Systems Modeling & Science for Geologic Sequestration

Project Number: LANL FE10-003 Task 3

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U.S. Department of Energy

National Energy Technology Laboratory

Carbon Storage R&D Project Review Meeting

Transforming Technology through Integration and Collaboration

August 18-20, 2015

Contributors

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Presentation Outline

- Benefit to the program
- Project overview
- Project technical status
- Accomplishments to date
- Future Plans
- Appendix

Benefit to the program

- Program goals being addressed:
  - Develop and validate technologies to ensure 99 percent storage permanence.
  - Develop technologies to improve reservoir storage efficiency while ensuring containment effectiveness.
- Project benefit:
  - The project is also developing science basis that can be used to assess impacts of CO_2 leakage in shallow aquifers and to characterize leakage through faults. This technology contributes to the Carbon Storage Program's effort of ensuring 99 percent CO_2 storage permanence in the injection zone(s).

Project Overview: Tasks

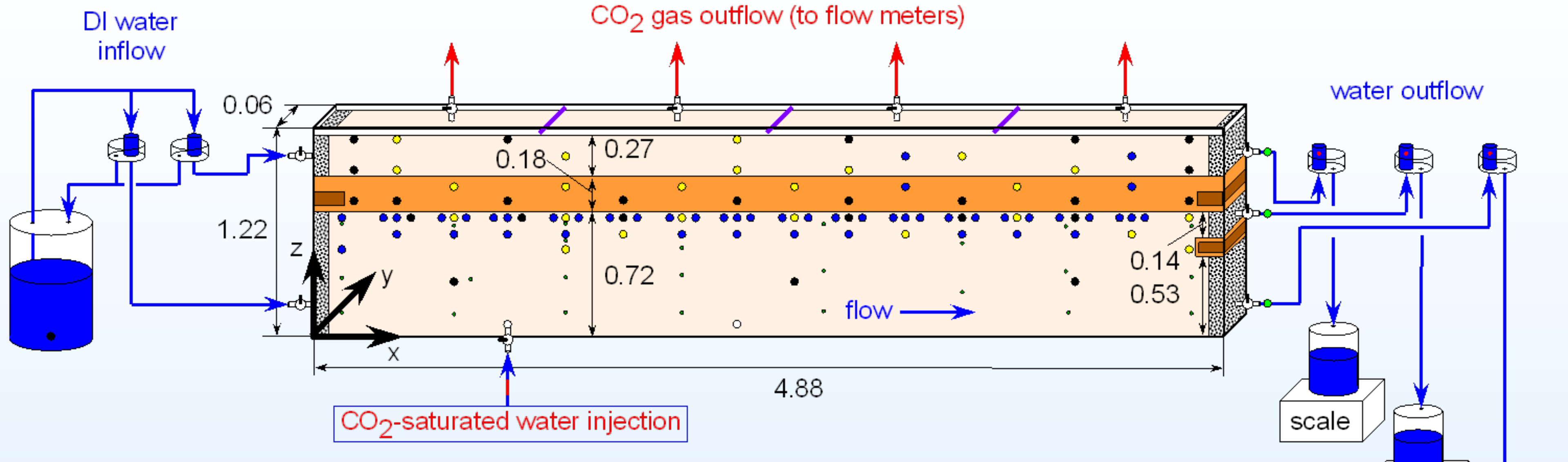
1. Characterize multi-phase CO_2 flow in groundwater aquifers through an integrated experimental-simulation approach
2. Characterize multi-phase CO_2-brine flow through faults
3. Develop and apply system modeling capabilities applicable to CCS storage operations:
   - Develop capabilities that can be used to evaluate water production and treatment for beneficial reuse: Completed
   - Develop system modeling capabilities for assessment of feasibility of long-term CO_2 storage at CO_2-EOR sites: Not discussed here

Characterization of CO_2-water multi-phase flow

Goals & Objectives

- Understand the process of gas exsolution, gas phase expansion and CO_2 migration to characterize the impacts of CO_2 & CO_2-dissolved water leakage in groundwater aquifer as well as to deploy efficient monitoring/mitigation approaches
  - What factors affect the spatiotemporal evolution of CO_2 migration
  - What role does heterogeneity play
  - Data to develop theory
- Integrated approach: intermediate scale experiments (1D column, 2D tank) coupled with numerical simulations

2-D Tank Experimental Setup

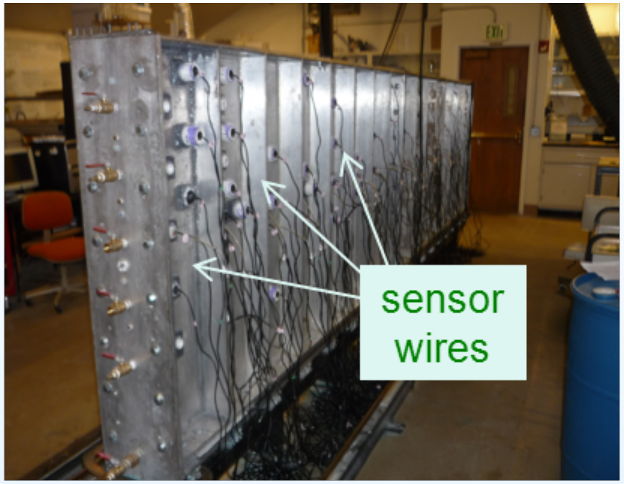


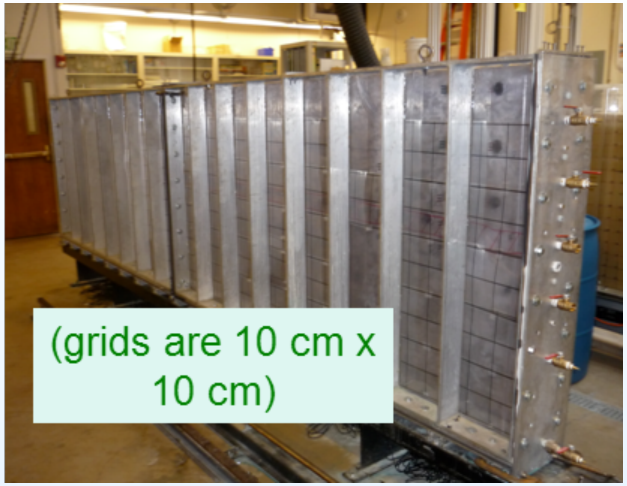
INSTRUMENTATION
- saturation sensor (EC-5)
- saturation & temperature sensor (EC-TM)
- saturation, EC, & temperature sensor (5TE)
- sampling port (for measuring dissolved CO_2)
- water temperature (EC-T) sensor port
- external dissolved CO_2 (InPro 5000i) and air temperature (EC-T) measurement port

