Laboratory Measurement of Geophysical Properties for Monitoring of CO_2 Sequestration

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Introduction

Geophysical techniques will be used in monitoring of geologic sequestration projects. Seismic and electrical geophysical techniques will be used to map the movement of CO_2 in the subsurface and to establish that the storage volume is being efficiently utilized and the CO_2 is being safely contained within a known region.

Rock physics measurements are required for interpretation of the geophysical surveys. Seismic surveys map the subsurface velocities and attenuation while electrical surveys map the conductivity. Laboratory measurements are required to convert field measurements of velocities, attenuation, or conductivity to CO_2 saturation.

Both seismic and electrical properties depend on the mineralogical composition of the rock, porosity, fluid content, and in situ stress state. Previous work on effects of CO_2 on seismic velocities is limited. Wang and Nur, 1989, measured both compressional (P-wave) and shear (S-wave) velocities on a number of sandstones saturated with n-hexadecane and then flooded with CO_2. They made measurements at different pore pressure and temperature conditions, finding that CO_2 caused P-wave velocities to substantially decrease under all conditions while S-wave velocities were decreased at high pore pressure and increased at low pore pressures. Wang et al, 1998, found that both P- and S-wave velocities decreased in a carbonate rock when CO_2 was injected at pore pressures from 1200 psi to 2600 psi.

There has been even less work on effects of CO_2 on electrical properties of rock. A search trial yielded no publicly available data.

Approach

Apparatus for making concurrent seismic and electrical measurements is shown in Figure 1. Samples measuring 1-½ inches in diameter by 3 inches long are placed in a rubber jacket, which contains four equally spaced electrodes in contact with the rock. The outer electrodes are current electrodes and the magnitude of the voltage drop across the sample is measured between the two inner electrodes spaced 1 inch apart.

