A PROBABILISTIC ASSESSMENT OF THE GEOMECHANICAL RESPONSE TO CO_2 INJECTIONS IN LARGE IGNEOUS PROVINCES

DE-FE0023381

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Presentation Outline

- Benefit to Program
- Project Overview
- Technical Status
- Accomplishments
- Synergy Discussion

Benefit to Program

- Geomechanical Research

  Applied to ***Wallula Basalt Sequestration Pilot Project***

  – Goal: Improve understanding of reservoir geomechanics

  – Goal: 99% storage permanence

    - Approach: Monte Carlo numerical simulation to assess the probability of tensile, shear, and breakdown failure within reservoir rock and overlying formations at Wallula site.

  – Goal: Improve accuracy of existing models to understand impacts of increasing P_f on reservoir permeability

    - Approach: Core-flood experiments to determine multi-phase fluid properties of variably saturated CRBG rock & measure stress-dependent permeability changes with increasing P_f

Benefits Statement

In pursuing this research, we consider (1) reservoir permeability is a first-order control on injection pressure accumulation during CO_2 injections, and (2) the spatial distribution of *in situ* CRBG fracture distributions is *a priori* unknowable at the scale of interest for industrial CCS operations (except within recovered drill cores). To address the relationship between injection pressure accumulation and reservoir permeability, we propose a series of core-flood experiments to measure relative permeability, gas-phase entry pressure, and stress dependent permeability in variably saturated (CO_2 and brine) basalt samples under reservoir conditions. These experimental results will be used as input parameters for Monte Carlo numerical models of CO_2 injections under three industrial-scale scenarios: (1) a 37 MW biomass fueled electrical generator, which is the proposed deployment scenario at the Wallula Site; (2) a 500 MW natural gas-fired power plant; and (3) a 1,000 MW natural gas-fired power plant. The Monte Carlo numerical models for each injection scenario are comprised of 100 equally probable synthetic reservoirs constructed such that fracture-controlled reservoir heterogeneity is the random variable, and borehole data from the the Wallula Site are explicitly reproduced in each reservoir domain. By combining the ensemble statistics from each Monte Carlo run (mean and variance of grid cell fluid pressure) with the *in situ* stress field in southeast Washington State, this project will result in a risk assessment of geomechanical reservoir failure for each of the proposed CCS scenarios. Successful completion of this project will directly contribute towards the Carbon Storage Program Goal “to improve reservoir storage efficiency while ensuring containment effectiveness” by addressing three of the six Geological Storage Technologies and Simulation and Risk Assessment (GSRA) Key Technologies: (1) fluid-flow, pressure, and water management; (2) geomechanical impacts; and (3) risk assessment. Moreover, this project will result in a generalizable and transferable risk assessment strategy for CCS deployment in basalt interflow zones, the result of which may compliment the NETL *Best Practices for: Risk Analysis and Simulation for Geologic Storage of* CO_2.

Project Overview: Goals and Objectives

- Project Goals
  - Produce a probabilistic assessment of geomechanical reservoir integrity at the Wallula Basalt Sequestration Site.
    - Test CO_2 injection scenarios with Monte Carlo numerical simulation
      - 37 MW biomass fueled electrical generator – proposed deployment scenario
      - 500 MW & 1000 MW natural gas-fired electrical generators
      - **Program goal:** Understand and assess the geomechanical behavior of increased reservoir pressure on fractures, faults, and sealing formations.
      - **Program goal:** 99% storage permanence
  - Develop a mechanistic model for predicting stress-dependent reservoir properties in CRBG basalt rock.
    - Core-flood experiments to measure relative permeability, capillary pressure, and permeability as a function of effective stress.
      - Incorporate results into Monte Carlo numerical simulations
      - **Program goal:** Improved accuracy of existing models

Technical Overview

- Reservoir characterization & simulation (Tasks 2 & 3)
  - Develop regional database of CRBG permeability
  - Assess spatial variability of regional CRBG permeability
  - Develop outcrop scale CRBG fracture network model with terrestrial LiDAR
    - Investigate CO_2 migration through CRBG fracture network at the sc/sub-critical boundary.
- Relative permeability core-flood experiments (Task 4).
  - Measure relative permeability and capillary pressure as functions of wetting phase saturation.
    - For implementation in numerical modeling framework.
    - In progress.
  - Develop mechanistic model of stress-dependent relative permeability.
    - In progress.

Technical Overview

- Numerical simulation (Task 5)
  - Quantifying effects of uncertainty in relative permeability
    - Presented in 2015
  - Monte Carlo numerical model of industrial-scale CO_2 injections.
    - Using stochastically generated property sets.
    - Incorporating k_{rel} & P_{cap} measurements.
    - Evaluating potential for coupled THMC simulator.
    - Complete.
- Geomechanical risk assessment (Task 6)
  - In Progress

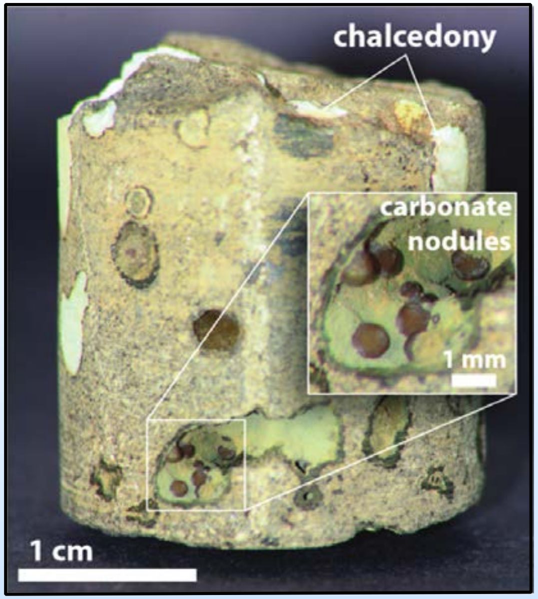
CCS in Basalt Reservoirs

PROCESS:

- CO_2 dissolution generates H^+ & HCO_3^-
- Basalt dissolution consumes H^+, and releases divalent cations $(Ca,Mg,Fe)^{2+}$.
- Carbonate precipitation consumes HCO_3^-
- Carbonate precipitation generates H^+, which further drives basalt dissolution

RECENT FIELD-SCALE PILOT PROJECTS:

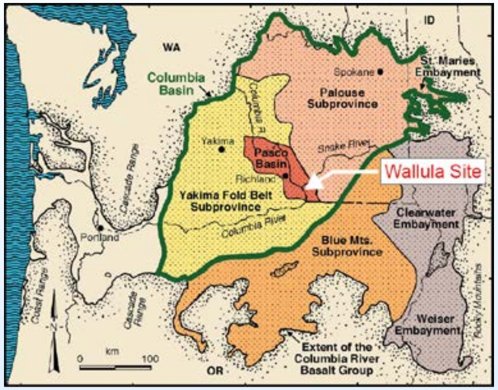
- CarbFix, Iceland: co-inject water & CO_2
  - 95% mineralization 2 years after injection (Matter et al. 2016, *Science*).
- **Wallula**, Washington, USA: ~1,000 metric tons $scCO_2$ in 2013.
  - Widespread mineralization in injection zone with distinct carbon isotope signature after 2 years (McGrail et al., *ESTL*, 2017).



