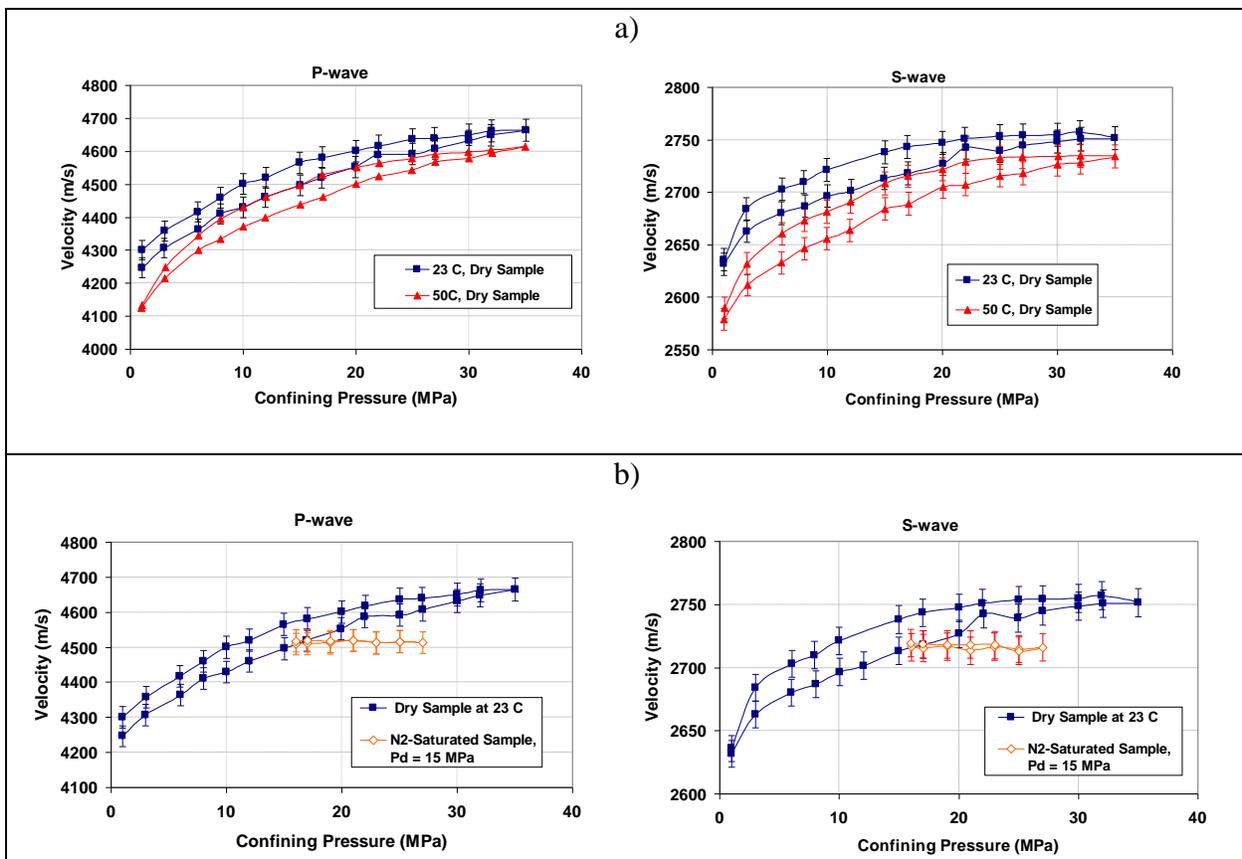


Fig. 4. (a) Dry and (b) nitrogen-saturated P- and S-wave velocities as a function of confining pressure for the dolostone sample. Error bars are shown. In (a), velocities recorded at 23°C and at 50°C are shown. The hysteresis of the “dry” velocity curves can be explained by the difference between the closing and opening rate of

the crack-like pores at a given pressure during pressurization and depressurization cycle, respectively (Sharma and Tutuncu, 1994). Pd = differential pressure.

