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

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Jeffrey Fitts, Catherine Peters, Kasparas Spokas, Princeton
Presentation Outline

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- 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 CO$_2$ 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 scCO$_2$ 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)
Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior

Duration (s) [secs -> years]
- 1 year
- 1 month
- 1 day
- 1 hour
- 1 min
- 1s

Seismic Moment (N.m) [Magnitude]

M_w = 6
M_w = 8

Annual Fossil Fuel Budget
~ 15 TW → 5 × 10^{20} Joules [500 EJ]

Ide et al., 2007; Peng & Gomberg, 2010
Requirements for Instability

1. Shear strength on the fault is exceeded - \( i.e. \)
   \[ \tau > \mu \sigma'_n \]

2. When failure occurs, strength is velocity (or strain) weakening - \( i.e. \)
   \[ a - b < 0 \]

2. That the failure is capable of ejecting the stored strain energy adjacent to the fault (shear modulus and fault length) - \( i.e. \)
   \[ \frac{G}{l} < K_c = \frac{(b-a)\sigma'_n}{D_c} \]

4. That effective normal stresses evolve that do not dilatantly harden the fault and arrest it via the failure criterion of \#1 - \( i.e. \)
   \[ 1 >> \nu_D = \frac{w^2}{k} \frac{\nu_s \eta}{K_s D_c} \]
Mineralogical Controls on Instability

Friction

Velocity Weakening (unstable slip)

Velocity Strengthening (stable slip)

Stability (a-b)

Velocity Weakening (unstable slip)

Velocity Strengthening (stable slip)

Frictional Response of Mixtures

[Ikari et al., Geology, 2011]

[Niemeijer et al., GRL, 2010]
Aseismic-Seismic Transition

Scale Dependence - the need for URLs and constrained experimentation at meso scale.

Roles of:
- Pressurization ($\sigma_n' \rightarrow 0$)
- Deformation ahead of the fluid front
- Mineralogical controls

[Guglielmi et al., Science, 2015]
Rate-State Friction [1]

Velocity Steps

R–S friction

\[ \mu = \mu_0 + a \ln \left( \frac{v}{v_0} \right) + b \ln \left( \frac{v_0 \theta}{D_C} \right) \]

\[ \frac{d\theta}{dt} = 1 - \frac{v \theta}{D_C} \] (Dieterich Evolution)

\[ \frac{d\theta}{dt} = -\frac{v \theta}{D_C} \ln \left( \frac{v \theta}{D_C} \right) \] (Ruina Evolution)

Dilation

\[ \frac{\Delta H}{H} \equiv \Delta \phi = -\epsilon \ln \left( \frac{v}{v_0} \right) = -\epsilon \ln \left( \frac{v_0 \theta}{D_C} \right) \]

Permeability Evolution

\[ \frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3 = (1 + \frac{\Delta H}{H})^3 \]
Rational Linkages: Rate-State Friction, Porosity and Permeability

\[
\dot{\phi}_{\text{plastic}} = -\frac{V}{D_c}(\phi_{\text{plastic}} - \phi_{ss}), \quad \phi_{ss} = \phi_0 + \varepsilon \ln \left( \frac{V}{V_0} \right), \quad \frac{k(\phi)}{k_0} = \left( \frac{\phi - \phi_c}{\phi_0 - \phi_c} \right)^n
\]

High Stiffness, positive dilatational coefficient
Frictional Stability-Permeability Experiments

Pressure Regulator $P_{down} = 0$ (Downstream)

Axial Pressure

Latex Membrane

Confining Pressure

LVDT

DI water $P_{up}$ (kPa) (Upstream)

Steel Shearing Platen

Shearing Direction

Silly Putty

Sample Coupon

Steel Spacer

Strain Gages

Steel Sleeve

Poro-Bar

Fracture Surface
Frictional Stability-Permeability Observations

**Velocity-stepping and Permeability**

Displacement (mm)

- Friction
- Original
- Filtered

Velocity-upstep

Permeability-response

**Permeability Evolution**

\[ \dot{e} = 0.0224 \text{ (n=2), } D_c = 50 \text{ [\mu m]} \]

**Permeability-Frictional Stability**

- Westerly granite
- Green River shale

Unstable | Stable

**Fracture permeability \([m^2]\)**

Displacement [mm]

- Calculated (With shear dilation effect)
- Calculated (No shear dilation effect)
Mineralogical Sample Space

Sample Space for Artificial Samples:

Frictional Stability:

Natural Samples:

1. Green River Shale (Colorado, USA);
2. Longmaxi Shale (Chongqing, China);
3. Marcellus Shale (Pennsylvania, USA);
4. Newberry Tuff (Oregon, USA);
5. Tournemire Shale (France);
6. Opalinus Shale (Switzerland)

Bulk mineralogy of caprock formations
(Ian Bourg LBNL NCGE)
Tectosilicate | Carbonate | Phyllosilicate
--- | --- | ---
Green River Shale | 45.44% | 51.96% | 2.60%

**Green River Shale - Permeability Enhancement**

**Green River Shale (Natural)**

- Friction
- Original
- Filtered

Before | After

Velocity-upstep results in a permeability increase due to dilation.

