Geophysical and Mineralogical Controls on the Rheology of Fracture Slip and Seal Breaching
DE-FE0023354

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Presentation Outline

• Benefits
• Project Overview
• Technical Status
  – Premise
  – Observations and Active Experimentation
    • Meso-Scale Observations
      – Appropriate Caprocks
      – Velocity-Stepping Experiments – permeability and stability
      – Slide-Hold-Slide Experiments – permeability and recurrence
    • Micro-Scale Observations
      – Sintering
      – xCT Imaging
  – Analysis at Micro-Scale
    • Digital Rock Physics (DRP) models – permeability and stability
    • Continuum – permeability and stiffness
• Accomplishments
• Synergistic Opportunities
• Summary
Benefit to the Program

Addresses:

Area of Interest 1, Geomechanical Research

……..to determine the constraints of whether seals transected by blind faults will fail seismically or aseismically when contacted by increased reservoir pressures including CO₂ and the implications of this rupture on seal breaching and loss of inventory.

Relevance to FOA ("in italics")

This project will provide:

"improved understanding of geomechanical processes and impacts critical to scCO₂ injection operations.

This [project specifically] includes [and integrates]: theoretical studies, [and] laboratory, work to:

(a) evaluate and assess the probability of induced seismicity;
(b) understand, characterize, and measure potential permeability changes from slip along existing faults; and
(c) understand and assess the geomechanical behavior and effects of increased reservoir pressure on fractures, faults, and sealing formations.”

This will include……..
Project Overview: Goals and Objectives

Examine geophysical and mineralogical controls of caprocks on:

- **Fault slip** – Stable/unstable or aseismic/seismic
- **Permeability evolution** – Sense and magnitude
- **Potential for seal breaching** – Permeability and capillary behavior

Including:

- *Nature, form and rates of weakening* that condition whether fractures and faults fail either seismically or aseismically
- *Nature, form and rates of healing* that define whether fractures may strengthen and then re-fail on multiple successive occasions, and
- *Permeability evolution (enhancement or destruction)* that is driven on fractures as a consequence of these behaviors
- Feedbacks on healing conditioned both by *physical and chemical transformations* and the redistribution of mineral mass driven by fluid transport.
Technical Status & Methodology

Background
• Felt seismicity
  – Stable versus unstable slip
    • Mineralogical controls
    • Geometric (stiffness) controls
• Seal breaching
  – Evolution of permeability and capillarity characteristics

Methodology
• Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)
  – Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)
  – Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)
  – Conduct Baseline Characterization of Natural and Synthetic Caprocks (Fitts)
• Laboratory Experimentation (Elsworth, Lead)
  – Evolution of Fault Rheology and Transport Parameters (Elsworth)
  – 3D Imaging of fault contact area, fault geometry, and mineralogy & textures (Fitts)
• Modeling for Response and for Caprock Screening (Elsworth, Lead)
  – Digital Rock Physics Modeling of Response (Elsworth)
  – Caprock Screening Heuristics (Peters, Fitts)
Fault Zones as Seals and Pathways

Little Grand Wash Fault, UT

[Patil et al., 2017; after Vrolijk et al., 2005]

Controls on Permeability Structure

Mineralogy
- Rotliegendes fault rocks
- Middle Jurassic fault rocks
- Cataclasites
- Disaggregation zones
- Phyllosilicate-framework fault rocks (PFFR)
- Clay smears

Stress and Mineralogy
- Disaggregation zones
- Cataclasites
- Clay smears
- PFFR or shaly gouge
- Shale smears

Dynamic Processes
- Structure
- Fluid Flow
- Reaction
- Alteration
- Mode of Failure
- Dilatancy
- Compaction
- Segmentation
- Roughness

Fault Core and Damage Zones
- Deformation and Across Fault Permeability Control: Localized process zone (gouge in fault core)
- Along-Fault Permeability Control: Fault damage zone (fractures)

[Yielding et al., 2010]

[IEAGHG, "Fault Permeability," 2016; after Faulkner et al., 2010]
Induced Seismicity

