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

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Presentation Outline

- Introduction
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- Project Overview
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- Project Structure
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Benefit to the Program

- Area of Interest 1: 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

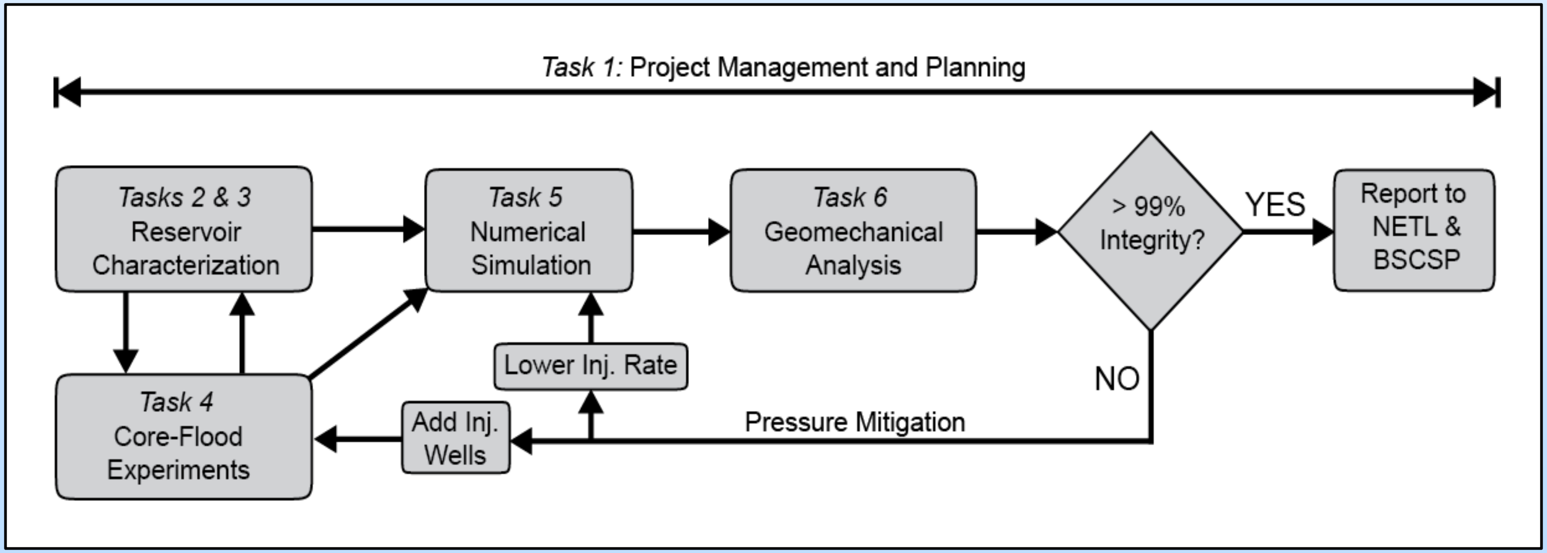
In pursuing this research, we consider (1) reservoir permeability is a first-order control on injection pressure accumulation during CO_2 injections, and (2) the spatial distribution of *in situ* CRBG fracture distributions is *a priori* unknowable at the scale of interest for industrial CCS operations (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 various 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

