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

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Derek Elsworth, Penn State

Jeffrey Fitts & Catherine Peters, Princeton

U.S. Department of Energy

National Energy Technology Laboratory

Carbon Storage R&D Project Review Meeting

Transforming Technology through Integration and Collaboration

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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_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…….

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

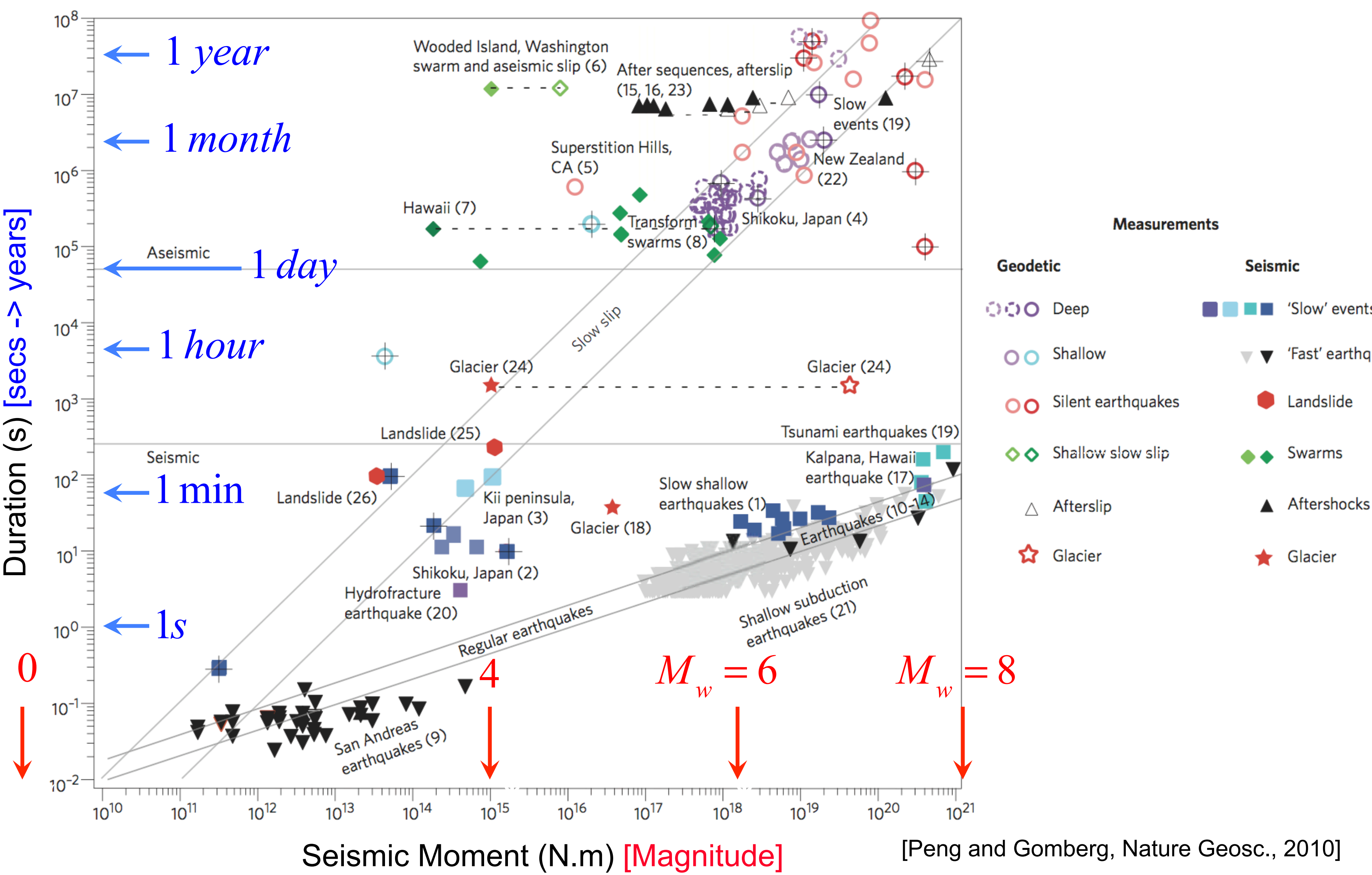
Background

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

Methodology

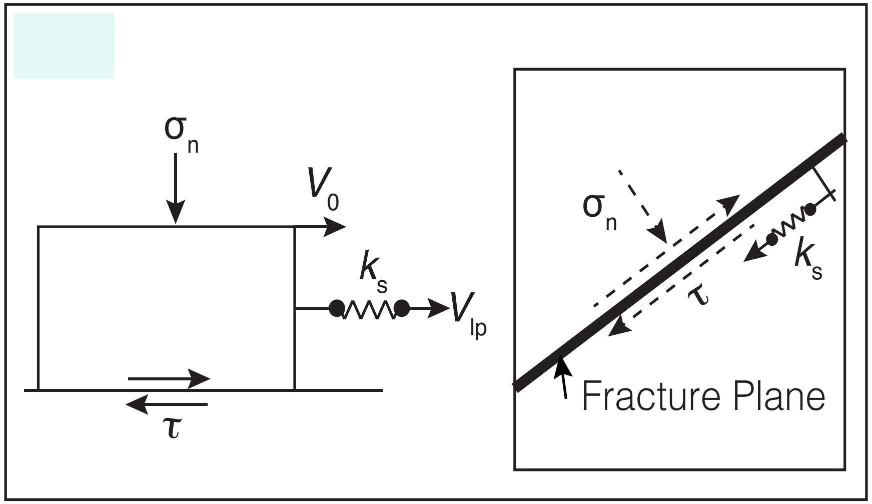
- **Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)**
  - Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)
  - Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)
  - Conduct Baseline Characterization of Natural and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

Seismic – vs- Aseismic Events



[Peng and Gomberg, Nature Geosc., 2010]

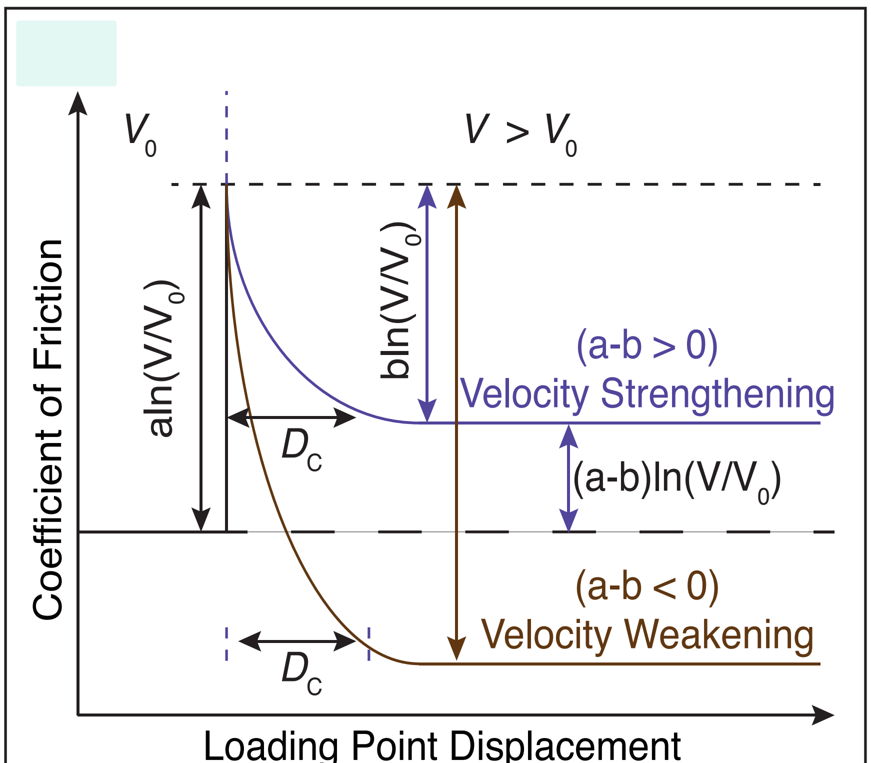
Requirements for Instability (Seismicity)



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

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

$$a-b$$



$$a-b>0$$

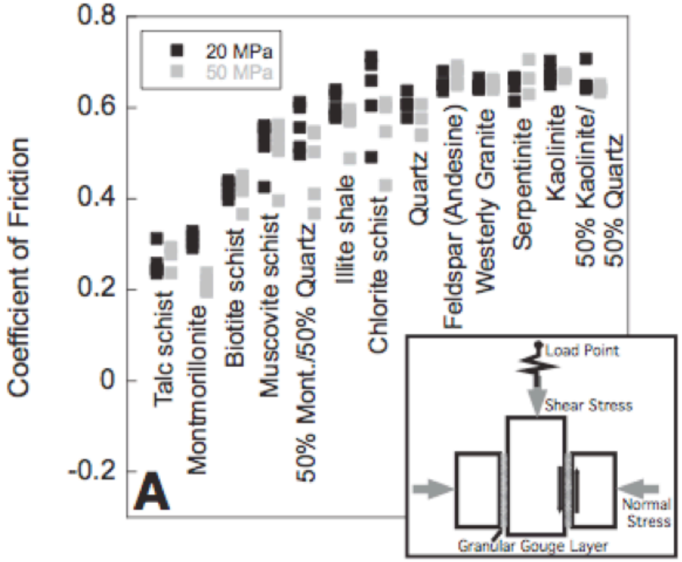
$$a-b<0$$

- $$K_c < K_s$$
- $$K_c > K_s$$

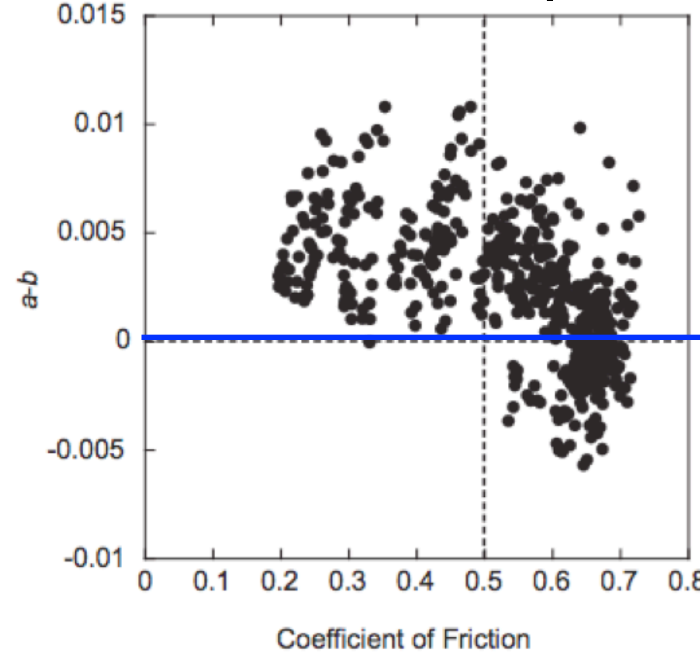
Stability mediated by a-b and K_c and upscaled *in situ* via K_s

Mineralogical Controls on Instability

Friction



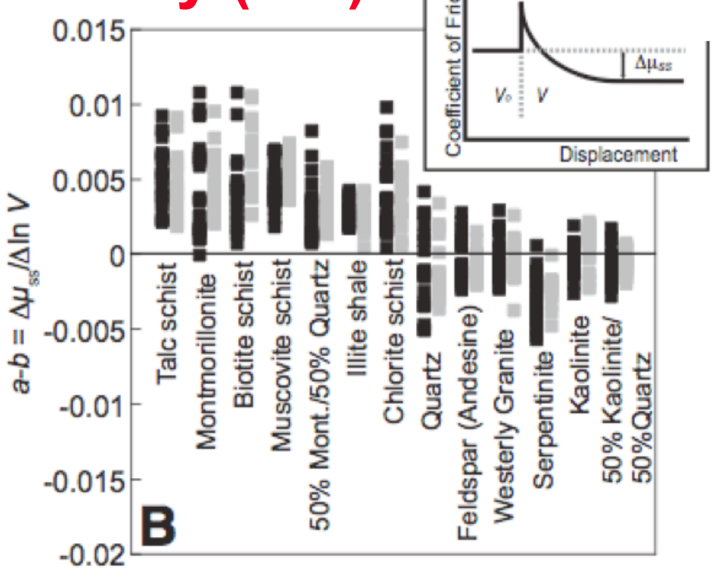
[Ikari et al., Geology, 2011]



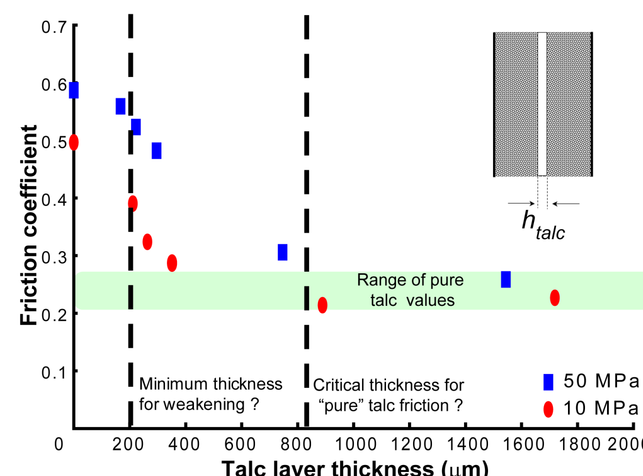
Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

Stability (a-b)



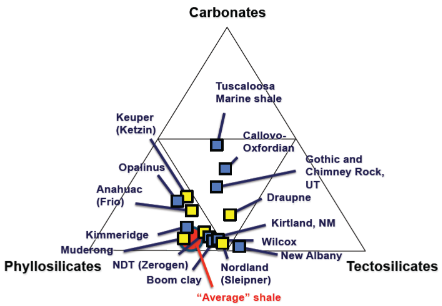
Frictional Response of Mixtures



[Niemeijer, Elsworth et al., GRL, 2009]