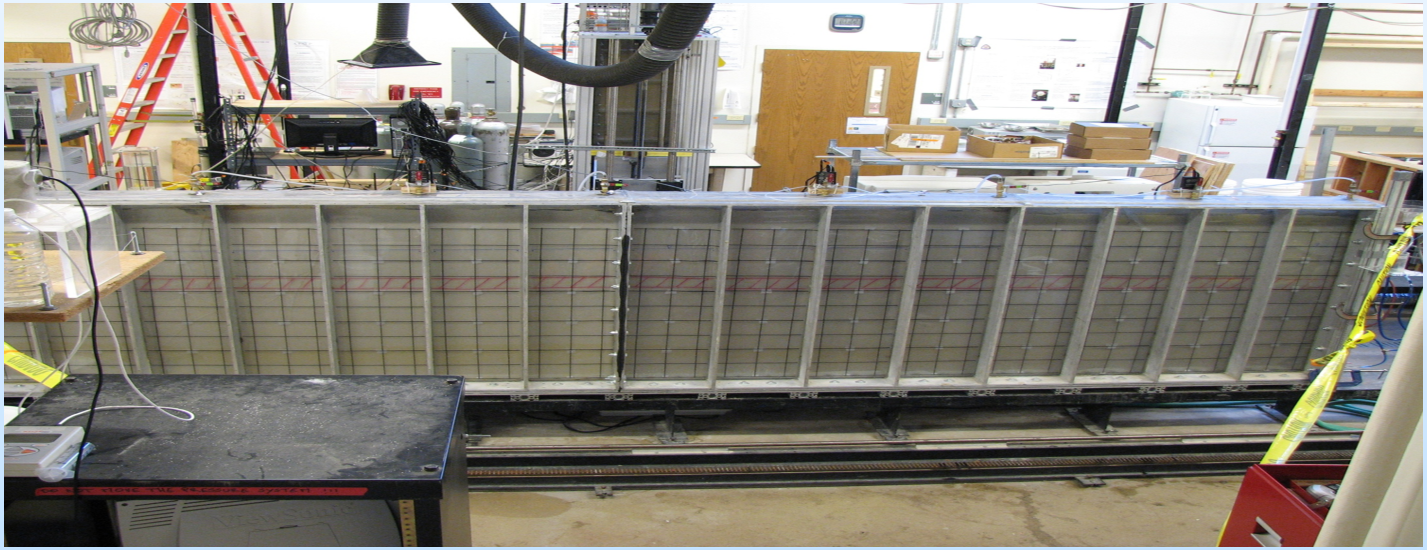
MATERIALS
- plastic baffle
- injection well
- coarse sand (Granusil #20/30)
- fine sand (Granusil #110 & 250)
- clay
- gravel boundary (Granusil #8)
- headspace (air and/or CO_2 gas)

- Measurements taken from sensors, flow meters and scales every minute
- Aqueous phase samples taken at various intervals and analyzed for dissolved CO_2 with an Ion Chromatograph