Wear products after slip.

Permeability increase: \( \Delta k/k_{\text{trans}} = 0.302 \)

(a - b) = 0.004
Phyllosilicate-dominant Artificial Sample - Permeability Decrease

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<thead>
<tr>
<th></th>
<th>Tectosilicate</th>
<th>Carbonate</th>
<th>Phyllosilicate</th>
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<tbody>
<tr>
<td>AS002</td>
<td>10%</td>
<td>10%</td>
<td>80%</td>
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Clay swelling concurrent with shear damage

Velocity-upstep results in a permeability decrease due to wear products and swelling
Nascent Friction-Stability-Permeability Relationships

**Observations**
- $d k / k_0$ increases with increased brittleness $(a-b)<0$
- $d k / k_0$ increases with increased frictional strength
- Roles of mineralogy and surface roughness?

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**Friction-Permeability Relationship**

- Tectosilicate Rich
- Clay Rich
- Carbonate Rich

**Stability-Permeability Relationship**

- Natural Sample
- Artificial Sample
- Velocity Strengthening
  - Stable (Aseismic Slip)
Quantifying fracture geometry with X-ray tomography

Developed 3D image segmentation method for complex fractures

‘TILT’ - for fractures with rough porous surfaces & wear products

www.tilt.princeton.edu

'Digital fractures' combine 3D xCT and fracture surface characterizations

2D fracture surface characterization
Detailed mineral spatial distribution and textures

3D xCT characterization
Aperture geometry, contacting asperities & coarse mineral distributions

Grey-scale xCT data
3D sulfide distribution
quaternary segmentation

Increasing calcite

uXRF & uXRD imaging at APS Sector 13 GSECARS

Inputs for simulating friction-stability-permeability evolution & deriving constitutive relations
Stability-Permeability Relations in Composites/Mixtures

**Mono-mineralic**

Friction

![Friction graph for mono-mineralic materials](image)

Stability (a-b)

![Stability graph for mono-mineralic materials](image)

**Multi-mineralic**

Friction

![Friction graph for multi-mineralic materials](image)

Stability (a-b)

![Stability graph for multi-mineralic materials](image)
Multi-Mineral Frictional Strength

DEM Model

Particle-Particle Frictional

RSF Notation

\[ \mu_p = \mu_{ref} + a \ln\left( \frac{V_{ss}}{V_{ref}} \right) \]

\[ \mu_{ss} = \mu_{ref} + (a-b) \ln\left( \frac{V_{ss}}{V_{ref}} \right) \]

\[ \mu = \begin{cases} 
\mu_p & D_{acc} = 0 \\
\mu_p - \left( \frac{\mu_p - \mu_{ss}}{D_c} \right) D_{acc} & D_{acc} \in (0, D_c) \\
\mu_{ss} & D_{acc} = D_c 
\end{cases} \]

Steady-State Friction

Reduction in Shear Strength

Talc Domination Effect

Shear Displacement

Load Point Velocity

Friction Coefficient

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Mixture Controls of Frictional Instability

Observations

[Moore & Lockner 2011]

Transition in Slip Stability ~10% - ~25%
Talc
Quartz-Talc Series

Analysis

Transition in Bulk Shear Strength
0% talc
100% talc
Transition in Slip Stability?

Stability Analysis

\( \mu \)

Displacement

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<th>Friction Coefficient</th>
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<table>
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<tr>
<th>Shear Displacement</th>
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Transition zone appears at \(~10\%\) to \(~25\%\) talc content

Transition zone appears at \(~2\%\) to \(~3\%\) talc content
Distributed heterogeneity:
Slipped contacts are distributed homogeneously in the sample, following critical shear band directions.

