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

DE-FE0023354

Derek Elsworth, Yi Fang, Chaoyi Wang, Yunhong Jia, Penn State
Jeffrey Fitts, Catherine Peters, Kasparas Spokas, Princeton

U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology, Innovation and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting
August 16-18, 2016

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

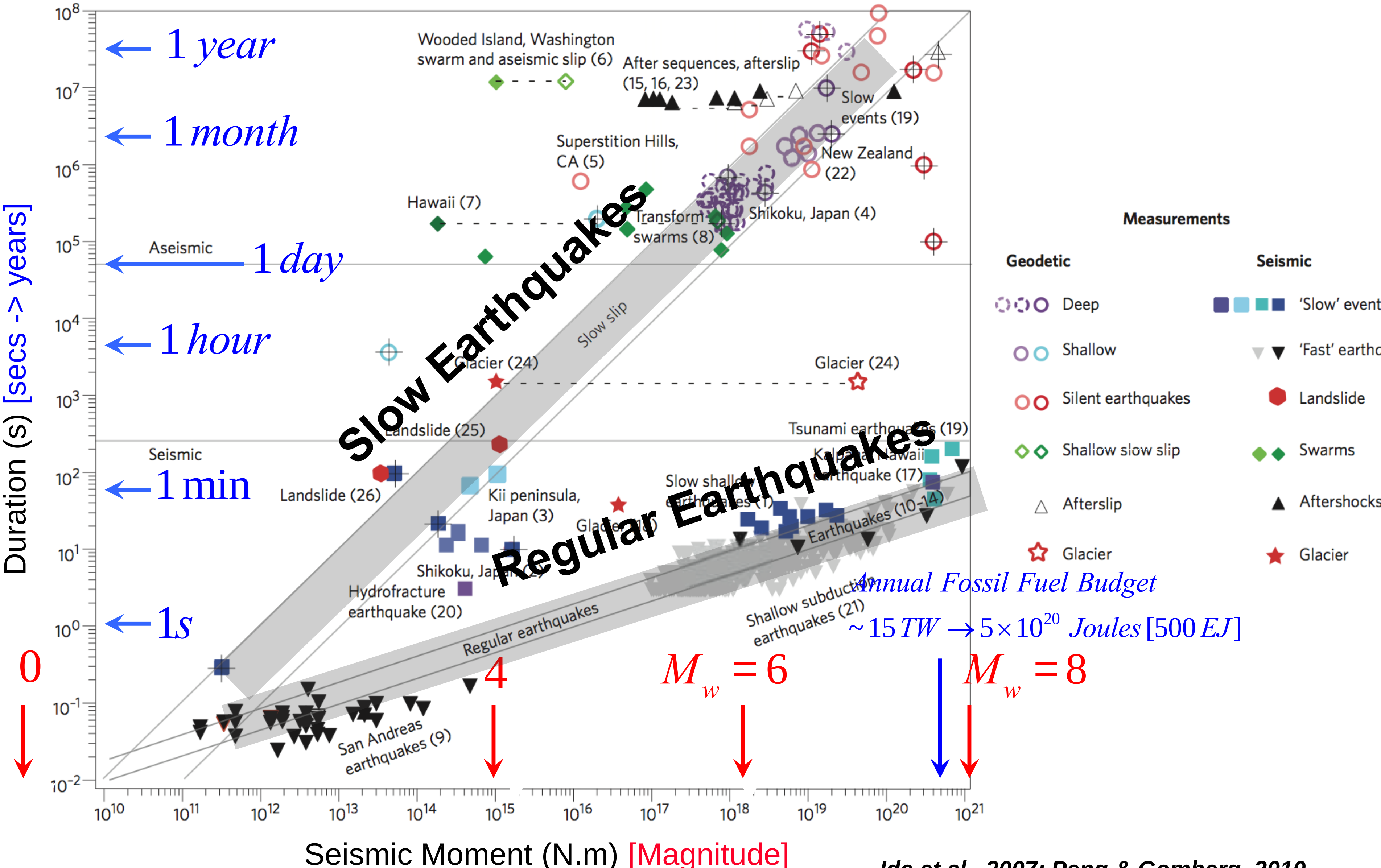
Background

- 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)

Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior

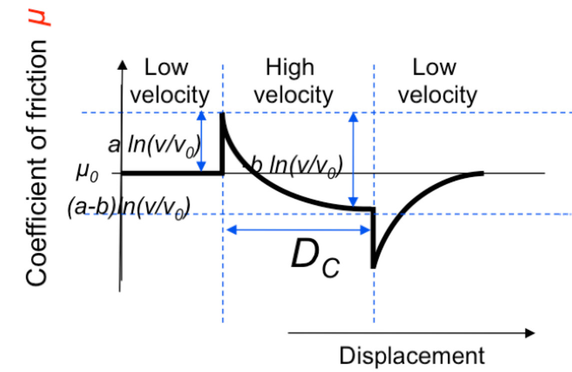


Ide et al., 2007; Peng & Gomberg, 2010

Requirements for Instability

1. Shear strength on the fault is exceeded – *i.e.*

$$\tau > \mu \sigma'_n$$

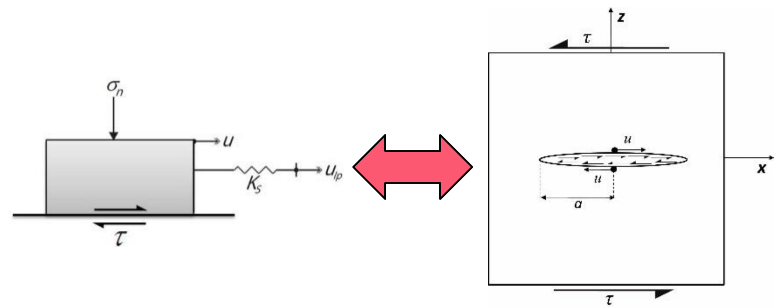


2. When failure occurs, strength is velocity (or strain) weakening - *i.e.*

$$a - b < 0$$

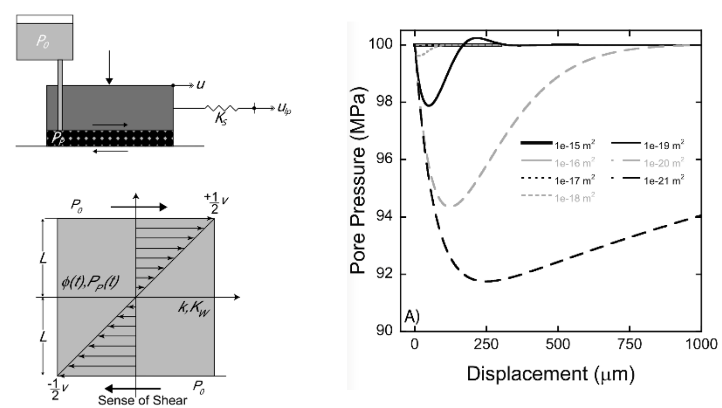
2. That the failure is capable of ejecting the stored strain energy adjacent to the fault (shear modulus and fault length) - *i.e.*

$$\frac{G}{l} < K_c = \frac{(b-a)\sigma_n'}{D_c}$$



4. That effective normal stresses evolve that do not dilatantly harden the fault and arrest it via the failure criterion of #1 – *i.e.*

