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

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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*.

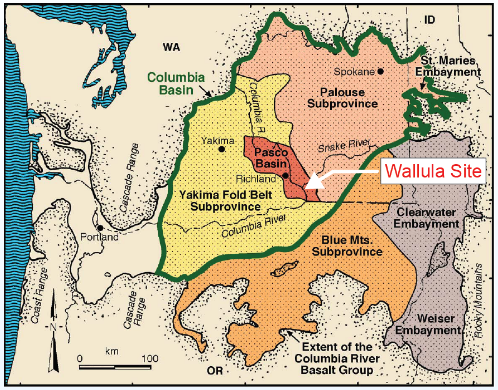
Project Overview: Goals and Objectives

- 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 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

- Geomechanical analysis for Slack Canyon #2 Flow Top
  - Borehole breakdown pressure (P_b)
  - Mohr failure envelope for intact rock mass
- Investigate k_{rel} parameter space with numerical simulations
  - Evaluate simulated P_f against failure criteria
- Core-flood experiments to assess reactivity
  - Permeability & porosity

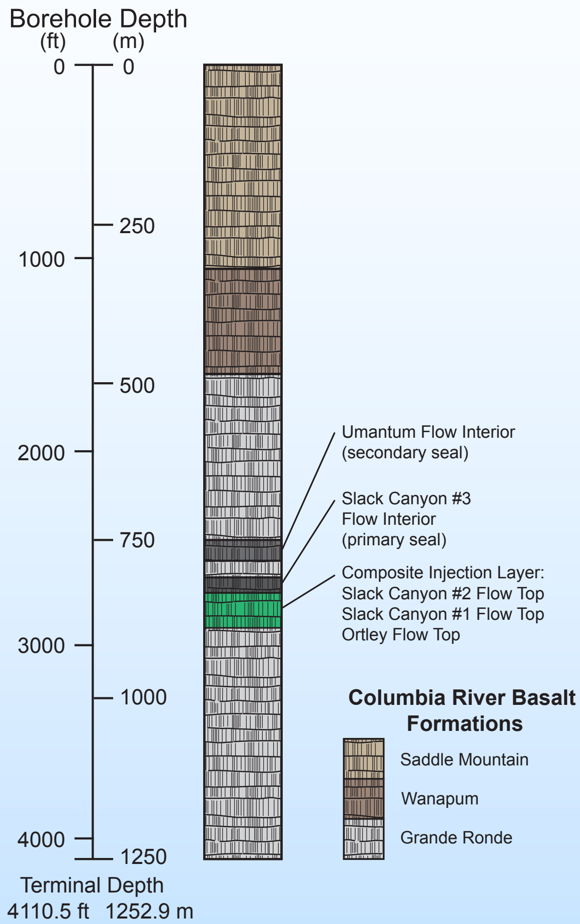
Site Map & Stress in SE Wash.

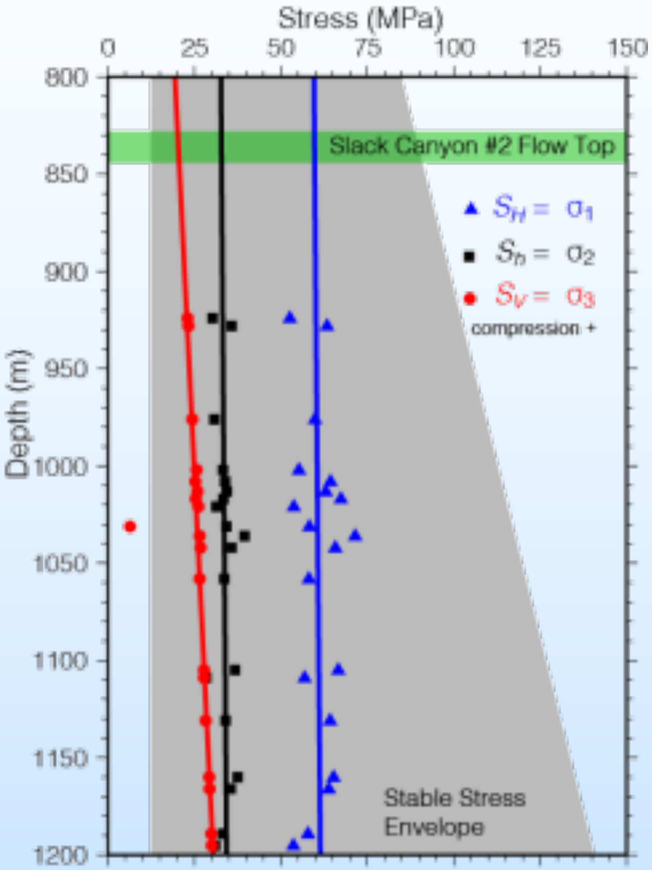


Modified after Reidel et al., 2002

CO_2 injection model in Slack Canyon #2 Flow Top.

How does k_{rel} parameter space influence injection pressure & failure criteria?





Data from Paillet and Kim, 1997

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Reservoir Failure Criteria

Breakdown Pressure (P_b)

$$P_b = \frac{3S_h - S_H + T_o - 2\eta P_f}{1 + \beta - 2\eta} = 12.75 MPa$$

T_o: tensile strength = 1.5 MPa
β: effective stress coefficient.
assume β = 1
η: poroelastic parameter

$$\eta = \frac{\alpha(1-2\nu)}{2(1-\nu)}$$

α: Biot Parameter = 1 – β_i/β_b
β_i: intact basalt compressibility
= 1.92E-11 MPa^{-1}
β_b: rock mass compressibility
= 4.81E-11 MPa^{-1}
v = Poisson's ratio = 0.3

Mohr Failure

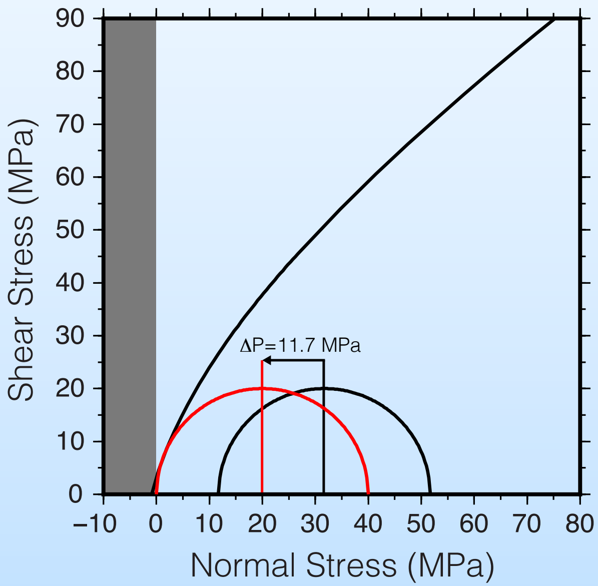
Strength envelope for basaltic rock mass. From Schultz,1993

$$\tau = (\sigma_n - \sigma_3)\sqrt{1 + \frac{m\sigma_c}{4\tau_{max}}}$$

σ_c: unconfined comp. strength = 37.5 MPa
m: emprirical rock mass parameter = 6.303

