U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

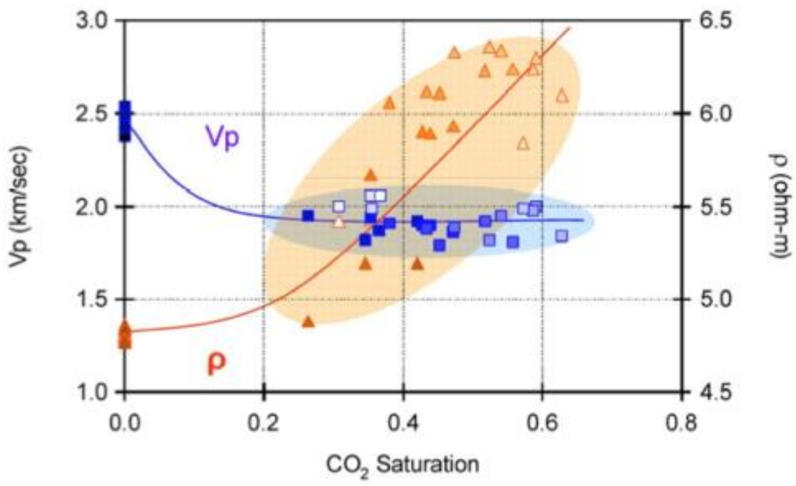
Push-pull well testing using CO_2 with active source geophysical monitoring

Project Officer:
William Vandermeer
Total Project Funding: $250,000
May 11, 2015

Principal Investigators: Oldenburg and Daley
Lawrence Berkeley National Laboratory

Project Motivation and Objective

- EGS benefits from ability to control fracture flow and fracturing (e.g., hydraulic or thermal fracturing).
- In order to control, need ability to characterize fractures.
- Natural and induced fractures are hard to image.
  - Seismic and electrical contrast is small for water-filled fractures
- In contrast, gas-filled fractures enhance contrasts.



From: Xue, Z., J. W. Kim, S. Mito, K. Kitamura, and T. Matsuoka. "Detecting and monitoring CO_2 with P-wave velocity and resistivity from both laboratory and field scales." In SPE International Conference on CO_2 Capture Storage and Utilization. Society of Petroleum Engineers, 2009

Relevance/Impact of Research

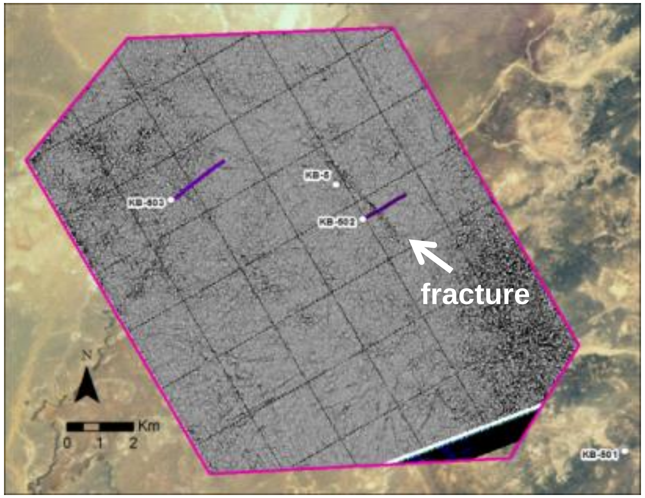
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Project Motivation and Objective

- Develop and demonstrate a new technology for characterizing fractured geothermal systems by modeling coupled:
  - CO_2 push-pull well testing
  - Active source geophysical monitoring
  - Well logging
- CO_2 injected for push-pull well testing has a strong preference for flowing in fractures (it is non-wetting).
- LBNL has advanced simulation and related inversion capabilities for CO_2 at geothermal conditions (TOUGH2/ECO2H, iTOUGH2).

Project Motivation and Objective

- We are bringing long experience with CO_2 from DOE's Fossil Energy program to bear on EGS.