Wallula sidewall core.
McGrail et al. (2017), Fig. 2

Columbia River Basalt Group

Layered assemblage of flood basalt flows



Modified after Reidel et al., 2002

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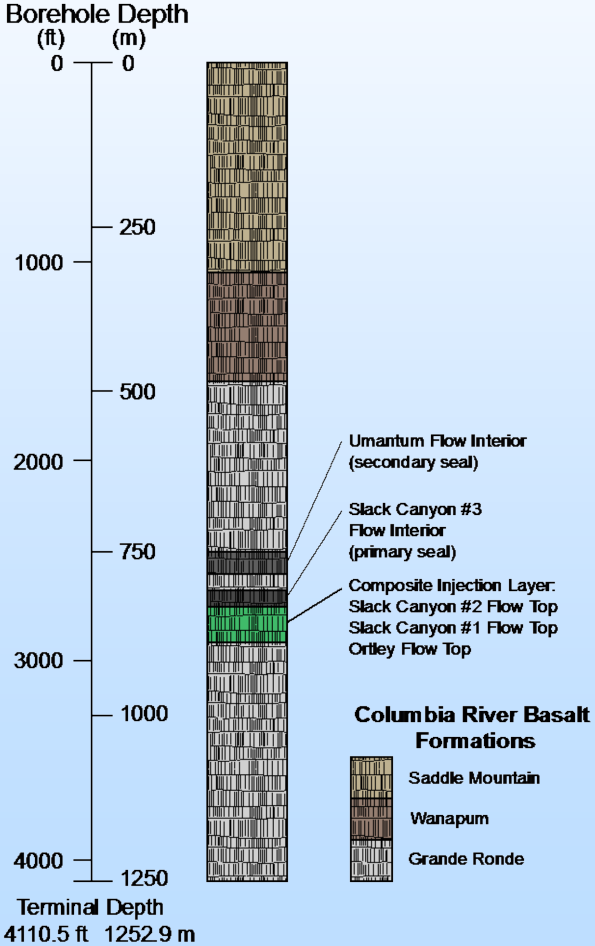
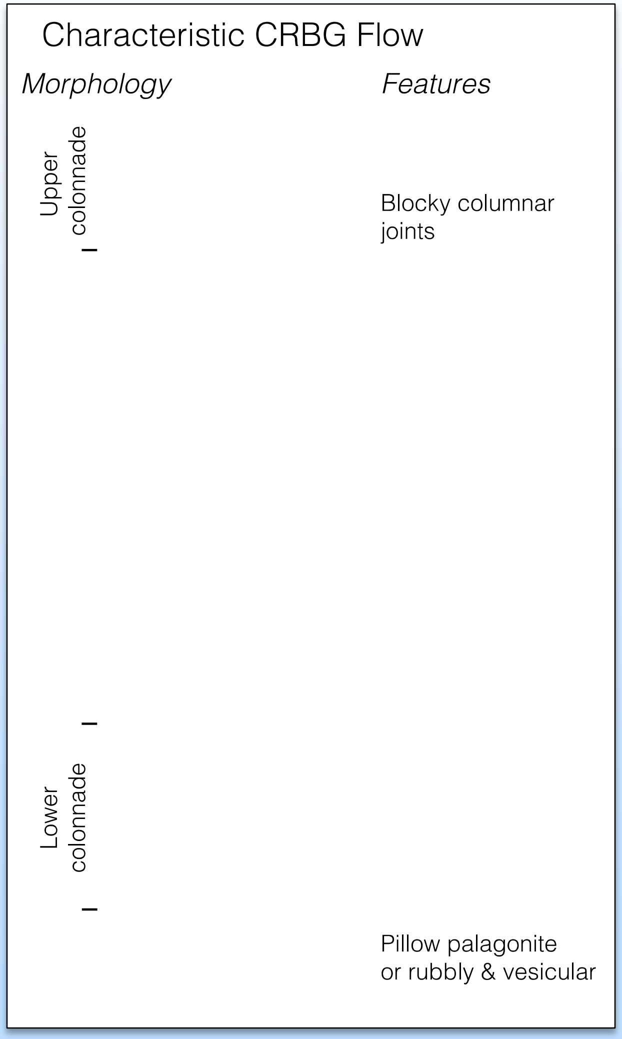
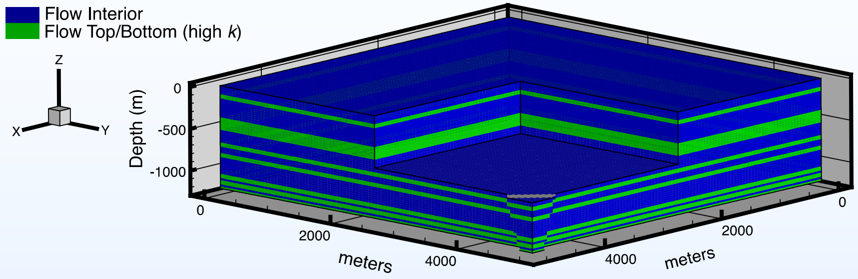
Generalized Wallula Borehole

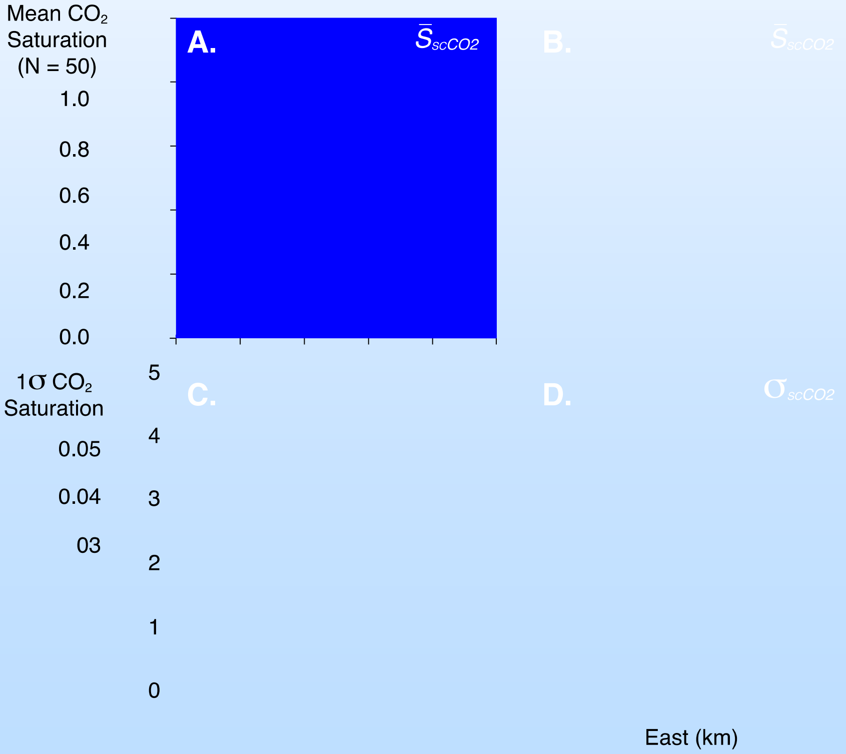




Modified after Mangan et al. (1986)

CRBG Reservoir Scale





Models and images by Richard S. Jayne, Ph.D. student at Virginia Tech.

PRELIMINARY MODEL SETUP:

- Generalized Wallula reservoir model
- 50 equally probable reservoirs
  - Reproduce Wallula borehole geology
  - Injection zone with equally probable, but spatially variable permeability distributions.
- CO$_2$ injection zone 775 – 875 m depth
- MINC representation for confining flow interior
- Industrial-scale scenarios: 10yrs at (1) $\Delta P = 12.7$ MPa & (2) $\dot{m} = 21.6$ kg/s

PRELIMINARY RESULTS:

- Permeability uncertainty in uppermost injection zone is superimposed as CO$_2$ saturation variability in fracture continuum of overlying flow interior.

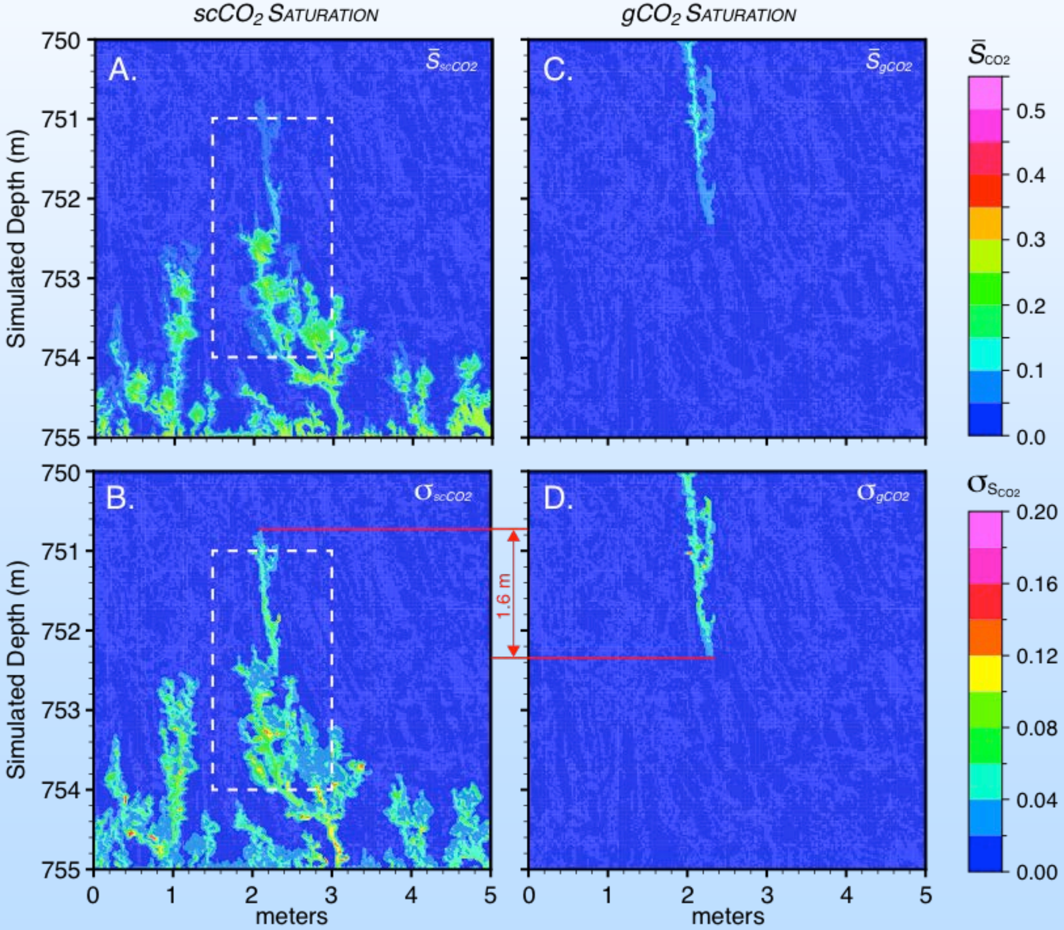
NEXT STEPS:

- Incorporate experimental k_{rel} measurements into flow interior (Task 4).
- Analyze modeling results as a risk profile for mechanical failure (Task 6).

