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 CO\textsubscript{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\textsubscript{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…….
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)
Seismic – vs- Aseismic Events

Mw = 8

Mw = 6

[Peng and Gomberg, Nature Geosc., 2010]
Requirements for Instability (Seismicity)

\[ K_c = \frac{\sigma_n (b - a)}{D_c} \]

\( a - b \)

\[ \begin{cases} 
  a - b > 0 \\
  a - b < 0 
\end{cases} \]

\[ K_c < K_s \]
\[ K_c > K_s \]

Stability mediated by \( a-b \) and \( K_c \) and upscaled \textit{in situ} via \( K_s \).
Mineralogical Controls on Instability

Friction

Stability (a-b)

Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

Frictional Response of Mixtures

[Ikari et al., Geology, 2011]

[Niemeijer, Elsworth et al., GRL, 2009]
Important mineralogical features of sealing units

Natural and idealized caprock mineralogy

Compositions of mixed rheological behavior?

Bulk mineralogy of caprock formations

(Euan Bourg LBNL NCGC)

Opalinus Claystone

(Mount Terri Project)

Green River Shale

(Chevron)
Imaging textures and composition of caprock matrix and fracture contacting asperities
3D mineralogy to construct digital rock models

➢ Map textures at scale of rheology experiment specimens

GIRI – Grinding Image Reconstruction Instrument
(A. Maloof, Princeton U.)

➢ Map composition of contacting asperities

X-ray microspectroscopy & diffraction

• Textures susceptible to permeability increase: continuous calcite-rich volumes
• Complex spatial variation of lithologies

• Relative solubility of asperities
• Characterize asperities with mixed mineral composition
Measuring (a-b) Values of Shale/Artificial Samples

1. Velocity step and SHS experiments: *a-b values* and healing rate

2. Measuring $D_c$ values to determine the critical stiffness and critical fracture length

3. Determine permeability evolution with different fracture roughness.

4. Coupling seismic behavior/stability and permeability evolution

5. Comparing the response to water and CO$_2$-brine

6. Develop a constitutive model that can predict or explain the changes in permeability
Evolution of Fault Rheology and Transport Parameters

Apparatus

ISCO PUMPS: res +/- 1 KPa
V1: Valve inlet fluid
V2: Valve outlet fluid
V3: Valve axial stress
V4: Valve confining pressure
V5: Safety valve
PT: Pressure transducers
Equipment Setup

- **PUMP A**
- **PUMP B**
- **PUMP C**
- Confining Pressure
- Saturated CO$_2$ brine $P_{CO_2} = 1.25$ MPa (Upstream)
- **CO$_2$ Gas Tank**
- **Labview**
- **Pressure Regulator** $P = 1.21$ MPa (Downstream)
- Axial Pressure
- Rubber Jacket
- **LVDT**
- Strain Gages
- Loading Cell
- Sample
- Fracture Surface
- Teflon Ring
- Aluminium Ring

**Saturated CO$_2$ brine $P_{CO_2} = 1.25$ MPa** (Upstream)
Importance of Loading Rates

Non-Heaviside

(a) Friction vs. Displacement (Without Friction Calibration)

Friction \( \mu \)
Loading Velocity

(b) Permeability vs. Displacement

Original
Filtered

Heaviside

(a) Friction vs. Displacement (Without Friction Calibration)

Friction \( \mu \)
Loading Velocity

(b) Permeability vs. Displacement

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

High Stiffness, positive dilatational coefficient
VS Experiments on Permeability

Confining pressure: 3 MPa

Fracture permeability [m$^2$]

Displacement [mm]

$v = 8.4 \mu m/sec$

$v = 0.8 \mu m/sec$

$v = 0.8 \mu m/sec$
Permeability – Competition of Dilation and Wear

Shear induced dilation relates to the permeability enhancement?

Both effects have impacts on permeability change.

Permeability enhancement due to dilation

Background

$\Delta H$

$\Delta k$

$k$

Time (or displacement)

velocity

$v$

$V_0$

Time (or displacement)

Dilation

Time (or displacement)

$\Rightarrow$
Detrending Permeability Data

\[ k = -2.01 \times 10^{-11} \ln(\text{disp}) + 6.51 \times 10^{-11} \]
Typical VS-k Data

\[ e = 0.0224 \ (n=2), \ D_c = 50 \]

\[ e = 0.0224 \ (n=2), \ D_c = 100 \]

\[ e = 0.0224 \ (n=2), \ D_c = 200 \]

Dilation coefficient is evaluated in experiment (but 2 order larger than that for gouge sample).
3D Imaging of fracture contact area, fracture geometry, and mineralogy & textures
Whole core x-ray tomography

In situ tomographic imaging of fractured cores during CO$_2$-acidified brine flow

Channelization of Indiana Limestone

- Need higher resolution and contrast to quantify fracture volume, contact area, fracture boundary geometry
- In situ x-ray tomography during slip and flow must be augmented with ex situ high resolution measurements

Experiments performed at NETL Morgantown
H Deng, JP Fitts, CA Peters, (Princeton U.) D Crandall, D McIntyre (NETL)
H Deng funded by ORISE Fellowship (Advisor: D McIntyre)
High resolution synchrotron xCT imaging

