Geologic Characterization for CO_2 Storage in California's Sacramento Basin

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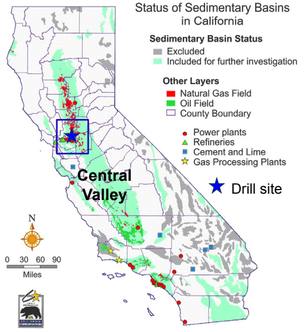
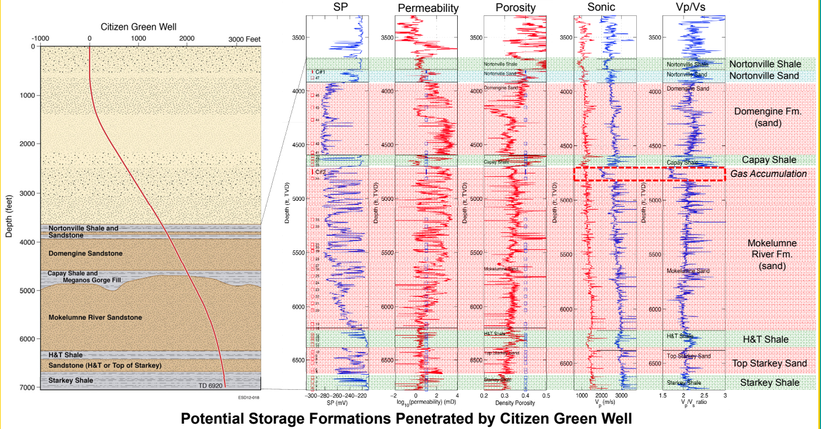
CO_2 Storage Opportunities in California's Sacramento Basin

- The Central Valley of California is the most promising on-shore CO_2 storage resource in WESTCARB territory, with an estimated capacity of 75-300 Gt. The Valley is divided into the Sacramento Basin in the north and the San Joaquin Basin in the south.
- In December 2011, WESTCARB drilled a stratigraphic well to assess the CO_2 storage potential of regionally extensive saline and gas-bearing formations in the southwestern Sacramento Basin.
- The Citizen Green well was drilled directionally to a vertical depth of 6,920 feet (2,109 meters) on King Island, an agricultural area near Stockton. Core samples and logging data are being analyzed at Lawrence Berkeley National Lab and shared with researchers at two of DOE's Frontier Energy Research Centers and several universities.
- CO_2 storage capacity of the sandstone formations and integrity of the overlying shale units are being evaluated. Simulations of CO_2 injection, multi-phase flow, and trapping mechanisms are being performed. The formations are laterally extensive, so the data will have regional application.





Potential Storage Formations Penetrated by Citizen Green Well

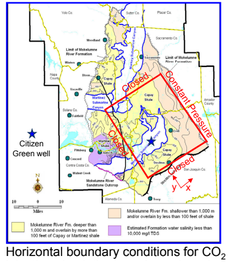
- **Domengine –** High permeabilities (3+ Darcies) observed on Combinable Magnetic Resonance (CMR) log. However, questionable stratigraphic seal at this location may decrease storage utility. Unconsolidated.
- **Mokelumne River** (primary target) **–** 1+ Darcy CMR permeabilities in the upper section where cores were unconsolidated sand. Thickness 1507 ft (460 m). Becomes tighter with depth; consolidated below 5500 ft (1676 m). Natural gas accumulation at Capay/Mokelumne River boundary suggests seal integrity.
- **Top Starkey Sandstone –** Considerably lower mean permeability, but several lobes show more promise with CMR permeability ~100 mD.

CO_2 Injection Simulation Based on Well Log Data

Use of Well Log and Sidewall Core Data for Simulated CO_2 Injection into Mokelumne River Sandstone

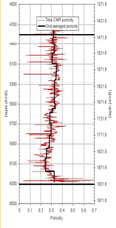
At the drill site, the Mokelumne River sandstone is gas-bearing in a pinnacle in the Meganos Gorge. The Capay shale overlies the pinnacle. The Domengine and Starkey sandstones are not intruded by the gorge.

- NMR Total Porosity is a good match with sidewall core helium porosimetry data
- NMR permeability estimates are good for formations encountered by the well
- 19 model layers estimated from well log permeability profile
- Model captures high permeability in upper half, downward fining in lower half
- Porosity and horizontal permeability are arithmetic mean of log values over layer interval
- Vertical permeability is harmonic mean of log values over layer interval
- Injection (well perforation) over the lower half of Mokelumne River Formation
- Injection partitioned by permeability-thickness product of each of the bottom 8 layers
- Model assumes no-flow boundary at overlying Capay Shale and 1.6° dip upward to ENE

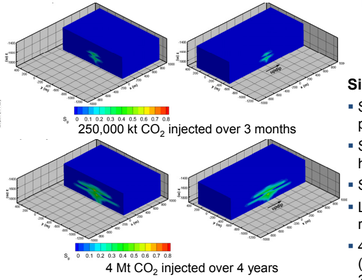


Horizontal boundary conditions for CO_2 injection simulation are shown in red.

