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

DE-FE0023354

Derek Elsworth, Penn State

Jeffrey Fitts & Catherine Peters, Princeton

U.S. Department of Energy

National Energy Technology Laboratory
DE-FOA0001037 Kickoff Meeting

November 12-13, 2014

Presentation Outline

- Benefits
- Project Overview
  - Goals and Objectives
  - Methodology
  - Outcomes
- Project Management
  - Organization Chart/Communications Plan
  - Task/Subtask Breakdown
  - Deliverables/Milestones/Decision Points
  - Risk Matrix
  - Proposed Schedule
- 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 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…….

Benefit to the Program

Relevance to FOA ("*in italics*") (Cont'd)

…..This will include:

"Improv[ing] *accuracy of existing models to understand:*

- *(a) the effects of scCO_2 injection on opened and closed faults and fractures at both the project and basin scales; and*
- *(b) the resulting impact on the permeability of the reservoir and sealing formations."*

Addresses *NETL's Carbon Storage Plan by:*

- *developing and validating technologies to ensure 99 percent storage permanence*
- *improving reservoir storage efficiency while ensuring containment effectiveness and*
- *developing best practices for monitoring, verification, accounting (MVA), and assessment; site screening, selection, and initial characterization.*

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.

Methodology

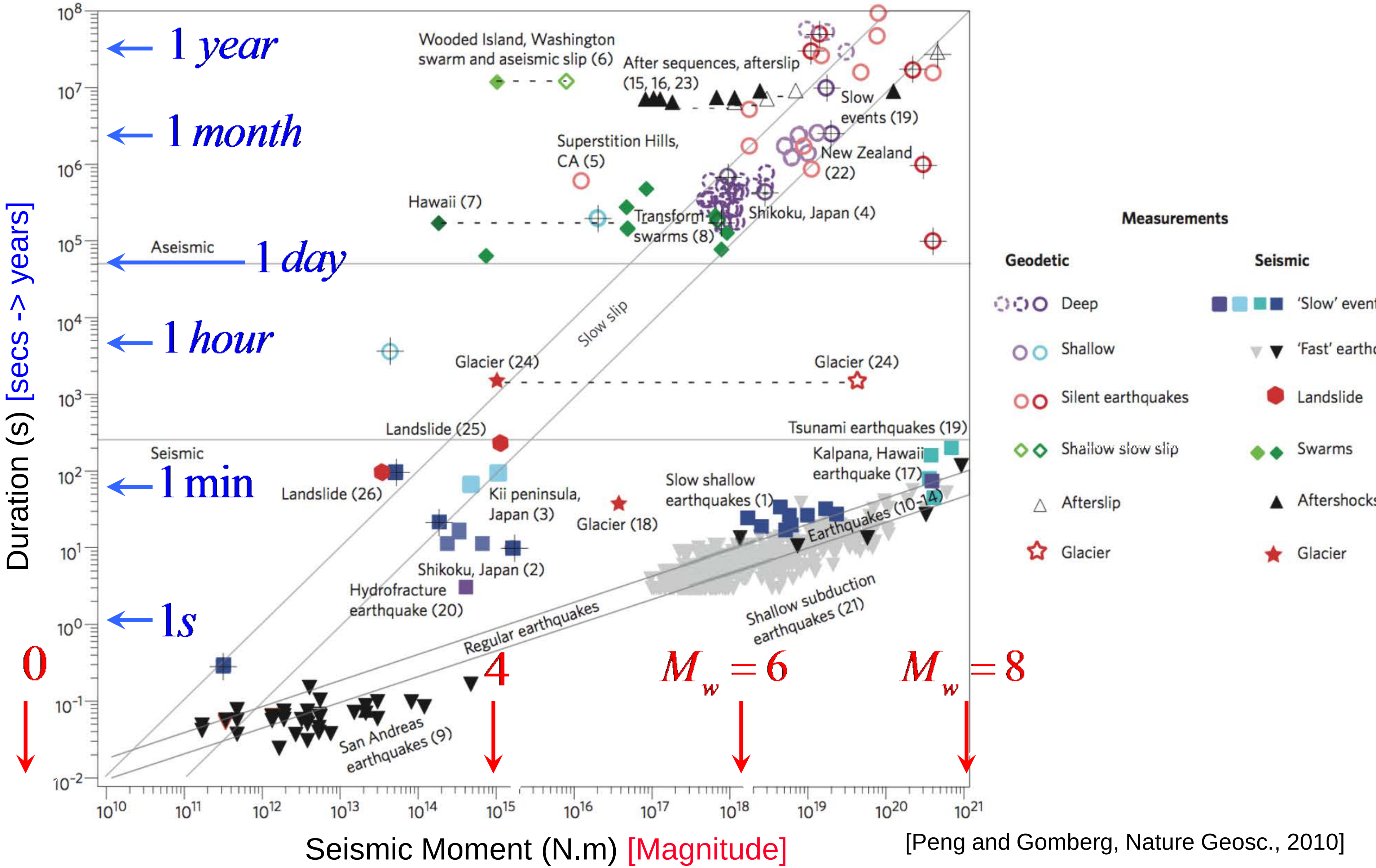
Background

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

Methodology

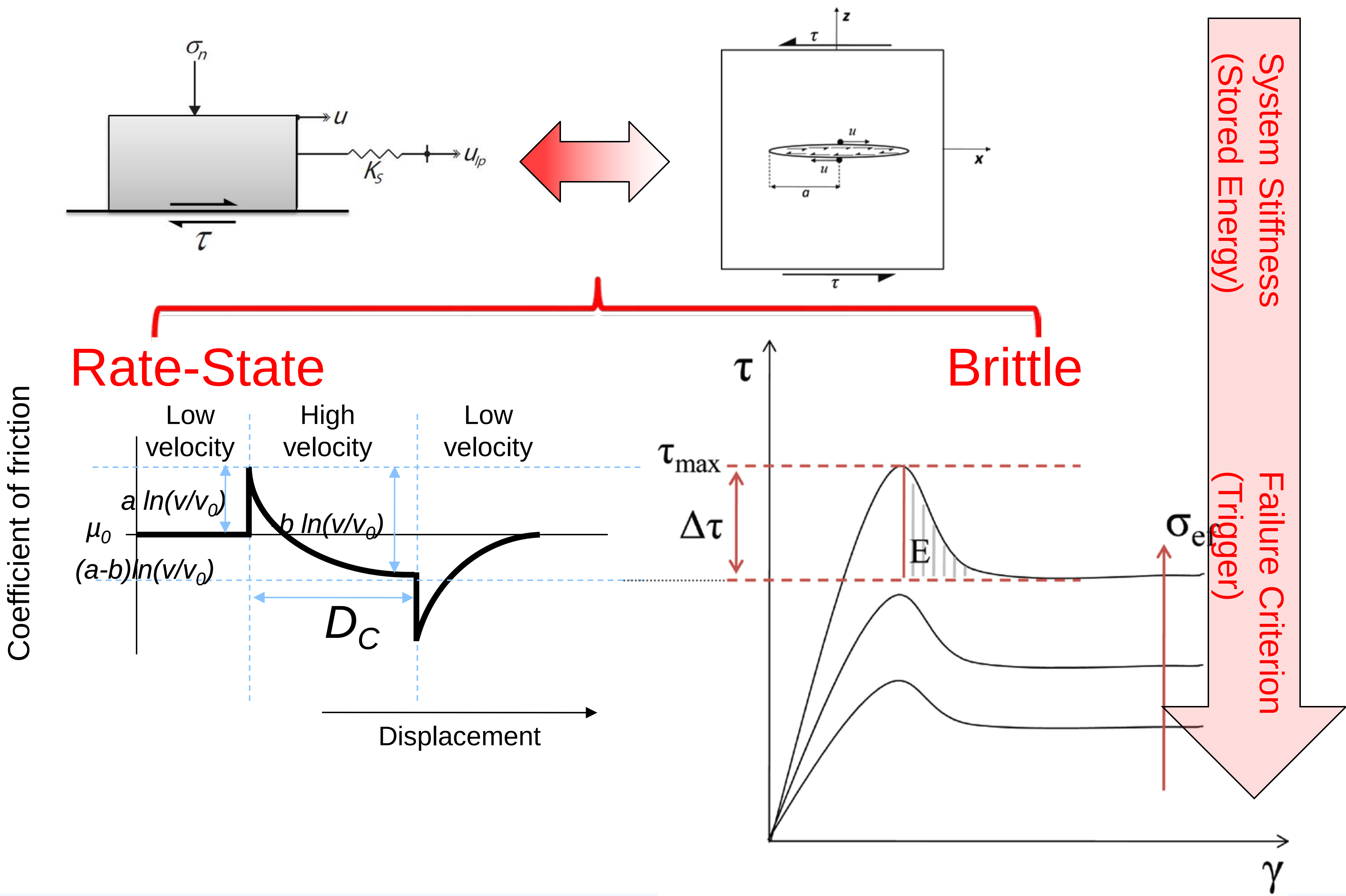
- Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)
  - Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)
  - Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)
  - Conduct Baseline Characterization of Natural and Synthetic 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

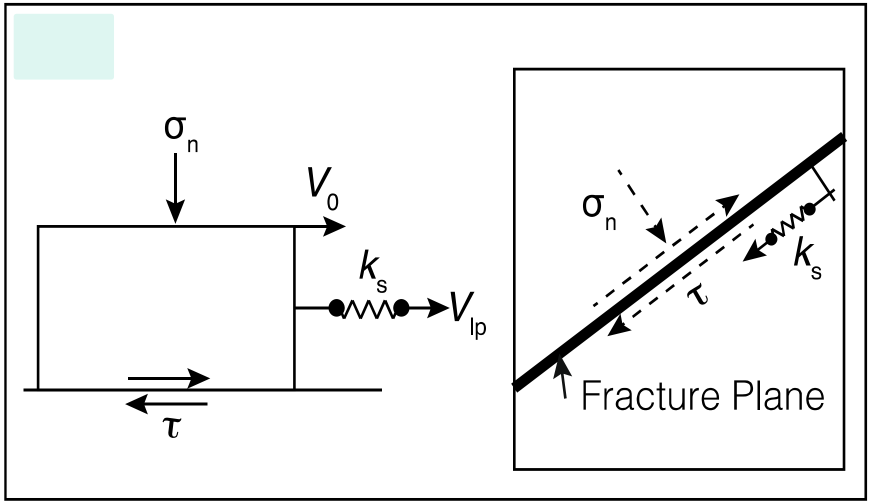


[Peng and Gomberg, Nature Geosc., 2010]