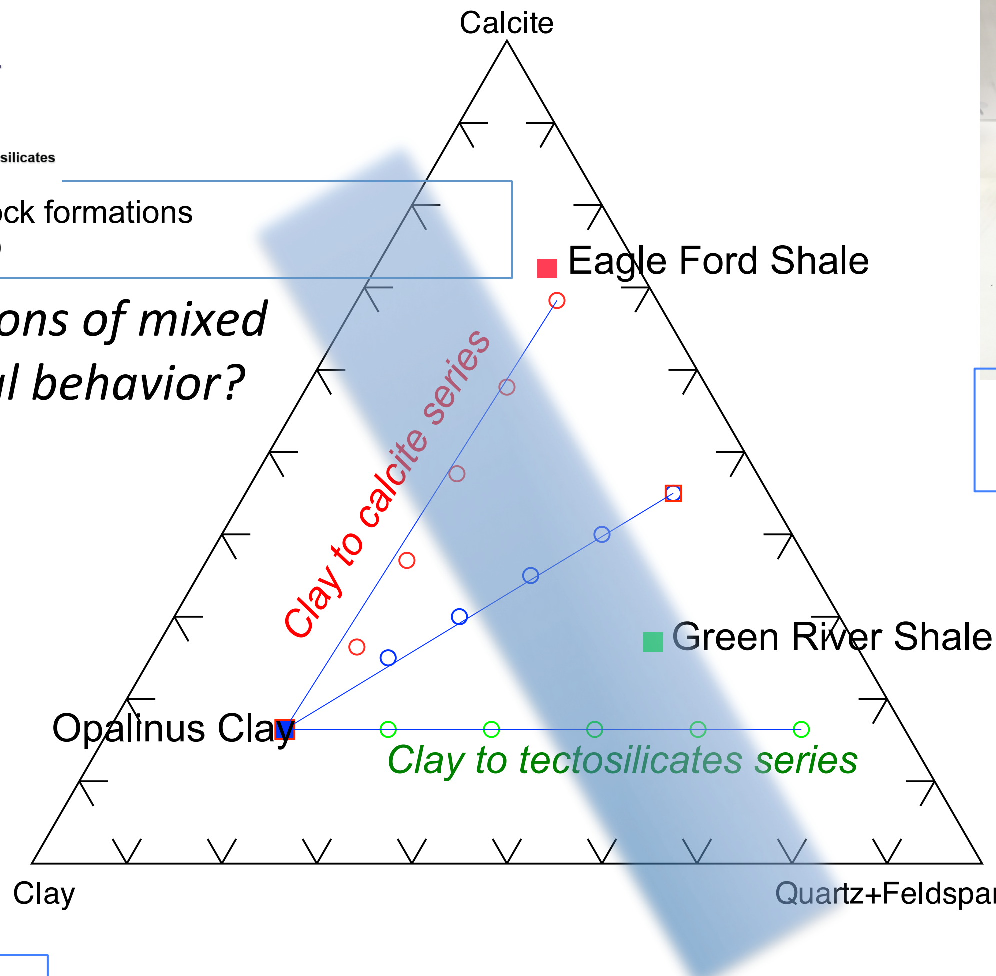
Important mineralogical features of sealing units

Natural and idealized caprock mineralogy



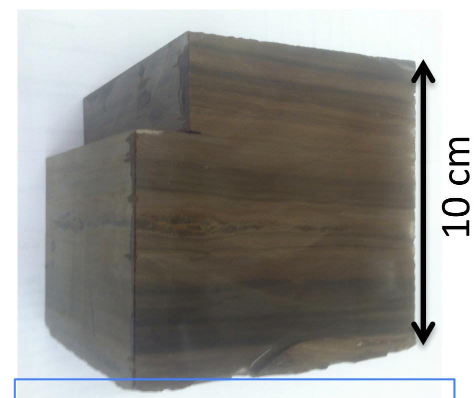
Bulk mineralogy of caprock formations
(Ian Bourg LBNL NCGC)

Compositions of mixed rheological behavior?



Eagle Ford Shale
(Kocurek Industries, Inc)

Opalinus Claystone
(Mount Terri Project)



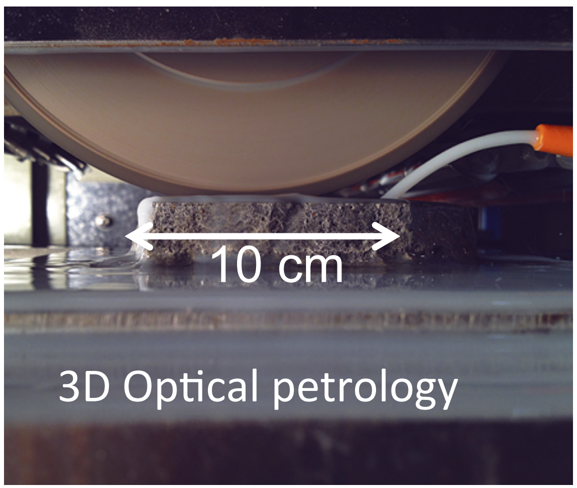
Green River Shale
(Chevron)

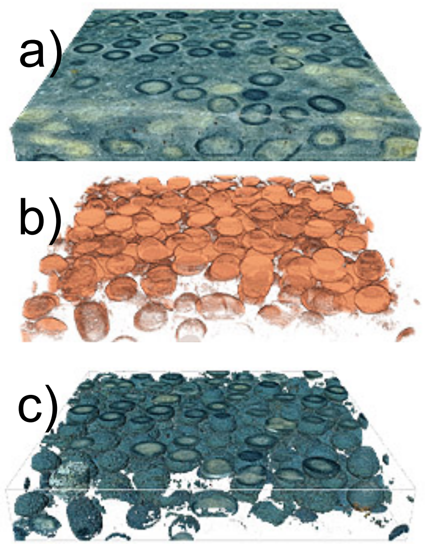
Imaging textures and composition of caprock matrix and fracture contacting asperities

3D mineralogy to construct digital rock models

- ➢ Map textures at scale of rheology experiment specimens

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

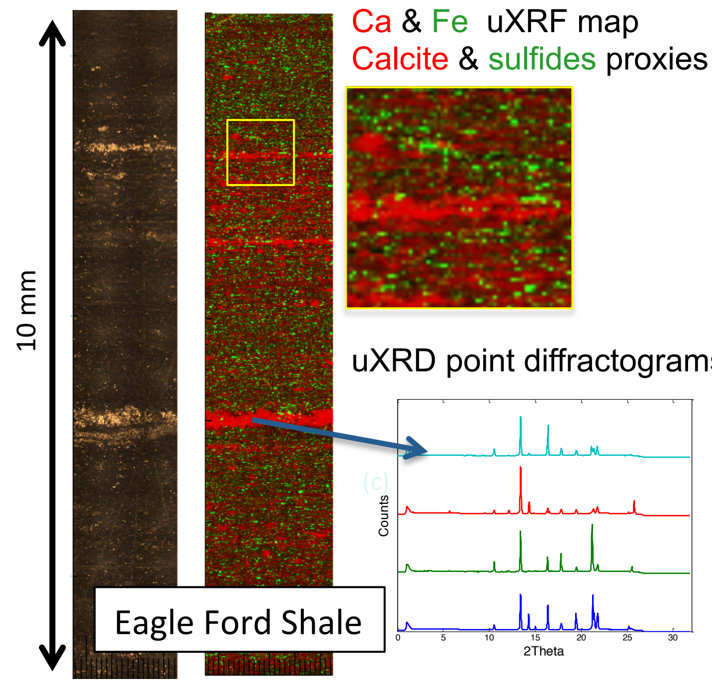




- Textures susceptible to permeability increase: continuous calcite-rich volumes
- Complex spatial variation of lithologies

- ➢ Map composition of contacting asperities

X-ray microspectroscopy & diffraction



- Relative solubility of asperities
- Characterize asperities with mixed mineral composition

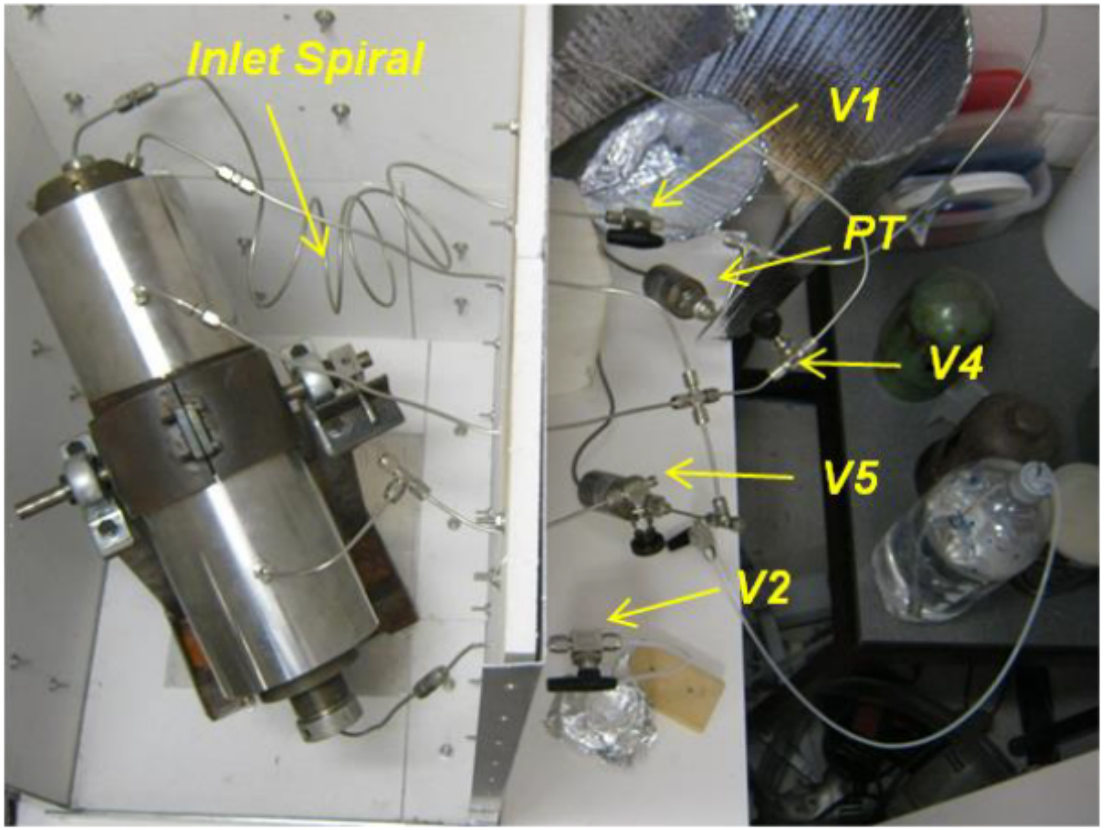
Permeability – Seismicity Coupling

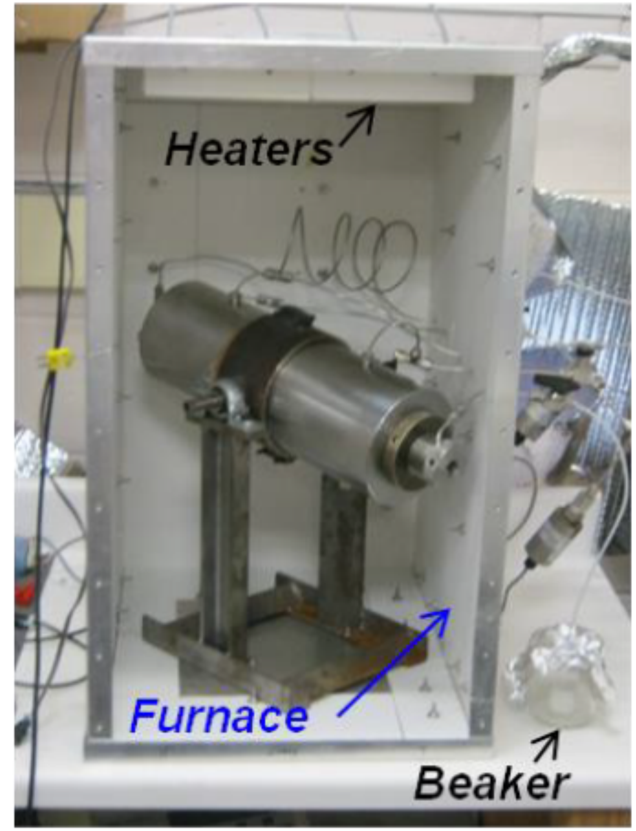
Measuring (a-b) Values of Shale/Artificial Samples