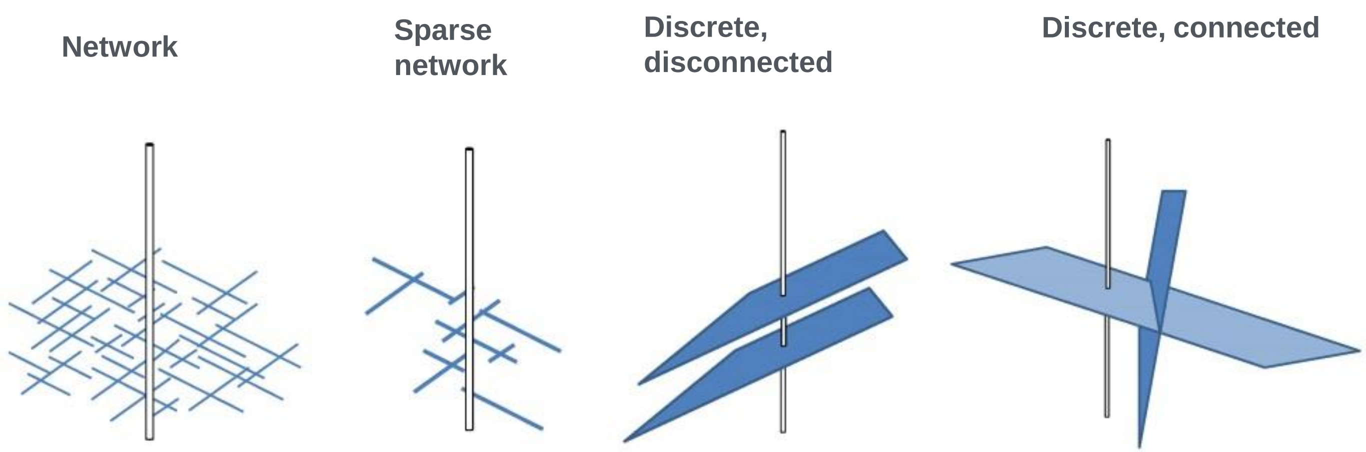
Fractures filled with CO_2 were imaged using active source seismic monitoring at the In Salah CO_2 storage project. Data show curvature attribute for a time-slice of 3D seismic data (LBNL).

This new technology will provide better characterization of

- Fracture spacing, aperture, connectivity, porosity, fracture-matrix flow, heat transfer potential

Scientific/Technical Approach

- In this project, we are modeling integrated CO_2 push-pull well tests with geophysical monitoring (active seismic and well logging) to characterize key fracture properties.
- The approach is joint inversion of modeled well-test and modeled geophysical monitoring data to estimate key properties of fractured geothermal reservoirs.



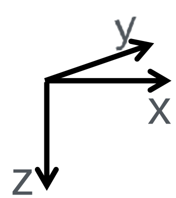
Scientific/Technical Approach

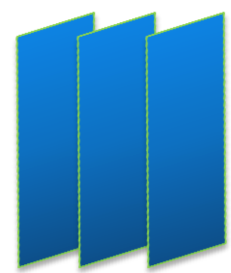
- Summary of project tasks:
  - Define relevant reservoir-fault characteristics
  - Carry out forward simulations of CO_2 injection and production
  - Design geophysical monitoring scenario
  - Carry out simulations of geophysical monitoring
  - Invert hydrologic and geophysical responses to push-pull with monitoring
  - Evaluate and assess results
  - Develop field validation plan

Accomplishments, Results and Progress

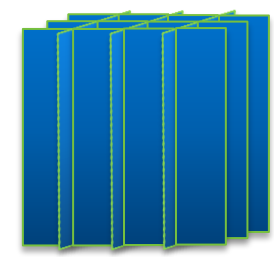
U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

- We defined possible fractures in a topological context. We are considering fracture sets of Topology X and XY primarily with varying degrees of connectivity to test and develop the push-pull CO_2 imaging and hydraulic testing approach.
- Many U.S. and European geothermal systems exhibit poorly connected vertical fracture sets (Topology X (= Y)).
  - Pyramid Lake
  - Gerlach
  - Buffalo Valley
  - Desert Peak
  - Soultz
  - Gross Schoenbach