Experimental Setup

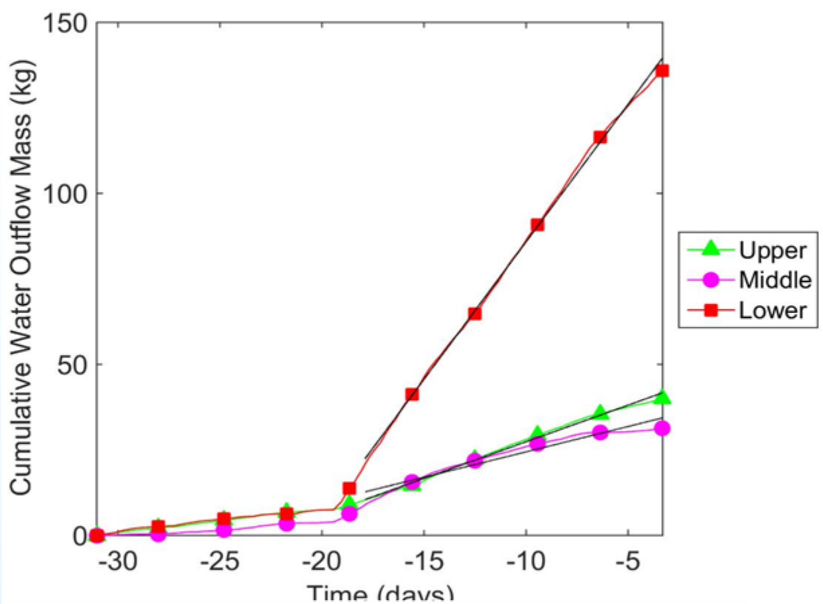


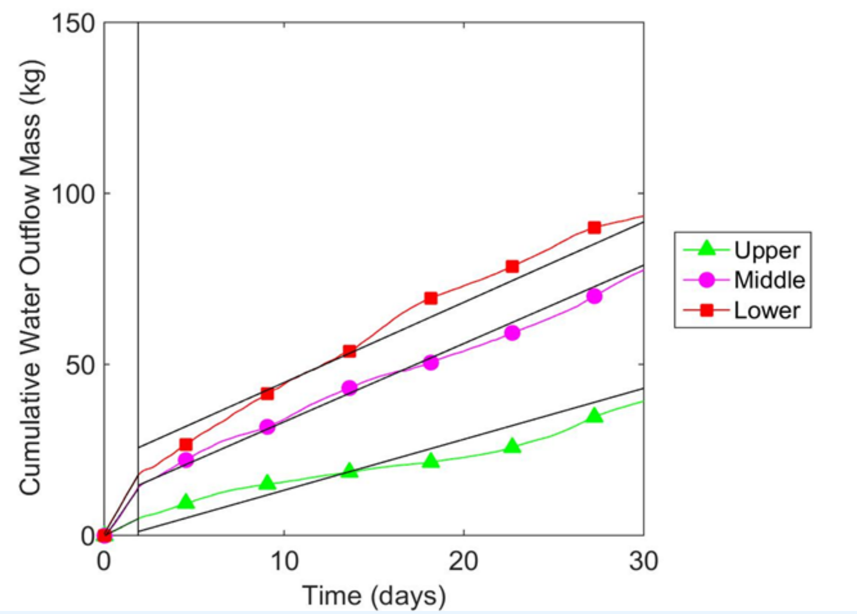


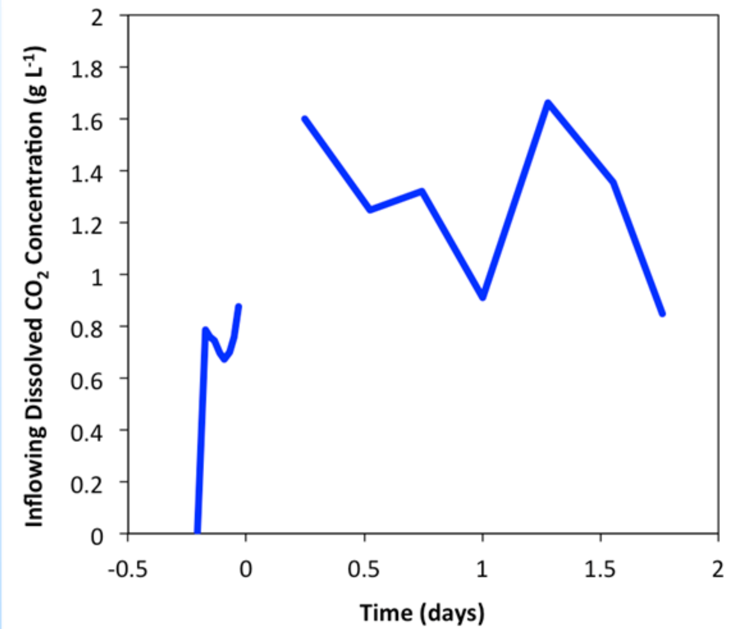


~ 2.5 months to pack and configure the tank

Experimental Conditions

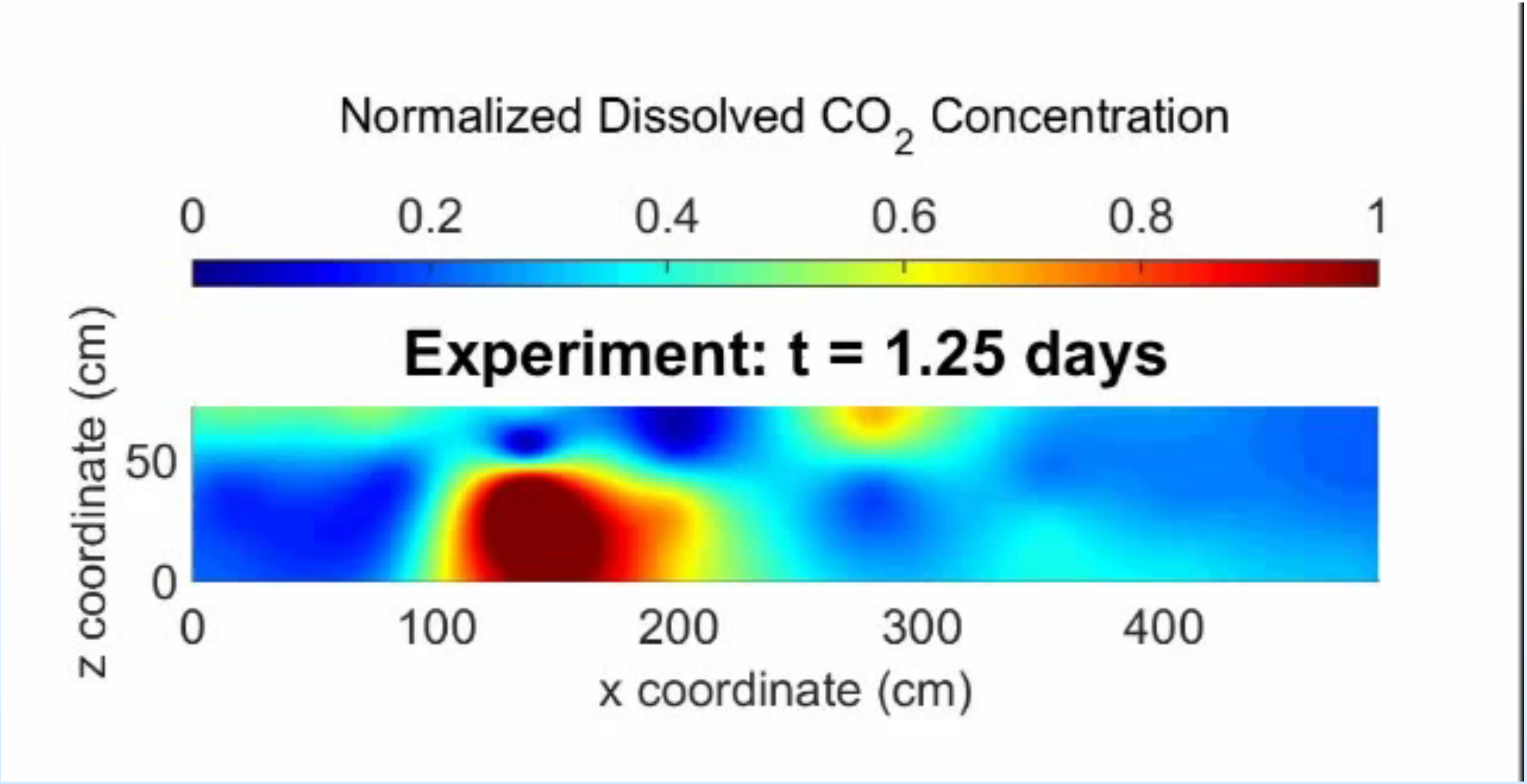






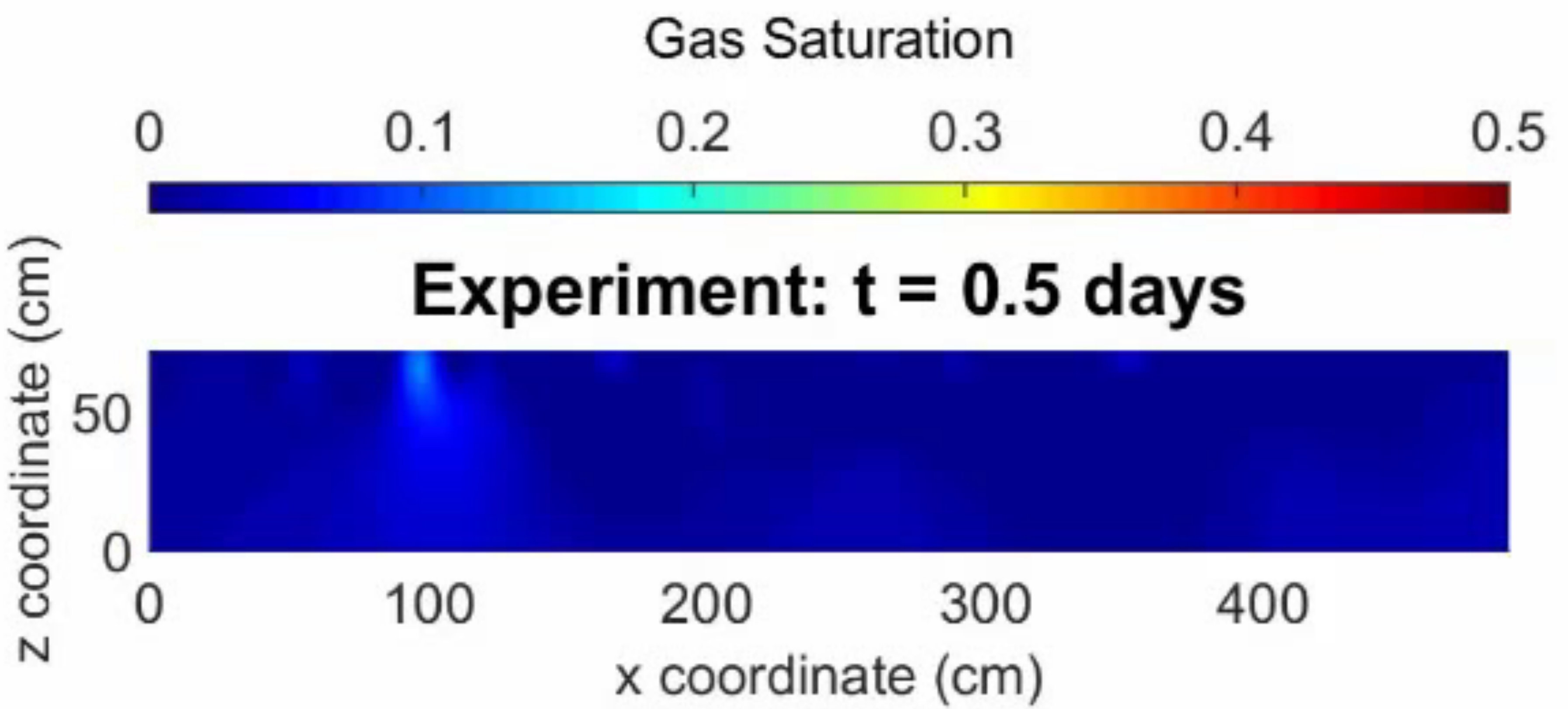
- CO_2-dissolved water injected for 2 days
- Continued observations for >30 days

Observed Dissolved CO_2 Migration



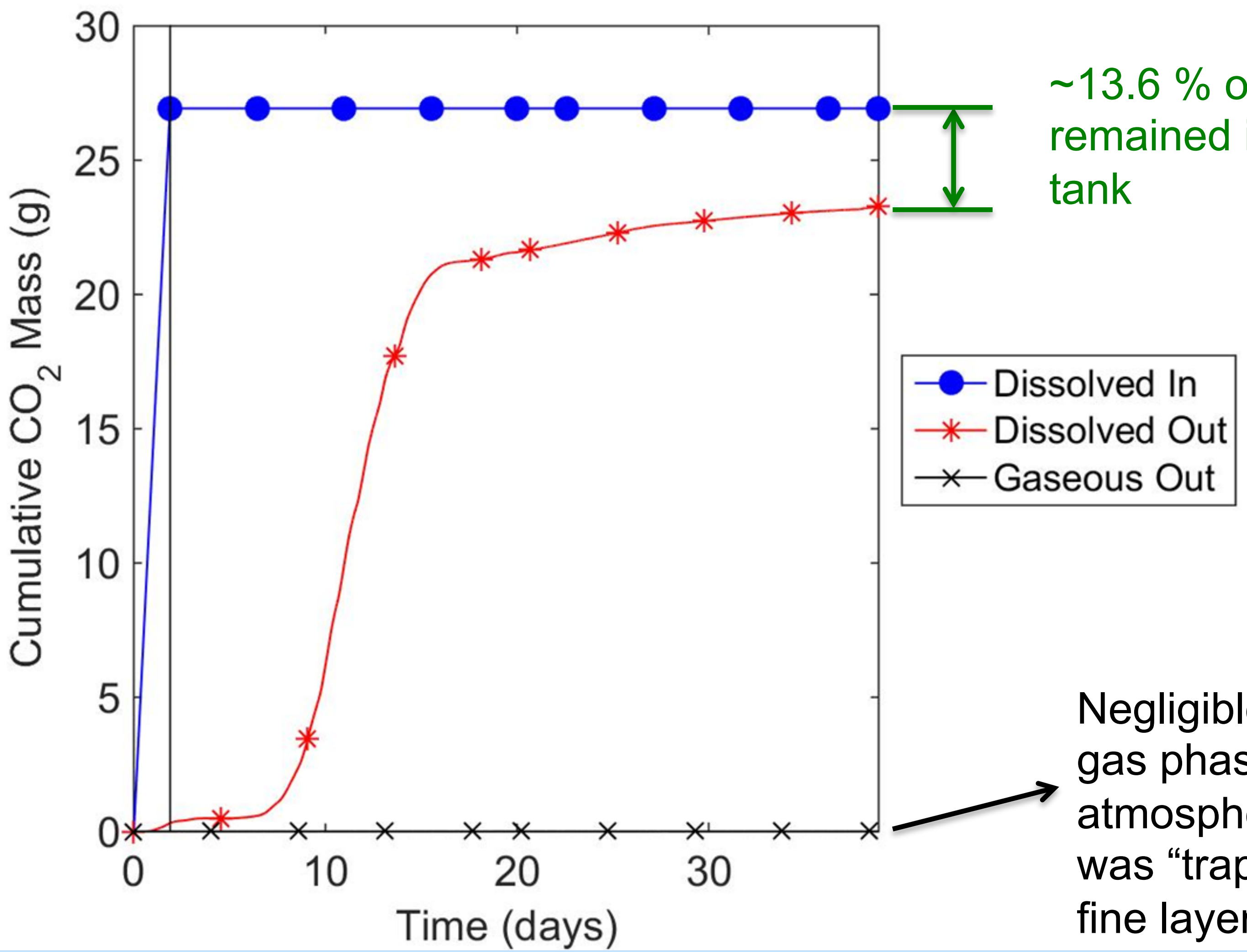
only the “lower aquifer” (region below fine sand layer) is shown

