

# **LABORATORY MEASUREMENTS OF SEISMIC WAVE VELOCITY BY CO<sub>2</sub> INJECTION IN TWO POROUS SANDSTONES**

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## **ABSTRACT**

Laboratory experiments were conducted to measure the compressional wave velocities under hydrostatic pressure in Shirahama and Tako sandstone with a porosity of 12% and 24%, respectively. In dry samples, the pressure dependence of velocity is ascribed to the difference in pore structures. Velocities were also measured to map the movement of the injected CO<sub>2</sub> within water-saturated samples during CO<sub>2</sub> injection. In the water-saturated samples, velocity changes caused by the CO<sub>2</sub> injection are typically on the order of -10%. We are conducting a series of seismic tomography experiments on porous sandstone samples to demonstrate the use of cross-well seismic profiling for monitoring the migration of CO<sub>2</sub> in geological sequestration projects.

## **INTRODUCTION**

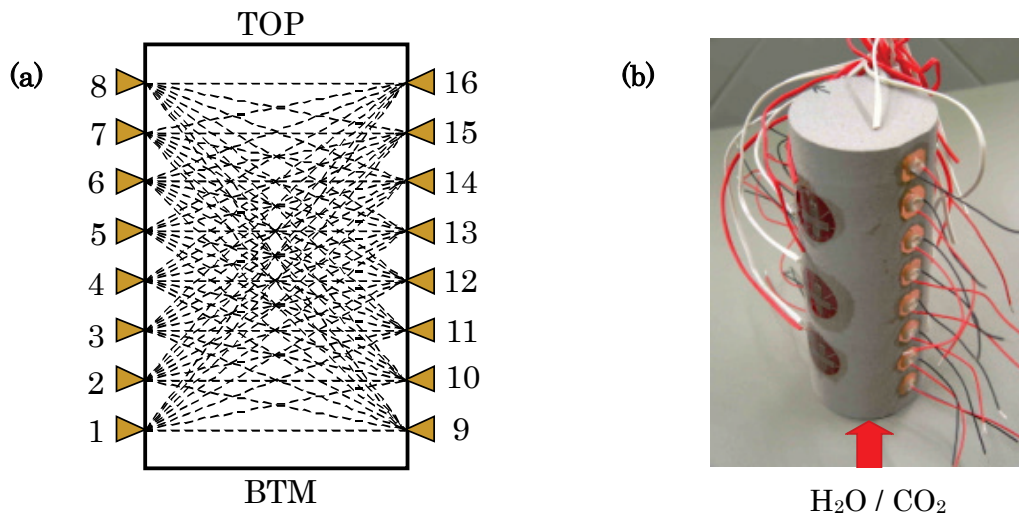
Wave velocity and attenuation in porous sandstone are widely studied in fields of reservoir engineering and geo-engineering[1]. As an example, during an enhanced oil recovery operation, there is a practical need to identify non-flooded compartments within the reservoir. Seismic survey provides substantial information concerning positions for new wells and modification of the existing depletion strategy[2]. Cross-well seismic tomography is considered as a promising monitoring method to map the movement of CO<sub>2</sub> in the subsurface[3]. The formation water, which existed in pore spaces within reservoir rocks, will be partially displaced by the injected CO<sub>2</sub>. This process will affect the propagation characteristics of the seismic waves. Seismic properties depend on the mineralogical composition of the rock as well as factors such as porosity, fluid content, and in-situ stress.

Previous works on effects of CO<sub>2</sub> flooding on seismic wave velocity show clearly that CO<sub>2</sub> flooding caused compressional wave (P-wave) velocities to substantially decrease[4,5]. Interpretation of seismic monitoring of CO<sub>2</sub> flooding requires an understanding of the effects of pore pressure buildup caused by the CO<sub>2</sub> injection and CO<sub>2</sub> saturation. Experimental studies, such as converting field measurements of wave velocities and attenuations to CO<sub>2</sub> saturation, support the interpretation of the survey results. We are conducting a series of seismic tomography experiments on porous sandstone samples to demonstrate the

use of cross-well seismic profiling for monitoring the migration of CO<sub>2</sub> in geological sequestration projects. In this paper, we present a preliminary result of measurements on velocity changes while injecting CO<sub>2</sub> into water-saturated Shirahama and Tako sandstone.