Approaches – Rate-State versus Brittle Behavior



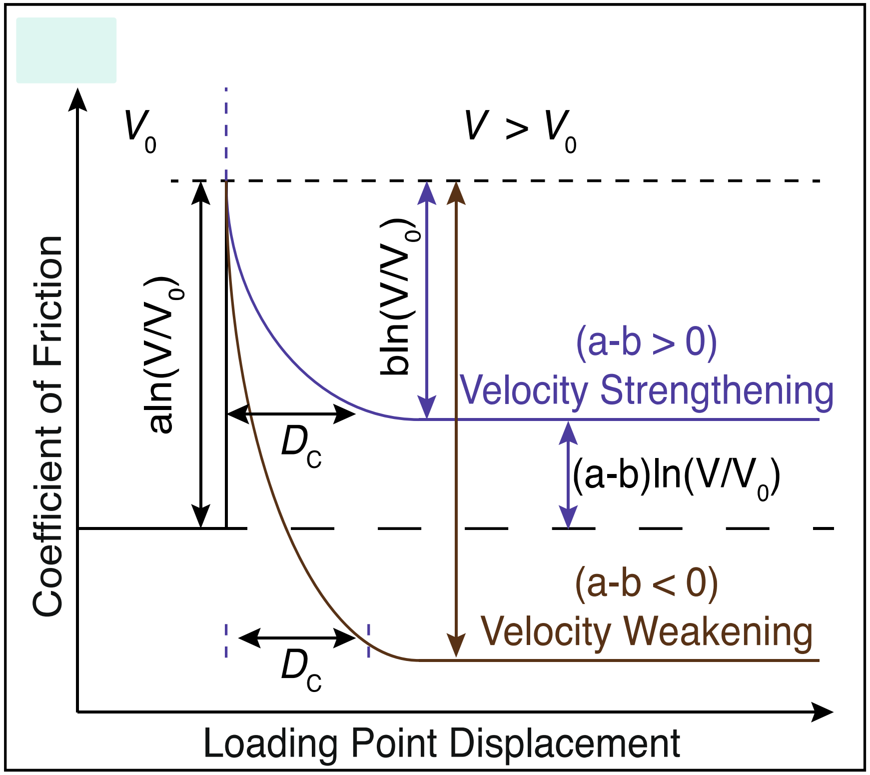
Requirements for Instability (Seismicity)



- τ: Shear stress
- σ_n: Normal stress
- K_s: Fracture stiffness
- V_0: Initial velocity
- V_{lp}: Load point velocity
- D_c: Critical slip distance

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

$$a-b$$



$$a-b>0$$

$$a-b<0 \quad \begin{cases} K_c < K_s \\ K_c > K_s \end{cases}$$

Stability mediated by a-b and K_c and upscaled *in situ* via K_s

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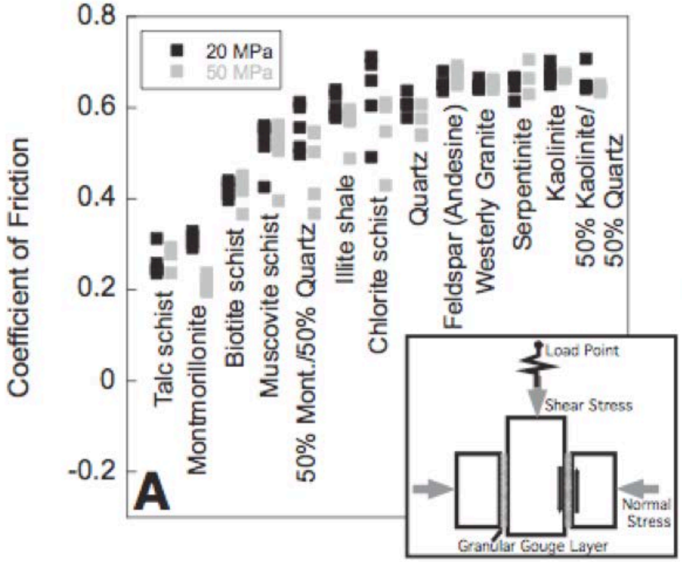
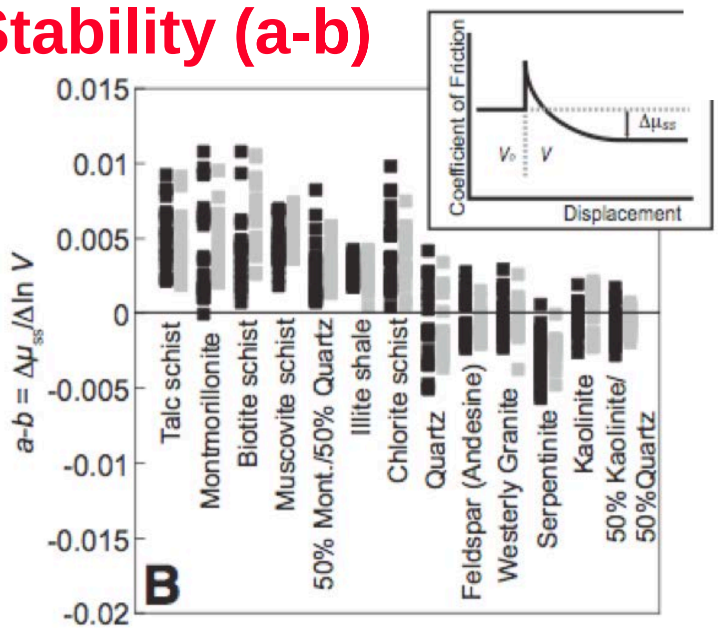
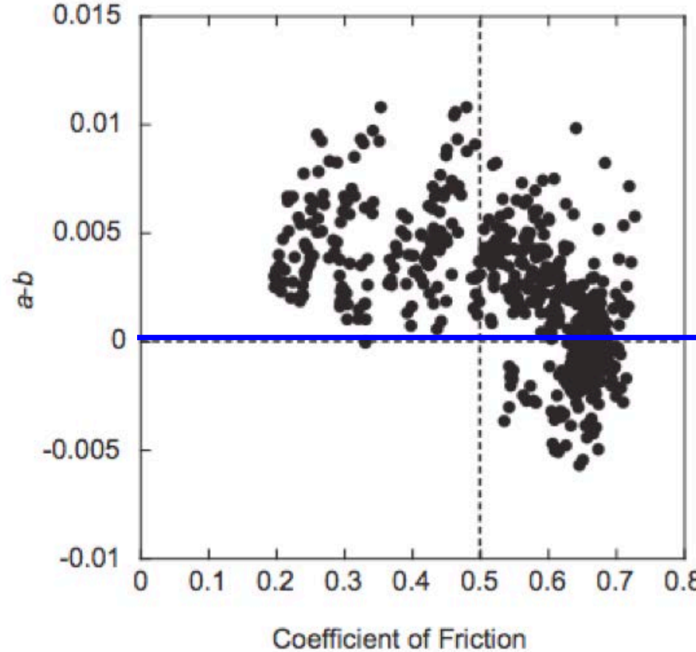
Mineralogical Controls on Instability

Friction



Stability (a-b)





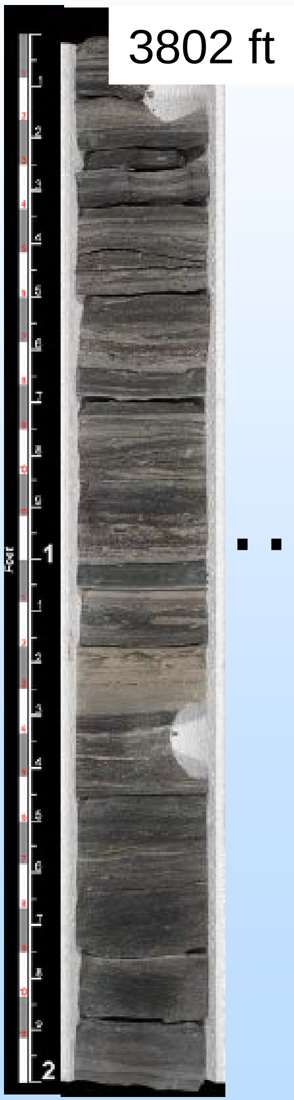
Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

[Ikari et al., Geology, 2011]

Primary sealing units within caprocks

Identify primary sealing units



. . .

FutureGen Industrial Alliance, Inc., Core No. 1, Wildcat, Morgan County, IL

Define properties relevant to rheology of fractures

- Petrology & lithology
- Diagenic features & cementation
- Calcite abundance & distribution
- Bulk mechanical properties
- Prevailing joints (fractures)
- Diagenic features in fractures
    - Carbonate filling
    - Fracture weathering
    - Clay content

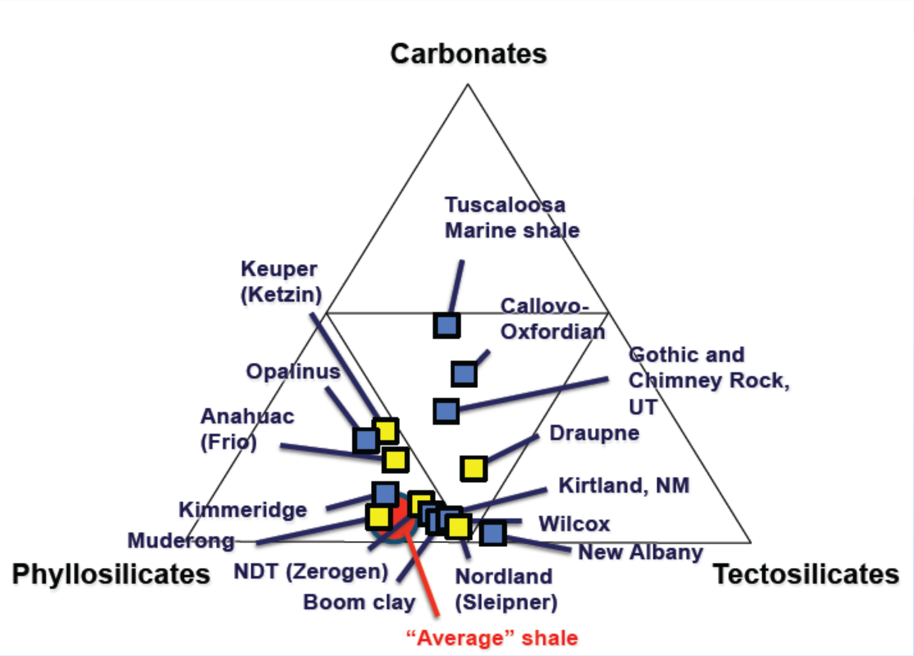
Collect, Synthesize and Characterize Sedimentary Formation Samples

Natural and idealized sealing units

Natural sealing units

Green River Shale
(Chevron)