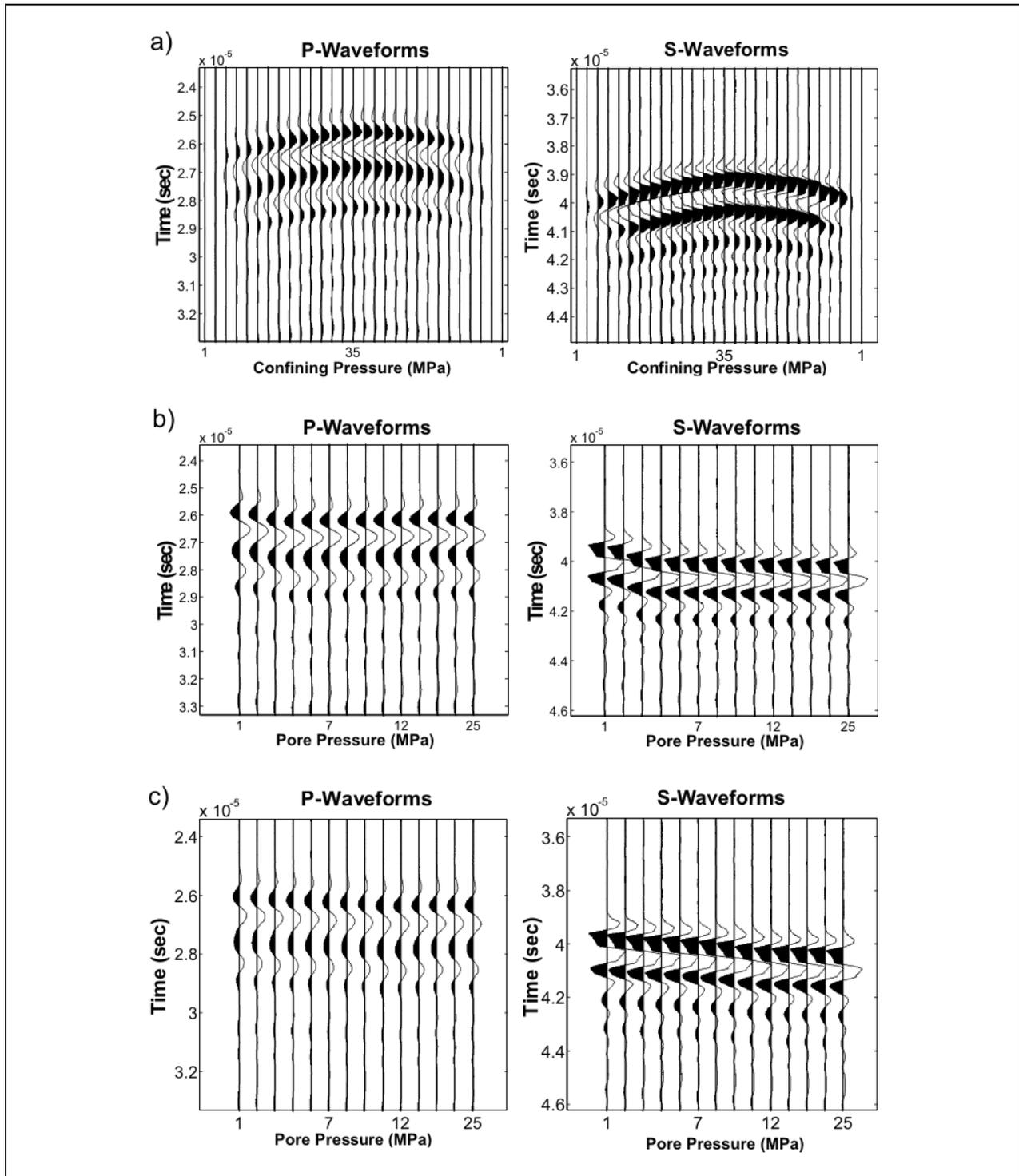


Fig. 5. Dry and CO_2 -saturated waveforms on the dolostone sample. (a): P- and S-waveforms on the dry sample. Measurements were done during up- and down pressurization cycles. Note how P- and S- wave travel times become faster with increasing confining pressure. (b): Waveforms that were acquired on the CO_2 -saturated sample at $T = 23^\circ\text{C}$; CO_2 was turning from gas to liquid in the pore space. (c): CO_2 was turning from gas to a supercritical fluid in the pores; $T = 50^\circ\text{C}$. Note the decrease of the S-wave travel times and the different

behaviours of the P-wave speeds (decrease at low pore pressure and slight increase at higher pore pressure) from the CO₂-saturated waveforms.

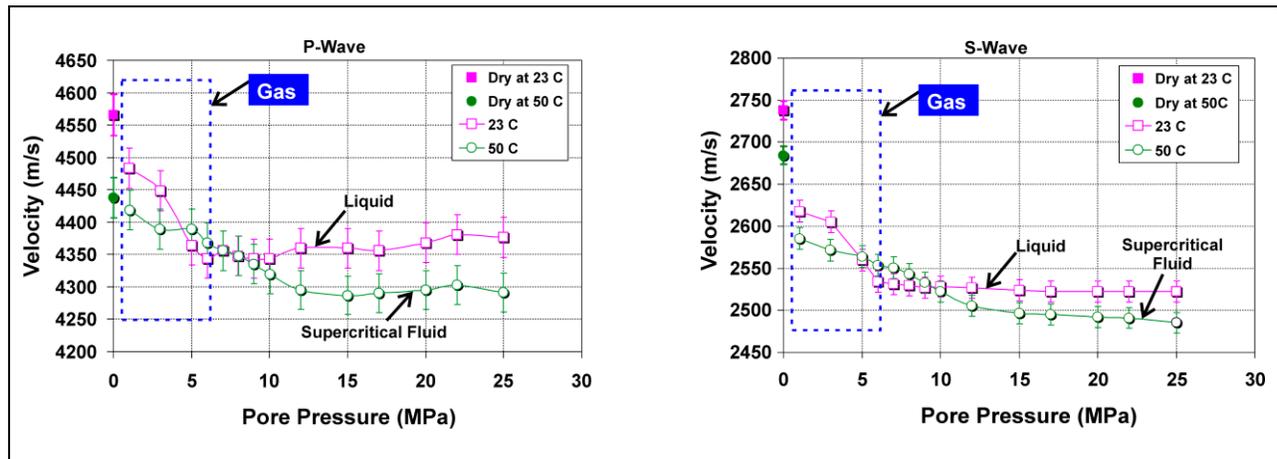


Fig. 6. CO₂ saturated P- and S-wave velocities of the dolostone sample for the two constant temperature runs at T = 23°C and T = 50°C while under a constant differential pressure of 15 MPa. Error bars are shown. Dry wave velocities obtained under a confining pressure of 15 MPa are plotted at pore pressure = 0 MPa to provide a reference for the changes seen. Black arrows indicate velocities when CO₂ is gas, liquid and a supercritical fluid in the pore spaces.

3.2. Ultrasonic measurements

Under dry (vacuum) conditions:

On the dry sample, and as expected, the compressional (P) and shear (S) wave velocities increase with confining pressure and decrease with temperature (Fig. 4a). Figure 5a shows the P- and S-waveforms recorded on the dry sample.

Under fluid-saturated conditions:

Only nitrogen- and CO₂-saturated measurements are provided in this sub-section. The measurements conditions were set up so that any variation in the recorded waveforms was due to change in the pore fluid physical properties. Thus, for each sample, a constant differential pressure of 15 MPa was maintained by varying the confining pressure accordingly to the pore pressure. Assuming that the equal amount of pore pressure increase cancelled the equal amount of confining pressure increase, any waveform variation observed was solely caused by pore fluid effects.