CRBG Outcrop Scale

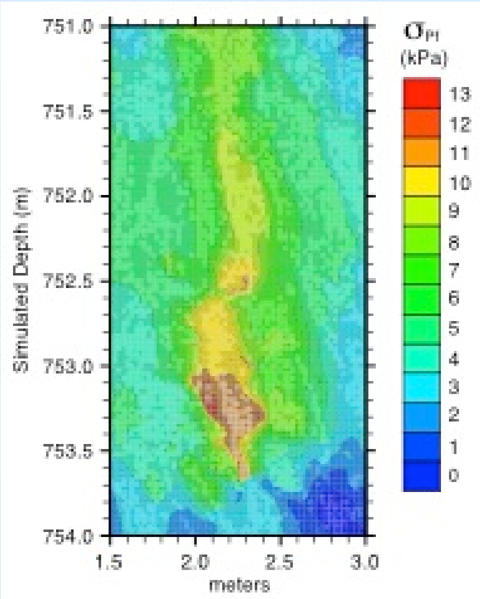
2-D Simulations of CO_2 entering basalt flow interior near critical point.

Monte Carlo model (N=50) w/ spatially random fracture permeability for 10 yr.



Gierzynski and Pollyea, *In Review* (*WRR*)

- CO_2 accumulates at fracture intersections.
- Permeability uncertainty accounts for ~1.6 m interval for phase change from $scCO_2$ to free gas phase CO_2.
- P_f variability focuses along conductive fractures, but impacts matrix.



Alec Gierzynski,
MS Virginia Tech (2016)

Core-Flood Experiments

Context

CO_2 injection in a basalt formation.

Fluid flow in basaltic rocks is governed by the permeable paths provided by fractures.

Problem

Increasing fluid pressure during injection may result in fracture dilation, which would increase the effective permeability of the rock, weakening the integrity of physical traps under long-term injection pressure.

Objective

Our goal is to **measure relative permeability and water saturation distribution** in a fracture during multiphase injection.

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Experimental Procedure

Core flooding → k & k_{rel}

X-Ray CT images → fracture aperture & satura

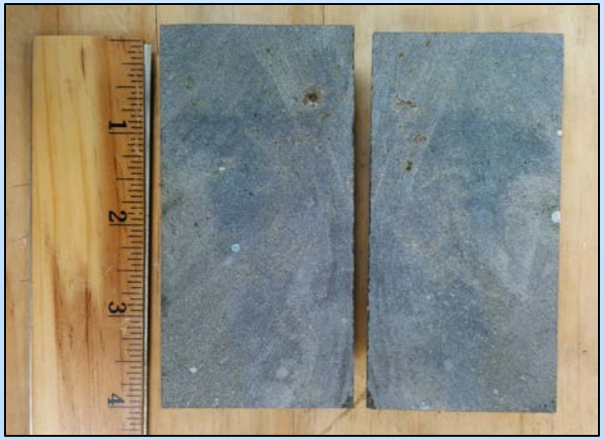
1. CT scan → dry fracture aperture & data for saturation calculation

2. N_2 injection at different flow rates -> gas permeability
   CT scan → gas fracture aperture

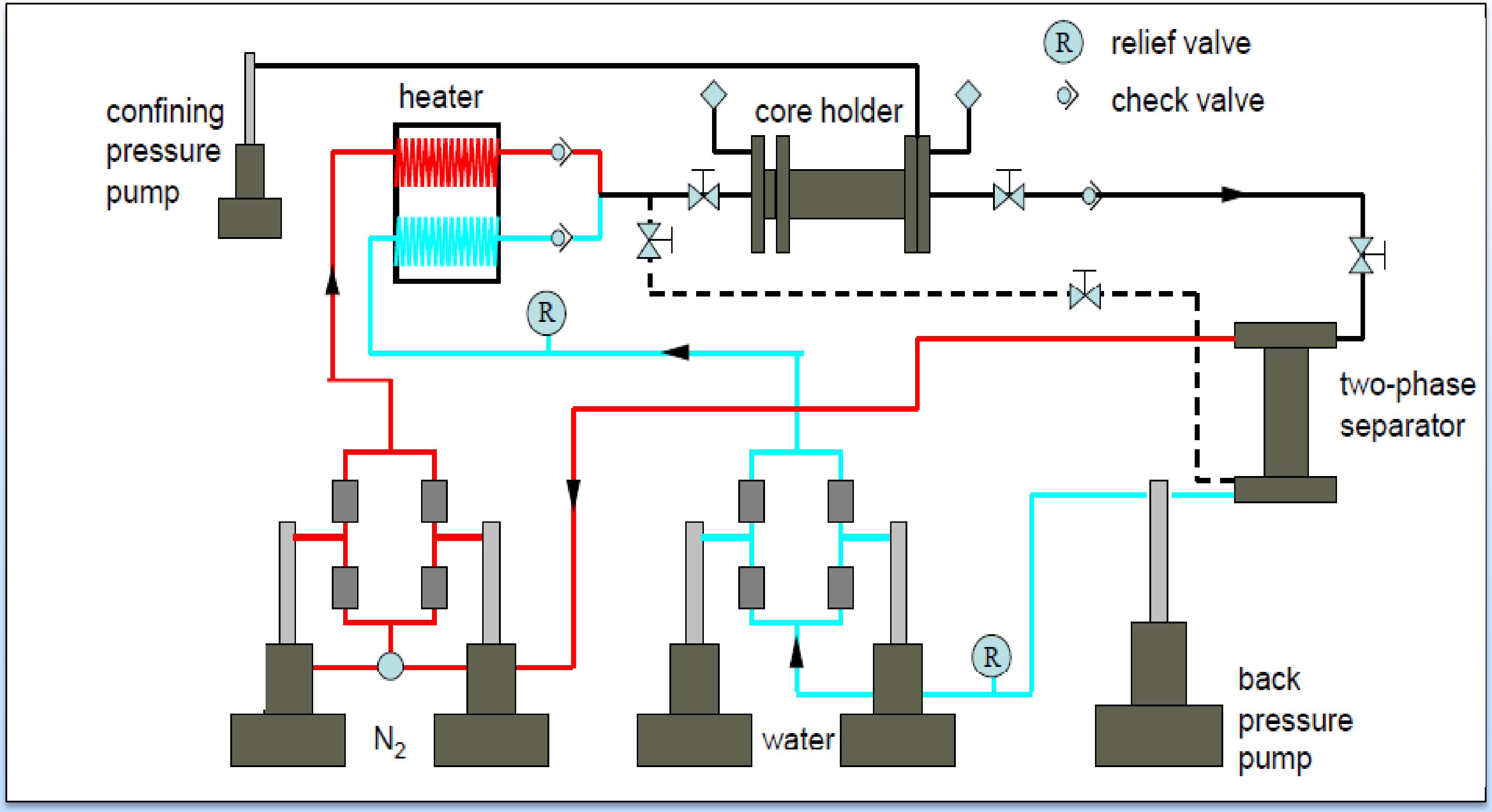
3. CO_2 injection

4. Water injection at different flow rates → water permeability
   CT scan → water fracture aperture & data for saturation calculation

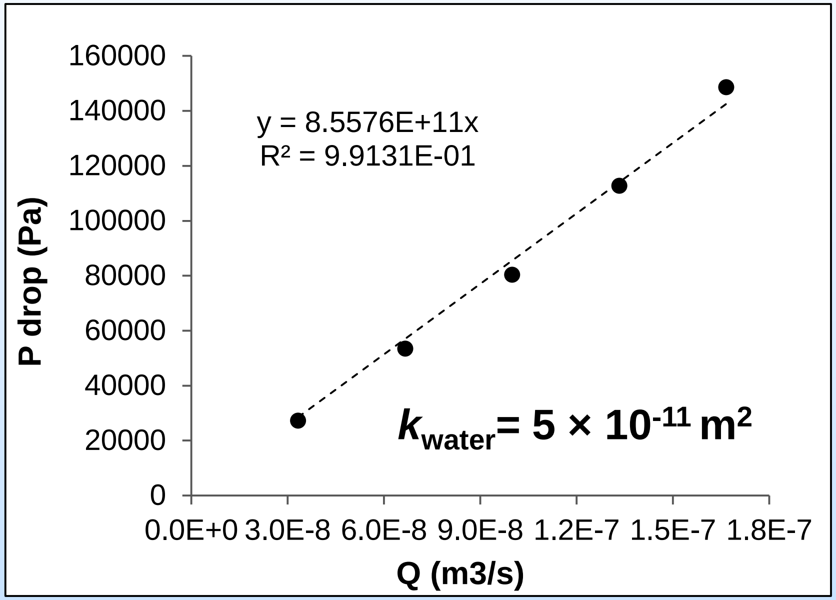
5. Multiphase injection: N_2 and water at different ratios at a constant total flow → relative permeability versus gas fraction-saturation
   CT scan → data for saturation calculation