$\sigma_{1,eff}$ = 51.7 MPa
$\sigma_{3,eff}$ = 11.7 MPa

ΔP at failure:
11.7 MPa



Parameters from Schultz, 1995, Limits on strength and deformation properties of jointed basaltic rock masses

Numerical Model Setup

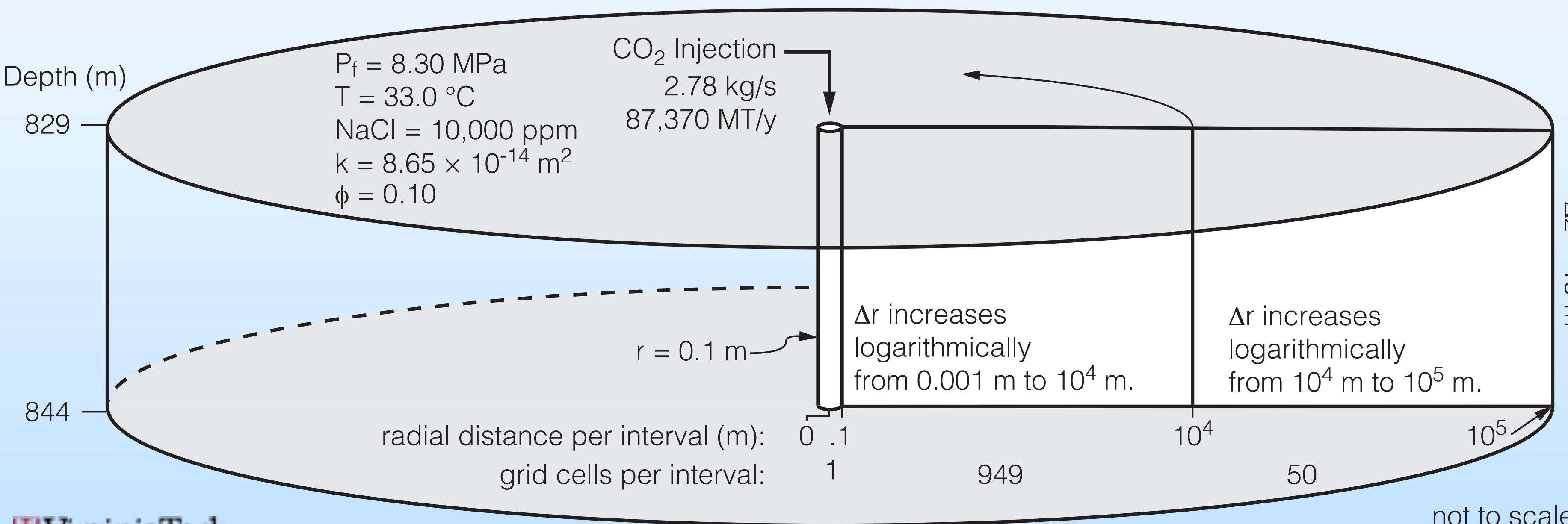
Simple 1D model to learn how k_{rel} parameters influence P_f

TOUGH3 (beta) with ECO2N equation of state

Properties from Wallula Site Characterization Report

10% of proposed CO_2 mass into Slack Canyon #2 flow top

High resolution grid (Δr = 1 mm) near well



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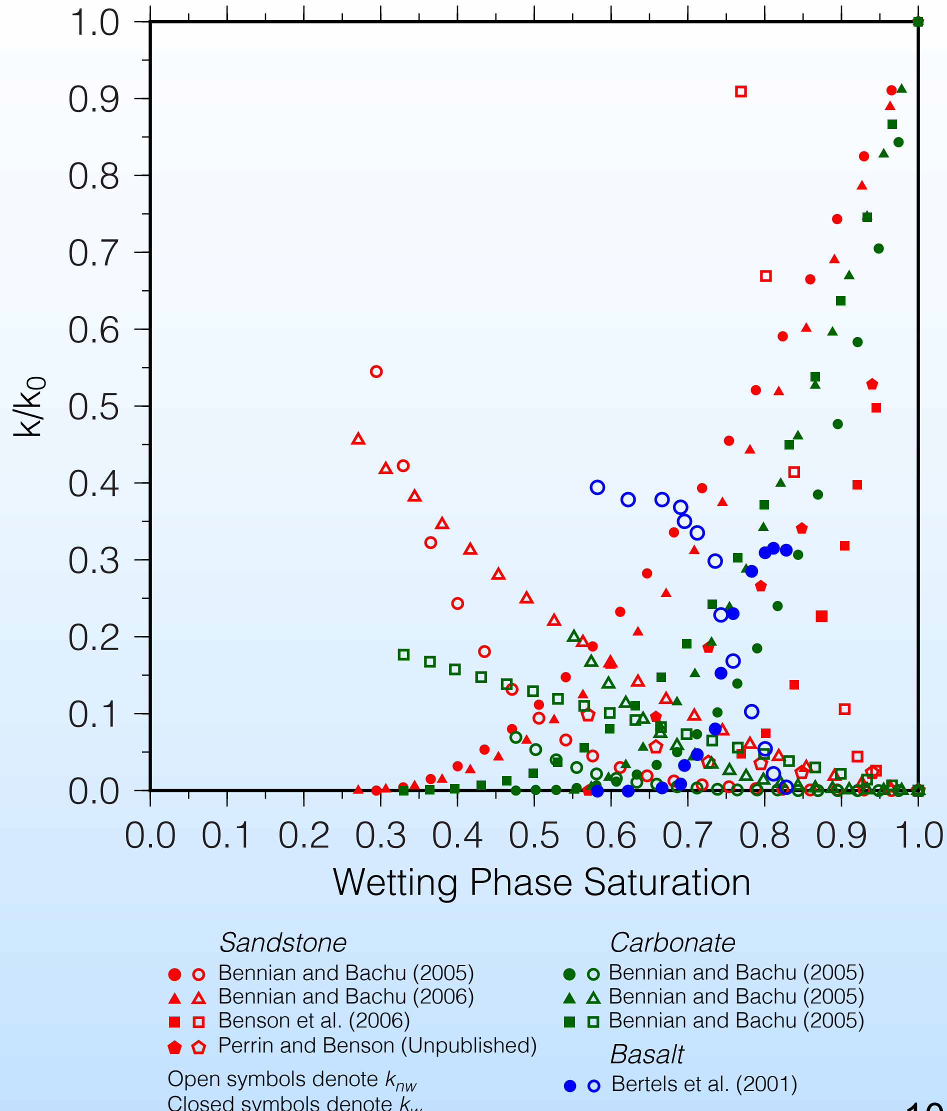
Relative Permeability