## EXPERIMENTS

Shirahama and Tako sandstone, having a porosity of 12% and 24% respectively, were used in this study. Cylindrical samples measuring 50 mm in diameter and 100 mm in length were sealed with silicone rubber sealant to exclude the oil used as the hydrostatic pressure medium. Sixteen piezo-electrical transducers with a center frequency of 1MHz and five pairs of cross-strain gages were cemented to the sample surface as shown in Figure 1.

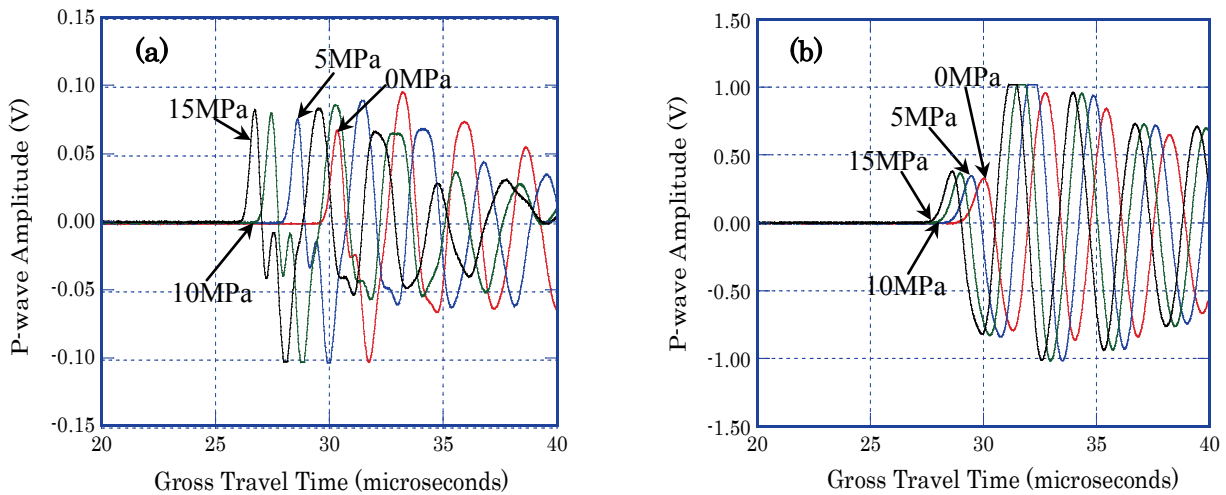


**Figure 1.** Locations of piezo-electric transducers and strain gages cemented on the sample. (a) Sixteen piezo-electric transducers numbered from 1 to 16, were arranged in 8 x 2 to monitor the movement of the CO<sub>2</sub> front along the longitudinal axis of the sample. (b) Cross-strain gages monitor local strains.

Dry samples were first subjected to hydrostatic pressure up to 25 MPa for Shirahama and 15MPa for Tako sandstone. P-wave velocity and strain were measured to examine their dependence on pore structure. The ultrasonic pulse transmission technique was used in this study. After the dry velocities were measured, the sample was saturated with distilled water, and remained inside of the vessel for CO<sub>2</sub> injection. The pore pressure was kept constant by a syringe pump to minimize velocity changes caused by pore pressure buildup during CO<sub>2</sub> injection. The CO<sub>2</sub> injection pressure was also controlled by another syringe pump. The P-wave velocity was measured to monitor the movement of CO<sub>2</sub> front within the sample while injecting CO<sub>2</sub>. P-wave velocity measurements were repeated on the same sample when the gaseous, liquid and supercritical CO<sub>2</sub> was injected respectively, to examine the phase dependence of the CO<sub>2</sub> front movement. The CO<sub>2</sub> was injected at a constant pressure ranged from 5 to 12MPa, and the flow rate depends on the sample's permeability, pressure and temperature conditions.