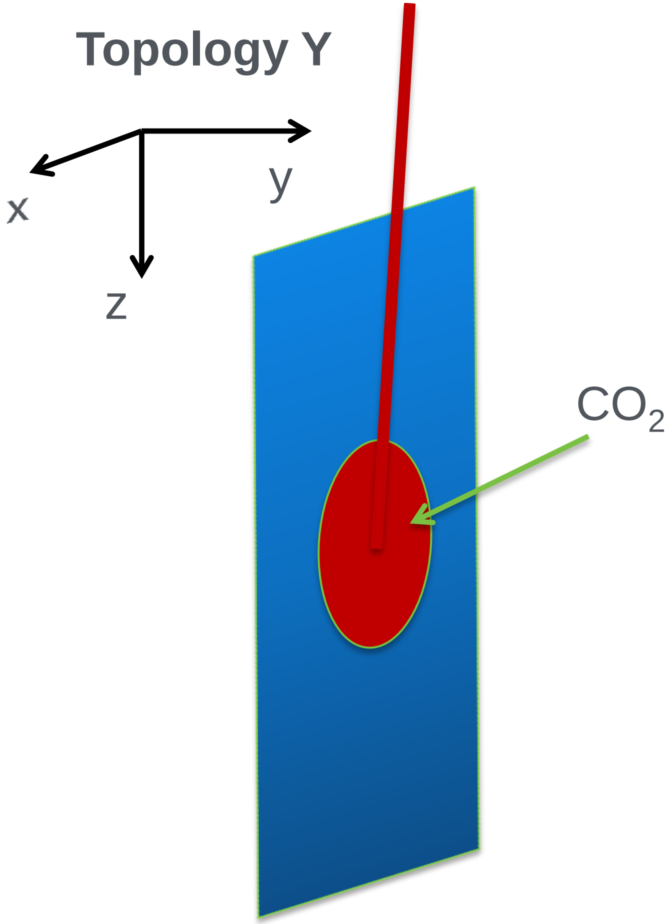
Topology X (= Y)



Topology XY

- We will simulate CO_2 injection and production and associated hydraulic response along with geophysical detection approaches to test the approach.

