# IN-SITU BOREHOLE SEISMIC MONITORING OF INJECTED CO2 AT THE FRIO SITE

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## INTRODUCTION

The U.S. Dept. of Energy funded Frio Brine Pilot provided an opportunity to test borehole seismic monitoring techniques in a saline formation in south-east Texas. A relatively small amount of $CO_2$ was injected (about 1600 tons) into a thin injection interval (about 6 m thick at 1500 m depth). Designed tests included time-lapse vertical seismic profile (VSP) and crosswell surveys which investigated the detectability of $CO_2$ with surface-to-borehole and borehole-to-borehole measurement.

## DATA ACQUISITION

Two time-lapse borehole geophysical surveys were acquired at the Frio site, a vertical seismic profile (VSP) and a crosswell seismic survey. A VSP uses surface sources with borehole sensors, while a crosswell survey uses borehole sources and sensors. Both surveys had baseline, pre-injection, data acquisition in July of 2004 and post injection data acquisition in late Nov., 2004 (approximately 1.5 months post injection). The VSP was intended to detect changes in seismic properties on the scale of 10's - 100's of meters around the injection well, while the crosswell survey was designed to detect changes between the injection and monitoring wells on the scale of 2 - 10 meters.

Both surveys used an 80-level, 3-component borehole geophone string with 7.6 m (25 ft.) spacing. The crosswell survey had 5 moves of the sensor string to acquire data at 1.5 m (5 ft.) spacing for both sensor and source. The crosswell source was an orbital vibrator (Daley and Cox, 2001) which generates both P- and S-waves, allowing imaging of compressional and shear properties, respectively. The VSP source was explosive shots at surface sites reoccupied after injection. Initial processing and analysis of the VSP data has provided measurement of seismic reflection amplitude changes on 3 azimuths, northwest, north and northeast of the injection well.

## VSP AND CROSSWELL RESULTS

A large change in VSP reflection amplitude (about 70%) from the Frio zone was observed and the results were compared favorably with flow modeling predictions of saturation (Figure 1). The difference in VSP response for each azimuth of acquisition indicates subsurface heterogeneity affecting saturation.

The crosswell data provided very good P- and S-wave tomographic images. The time-lapse tomographic image mapped large changes in P-wave velocity (up to 20%), with well defined boundaries, due to the $CO_2$ plume (Figure 2). The S-wave tomogram shows no measurable change except at the injection well near the perforations.

The results of both VSP and crosswell demonstrate that CO2 injected in brine reservoirs can be spatially located with borehole seismic techniques. Estimates of CO2 saturation from the seismic response are difficult due to complex rock physics which require site dependent models usually obtained from laboratory core studies.

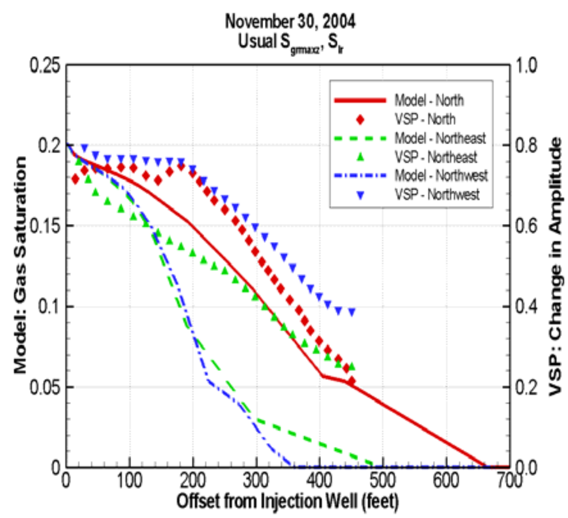


*Figure 1. Change in VSP reflection amplitude (symbols), as a function of offset from injection well, for each of three azimuths, along with modeled gas saturation (lines)along the same azimuths. Gas saturation modeling courtesy of C. Doughty.*

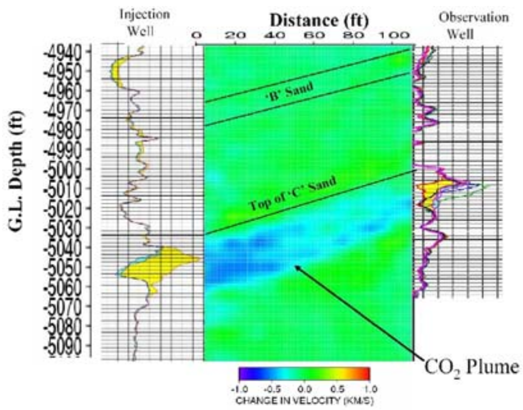


*Figure 2. Crosswell tomogram showing the change in seismic velocity within the reservoir due to CO2 injection, along with pulsed neutron logs showing changes measured at the boreholes.*

## NEW MONITORING METHODOLOGIES

Having successfully applied VSP and crosswell imaging techniques, we investigated the data acquired at the Frio site for application of new methodologies. One promising potential application is the monitoring of acoustic signals for the purpose of characterizing out-of-casing fluid flow. While seismic sensors are deployed in the borehole, background 'noise' can be continuously monitored. Both recent and older studies suggest the possibility of multi-phase fluid flow detection using noise spectra in the 0-5 KHz range (McKinley, et al, 1972; Wang, et al., 1999). Although, noise studies were not initially planned for the Frio CO2 injection experiment we later included noise analysis as it potentially contained useful information.