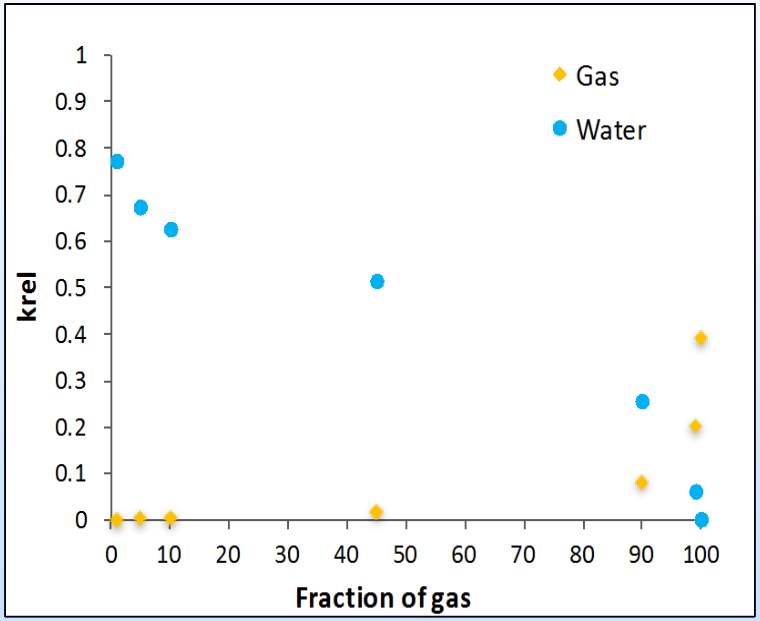
Experimental Apparatus



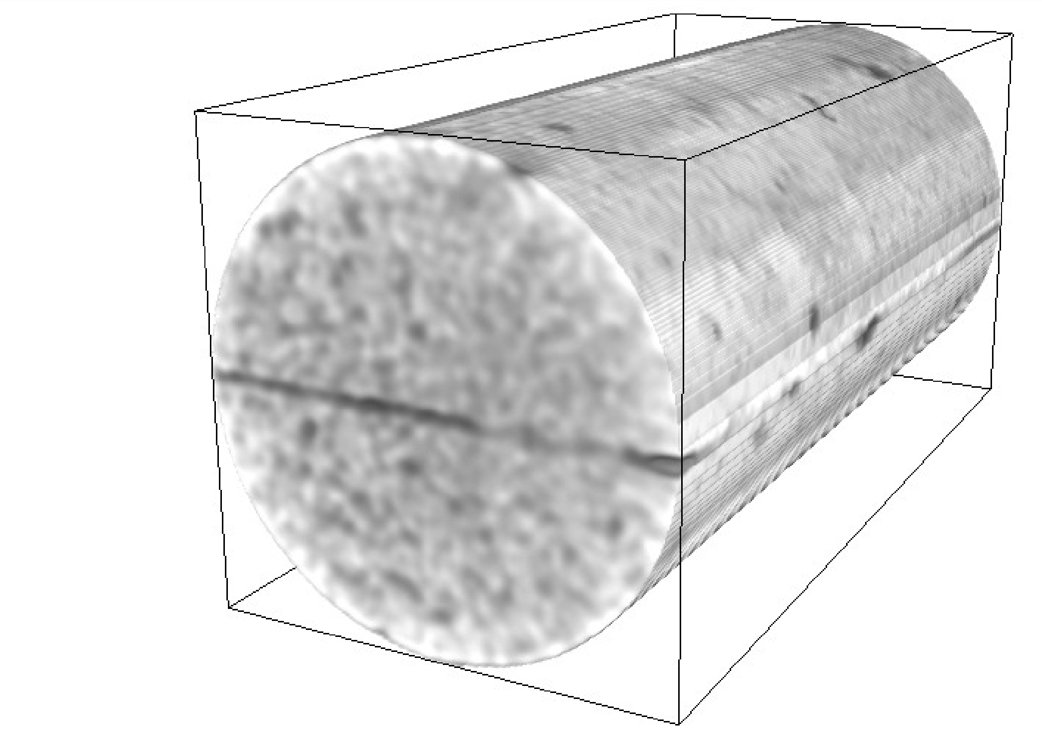
Core Flood Data



$k_{water} = 5 \times 10^{-11}\ m^2$



Data from CT Scan Images



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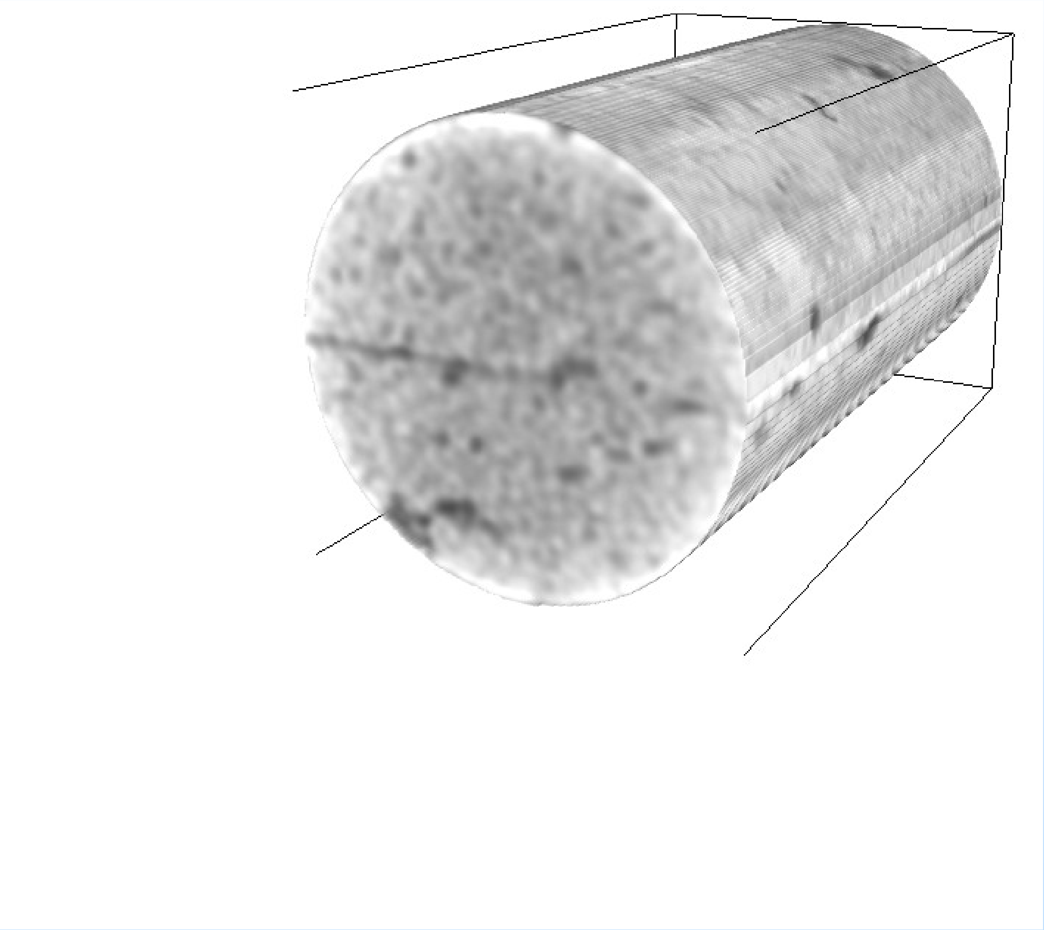

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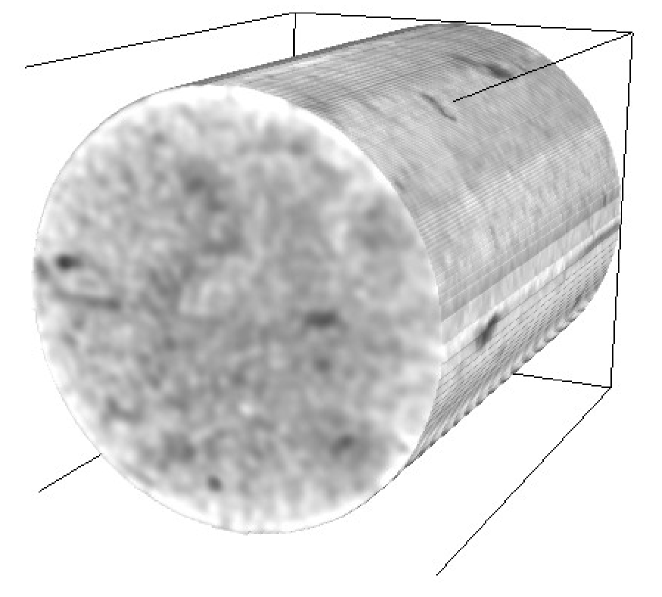