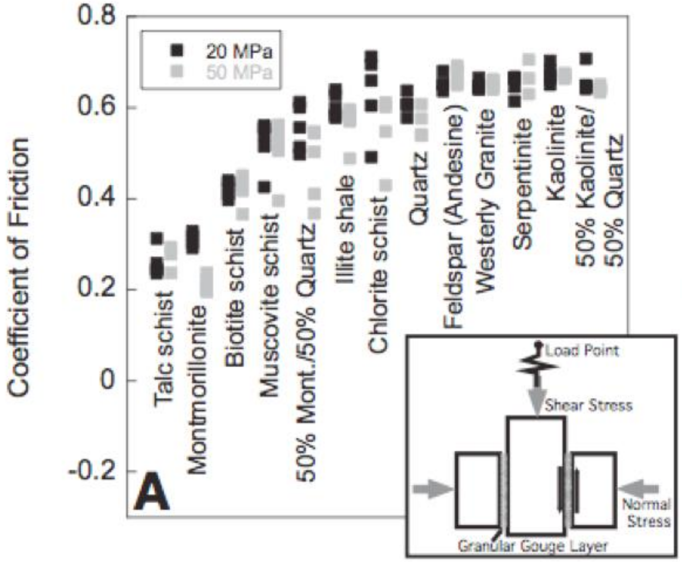
$$1 >> v_D = \frac{w^2}{k} \frac{v_s \eta}{K_s D_c}$$

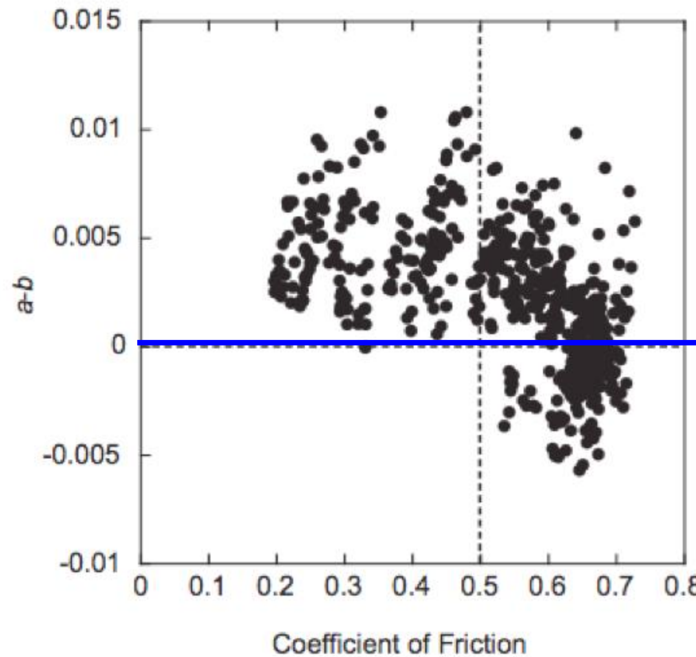


Mineralogical Controls on Instability

Friction

[Ikari et al., Geology, 2011]

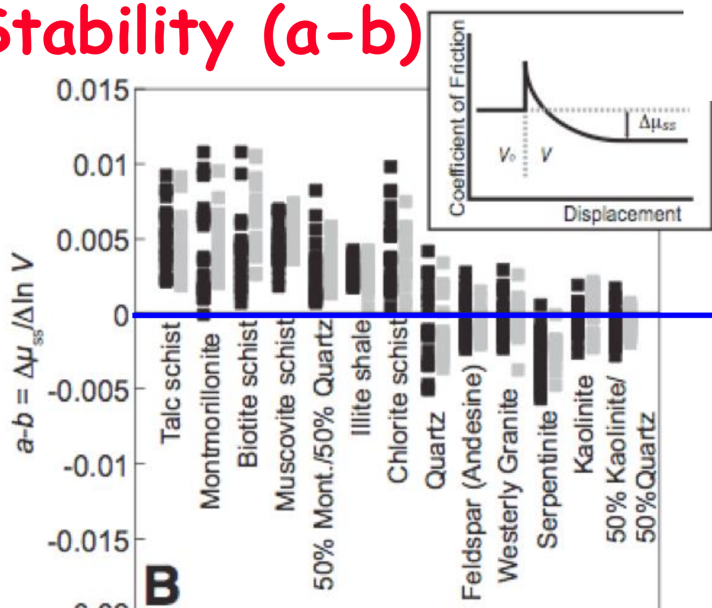




Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

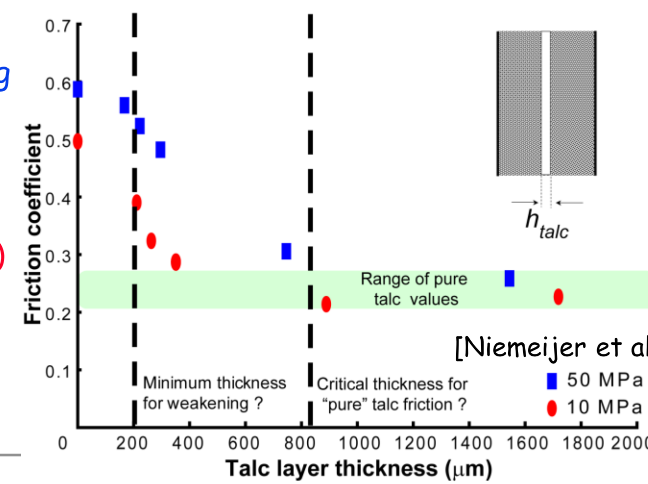
Stability (a-b)



Velocity Strengthening (stable slip)

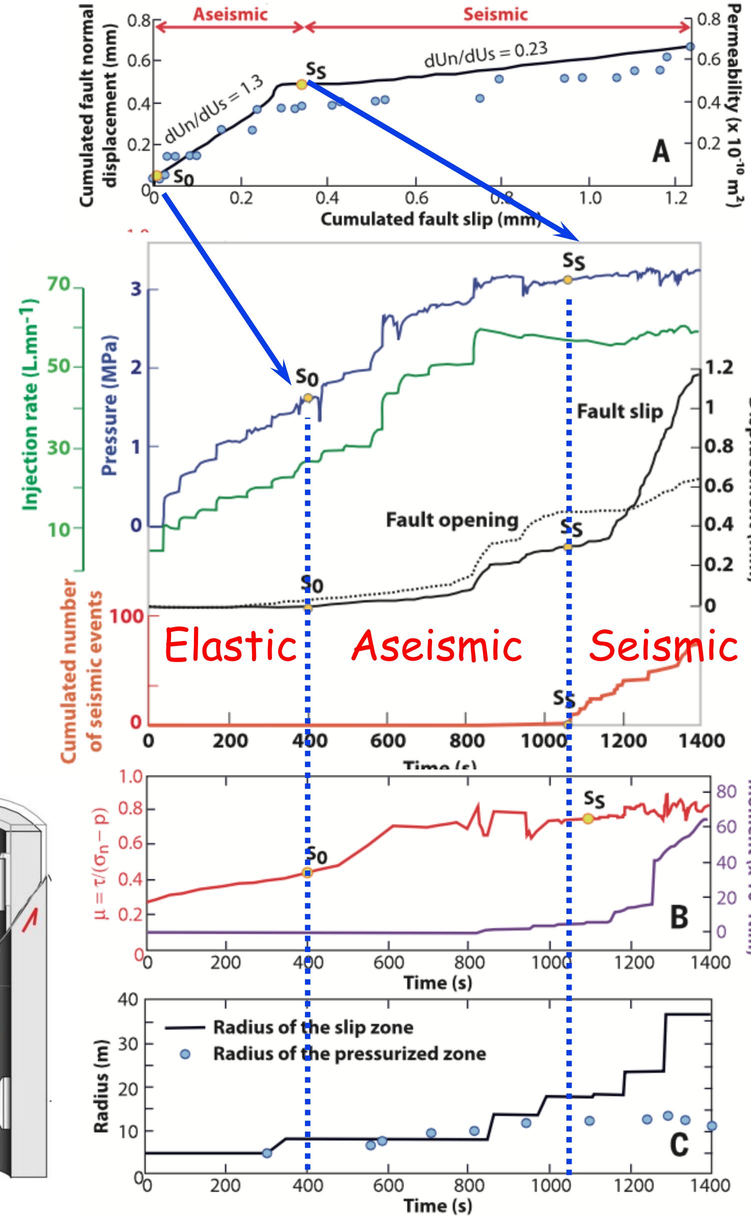
Velocity Weakening (unstable slip)