Seismic noise in fluid-filled boreholes is primarily represented by vertically propagating tube waves. Tube waves have low attenuation and their velocities are usually below 1500 m/s. Tube wave velocities are sensitive to rock properties behind the casing and to the quality of casing contact with rock formation. Figure 3 shows noise amplitudes along the injection well at different frequencies for pre- and post-injection surveys. Notable changes are observed at 4950 ft and 5050 ft. The 4950 ft interval shows decreasing amplitude as frequency becomes higher, corresponding to a two-phase flow pattern. The amplitude distribution for the injection interval shows the highest peak at intermediate frequencies possibly indicating presence of both one-phase and two phase flows. This interpretation could be more conclusive if higher frequencies were recorded in the data (at least up to 2 KHz). Currently traces have frequencies up to 420 Hz. Analysis of acoustic 'noise' due to fluid flow could be a potential method of monitoring the bonding between casing and the formation. If proven robust, such measurements can give locations of weak zones behind casing. permanent emplacement of seismic sensors behind casing is a proposed method for obtaining continuous noise monitoring as well as time-lapse VSP and crosswell data.

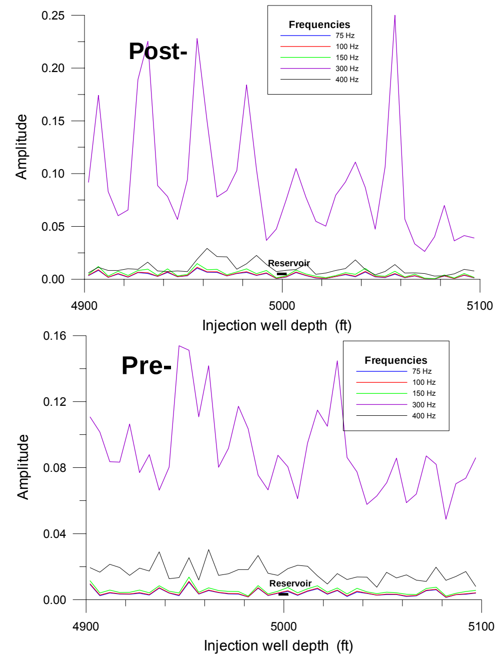


*Figure 3. Noise amplitudes along the injection well at different frequencies for pre- (bottom panels) and post- (upper panels) injection surveys for 4900-5100 ft depth interval.*

## SUMMARY

Borehole seismic acquisition at the Frio site provided in-situ estimates of the spatial distribution of injected CO2, with high resolution between injection and monitoring wells (crosswell), and at larger distances, on different azimuths (VSP). These results demonstrate the applicability of seismic monitoring to CO2 storage in saline reservoirs.

Noise monitoring methodologies were investigated using the borehole emplaced seismic sensors. Intriguing results indicate that seismic sensors can be used to detect and monitor fluid flow in the near wellbore region.

The combined usefulness of active source surveys (VSP or crosswell) and acoustic monitoring point to the need for permanently emplaced seismic sensors to monitor CO2 sequestration.

## REFERENCES

Daley, T.M. and Cox, D. *Orbital vibrator seismic source for simultaneous P- and S-wave crosswell acquisition*, Geophysics, 66, 1471-1480, 2001.

Wang, J, van der Spek, A. Georgi, D.T. and D. Chace, *Characterizing sound generated by multiphase flow*, Society of Petroleum Engineers, Annual Meeting paper SPE 56794. 1999.

McKinley, R.M., Bower, F.M., and R.C. Rumble, *The structure and interpretation of noise from flow behind cemented casing*, Society of Petroleum Engineers, Annual Meeting paper SPE 3999, 1972.

## ACKNOWLEDGMENT

This work was supported by the GEO-SEQ project, the National Energy Technology Laboratory, U.S. Department of Energy, under Contract No. DE-AC02-05CH11231. Thanks to Paulsson Geophysical for support of sensor deployment, Don Lippert and Rob Trautz for help with data acquisition, John Peterson for tomographic inversion and Chris Doughty for discussion and flow modeling.