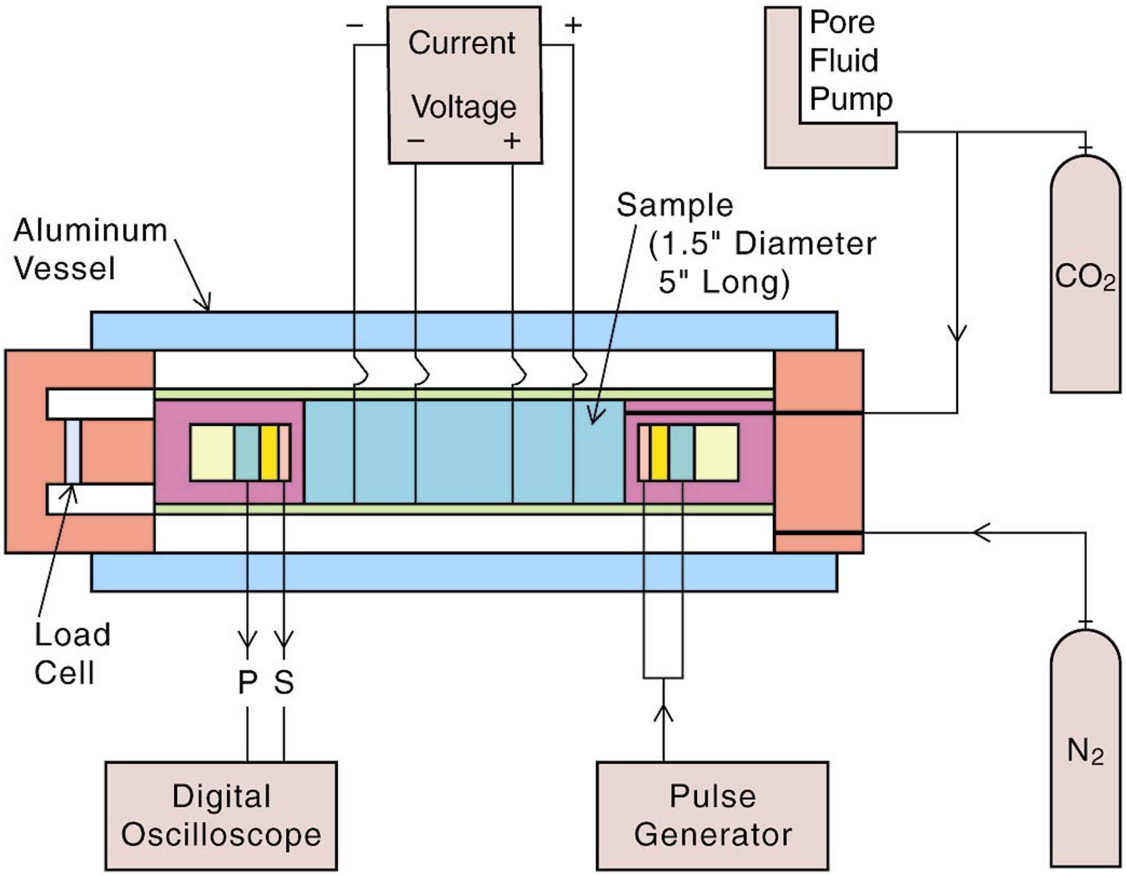

Figure 1. Schematic cross-section of experimental apparatus used for concurrent seismic and electrical measurements.

Seismic transducers are mounted at the ends of the sample for pulse transmission tests. Each transducer contains piezoelectric elements with a center frequency of 500 kHz. Only compressional (P-wave) measurements were made in these tests. Pore fluids are provided to the sample through ports in the seismic transducers. Axial load is also applied through the transducers and measured by a load cell in series with the transducers.

An aluminum confining vessel is used. This limits the maximum allowable confining pressure but enables use of X-ray CT imaging to evaluate fluid phase distribution in the sample.

Test conditions were applied so that electrical and seismic properties could be measured as the CO_2 passed from the gas phase through the critical point to liquid-like properties. Effective stress conditions were representative of moderate depth reservoir conditions. Measurements were made at a confining pressure of 1500 psi. At this level, the axial stress on the sample was about 480 psi. For tests in which pore pressures were in excess of 480 psi, the measured axial load was equal to the pore pressure.

Measurements were first made under brine-saturated conditions, beginning with a pore pressure of 300 psi and increasing to about 950 psi. The pore pressure was then reduced to 300 psi and CO_2 was injected. The CO_2 was flushed through the core against a back pressure of 300 psi until a residual brine saturation was achieved. At this point the outlet valve was closed and the brine saturation held constant while the CO_2 pressure was increased.

Results

Tests were conducted on a sample of Berea sandstone using brine of two resistivities, 3.5 Ω-m and 1.1 Ω-m. Berea has a porosity of about 20% and a permeability in the range of 150-300 millidarcies. Results of the electrical measurements are shown in Figure 2. The resistivity of the sandstone saturated with 1.1 Ω-m brine was about 17 Ω-m and when saturated with 3.5 Ω-m brine about 43 Ω-m. The resistivity was constant for each brine concentration over the range of pore fluid pressures used in the tests.

