A probabilistic assessment of the geomechanical response to CO_2 injections in large igneous provinces

DE-FE0023381

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U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 16-18, 2016

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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

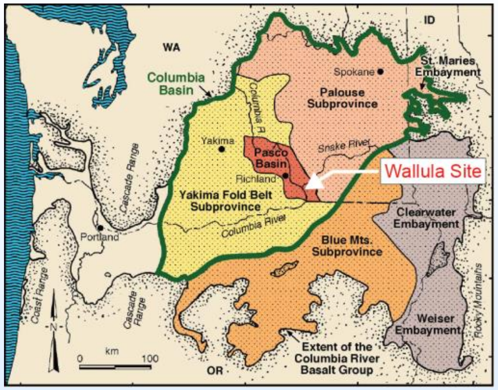
- Reservoir characterization & simulation (Tasks 2 & 3)
  - Develop regional database of CRBG permeability
  - Assess spatial variability of regional CRBG permeability
  - Develop outcrop scale CRBG fracture network model with terrestrial LiDAR
    - » Investigate CO_2 migration through CRBG fracture 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.
    - » Planned for 2017.

Technical Overview

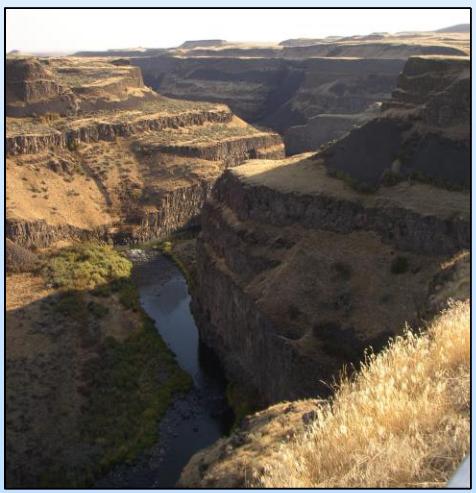
- Numerical simulation (Task 5)
  - Quantifying effects of uncertainty in relative permeability
    - Presented in 2015
  - Monte Carlo numerical model of industrial-scale CO_2 injections.
    - Using stochastically generated property sets.
    - Incorporating k_{rel} & P_{cap} measurements.
    - Evaluating potential for coupled THMC simulator.
    - Currently in progress.
- Geomechanical risk assessment (Task 6)
  - Planned for 2017

Columbia River Basalt Group

Layered assemblage of flood basalt flows



Modified after Reidel et al., 2002



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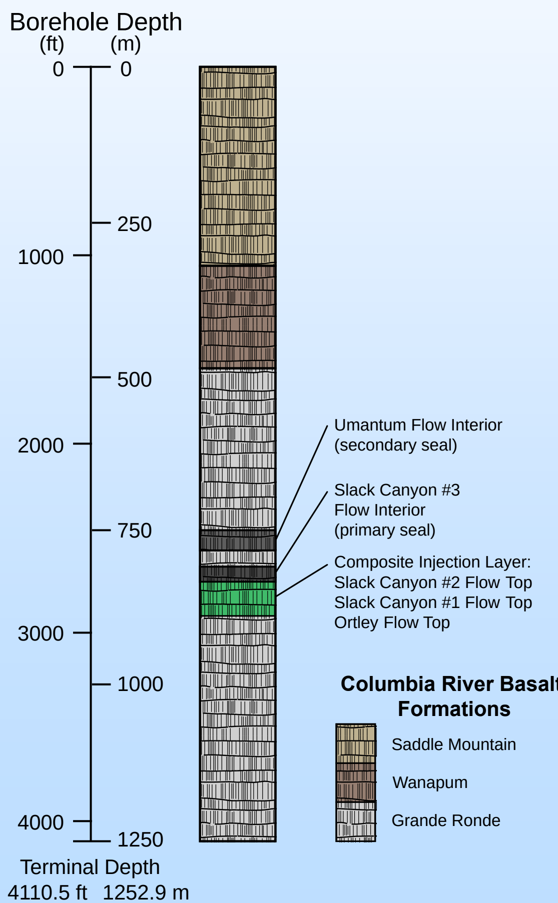
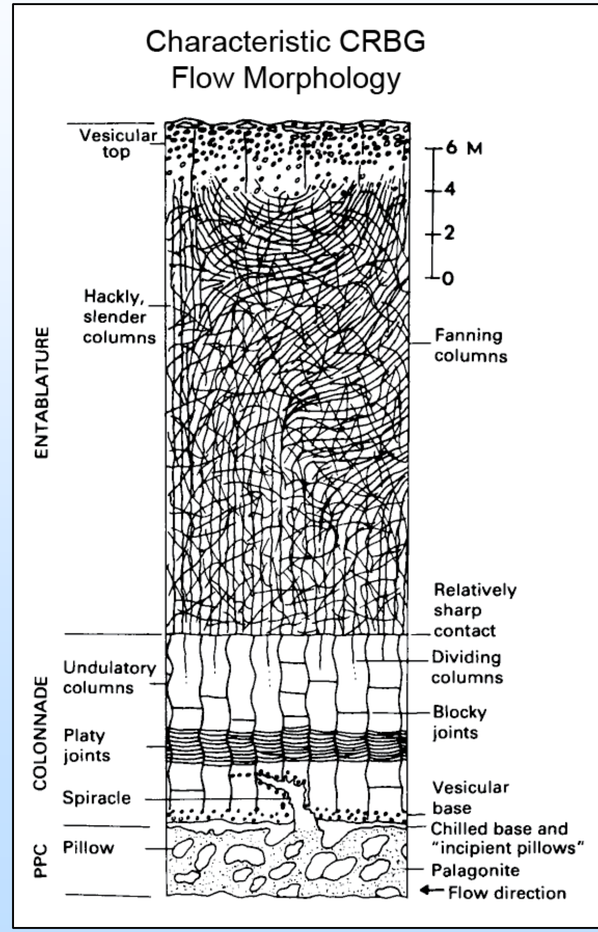
Generalized Wallula Borehole



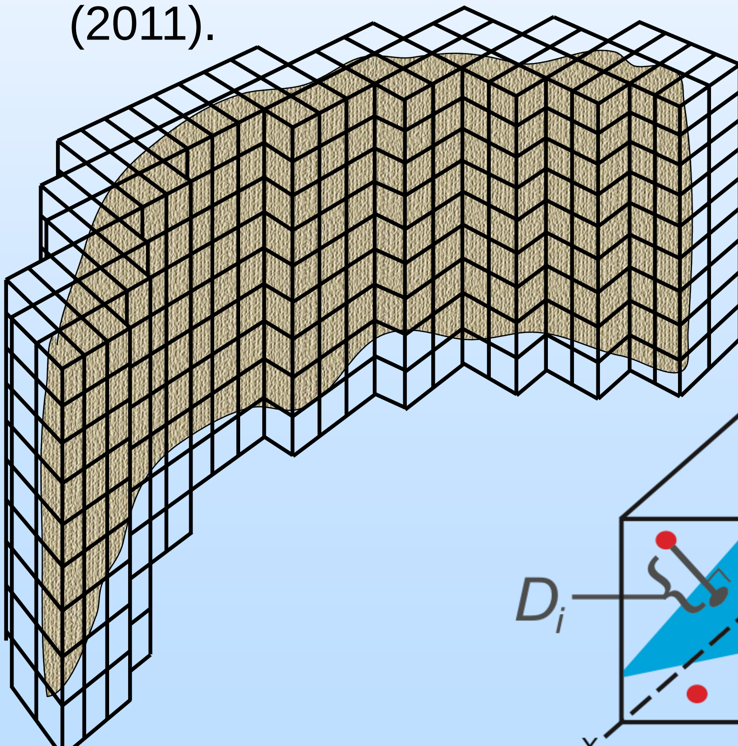


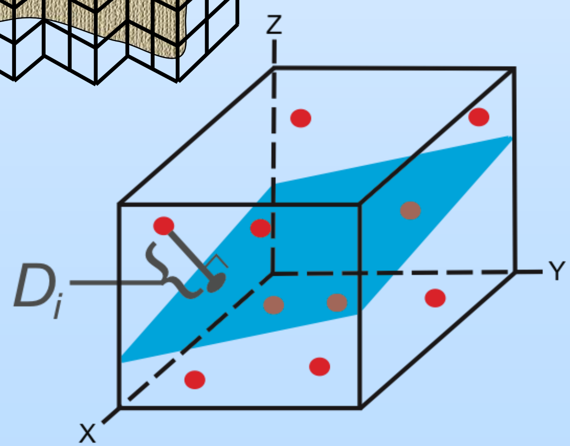
Modified after Mangan et al. (1986)

Field Work

Acquire terrestrial LiDAR scans of outcrop fracture networks to image fracture networks.

Process point cloud data with surface roughness algorithm Pollyea and Fairley (2011).