Frictional Response of Mixtures

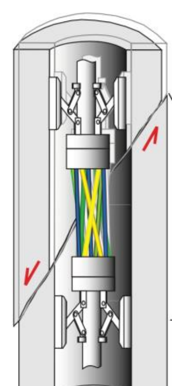


[Niemeijer et al., GRL, 2010]

Aseismic-Seismic Transition



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



Roles of:

Pressurization $(\sigma_n' \to 0)$

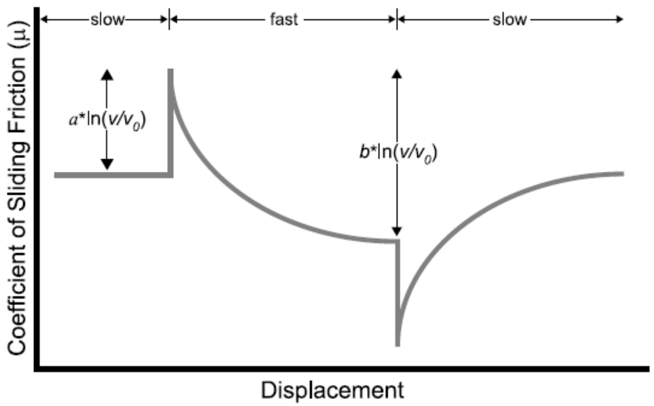
Deformation ahead of the fluid front

Mineralogical controls

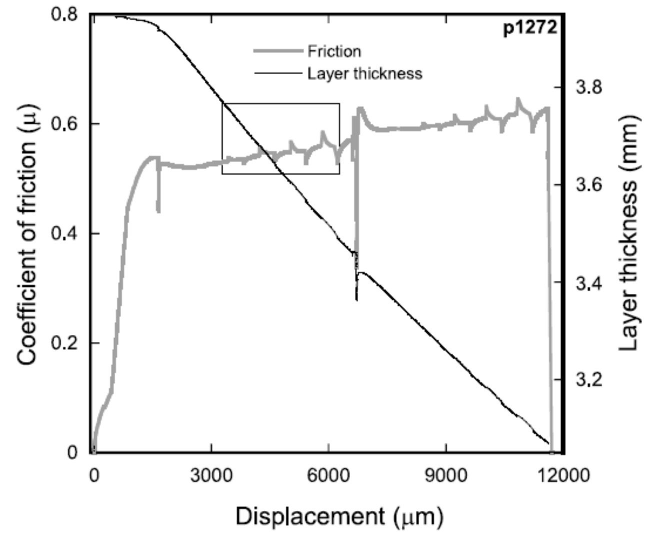
[Guglielmi et al., Science, 2015]

Rate-State Friction [1]

Velocity Steps



Multiple Velocity Steps



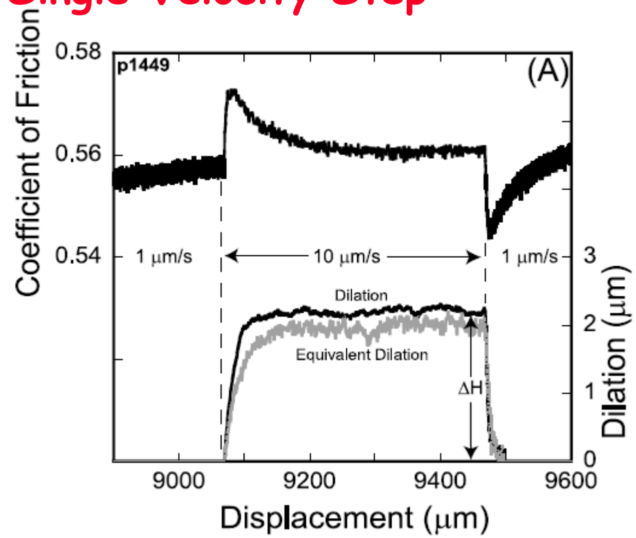
R-S Friction

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

$$\frac{d\theta}{dt} = 1 - \frac{v\theta}{D_C} \quad \text{(Dieterich Evolution)}$$

$$\frac{d\theta}{dt} = \frac{-v\theta}{D_C} \ln\left(\frac{v\theta}{D_C}\right) \quad \text{(Ruina Evolution)}$$

Single Velocity Step



Dilation

$$\frac{\Delta H}{H} \cong \Delta\phi = -\epsilon \ln\left(\frac{v}{v_0}\right) = -\epsilon \ln\left(\frac{v_0 \theta}{D_c}\right)$$

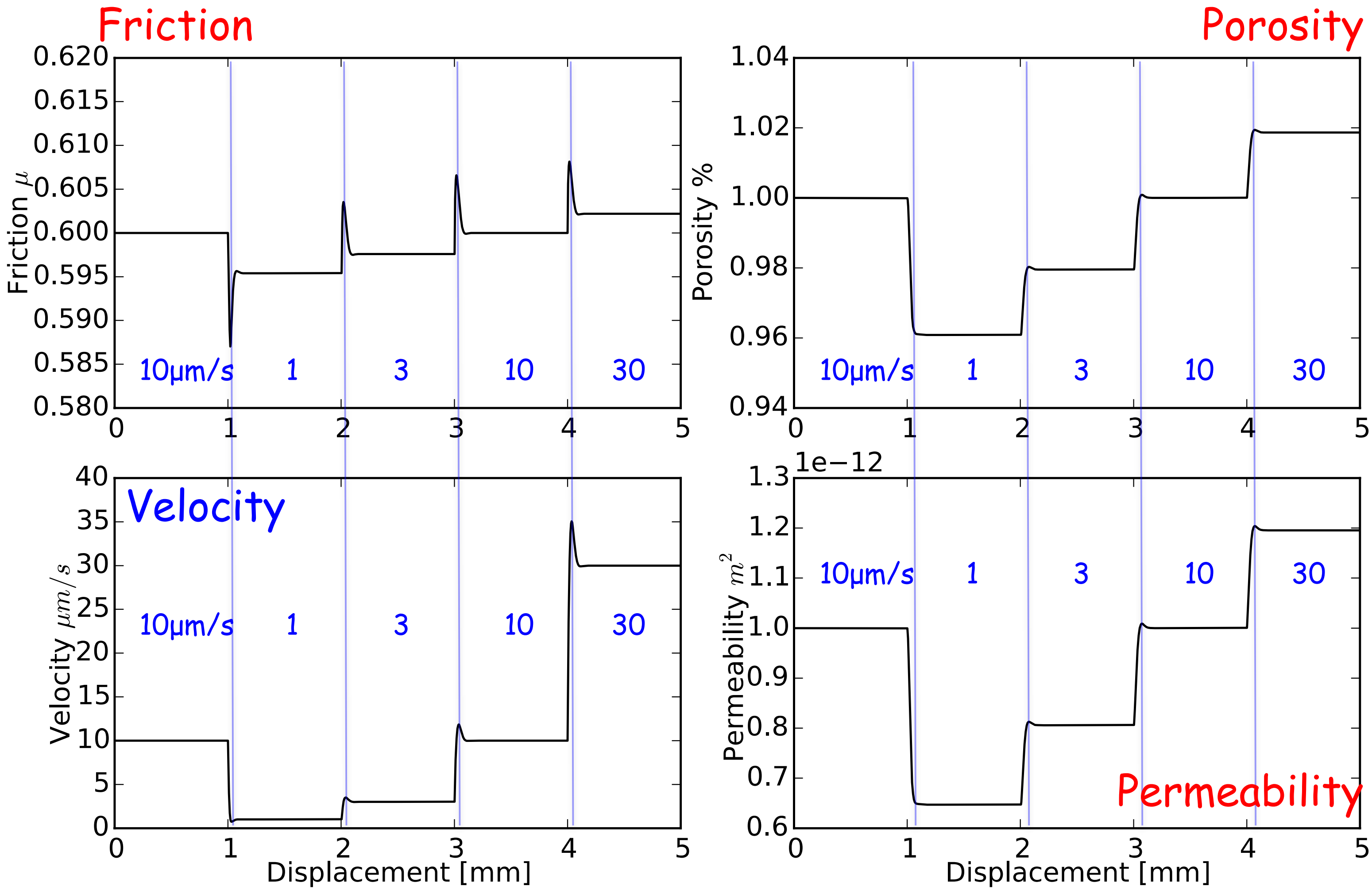
Permeability Evolution

$$\frac{k}{k_0} = \left(1 + \frac{\Delta b}{b_0}\right)^3 = \left(1 + \frac{\Delta H}{H}\right)^3$$