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

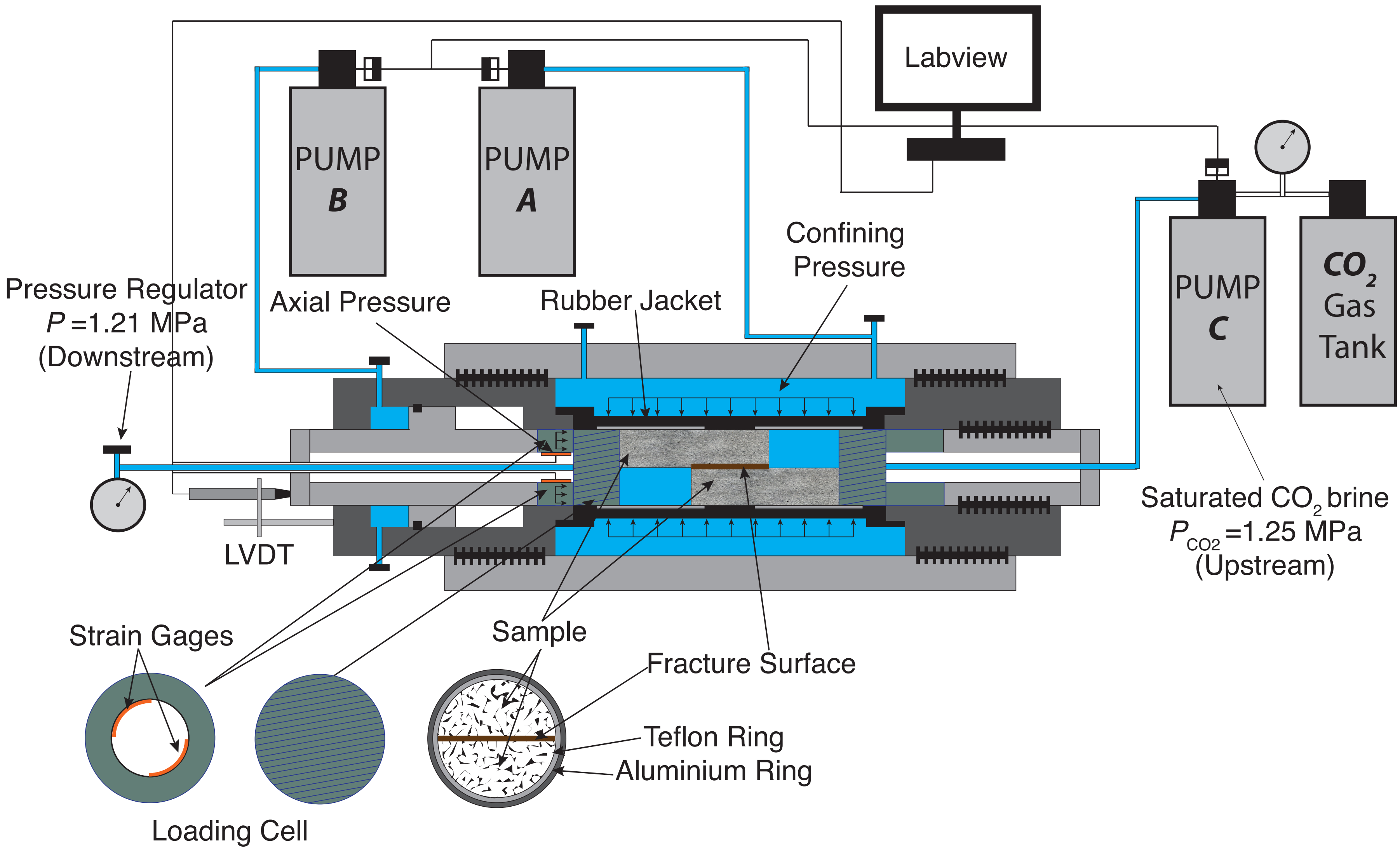
V3: Valve axial stress

V4: Valve confining pressure

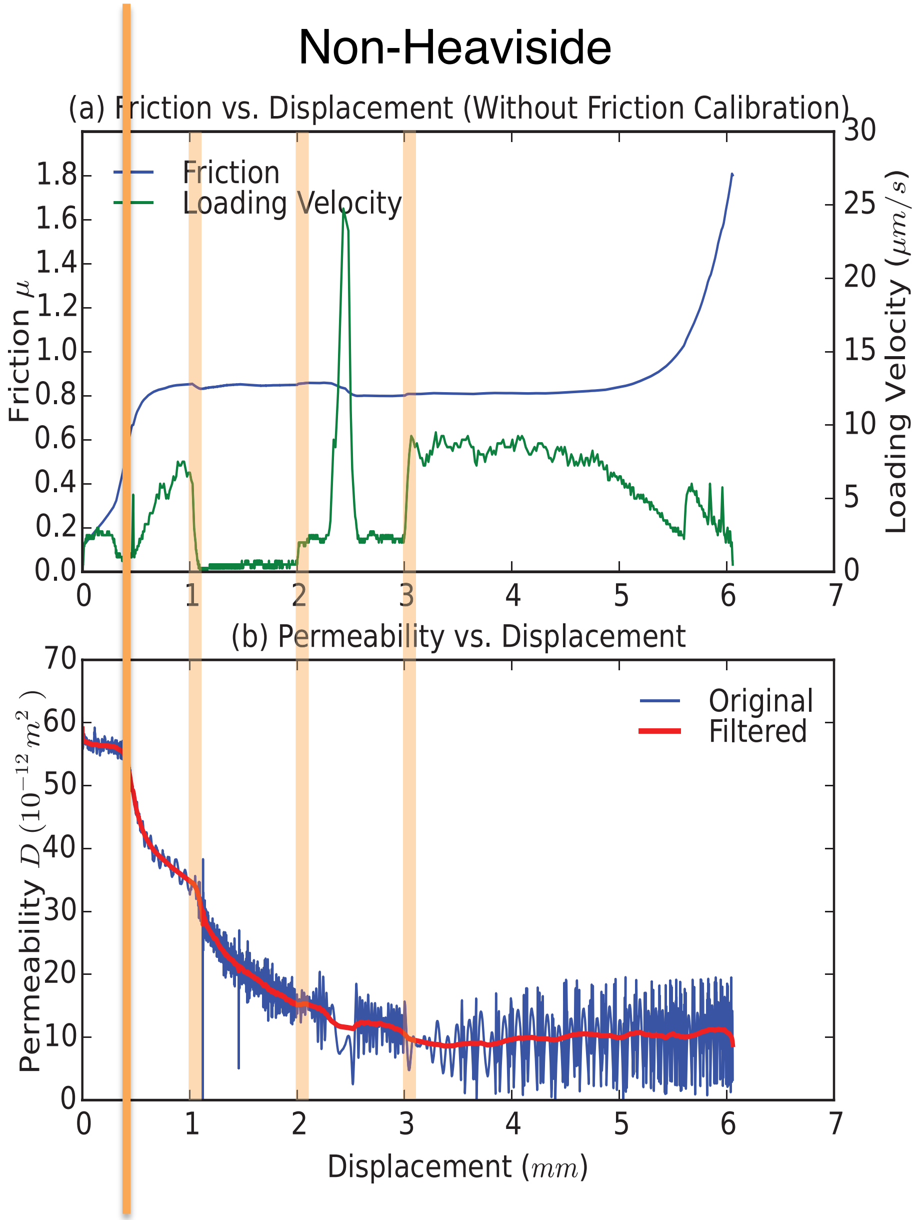
V5: Safety valve

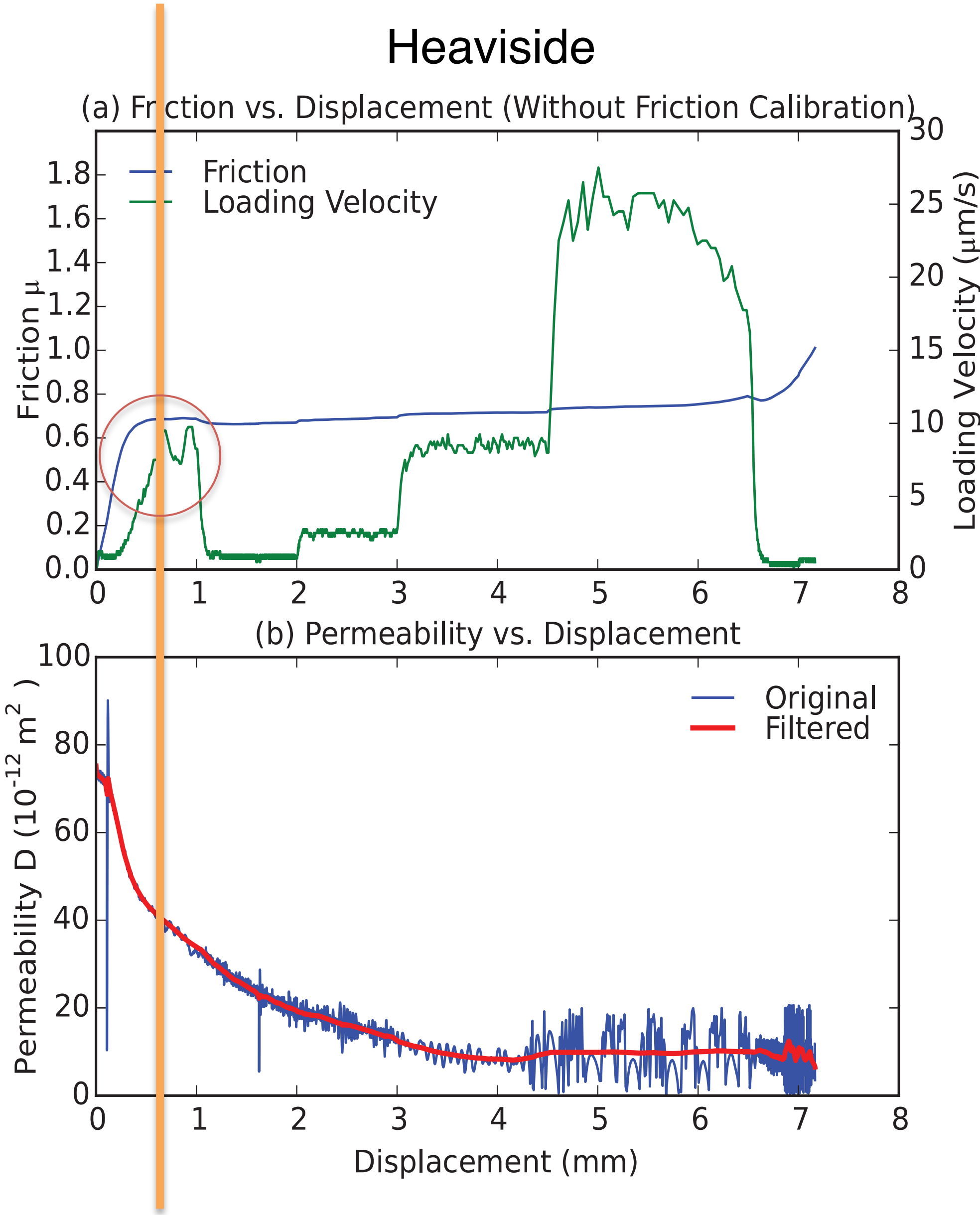
PT: Pressure transducers

Equipment Setup



Importance of Loading Rates

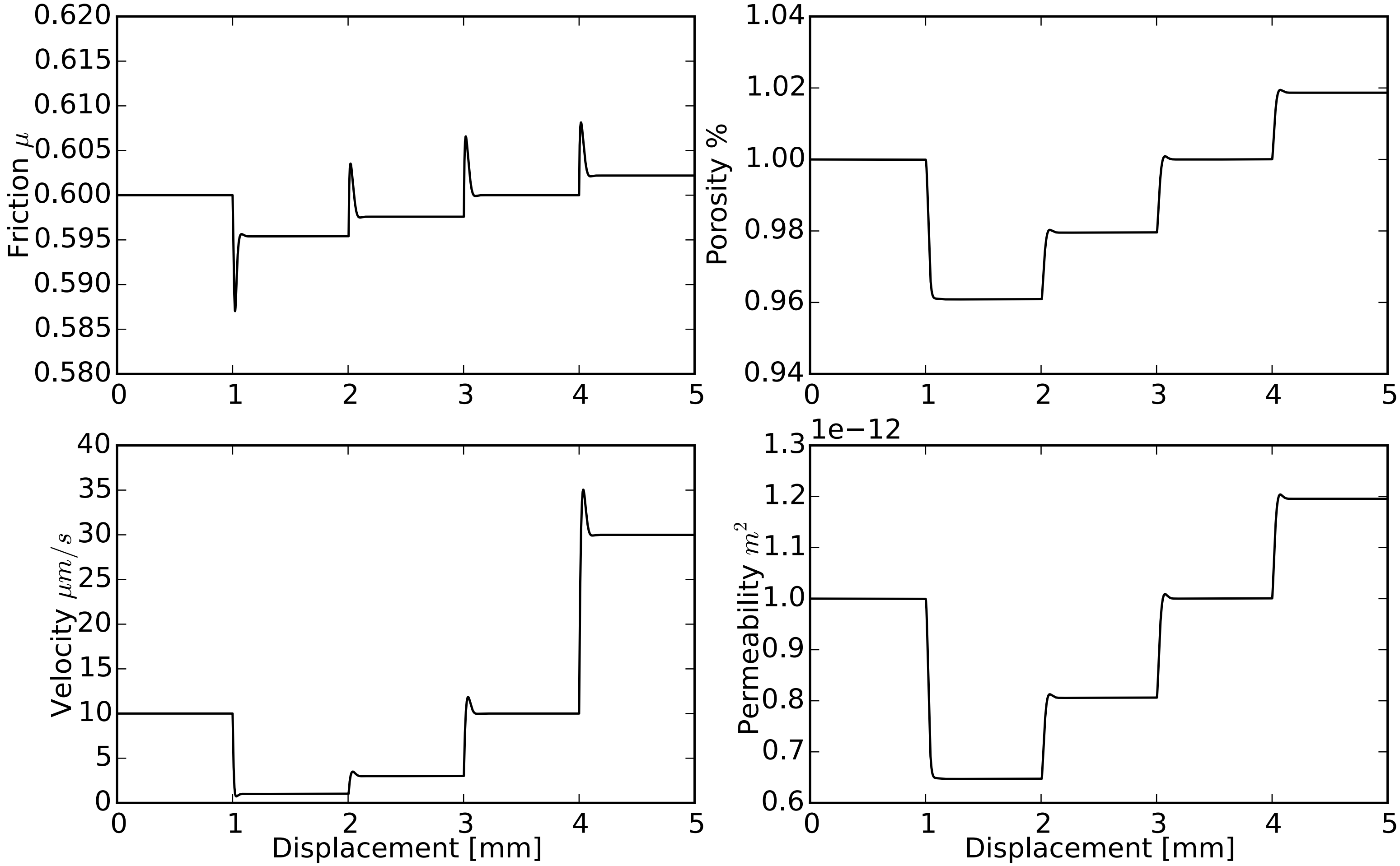




Rate-State Friction, Porosity and Permeability

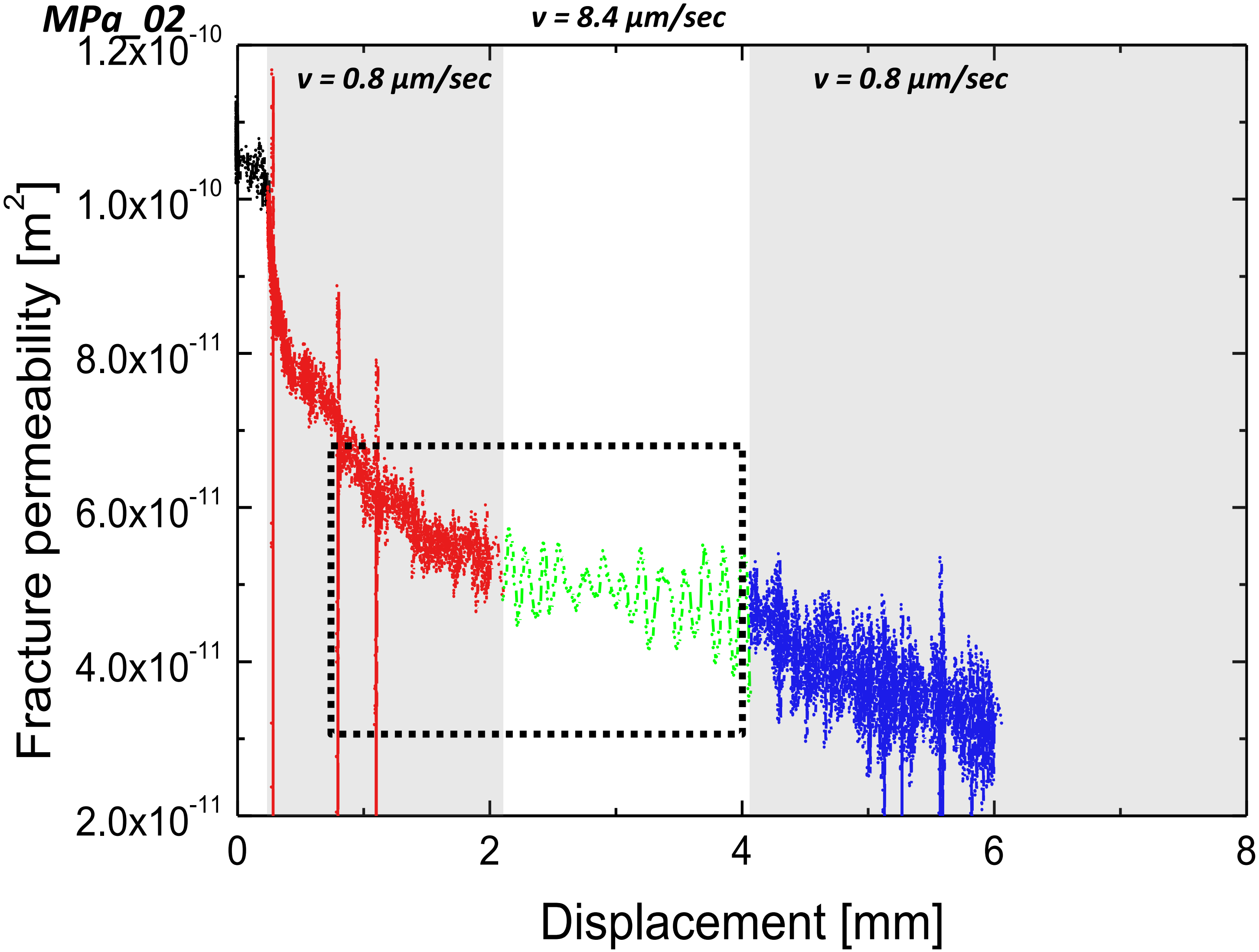
$$\dot{\phi}_{plastic} = -\frac{V}{D_c}(\phi_{plastic} - \phi_{ss}), \quad \phi_{ss} = \phi_0 + \varepsilon \ln\left(\frac{V}{V_0}\right), \quad \frac{k(\phi)}{k_0} = \left(\frac{\phi - \phi_c}{\phi_0 - \phi_c}\right)^n$$