Alec Gierzynski, MS Student at Virginia Tech

CRBG Fracture Networks

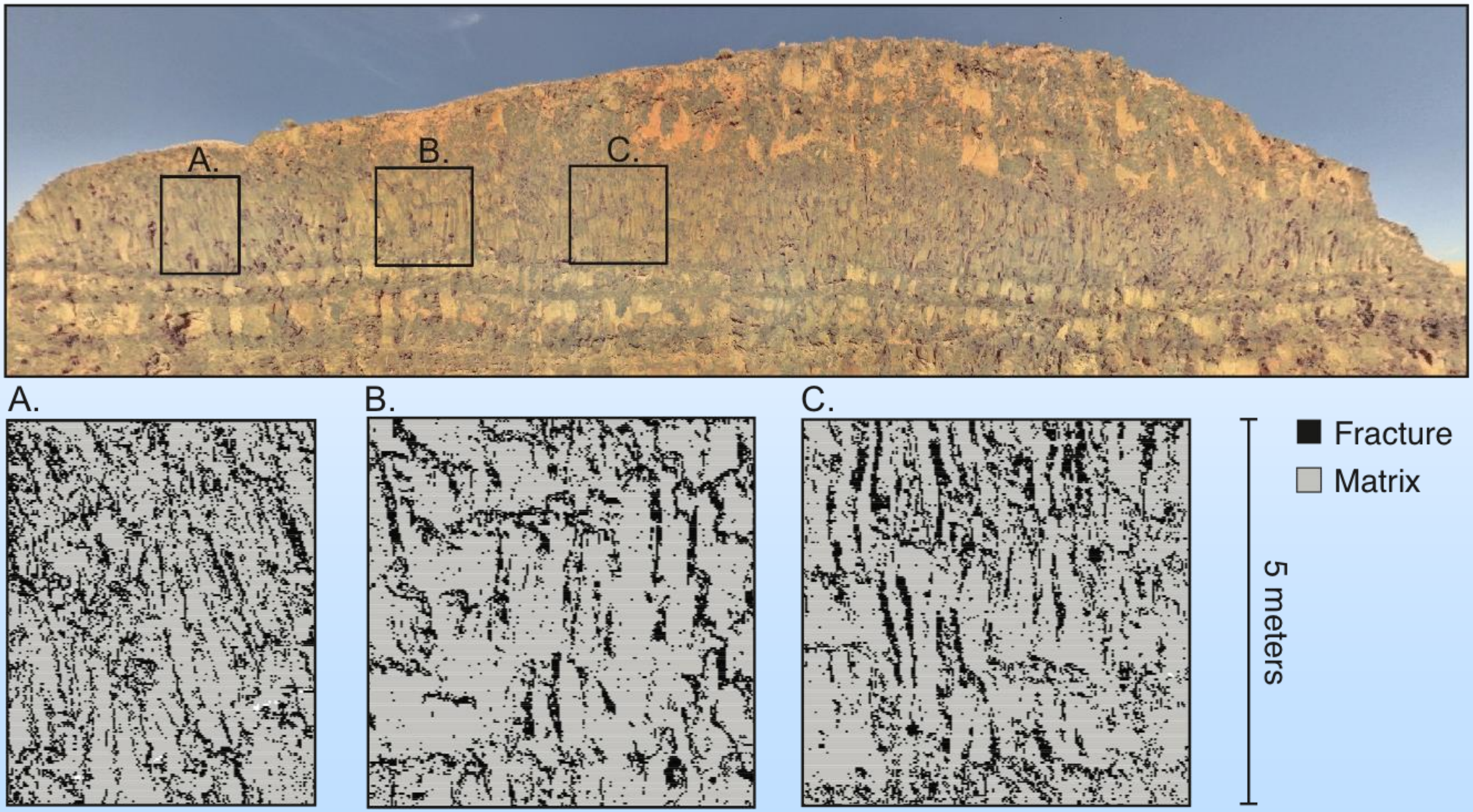
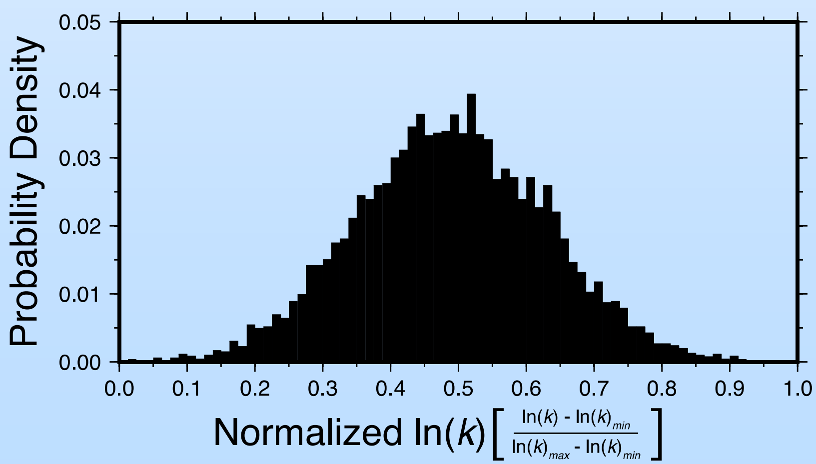


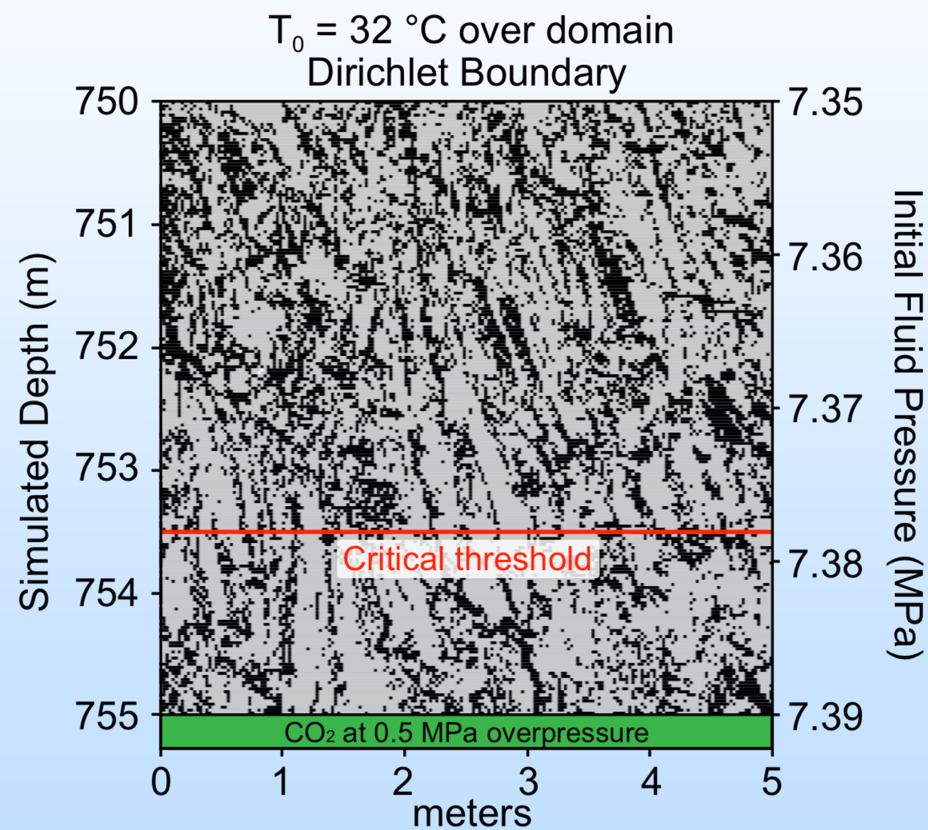
Image and analysis by Alec Gierzynski, MS Student at Virginia Tech

CRBG Outcrop Scale Modeling

For a given effective permeability, how much variability in CO_2 migration?

- 50 equally probable realization of same 2-D fracture network ($\Delta x = \Delta z = 2.5$ cm).
- Fracture permeability is spatially random.
  - $k_{eff} = 10^{-18}$ m^2
  - $k_{matrix} = 10^{-20}$ m^2
  - Solve weighted geomean for $\bar{k}_{fracture} = 10^{-16}$ m^2.
- Variability about mean $\bar{k}_{fracture}$ constrained by CRBG fracture apertures (Lindberg, 1989).