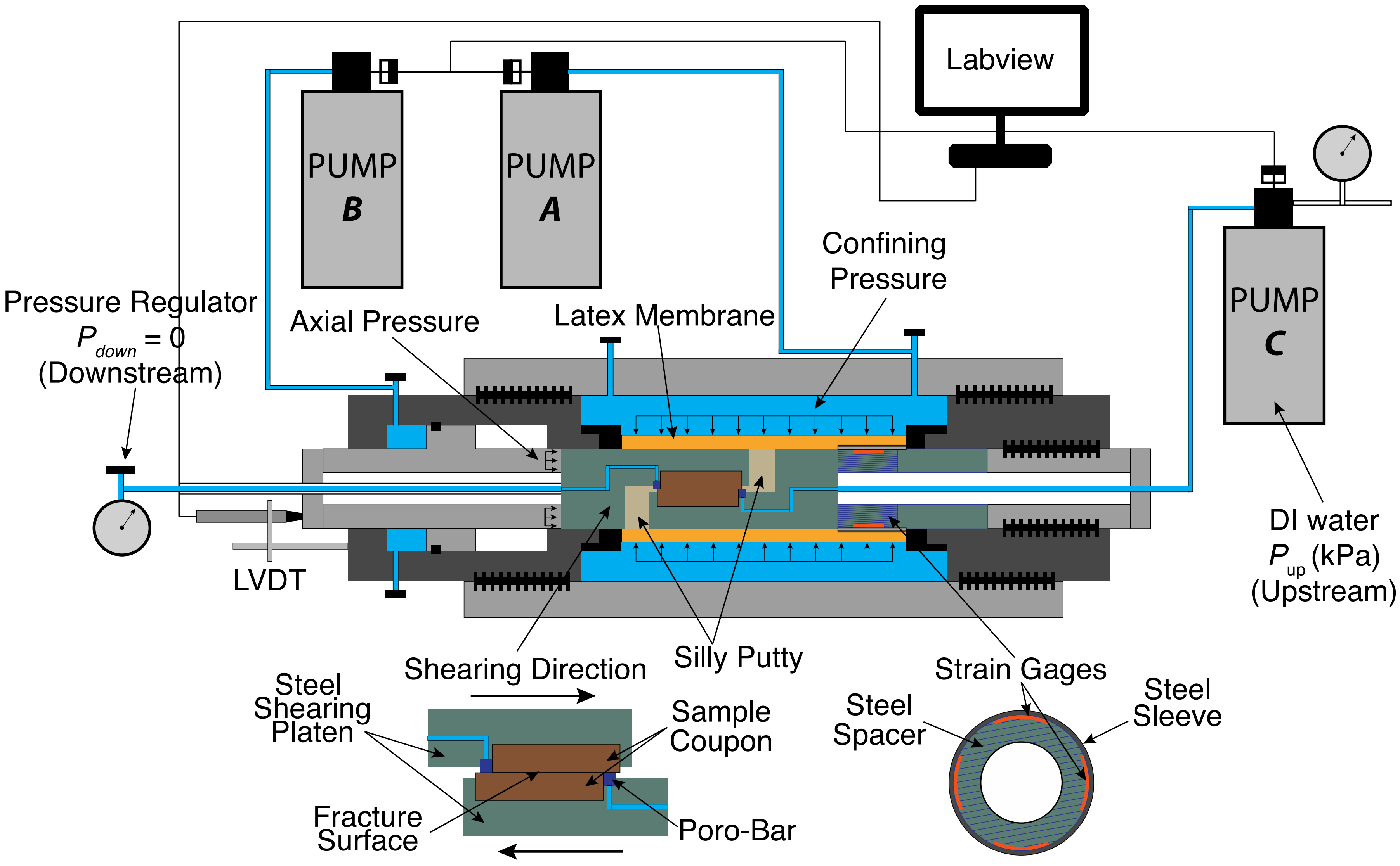
Rational Linkages: Rate-State Friction, Porosity and Permeability