High Stiffness, positive dilatational coefficient

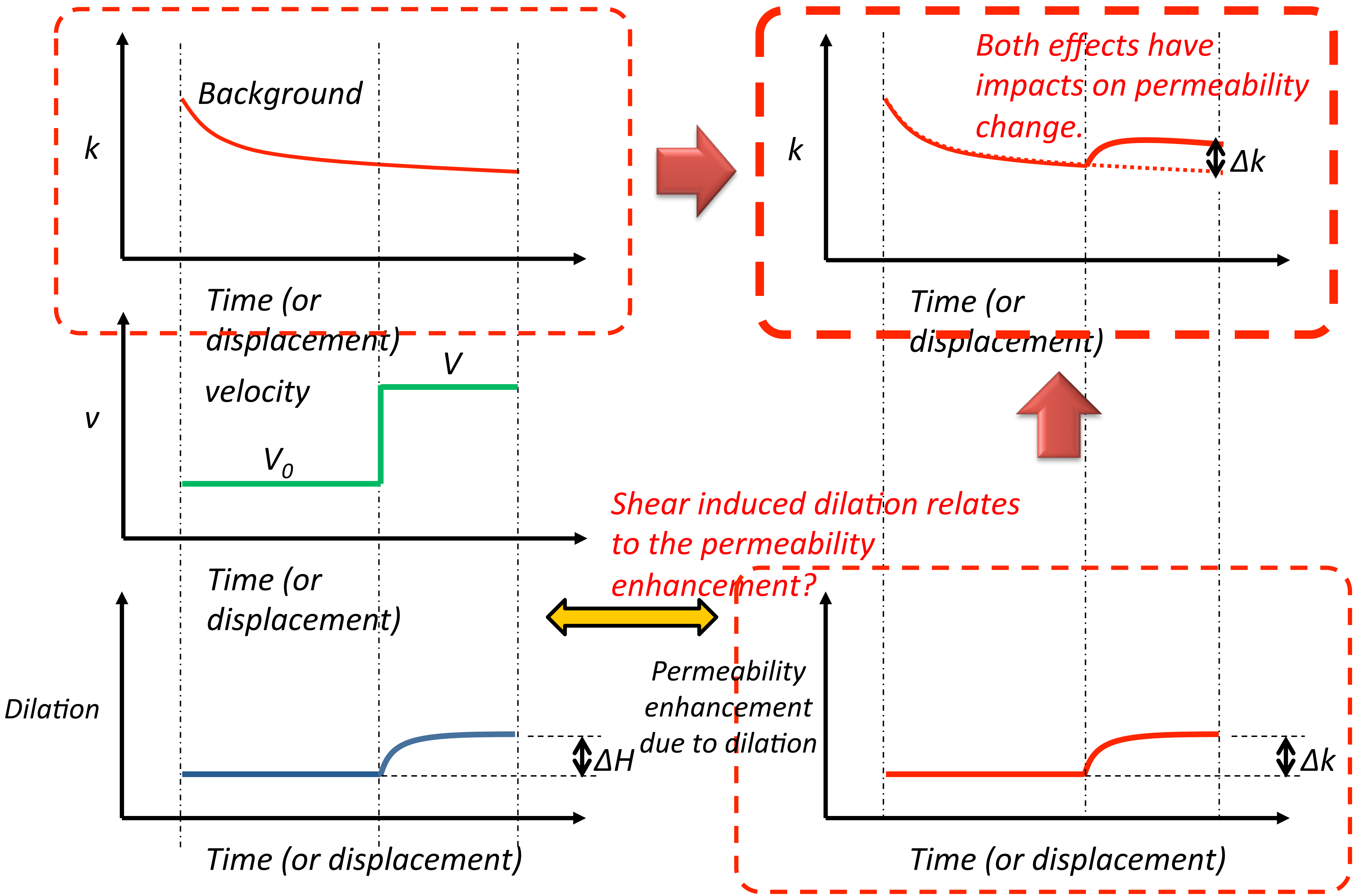


VS Experiments on Permeability

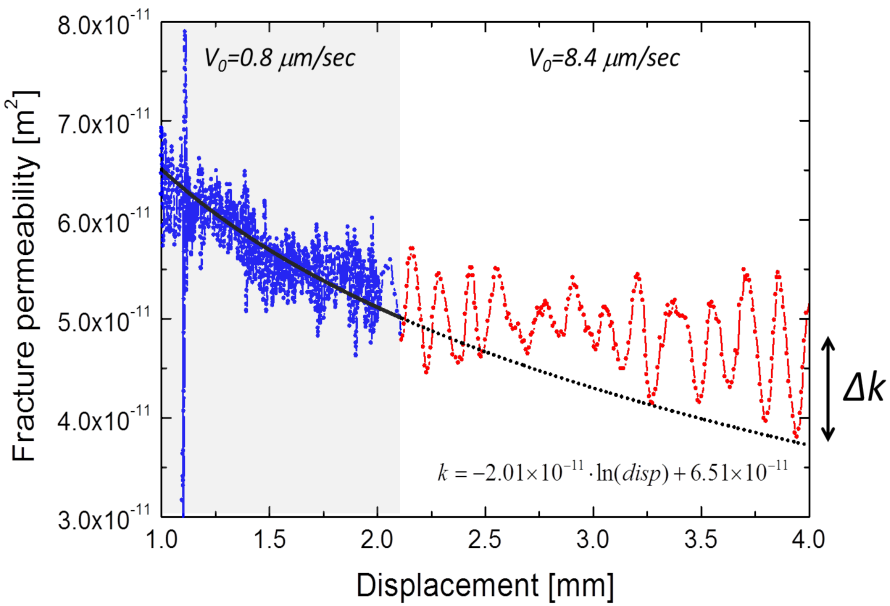
Confining pressure: 3 MPa_02

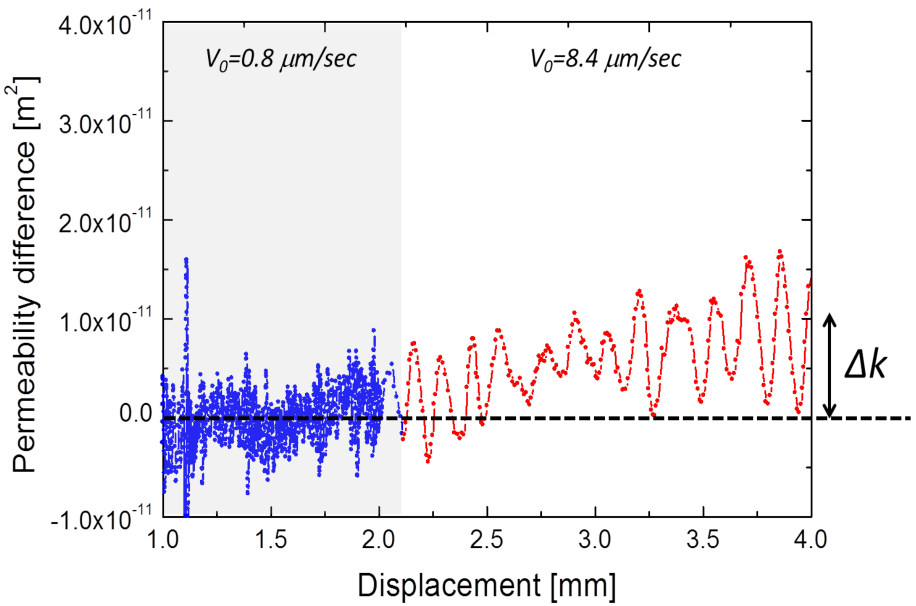


Permeability – Competition of Dilation and Wear



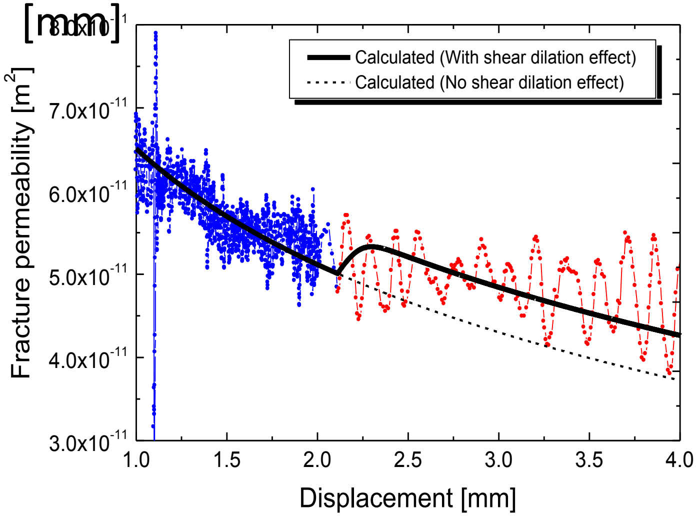
Detrending Permeability Data



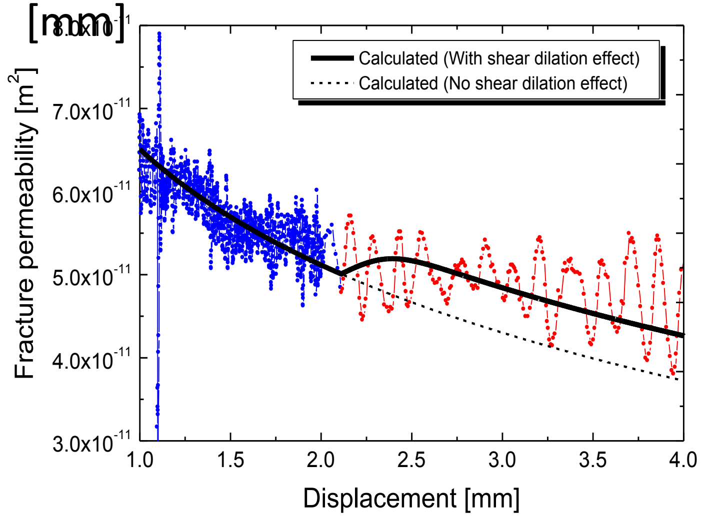


Typical VS-k Data

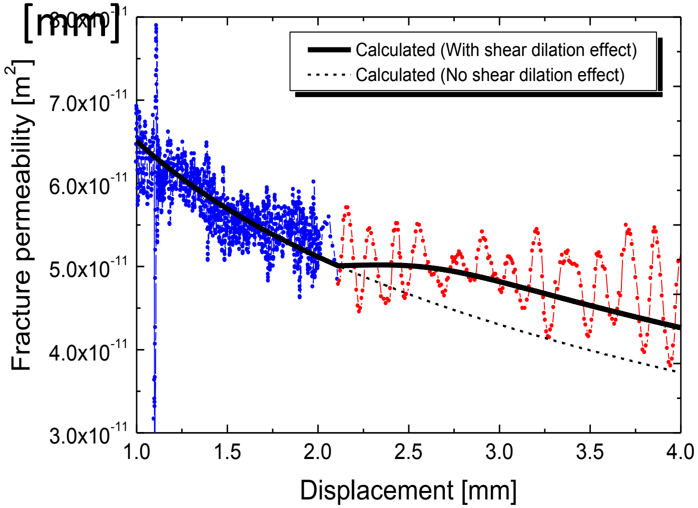
e=0.0224 (n=2), Dc=50 [mm]



e=0.0224 (n=2), Dc=100 [mm]



e=0.0224 (n=2), Dc=200 [mm]