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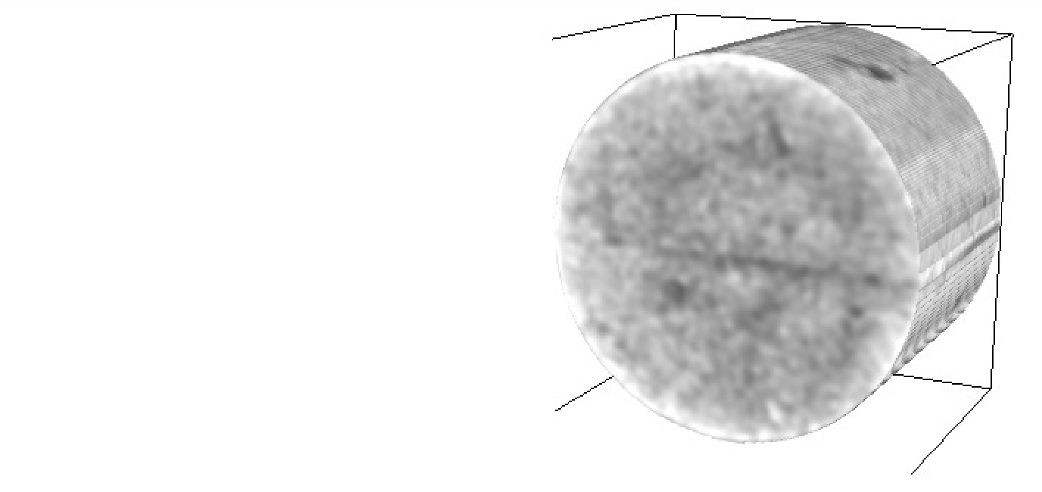

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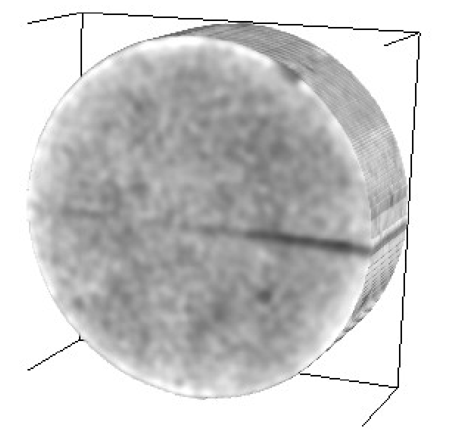

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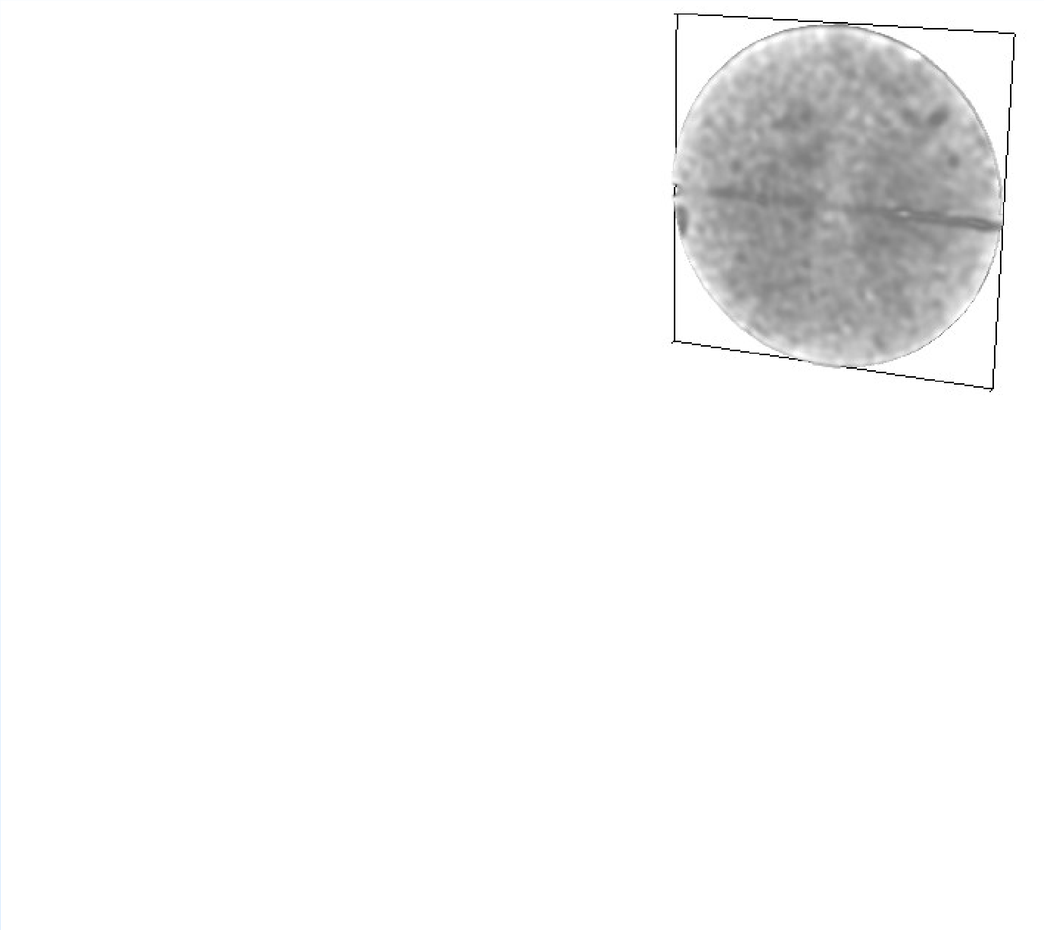

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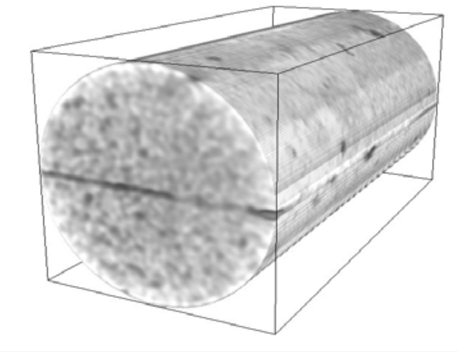
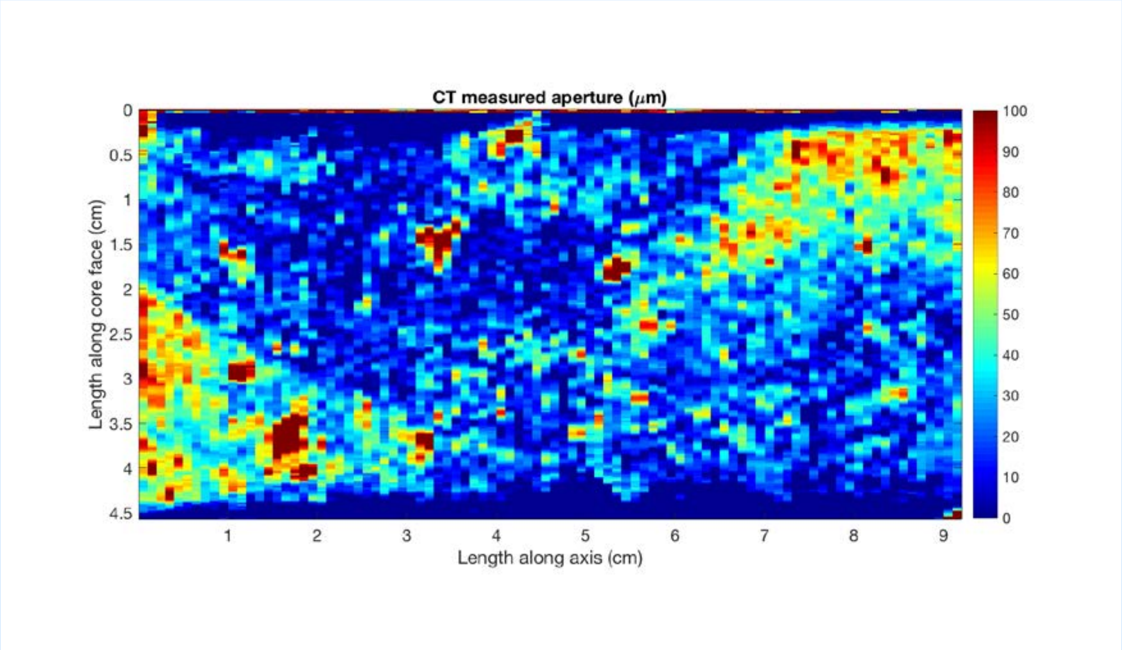
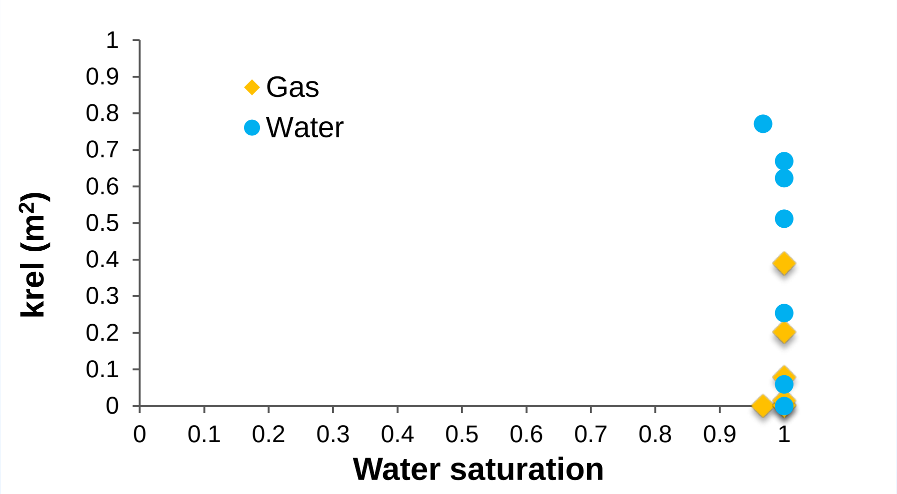