Nitrogen-saturated measurements: Prior to CO₂-saturated measurements, each sample was subjected to constant differential pressure measurement of 15 MPa under inert nitrogen gas saturation. In general within a fluid, the bulk modulus and density are the physical properties that will influence wave propagation; bulk modulus has a direct proportional effect while density has an inverse proportional effect on wave velocities. As change in the nitrogen properties (density, bulk modulus) only slightly affects sound waves travel times under the range of pressure and temperature conditions used in this study (Lemmon et al., 2011), no substantial change in the P- and S- wave velocities meant that the applied differential pressure was the main factor controlling the variation of the velocity. This behaviour of the wave velocities did lend confidence to selecting the set of 'high-quality' measurements that were suitable for the purpose of our study. Figure 4b shows that P- and S-wave velocities barely changed when both confining and pore pressures were increased at the same rate. This suggests that the effective stress that controlled the elastic response of the rock remained almost constant during the nitrogen-saturated measurements.

CO₂-saturated measurements: Results presented here are from measurements made at constant temperature (23 °C and 50 °C) with the pore pressure varying from 1 MPa to 25 MPa in each case. As pore pressure increases, for the lower temperature runs (23°C), CO₂ changed from a gas phase to a liquid phase in the pore spaces while for the higher temperature runs (50°C), CO₂ changed from a gas phase to the supercritical fluid phase (See arrows (i) and (ii) in Fig. 1). The wave velocities of the two constant temperature runs are plotted in figure 6. On these plots, velocities of the dry sample at a differential pressure of 15 MPa are also shown. P- and S-waveforms of the CO₂-saturated sample are shown in figures 5b and 5c.

Once CO₂ gas was injected into the sample, irrespective of the temperatures, both P- and S-wave velocities decreased with the pore pressure. The drop of the P- and S-wave velocities was more immediate for the low temperature run; the large drop occurred at a pore pressure of about 5 to 7 MPa and 10 to 15 MPa for the low temperature (T = 23 °C) and high temperature (T = 50 °C) runs, respectively. At 23 °C, the immediate nature of the wave responses was likely due to the sharp contrast in the density of the CO₂ when the gas-liquid boundary was traversed. Overall, the decrease of the P- and S- waves travel times right before the gas-liquid and gas-supercritical fluid transitions were up to 3%. Over the phase transition, P –wave velocity recovered while S-wave speed kept decreasing. The recovery of the P-wave velocity was gradual and was up to 1 % at a pore pressure of 25 MPa. The total drop of the S-wave travel times was up to 4 % over the entire 1 to 25 MPa pore pressure interval.

4. Conclusion

An experimental procedure has been set up to inspect the effects of CO₂ on the seismic properties of rocks. The series of measurements allows for the assessment of the effects of the CO₂ phase changes (gas to liquid and gas to supercritical fluid) on the overall rock seismic behaviour. CO₂ phase changes (gas to liquid and gas to supercritical fluid) are marked by a drop in velocities of up to 4% over the entire 1 to 25 MPa pore pressure interval used in this study. The abruptness in the velocity change differs significantly between the gas-liquid and gas-supercritical fluid transitions; and the gradual variations seen for the latter suggest that this will be difficult to detect using seismic reflection methods. Real situations sometimes differ from the experimental conditions set up in this study as CO₂ may coexist with other in-situ fluids in the pore space. However, this study provides an end member understanding of the possibilities with CO₂ in the pore space, which is critical for the setup of an accurate monitoring of CO₂ plume in the subsurface. In fact, any change in the conditions of pressure and temperature of a CO₂ storage area or any upward migration of the CO₂ towards the surface could lead to the transformation of CO₂ into either a gas or a liquid or a supercritical fluid.

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