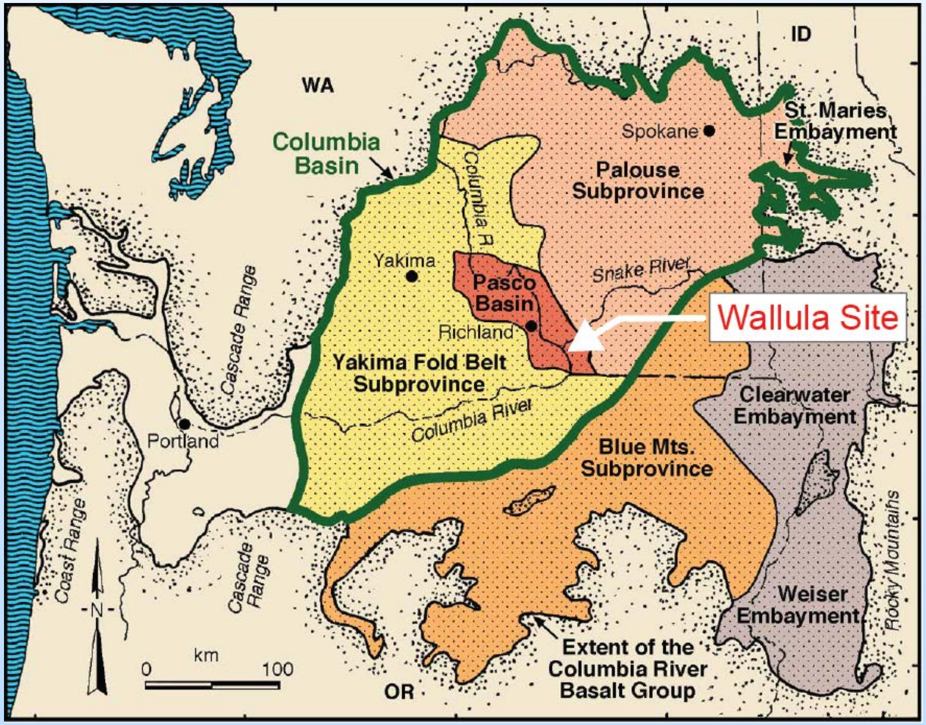
Methodology: Overview

- Reservoir characterization
- Core-flood experiments
- Numerical simulation
- Geomechanical analysis



Methodology: Site Map

- Wallula Basalt Sequestration Pilot Project
  - Began Site Characterization in 2007
  - Completed 1,000 metric ton injection in August 2013