Uncertainty abounds in CO_2-brine k_{rel} within basalts

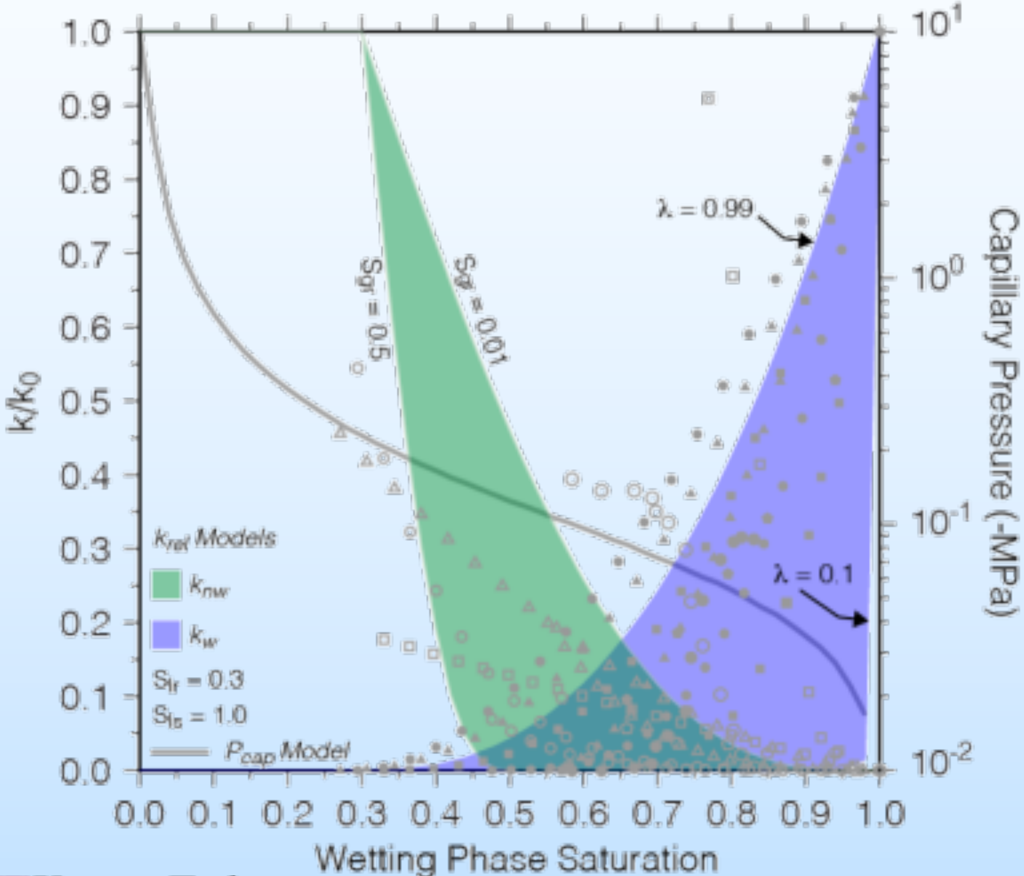
- Sandstone & carbonate data from CO_2-brine experiments.
- Basalt data with nitrogen and pure water.

Relative permeability in CO_2-brine is moderate to highly interfering.



Test variability in k_{rel} to P_f

Set up van Genuchten (1980) relative permeability model to cover range of existing k_{rel} data



k_w drop controlled by phase interference parameter (λ)

$$k_w = \sqrt{S^*}\left(1-\left(1-\left(S^*\right)^{1/\lambda}\right)^{\lambda}\right)^2$$

$$S^* = \left(S_l - S_{lr}\right)/\left(S_{ls} - S_{lr}\right)$$

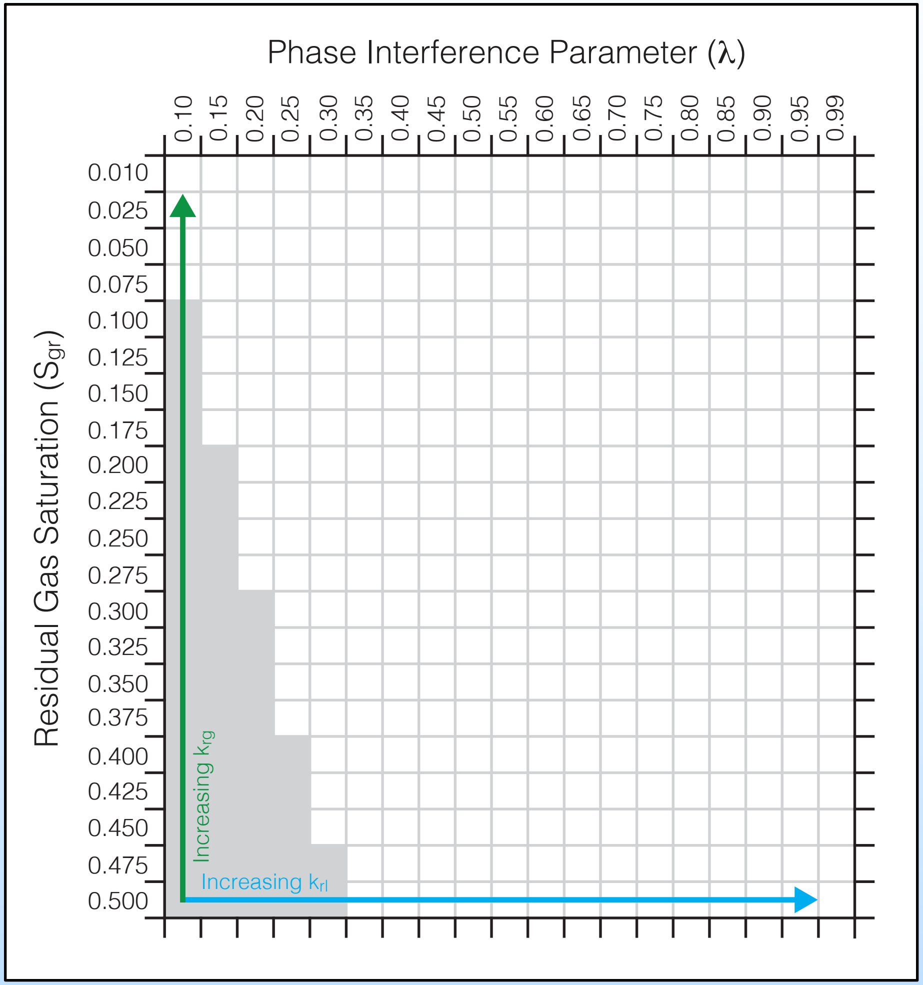
k_{nw} reduction controlled by residual saturation (S_{gr})