Idealized sealing units

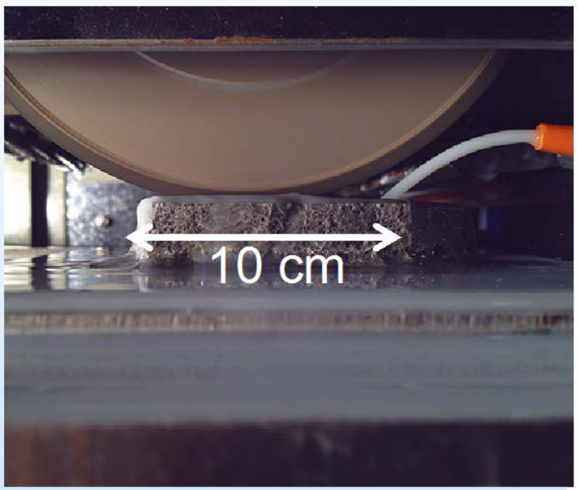


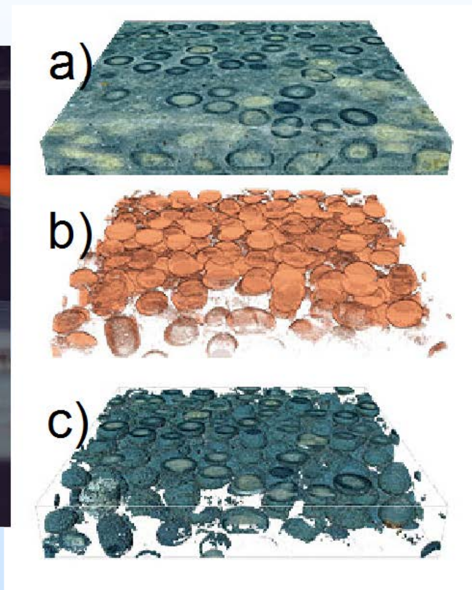
Bulk mineralogy of caprock formations
(Ian Bourg LBNL NCGC)

Synthesis of sedimentary rock analogues
(Brok et al. 1997 Geomaterials 325, 487)

Conduct Baseline Characterization of Natural and Synthetic Caprocks
3D mineralogy to construct digital rock models

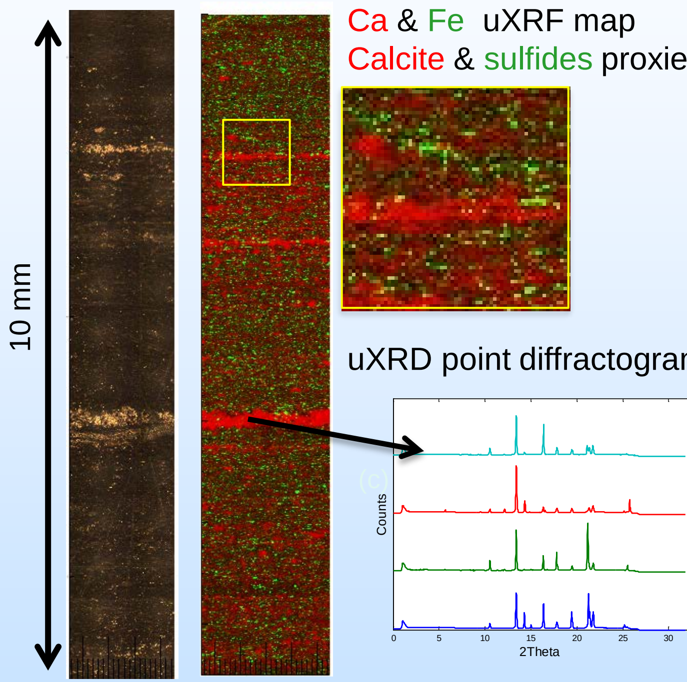
GIRI – Grinding Image Reconstruction Instrument
(A. Maloof, Princeton U.)





- 3D optical petrology
- Scale of rheology experiment specimens
- ~1um resolution
- High mineral selectivity of visible light
- Advanced segmentation methods

Bulk & high-resolution 2D composition



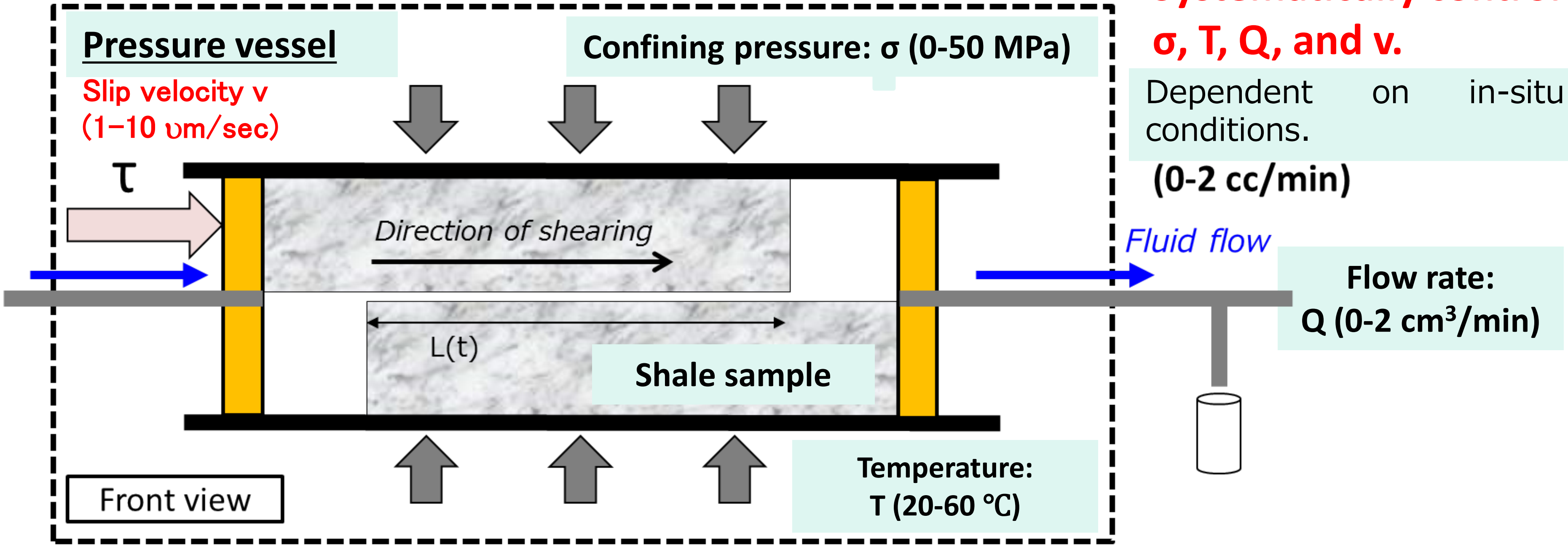
- Bulk XRF & XRD
- 2D imaging of thin sections
  - SEM with EDS
  - X-ray microscopy

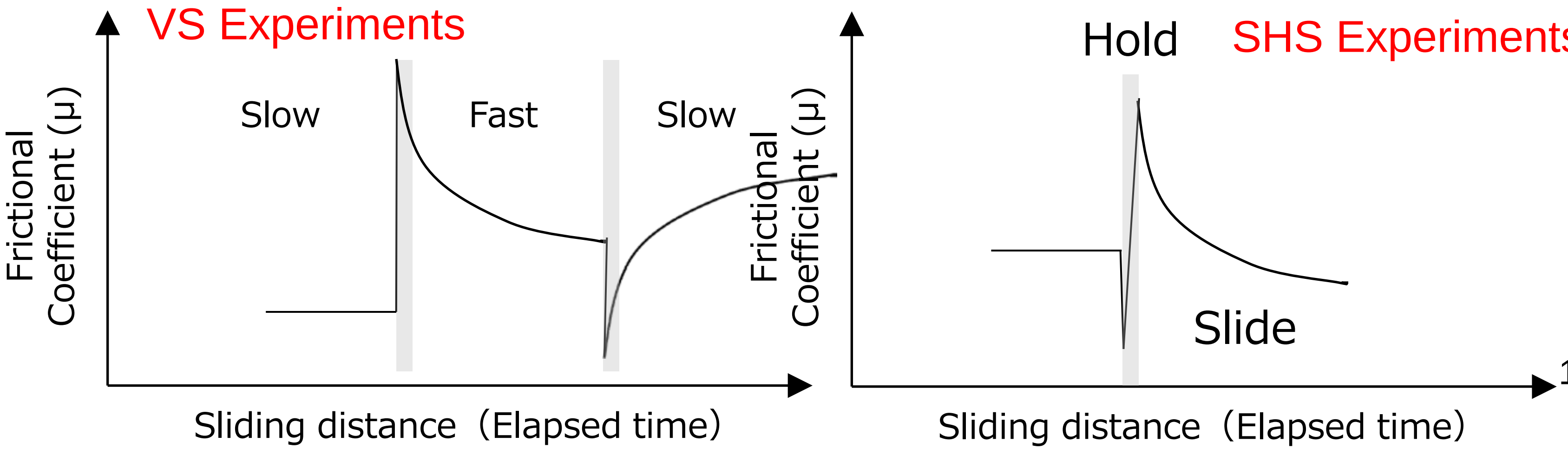
Evolution of Fault Rheology and Transport Parameters
Experimental Methodology

Concurrent Flow-Through, Velocity-Stepping and Slide-Hold-Slide experiments

Systematically control σ, T, Q, and v.

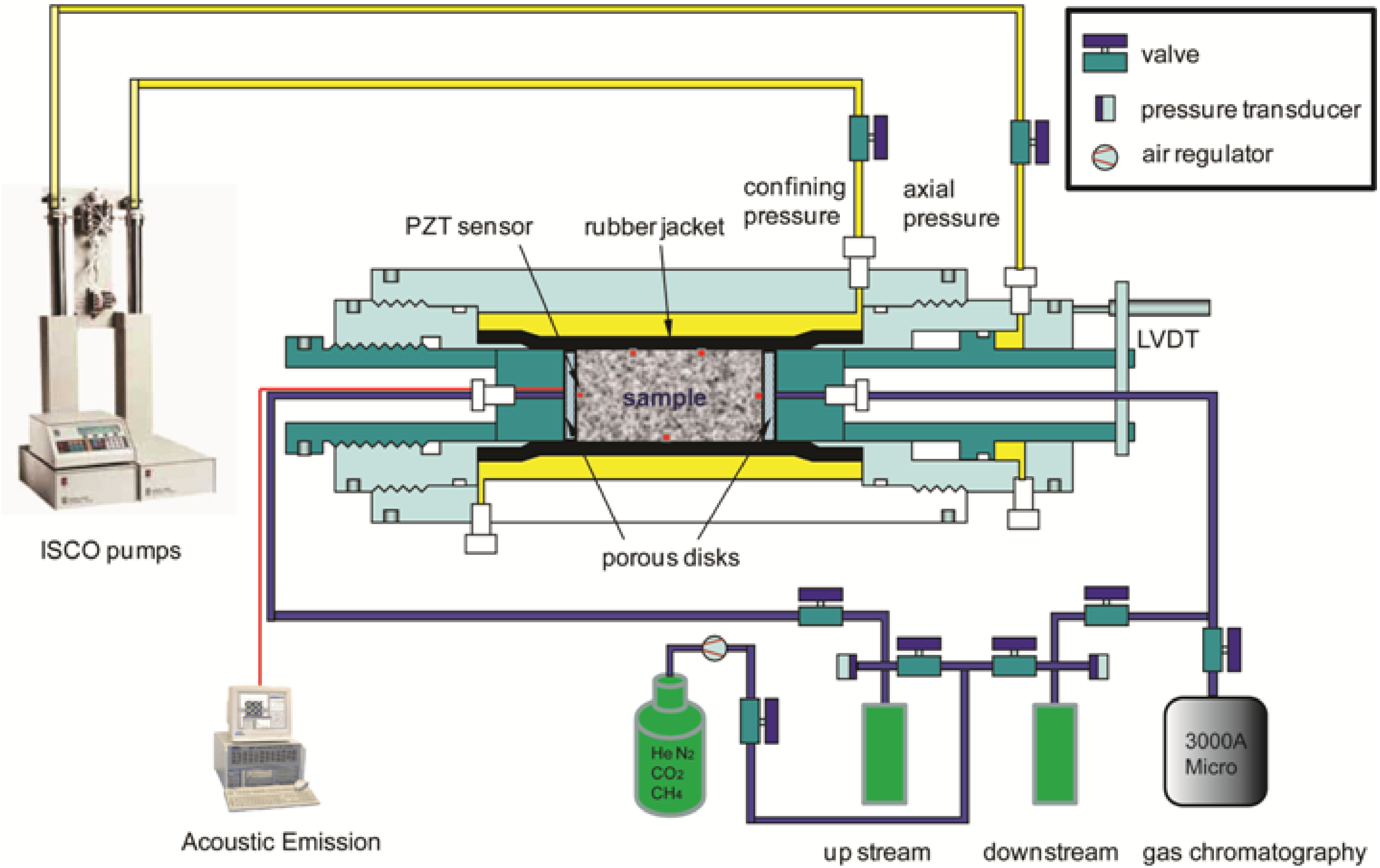
Dependent on in-situ conditions.