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

High Stiffness, positive dilatational coefficient

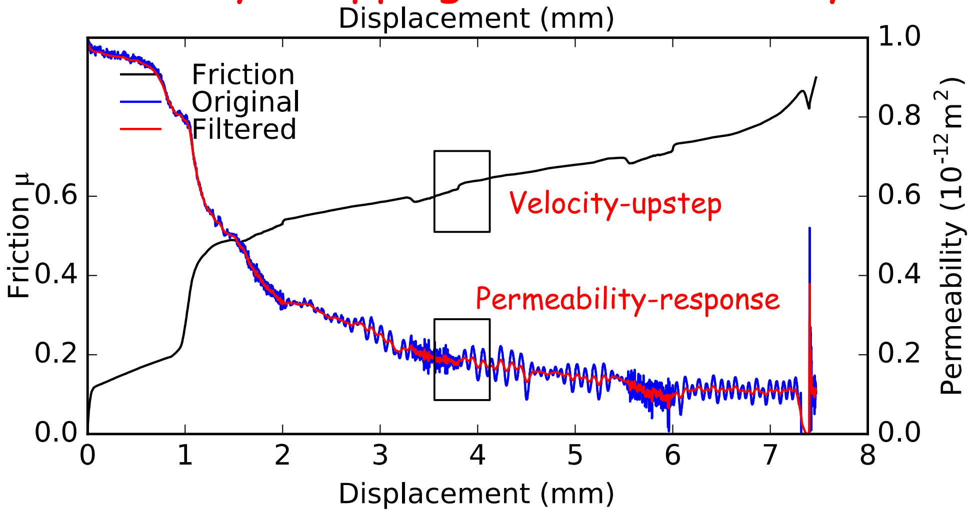


Frictional Stability-Permeability Experiments

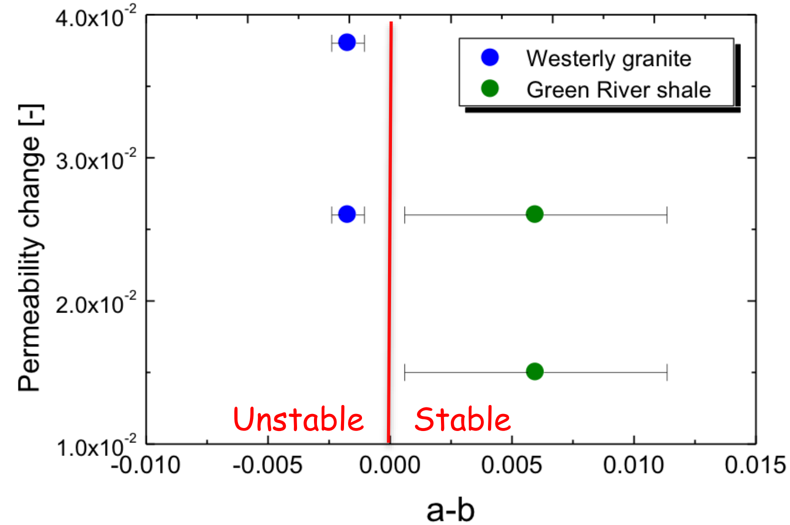


Frictional Stability-Permeability Observations

Velocity-stepping and Permeability

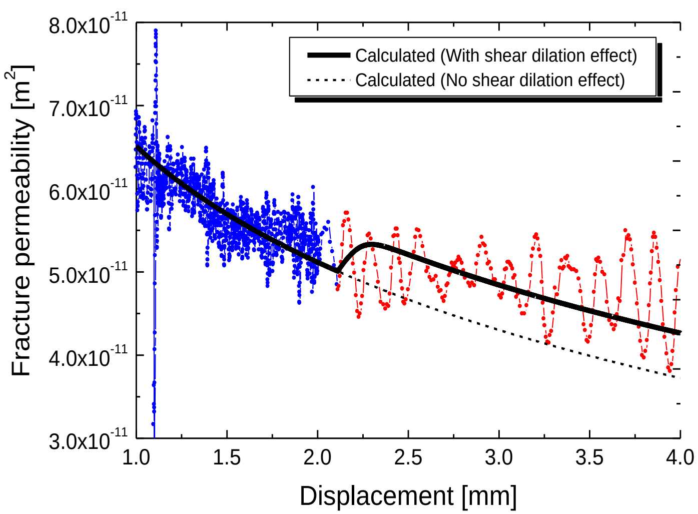


Permeability-Frictional Stability

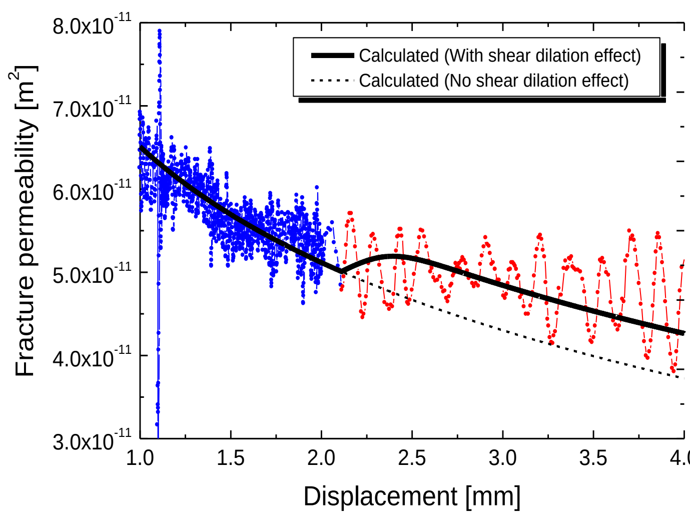


Permeability Evolution

ε=0.0224 (n=2), Dc=50 [μm]

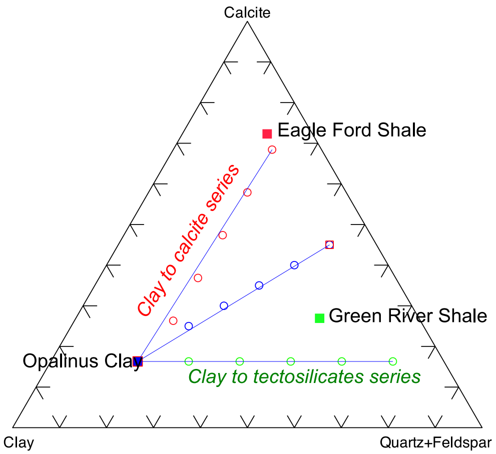


ε=0.0224 (n=2), Dc=100 [μm]

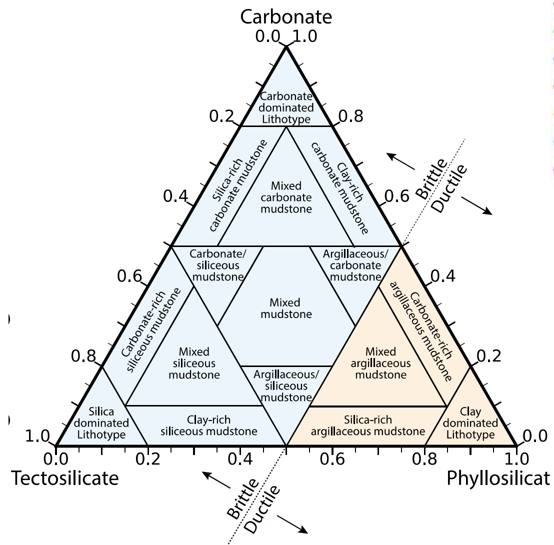


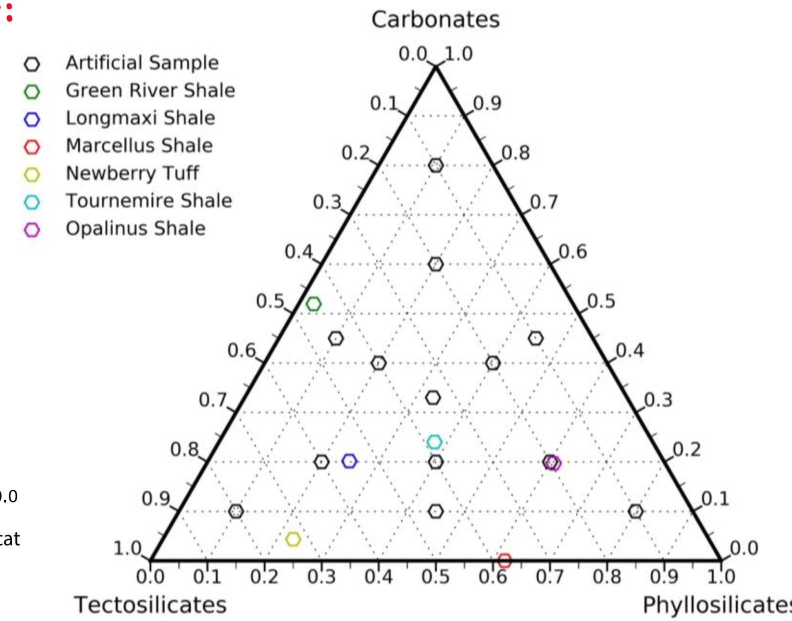
Mineralogical Sample Space

Sample Space for Artificial Samples:



Frictional Stability:





Natural Samples:

(1) Green River Shale (Colorado, USA);

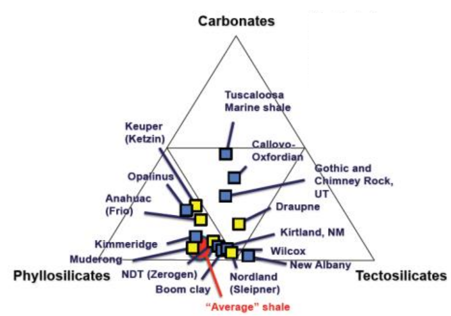
(2) Longmaxi Shale (Chongqing, China);

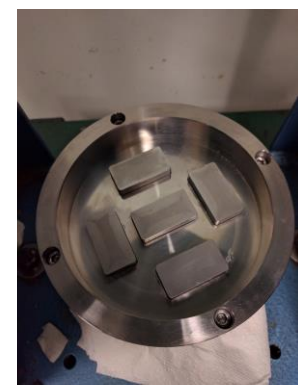
(3) Marcellus Shale (Pennsylvania, USA);

(4) Newberry Tuff (Oregon, USA);

(5) Tournemire Shale(France);

(6) Opalinus Shale (Switzerland)