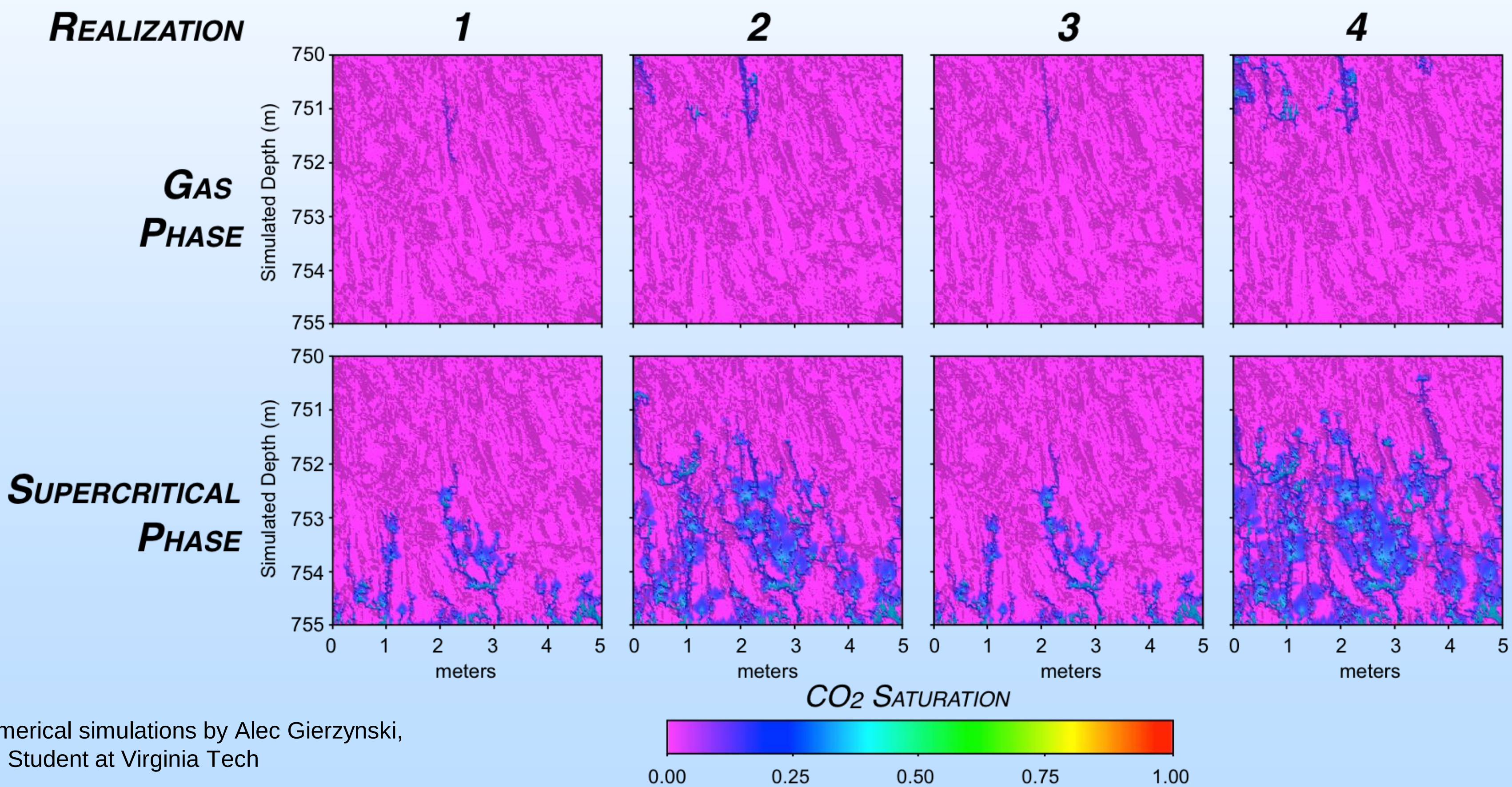


Numerical simulations with TOUGH3 (beta) and equation of state module ECO2M.

CRBG Outcrop Scale Modeling

Preliminary results for 4 equally probable fracture permeability distributions

- Same fracture network
- Same k_{eff}
- Same $k_{fracture}$ distribution
- Spatially random $k_{fracture}$



Numerical simulations by Alec Gierzynski,
MS Student at Virginia Tech

CRBG Regional Permeability

Pump test results from Wallula borehole:

- Flow Interiors $k \approx 10^{-20}$ m^2
- Flow Tops $k \approx 10^{-13}$ m^2

Research question: How does permeability vary away from borehole?

Address with geostatistical analysis:

- Compile spatially referenced GIS database for <u>flow top</u> *k*.
- 429 *k* values taken from literature.

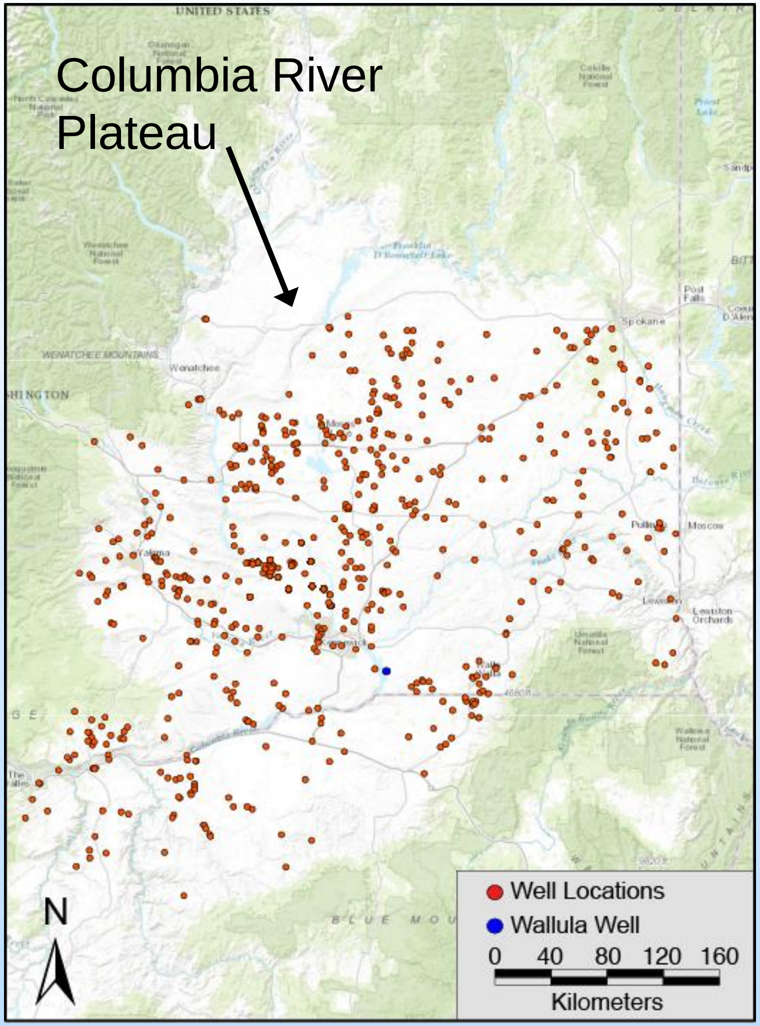


Image by Richard S. Jayne, Ph.D. student at Virginia Tech

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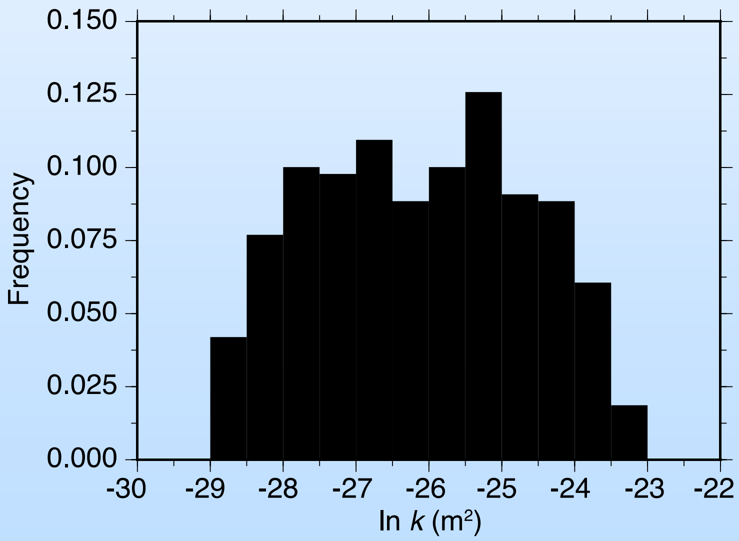
CRBG Permeability

Database Assessment

Flow top *k* values:

min = 1.68×10^{-13} m^2
max = 4.21×10^{-11} m^2
mean = 6.87×10^{-12} m^2
N = 429



Most *k* values < 100 m depth

Apply depth-dependent scaling per Saar and Manga (2004)

$$k(z) = k_0 e^{\frac{-z}{250m}}$$

For injection zone at 830 m depth:

$$k(z = 830m) = 6.87 \times 10^{-12} m^2 e^{\frac{-830m}{250m}}$$
$$= 2.48 \times 10^{-13} m^2$$

Wallula Injection Zone *k* ≈ 10^{-13} m^2

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CRBG Regional Permeability

Quantify spatial variability

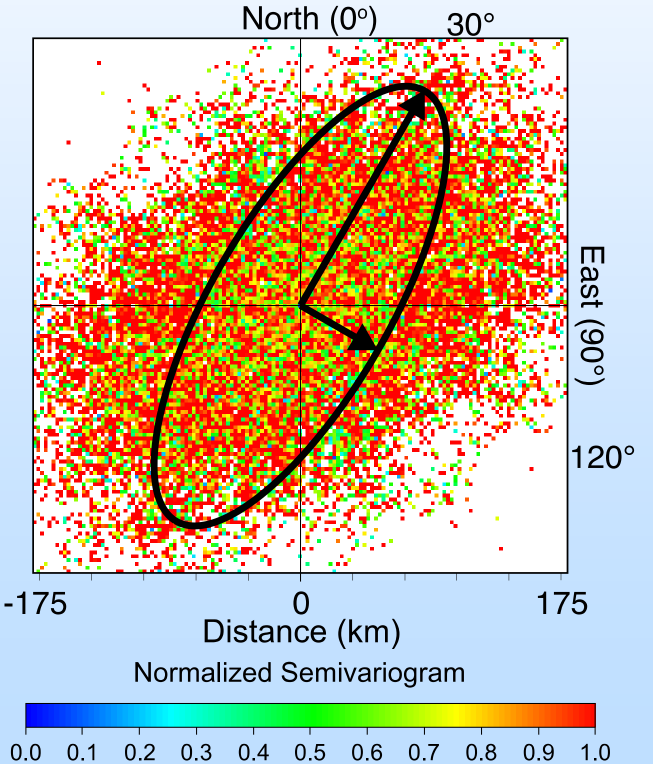
of CRBG permeability with semivariogram analysis

Semivariogram

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N} (k_i - k_{i+h})^2$$

- Measure of dissimilarity for lagged intensity variable.
- Variogram map computes experimental semivariogram for all lag distances in all directions
- Useful for identifying spatial anisotropy.