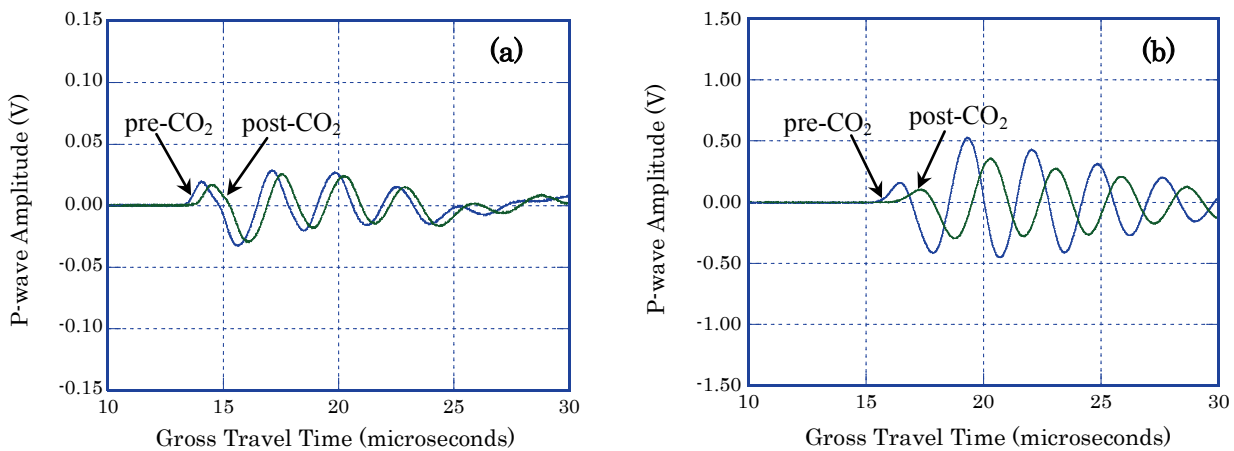
## RESULTS

Figure 2 shows, as an example, the recorded P-wave forms in dry samples. As the hydrostatic pressure increased, the travel times decreased and amplitudes increased for both Shirahama and Tako sandstone. Changes in travel time are more remarkable in Shirahama than those in Tako sandstone.



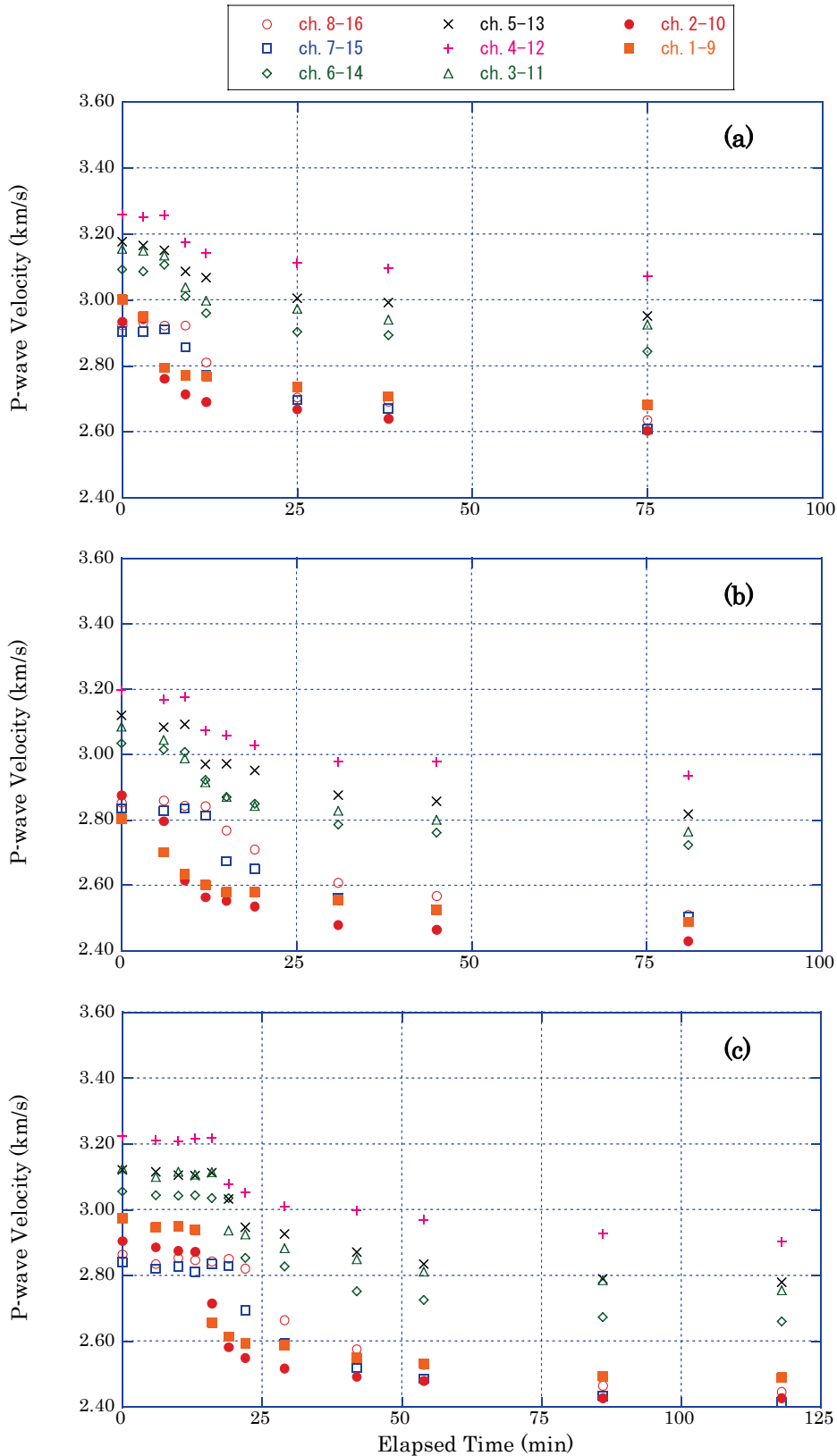
**Figure 2.** Examples of P-waves in Shirahama sandstone (a) and Tako sandstone (b) under hydrostatic pressures of 0, 5, 10 and 15MPa, respectively. As the pressure increases, the travel-times decreased and the amplitudes increased in both samples.