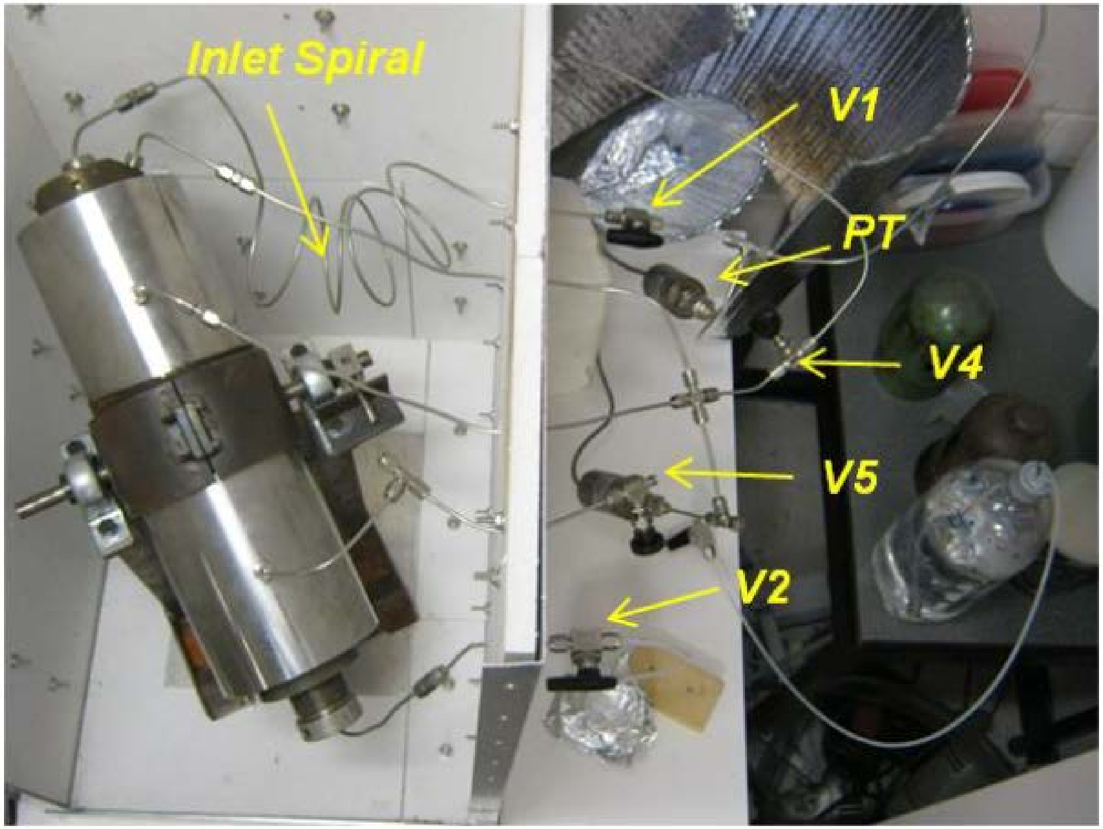
Evolution of Fault Rheology and Transport Parameters