Variogram Map of CRBG permeability



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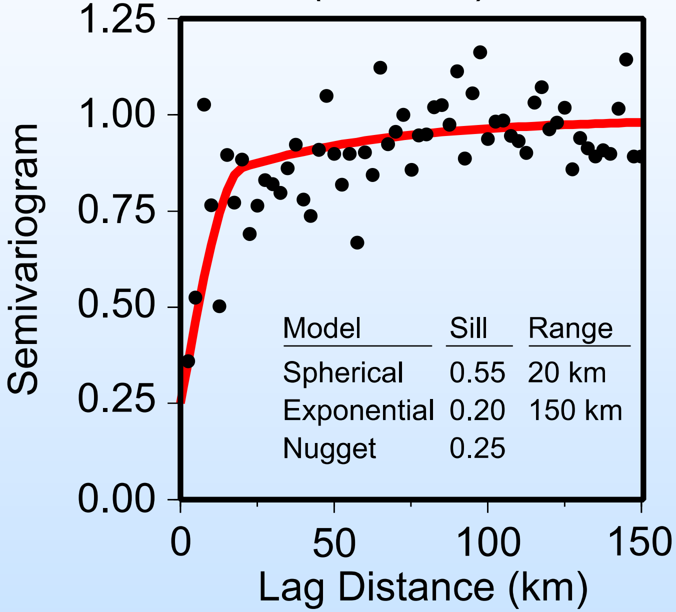
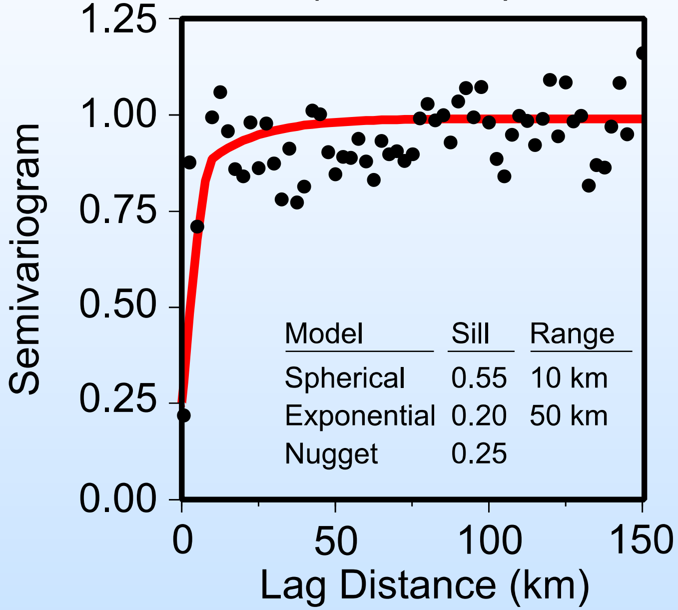
CRBG Regional Permeability

Long Range Correlation (N30°E)



Short Range Correlation (N120°E)



Anisotropic permeability correlation ratio is ~3:1.

Suggests permeability in CRBG flow top is spatially correlated at scale of CO_2 sequestration reservoir.

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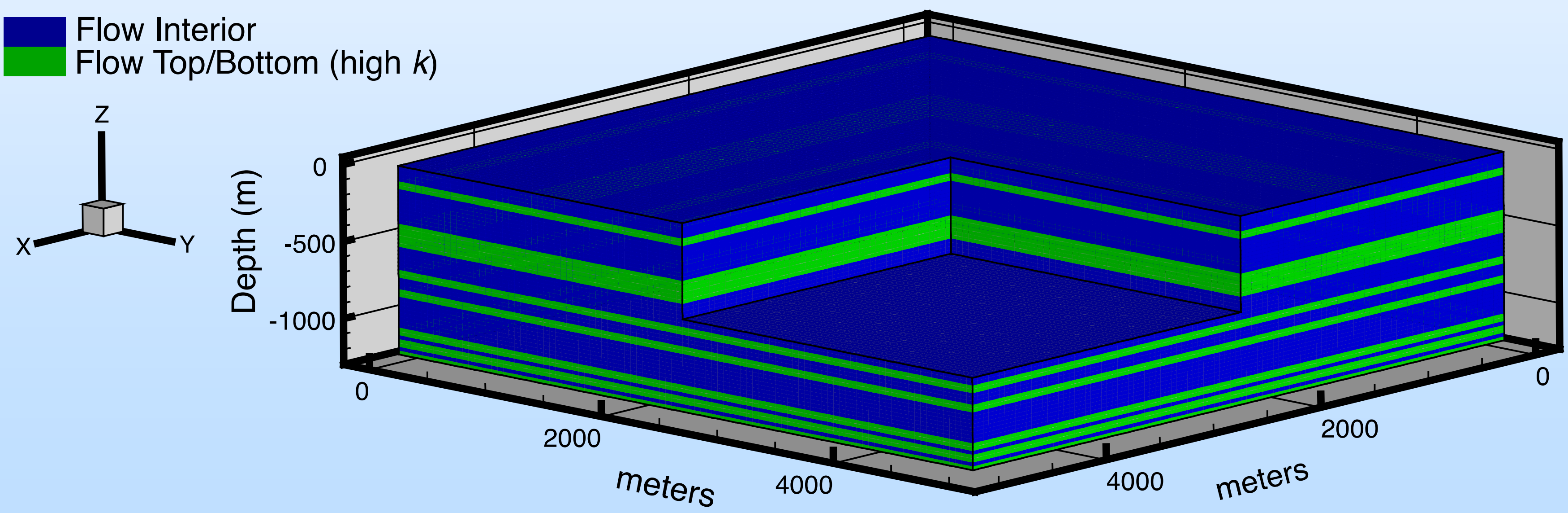
Images by Richard S. Jayne, Ph.D. student at Virginia Tech

CRBG Reservoir Simulation

Next steps (currently in progress):

- Develop 50 equally probable stochastic permeability fields for flow interiors (green shading)
- Condition on Wallula borehole; cdf of CRBG permeability & semivariogram correlation
- Incorporate outcrop scale results into multiple interacting continua (MINC) for domain for fracture-fracture and fracture-matrix flow

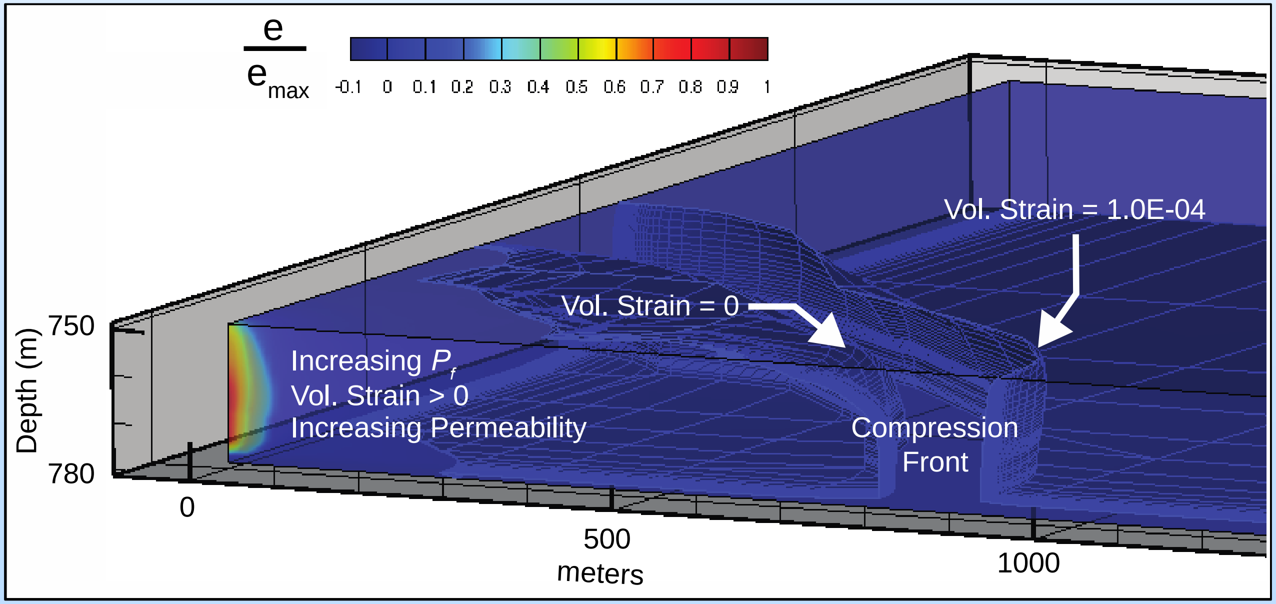


Numerical Simulation

Presently working on hydromechanical coupling.