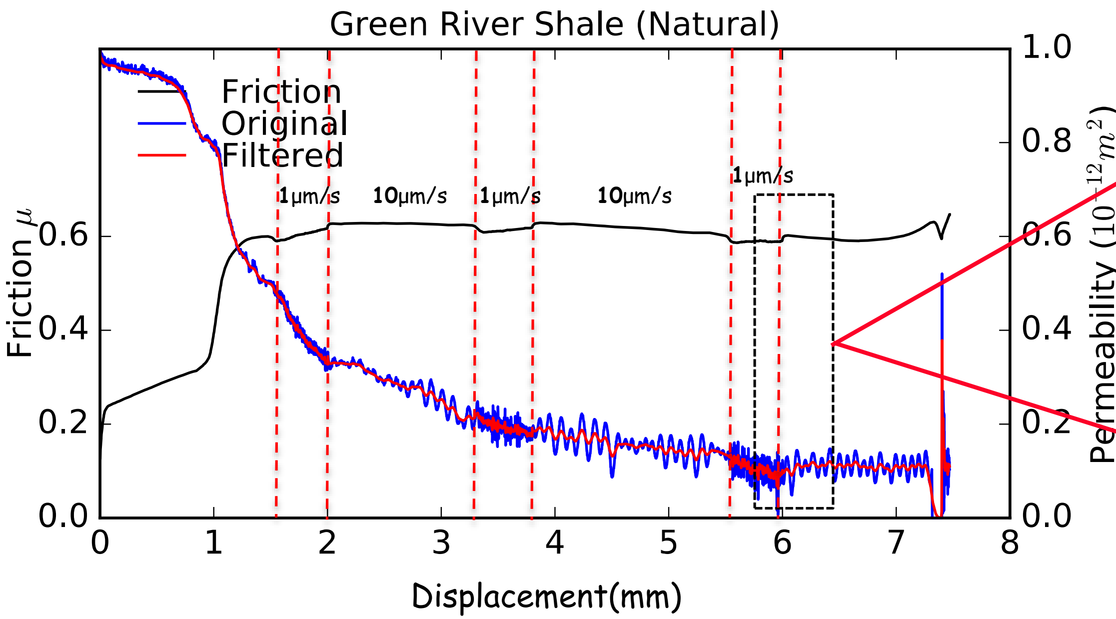


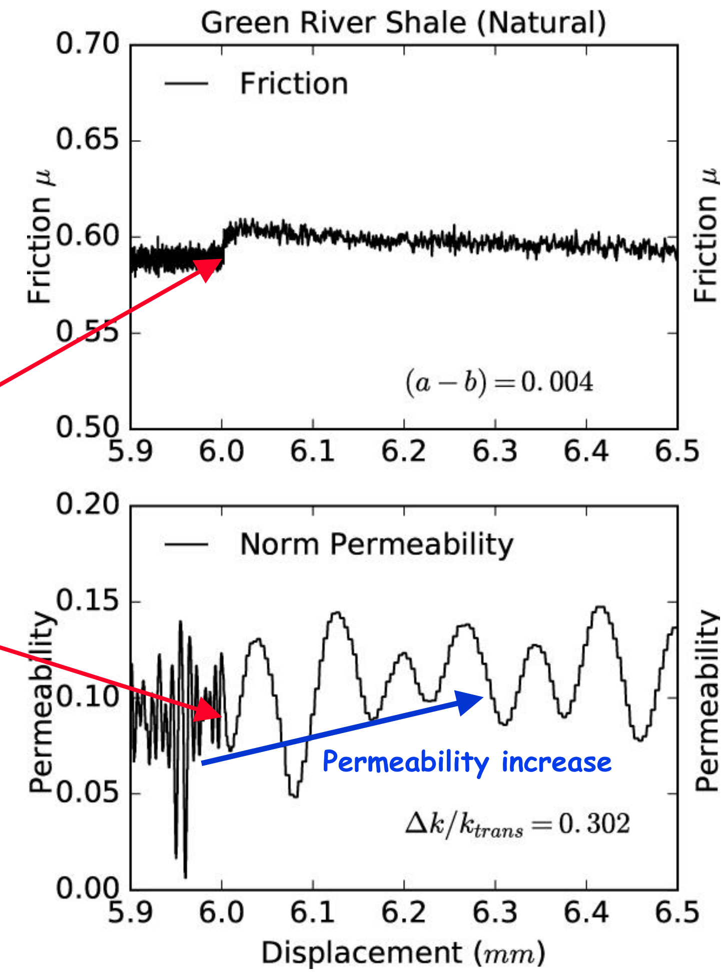


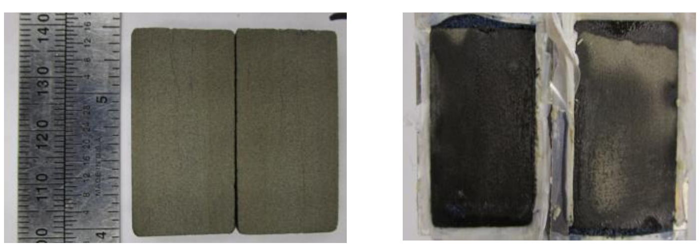
Bulk mineralogy of caprock formations
(Ian Bourg LBNL NCGC)