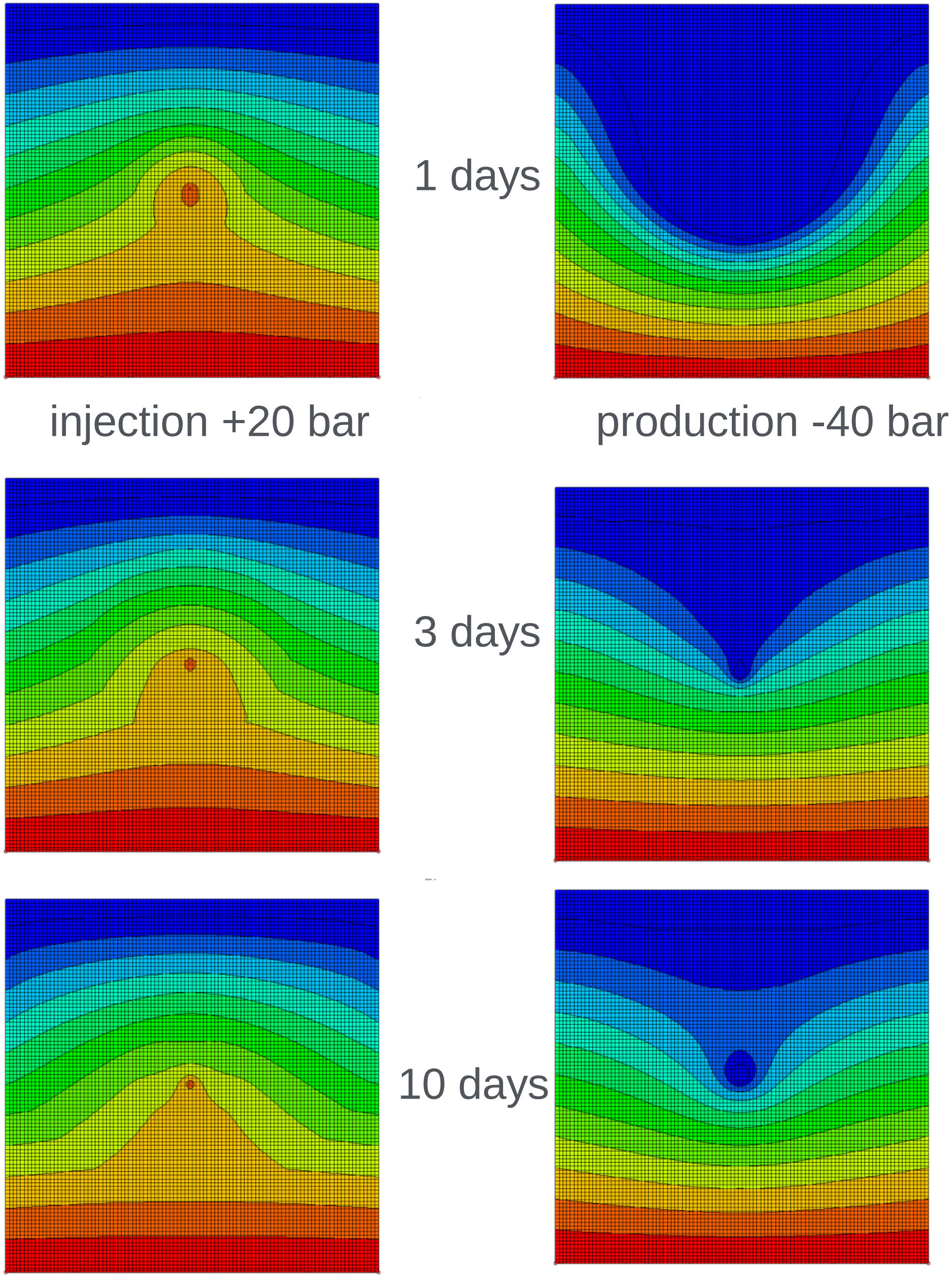
Preliminary Simulation Results



Fracture geometry
The geometry is a simple vertical fracture (topology ***y***), which has dimensions of:
x = 500 m, with 5 m cell side length;
y = 10^{-4} m, just 1 cell;
z = 500 m, with 5 m cell side length.
Gravity is parallel to z.

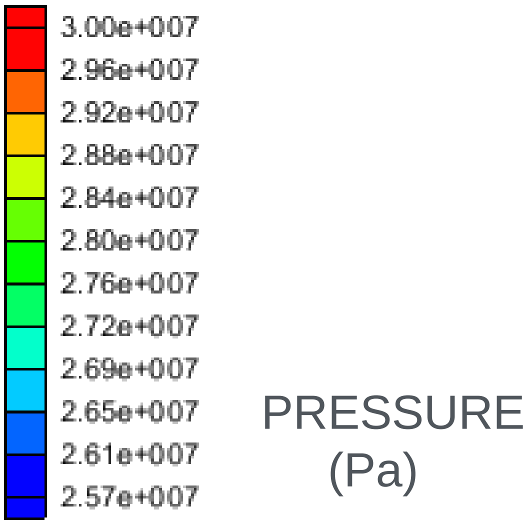
Fracture boundary conditions
To simulate a well-connected fracture, all four boundaries are constant P, T, x (conditions don’t change)

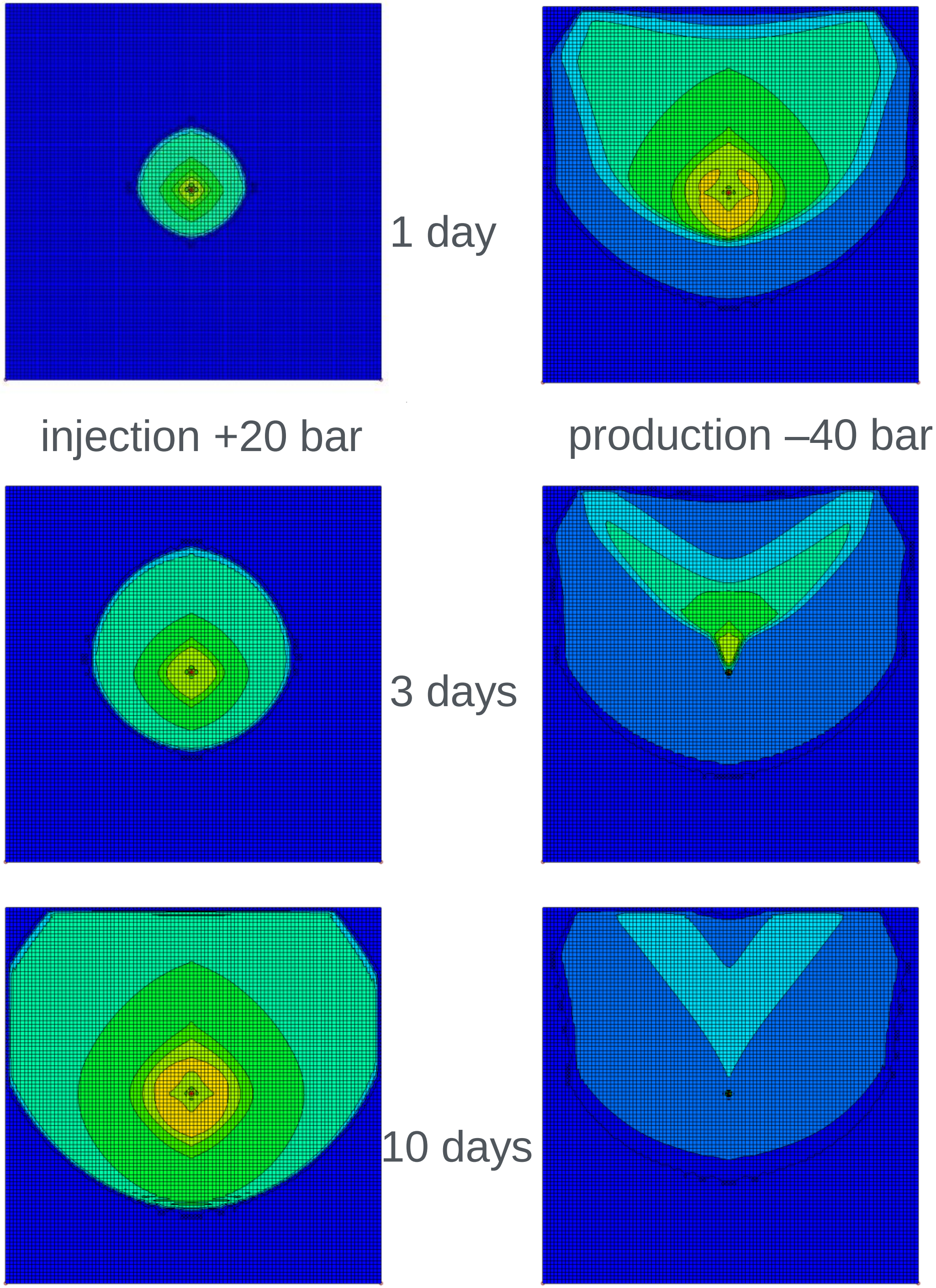
Fracture properties
Density = 2650 kg/m^3
Porosity = 0.20;
Two cases:
1) Permeability = 1.0 *10^{-12} m^2 in all directions;
2) Permeability = 1.0 *10^{-13} m^2 in all directions;
Formation heat conductivity = 2.1 W/(m ^oC);
Rock grain specific heat = 1.0 *10^3 J/(kg ^oC).