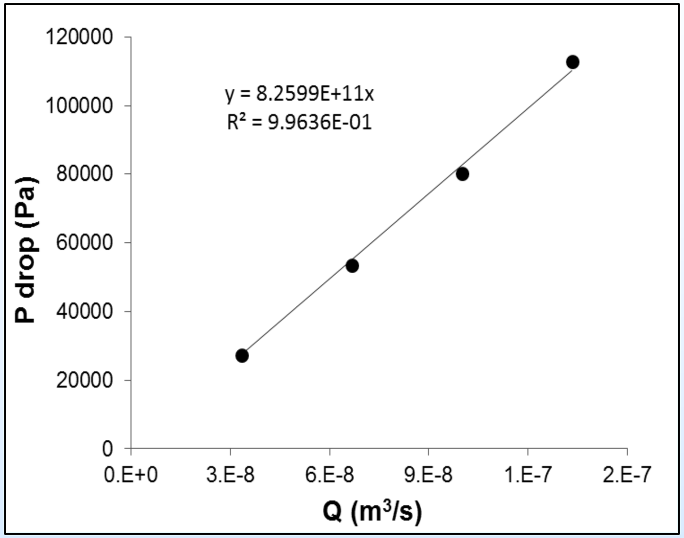
- Promising results with TRM (Kim et al., 2015)
  - Couples reactive nonisothermal multiphase fluid flow and poroelastic deformation, including Mohr-Coulomb & tensile failure.
  - Flow & mechanics are computed in serial on single processor
    - Limits problem size to ~125k grid blocks.
  - Will permit fluid-rock interaction & reactive permeability alteration in future studies.

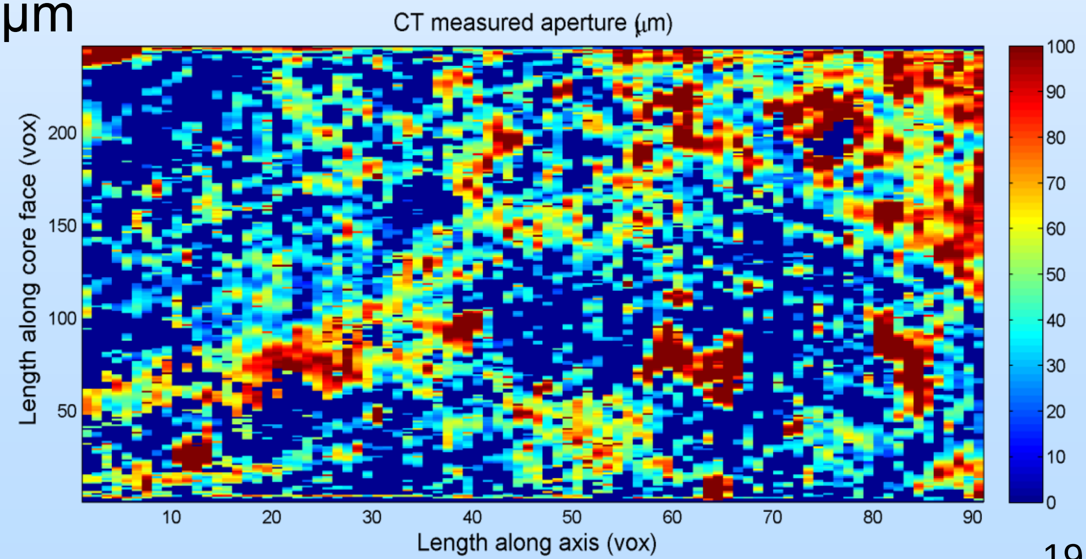
Very preliminary THM simulation of CO_2 injection into synthetic reservoir. TRM w/ ECO2N



Core-Flood Experiments

- Basalt core measurements started in January 2016
- Obtained CRBG cores from PNNL
  - 9.4 cm length
  - 4.6 cm diameter
  - Saw-cut fracture (first experiment)
  - Aperture variation measured by CT
    - Avg. aperture = 35.6 μm
  - $k_{fracture}$ = 36 Darcy





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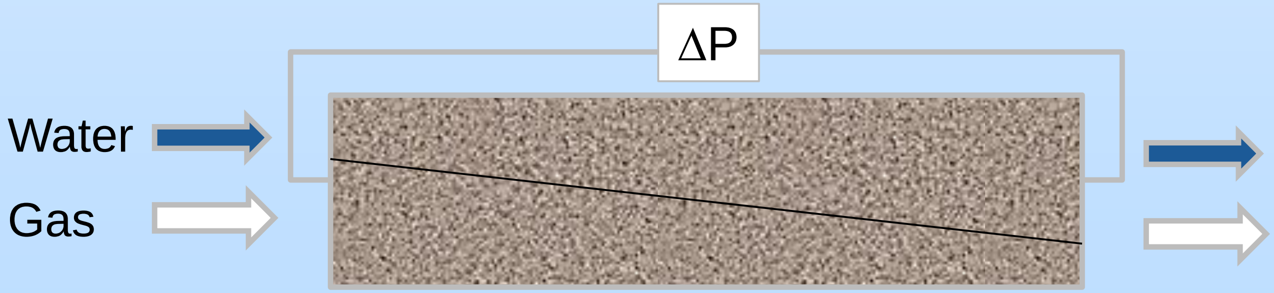
Relative Permeability Experiments

- Measurements of relative permeability with N_2 and water
- Starting with N_2 to get non-reactive k_{re}
- Steady state relative permeability measurements made by co-injecting gas and water
- Saturation measured using X-ray CT
- Preliminary results similar to N_2-water measurements from Bertels et al. (2001) and Huo and Benson (2016)
- Highly interfering flows between water and gas



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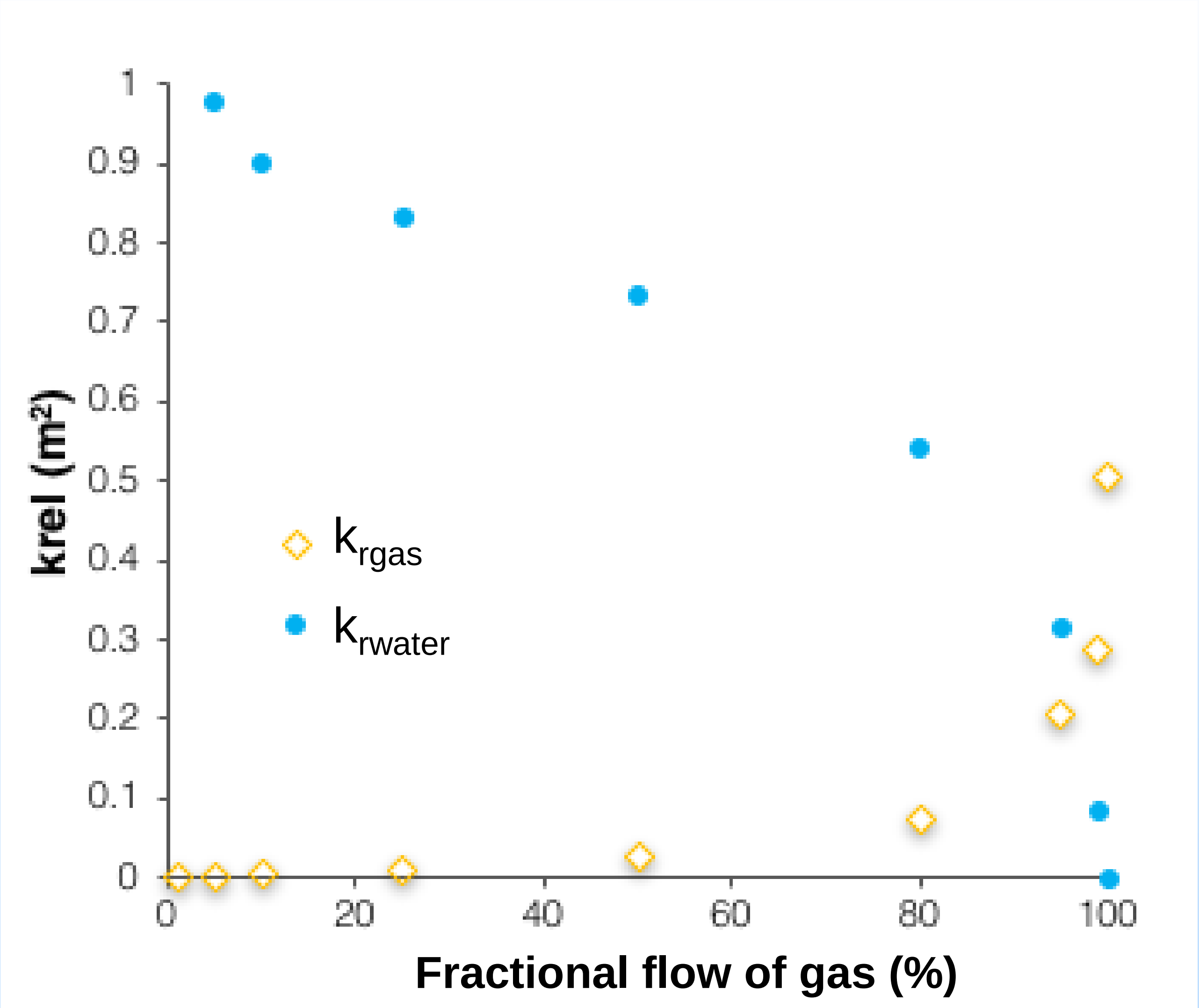
Relative Permeability Measurements