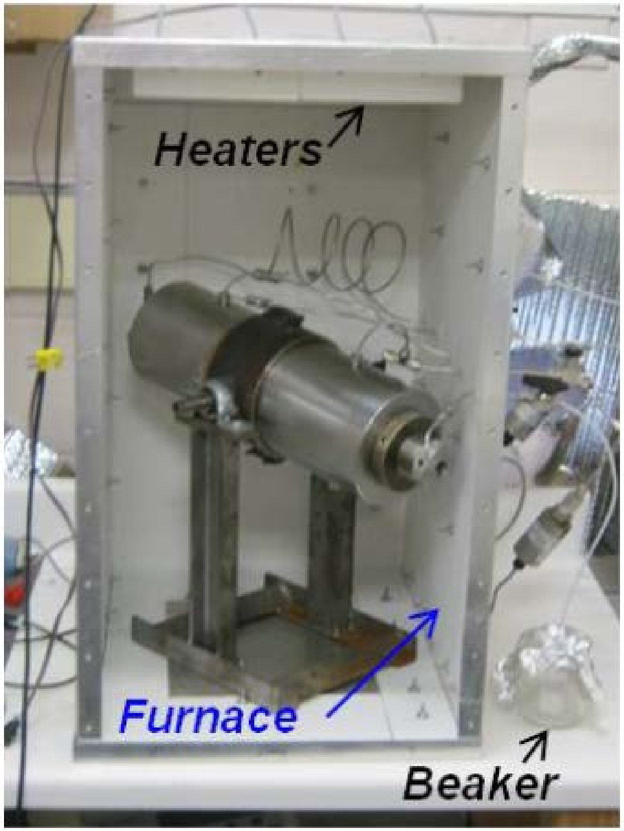
Experimental Arrangement



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

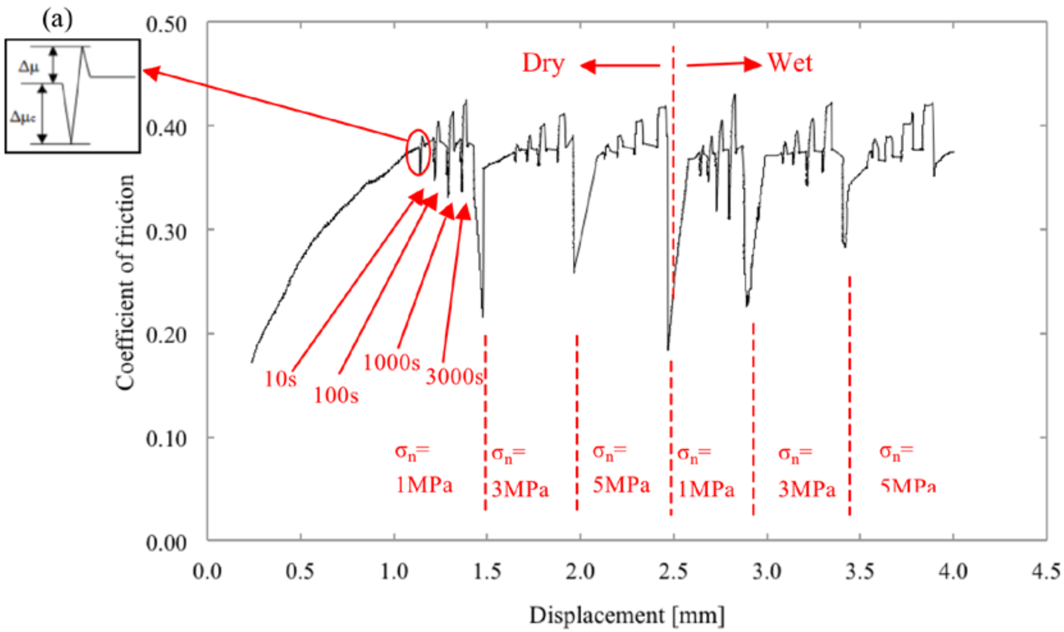
V4: Valve confining pressure

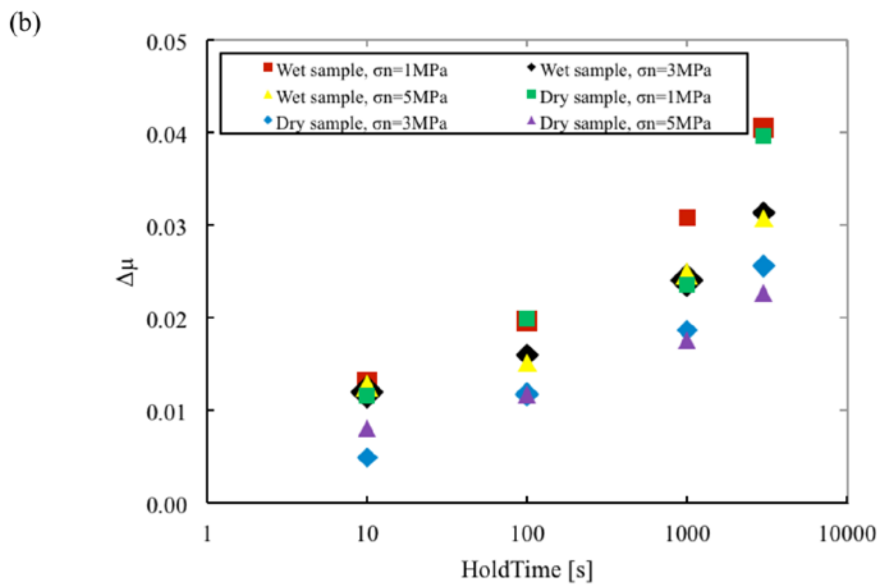
V5: Safety valve

PT: Pressure transducers

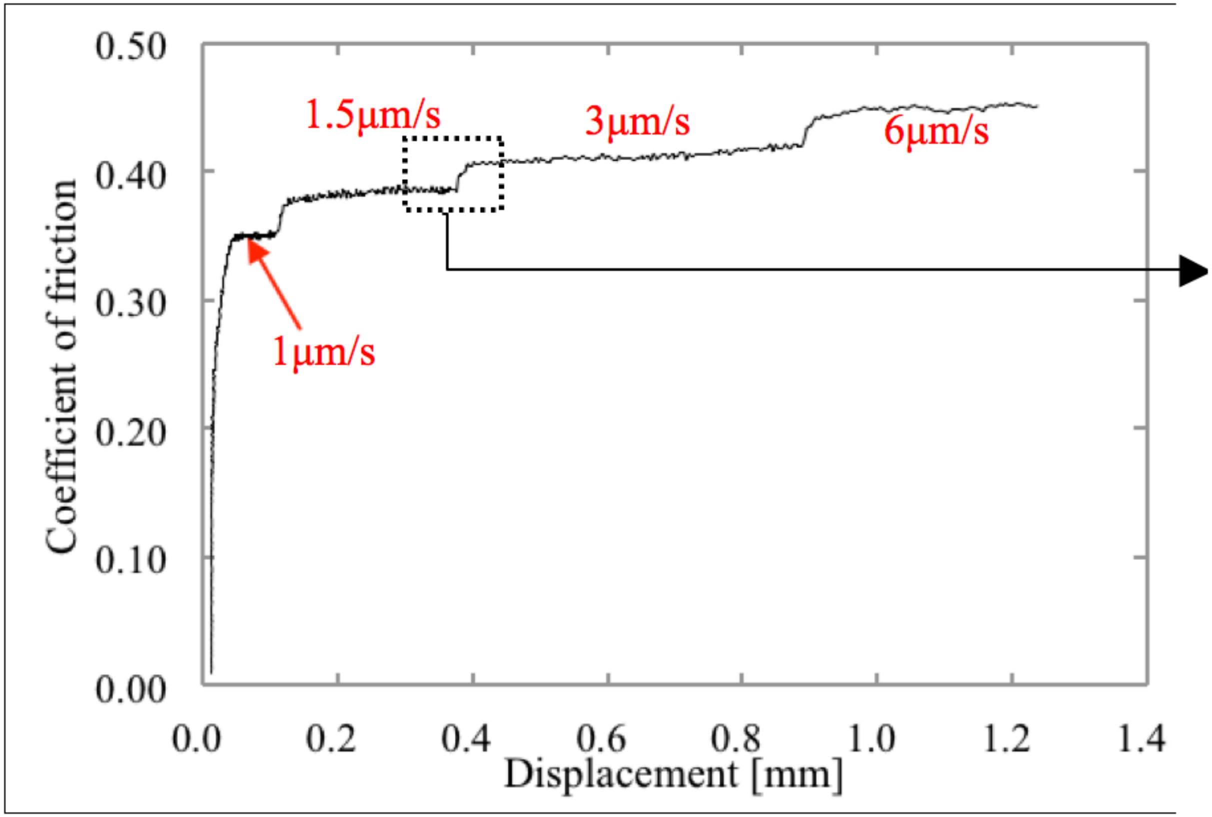
Evolution of Fault Rheology and Transport Parameters

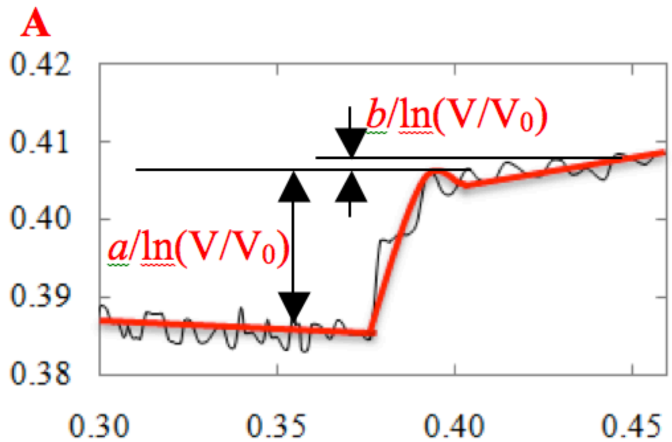
Healing Rate (SHS) Experiments





Evolution of Fault Rheology and Transport Parameters
Frictional Instability (VS) Experiments





V_0=1.5µm/s

V=3µm/s

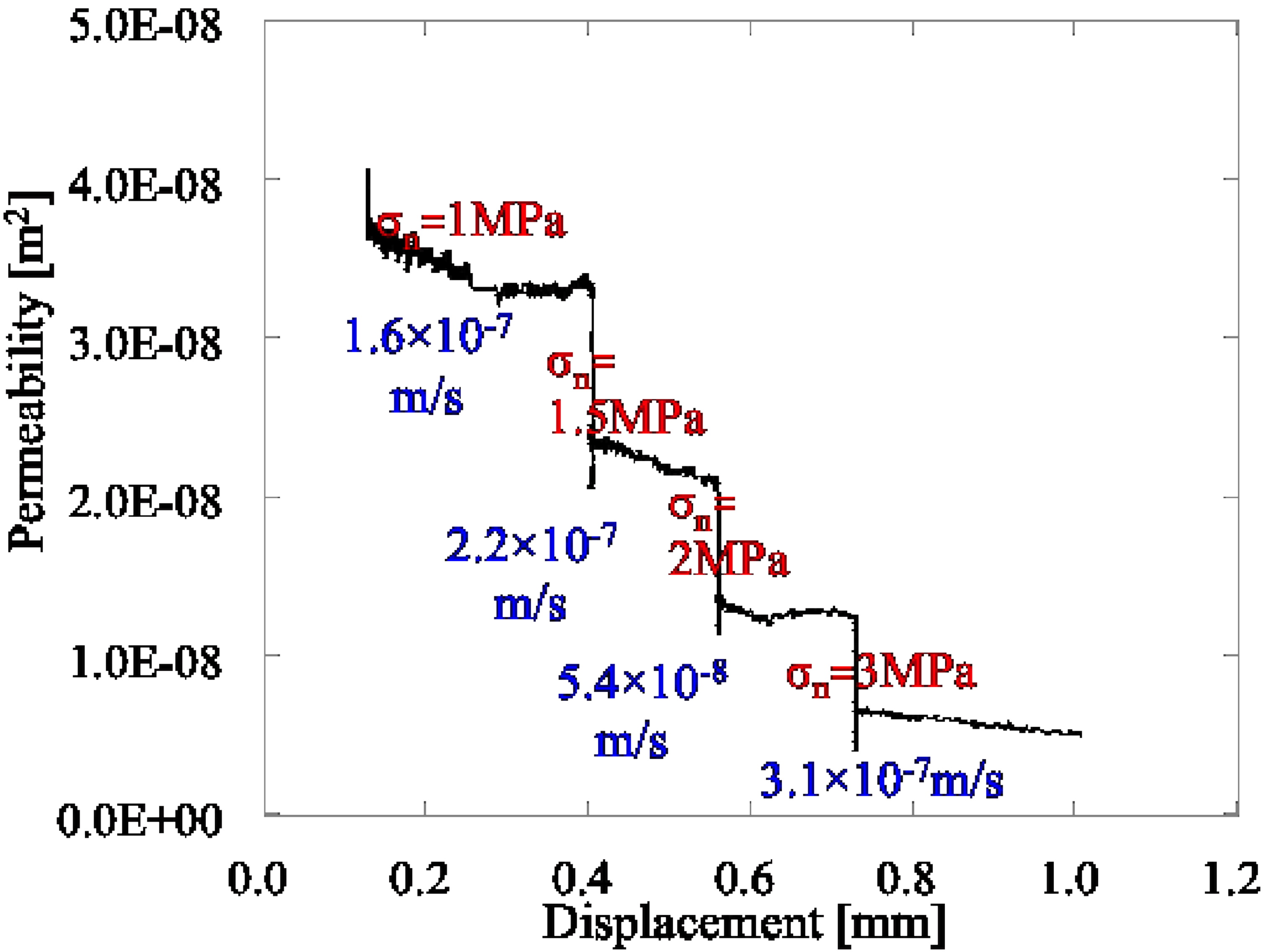
a=0.033033

b=-0.008518

a-b=0.04155

Evolution of Fault Rheology and Transport Parameters

Sliding Concurrent Permeability Measurement



Evolution of Fault Rheology and Transport Parameters

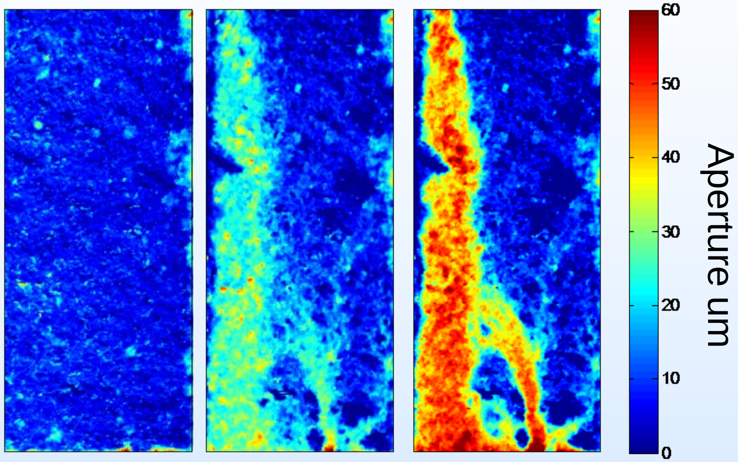
Experimental Parameters

Process	Experimental Variable		Experimental Range	Measured Output
Thermal	Temperature	T	$20° \rightarrow 200°C$	T_f
Hydraulic	Fluid flux or pressure	q_f or dp		$q_f \rightarrow k \rightarrow \Delta b$ or Δn
	Fluid saturation	S_w	$S_{w0} \rightarrow 100\%$	
Mechanical	Normal stress & Strain rate	σ_n and $\dot{\epsilon}$	$0 \rightarrow 100$ Mpa; $10 \rightarrow 10^6$ nm/s	$\dot{\varepsilon} \rightarrow \Delta \dot{b}$ or $\Delta \dot{n}$
	Shear stress & Strain rate	τ or $\dot{\gamma}$	$0 \rightarrow 50$ Mpa; $10 \rightarrow 10^6$ nm/s	$\dot{\gamma}$
Chemical	Aqueous	H_2O & CO_2		$q_f[Si] \rightarrow \dot{M} \rightarrow \Delta \dot{b}$ or $\Delta \dot{n}$

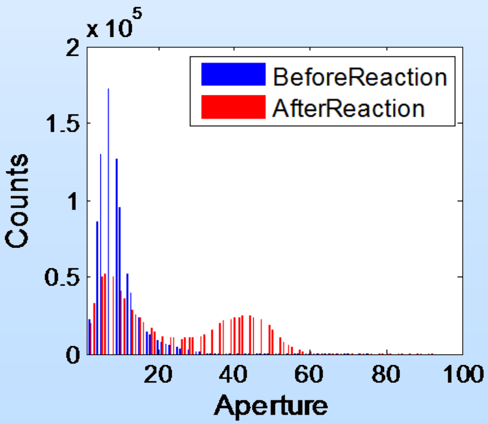
Table 1. Matrix of experimental variables. Measured outputs of fluid flux (q_f), normal stress and shear strain rates ($\sigma_n; \dot{\gamma}$), dissolved mass effluxes ($\dot{M}$), and pre- and post-test profilometry all provide independent estimates of the evolution of fracture permeability (k), and related aperture (b), and porosity (n).