Observed Gaseous CO_2 Evolution



only the "lower aquifer" (region below fine sand layer) is shown

Macroscopic CO_2 Mass Balance



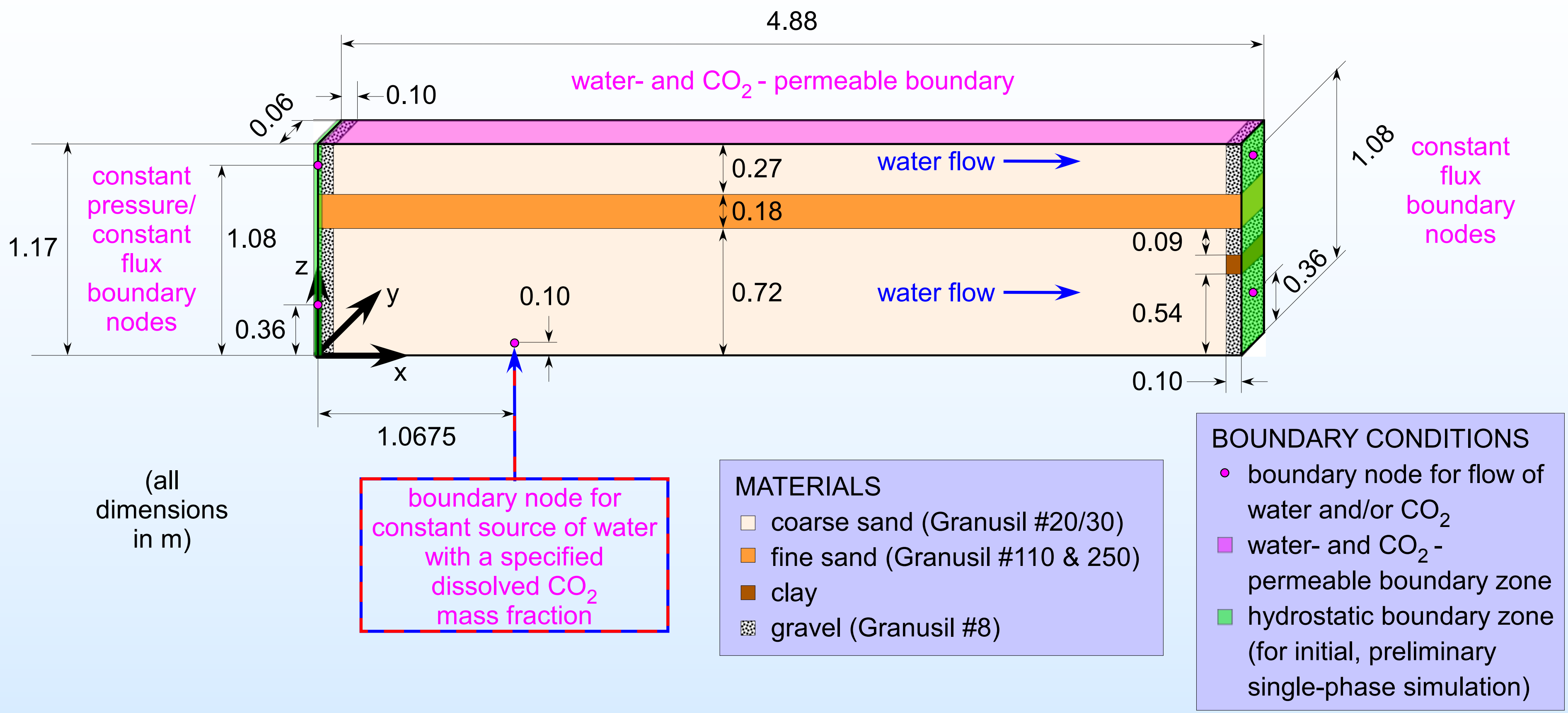
~13.6 % of injected CO_2 remained inside the tank

Negligible release of gas phase CO_2 to the atmosphere (gas phase was "trapped" under the fine layer)

Key Findings

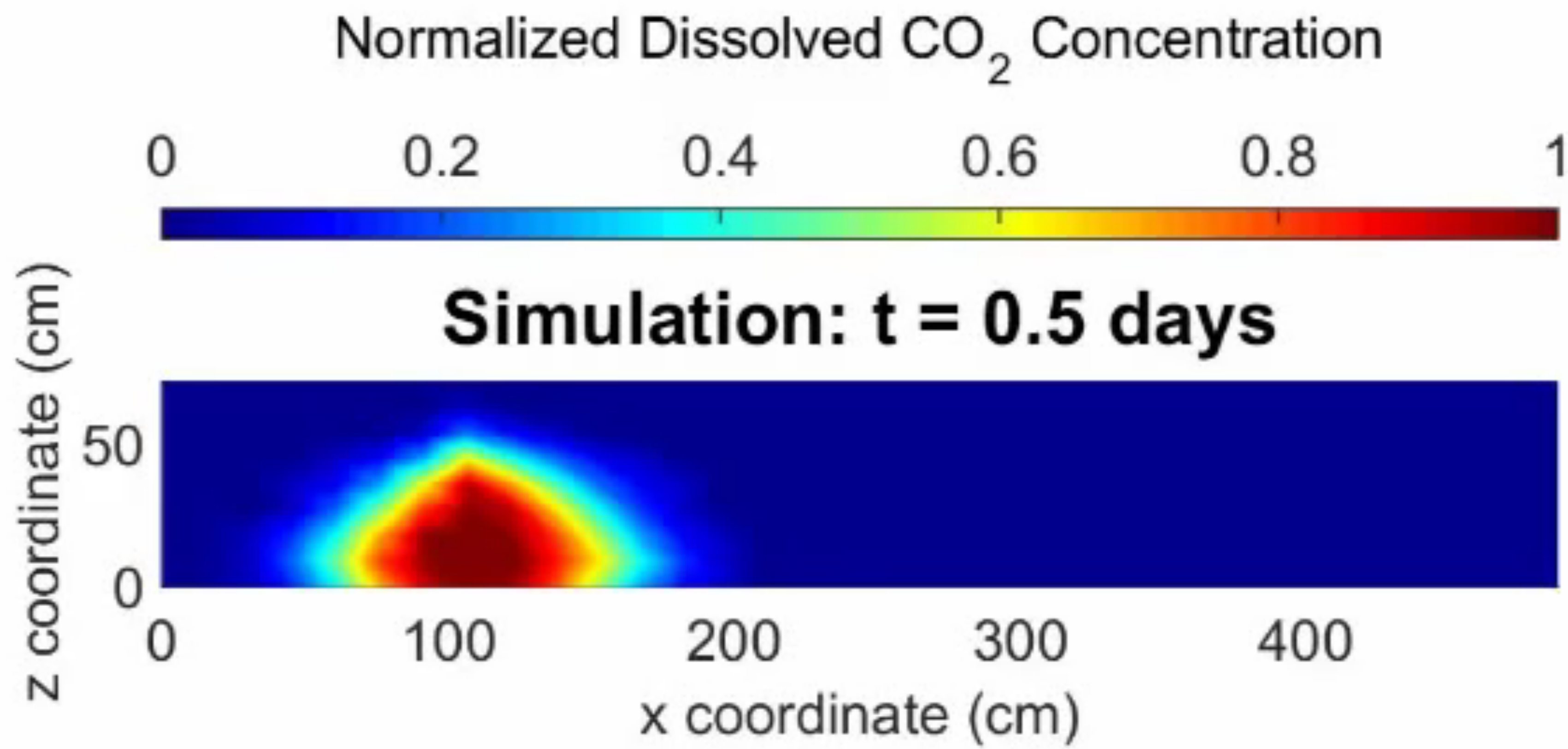
- Permeability contrast (heterogeneity) affects CO_2 gas phase migration:
  - Under the conditions of buoyancy-dominated flow even lower permeability sands can help prevent upward migration of gaseous CO_2
- Background flow affects the existence of free-phase CO_2:
  - Higher fraction of CO_2 in dissolved-form
- Dissolved CO_2 plume primarily remains at the bottom
- CO_2 remains in the water (primarily dissolved) well after leakage stops
- Important implications on monitoring and mitigation