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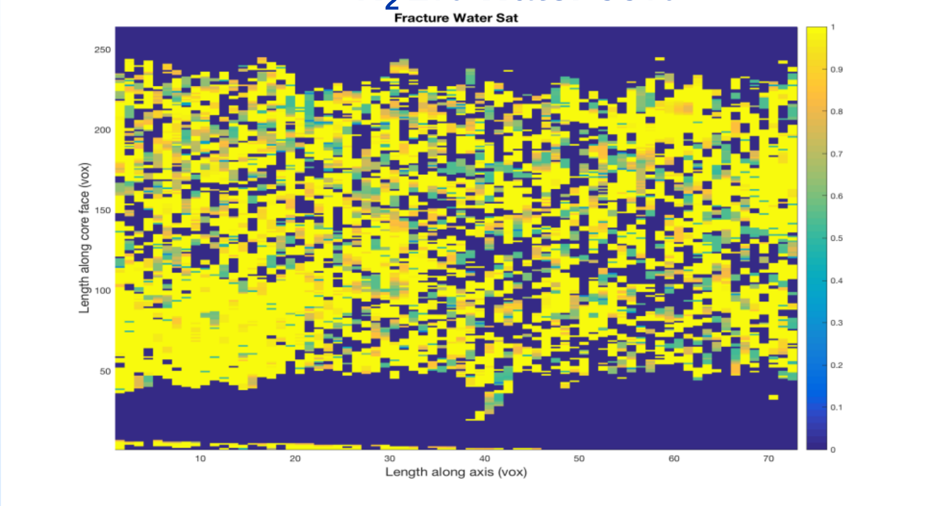
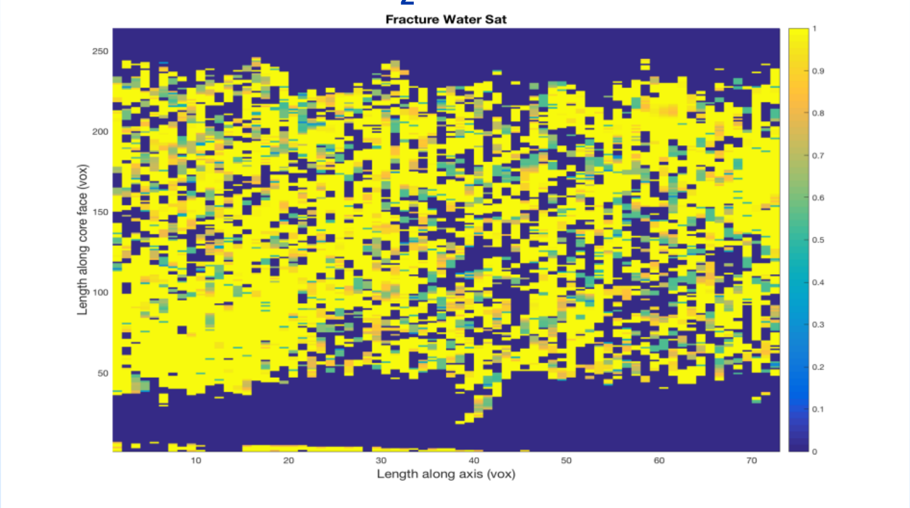
Fracture Saturation Measurements

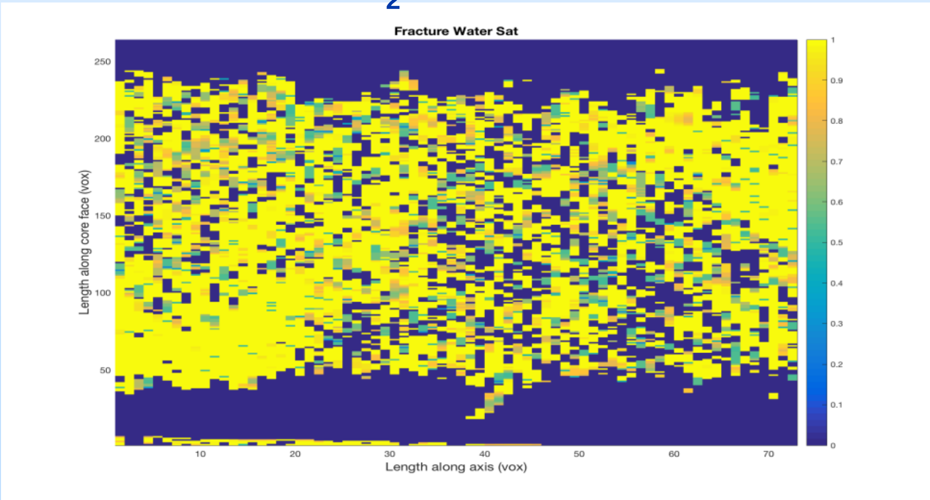
N_2 1% Water 99%



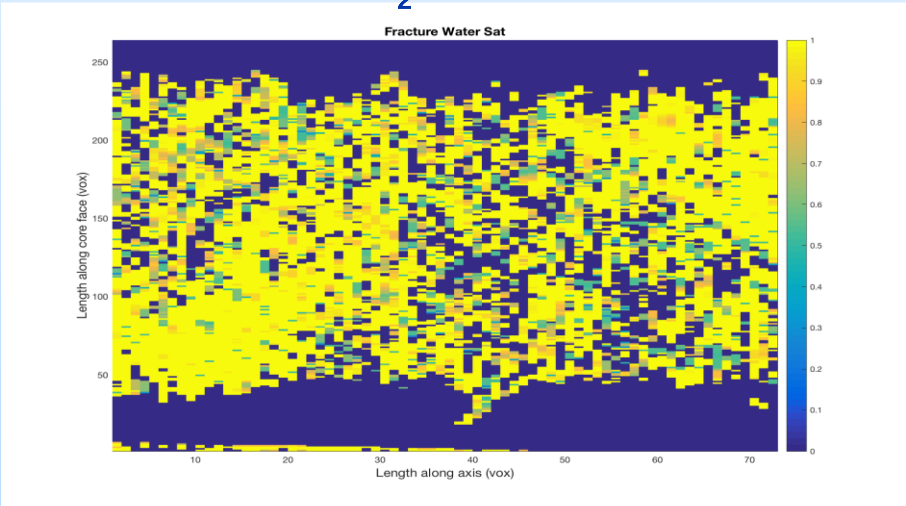
N_2 5% Water 95%



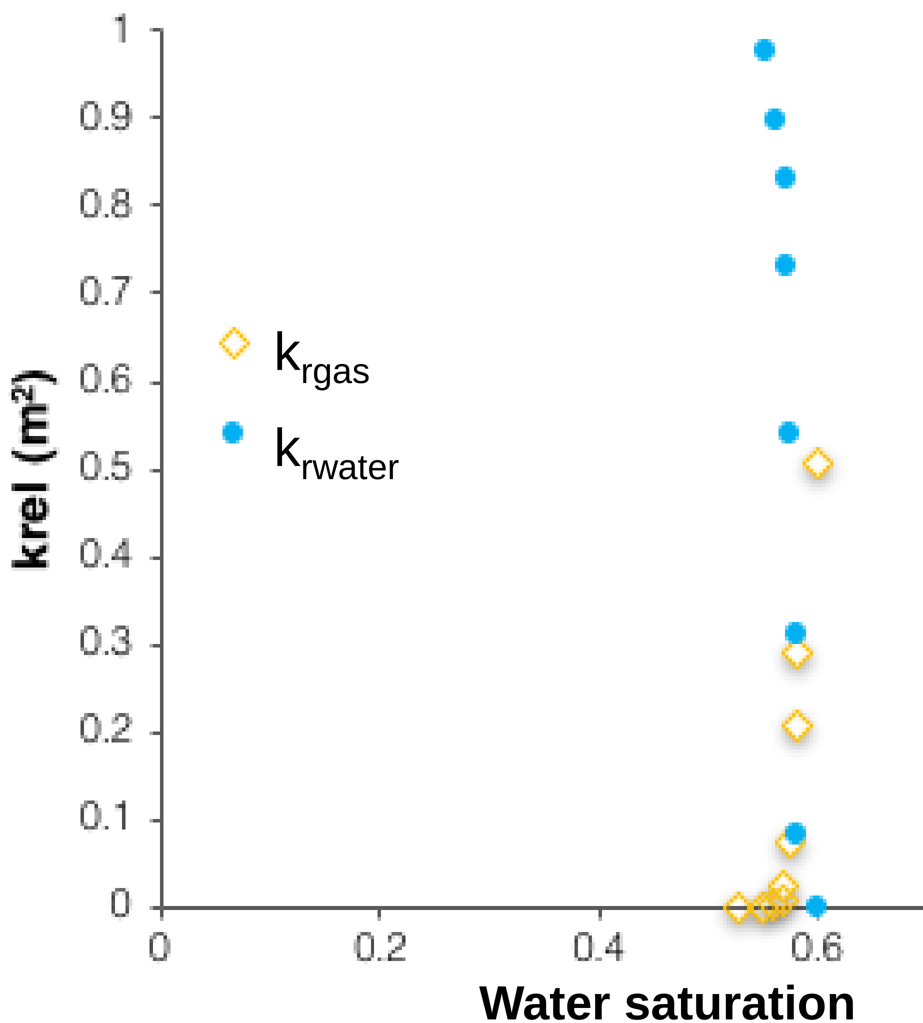
N_2 10% Water 90%



N_2 25% Water 75%



Relative Permeability vs. Saturation



But, we still need to do better on the saturation measurements.