$$k_{nw} = \left(1-\hat{S}\right)^2\left(1-\hat{S}^2\right)$$

$$\hat{S} = \left(S_l - S_{lr}\right)/\left(1 - S_{lr} - S_{gr}\right)$$

Test variability in k_{rel} to P_f

Simulate CO_2 injection into Slack Canyon #2 flow top over 399 unique combinations of λ and S_{gr}



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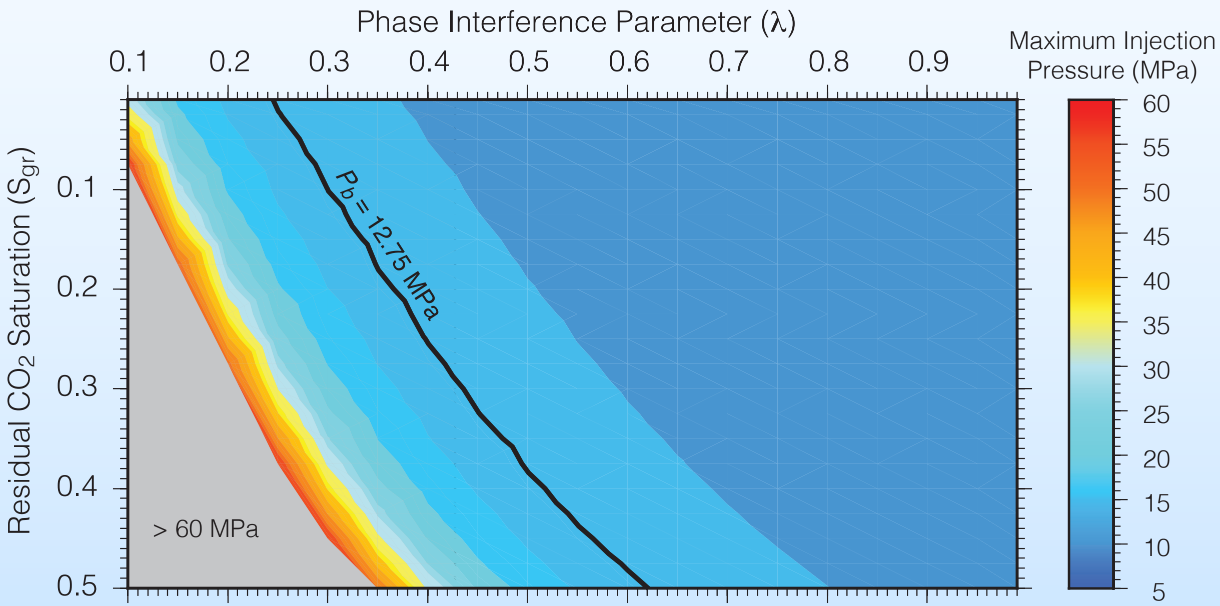
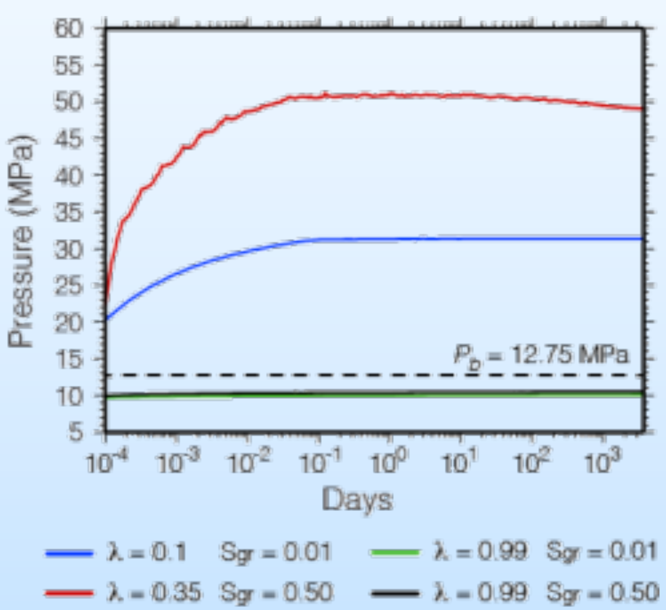
Injection Pressure Response

Below breakdown across ~2/3 of parameter space.

k_{nw} strongly influences injection pressure magnitude.