Fracture Aperture

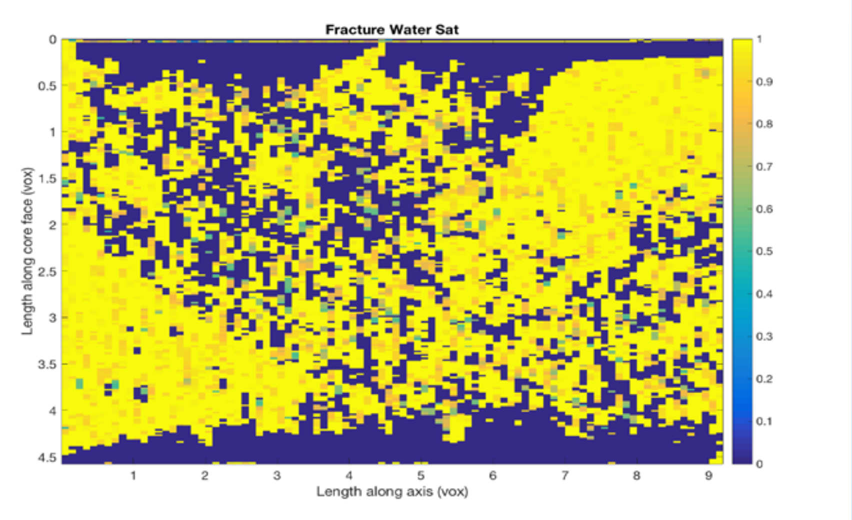
Dry scans: mean=26 µm, median=21 µm



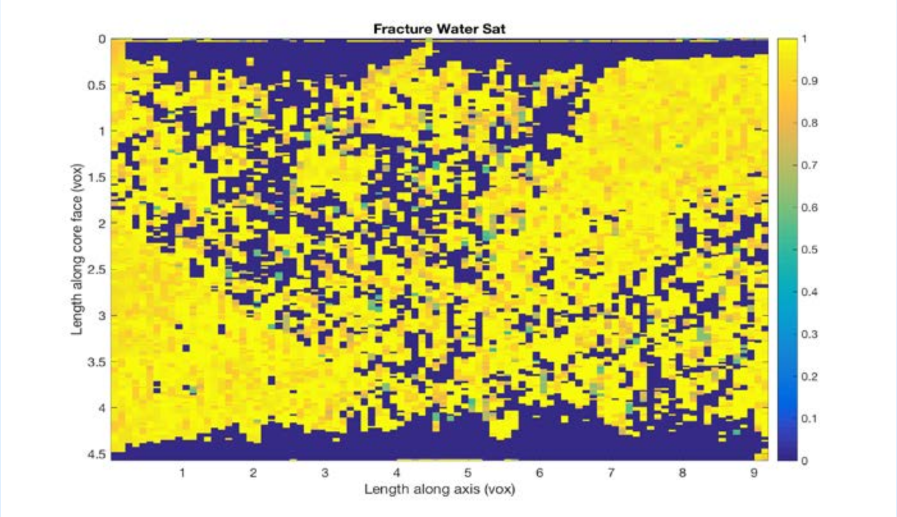
Combined CT & Core Flood Data



Multiphase flow shifts quickly from being dominated by one phase to another phase after a critical value of the non-wetting phase saturation is reached.

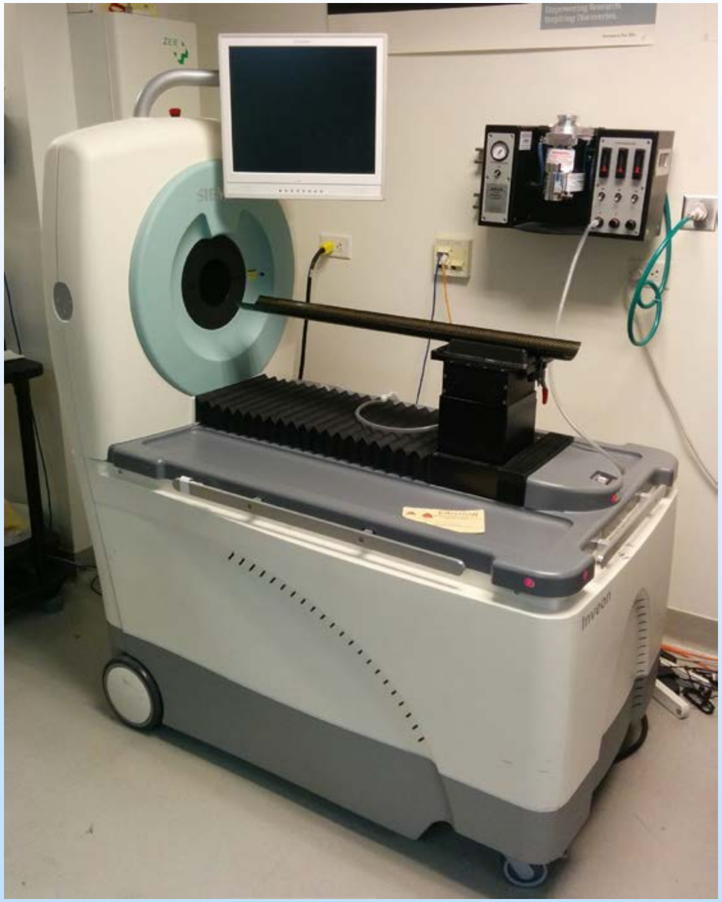


1% N2, 99% Water



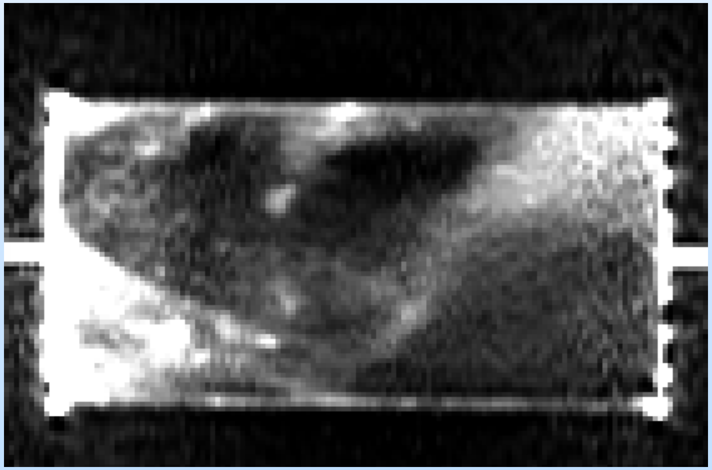
100% N2, 0% Water

PET Scan Experiment



The Positron Emission Tomography (PET) relies on the production of emitting radionuclides that are detected with an array of photon detectors that surround the core.