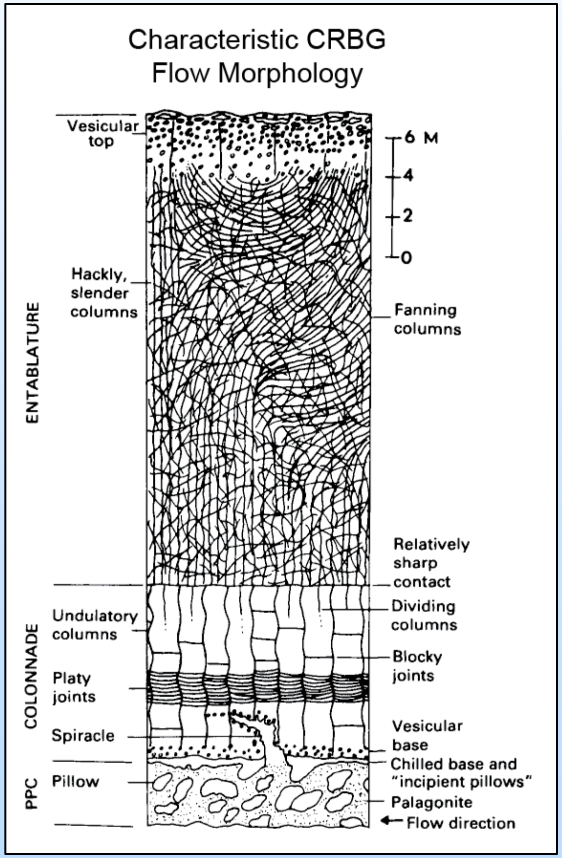


Modified after Reidel et al., 2002

Reservoir Characterization

- Columbia River Basalt Group
  - Layered assemblage of flood basalt flows

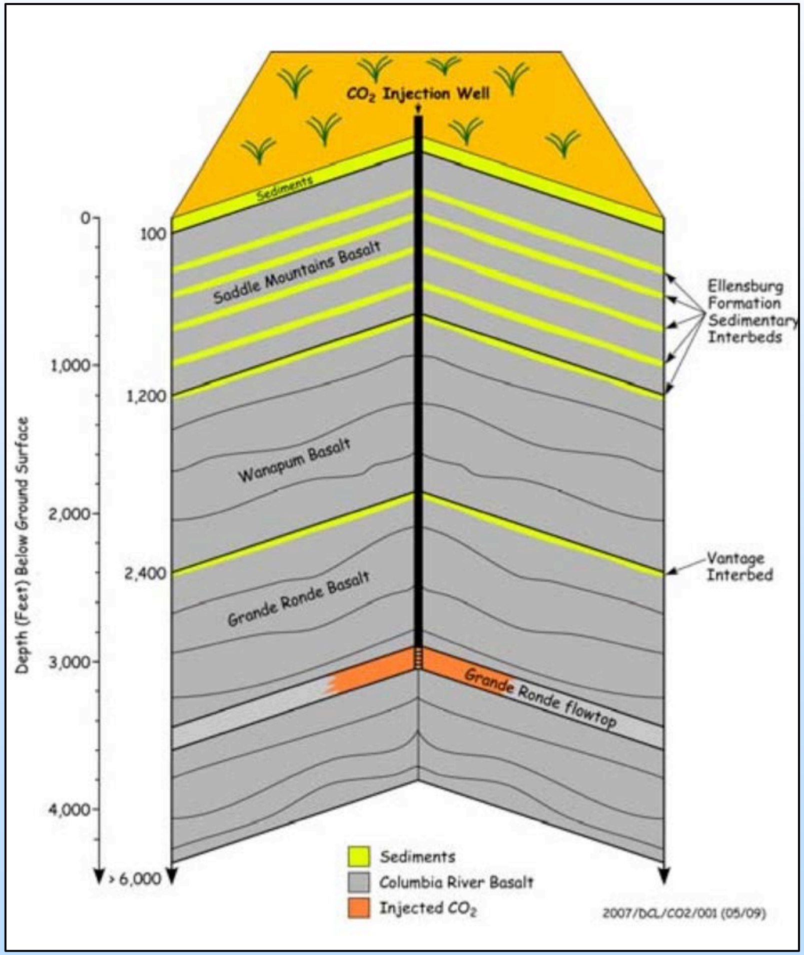
Photo Credit: William Borg, Creative commons license



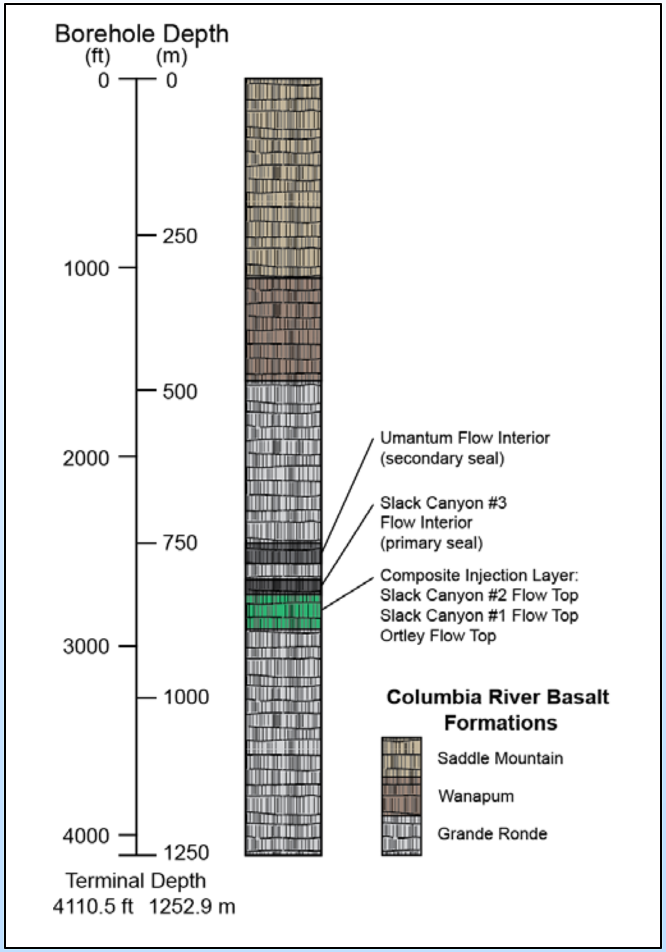
Modified after Mangan et al. (1986)

Reservoir Characterization

- Wallula Site Borehole Geology



Spane et al. (2007)