Green River Shale- Permeability Enhancement

	Tectosilicate	Carbonate	Phyllosilicate
Green River Shale	45.44%	51.96%	2.60%







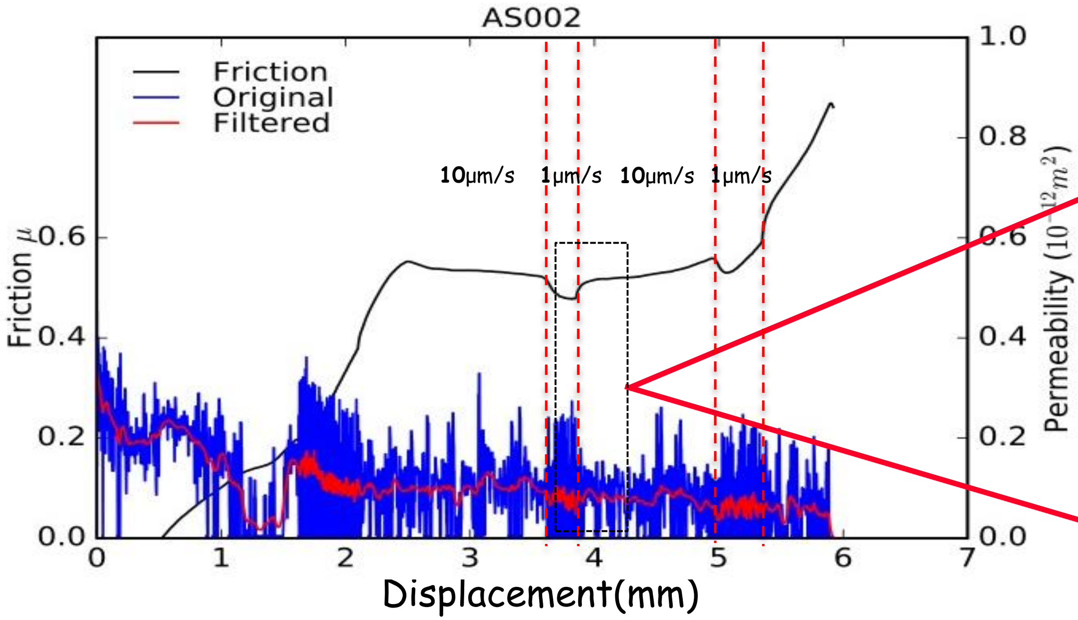
Before After

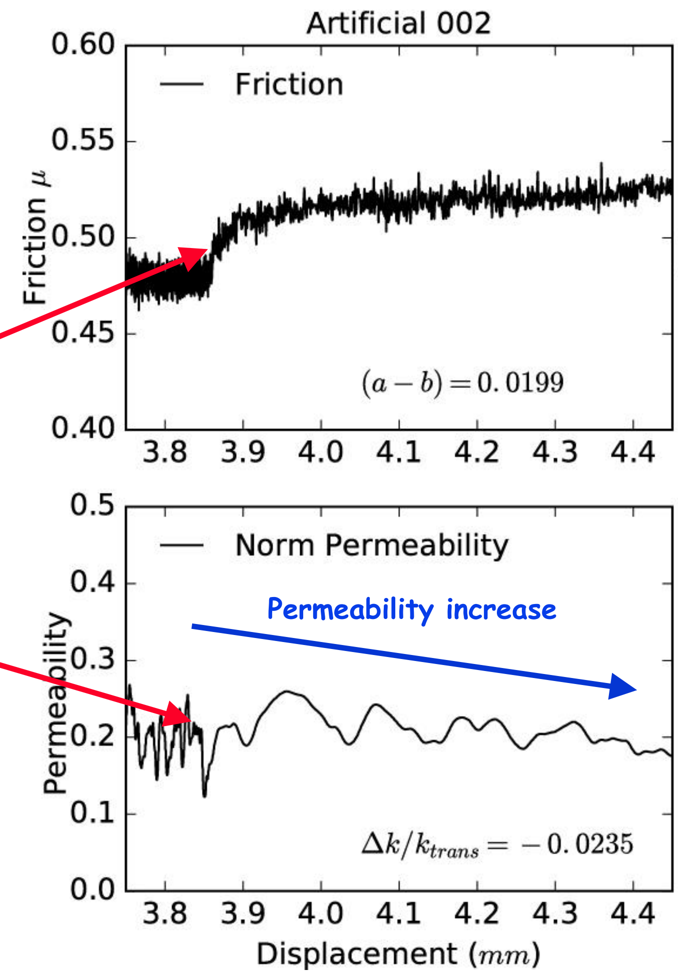
Wear products after slip

Velocity-upstep results in a permeability increase due to dilation

Phyllosilicate-dominant Artificial Sample- Permeability Decrease

	Tectosilicate	Carbonate	Phyllosilicate
AS002	10%	10%	80%



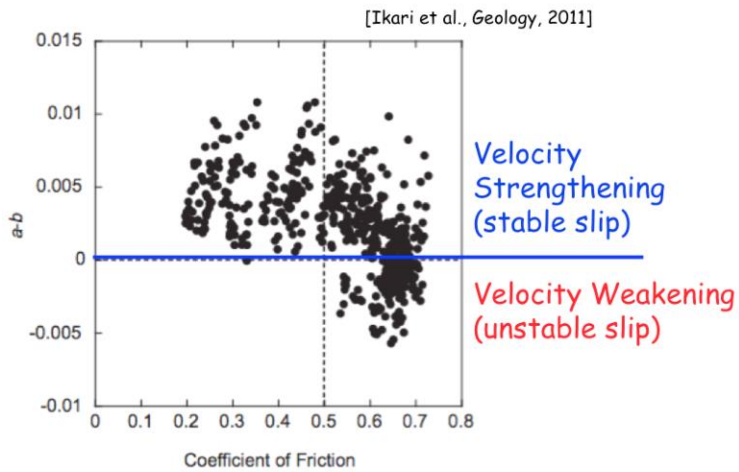


Before After

Clay swelling concurrent with shear damage

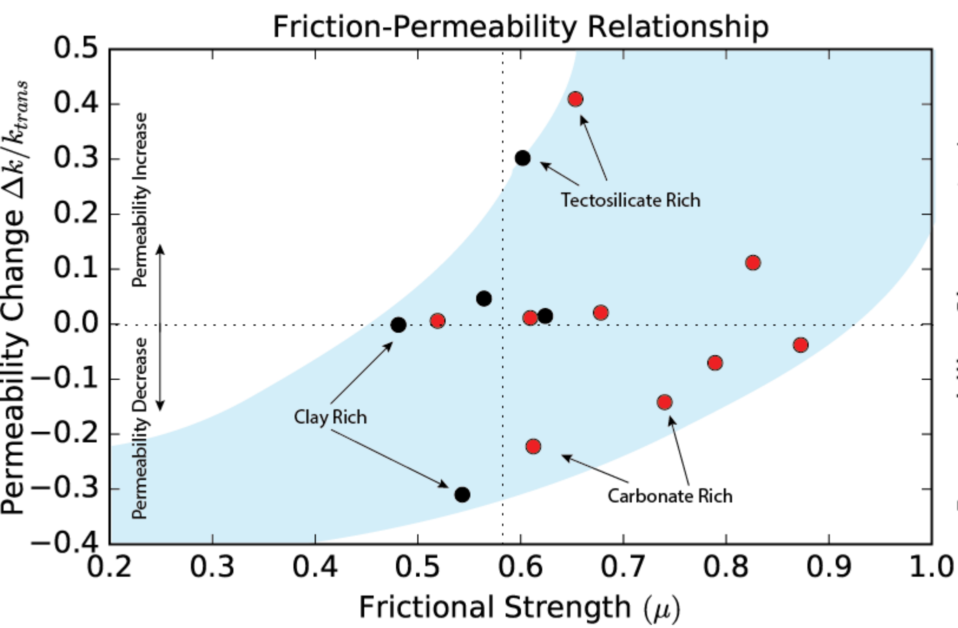
Velocity-upstep results in a permeability decrease due to wear products and swelling

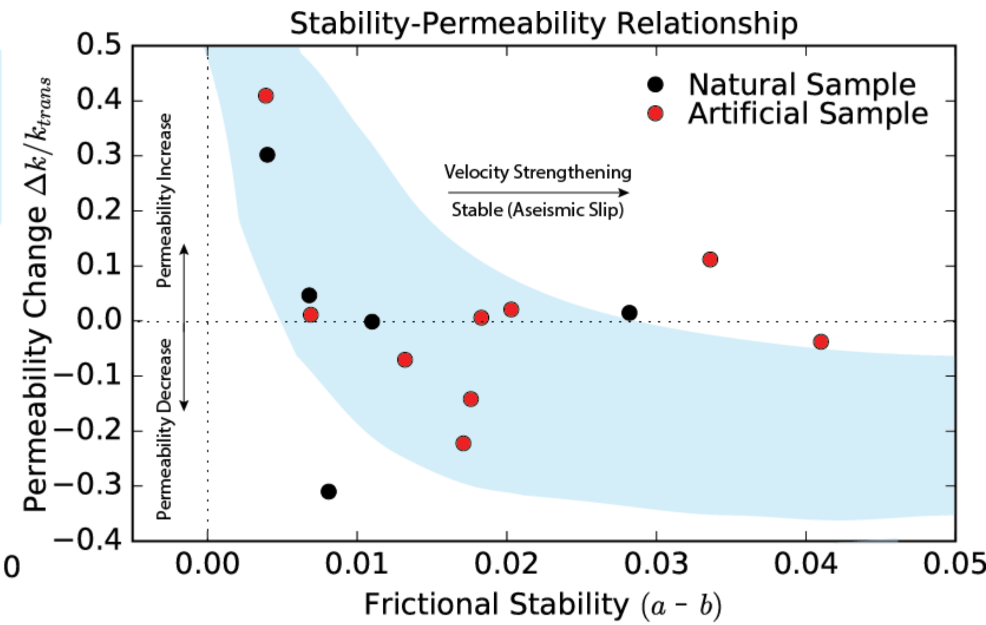
Nascent Friction-Stability-Permeability Relationships



Observations

- dk/k0 increases with increased brittleness (a-b)<0
- dk/k0 increases with increased frictional strength
- Roles of mineralogy and surface roughness?