Tracer used: ^{18}F (Fluorine radioisotope)



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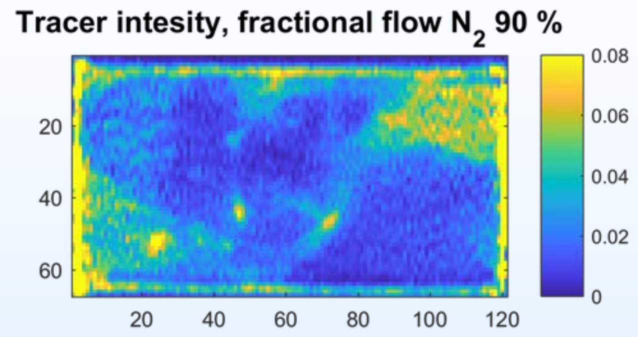
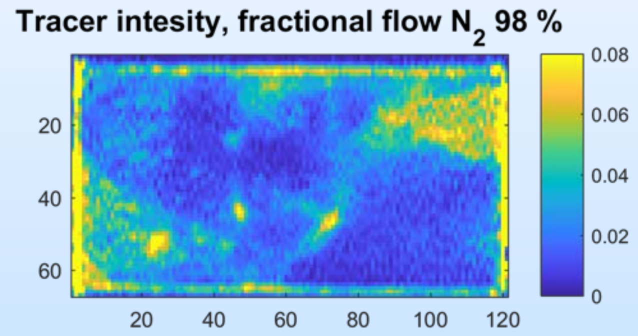
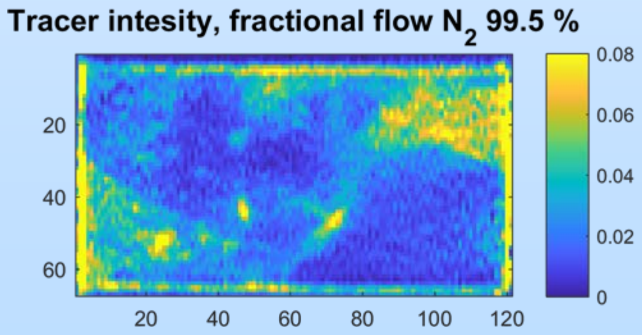
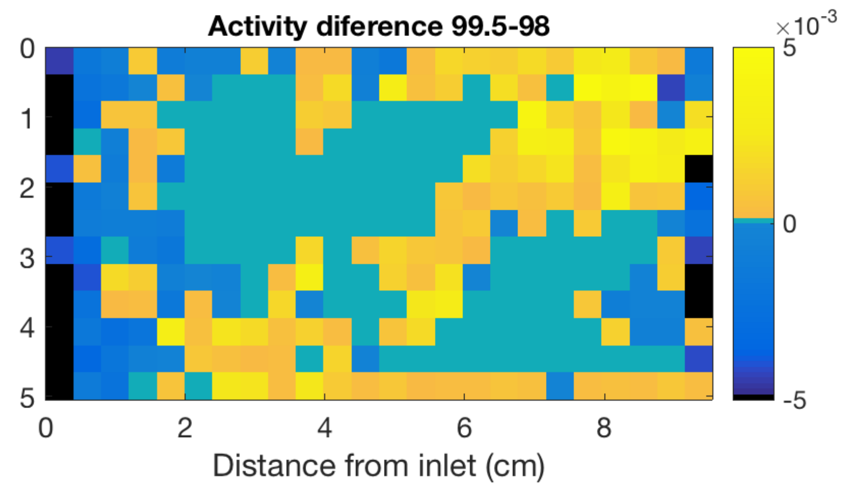
Tracer Intensity Maps (Current Work)


Tracer intesity, fractional flow N_2 90 %


Tracer intesity, fractional flow N_2 98 %


Tracer intesity, fractional flow N_2 99.5 %

Same experiment with PET imaging to look for gas flow path.


Activity diference 99.5-98

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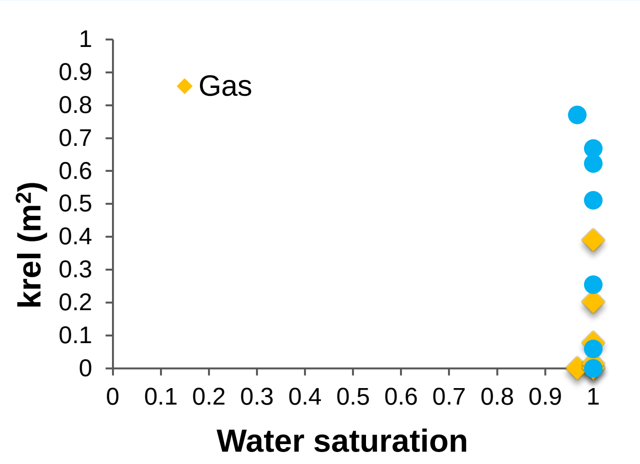
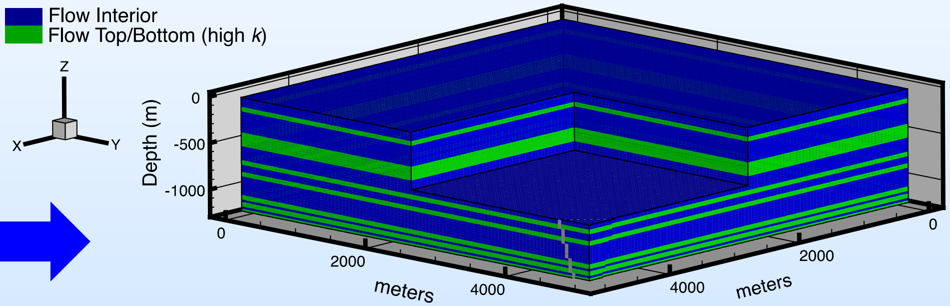
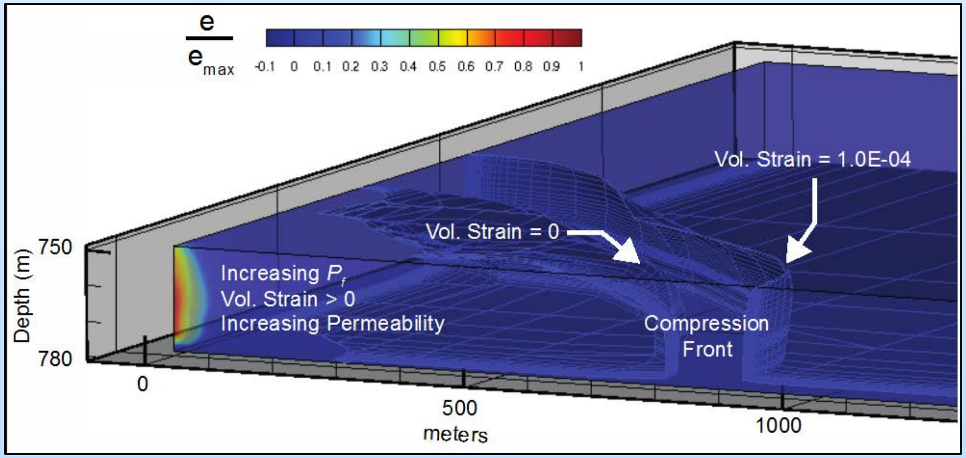
Next Steps

Complete stress-dependent k_{rel} experiments & develop geomechanical risk model by incorporating k_{rel} measurements in basalt core into flow interior for Monte Carlo simulation of industrial scale CCS in flood basalt.





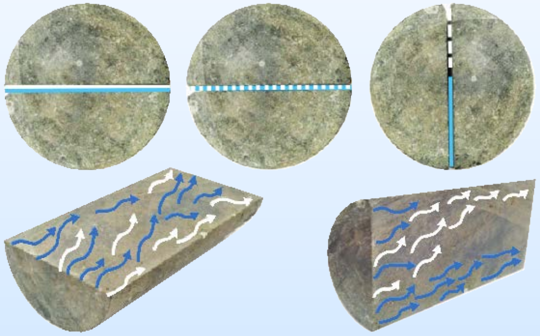


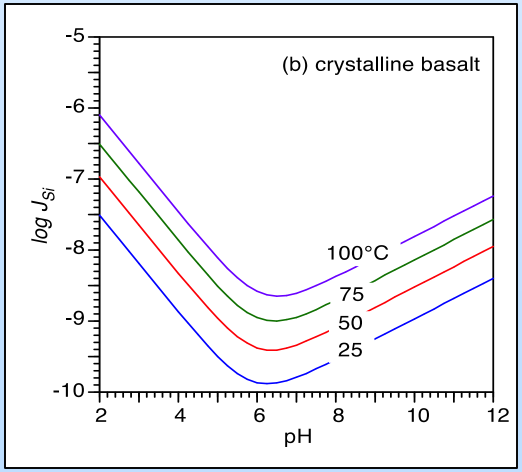
Very preliminary THM simulation of CO_2 injection into synthetic reservoir. TREACT-MECH w/ ECO2N

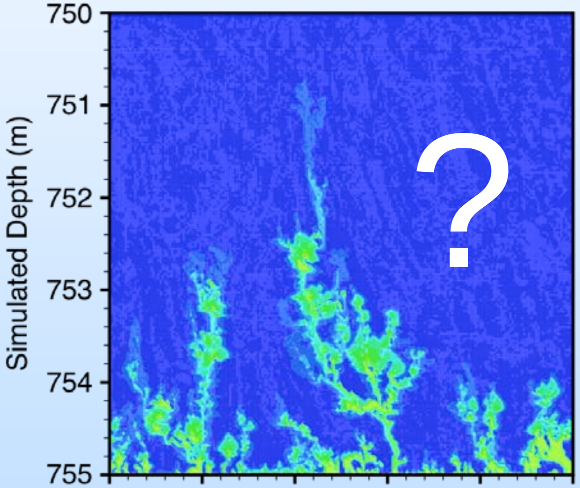
Next, Next Steps?