Reference: Downey, C., J. Clinkenbeard, 2011, *Studies Related to Geologic Carbon Sequestration Potential in California*, California Geological Survey, CEC



Nuclear Magnetic Resonance (NMR) log data and selected porosity/permeability layers

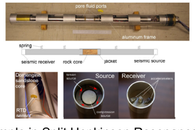


Simulated CO_2 Injection Results

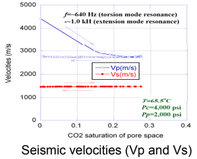
- Strong lateral flow within high-permeability layers
- Strong vertical buoyancy flow within high-permeability layers
- Slight up-dip migration
- Low permeability baffles greatly reduce effective vertical permeability
- 4 Mt CO_2 plume diameter ~3900 ft (1200 m), height 1150 ft (350 m), still 360 ft (110 m) below top of reservoir

Supercritical CO_2 Injection and Brine Re-injection Experiment, with Concurrent X-ray CT Imaging

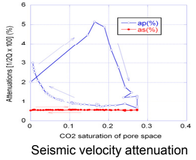
- Sample: Domengine sandstone core (6" long, 1.5" diameter, >2-3 Darcy permeability, ~30% porosity) from the Black Diamond Mine, located 39 km (24 mi) WSW of the Citizen Green well
- Test conditions: Confining pressure = 4,000 psi, pore pressure = 2,000 psi, temperature = 56.6°C, the estimated in-situ conditions at the top of the high-permeability section of the sedimentary unit. Brine is a 1% NaCl (10,000 mg/l) solution
- Measurements: Resonance frequency and attenuation (to calculate seismic velocities, V_p and V_s) and pH of the effluent brine.



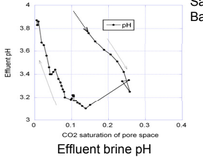
Sample in Split Hopkinson Resonance Bar apparatus for seismic experiment



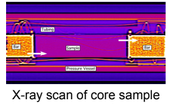
Seismic velocities (Vp and Vs)



Seismic velocity attenuation



Effluent brine pH



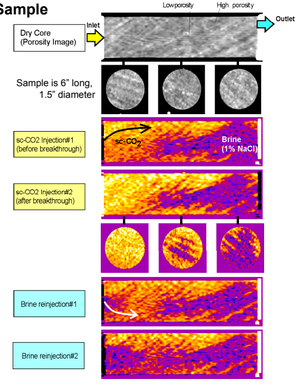
X-ray scan of core sample in seismic apparatus

Core Sample Petrophysical Analysis

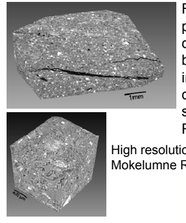
CT Scans of Domengine Sandstone Sample

- Dry core (black and white) images: Longitudinal and three cross-section CT scans. Lighter tones are lower porosity (higher density); darker tones are higher porosity (lower density). Layering is clearly visible.
- Center color images: CT scans showing the location of supercritical CO_2 injected into the brine-filled core, before and at breakthrough. Flow is left to right. Yellow/orange colors represent lower density from higher CO_2 saturation; purple/blue colors represent higher density where the core is still brine-saturated.
- Bottom two color images: Scans showing that as brine is re-injected, it follows a path of lower CO_2 saturation.
- The different invasion behavior of sc-CO_2 versus brine results from the very high permeability of the rock and the density difference between the two fluids (buoyancy). At the experimental pore pressure of 2,000 psi and temperature of 56.6°C, the density of the 1% NaCl brine is ~0.991 g/cc and the sc-CO_2 is 0.59 g/cc.

LBNL Petrophysical CT Scanner



Virtual Petrophysics

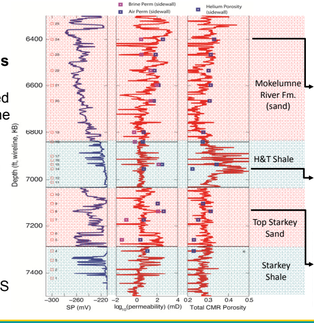


For GCS characterization, the evaluation of petrophysical properties, particularly relative permeability for predictive modeling studies, has the high costs of acquiring continuous core and conducting core flood experiments. Alternatively, petrophysical data for multiphase flow models can be acquired by scanning small samples (e.g., sidewall cores) at high resolution using 3D micro-CT imaging (micron resolution) and conducting pore scale modeling. Reduced imaging and computational costs are making this viable in some cases. To test this approach, we are scanning sidewall cores at LBNL's Advanced Light Source for 3D microstructure and modeling permeability. Results are compared with single phase permeability lab tests.

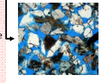
High resolution scans of a shale lens in the Mokelumne River Fm. from ~4700 ft TVD

Sidewall Core Analysis

Basic petrophysical properties were measured for sidewall cores from the well. Porosity and permeability were generally consistent with CMR log data. Surprisingly, high permeabilities were measured for the Top Starkey sand (432 mD) suggesting this deep horizon is a potential GCS target.

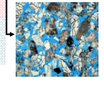


Thin Section, 10x



Sidewall #24
5782 ft TVD
Lower Mokelumne
Porosity 33%
Air Perm. 367 mD

Sidewall #14
6315 ft TVD
H&T Shale
Porosity 22%
Air Perm. < 5 mD



Sidewall #8
6496 ft TVD
Top Starkey Sand
Porosity 31%
Air Perm. 432 mD

Surface Texture, 1x

Confirms Lower Mokelumne as injection target

Confirms Top Starkey as injection target