Time-series injection pressure



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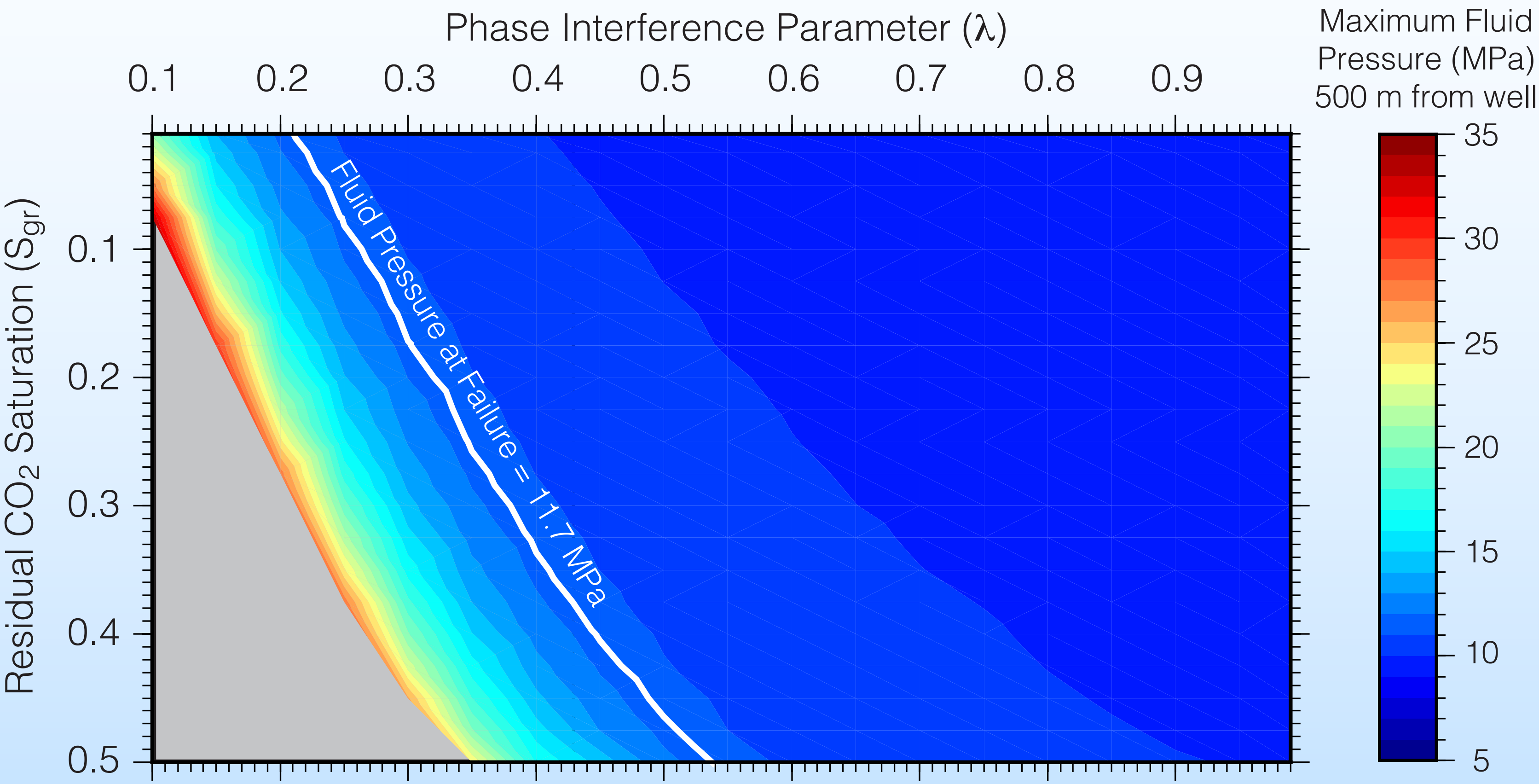
Mohr Failure in Far-Field

Mohr failure only for most restrictive parameter sets.

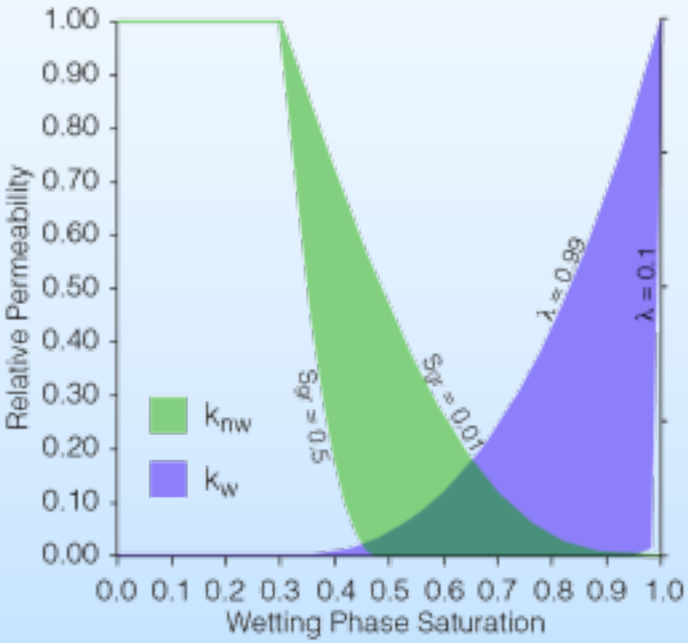
(at 87,730 MT/yr)