What if relative permeability and mineralization potential depend on fracture orientation in basalt fracture networks?

CRBG Outcrop Hells Gate State Park, Idaho







Storage effectiveness, efficiency, & permanence?

Questions?

Accomplishments to Date

- Reservoir characterization
  - Develop spatially referenced CRBG permeability database
  - Complete regional scale geostatistical analysis of CRBG permeability
  - Simulate outcrop scale fracture networks with terrestrial LiDAR
- Numerical simulation
  - Complete modeling experiment to quantify geomechanical effects of relative permeability uncertainty.
  - Complete outcrop scale modeling study of CO_2 flow in basalt fracture network.
  - Complete reservoir scale modeling study on the effects of permeability uncertainty for CCS in basalt reservoir.
- Core-flood experiments
  - Develop experimental method for k_{rel} in basalt fracture
  - Initial N_2-water relative permeability experiment

Synergy Opportunities

- Micro-structural analysis?
- Fluid-rock interactions?
- Permeability-porosity scaling with mineralization

Summary

Key Findings

- Multiphase flow shifts quickly from being dominated by one phase to another phase after a critical value of the non-wetting phase saturation is reached.
- Pressure accumulation is sensitive to relative permeability effects, even at low injection rate.
  - k_{nw} strongly influences maximum pressure build-up
- CO2 accumulates at fracture intersections during buoyancy driven flow in basalt fracture network.

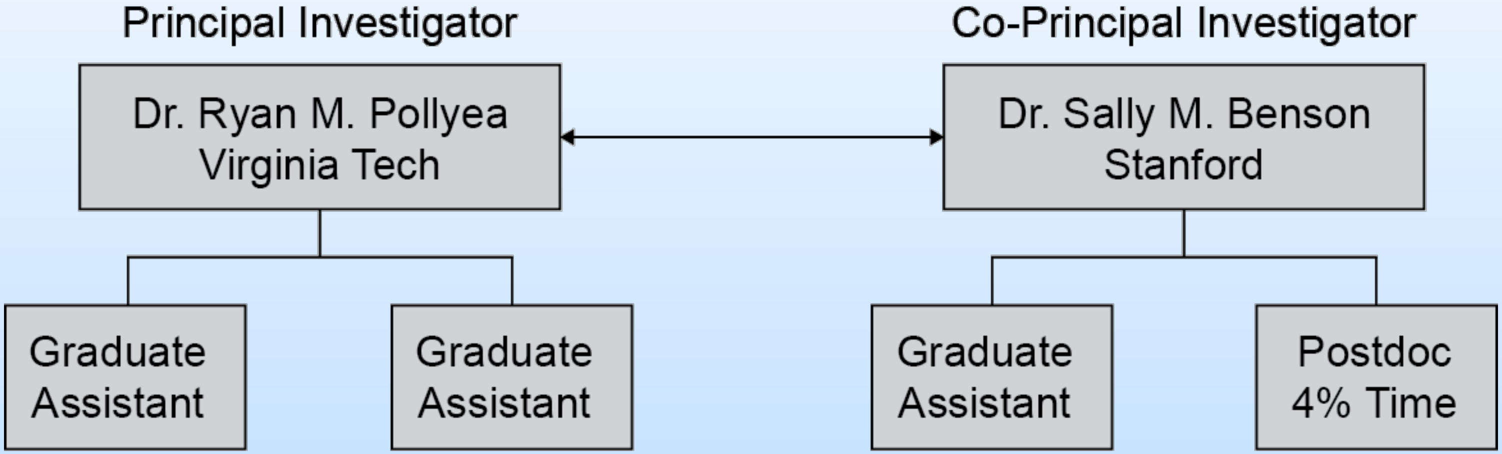
Future Plans

- Integrate k_{rel} model into reservoir scale model.
- Reservoir scale, model-based risk model of geomechanical effects at Wallula site.
- Mechanistic model of stress-dependent relative permeability.

Appendix

- These slides will not be discussed during the presentation, but are mandatory

Organization Chart



Principal Investigator

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Co-Principal Investigator

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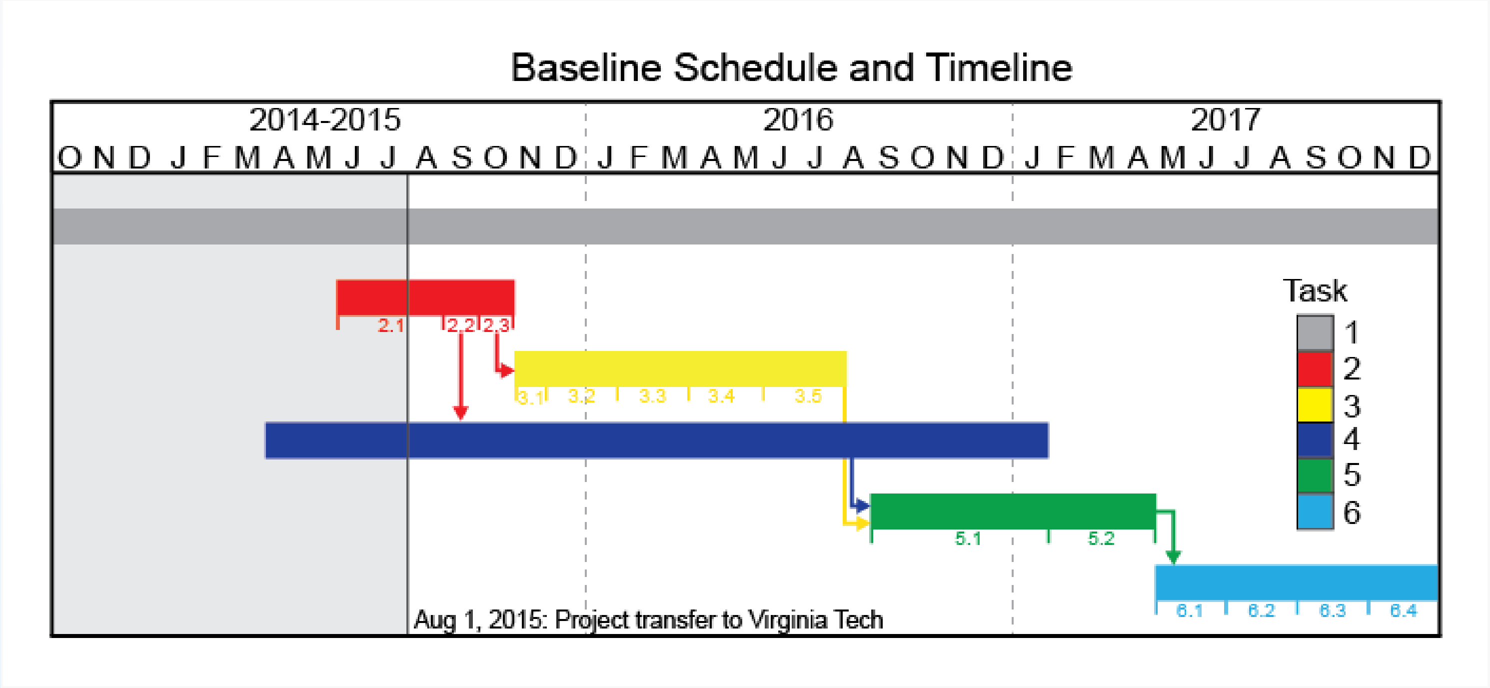
Graduate Assistant

Graduate Assistant

Graduate Assistant

Postdoc
4% Time

Gantt Chart


Baseline Schedule and Timeline

Bibliography

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Gierzynski, A.O. and Pollyea, R.M. Three-phase CO_2 flow in a basalt fracture network. In Review with *Water Resources Research*, submitted 15 May 2017.

Pollyea, R.M. and Rimstidt, J.D., 2017. Rate equations for modeling carbon dioxide sequestration in basalt, *Applied Geochemistry*, v. 81, p. 53 – 62. available at: http://www.sciencedirect.com/science/article/pii/S0883292716305182

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Jayne, R.S. and Pollyea, R.M. 2017. A spatial correlation model of permeability on the Columbia River Plateau. American Geophysical Union Fall Meeting, 11 – 15 December, New Orleans, Louisiana (abstract submitted).

Gran, M., Zahasky, C., Garing, C., Pollyea, R.M., and Benson, S.M. 2017. Experimental study of relative permeability and saturation variations in a fractured basalt core. 9th International Conference on Porous Media & Annual Meeting (InterPore), 8–11 May, Rotterdam, Netherlands.

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Pollyea, R.M. 2015. System response as a function of relative permeability in geologic CO_2 sequestration. American Geophysical Union Fall Meeting, 14 – 18 December, San Francisco, California. Abstract H52F-05.