In situ tomographic imaging of fractured cores during CO_2-acidified brine flow

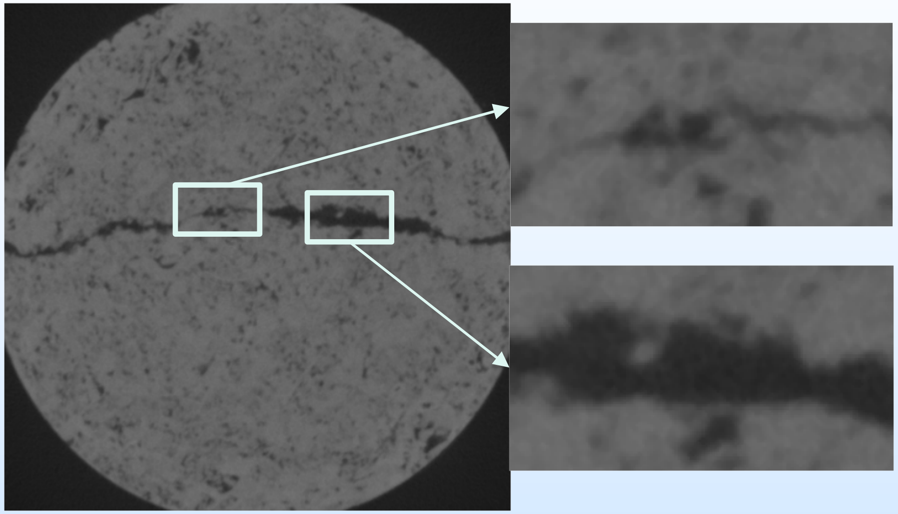
Channelization of Indiana Limestone



0 hr 24.3 hr 57.7 hr



Single xCT slice at ~30um voxel dimension



25 mm dia. fractured core

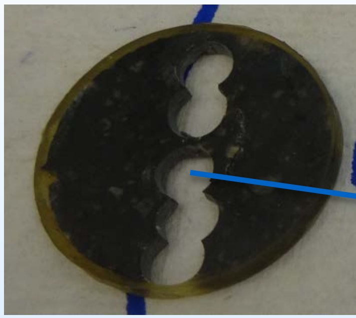
- Need higher resolution and contrast to quantify fracture volume, contact area, fracture boundary geometry
- In situ x-ray tomography during slip and flow must be augmented with ex situ high resolution measurements

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)

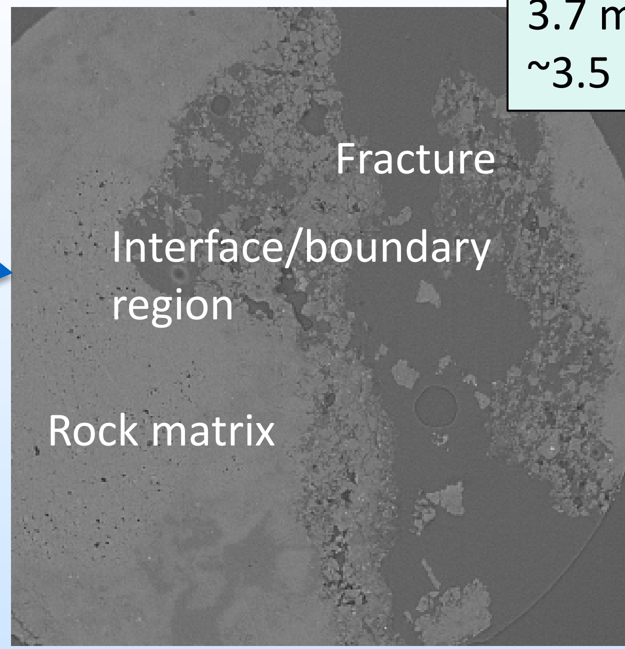
3D Imaging of fault contact area, fault geometry, and mineralogy & textures

Synchrotron based x-ray tomography

High resolution synchrotron xCT imaging



25 mm dia.
Epoxy-stabilized fractured core



3.7 mm dia. Subcore
~3.5 um voxel dim.

Amherstberg caprock formation

Physical changes at fracture surface and within boundary region

- Porosity
- Pore network structure
- Accessible surface area
- Asperity mineralogy

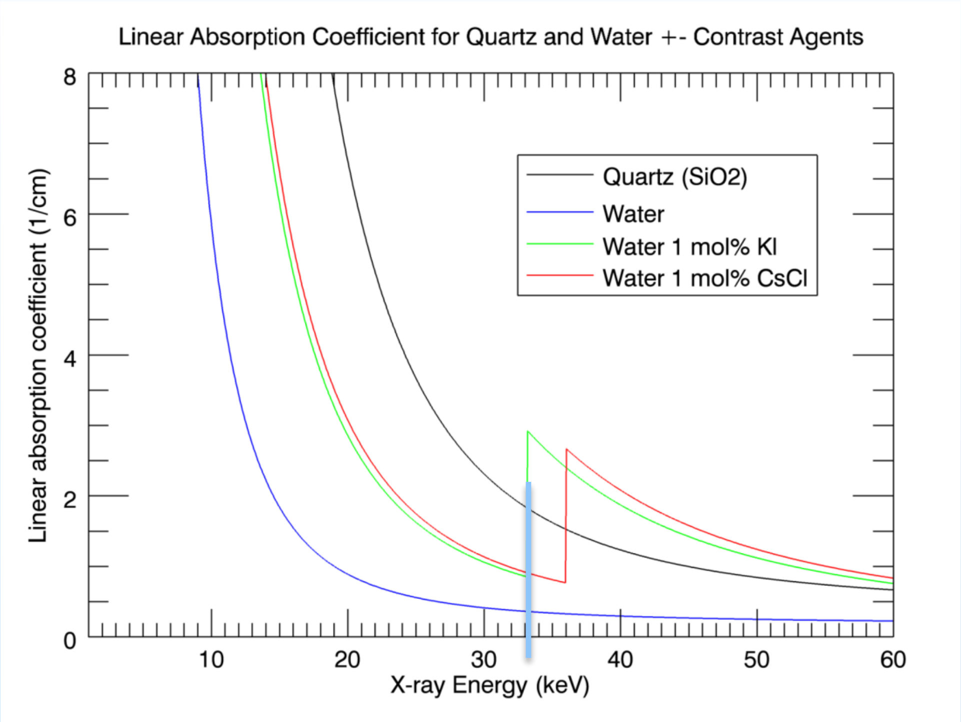
Will impact

- Rheology of fracture
- Transmissivity/Permeability

xCT slice of epoxy-stabilized fracture after CO_2-acidified brine flow
(sample from Ellis et al. 2011 GHGS&T 1(3), 248)

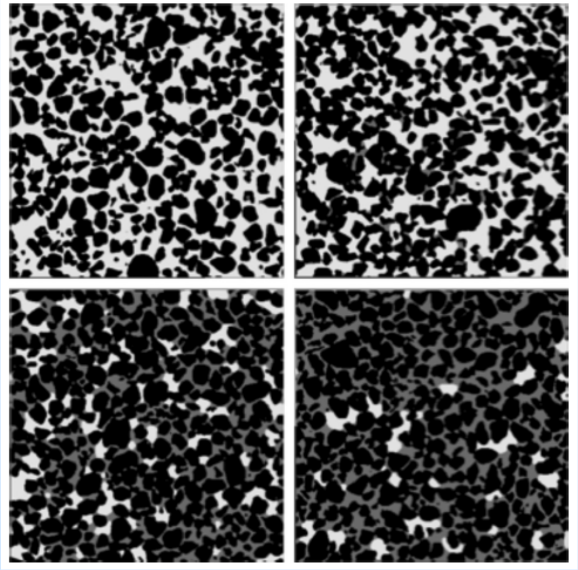
3D Imaging of fault contact area, fault geometry, and mineralogy & textures
Synchrotron based x-ray tomography

Differential absorption x-ray tomography



(M. Rivers, U. Chicago, GSE CARS)

Water phase doped with cesium



X-ray differential absorption tomography at the Cs K-edge shows how CsCl-doped water (grey phase) is imbibed into Ottawa sand (black), stranding pockets of air (white)

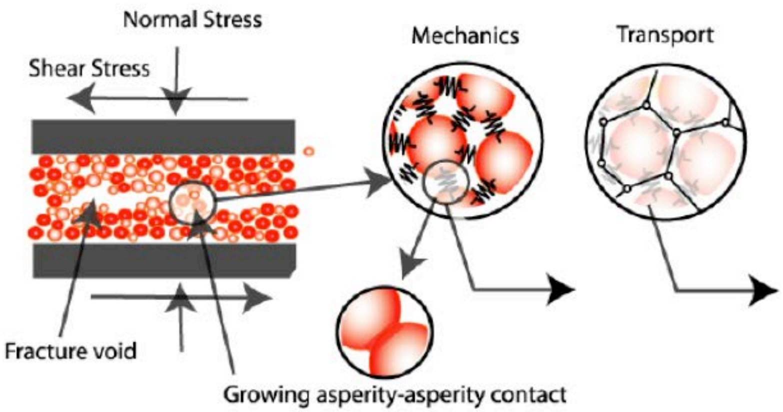
(C. Willson et al., 2012, ASTM Geotech. Testing J., 35(6) 911)

- Superior fracture-mineral contrast
- Quantification of fracture volume & boundary porosity
- Phase contrast tomography to see grain boundaries

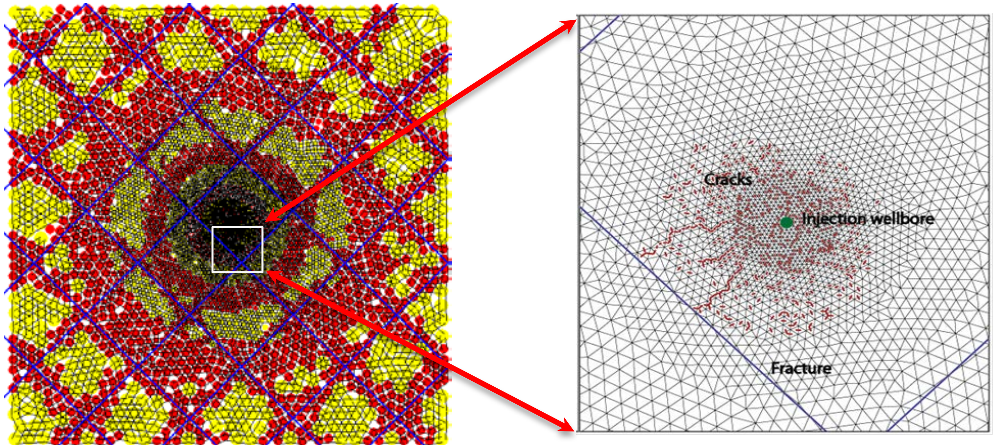
Digital Rock Physics Modeling of Response
Discontinuum Approaches

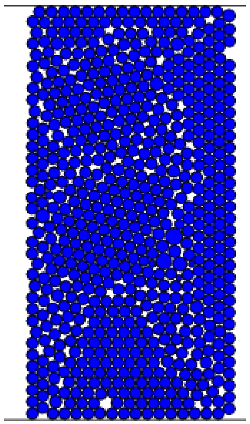
Granular Models for Synthetic Rock Masses