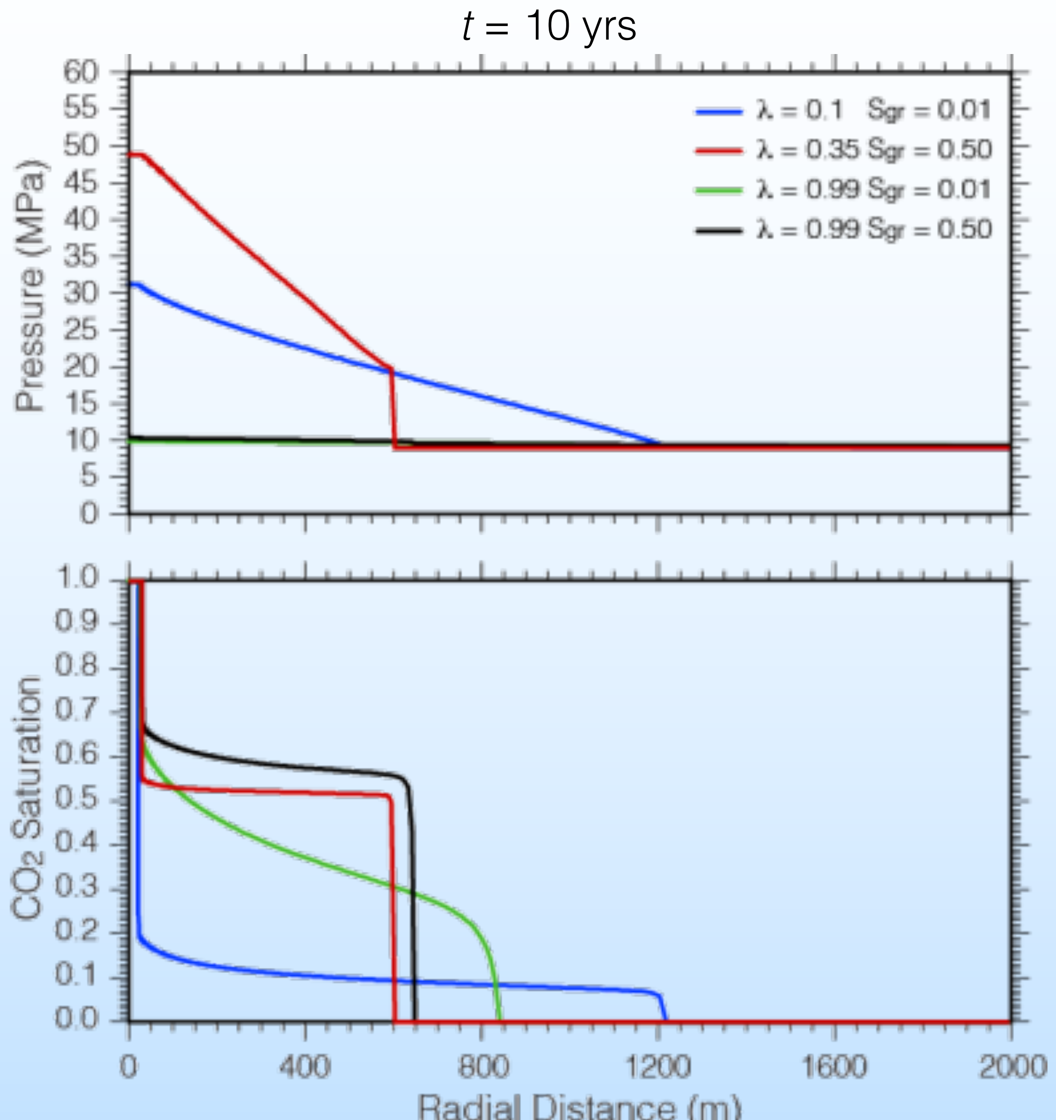


CO_2 & Pressure Distribution

Discrete wetting front when k_{nw} drops sharply

Discrete pressure front when k_w drops sharply





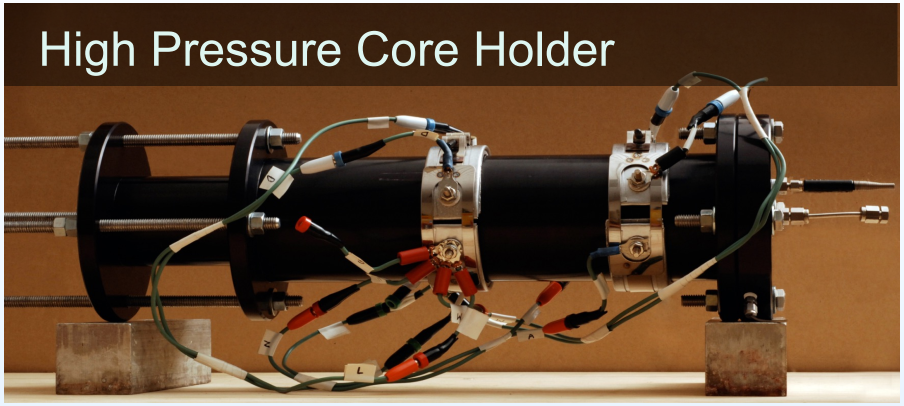
Core-Flood Experiments

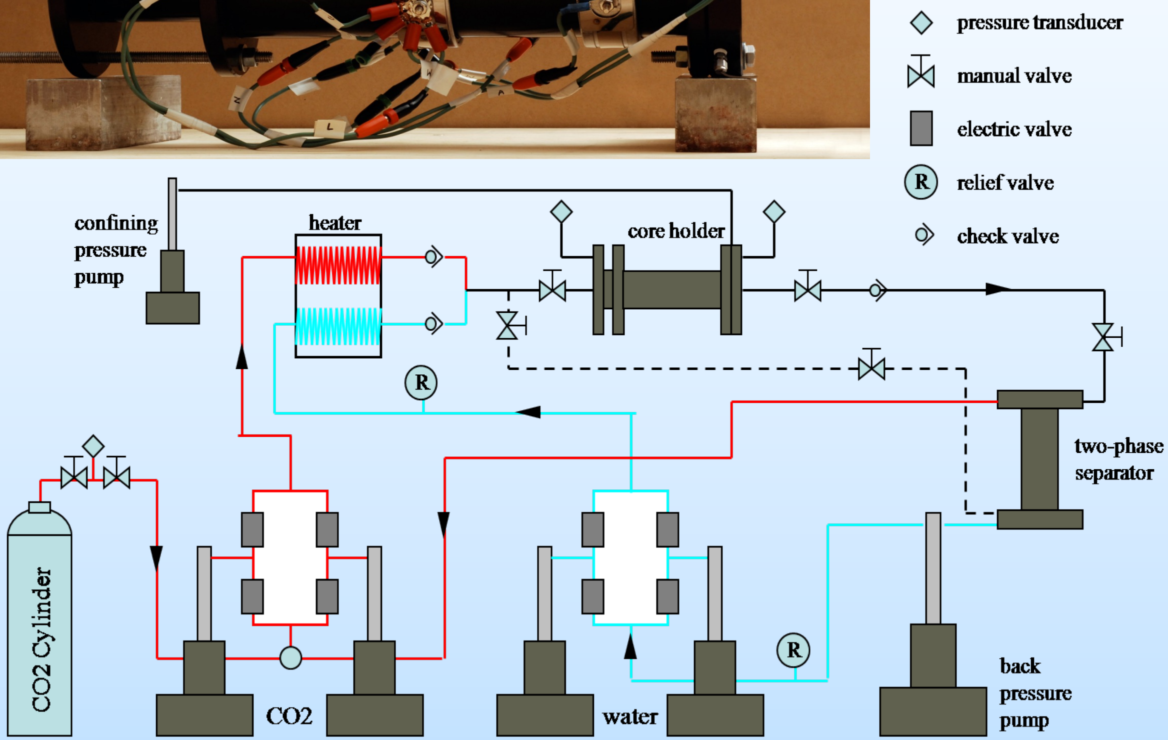
Methodological development is complete & experiments are now able to be performed reliably

- ✓ Fracture apertures under changing stress
- ✓ Permeability
- ✓ Relative permeability
- ✓ Fracture saturation
- ✓ Capillary pressure

Core-Flood Experiments

Core-Flood Visualization Facility





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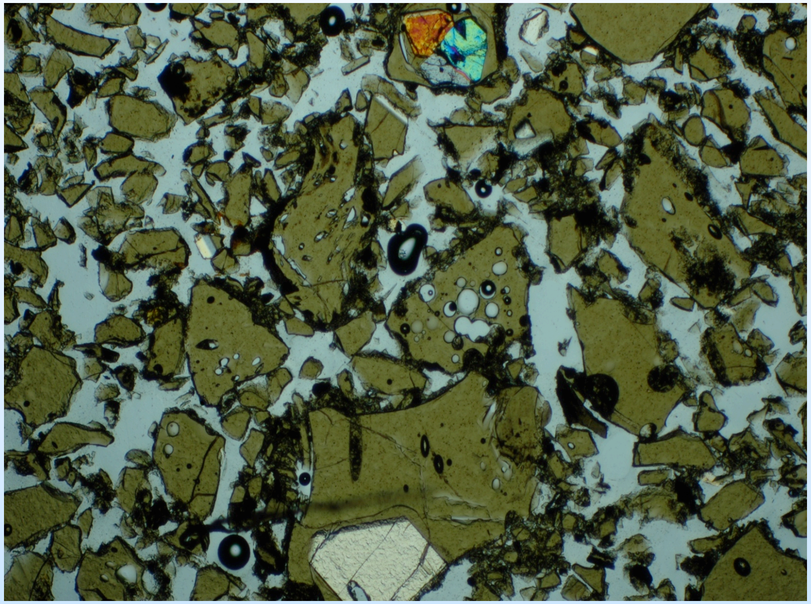
Core-Flood Experiments