Reservoir Characterization

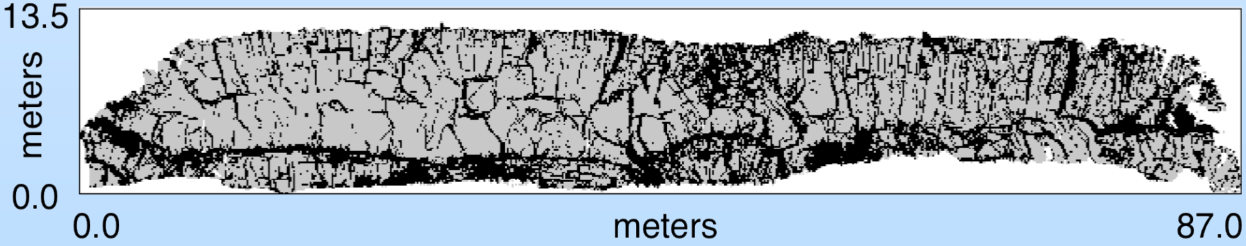
- Stochastic continuum at km scale
  - Combine Wallula test bore geology and fracture correlation models from observable outcrops
    - Fracture correlation models based on LiDAR-derived fracture maps.
  - Simulate 100 equally probable synthetic reservoirs in three dimensions
    - Cartesian grid with 30 m × 30 m × 30 m grid cells
    - 7.5 km lateral extent; 1.2 km vertical extent
    - 2.5 M gridblocks per reservoir
    - Each reservoir reproduces known geology and inferred fracture correlation structure

Field Sampling

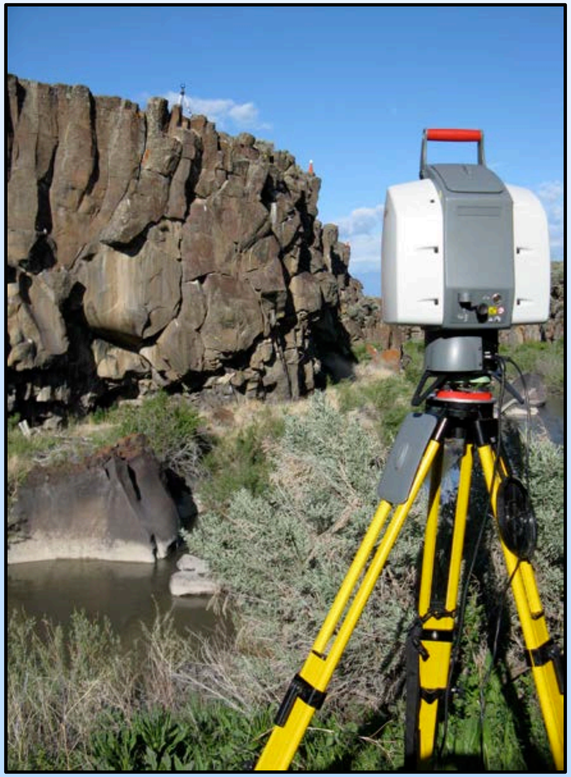
- Terrestrial LiDAR scans at Grande Ronde Formation outcrops.

Example from East Snake River Plain, Idaho

Generate spatially referenced fracture distribution from point cloud



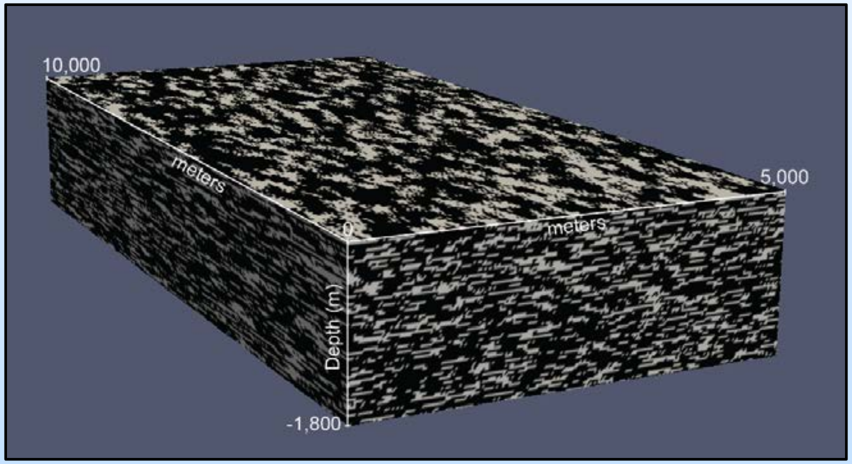
Pollyea and Fairley, *Geology*, 2011



Reservoir Simulation

- Simulate 100 synthetic reservoirs using a trimodal stochastic continuum.
  - rubbly flow tops
  - entablature
  - lower colonnade
- Generate reservoirs by sequential indicator simulation