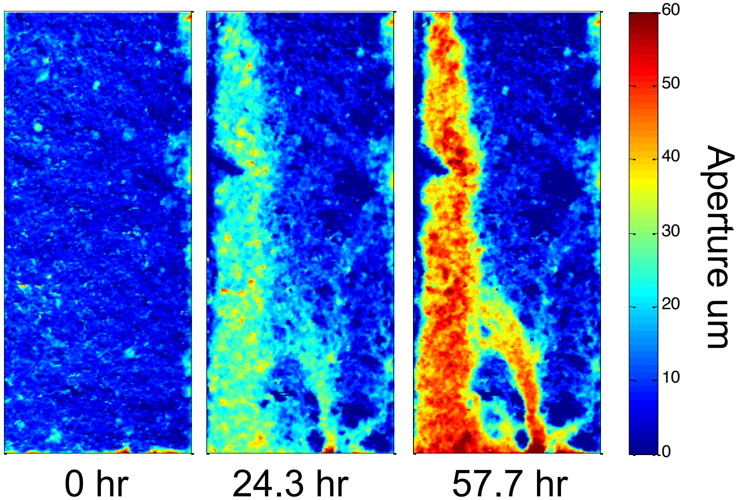
Dilation coefficient is evaluated in experiment (but 2 order larger than that for gouge sample).

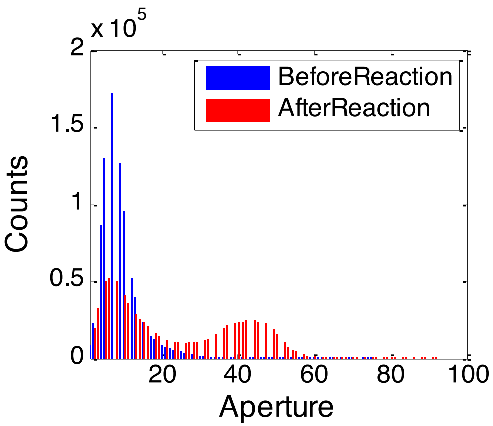
3D Imaging of fracture contact area, fracture geometry, and mineralogy & textures

Whole core x-ray tomography

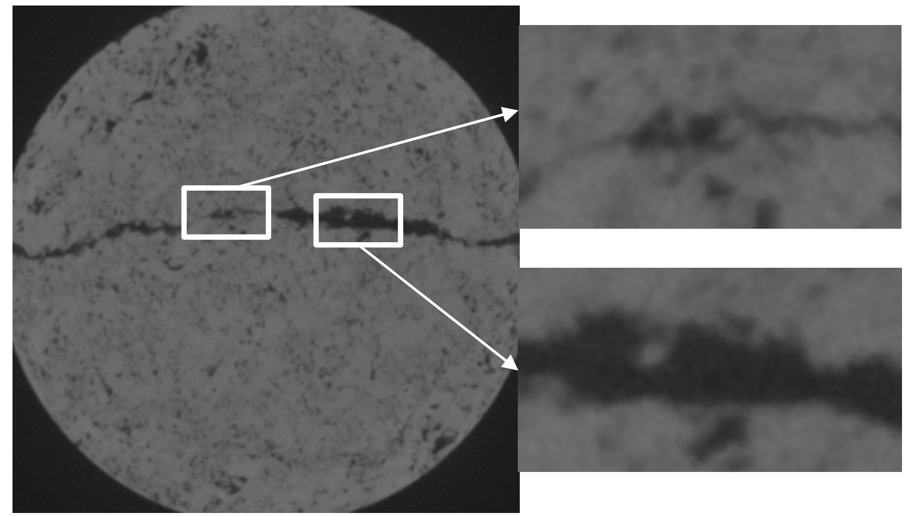
In situ tomographic imaging of fractured cores during CO_2-acidified brine flow

Channelization of Indiana Limestone





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

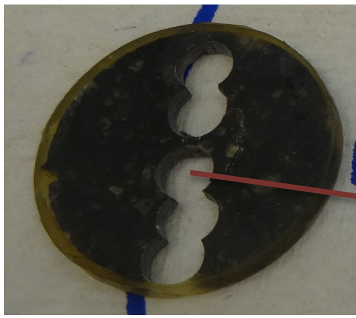
H Deng, JP Fitts, CA Peters, (Princeton U.) D Crandall, D McIntyre (NETL)

H Deng funded by ORISE Fellowship (Advisor: D McIntyre)

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

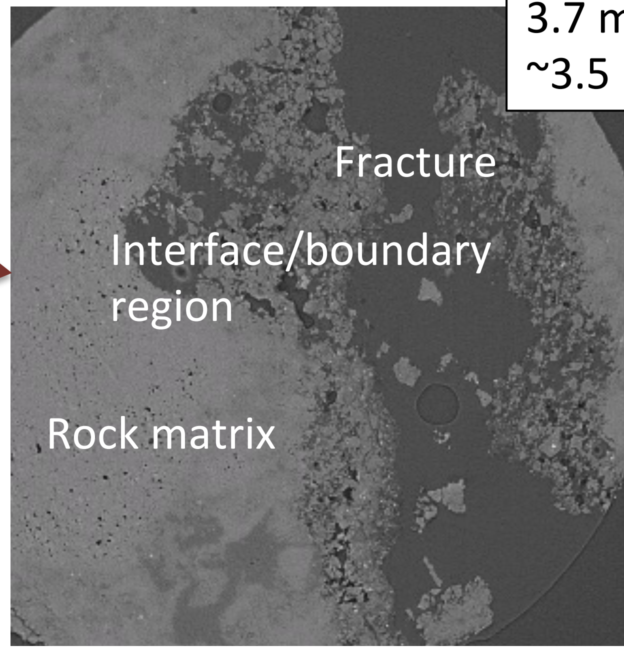
Synchrotron based x-ray tomography

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

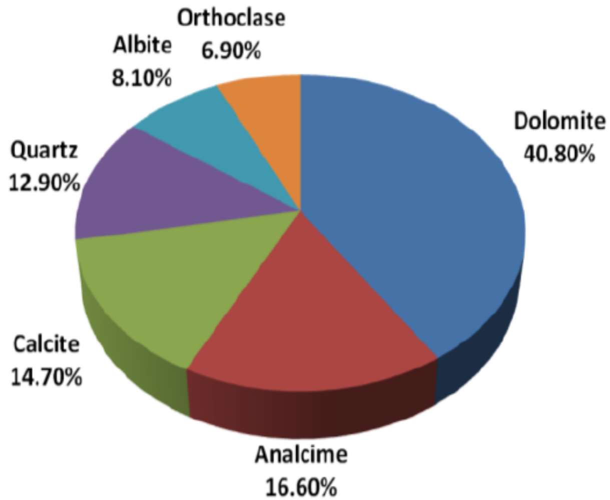
- Rheology of fracture
- Transmissivity/Permeability

xCT slice of epoxy-stabilized fracture after CO_2-acidified brine flow

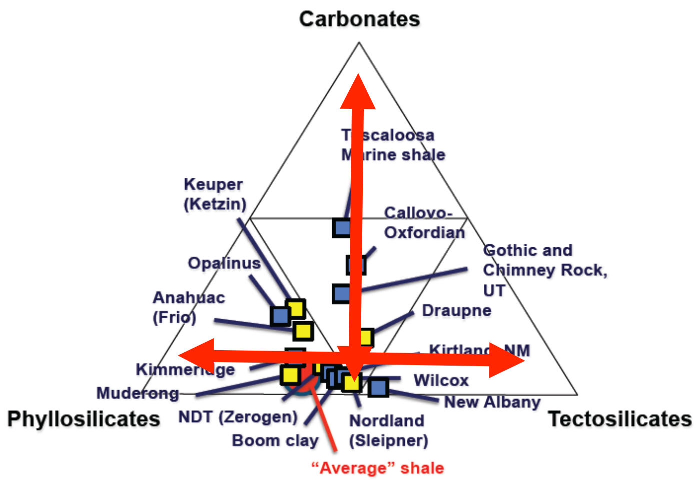
(sample from Ellis et al. 2011 GHGS&T 1(3), 248)

Synthetic Caprock Analog

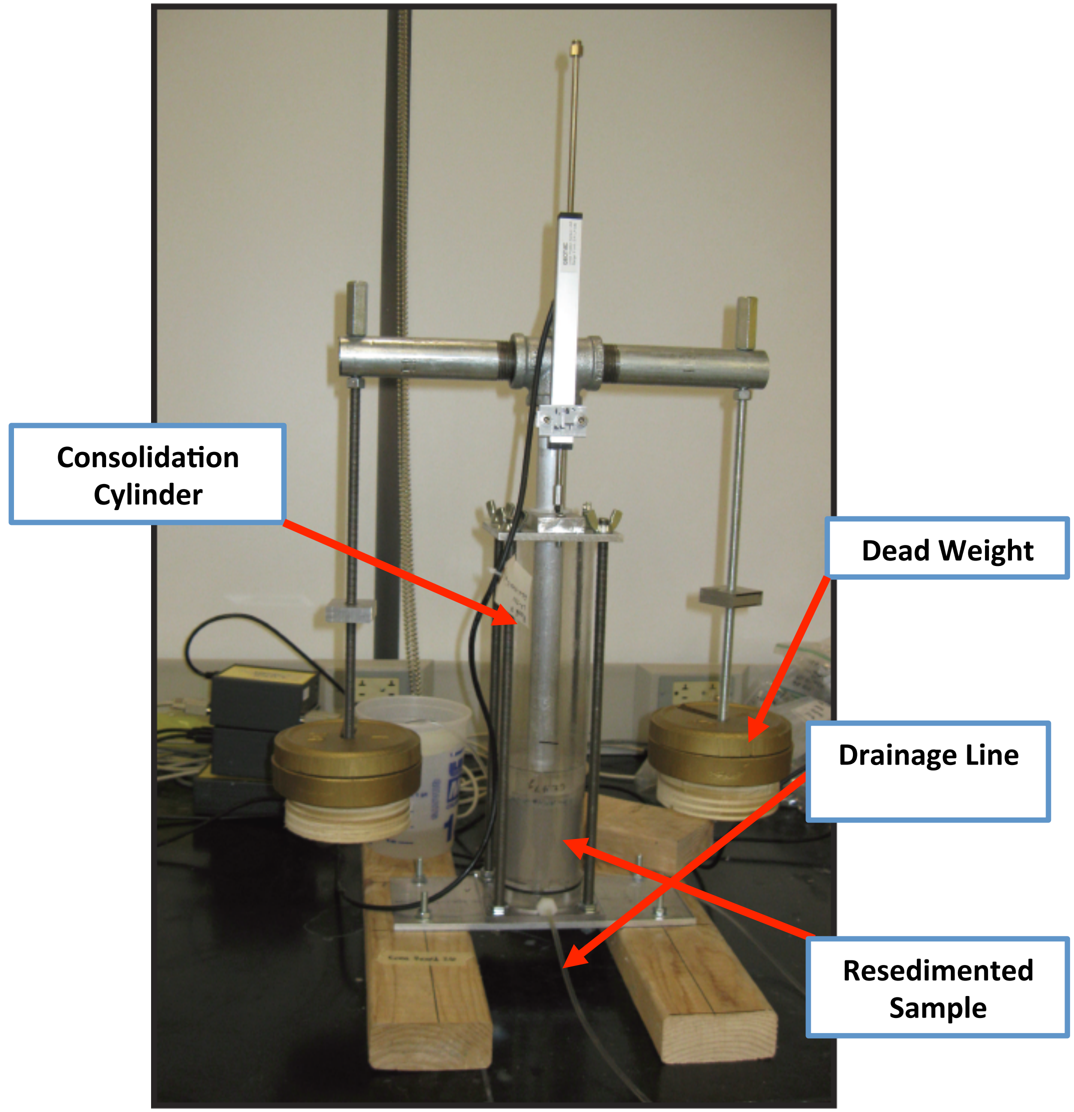
Reproduce Mineralogically Complex Sedimentary Caprock Formation