Numerical Model Setup: FEHM



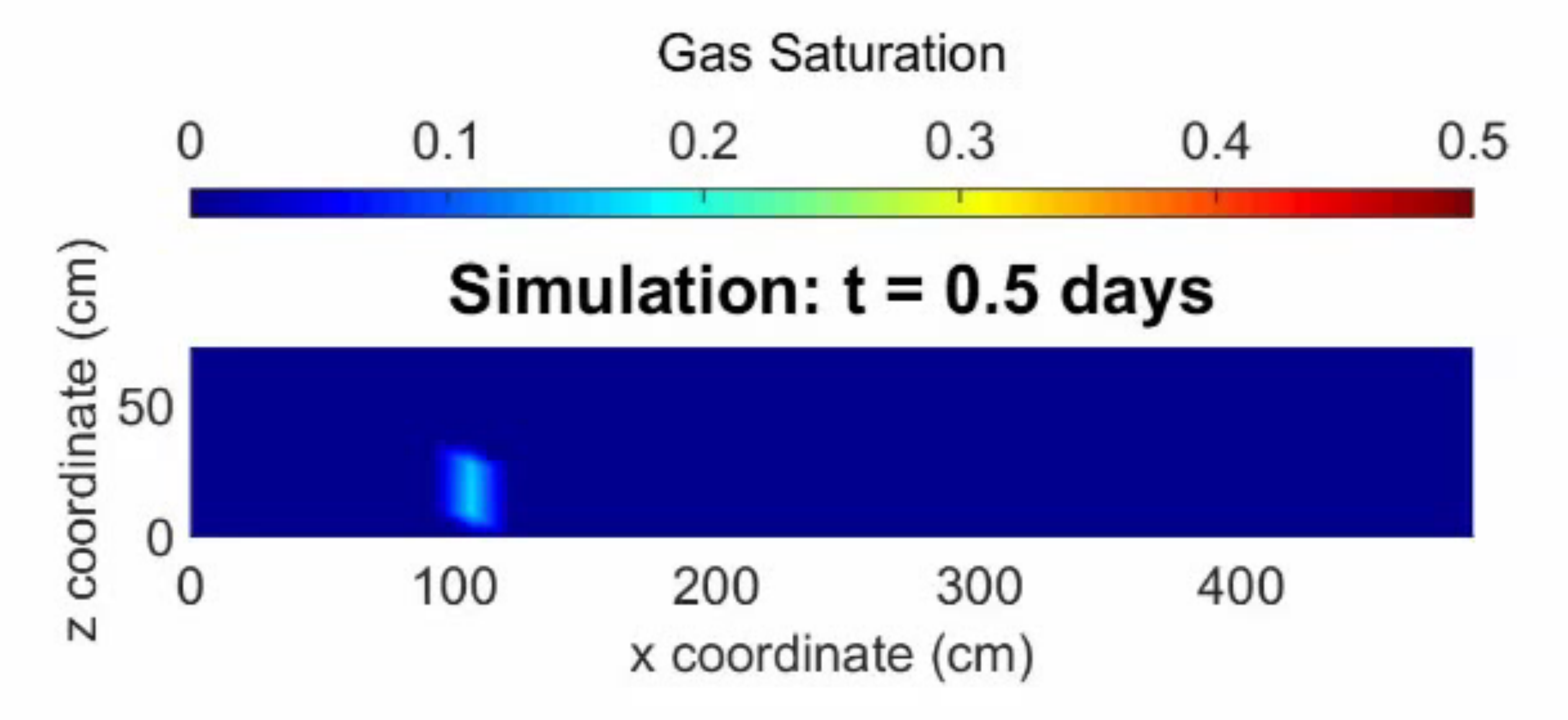
- **Flow rates** were taken from linear regressions of experimental cumulative water ouflow curves

Simulation Results: Dissolved CO_2 Migration



only the "lower aquifer" (region below fine sand layer) is shown

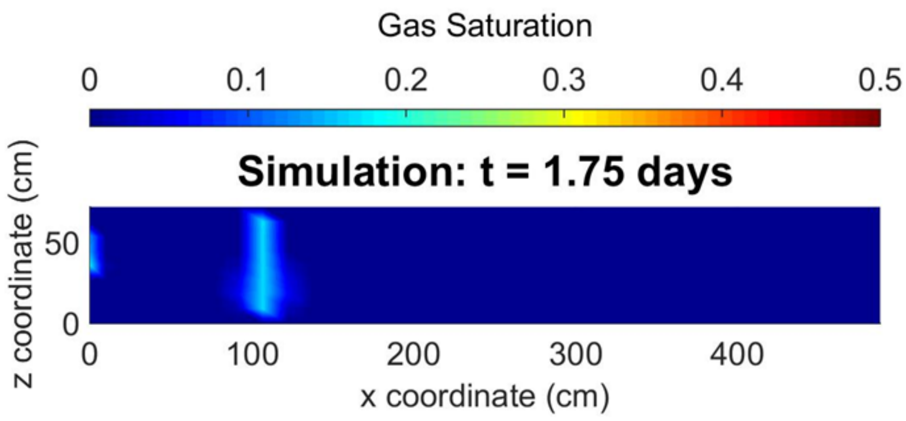
Simulation Results: Gaseous CO_2 Evolution



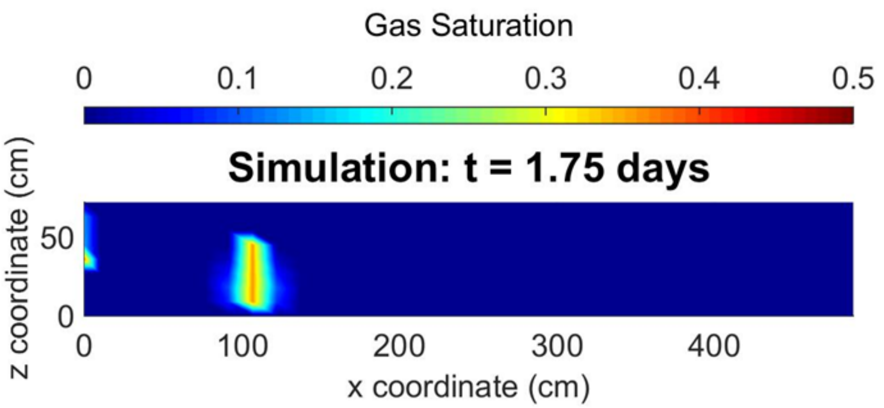
only the "lower aquifer" (region below fine sand layer) is shown