Synthetic ESRP reservoir using bimodal continuum



Pollyea et al. *GSA Bulletin*, 2014

Reservoir Simulation

- Correlation structure for each continua is inferred using semivariogram correlation structure from LiDAR-derived fracture map.
  - Fracture maps are subdivided into each continua
  - Experimental semivariograms are computed and modeled for each continua
- Synthetic reservoirs (N=100) are conditioned to reproduce borehole geology.
- Uncertainty away from borehole is constrained by semivariogram correlation

Effective Permeability

- Bulk permeability for each continua is inferred from pumping tests in Wallula test bore.
- Depth-dependent permeability is applied using Saar and Manga (2003)
- Fit *k* to field data with decay constant (α)

$$k(z) = \begin{cases} k_{zs} e^{\frac{-z}{\alpha}} & , \quad z \le 800\ m^{1} \\ k_{zd} \left(\frac{z}{d}\right)^{-3.2} & , \quad z > 800\ m^{2} \end{cases}$$

Core-Flood Experiments

- Combine high-pressure core-flood apparatus with X-ray CT scanning to simultaneously measure:
  – Fracture aperture
  – Stress-dependent fracture permeability
  – Relative permeability
  – Capillary pressure

Core-Flood Experiments

- Example of stress-dependent aperture from Berea sandstone.

Numerical Simulation

- Simulate industrial scale CO_2 injections for three scenarios:
  - 37 MW biomass-fueled electrical generator
    - Proposed deployment scenario for Wallula Site
    - ~1.6 kg s^{-1}
  - 500 MW & 1,000 MW gas-fired power plants
    - ~21.6 & 43.2 kg s^{-1}
- Inject CO_2 between 840 m and 900 m depth
  - Proposed injection zone at Wallula Site
  - Slack Canyon #1 and Slack Canyon #2 flow tops

Numerical Simulation

- Monte Carlo modeling for each scenario
  - 100 individual simulations
  - Incorporate capillary pressure & relative permeability curves from core-flood experiments
  - Apply regional heat flux, 65 mW m^{-2} across bottom of domain
- TOUGH2-MP/ECO2N
  - Run simulations on NIU computing cluster
    - 60 nodes with 12 CPUs per node

Numerical Simulation

- Use step-wise process for incorporating stress-dependent permeability
  - Run initial set if simulations for 60 days
  - Export state of system at highest P_f
    - ESRP simulations suggest $P_{f,max}$ within 30 days
  - Augment bulk reservoir permeability on the basis of $P_{f,max}$ and results from core-flood experiments
  - Restart simulation for 20 years
- From yesterday's session it appears that TOUGH2/FLAC3D or TOUGH2-CSM may be a feasible option.

Numerical Simulation

- For each scenario, use E-Type estimates of gridblock P_f to assess ensemble behavior:
  - Mean P_f at each gridblock (x,y,z):

$$\bar{P}_{f(x,y,z)} = \frac{1}{100}\sum_{i=1}^{100} P_{f,i(x,y,z)}$$

  - P_f variance at each gridblock (x,y,z):

$$s^2 = \frac{1}{100}\sum_{i=1}^{100} (P_{f,i(x,y,z)} - \bar{P}_{f,(x,y,z)})^2$$

State of Stress in E. Washington

- $\sigma_1 = S_H$, $\sigma_3 = S_V$
- Data from Hanford
  - Paillet and Kim, 1987
  - 60 km NW of Wallula Site
- Use stress state and P_f to evaluate
  - Shear failure
  - Fracture dilation
  - Tensile failure