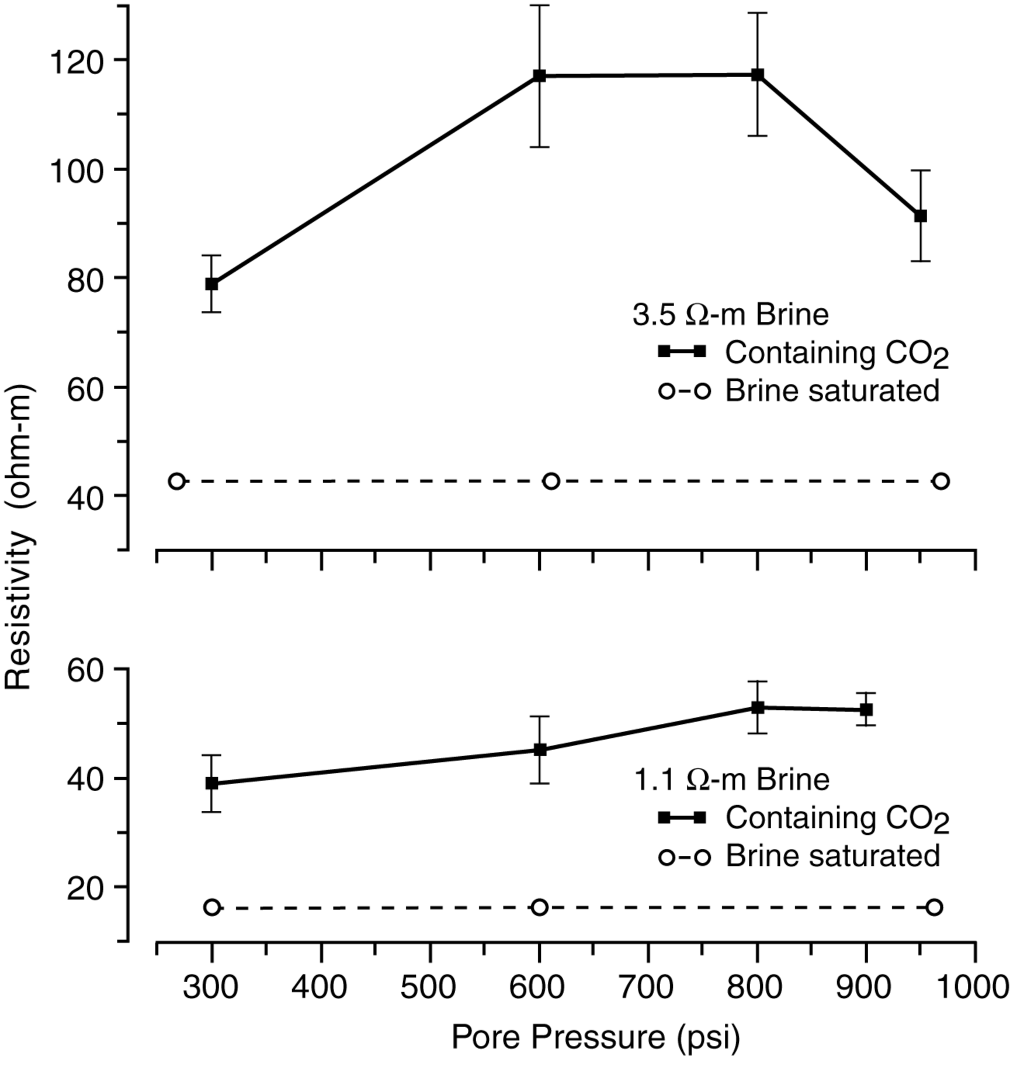

Figure 2. Results of resistivity measurements on Berea sample saturated with brine and then flooded with CO_2 at 300 psi.

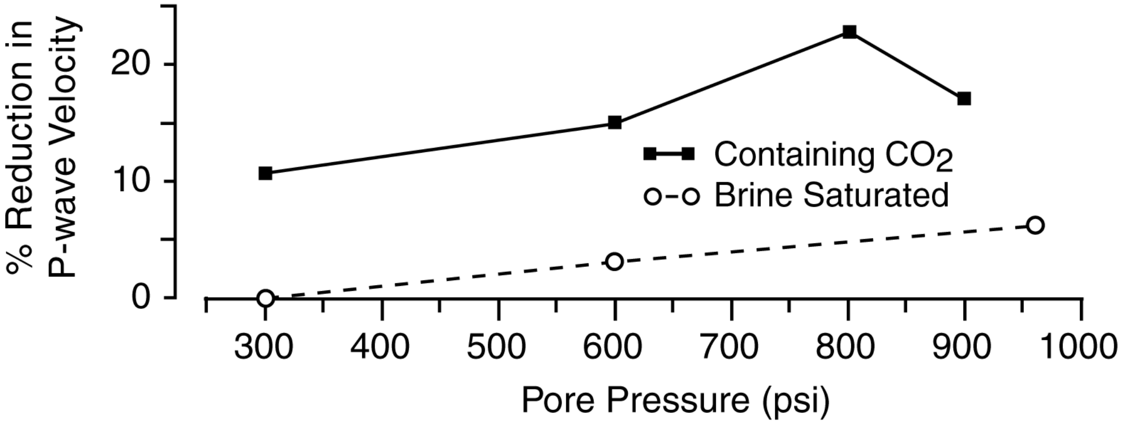

Figure 3. Changes in P-wave velocity for Berea sample saturated with 1.1 Ω–m brine and then flooded with CO_2 at 300 psi.