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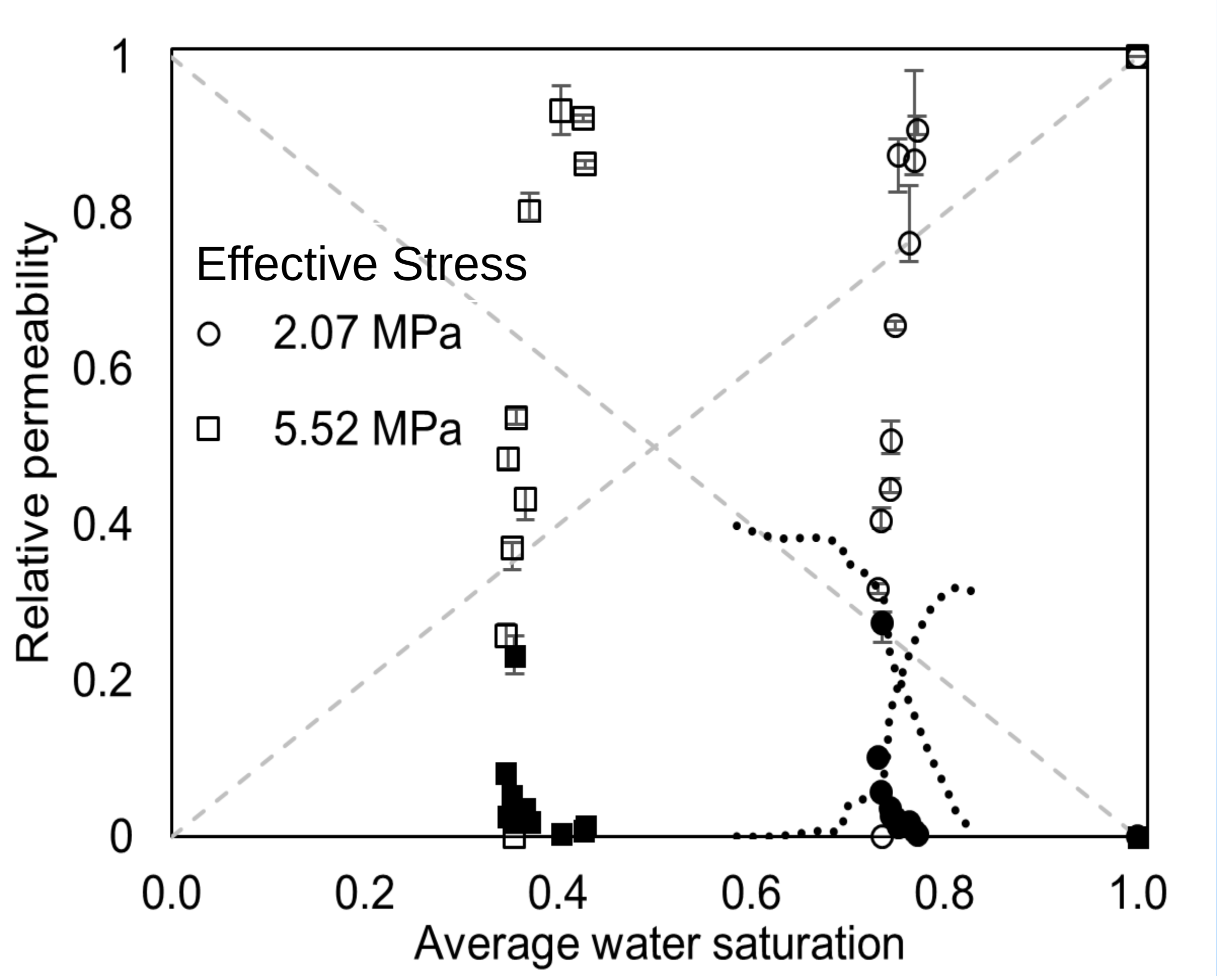
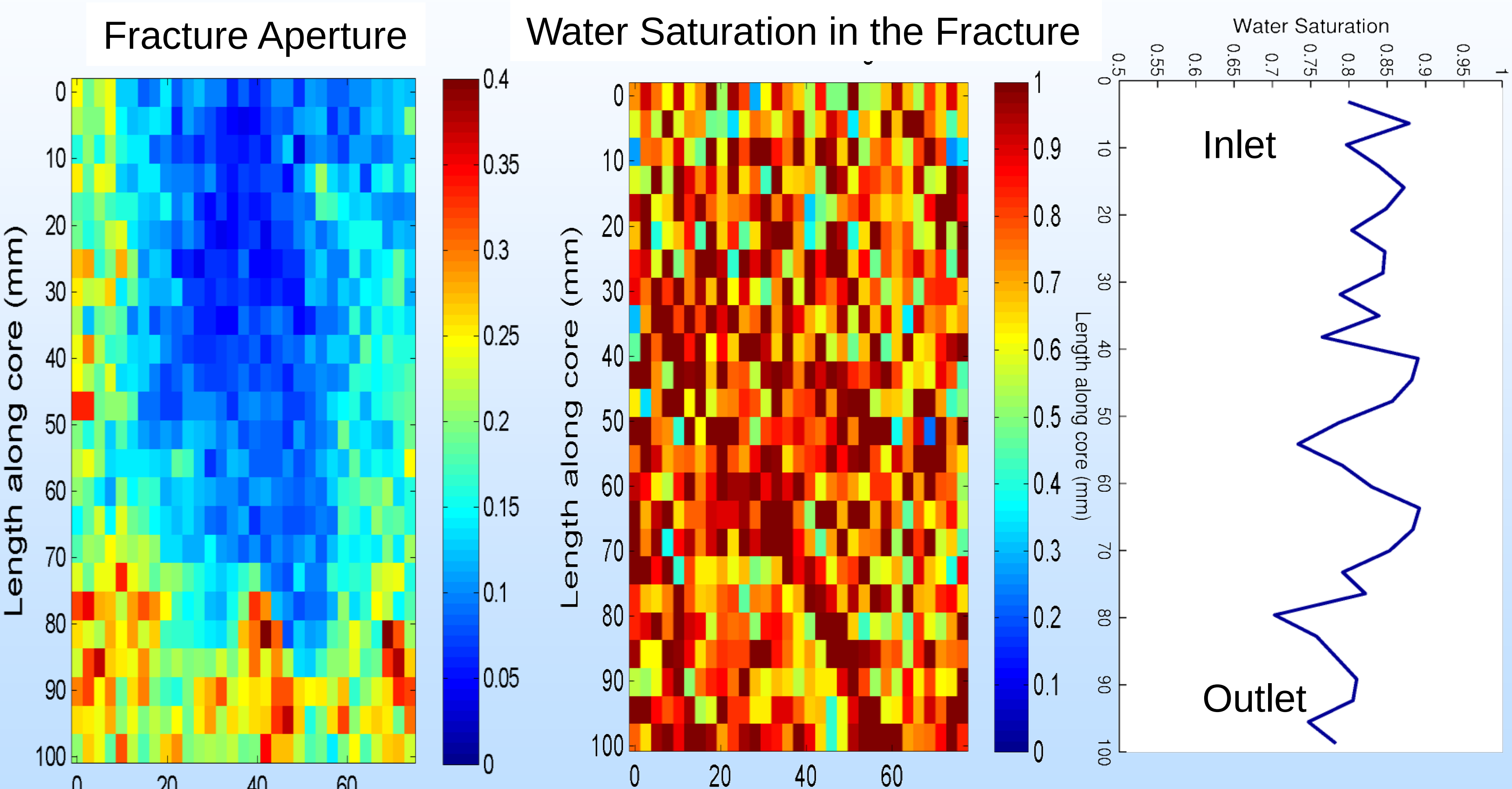
Basalt Relative Permeability Measurements Similar to Other Rocks



Huo, D., & Benson, S. M. (2016). Experimental Investigation of Stress-Dependency of Relative Permeability in Rock Fractures. *Transport in Porous Media*, 1-24.