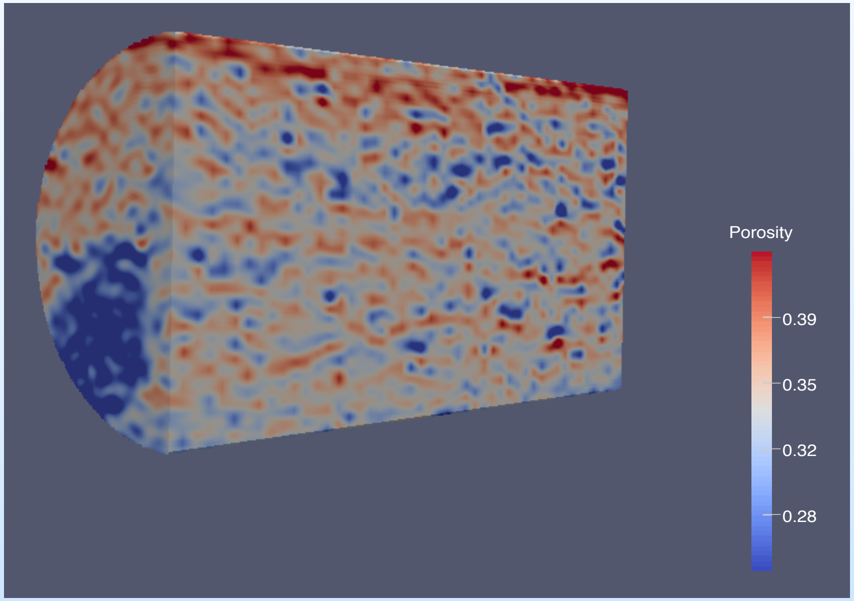
Influence of geomechanical reactions on transport properties

Basalt tuff is used as an end-member to understand reactivity of the glass fraction of basalt and its influence on transport properties

Thin Section of Basaltic Tuff



3-D Image of Basaltic Tuff Porosity



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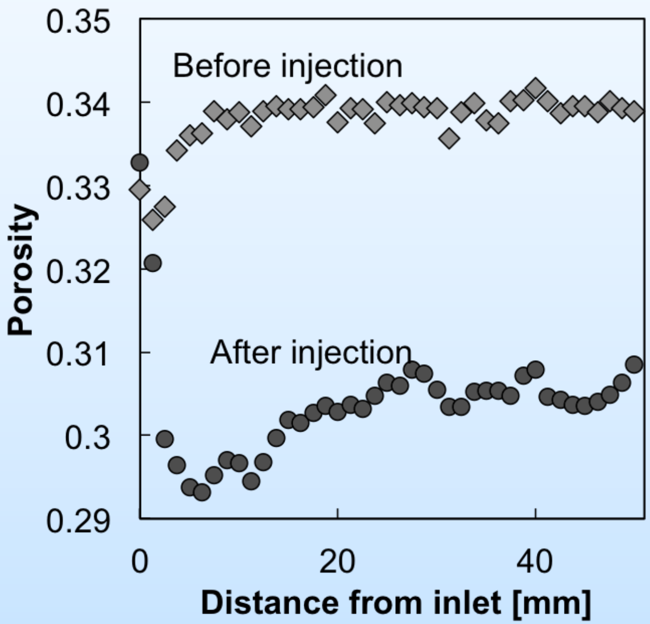
Core-Flood Experiments

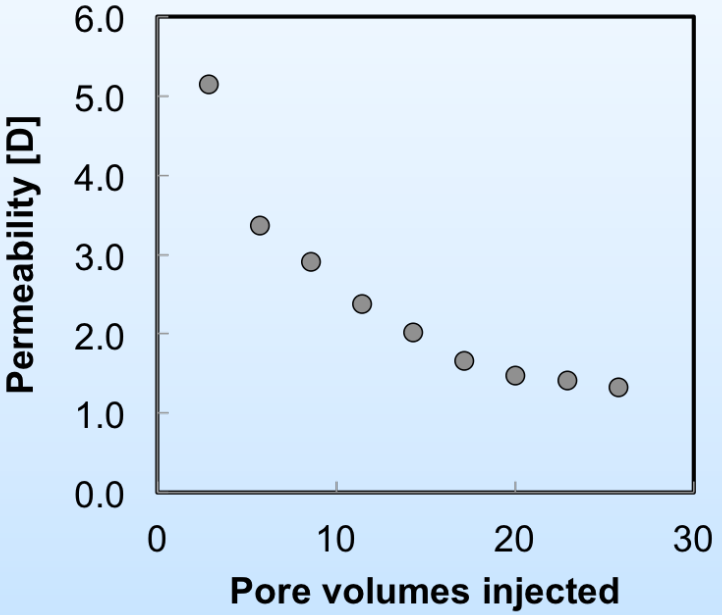
Basalt tuff is highly reactive

Exposure to carbonated brines quickly reduces permeability and porosity

Porosity change



Permeability change



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Accomplishments to Date

- Build database of CRBG properties
  - *In situ* stress data from Hanford
  - Saturated and unsaturated hydraulic properties from literature
  - Mechanical properties for intact rock mass
- Geomechanical analysis for Slack Canyon #2 Flow Top
  - Borehole breakdown pressure (P_b)
  - Mohr failure envelope for intact rock mass
- Investigate k_{rel} parameter space with numerical simulations
  - Evaluate simulated P_f against failure criteria
- Core-flood experiments to assess reactivity
  - Experimental procedures are complete
  - Initial experiments show basaltic tuff is highly reactive
    - » Rapid change in porosity & permeability

Synergy Opportunities

– Coupled thermal-hydro-mechanical modeling
– Lab-scale to field-scale

Summary

Key Findings

- Pressure accumulation is sensitive to relative permeability, even at low injection rate.
  - k_{nw} strongly influences maximum pressure build-up
- Far-field failure is unlikely for simulation scenarios tested here.
- Basaltic tuff is highly reactive.
  - Rapid drop in porosity & permeability