[Elsworth et al., Science, 2016]
Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior

Ide et al., 2007; Peng & Gomberg, 2010
Seismic - Aseismic Transition
Full Spectrum of Slip Behaviors

\[ K_c = -\frac{(\sigma_n - p)(a - b)}{D_c} > \frac{G}{l} = K \]

Promote Aseismic Response: \( K_c < K \)
Otherwise Seismic Slip if: \( K_c > K \)
Increase: \( K_c; (\sigma_n - p); (a - b); l \)
Decrease: \( D_c; G \)
Recurrence Requires: Healing

[Adapted from C.J. Marone, Pers. Comm., 2017]
Maximum Event Magnitude - Equivalent Porous Medium

Moment Magnitude (Deviatoric)

\[ M = AG\Delta u \]
\[ M = a^3G\frac{\Delta u}{a} \]
\[ M = VG\gamma \]
\[ M = V\Delta \tau \]
\[ \Delta \tau = \frac{M}{V} \]

\[ \Delta \tau \cdot (1 - c) = \mu \cdot \Delta \sigma' \]

Stress-Strain (Spherical)

\[ \Delta \sigma' = \Delta \sigma - \alpha \Delta p \ (\Delta \sigma = 0) \]
\[ \alpha \Delta p = K \frac{\Delta V}{V} \]
\[ \alpha \Delta p = \frac{2}{3} \frac{(1 + \nu)}{(1 - 2\nu)} \frac{G}{V} \frac{\Delta V}{V} \]

\[ M = \frac{2}{3 (1 - 2\nu)} \frac{1}{(1 - c)} \mu G \Delta V \]

\[ M = \frac{1}{(1 - c)} G \Delta V \]

\[ \begin{cases} \nu = 0.25 \\ \mu = 0.6 \end{cases} \]

Modified from [McGarr, JGR, 1976 & 2014]
Maximum Anticipated Moment Magnitude – M or M_dot? 
M_{Gross} or M_{Net}? Triggered vs Induced?

After [McGarr, JGR, 2014]
Maximum Event Magnitude – Penny-Shaped Crack

Moment Magnitude (Deviatoric)

\[ M = AG\Delta\bar{u} \]

\[ \Delta\bar{u} = \frac{8(1-\nu)\DeltaTa}{3(2-\nu)G\pi} \]

\[ M = AG\frac{8(1-\nu)\DeltaTa}{3(2-\nu)G\pi} \]

\[ \Delta\tau = \frac{M\pi(2-\nu)}{Aa8(1-\nu)} \]

\[ \Delta\tau \cdot (1-c) = \mu \cdot \Delta p \]

Stress-Strain (Spherical)

\[ \frac{\Delta V}{A} = \frac{16(1-\nu^2)\Delta p a}{3\pi E} \]

\[ \Delta p = \frac{\Delta V}{Aa} \frac{3\pi E}{16(1-\nu^2)} \]

\[ M = \frac{1}{(2-\nu)(1-c)}\mu G\Delta V \]

\[ M = \frac{1}{(1-c)^{24}} G\Delta V \]

\[ M = \frac{1}{(1-c)^{3}} G\Delta V \]

\[ \nu = 0.25 \]

\[ \mu = 0.6 \]
Nascent Friction-Stability-Permeability Relationships

Observations
- $\frac{dk}{k_0}$ increases with increased brittleness $(a-b)<0$
- $\frac{dk}{k_0}$ increases with increased frictional strength
- Roles of mineralogy and surface roughness?