Textured/layered:
Slipped contacts are distributed inside talc/weak layer, forming a localized shear zone, forcing most slip to evolve within this zone.
Evolution of Layer thickness, Coord. Num, and Porosity

Dilation

\[
\frac{\Delta H}{H} \equiv \Delta \phi = -\varepsilon \ln \left( \frac{v}{v_0} \right) = -\varepsilon \ln \left( \frac{v \theta}{D_e} \right)
\]

Permeability Evolution

\[
k = k_0 \left(1 + \frac{\Delta b}{b_0} \right)^3 = \left(1 + \frac{\Delta H}{H} \right)^3 \approx \left(1 + \Delta \phi \right)^3
\]
Coupling Reactive Transport and Mechanical Deformation

Research Questions & Methods
• For fractures in carbonate rocks exposed to acidified brine, how does the coupling of geochemical and geomechanical processes affect the pattern of dissolution and the subsequent evolution of fracture transmissivity?
• How does mineral heterogeneity impact the evolution of fracture geometry and transmissivity?
  • Keeping constant initial fracture geometry, pressure gradient, and inlet chemistry.

Approach: 2D Fracture Flow Model with Coupled Reactive Transport and Mechanical Deformation

2D Carbonate Reactive Transport Model
1. Transport
\[ \frac{\partial}{\partial x} \left[ b^3(x,y) \frac{\partial h(x,y)}{\partial x} \right] + \frac{\partial}{\partial y} \left[ b^3(x,y) \frac{\partial h(x,y)}{\partial y} \right] = 0 \]

1. Speciation
\[ CO_2(aq) + H_2O \leftrightarrow H_2CO_3(aq) \]
\[ H_2CO_3(aq) \leftrightarrow H^+_1(aq) + HCO_3^{-}(aq) \]
\[ HCO_3^{-}(aq) \leftrightarrow H^+_2(aq) + CO_3^{2-}(aq) \]
\[ H_2O \leftrightarrow H^+_2(aq) + OH^{-}_1(aq) \]

1. Reaction
\[ R = A \times k_f \times \left( 1 - \frac{IAP}{K_{sp}} \right) \]
\[ k_f = k_1(a_{H^+}) + k_2(a_{H_2CO_3}) + k_3(a_{H_2O}) \]

Mechanical Deformation Model
1. Elastic Column Compression (ΔLi)
\[ \Delta L_i = f_i \frac{L_i^0}{E \pi a^2} \]

1. Elastic half-wall deformation (Wi)
\[ W_i = f_i \times \frac{8(1 - \nu^2)}{\pi^2 E a} I_4(a) + f_j \times \frac{8(1 - \nu^2)}{\pi^2 E a} I_3(\eta_{ij}, a) \]
Pyrak-Nolte & Morris, 2000
100% Pure Limestone

Amherstburg Limestone

Eagle Ford Shale

Initial Mineralogy

Aperture Change after 40 Hrs of Reaction

Contact Points

Aperture Change Vertical Profile

0 MPa

50 MPa

Direction of Flow
• When the rock is spatially homogenous mineralogically, transmissivity remains controlled by unreacted downstream apertures

• When the rock includes areas of nonreactive minerals, the reactive front penetrates farther downstream faster, however certain mineral distributions can also inhibit channel formation

• When mineral dissolution is combined with constant normal mechanical load, fracture closure delays transmissivity increase

• Future Projects:
  – Effect of reactive transport along fracture interfaces on fracture frictional properties
Accomplishments to Date

ACCOMPLISHMENTS

– Caprock Mineralogy
  • Broad range of samples acquired: Eagle Ford, Green River Shale and Opalinus….
  • Frictional strength of fabricated samples consistent with natural samples

– 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 $d_k$)

– 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
  • 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
  • DRP models of Biot and transport properties

– Integrating modeling and experiments and imaging
Synergistic Opportunities

- TILT.princeton.edu
- Linkages with:
  - Projects exploring petrophysical characterization as methods to deploy findings
  - 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
Appendix

Following
Communication plan:
- Biweekly Skype [Oct 23; Nov 6, ....]
- Biannual meeting
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<td><strong>Task 2 -- Collect, synthesize and characterize sedimentary formation samples</strong></td>
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<td>SubTask 2.1 – Collect Homogeneous and Mineralogically Complex Sedimentary Rocks</td>
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<td>SubTask 2.2 – Sinter Mineral Mixtures to Create(Fitts) Idealized Analogs of Sedimentary Rocks</td>
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http://dx.doi.org/10.1007/s00024-015-1099-5


Elsworth, D. 2016. Creating and sustaining the reservoir – the key ingredient for all unconventional energy resources. Launch Ceremony, International Research Center for Unconventional Geomechanics, Northeastern University, Shenyang. May 23. [Invited]

Elsworth, D. 2016. Creating and sustaining the reservoir – the key ingredient for all unconventional energy resources. 3rd Int. Symp. on Unconventional Geomechanics. Wuhan. May 21-22. [Keynote]