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



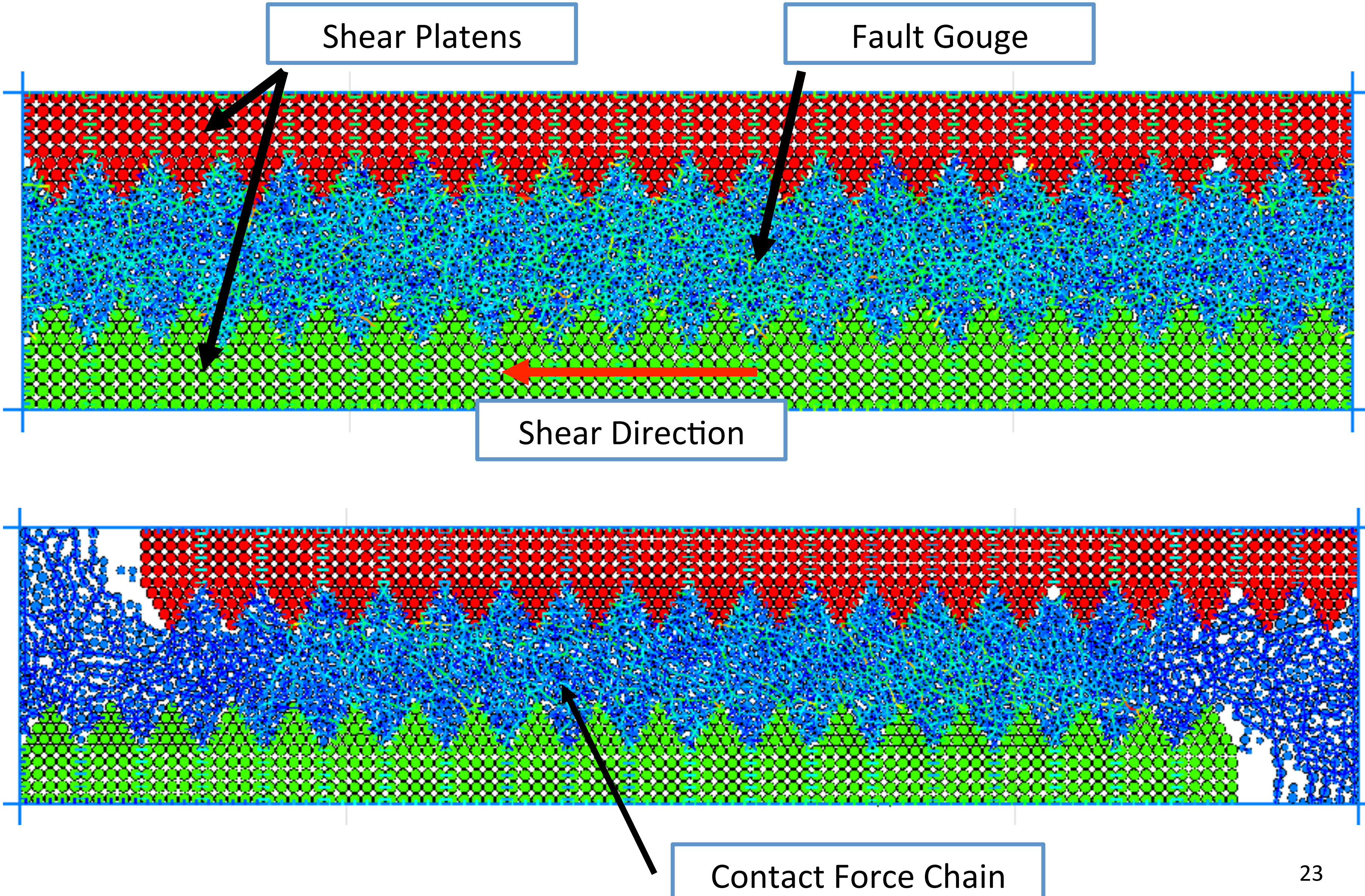
Anticipated mineral content distribution of fabricated sample



Resedimentation Apparatus Assembly (Schneider et al., 2011)

Digital Rock Physics Modeling of Response

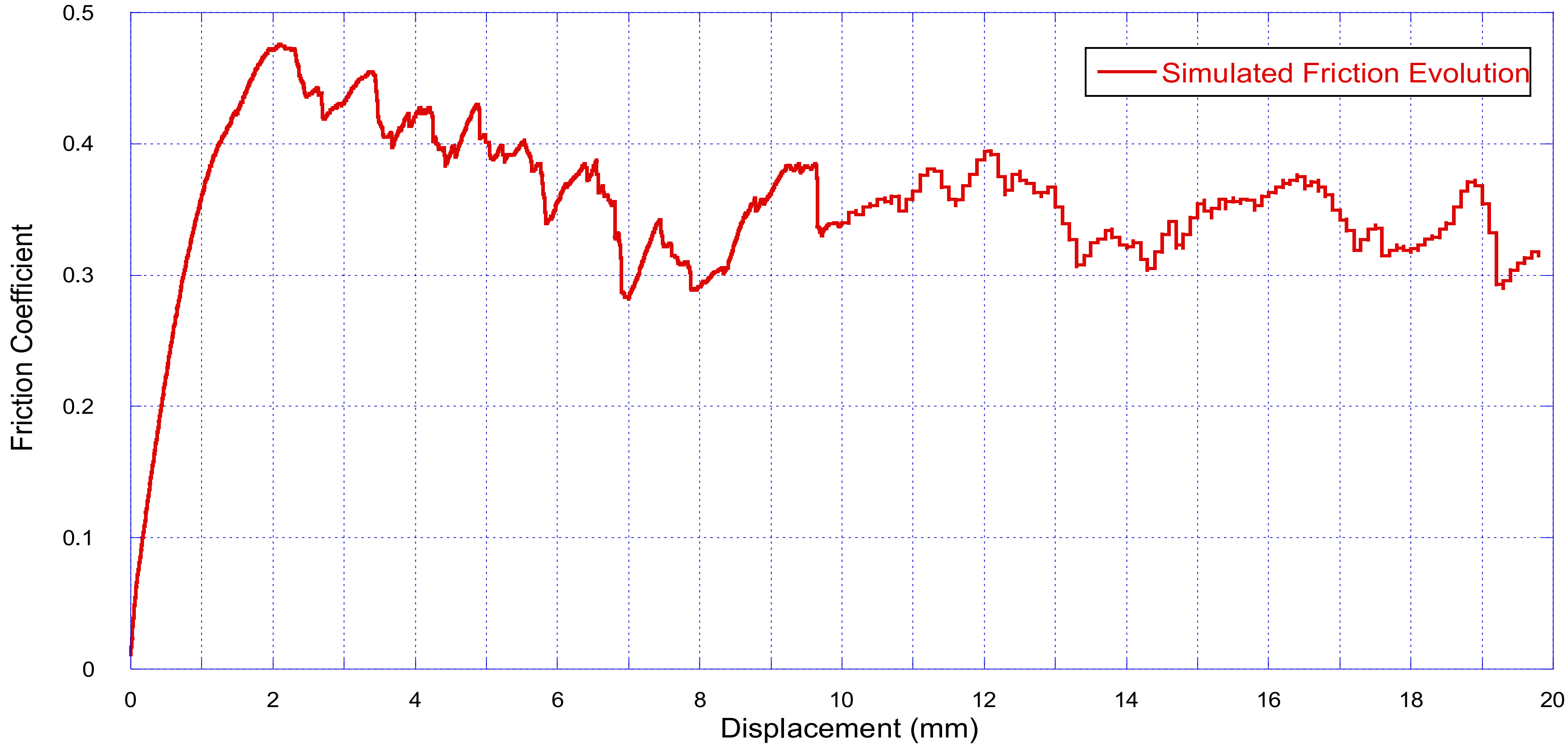
Rheological and Transport Models of Fractures



Digital Rock Physics Modeling of Response

Simulated Friction Response

Typical Friction Evolution without Velocity Step

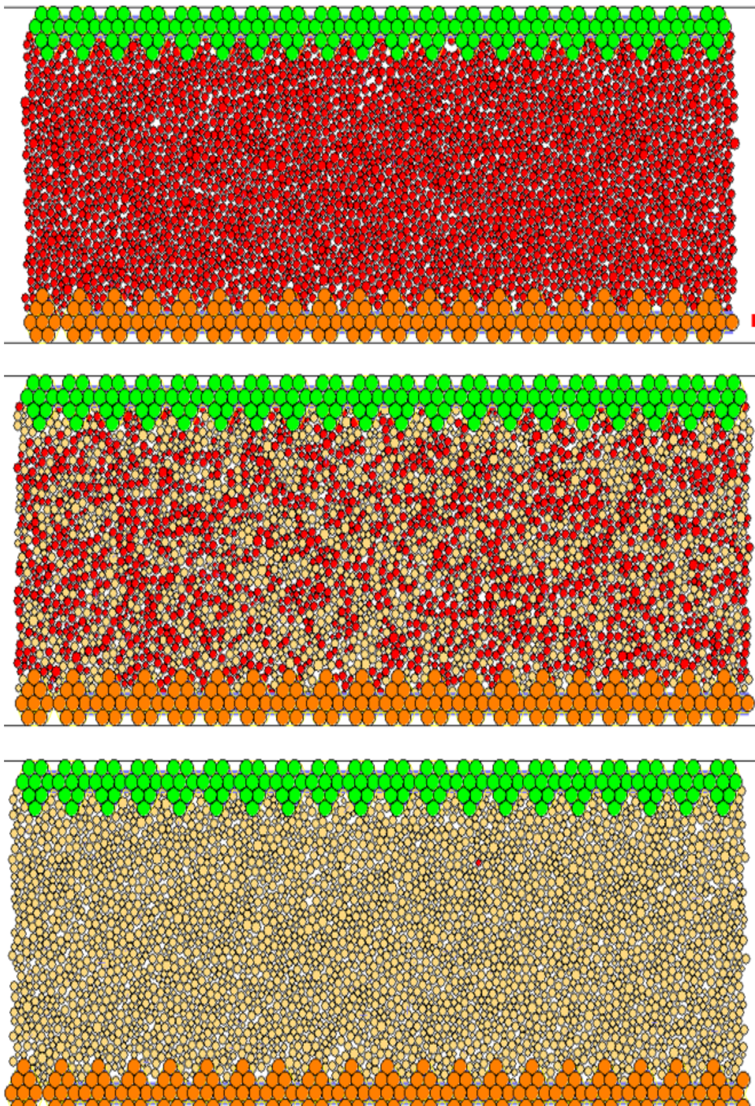


- **Shear strength varies with mineral properties (modulus, inter-particle friction, contact condition).**

- **Shear strength slowly decrease because of loss of contacting area while shearing.**

Digital Rock Physics Modeling of Response

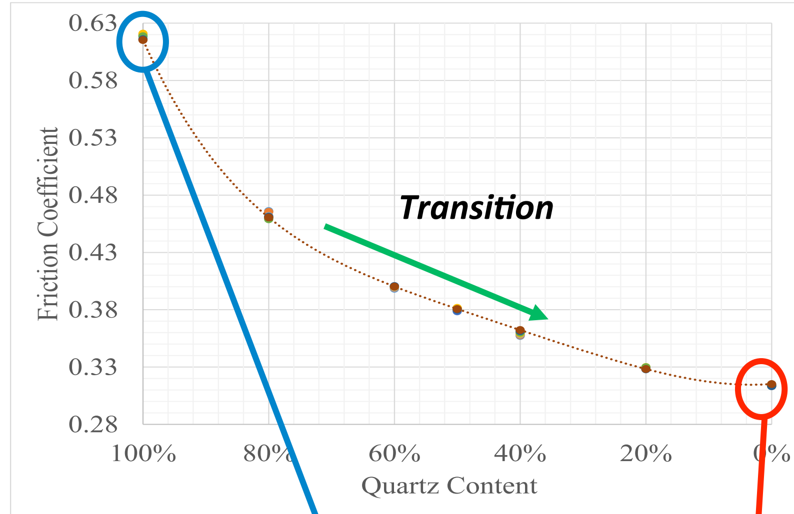
Mineralogical Influence on Shear Strength of Simulated Fault Gouge



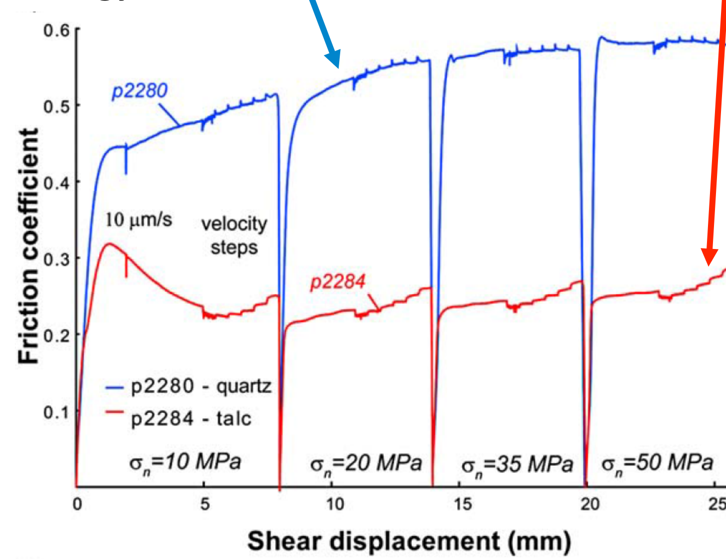
100% Talc

50% Talc
50% Quartz

100% Quartz



Mineralogy Effect on Friction Evolution

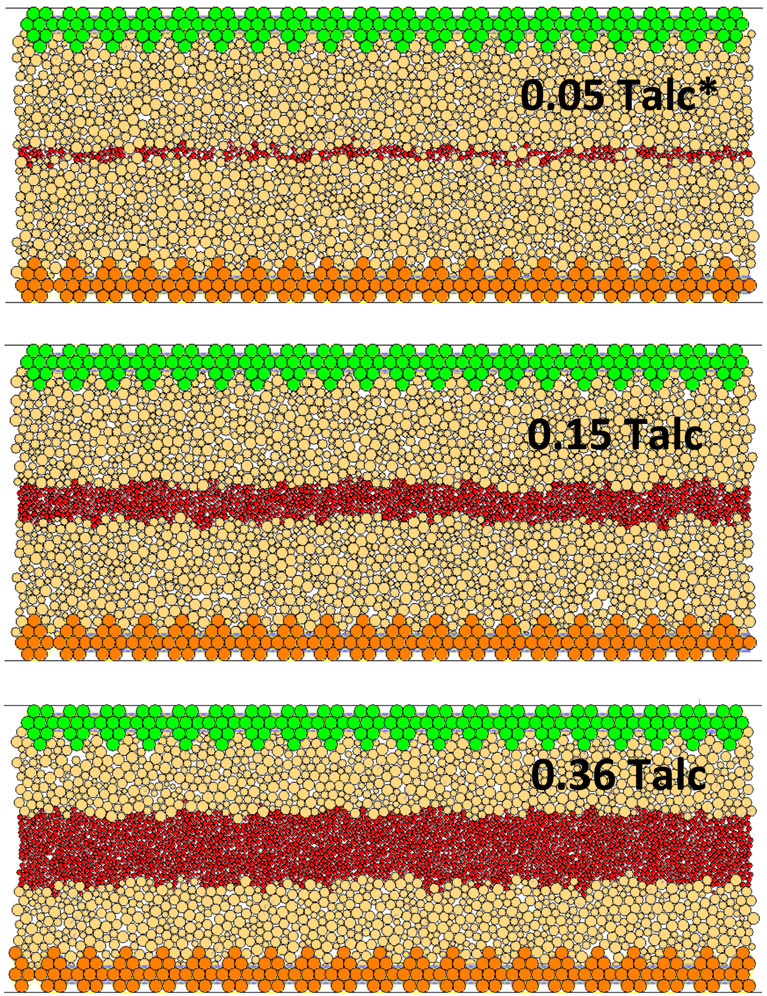


Shear strength of artificial fault gouge with 100% quartz or 100% talc (Niemeijer, 2010)