Shear Failure

- Nature of fanning entablature fractures suggests a subset is likely in optimal orientation for failure.
  - Unknowable *a priori*
  - For conservative estimate, assume all fractures are optimally aligned
- Compute failure probability for all gridblocks
  - Emphasis on overlying seal rocks
  - Failure probability < 1% by Mohr-Coloumb:

$$\bar{S}_{V,eff(x,y,z)}(t) - 3s_{(x,y,z)} > S_H[(\mu_s^2+1)^{1/2}+\mu_s]^{-2}$$

Fracture Dilation

- Fracture specific stiffness (κ) describes the relationship between $\sigma_{n,eff}$ and aperture (e)
  - For crystalline rocks, $\kappa \approx 100$ MPa mm^{-1}
- At Wallula Site, smallest σ_n affects fractures in S_H-S_h plane
  - Here, we propose a conservative criterion for fracture dilation in sealing entablature
    - $S_{V,eff} \leq 5$ MPa, corresponds to Δe of 0.1 mm
    - Assessing >1% probability of dilation for each gridblock:

$$\bar{S}_V - [\bar{P}_{f(x,y,z)}(t) + 3s_{(x,y,z)}] \leq 5MPa$$

Tensile Failure

- Compute borehole breakdown pressure (P_b) for gridblocks assigned to injection well:

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

T_o: tensile strength
η: poroelastic parameter
incorporates Poisson's ratio
& Biot compressibility parameter
β: effective stress coefficient
Reasonble constraints extant in the literature for CRBG basalts.

- To quantify risk of borehole breakdown > 1%, replace P_f with $\bar{P}_{f(x,y,x)} + 3s_{(x,y,z)}$ for injection well gridblocks.