Introduction of CO_2 caused a significant increase in resistivity of the sample. The resistivity of the sample in the test using 1.1 Ω-m brine increased from 17 Ω-m to 38 Ω-m while that for the test using 3.5 Ω-m brine increased from 43 Ω-m to about 80 Ω-m. Increasing the pressure of the CO_2 in the gaseous phase caused an increase in sample resistivity. Behavior above the critical point differed for the different brine concentrations. For the 1.1 Ω-m brine test the resistivity at 900-psi pore pressure (above the critical point) was about equal to that at 800 psi. The 3.5 Ω-m brine test showed a decrease in resistivity between 800-psi pore pressure and 950 psi. Further testing needs to be done to evaluate changes in resistivity in the region of the critical point of CO_2. The error bars shown in Figure 2 represent uncertainty in the measurement due to noise contamination at low voltage levels.

Figure 3 shows the percent reduction in P-wave velocity at various test conditions using the velocity of the sample saturated with 1.1. Ω-m brine at 300-psi pore pressure as reference. Results for the test using 3.5 Ω-m brine showed the same trends. When fully saturated by brine, increasing the pore pressure from 300 psi to 950 psi caused a 6% reduction in P-wave velocity. This is consistent with the typical observations that seismic velocities decrease as effective pressure decreases. (Nur and Simmons, 1969, Sayers et al, 1990.)

Injection of CO_2 caused a significant reduction in P-wave velocity. At 300-psi pore pressure, flushing the sample with gaseous CO_2 caused an 11% reduction in velocity. This reduction was due to replacement of the liquid brine by low density, low modulus gas phase CO_2. The further reduction caused by increasing CO_2 pressure to 600 psi was similar to that observed for the brine saturated test and is therefore considered to be due to a reduction in effective stress. The reduction upon pressurization to 800 psi was more than would be expected from effective pressure changes. It is consistent with a rapid reduction in the velocity of CO_2, which has been observed near the critical point (Wang et al 1998). At 900-psi pore pressure the velocity recovers, reflecting the change to liquid-like properties above the critical point. The velocity is less than that for brine saturated conditions because of the lower density and bulk modules of the CO_2.

The recovery in P-wave velocity at 900-psi pore pressure differs from previous observations made by Wang and Nur (1989), which showed a continuing reduction in velocity as pore pressure increased. The differences in velocity trends may reflect different experimental procedures. Wang and Nur flooded hydrocarbon-saturated samples with high pressure CO_2 and then reduced pore pressures. We injected low pressure gaseous CO_2 into a brine saturated sample, probably resulting in a much more heterogeneous distribution of fluid phases than in the Wang and Nur tests.

Waveforms from the seismic measurements using 1.1 Ω-m brine are shown in Figure 4. The lower figure compares waveforms for different pore pressures in the brine-saturated test. The increased attenuation is a trend typically observed when effective stress decreases and may be due to scattering loss associated with imperfect grain contacts (Ita et al, 1993, and Nihei et al, 1995). Comparing the lower and upper figures shows that injection of CO_2 at 300-psi backpressure resulted in significant attenuation of the first arrival. Additional attenuation occurred as pore pressure was increased to 800 psi. Injection of low viscosity CO_2 into a brine-saturated rock would be expected to result in an unstable displacement front and, consequently, a heterogeneous distribution of fluid phases. Previous work suggests that significant attenuation due to scattering can occur when fluids of different densities are heterogeneously distributed in samples (Geller and Myer 1995). The large recovery in amplitude at 900 psi CO_2 pressure reflects the abrupt change in CO_2 properties from gaseous to liquid-like. The increase in density and bulk modules would reduce the contrast between the brine and CO_2 and reduce scattering losses.

Application

As part of the GEO-SEQ project (Benson and Myer, 2001) crosswell and single well seismic, and crosswell electromagnetic (EM) methods are being developed and evaluated as monitoring techniques. An early opportunity to begin field evaluation of these technologies has been provided by a pilot CO_2 flood being conducted by Chevron in the Lost Hills, California, oil field. The pilot targets the producing interval in the Belridge Diatomite, a member of the Monterey Group. The top of the diatomite is at a depth of about 1400 feet and extends to a depth of about 2100 feet. The diatomite reservoir rock is characterized by high porosity (40%-60%) but low permeability (<1-10 millidarcies). Because of the low permeability, production is stimulated by hydrofracturing and water flooding which was begun in 1990.