25 mm dia. Epoxy-stabilized fractured core

Amherstberg caprock formation

xCT slice of epoxy-stabilized fracture after CO$_2$-acidified brine flow

(sample from Ellis et al. 2011 GHGS&T 1(3), 248)
Synthetic Caprock Analog
Reproduce Mineralogically Complex Sedimentary Caprock Formation

Mineral content of green river shale sample by X-ray diffraction (Yildirim, 2014)

Anticipated mineral content distribution of fabricated sample

Resedimentation Apparatus Assembly (Schneider et al., 2011)
Digital Rock Physics Modeling of Response

Rheological and Transport Models of Fractures

Shear Platens

Fault Gouge

Shear Direction

Contact Force Chain
Shear strength varies with mineral properties (modulus, inter-particle friction, contact condition).

Shear strength slowly decrease because of loss of contacting area while shearing.
Digital Rock Physics Modeling of Response
Mineralogical Influence on Shear Strength of Simulated Fault Gouge

Mineralogy Effect on Friction Evolution

Shear strength of artificial fault gouge with 100% quartz or 100% talc (Niemeijer, 2010)
Quartz with Weak Talc Layer

*0.05 Talc*

*0.15 Talc*

*0.36 Talc*

*: Relative thickness of talc layer to the gouge thickness (6 mm)

**Digital Rock Physics Modeling of Response**

**Mineralogical Influence on Shear Strength of Simulated Fault Gouge**

Shear Strength vs. Weak Layer Thickness

Plot of steady state friction (at $v = 10 \text{ mm/s}$) vs. talc interlayer thickness (Neimeijer et al. 2010)
Modeling Fracture Evolution: Coupling Reactive Transport & Geomechanics

Reactive Transport Model

i) Transport
\[ \frac{\partial(bC)}{\partial t} = -\nabla \cdot (\hat{q}C) + \nabla \cdot (bD \cdot \nabla C) + R(C) \]

ii) Aqueous Speciation
\[
\begin{align*}
CO_2(aq) + H_2O & \leftrightarrow H_2CO_3(aq) \\
H_2CO_3(aq) & \leftrightarrow H^+(aq) + HCO_3^-(aq) \\
HCO_3^-(aq) & \leftrightarrow H^+(aq) + CO_3^{2-}(aq) \\
H_2O & \leftrightarrow H^+(aq) + O_2(aq) \\
[H^+] = [OH^-] + [HCO_3^-] + [CO_3^{2-}] 
\end{align*}
\]

iii) Dissolution Kinetics
\[
\begin{align*}
CaCO_3(s) + H^+(aq) & = Ca^{2+}(aq) + HCO_3^-(aq) \\
CaCO_3(s) + H_2CO_3(aq) & = Ca^{2+}(aq) + 2HCO_3^-(aq) \\
CaCO_3(s) + H_2O(aq) & = Ca^{2+}(aq) + HCO_3^-(aq) + OH^-(aq)
\end{align*}
\]

Fracture Specific Stiffness = \[ \frac{\Delta \sigma}{\Delta d} \]

Mechanical Deformation Model

- Pyrak-Nolte & Morris, 2000
- Model fracture as two half spaces separated by cylindrical asperities

Reactive transport simulation results
- Aperture map evolution

- Reaction time (Hrs)

- 5.04 cm
Stressing Reacted Fractures

Permeability (m²/s)

Stiffness (MPa/mm)

White = contact area

0 Hrs

18 Hrs

30 Hrs

42 Hrs

Δσ

Δt

0 MPa

70 MPa

0 MPa

70 MPa

0 Hrs

18 Hrs

30 Hrs

42 Hrs

Δσ

Δt

0 MPa

70 MPa

0 Hrs

18 Hrs

30 Hrs

42 Hrs

Δσ

Δt

0 MPa

70 MPa
Accomplishments to Date

- Caprock Mineralogy
  - Defined range of anticipated caprocks
  - Prescribed experimental suite
  - Acquired samples: Eagle Ford, Green River Shale and Opalinus
- VS and SHS Experiments
  - Refined experimental equipment and protocols
  - Completed first shale observations with water
  - Developed mechanisms-based understanding of evolution RSF-k
- Imaging
  - Frozen post-test fractures
  - Completed first imaging and segmentation of sheared fractures in vivo
- Modeling
  - Developed DRP models for friction – compared with mixtures data
  - Developed RT models for stiffness and permeability evolution of fractures
Synergistic Opportunities

- [TILT.princeton.edu](http://TILT.princeton.edu)
- Linkages with URLs and field experimentation
  - Seismicity-permeability correlations
  - Linkages across scales for upscaling
- Concurrent NETL projects
  - Linkage between structural domains and materials
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
Organization Chart/ Communication Plan

Communication plan: Biweekly Skype [Oct 23; Nov 6, ...] Biannual meeting
## SCHEDULE of TASKS and MILESTONES

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### Gantt Chart

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### Key
- **ON** = January
- **DJ** = December
- **FMAMJ** = January, February, March, April, May
- **AS** = September, October
Bibliography