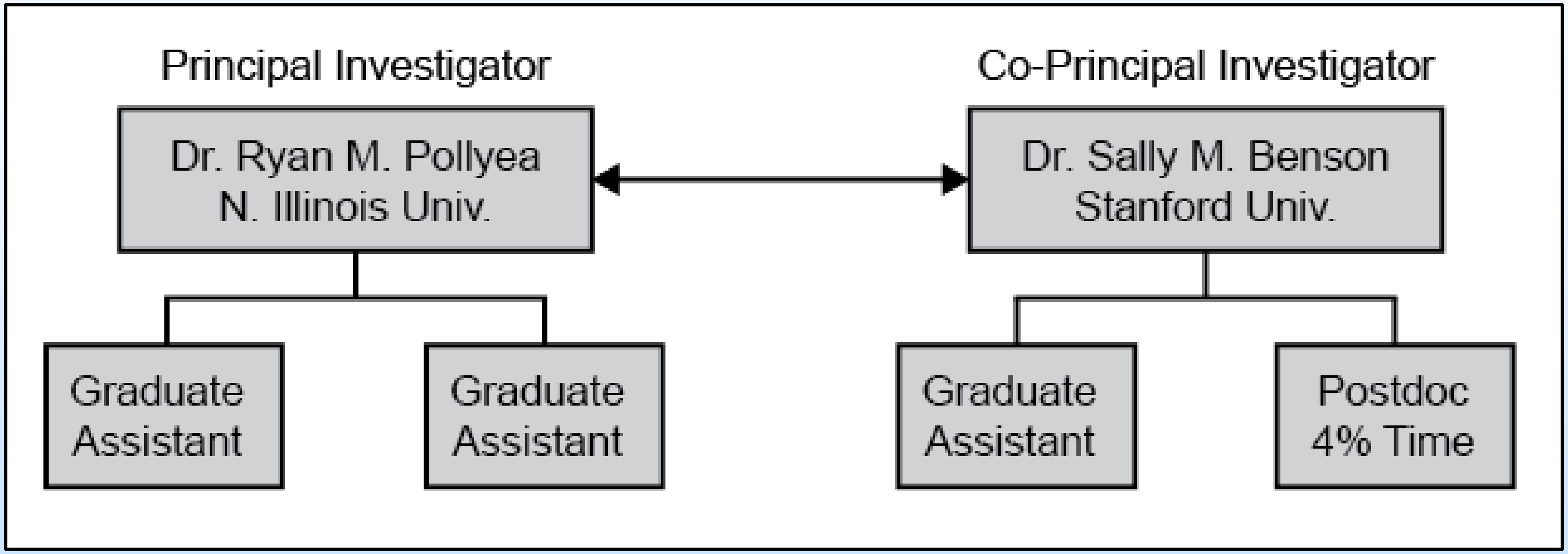
Expected Outcomes

- Probabilistic risk assessment of reservoir geomechanics at Wallula Basalt Sequestration Pilot Project.
  - Successful completion will move Wallula site closer to Development Phase
  - Product: Report to Big Sky Carbon Sequestration Parternship & NETL
  - Product: Updated information for Wallula site fact sheet.

Expected Outcomes

- Generalized approach for simulation-based risk assessment suitable for inclusion in NETL *Best Practices for Risk Analysis and Simulation for Geologic Storage of* CO_2
- Mechanistic models of stress-dependent permeability, relative permeability, and capillary pressure for variably saturated CRBG reservoir rock.
  - Product: Data for NETL eXchange
  - Product: Summary report to NETL

Organization Chart/ Communication Plan



Task/Subtask Breakdown

- Task 1.0: Project management & planning
  - All management & reporting activities
- Task 2.0: Field sampling
  - Subtask 2.1: Pre-mobilization
    - Procurement, planning, etc.
  - Subtask 2.2: Rock sampling
    - Collect representative samples of Grande Ronde basalt.
  - Subtask 2.3: LiDAR scanning
    - Obtain terrestrial laser scan data from outcrop

Task/Subtask Breakdown

- Task 3.0: Reservoir Simulation
  - Subtask 3.1: LiDAR data analysis
    - Develop fracture maps and define each continuum.
  - Subtask 3.2: Semivariogram analysis
    - Compute experimental semivariogram and model structure(s) for each continua
  - Subtask 3.3: Borehole interpretation
    - Transform Wallula borelog into stochastic continuum
  - Subtask 3.4: Permeability upscaling
    - Use DFN of each continua to quantify matrix-matrix and fracture-matrix permeability

  - Subtask 3.5: Sequential indicator simulation

Task/Subtask Breakdown

- Task 4.0: Core Flood Experiments
  – Provide reliable measurements of CO_2/brine relative permeability and capillary pressure measurements over a range of effective stress from 0.3 to 20 MPa.
  – Develop a mechanistic model of stress-dependent permeability in variably saturated CRBG rock samples.

Task/Subtask Breakdown

- Task 5.0: Numerical Simulation
  - Subtask 5.1: Build models
    - Initial conditions, incorporate k_{rel} & P_{cap} models, etc.
    - Monte Carlo simulations for each scenario
  - Subtask 5.2: Data processing
    - For each scenario, compute E-Type estimates for primary (P, T, saturation) and secondary variables (fluxes).

Task/Subtask Breakdown

- Task 6.0: Geomechanical Risk Assessment
  - Subtask 6.1: Shear failure
  - Subtask 6.2: Fracture dilation
  - Subtask 6.3: Borehole breakdown
  - Subtask 6.3: Far-field tensile failure

  For each subtask, use E-type estimates of P_f to compute failure probability at each gridblock in each scenario.

Deliverables / Milestones / Decision Points

- Decision Point – Subtask 2.1
  - – Outcrop selection: Requires laser scanner within ~200 m of exposure while permitting safe operation.
- Decision Point - Subtask 5.1
  - – If individual simulation run times exceed 4 days, then may require shortening simulation time from 20 years to 10 years.
    - Test runs on NIU cluster suggest this will not be a significant hurdle.