The CO_2 pilot utilizes a 1.25 acre pattern with injection taking place in two hydrofractured intervals at depths of 575 feet to 1785 feet, and 1825 feet to 2035 feet. The CO_2 injection pressure is held at 800 to 900 psi. Pre-injection reservoir pressures range from about 350 psi to about 950 psi (depending on depths and unit) at a temperature of around 108^{o} F. Under these conditions it is anticipated that the CO_2 will be in the gaseous phase in some regions of the reservoir.

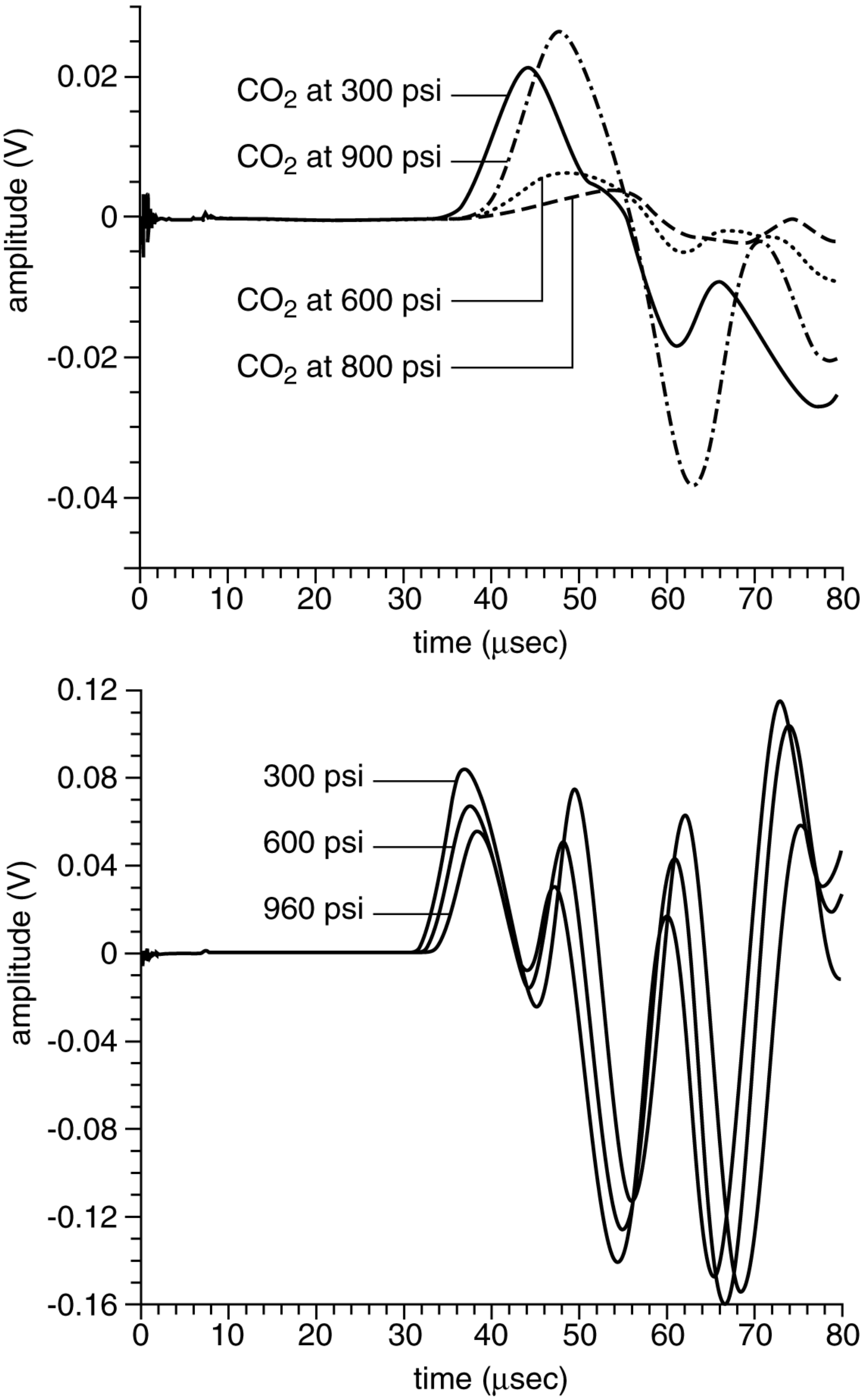

Figure 4. Waveforms for Berea sample saturated with 1.1 Ω–m brine and then flooded with CO$_2$ at 300 psi.