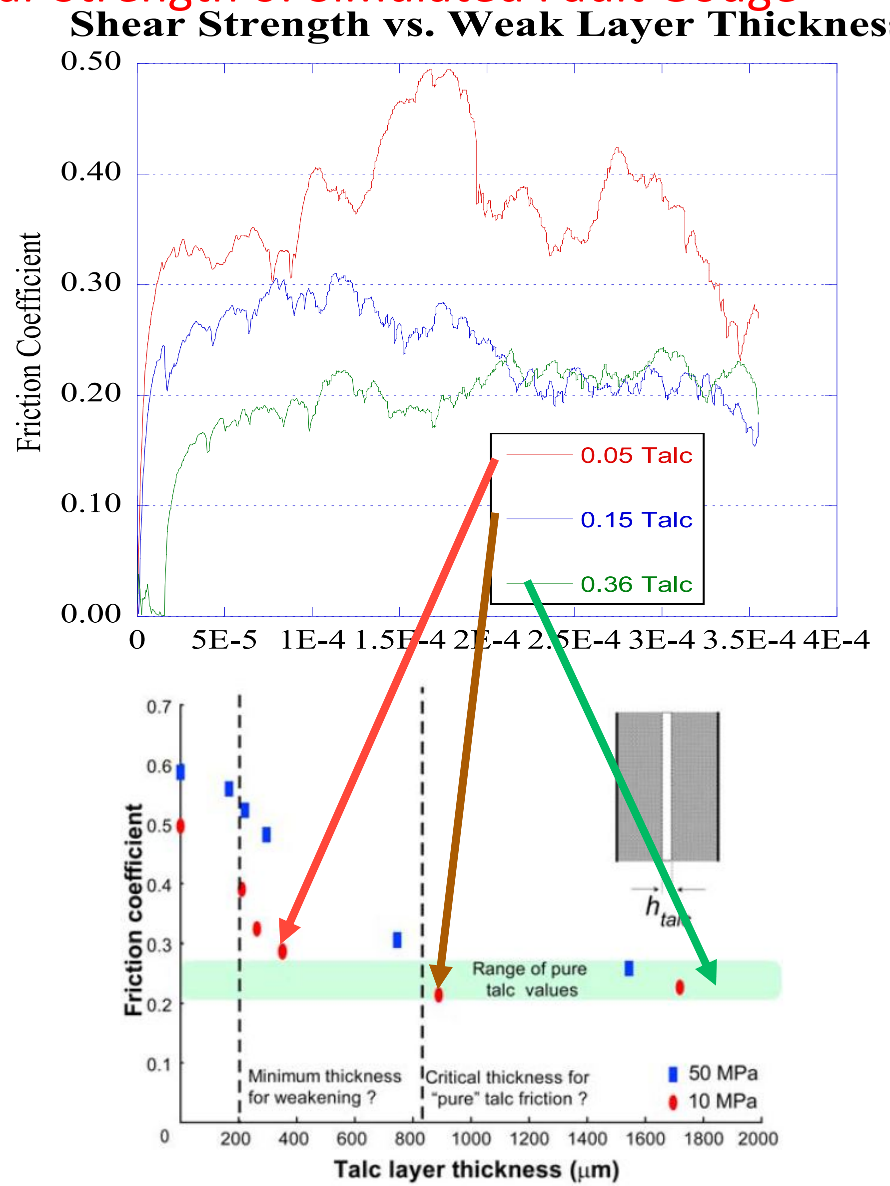
Digital Rock Physics Modeling of Response

Mineralogical Influence on Shear Strength of Simulated Fault Gouge

Quartz with Weak Talc Layer



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



Plot of steady state friction (at v = 10 mm/s) vs.talc interlayer thickness (Neimeijer et al. 2010)

Modeling Fracture Evolution: Coupling Reactive Transport & Geomechanics

PRINCETON UNIVERSITY

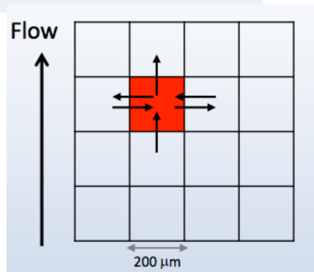
Reactive Transport Model

i) Transport

$$\frac{\partial(bC)}{\partial t} = -\nabla \cdot (\vec{q}C) + \nabla \cdot (bD \cdot \nabla C) + R(C)$$

ii) Aqueous Speciation

$$CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_{3(aq)}$$
$$H_2CO_{3(aq)} \leftrightarrow H^+_{(aq)} + HCO^-_{3\,(aq)}$$
$$HCO^-_{3\,(aq)} \leftrightarrow H^+_{(aq)} + CO^{-2}_{3(aq)}$$
$$H_2O \leftrightarrow H^+_{(aq)} + O_{2(aq)}$$
$$[H^+] = [OH^-] + [HCO_3^-] + [CO_3^{-2}]$$



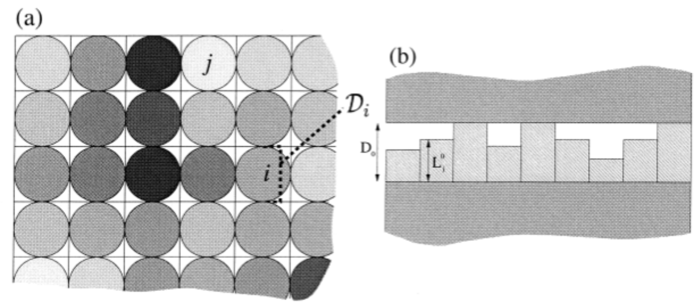
iii) Dissolution Kinetics

$$CaCO_{3(s)} + H^+_{(aq)} = Ca^{2+}_{(aq)} + HCO^-_{3(aq)}$$
$$CaCO_{3(s)} + H_2CO_{3(aq)} = Ca^{2+}_{(aq)} + 2HCO^-_{3(aq)}$$
$$CaCO_{3(s)} + H_2O_{(aq)} = Ca^{2+}_{(aq)} + HCO^-_{3(aq)} + OH^-_{(aq)}$$

$$R = Ak\left(1 - \frac{a_{Ca^{2+}}a_{CO_3^{2-}}}{K_{sp}}\right)$$

Mechanical Deformation Model

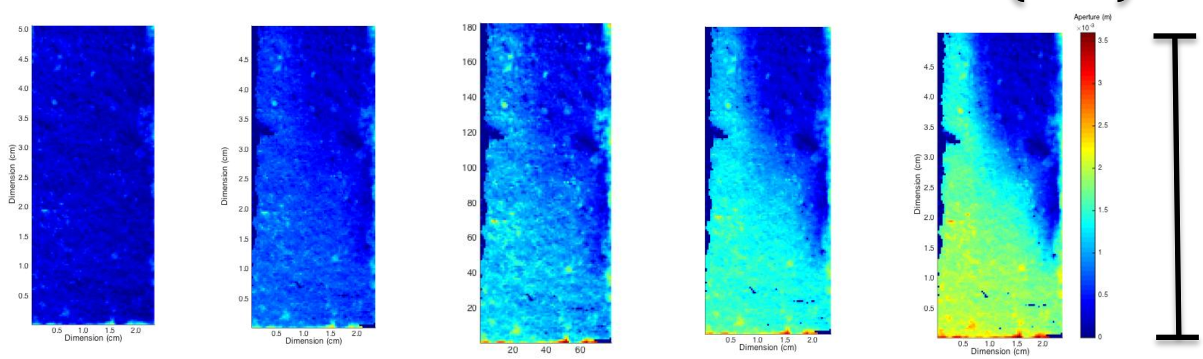
- Pyrak-Nolte & Morris, 2000
- Model fracture as two half spaces separated by cylindrical asperities