![Graph showing Friction-Permeability Relationship](image)

![Graph showing Stability-Permeability Relationship](image)
Seismicity-Permeability Linkages – Natural Samples

- Newberry Tuff
- Marcellus Shale
- Tournemire Shale
- Artificial Samples
- Artificial Samples with > 80% carbonate

![Graphs showing relationships between seismicity, permeability, phyllosilicate content, carbonate content, and tectosilicate content.](image-url)
Role of Roughness - Fabricated Fracture Surfaces

3D printed fracture casts with different geometric features

- Full amplitude [Double wavelength]
- Half amplitude [Double wavelength]
- Full amplitude [Anisotropic]
Net Friction and Permeability Evolution

Case $D_x$  
Full amplitude  
[Anisotropic - x]

Case $D_y$  
Full amplitude  
[Anisotropic - y]

Case $E$  
Smooth

Large drop in permeability
Healing – Necessary Component of the Seismic Cycle

Shear Stress and Permeability Evolution

• Increasing shear stress peak is observed with increasing hold time (Frictional Healing)
• Permeability declines overall with temporal response to shear events
• Permeability decline is fast at initial stage then become slower

Experimental Notes
• Permeability of Green River shale #600 grit became unresolvable after initial shear
• Westerly granite #150 grit stopped at ~150 min due to limited pump capacity
• 8th shear applied to Westerly granite #600 grit after 5000 seconds

Graph showing shear stress and permeability over time.
Shear Permeability Enhancement

**Shear Induced Permeability Enhancement**

- Later stage shear slip + Incremented duration of prior slip → Significant permeability enhancement
- Permeability continuously decreases during hold (Pressure solution?)
- Prior slip permeability recovery took 70 minute after slip ⑦, WG #600 grit case
- Permeability increase appears to be linear to slip distance
- The enhancement is least apparent with rougher surface granite (WG #150 grit)
Pressure solution

- Permeability reduction due to pressure solution in all cases seems to follow power law decay \( k = k_0 t^{-p} \) with power \( p = -0.37 \)
- The enhancement can be significant after extremely long (natural scale) holds
- Can this be applied to natural hydraulic systems?

Permeability change and earthquake catalog \((M_L > 3)\) in southern California [Elkhoury et. al., 2006]
**Shear Permeability Enhancement**

**Magnitude of Permeability Enhancement**

*Absolute perm increase:* rougher granite > smoother granite > shale

*Normalized perm increase:* shale > smoother granite > rougher granite

**Shear permeability increase with duration of prior hold time for Westerly granites**

Shear permeability slightly decreases with prior hold time for Green River shale

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![Graph showing permeability increase with hold duration for different materials.](image)
Stick-Slip Response

Response to Laboratory Earthquakes (Stick Slip)

Shear Stress ➔ Flowrate

Flowrate (ml/min)

Time (hr)

V_l=1µm/s  V_l=0.1µm/s Shear Stress ➔

Flowrate

Flowrate (ml/min)

Time (hr)

V_l=0.1µm/s

Shear Stress ➔

Flowrate

Flowrate (ml/min)

Time (hr)

CIC


T-K-28

2.38

T-K-34

2.30

2.26

T-K-34

2.38

T-K-34

2.30

2.26

T-K-34

2.38

T-K-34

2.30

2.26
Frictional-Stability-Permeability and Reaction

Experiments:

- Eagle Ford Shale
- Two fluids:
  - pH 2.5
  - pH 7.8
- xCT Imaging before and after flow
1. Permeability change during compression of fracture coupons.
   - From 250 kPa to 2500-3000 kPa confining pressure.
   - Compression of porous altered layer leads to lower permeability, likely due to compaction/creation of gauge.

2. Permeability evolution during first 1.5mm of slip.
   - Permeability does not evolve systematically, likely controlled by unique sample geometries.
   - Maximum permeability increase observed for sample with altered layer and vice versa.
Frictional-Stability-Permeability and Reaction

Results suggest samples exposed to a pH 2.5 brine that formed an altered layer have a lower coefficient of friction relative to samples exposed to a pH 7.8 brine. We hypothesize this is due to the formation of a gouge layer due to the compaction of the altered layer.

Rate-State Friction: \( u = u_i + (a-b)\ln(V/V_i) \) (Dieterich, 1981)

Results suggest no clear trend for changes in rate-state friction due to the formation of an altered layer/gouge. This may be due to apparatus resistance influence or unique sample geometries.
Stability–Permeability Relations in Composites/Mixtures

Mono-mineralic

Multi-mineralic

Friction

Stability (a-b)

[Ikari et al., Geology, 2011]
CO₂ bleached sandstone and siltstone showed lower fracture toughness (Major et al. 2014)

Lower Fracture Toughness

Unaltered Entrada Sandstone:
- quartz rich, minor feldspar and calcite, with hematite coating.