Prior to CO_2 injection single well seismic, crosswell seismic in two frequency ranges, and crosswell EM surveys were performed (Daley et al, 2000). The crosswell surveys were performed between two monitoring wells (OB-C1 and OB-C2) located 88 feet apart and straddling an injection well. The EM survey was conducted by Electromagnetic Instruments, Inc. with data collection at a frequency of 760 Hz. Preliminary tomograms of seismic velocity and electrical resistance from these surveys are shown in Figure 5. The seismic data was collected with a high frequency (>2000 Hz) piezoelectric source. Repeat surveys will be performed after CO_2 injection has been underway for some time. Analysis of the differences between pre and post injection surveys will be used to quantify the location and amount of CO_2 in the region sampled by the surveys.

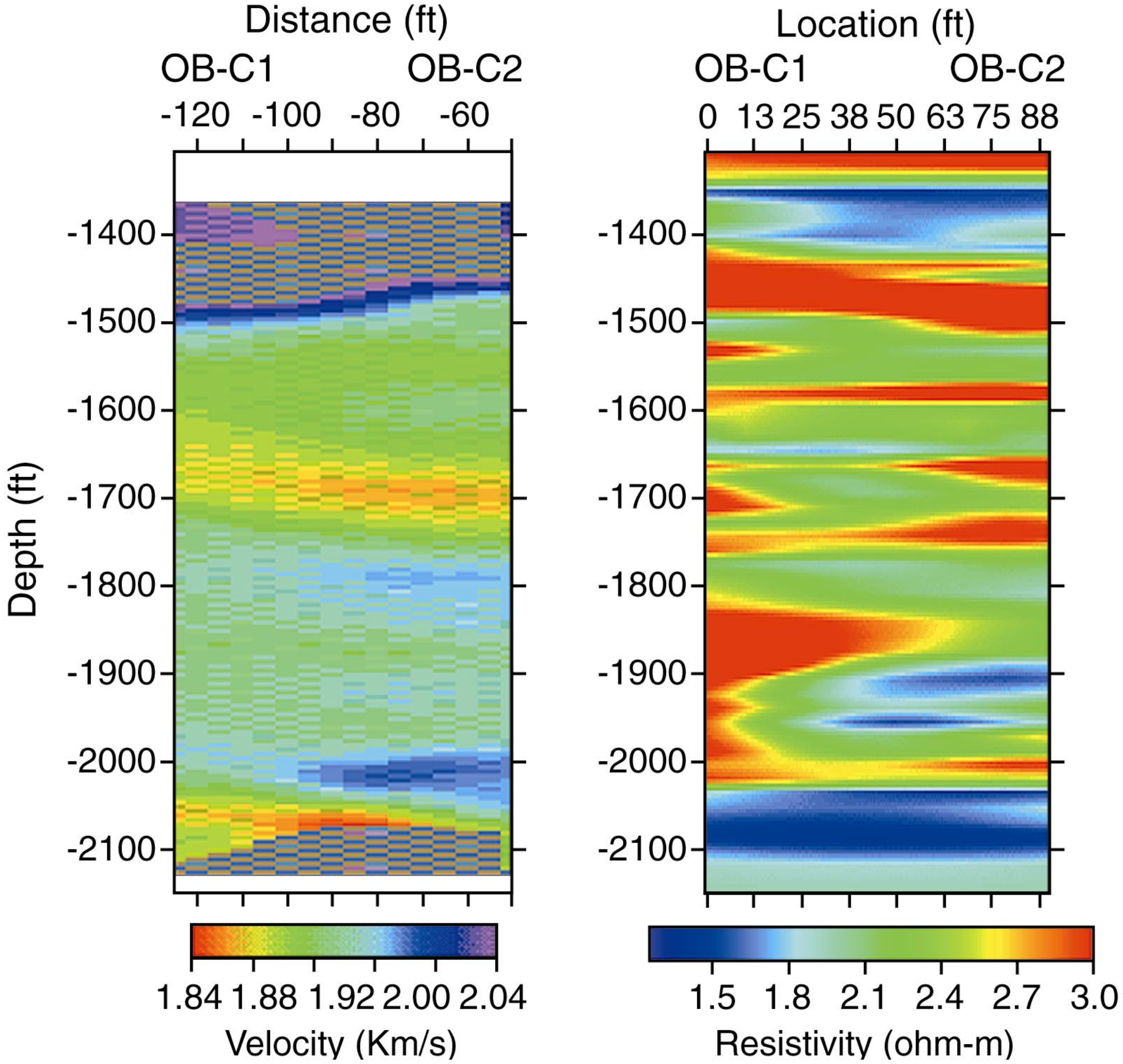

Figure 5. Preliminary pre-injection seismic and electromagnetic tomograms for crosswell surveys at Lost Hills CO_2 monitoring study.

Differences between seismic and EM tomograms as seen in Figure 5 are to be expected since one survey senses seismic velocities and the other electrical resistivity. Differences between velocity and electrical measurements are seen on a positive aspect of this monitoring approach in that these differences can be used to further constrain interpretation of the geophysical measurements. Laboratory measurements of seismic and electrical properties are essential to interpretation of field measurements since they provide quantitative relationships between seismic and electrical parameters and the quantity of CO_2 in the rock of interest.

Future Activities

Results of laboratory seismic and electrical measurements on Berea sandstone containing brine and CO_2 show trends that indicate that field measurements of these properties can be used to detect and monitor CO_2. Quantitative relationships need to be developed for each rock type. Thus, future work in support of the monitoring tests at Lost Hills will be conducted on diatomite reservoir rock cores.

The laboratory measurements showed that displacement of brine by CO_2 will result in an increase in resistivity and a decrease in seismic velocities and amplitudes. Seismic measurements (and perhaps electrical) will be sensitive to the CO_2 phase changes occurring at the critical point. Seismic properties may be affected by the quantity as well as the distribution of the phases.