Numerical Model Sensitivity Analysis

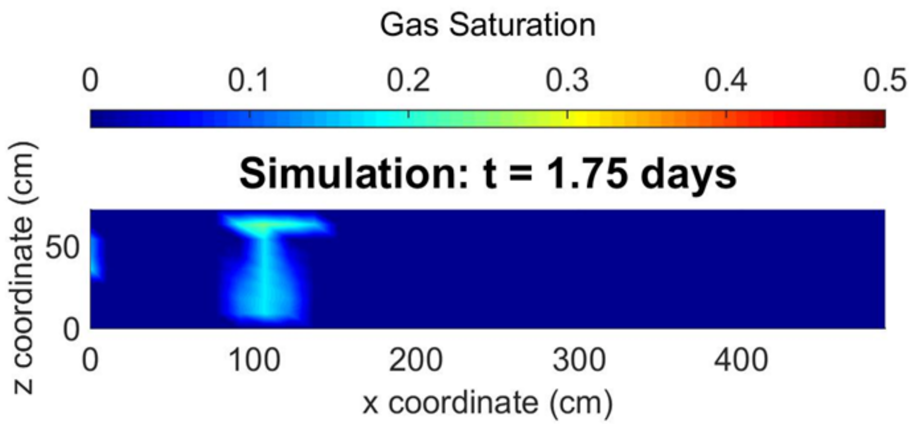
Lower air entry pressure



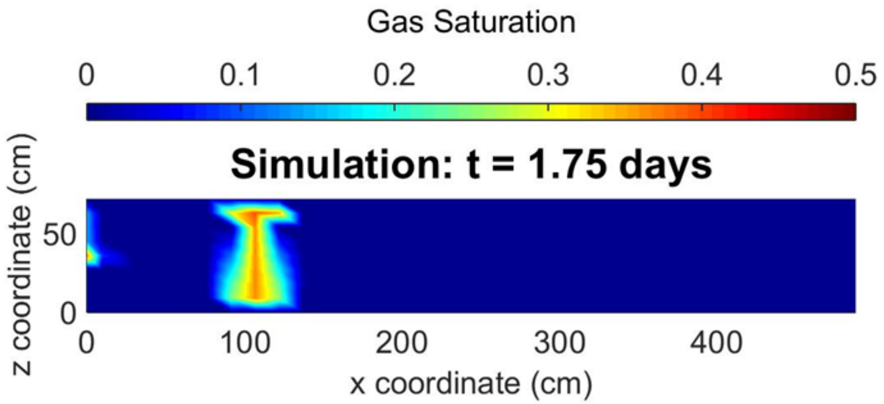
Higher residual gas saturation



Higher saturation pressure

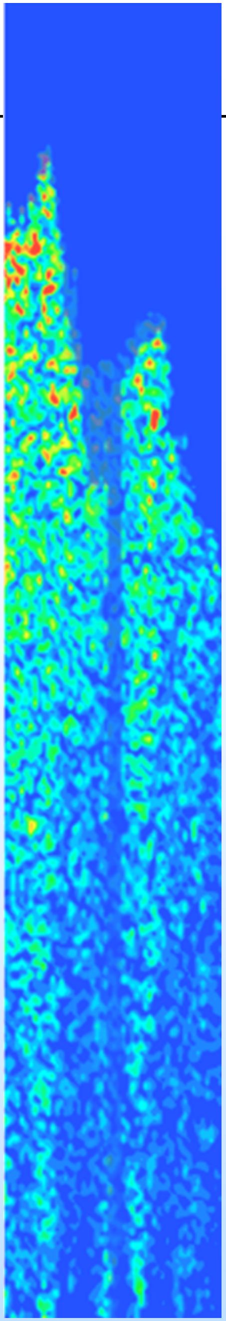


All three parameters adjusted



Each image shows the gas phase near the end of the CO_2-water injection period

Characterization of multi-phase CO_2-brine flow along faults

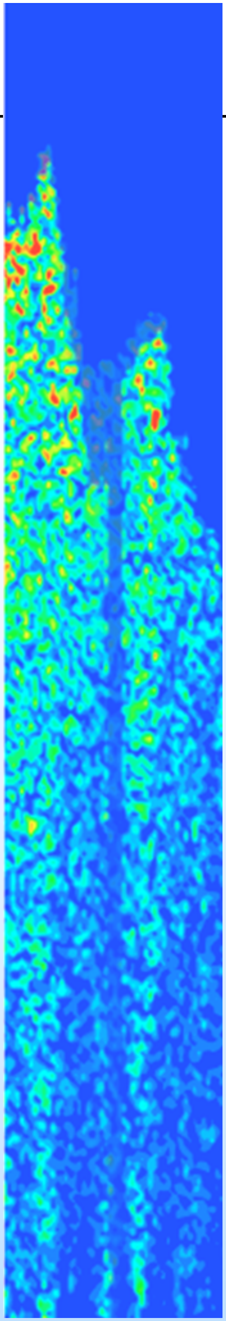


Objectives

- Activation/rupture of faults and subsequent leakage of CO_2 is one of the concerns related to containment (Zoback & Gorelick, 2012)

- Using numerical simulations our objective is to answer:
  - Can the rupture be detected with pressure monitoring in the reservoir?
  - How much CO_2 might leak upward through the ruptured fault before detection?
  - How does the process of CO_2/brine flow through the complex fault geology evolve?