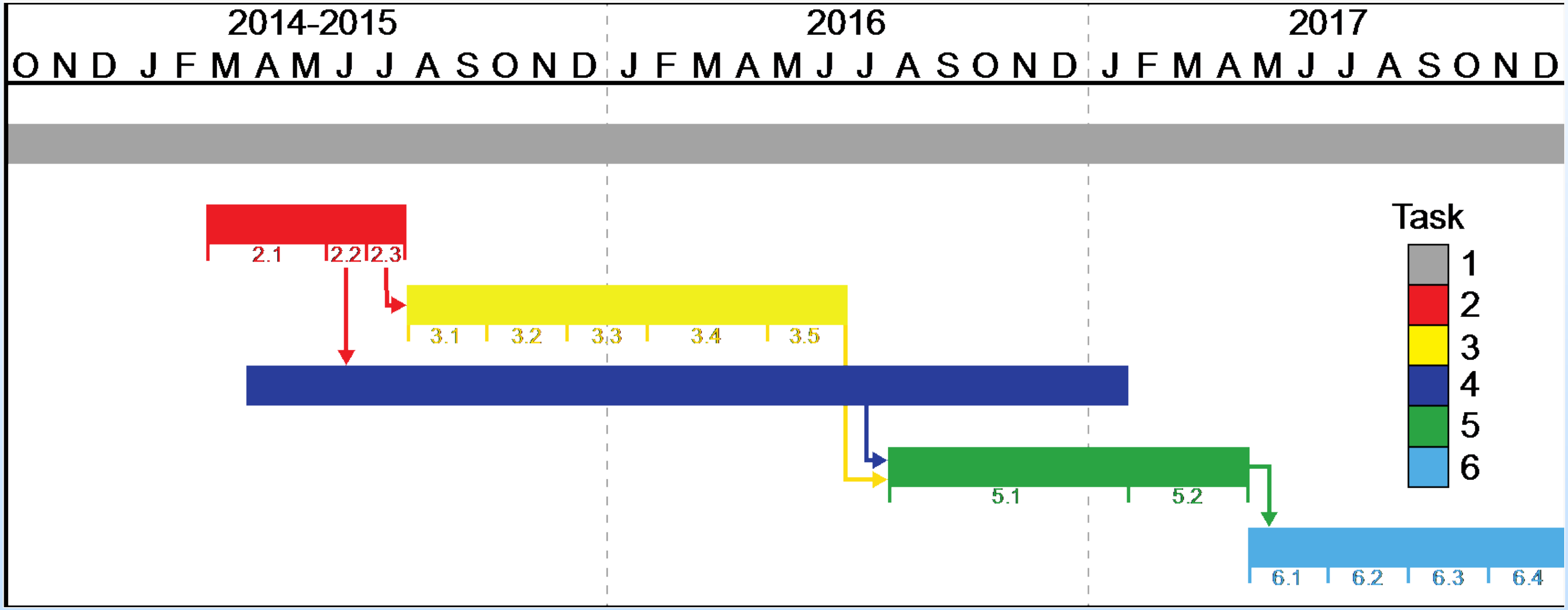
Deliverables / Milestones / Decision Points

Task/ Subtask	Milestone Title	Planned Completion Date	Verification Method
1.0	Project Management Plan	1/30/2015	PMP File
1.0	Kickoff Meeting	3/31/2015	Presentation File
2.0/2.3	Complete field data acquisition	7/31/2015	LiDAR data provided to DOE
3.0	Complete reservoir characterization	6/30/2016	Reservoir data and images provided to DOE
4.0	Multiphase flow measurements in fractured basalt	7/15/2016	Summary report on multiphase CRBG properties
4.0	Stress dependent permeability results	1/31/2017	Summary report on stress-dependent CRBG permeability
5.0	Complete numerical simulations	4/30/2017	Summary report on simulation results
6.0	Complete geomechanical risk asessment	12/31/2017	Final report on geomechanical risk assessment at Wallula Site

Risk Matrix

- Field work
  - Occupational health & safety in the field
    - Slip/trip/fall hazards while working on rocky terrain
  - Equipment malfunction
  - Weather risk
- Minimal risks associated with numerical simulations and k_{rel} & P_{cap} measurements.

Proposed Schedule



Technical component is scheduled to begin in 2015

Summary

- Monte Carlo numerical simulations of CO_2 sequestration at Wallula Pilot Project.
  - Three injection scenarios: 37, 500, & 1,000 MW
  - Model constraints:
    - Borehole geology
    - Fracture correlation structure from analog outcrops
    - P_{cap} & k_{rel} measurements from representative CRBG samples
- Mechanistic model of stress dependent permeability in CRBG

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