Micro-Model

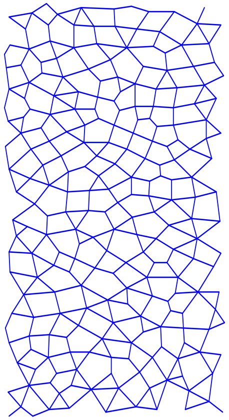


Nested Structured Model

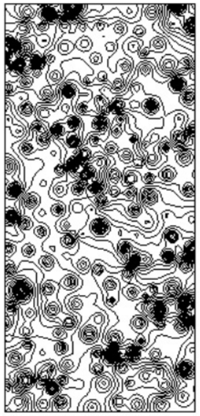




Solid sample



Fluid network



Permeability distribution

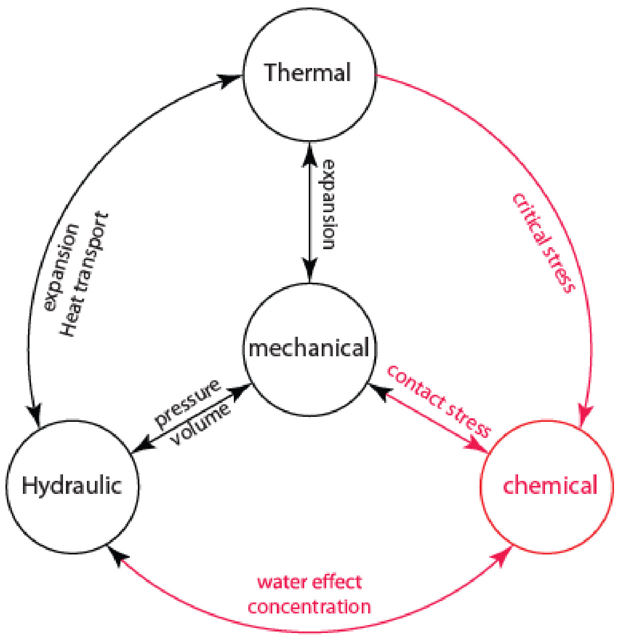
Science questions:

Approaches to represent the complex failure and deformation response of structured media, e.g.:

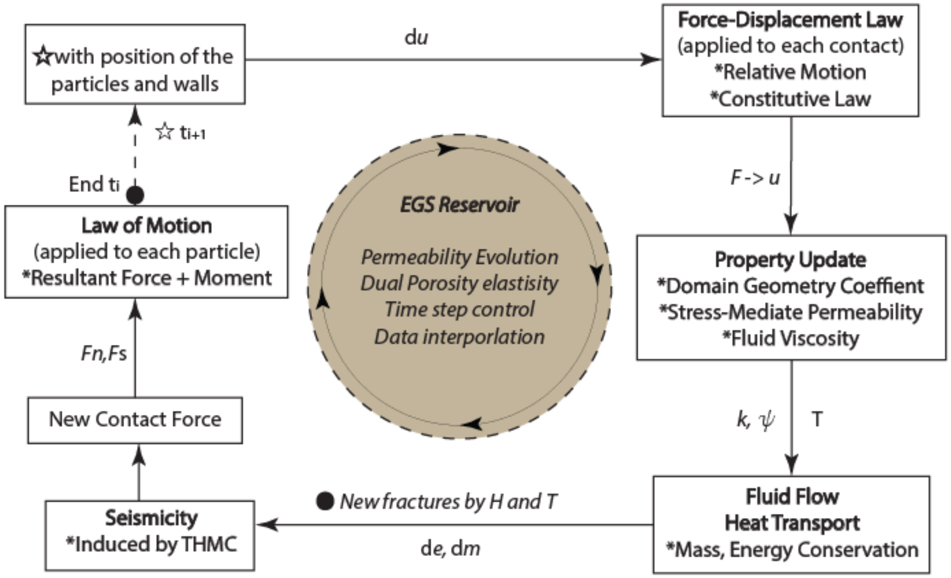
1. Mechanisms of chemical compaction
2. Styles of failure
3. Event size/timing of induced seismicity, roles of:
   1. Healing rates for repeat seismicity
   2. Weakening rates for seismic vs aseismic
4. Stress-mediated reaction rates
5. Feedbacks between processes
6. ………………

Digital Rock Physics Modeling of Response
Process Logic

Feedbacks



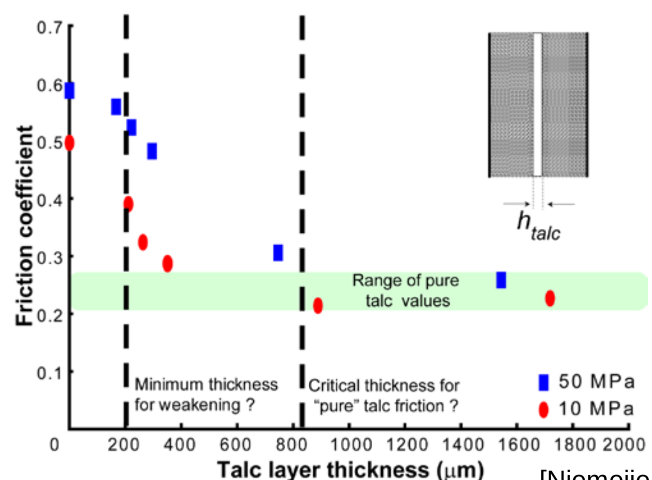
Interactions



Key Points:

1. Accommodate appropriate response from experimental observations
   1. Velocity strengthening/weakening
   2. Relative stiffness effects
   3. Roles of heterogeneity and structure
2. Screening for:
   1. Stability/Instability
   2. Permeability evolution

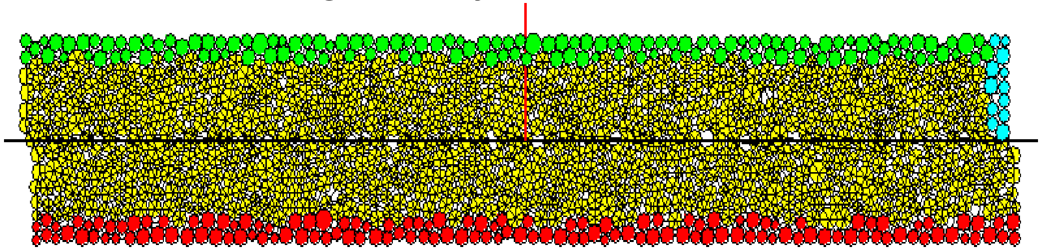
Frictional Response of Mixtures



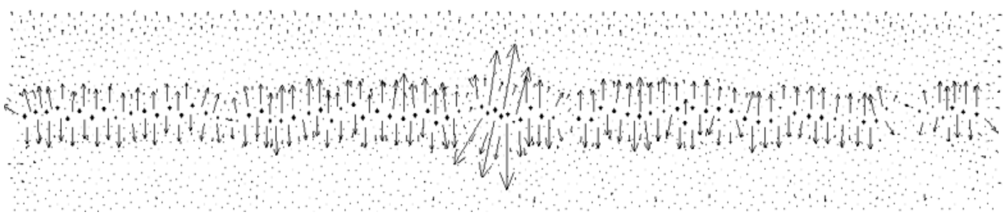
[Niemeijer et al., 2009]

Rheological and Transport Models of Fractures

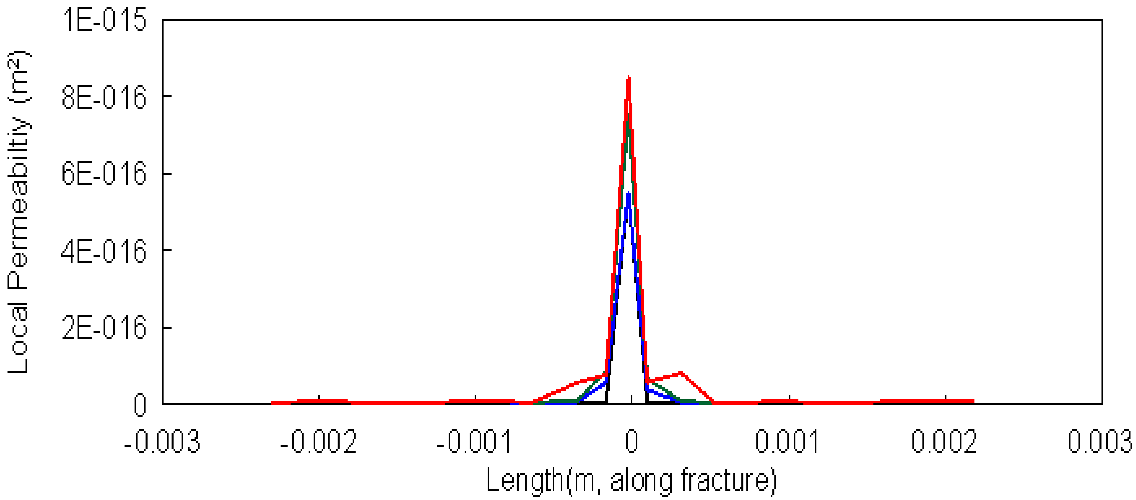
Sheared fracture geometry



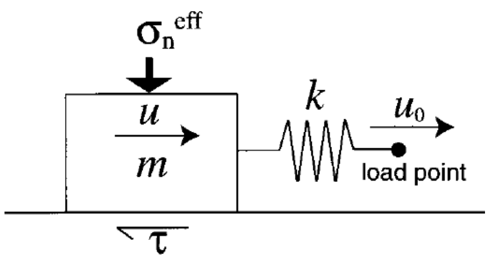
Displacement profile



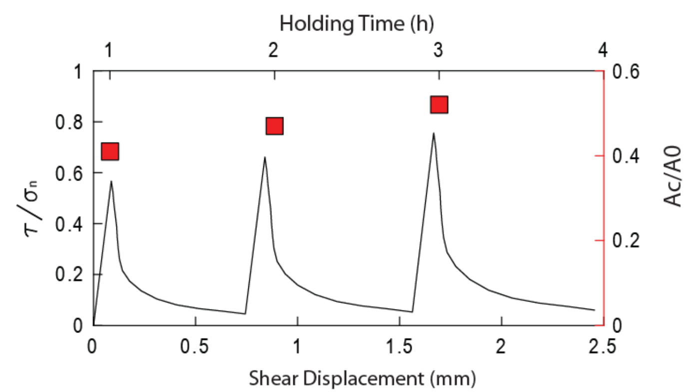
Permeability evolution



Block-slider model



Strength evolution



Caprock Screening Heuristics

Synthesize Basin-scale formation properties with Rheology model results

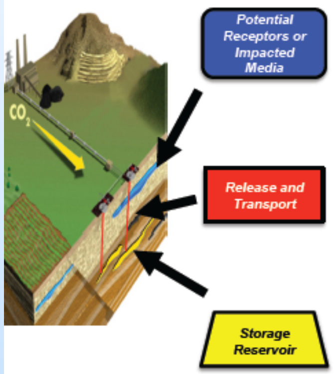
Caprock/site-specific risk assessments: *How are slip behaviors affected by different mineralogies and textures of caprocks?*

National Risk Assessment Partnership (NRAP): *provide science base for methodologies to calculate "defensible, quantitative, site-specific risk profiles"*