Exp. 3.2 → $k = 10^{-12}\ m^2$

Note the large pressure anomaly developing at the start of production, which decreases as the CO_2 flows back into the well.

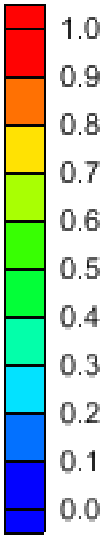




Exp. 3.2 → k = 10^{-12} m^2

Note that:

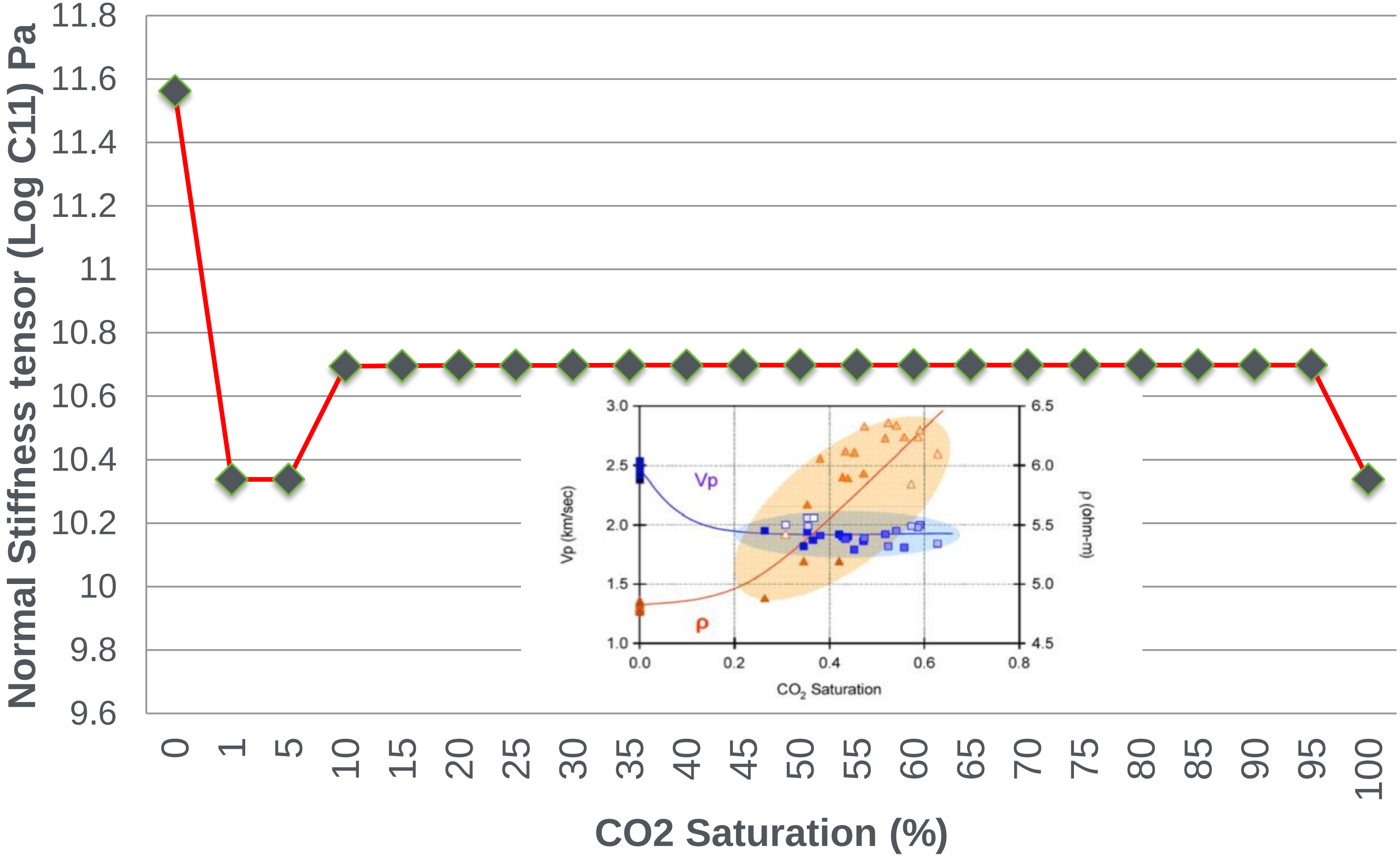
- Higher permeability leads to larger extent of plume.
- Buoyancy effects become particularly relevant during production.