Fracture Specific Stiffness = $\frac{\{\Delta\sigma\}}{\{\Delta d\}}$

Reactive transport simulation results

- Aperture map evolution

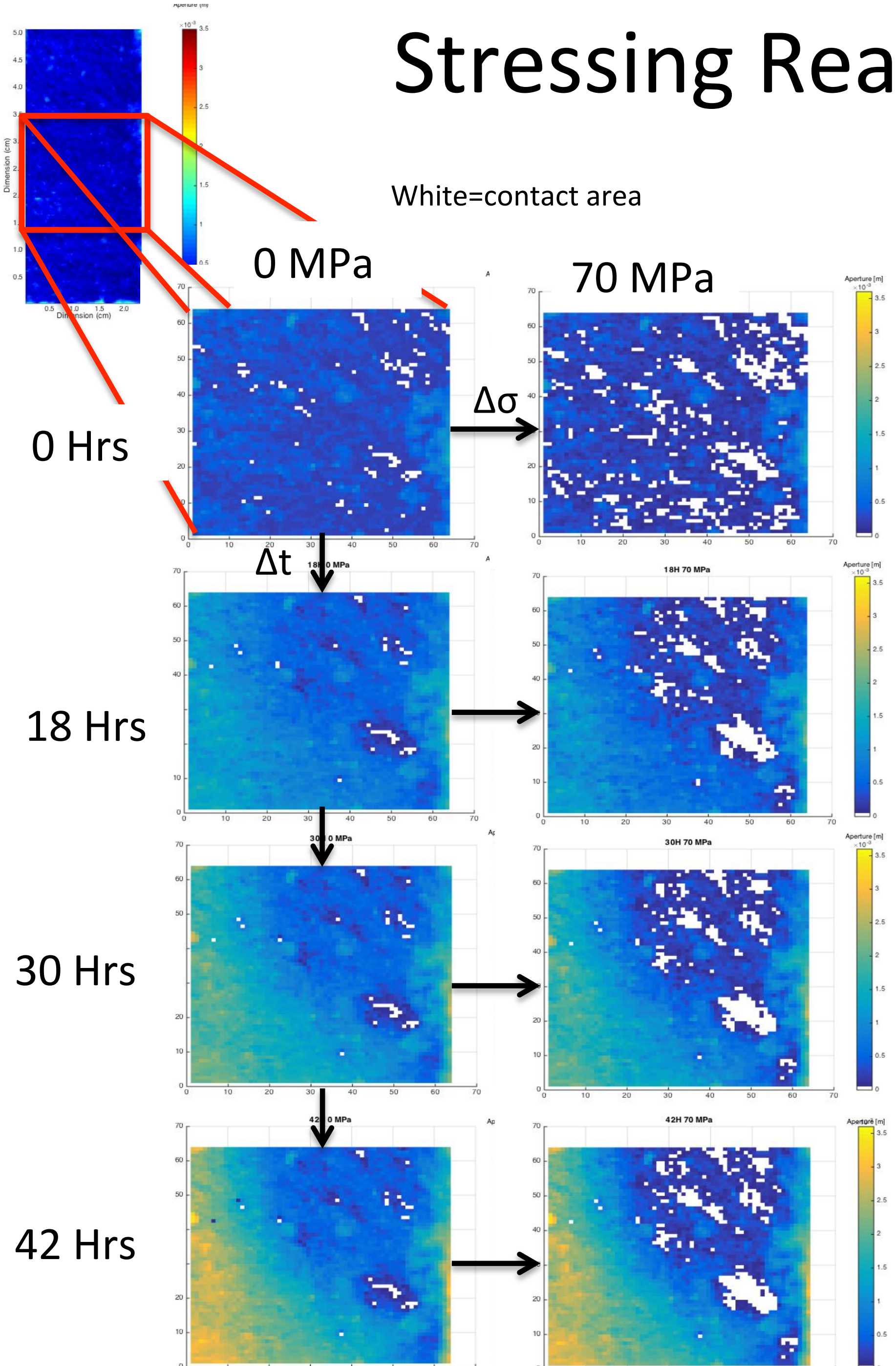


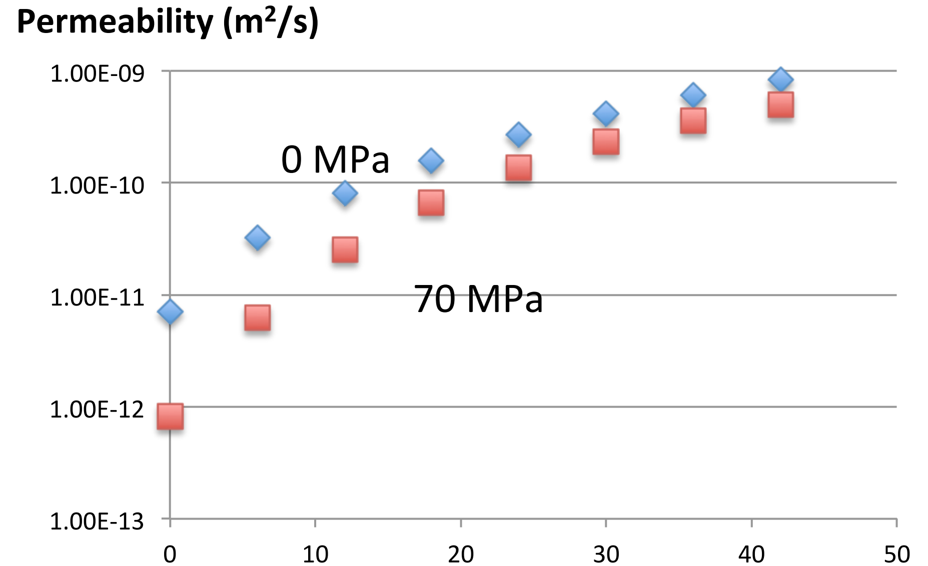
5.04 cm

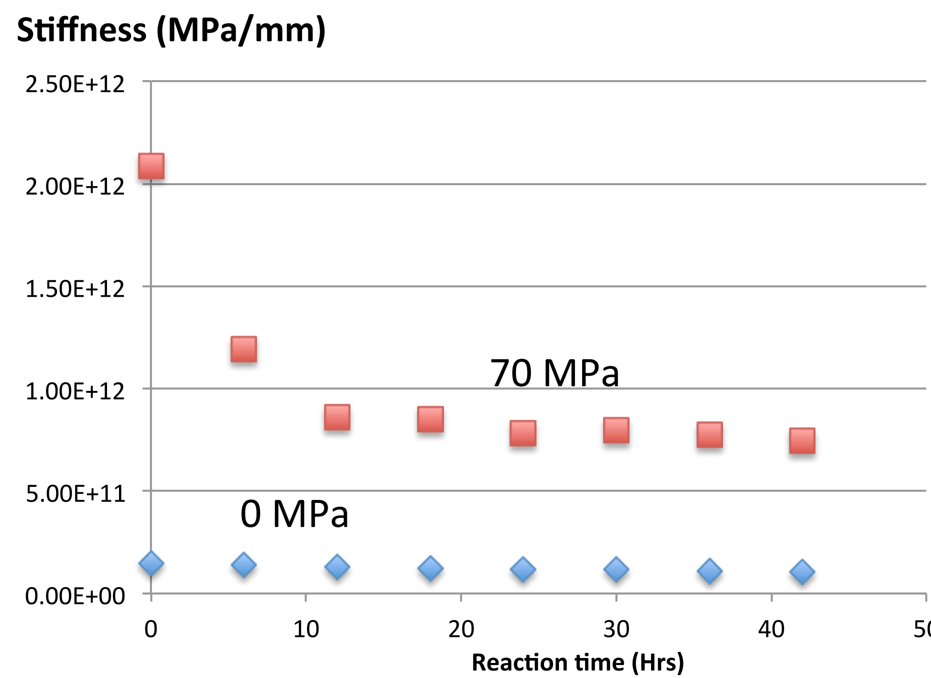
0 12 24 36 42

Reaction time (Hrs)

Stressing Reacted Fractures





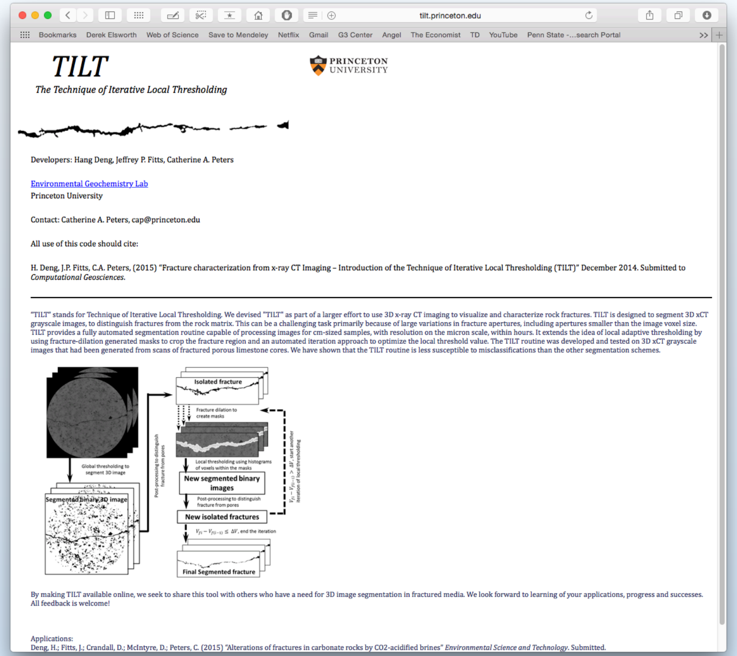


Accomplishments to Date

- 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
- Linkages with URLs and field experimentation
    - Seismicity-permeability correlations
    - Linkages across scales for upscaling
- Concurrent NETL projects
    - Linkage between structural domains and materials



tilt.princeton.edu

TILT

The Technique of Iterative Local Thresholding

PRINCETON UNIVERSITY

Developers: Hang Deng, Jeffrey P. Fitts, Catherine A. Peters

Environmental Geochemistry Lab
Princeton University

Contact: Catherine A. Peters, cap@princeton.edu

All use of this code should cite:

H. Deng, J.P. Fitts, C.A. Peters, (2015) "Fracture characterization from x-ray CT Imaging – Introduction of the Technique of Iterative Local Thresholding (TILT)" December 2014. Submitted to *Computational Geosciences.*

"TILT" stands for Technique of Iterative Local Thresholding. We devised "TILT" as part of a larger effort to use 3D x-ray CT imaging to visualize and characterize rock fractures. TILT is designed to segment 3D xCT grayscale images, to distinguish fractures from the rock matrix. This can be a challenging task primarily because of large variations in fracture apertures, including apertures smaller than the image voxel size. TILT provides a fully automated segmentation routine capable of processing images for cm-sized samples, with resolution on the micron scale, within hours. It extends the idea of local adaptive thresholding by using fracture-dilation generated masks to crop the fracture region and an automated iteration approach to optimize the local threshold value. The TILT routine was developed and tested on 3D xCT grayscale images that had been generated from scans of fractured porous limestone cores. We have shown that the TILT routine is less susceptible to misclassifications than the other segmentation schemes.

By making TILT available online, we seek to share this tool with others who have a need for 3D image segmentation in fractured media. We look forward to learning of your applications, progress and successes. All feedback is welcome!

Applications:
Deng, H.; Fitts, J.; Crandall, D.; McIntyre, D.; Peters, C. (2015) "Alterations of fractures in carbonate rocks by CO2-acidified brines" *Environmental Science and Technology*. Submitted.

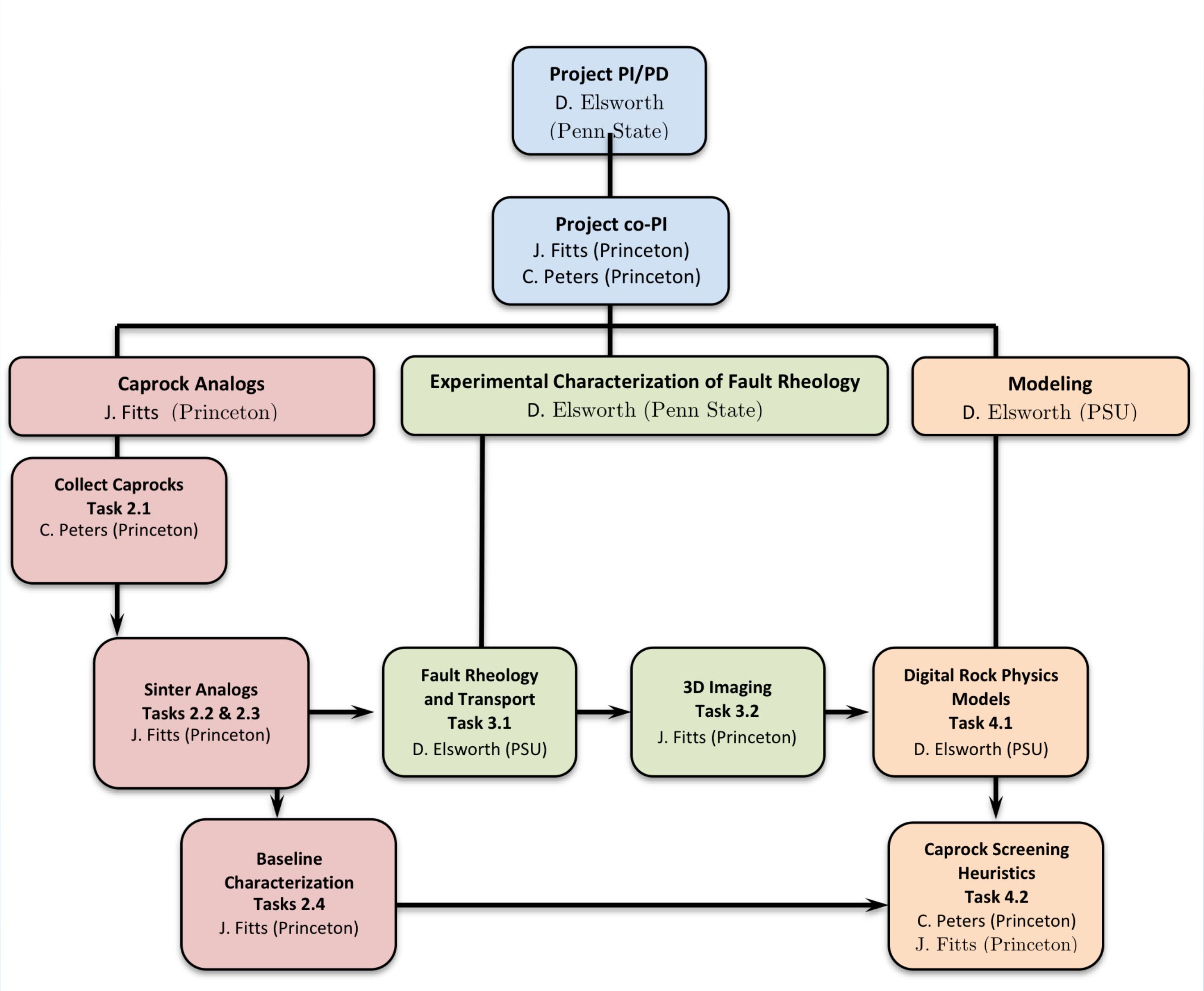
Summary

- 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.

Appendix

Following

Organization Chart/ Communication Plan



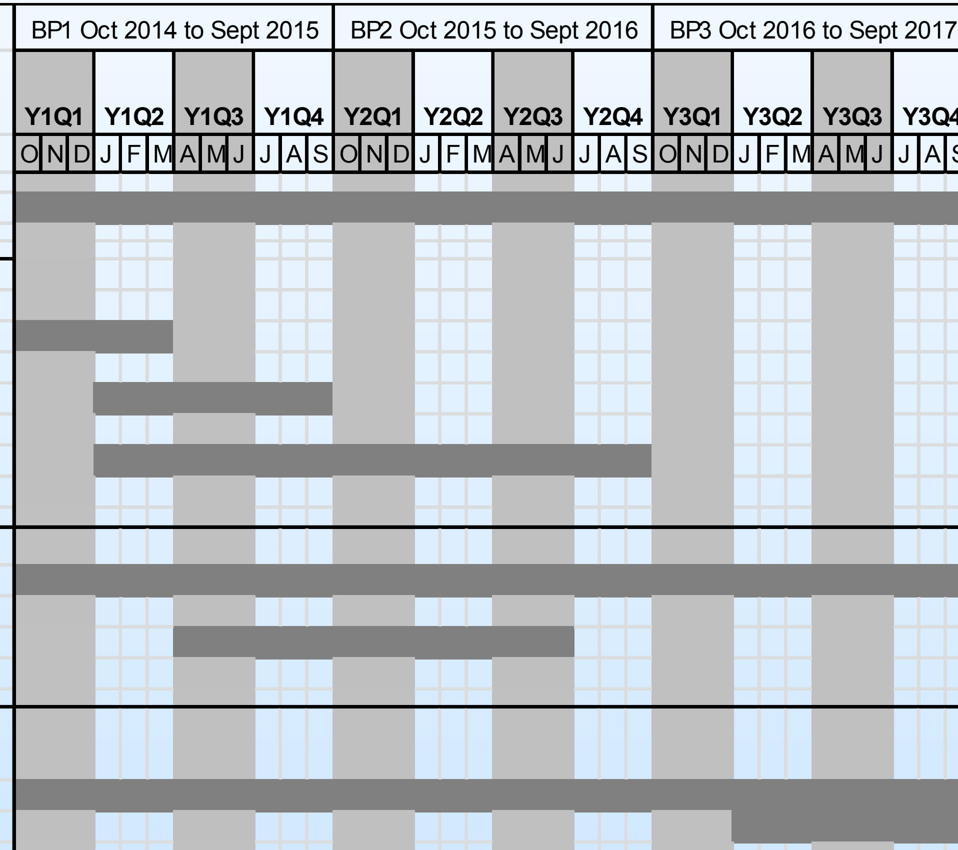
Communication plan: Biweekly Skype [Oct 23; Nov 6, ….]

Biannual meeting

Gantt Chart

SCHEDULE of TASKS and MILESTONES

	PI
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



Bibliography

- Zhong, Z., Elsworth, D., Hu, Y. (2015) Evolution of strength and permeability in stressed fractures with fluid-rock interactions. In press. Pure and Applied Geophys., 40 pp.
- Ellis, B.R. and Peters, C.A. (2015) 3D mineral characterization of reactive fractures: Combining X-ray tomography and electron microscopy. In press. *Advances in Water Resources*, 30 pp.