Geomechanical risk profiles based on properties of primary sealing units

- Mineral content and distribution (e.g., calcite, clay)
- Predominant bedding features
- Fracture interfacial composition, structure and texture

Key NRAP Focus for First Generation Risk Profile Development



Receptors

- *Groundwater/Atmosphere*
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators
  - evaluate assumption that mass transfer between sub-systems has negligible impact;
- *Ground Motion*
  - develop robust numerical models for simulating ground deformation as function of stress changes
  - perform systematic realizations across ranges in key parameters
  - develop robust abstractions of responses as functions of key parameters
  - develop robust protocol for integrating information to/from multiple simulators

Release/Transport

- *Wellbores*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective wellbore permeabilities observed in various environments
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability
- *Faults/Fractures*
  - perform systematic realizations across ranges in key parameters
  - conduct robust analysis of effective permeabilities for various types of seals
  - develop time-varying permeability models
  - develop coupled geomechanics models to estimate change in permeability

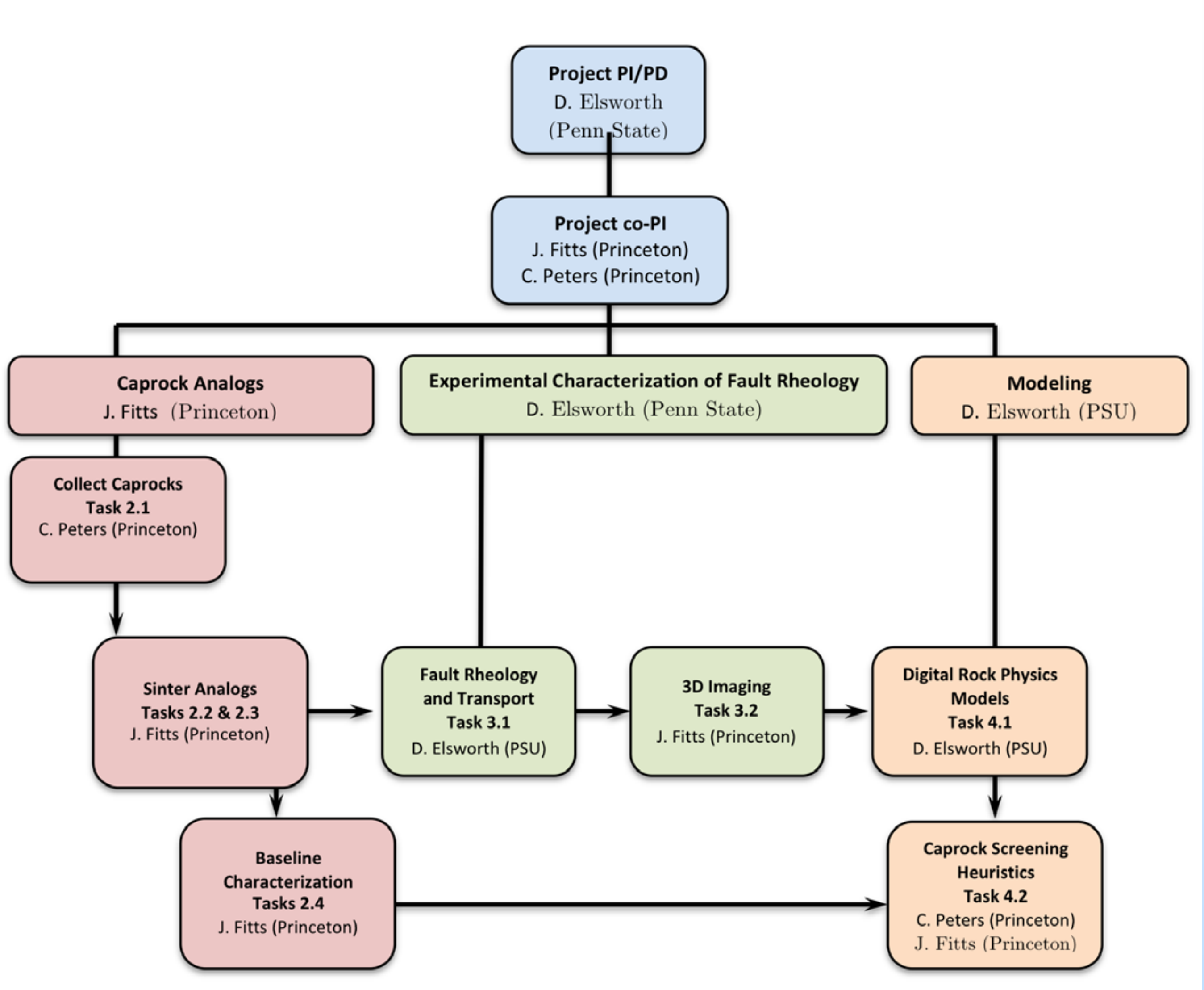
Storage Reservoirs

- *Pressure/Saturation/Stress*
  - develop robust protocols for passing information to/from multiple simulators
  - develop abstractions for pressure-saturation evolution for coupled flow-reaction-geomechanics

Expected Outcomes

- Provide a fundamental understanding of the key mechanical and mineralogical/chemical processes influencing:
  - Seismic and aseismic reactivation of faults/fractures – felt seismcity
  - Healing of faults/fractures – event recurrence
  - Evolution of multiphase flow and transport properties
- Develop methodologies for:
  - Integration of process measurements and imaging at microcscale
  - 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.

Organization Chart/ Communication Plan



Communication plan: Biweekly Skype [Oct 23; Nov 6, ….]

Biannual meeting

Task/Subtask Breakdown

Subtask 2.1 Collect Homogeneous and Mineralogically Complex Sedimentary Rocks

- Q2 – Survey of mineral assemblages, textural heterogeneities and sedimentary features of caprocks that impact fault slip

Subtask 2.2 Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks

- Q3 – Demonstrate sintering method to synthesize idealized analogs of sedimentary rocks

Subtask 3.1 Evolution of Fault Rheology and Transport Parameters

- Q4 – Demonstrate congruence in fault rheology and permeability evolution in natural caprocks and sintered analogs
- Q8 – Demonstrate the importance of mineralogical controls on fault rupture in defining the transition from seismic to aseismic response
- Q12 – Define mineralogical and textural controls on permeability evolution in caprocks and their analogs

Subtask 3.2 3D Imaging of fault contact area, fault geometry, and mineralogy & textures

- Q4 – Demonstrate novel in situ 3D imaging during rheology and reactive flow experiments
- Q8 – Demonstrate novel high-resolution 3D imaging and methods required to parameterize and generalize digital rock physics models

Subtask 4.1 Digital Rock Physics Modeling of Response

- Q4 – Develop a mechanistic understanding of sintering using mineral aggregates
- Q8 – Verify extensions of rate state response from grain to basin scale – charting transitions from seismic to aseismic response
- Q12 – Define critical compositional and textural constraints on the transition from seismic to aseismic rupture

Subtask 4.2 Caprock Screening Heuristics

- Q12 – Develop practical heuristics for screening caprocks

Deliverables

Reporting of results

- Professional meetings
- Peer reviewed literature (see following)
- Coordination with:
  - National Labs
  - Regional Compacts
  - URL Networks

Deliverables (Cont'd)

Subtask 2.1 Collect Homogeneous and Mineralogically Complex Sedimentary Rocks

- Q2 – Survey of mineral assemblages, textural heterogeneities and sedimentary features of caprocks that impact fault slip

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Milestones

Task/ Sub Task	Milestone Title	Planned Comp. Date	Verification Method
1.0	Project Management Plan	M0	PMP file
1.0	Kickoff Meeting	Q1	Agenda & Presentation file
2.0	**Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)**		
2.1	Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)	Q2	Agenda and presentation file from project biannual meeting
2.2	Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)	Q4	Agenda and presentation file from project biannual meeting
2.3	Conduct Baseline Characterization of Natural and Synthetic Caprocks (Fitts)	Q8	2nd year report
3.0	**Laboratory Experimentation (Elsworth, Lead)**		
3.1	Evolution of Fault Rheology and Transport Parameters (Elsworth)	Q2, Q4 Q6, Q8 Q10, Q12	Agenda and presentation file from project biannual meeting
	3D Imaging of fault contact area, fault geometry, and mineralogy & textures (Fitts)		Data archive shared with DOE and Task 4.1
4.0	**Modeling for Response and for Caprock Screening (Elsworth, Lead)**		
4.1	Digital Rock Physics Modeling of Response (Elsworth)	Q2, Q4 Q6, Q8 Q10, Q12	Data archive shared with DOE and Task 4.2
4.2	Caprock Screening Heuristics (Peters, Fitts)	Q12	Final report

Decision Points

- **Close of Year 1:** No-Go if unable to recover samples or to sinter analogs with strength within 10% of natural samples.
- **Close of Year 2:** No-Go if resolution of imaging is insufficient to resolve processes of relevance for the digital rock physics models.

Risk Matrix

For the proposed laboratory investigation there appear few risks. However, principal risks relate to:

- ***Inability to Recover Samples:*** If we are unable to recover samples from any particular source then many analogs exist to cparocs and are quarry accessible as dimension stone.
- ***Inability to Access Beamline:*** Some beamline facilities are undergoing changes in funding availability. Sufficient options exist to exchange locations for beamline.
- ***Imaging Resolution:*** The imaging is required to be sufficiently high resolution to be able to distinguish chemical precipitation and dissolution processes. If insufficiently high resolution, then limiting sample size is one method to improve resolution.
- ***CO_2 as an Asphyxiant:*** CO_2 will be used in the experiments. We routinely use CO_2 in our experiments with no mishaps to date. Laboratory protocols have been sufficient.

Proposed Schedule

SCHEDULE of TASKS and MILESTONES		BP1 Oct 2014 to Sept 2015				BP2 Oct 2015 to Sept 2016				BP3 Oct 2016 to Sept 2017			
	PI	Y1Q1	Y1Q2	Y1Q3	Y1Q4	Y2Q1	Y2Q2	Y2Q3	Y2Q4	Y3Q1	Y3Q2	Y3Q3	Y3Q4
		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
Task 1 -- Project management and planning	Elsworth												
Task 2 -- Collect, synthesize and characterize sedimentary formation samples	Fitts												
SubTask 2.1 – Collect Homogeneous and Mineralogically Complex Sedimentary Rocks	Peters												
SubTask 2.2 – Sinter Mineral Mixtures to Create(Fitts) Idealized Analogs of Sedimentary Rocks	Fitts												
SubTask 2.3 – Conduct Baseline Characterization of Natural and Synthetic Caprocks (Fitts)	Fitts												
Task 3 -- Laboratory Experimentation	Elsworth												
Subtask 3.1 -- Evolution of Fault Rheology and Transport Parameters	Elsworth												
Subtask 3.2 -- 3D Imaging of fault contact area, fault geometry, and mineralogy & textures	Fitts												
Task 4 -- Modeling for Response and Caprock Screening	Elsworth												
Subtask 4.1 -- Digital rock physics of response	Elsworth												
Subtask 4.2 -- Caprock screening heuristics	Peters/Fitts												

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 microcscale
  - 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.