Altered Entrada Sandstone:
- hematite coating is dissolved, replaced by goethite, no significant change in quartz, feldspar, and calcite.

(Major et al. 2014)
DEM Model Setup

(Marone, 1999)
Shear Strength -- Unaltered vs Altered

Evolution of friction at 10 MPa normal stress [other normal stresses (5, 15 MPa) show similar trend].

- CO₂ altered synthetic gouge shows LOWER frictional strength (shear strength) than unaltered synthetic gouge.
- Unaltered gouge shows HIGHER shear strength with more coating particles.
Slip-Stability - Unaltered versus Altered

After Alteration

Unaltered – Potentially Unstable

Altered - Potentially Stable

Velocity Up-step

Velocity Down-step

UP-Unaltered

DOWN-Unaltered

(a-b)
Permeability Evolution

- **Unaltered--Hematite coating**
- **Altered--Goethite coating**

Increase in Permeability (unaltered)
Lower Magnitude Increase (altered)

Shear Displacement (micron)

K/K0

Velocity (micron/s)
Accomplishments to Date

ACCOMPLISHMENTS

– VS and SHS Experiments
  • Mechanisms-based seismicity-permeability evolution RSF-k
  • VS experiments on broad suite of natural and artificial samples
  • Nascent stability-permeability relations (indicate larger stability smaller dk)
  • Important role of healing on perm-cycle confirmed
  • Important role of reactive transport on perm-evolution and potentially on stability
– Imaging
  • Frozen post-test fractures
  • Completed first imaging and segmentation of sheared fractures
– Modeling
  • DRP models for friction and stability – gouge - compared with mixtures data
    – Enables testing of laboratory data for stability and permeability
    – Extended to CO₂ altered samples
  • Developed RT models for stiffness and permeability evolution of fractures

ONGOING

– Refine Mechanistic Understanding of Behaviors
  • VS stability experiments – systematic roles of mineralogy and additionally roughness
  • SHS experiments for healing and recurrence and consequences for multiphase flow
  • Reactive transport properties on sheared fractures
– Integrating modeling and experiments and imaging
Synergistic Opportunities

- [TILT.princeton.edu](http://TILT.princeton.edu)
- Linkages with:
  - Explored broad suite of mineralogies that are applicable to various CO$_2$ demonstration projects and others
  - Projects exploring field scale response - URLs and field experimentation (Guglielmi, Aix-Marseille & LBNL)
    - Seismicity-permeability correlations
    - Linkages across scales for upscaling
    - LSBB (Carbonate), Tournemire (Shale), Mt Terri (Shale)
  - Imaging *in vivo* (Dustin Crandall)
Summary

- Rupture of caprocks is a potentially important issue in CCS where:
  - Large overpressures may result from CO$_2$ injection
  - May result in seismic (felt) or aseismic rupture
  - May result in loss of inventory

- Absent and needed are data/information to constrain:
  - Seismic and aseismic reactivation of faults/fractures – distribution of felt/aseismic events?
  - Healing of faults/fractures – what are event recurrence intervals?
  - Evolution of multiphase flow and transport properties – likelihood of breaching and loss?

- Develop methodologies for:
  - Integration of process measurements and imaging at microscale
  - Scaling microscale-to-mesoscale via digital rock physics models as a new tool

- Apply to CCS by:
  - Enabling the screening of potential caprock materials for suitability and durability
  - Providing a consistent view of the likelihood and consequences of breached seals on seismic risk and loss of inventory for candidate CO$_2$ storage reservoirs.
Appendix Following
Communication plan: Biweekly Skype [Oct 23; Nov 6, ....] Biannual meeting
## SCHEDULE of TASKS and MILESTONES

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Bibliography - Presentations