Borehole Seismic Monitoring of Injected CO$_2$ at the Frio Site

* Daley, T M (tmdaley@lbl.gov), Lawrence Berkeley National Lab., 1 Cyclotron Rd, Berkeley, CA 94720
Myer, L (lrmyer@lbl.gov), Lawrence Berkeley National Lab., 1 Cyclotron Rd, Berkeley, CA 94720
Hoversten, G M (gmhoversten@lbl.gov), Lawrence Berkeley National Lab., 1 Cyclotron Rd, Berkeley, CA 94720
Peterson, J E (jepeterson@lbl.gov), Lawrence Berkeley National Lab., 1 Cyclotron Rd, Berkeley, CA 94720

The recently completed CO$_2$ injection in the brine aquifer of the Frio Formation in southeast Texas provided an opportunity to test borehole seismic monitoring techniques. Designed tests included time-lapse VSP and crosswell surveys which investigated the detectability of CO$_2$ with surface-to-borehole and borehole-to-borehole measurement. The VSP method uses surface seismic sources in conjunction with borehole sensors to measure the seismic properties (such as velocity and reflection strength) in the vicinity of the borehole. By moving the source location, seismic properties can be mapped spatially around the sensor well. A large change (about 70%) in VSP reflection amplitude from the Frio zone was observed. Because of the relatively small amount of CO$_2$ injected (about 1600 tons), and the thin injection interval (about 6 m thick at 1500 m depth), CO$_2$ detectability by the VSP method was not an assumed certainty. The initial result is therefore quite promising for use of the VSP method. The crosswell method measures wave propagation between wells and can tomographically image the interwell volume. The crosswell survey was conducted using the injection well (for sensors) and a nearby monitoring well (for the source) which is about 30 m offset. Crosswell source locations were centered on the injection interval. The crosswell sensors were also centered on the injection interval, which is the 6-7 m thick, upper C sand in the Frio formation which is at a depth of about 1500 m. Initial analysis of the crosswell data shows good quality P- and S-wave direct arrivals. Time-lapse tomographic imaging maps the changes in velocity (up to 1 km/s) due to the CO$_2$ plume.
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T.M. Daley, L.R. Myer, G.M. Hoversten, J.E. Peterson
all at
Lawrence Berkeley National Laboratory

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Outline

• Background of the CO2 Sequestration Pilot
• Goals and Design of Time-Lapse Seismic
• Crosswell Seismic
  — Acquisition Equipment
  — Tomography results P and S
• VSP
  — Acquisition Geometry
  — Time-Lapse Change
• Summary/Conclusion
Injection interval ~7 m at 1530 m depth

~1600 metric tons CO2

Well spacing ~30 m

Dip ~20 deg.

Frio ‘C’ Sandstone: porosity 30%, permeability 1.5 Darcys, brine filled

150 bar, 53 deg. C, supercritical CO2
Goals of Seismic Monitoring

- **Crosswell**
  - Spatial mapping of CO2 between wells
  - Combine with other measurements to estimate CO2 saturation between wells.

- **VSP**
  - Spatial mapping of CO2 beyond the well pair
  - Imaging of nearby structure (faults, etc)
Data Acquisition

• Orbital vibrator source for simultaneous P and S crosswell; VSP source was explosive
• Used P/GSI 80 level 3-component sensor string for both crosswell and VSP
• Crosswell 1.5 m spacing, VSP 4 m spacing
• Pre Injection Survey: July, 2004
• Post Injection Survey: Nov. 28, 2004 (1.5 months after injection)
• Both wells’ perforations were cemented during both surveys
Orbital Vibrator Borehole Seismic Source

- Fluid Coupled
- Rotating eccentric mass
- ~70 Hz to 360 Hz
- ~8 second sweep
- Generates P and S
- SH wave decoupled from P-wave -> better S time picks
VSP 3-C Senor in Tubing and Pod

Sensor Package
Sensor String Deployment Depths
80 levels at ~8m spacing

Paulsson Sensor Locations - VSP Site 3

Depth (m)

VSP

Crosswell Fans
Example Crosswell Time Picks

P-Wave

S-Wave
Constant 30ft Offset (Along Dip)
P-wave

Pre Injection

Post Injection

Depth (m)

Time (ms)
Tomographic Inversion

- *Invert difference; not difference inversions*
- **2 m pixel size**
- Limit ray angle (no long offsets, > 100 m)
- Correct for deviation of wells
- Use straight ray projection
- Apply static correction (borehole effects)
- Plotting interpolated to 0.5 m
Pre - Post Velocity Difference

P-Wave

S-Wave

Depth (m)

Offset (m)

Injection Zone

Injection Zone

1475

1530

1600

1500

1560

-1.0 -0.5 0.0 0.5 1.0

CHANGE IN VELOCITY (KM/S)

-0.2 -0.1 0.0 0.1 0.2

CHANGE IN VELOCITY (KM/S)
Seismic P-wave and Pulsed Neutron Logs

- **Depth (ft)**
  - Top of 'C' Sand: 1505 ft
  - Top of 'B' Sand: 1530 ft
  - CO₂ Plume: 1550 ft

- **Depth (m)**
  - Top of 'C' Sand: 0 m
  - Top of 'B' Sand: 30 m

**Legend:**
- Injection Well
- Monitor Well
- 'B' Sand
- 'C' Sand
- CO₂ Plume

**Color Scale:**
- Change in Velocity (km/s)
  - -1.0 to 1.0
VSP Shot Points

N

Wells

500 m

1  2  3  4  5  6  8  9

Frio Crosswell

Lawrence Berkeley National Laboratory
Processing for Time Lapse Reflection Amplitude Change

• Apply static shifts from explosive shot monitor. Edit noisy traces, sort by depth, etc.
• Use F-K filters to remove downgoing and enhance upgoing energy.
• For time-lapse change: normalize reflection amplitude using a shallower reflector above the frio.
• Calculate change in reflection amplitude
Site 1 (North, Up Dip) Reflection Section

Pre Injection
Post Injection

Two-way travel time

Depth (m)

1200 1500 1200 1500

1000

Control Reflection
Frio Reflection
Major change in Frio due to CO2 injection. Smaller change below Frio probably due to transmission through Frio.
Site 1 (North): Estimated Plume Size

Over 70% increase in peak reflection amplitude. This is a strong response.

What is cut-off point for plume edge? Pending a rock physics model for Frio.
Comparison of VSP and Modeled Gas Saturation
Conclusions

Data Acquisition

• Orbital vibrator provides quality P and S crosswell data
• 80-level 3-component sensor string good for VSP and crosswell

CO2 Detection

• Crosswell seismic images the ~800 m/s velocity change due to CO2 plume between wells
• VSP easily “sees” the plume as ~70% increase in reflection amplitude → some surface monitoring is possible without full 3D surface seismic.
• VSP measured azimuthal variation in reflection change
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- Thank you for your attention!