Approach

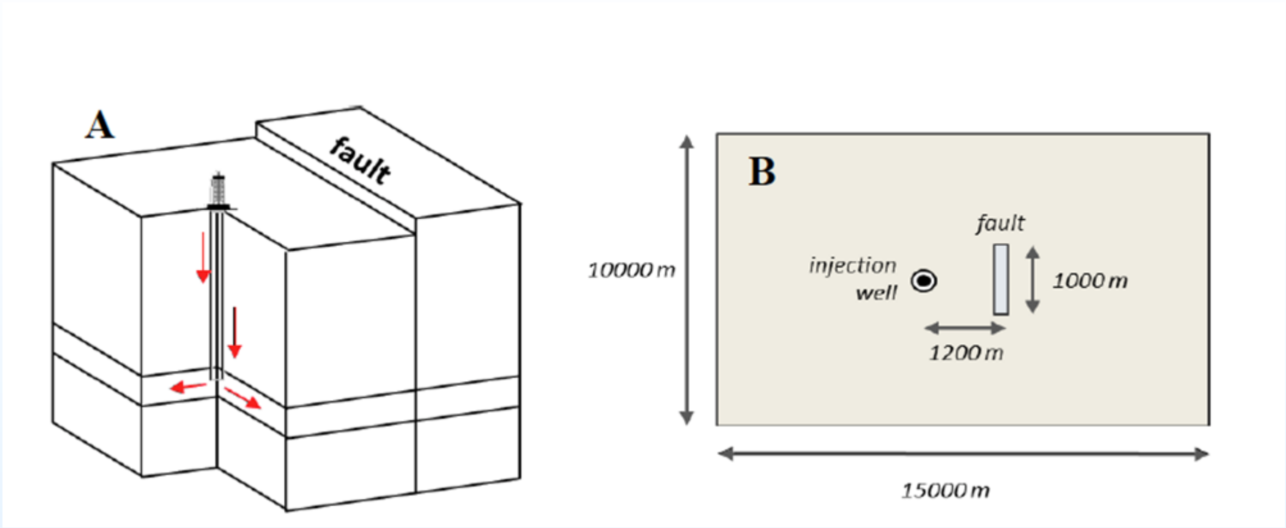


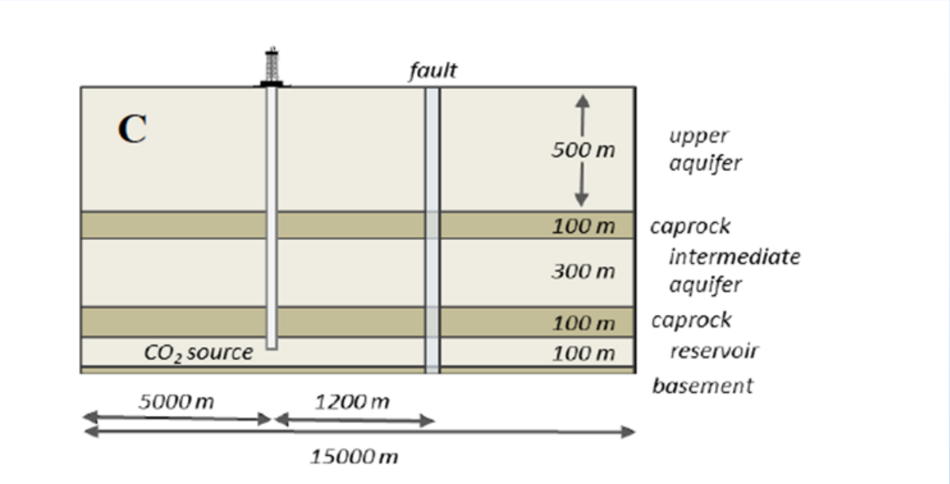
Numerical simulations using FEHM:

1. Reservoir-scale simulations of CO_2/brine migration along faults post-rupture due to overpressurization
   - Scenario: activation of a critically stressed “unknown” fault
   - Fault rupture process not explicitly modeled
   - Permeability of fault increased in over-pressure exceeded “critical” threshold
   - Monte-Carlo simulations varying a range of parameters

2. Fault-scale simulations of reactive transport of CO_2 in heterogeneous fault zones
   - Explicitly simulate heterogeneous damage zone, fault core
   - Determine impact of self-sealing driven by depressurization, degassing, and calcite precipitation

Conceptual Model for Fault Rupture Simulations





Details in Keating, E.H., Dai, Z., Dempsey, D. Pawar, R. 2014. Effective detection of CO_2 leakage: a comparison of groundwater sampling and pressure monitoring, Energy Procedia, 63, 4163-4171.

Monte-Carlo Simulations

Variable	Min	Max	Unit
Distance from injector to fault	1000	5000	m
Fault width	1	50	m
Reservoir permeability	-15	-12	Log (m2)
Overpressure at injection well	2	15	MPa
Critical overpressure for fault rupture	0.5	10	MPa

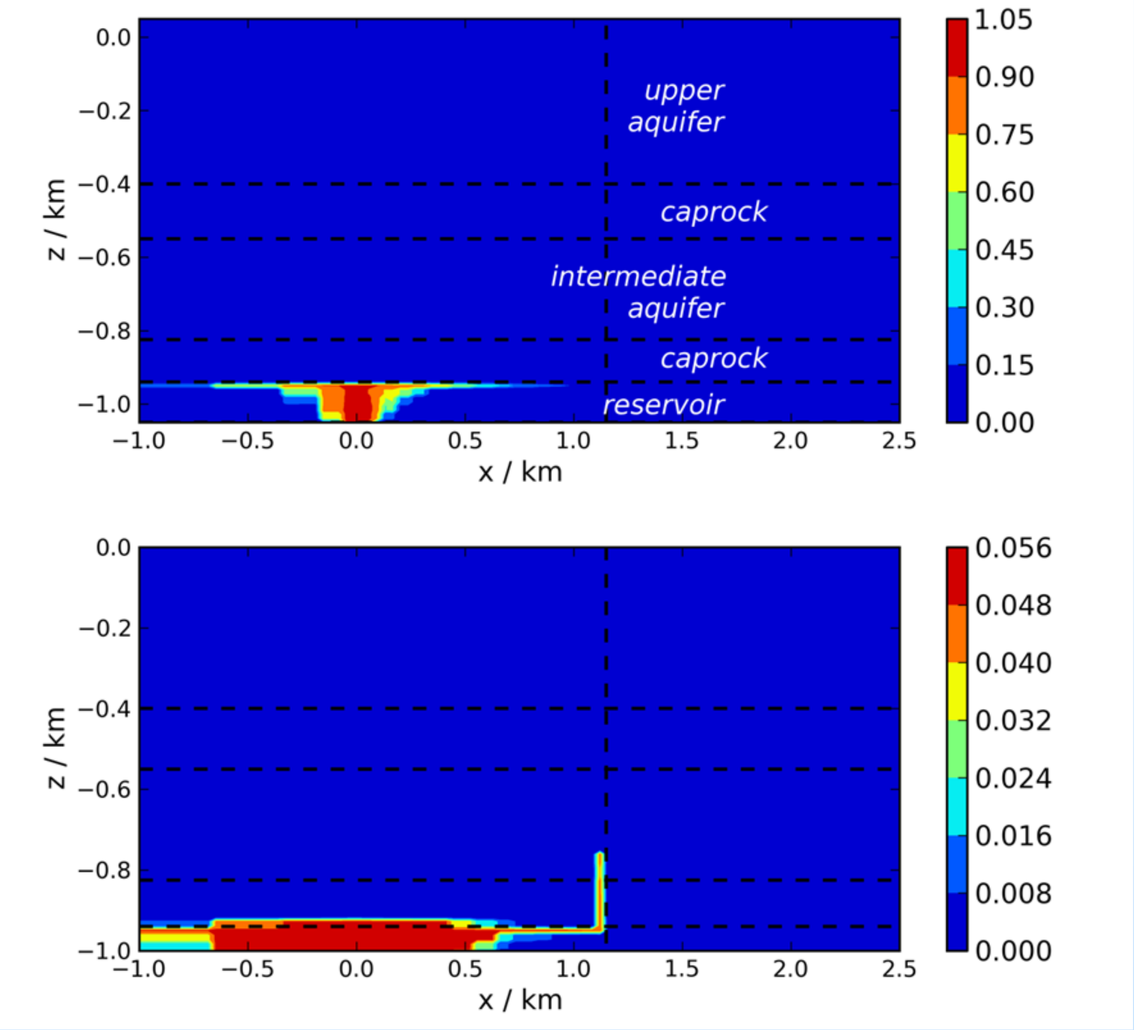
Wide range of scenarios: ~ 200 Simulations Runs

Example Simulation Result

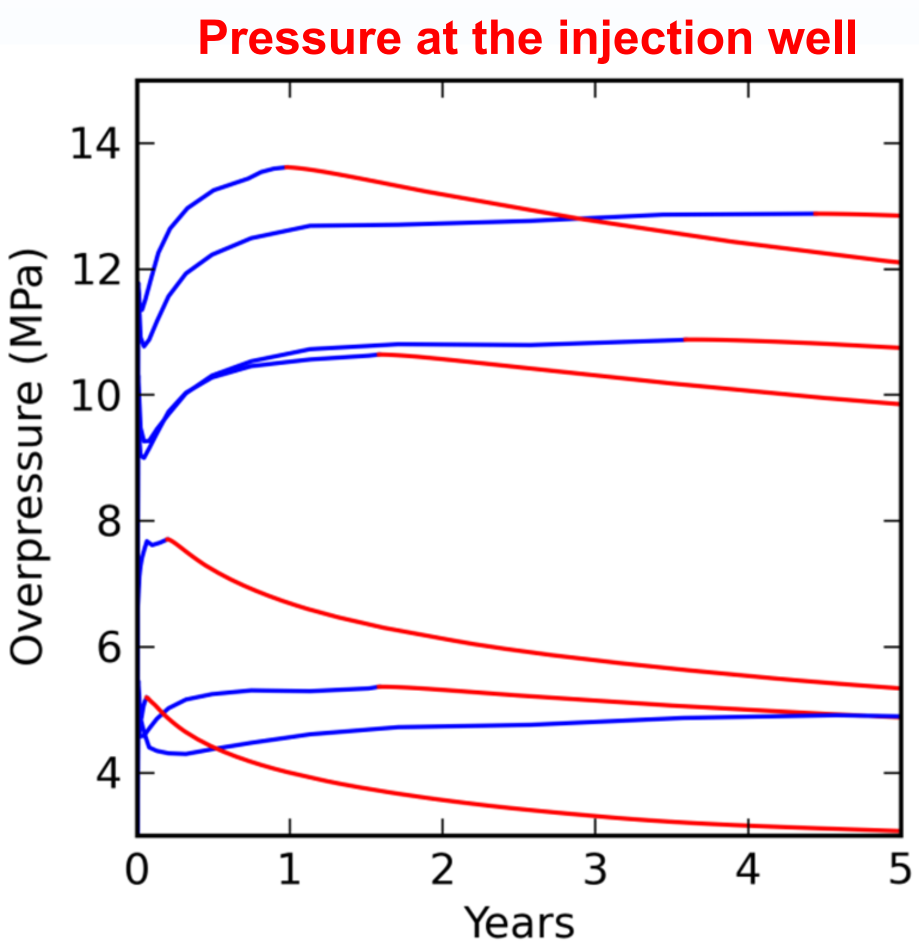
~ 3 years after rupture.