Considerable further work is required to understand both electrical and seismic properties of rock containing CO_2. Relationships between resistivity and CO_2 saturations are needed. Much more work needs to be done to establish relationships between geophysical properties and fluid phases near the critical point. Effects of fluid displacement mechanics on the phase distribution in the rock and resulting affects on geophysical parameters also need to be evaluated.

Acknowledgements

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References

Benson, S., and Myer, L.R., The GEO-SEQ project: First year status report, *Proceedings of First National conference on Carbon Sequestration*, (this volume) 2001.

Daley, T., Majer, E., Gritle, R., and Benson, S., Borehole seismic monitoring of CO_2 injection in a diatomite reservoir, *EOS, Transactions of American Geophysical Unions*, Vol. 81, page F272, 2000.

Geller, J.T., and Myer, L.R., Ultrasonic imaging of organic liquid contaminants in unconsolidated porous media, *Journal of Contaminant Hydrology*, vol. 19, No. 3, 1995.

Ita, S., Cook, N., Myer, L.R., and Nihei, K., Effects of stress anisotropy on the static and dynamic properties of berea sandstone, *International Journal of Rock Mechanics and Mining Sciences*, Vol. 30, No. 7, pp. 785-788, 1993.

Nihei, K.T., Myer, L.R., and Cook, N.G.W., Numerical simulation of seismic wave propagation in granular rock with a multiple grain boundary integration equation, *J. Acoust. Soc. Am.*, Vol. 97, No. 3, pp. 1423-1434, 1995.

Nur, A., and Simmons, G., Stress-induced velocity anisotropy in rocks: An Experimental study, *J. Geophys. Res.*, Vol. 74, page 6667, 1969.

Sayers, C.M., Van Munster, J.G., and King, M.S., Stress-induced ultrasonic anisotropy in Berea sandstone, *Int. J. Rock Mech. Mining, Sci. Geomech. Absts.*, Vol. 27, pp. 429-436, 1990.

Wang, Z., and Nur, A., Effect of CO_2 flooding on wave velocities in rocks and hydrocarbons, *Soc. Petr. Eng. Res. Eng.*, Vol. 3, pp. 429-439, 1989.

Wang, Z., Cates, M., and Langan, R., Seismic monitoring of a CO_2 flood in a carbonate reservoir: A rock physics study, *Geophysics*, Vol. 63, No. 5, pp. 1604-1617, 1998.