In the water-saturated samples, pre-existing pore water in pore space will be displaced partially by the injected  $\text{CO}_2$ , and this process cause changes in P-wave forms. Figure 3 shows an example of P-wave forms obtained from pre- and post- $\text{CO}_2$  injection in Shirahama and Tako sandstone. Comparing the travel times and amplitudes of the P-waves before and after injecting  $\text{CO}_2$  in Figures 3a and 3b, it is clear that  $\text{CO}_2$  injection caused significant changes in both samples.



**Figure 3.** Examples of P-waves obtained from pre- and post- $\text{CO}_2$  injection in Shirahama (a) and Tako sandstone (b). As injecting the gaseous  $\text{CO}_2$  into the samples, the travel-times increased and amplitudes decreased in both samples.

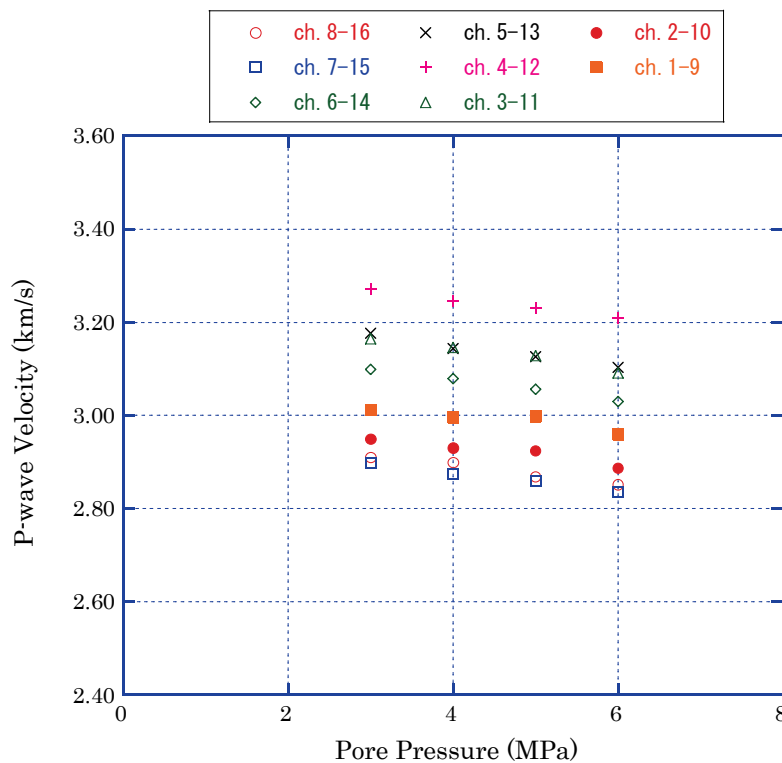
The variation of P-wave velocity is a good indicator for monitoring  $\text{CO}_2$  migration in water-saturated samples. Figure 4a, 4b and 4c show the results of P-wave velocity changes when the gaseous, liquid and supercritical  $\text{CO}_2$  was injected respectively into the Tako sandstone sample. In each figure, as starting  $\text{CO}_2$  injection, velocities at first remained almost constant for several minutes and then began to decrease gradually before finally reaching a new constant.