Positron Emission Tomography Imaging of Fracture Saturation



First measurements made in a natural basalt fracture.

Relative Permeability Measurements

Next Steps:

- Positron emission tomography for improved saturation measurements
- Experiments on real rock fractures in basalt (we have these cores)
- CO_2-brine k_{rel} experiments
  - Assess reactive k_{rel} alteration
- Perform experiments over range of confining pressures
- Mechanistic model for stress-dependent k_{rel}

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 (presented in 2015)
  - Begin outcrop scale modeling study of CO_2 transport in CRBG fracture network.
  - Receive training at LBNL on coupled THMC simulator, TRM
- Core-flood experiments
  - Initial basalt permeability experiment
  - Initial N_2-water relative permeability experiment

Synergy Opportunities

- Scaling micro-structural analysis to outcrop &/or fields scales.
- Incorporating kinetic dissolution models for basalt CO_2 reactivity
- Permeability-porosity scaling with mineralization

Summary

Key Findings

- Pressure accumulation is sensitive to relative permeability, even at low injection rate.
  - k_{nw} strongly influences maximum pressure build-up
- Model of regional-scale permeability anisotropy
- Basalt k_{rel} is highly interfering

Future Plans

- Stochastically generated reservoir models.
  - MINC representation of reservoir-scale fracture system.
- Improve fracture saturation measurements in basalt fracture.
- Mechanistic model of stress-dependent relative permeability.
- Integrate k_{rel} model into reservoir scale model.
- Numerical simulation to quantify risk of geomechanical reservoir failure.

Bibliography

Peer-reviewed publications:

- Pollyea, R.M., 2016, Influence of relative permeability on injection pressure and plume configuration during CO_2 injections in a mafic reservoir: *International Journal of Greenhouse Gas Control*, v. 46, p. 7 – 17. available at: http://www.sciencedirect.com/science/article/pii/S1750583615301729

Conference abstracts (**bold** denotes student author):

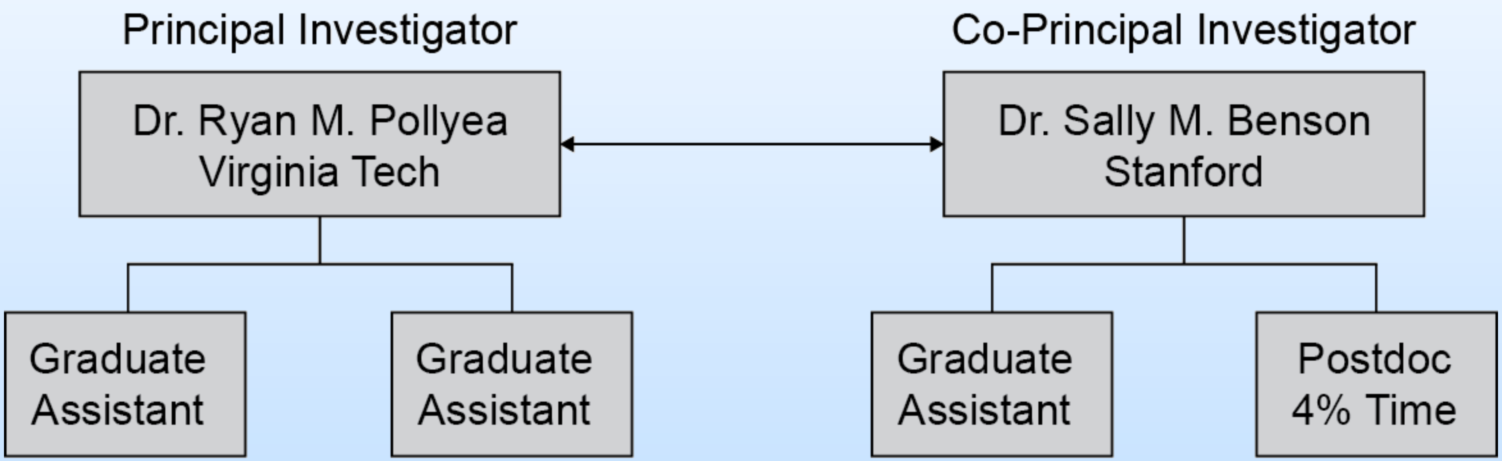
- **Gierzynski, A.G.** and Pollyea, R.M., 2016, Quantifying the effects of spatial uncertainty in fracture permeability on CO_2 leakage through Columbia River Basalt Flow interiors. American Geophysical Union Fall Meeting, 12 – 16 December, San Francisco, California (abstract submitted).
- **Jayne, R.S.** and Pollyea, R.M., 2016, Constraining the effects of permeability uncertainty for geologic CO_2 sequestration in a basalt reservoir. American Geophysical Union Fall Meeting, 12 – 16 December, San Francisco, California (abstract submitted).
- **Gierzynski, A.G.** and Pollyea, R.M., 2016, Quantifying the effects of spatial uncertainty in fracture permeability on CO_2 leakage through caprocks during geologic CO_2 storage in continental flood basalts. Geological Society of America Annual Meeting, 25 – 28 September, 2016. (Abstract selected for oral presentation.)

Bibliography

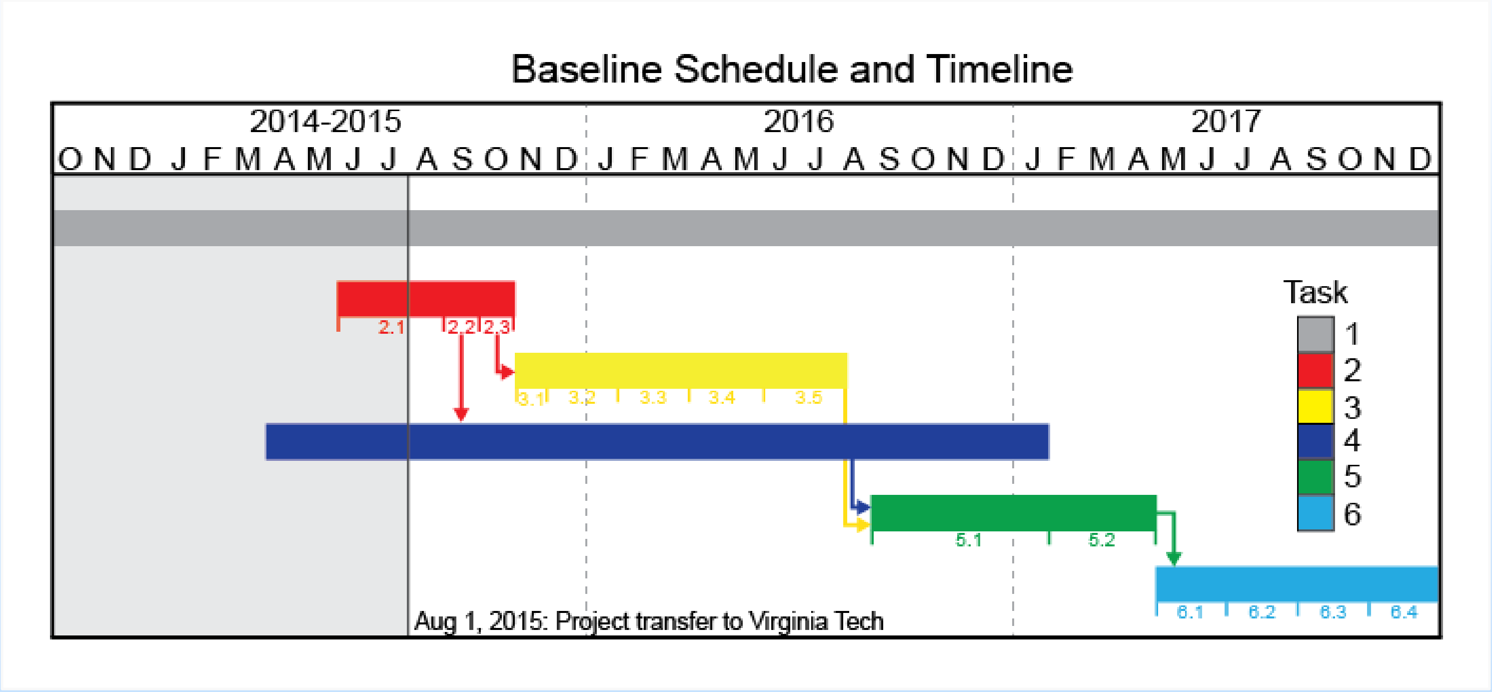
Conference abstracts (cont.):

- Pollyea, R.M. and Rimstidt, J.D., 2016, A kinetic rate model for crystalline basalt dissolution at temperature and pressure conditions relevant for geologic CO_2 sequestration. American Geophysical Union Fall Meeting, 12 – 16 December, San Francisco, California (abstract submitted).
- Pollyea, R.M. System response as a function of relative permeability in geologic CO_2 sequestration. American Geophysical Union Fall Meeting, 14 – 18 December, San Francisco, California.

Organization Chart



Gantt Chart



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