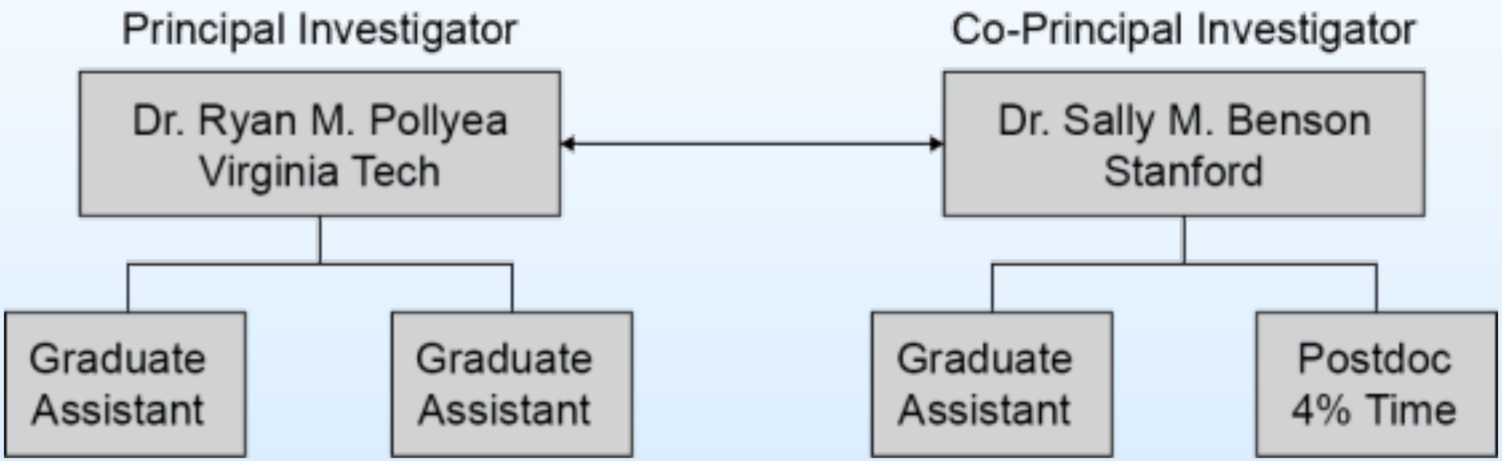
Future Plans

- Field work scheduled for Fall 2015 to obtain LiDAR scans of CRBG fracture networks.
- Reservoir characterization and stochastic simulation for Monte Carlo modeling.
- Thin sections for petrographic analysis.
- Capillary pressure measurements
- Stress-dependent permeability experiments

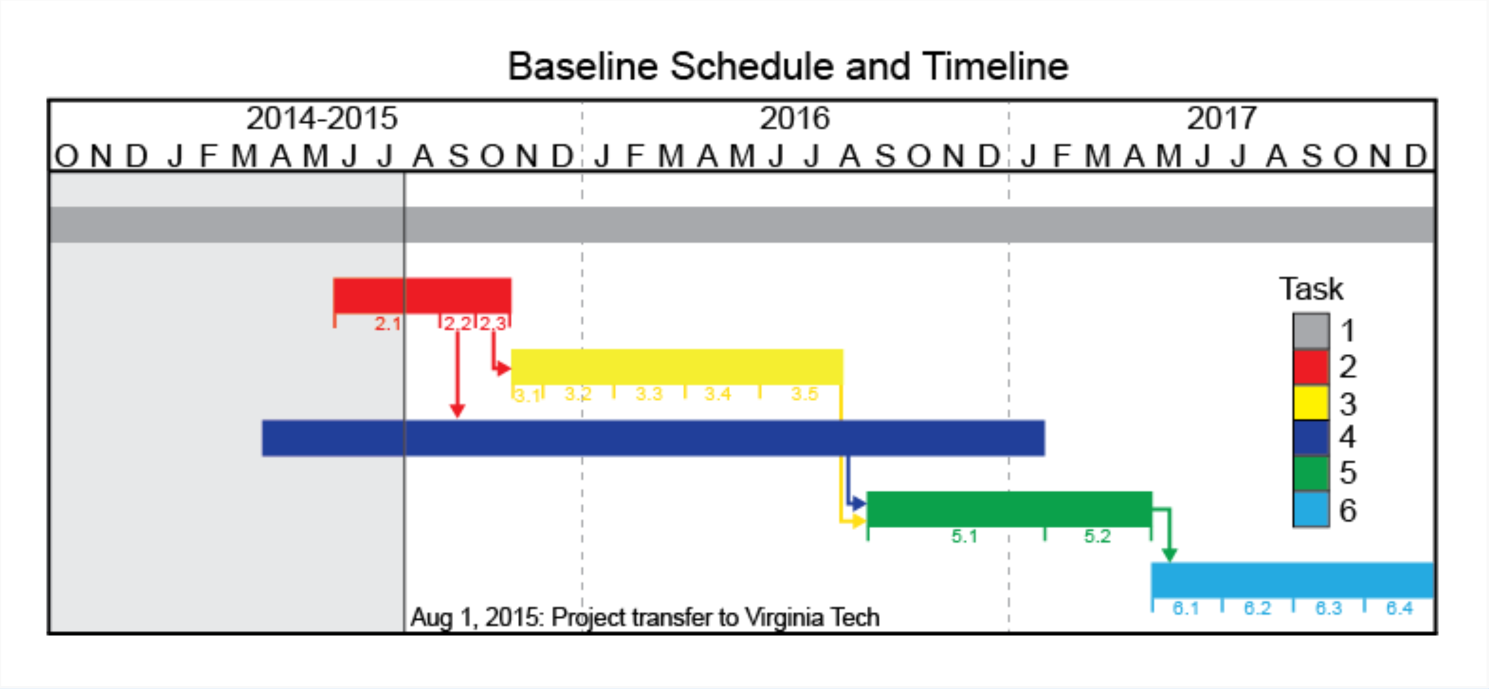
Appendix

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

Organization Chart



Gantt Chart



Baseline Schedule and Timeline
2014-2015
2016
2017
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
2.1
2.2
2.3
3.1
3.2
3.3
3.4
3.5
5.1
5.2
6.1
6.2
6.3
6.4
Task
1
2
3
4
5
6
Aug 1, 2015: Project transfer to Virginia Tech

Bibliography

Project started Jan 1, 2015 – draft manuscripts are underway.