**Figure 4.** Curves of velocity changes versus the elapsed time, as injecting the gaseous, liquid and supercritical  $\text{CO}_2$  into the water-saturated Tako sandstone. The sample was subjected to pressures of 5MPa (a), 10MPa (b) and 15MPa (c), respectively. In each figure, the P-wave velocities of ch.1-9 and ch.2-10 decreased first, and then other channels located higher position began to show similar changes, ascribed to the injected  $\text{CO}_2$  migrated from the bottom to the top of the sample. This result suggests that displacement occurred between the pore water and the injected  $\text{CO}_2$  within the pore structure of the sample.

In Figures 4a, 4b and 4c, CO<sub>2</sub> was provided at the bottom end surface of the Tako sandstone sample at a constant pressure of 5, 8 and 12MPa respectively, and the pore pressures were kept constant at a pressure of 2MPa lower than the CO<sub>2</sub> injection pressure in each case. We take Figure 4a as an example to examine the velocity changes caused by the CO<sub>2</sub> injection. When the gaseous CO<sub>2</sub> was injected into the sample, velocities of ch.1-9 and ch.2-10 began to decrease first, and the velocity of ch.8-16 located close to the top end surface of the sample began to decrease in about 12 minutes and reached a stable state in about 75 minutes. The rate of decrease in velocities of channels located at the middle part of the sample is about 4% lower than that of other channels. This pattern of velocity change is common for all channels in Figures 4b and 4c. The maximum rate of decrease in velocity caused by injecting gaseous, liquid and supercritical CO<sub>2</sub>, was 10%, 12% and 16% respectively.

Figure 5 shows an example of effects of pore pressure on p-wave velocity in Tako sandstone. The sample was subjected to hydrostatic pressure of 10MPa and the P-wave velocity changes were measured when the pore pressure was increased from 3 to 6MPa, while the hydrostatic pressure was kept constant. The P-wave velocities of all channels decreased about 2% caused by increasing the pore pressure.



**Figure 5.** Curves of velocity changes versus the pore pressure, when the Tako sandstone sample was subjected to a constant pressure of 10MPa. Velocities decreased about 2%, as increasing the pore pressure from 3 to 5MPa.

## DISCUSSION AND CONCLUSIONS

In most previous experimental studies on the effects of CO<sub>2</sub> flooding, wave velocity was measured along the CO<sub>2</sub> flow direction, parallel to the longitudinal axis of the sample. In this study, we successfully monitored the migration of the CO<sub>2</sub> front, as evidenced by the P-wave velocity changes. As injecting CO<sub>2</sub> into the sample, the pre-existing water in pore space was displaced by the injected CO<sub>2</sub>, and the P-wave velocity decreases were caused by the compressibility contrast between the injected CO<sub>2</sub> and the pore water.

In the actual operation of injecting CO<sub>2</sub> into aquifers, the pore pressure buildup caused by the CO<sub>2</sub> injection is an unavoidable problem and this phenomenon depends strongly on the permeability of the reservoir rock. In field measurements, low-velocity zones are ascribed to the combined effects of CO<sub>2</sub> saturation and pore pressure buildup. In this study, we focused on the effect of CO<sub>2</sub> saturation by keeping the pore pressure constant during CO<sub>2</sub> injection. Our results show that P-wave velocity change is a good indicator for monitoring CO<sub>2</sub> migration in water-saturated sandstone.

Wang et al.[5] suggested that shear wave velocity is useful for separating the pore pressure effect from the combined effects because S-wave velocity is insensitive to CO<sub>2</sub> saturation, but sensitive to pore pressure increases. For example, if a zone shows a large decrease in P-wave velocity but little change in S-wave velocity, it is very likely swept by CO<sub>2</sub> at a pore pressure near the original reservoir pore pressure. On the other hand, if a zone shows a large decrease in both P- and S-wave velocities, it is probably swept by CO<sub>2</sub> with pore pressure buildup. This is a task for our future experimental studies.

Our results show that the pore size distribution significantly affects P-wave velocity in dry sandstone samples in this study. The remarkable increase of P-wave velocity in Shirahama sandstone is ascribed to the closure of micropores with low aspect ratio under hydrostatic pressure. The P-wave velocity changes during CO<sub>2</sub> injection suggested that seismic wave monitoring is a useful tool for mapping the movement of the injected CO<sub>2</sub> in reservoir rocks.

## ACKNOWLEDGMENTS

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