$$
\begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{xz} \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \times \begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ 2\epsilon_{yz} \\ 2\epsilon_{xz} \\ 2\epsilon_{xy} \end{bmatrix}
$$

- Using simulated fracture, saturation, and CO_2 properties, we have calculated the stiffness component C11.
- C11 represents the stiffness of normal stress to normal strain, located at the top left of the stiffness tensor matrix (above).
- For our work on fracture stiffness, C11 represents the stiffness in the direction normal to the fracture plane.
- Because the fluid influence on the shear modulus can be neglected, the normal stiffness is especially important for seismic detection of the fluid effect.

C11 vs. CO_2 Saturation
(C11 = Effective Normal Stiffness)



Accomplishments, Results and Progress

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
M1.2 Ppt summarizing end-member fracture characteristics	Same	Jan. 4, 2015
M2.1 Ppt summarizing simulations of CO2 well tests in fracture	Same	Mar. 13, 2015

- Expected outcome is demonstration by modeling of the coupled push-pull hydrologic and geophysical monitoring approach to characterize fractures.
- A field validation plan will be developed as the last task.

Future Directions

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Milestone or Go/No-Go	Status & Expected Completion Date
G2.3 Show through simple model that typical CO2 saturations in fractures can be imaged by seismic and/or well logging approaches.	In progress. Preliminary calculation of C11 shows strong sensitivity to CO_2 saturation. Expected completion September 2015.
M3.1 Ppt summarizing design of geophysical monitoring scenario	March 2016
M3.3 Ppt summarizing design of well-logging scenario	March 2016
M4 Ppt summarizing simulation of well logging	June 2016
G4 Demonstrate ability to simulate seismic imaging of CO2 in a fractured reservoir	September 2016
M5.2 Ppt summarizing inversion of virtual geophysical data	December 2016
G5 Demonstrate ability to jointly invert well-test, geophysical, and well logging data to estimate fracture locations and properties	March 2017
M6 Written final report	June 2017
M7 Written plan prospectus for potential field deployment	September 2017

Mandatory Summary Slide

- CO_2 injected for push-pull well testing has a strong preference for flowing in fractures.
- Seismic wave speed, electrical resistivity, and well logging are sensitive to CO_2 saturation.
- This project examines integrated use of CO_2 push-pull well tests with geophysical monitoring to characterize key fracture properties.
- The approach is joint inversion of modeled well-test and modeled geophysical monitoring data to estimate key properties of fractured geothermal reservoirs.
- We are making steady progress toward project goals.