Free-phase CO_2 plume migration

Dissolved CO_2 plume migration



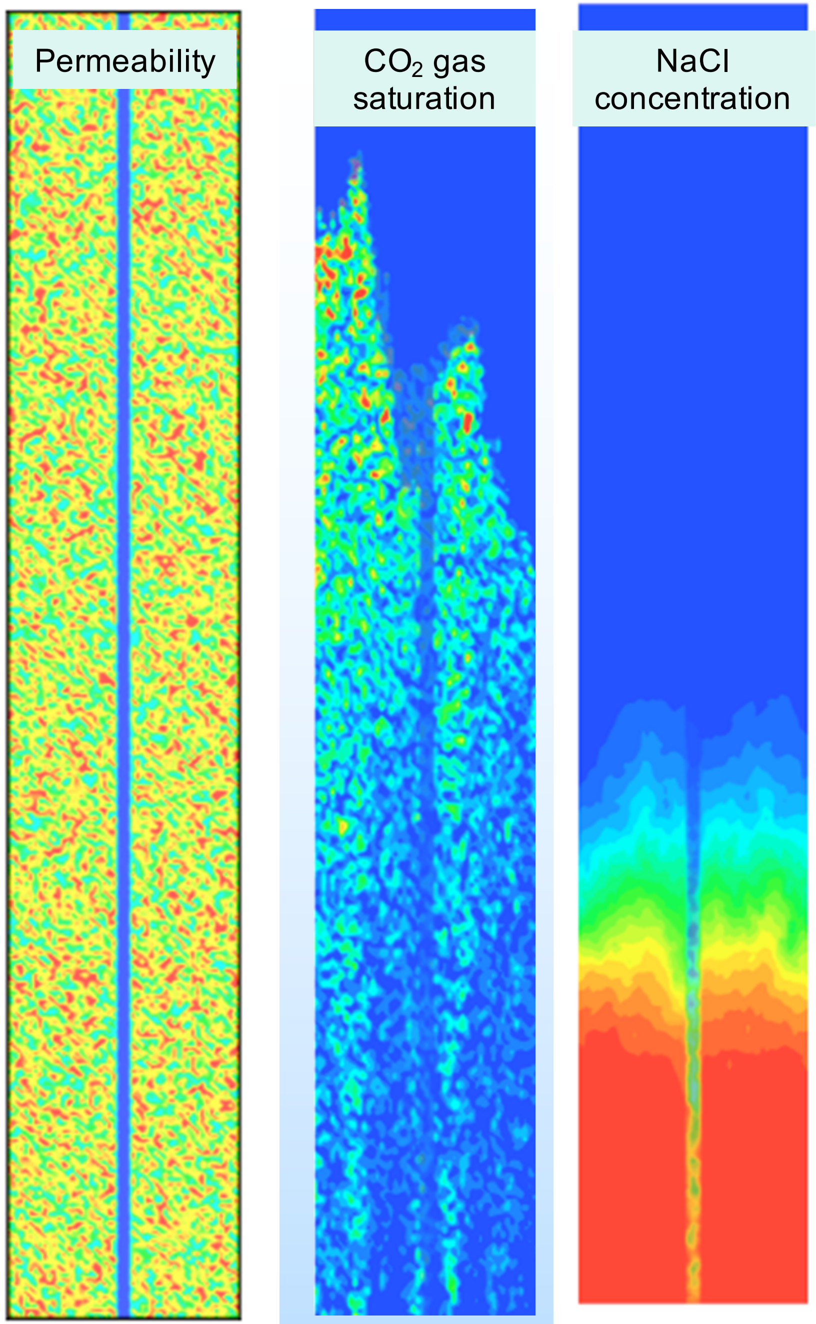
Key Findings



---- pre-rupture
---- post-rupture

- In the large majority of cases, fault rupture is readily detectible by rapid pressure drop at the injection well.
  - In 98% cases pressure at injection well decreased by > 300 KPa.
- There are significant delays between rupture and CO_2 plume breakthrough at base of fault. In most cases, free-phase CO_2 plume had not reached base of fault 5 years post-rupture.

Numerical studies of CO_2 and brine leakage along faults



Fault-scale simulations of reactive transport of CO_2 in heterogeneous fault zones

- Capture effect of complexity in fault geology: core, damage zone
- Coupled processes: multi-phase flow, phase change, CO_2/brine dissolution/precipitation, density change

Preliminary results:

- Heterogeneity within the fault zone affects gas phase evolution and migration
- “Self-sealing” caused by degassing and calcite precipitation is unlikely to reduce permeability/porosity significantly on relevant time scales

Accomplishments to Date

- Developed system model for produced water treatment (CO_2-PENS WTM): Available for public use
- Completed 1-D column experiments as well as related simulations and 1 set of 2-D tank experiments on post CO_2 leakage multi-phase flow in groundwater aquifer
- Developed ROM for CO_2 storage capacity estimation during EOR operations
- Completed study on applicability of pressure monitoring for fault rupture detection
- Initiated study on characterization of coupled processes during CO_2 & brine leakage along fault capturing fault geologic complexity
- 7 Peer-reviewed journal publications, 1 journal article in press, 2 journal articles under preparation (to be submitted to IJGGC)
- Multiple presentations at international meetings: 2015 InterPORE, 2014 Fall AGU (2), GHGT12 (4), 2014 IEAGHG Joint Network Meeting, 2014 CCSU meeting (4), 2013 Fall AGU (3).

Synergy Opportunities

- Collaboration on groundwater leakage characterization and impacts: NETL
- Collaboration on development of reduced order models for estimating storage capacity during CO_2-EOR operations: EERC, Battelle, Princeton, U. Wyoming

Key Findings, Future Plans

- Significant results with practical implications:
  - Groundwater leakage impacts, fault rupture monitoring
- Extensive experimental data on CO_2-brine leakage in 1-D columns: available for model development and testing

Future Plans:

- Complete 2-D tank experiments with increased complexity (heterogeneous sand packing) and associated numerical simulations:
  - Data sets and parametric analysis on effect of groundwater hydrologic parameters on CO_2 migration and implications on monitoring/mitigation
- Complete fault flow characterization study to include fault complexities
  - Development of relationships to calculate effective CO_2 leakage rates along faults incorporating fault complexities
- Complete development of reduced order models to calculate CO_2 storage capacity during EOR operations

Appendix

Organizational Chart

- PI: Rajesh Pawar
- Program Manager: George Guthrie
- Team Members:
  - Jeri Sullivan: Water treatment system modeling
  - Shaoping Chu: Water treatment system modeling
  - Prof. Tissa Illangasekare (Colorado School of Mines): CO_2 release experimental characterization
  - Michael Plampin (Colorado School of Mines): CO_2 release experimental characterization
  - Mike Porter: Numerical simulation of CO_2 release experiments
  - Elizabeth Keating: Fault flow characterization
  - Zhenxue Dai: ROM for CO_2 storage capacity in EOR

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