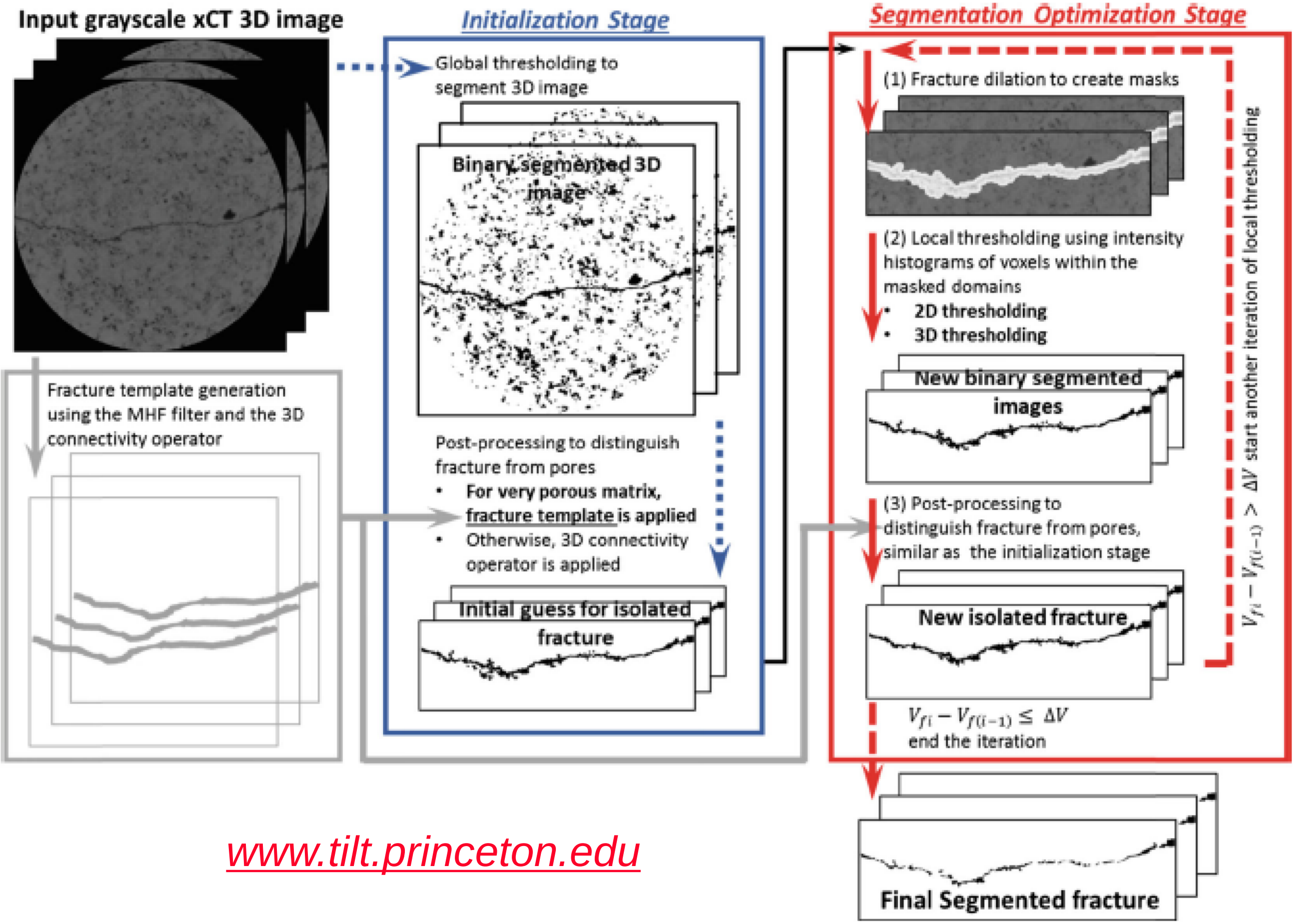
Quantifying fracture geometry with X-ray tomography

Post flow/shear subcores for xCT

xCT imaging at APS Sector 13 GSECARS

Developed 3D image segmentation method for complex fractures

'TILT' - for fractures with rough porous surfaces & wear products

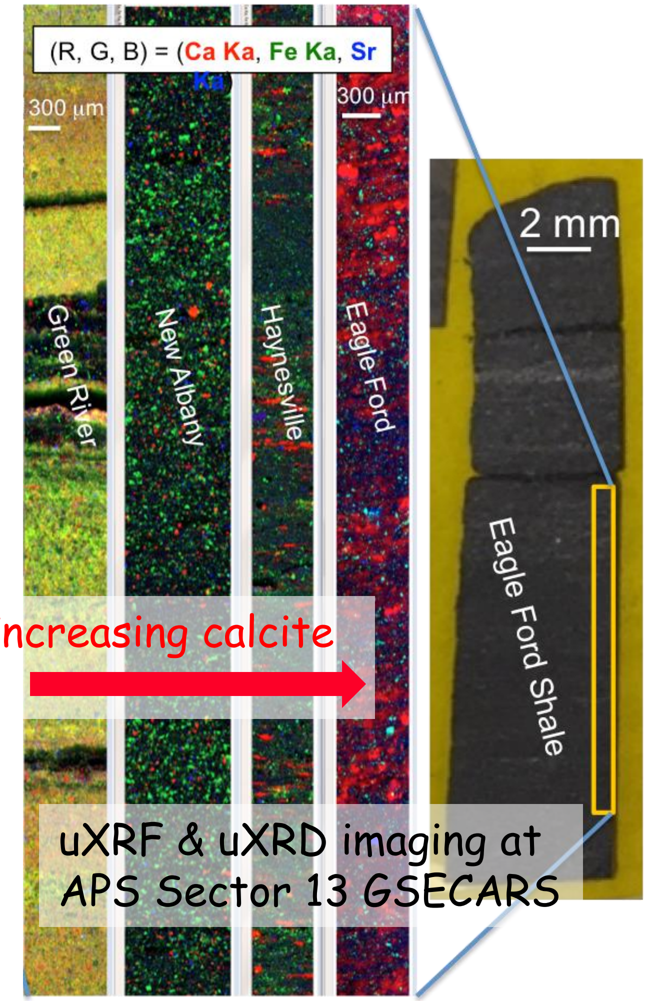


www.tilt.princeton.edu

Deng, H., Fitts, J.P. & Peters, C.A. Comput Geosci (2016) 20: 231.

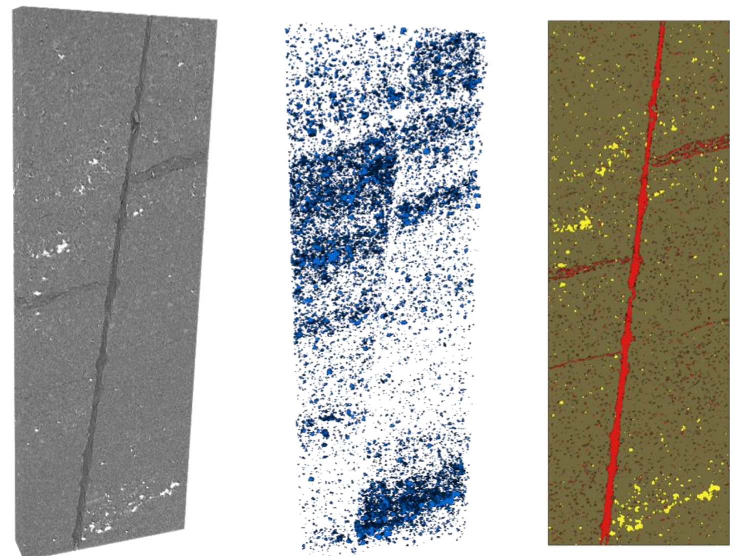
'Digital fractures' combine 3D xCT and fracture surface characterizations

<u>2D fracture surface characterization</u>
Detailed mineral spatial distribution and textures



\+

<u>3D xCT characterization</u>
Aperture geometry, contacting asperities & coarse mineral distributions



Grey-scale xCT data

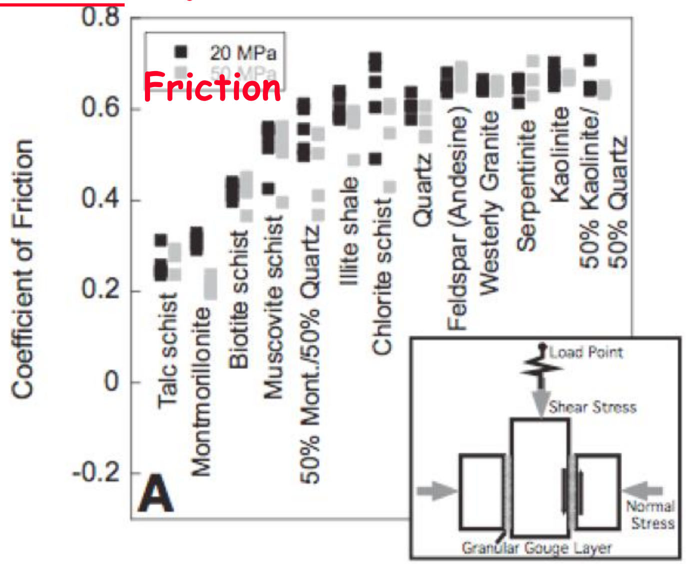
3D sulfide distribution

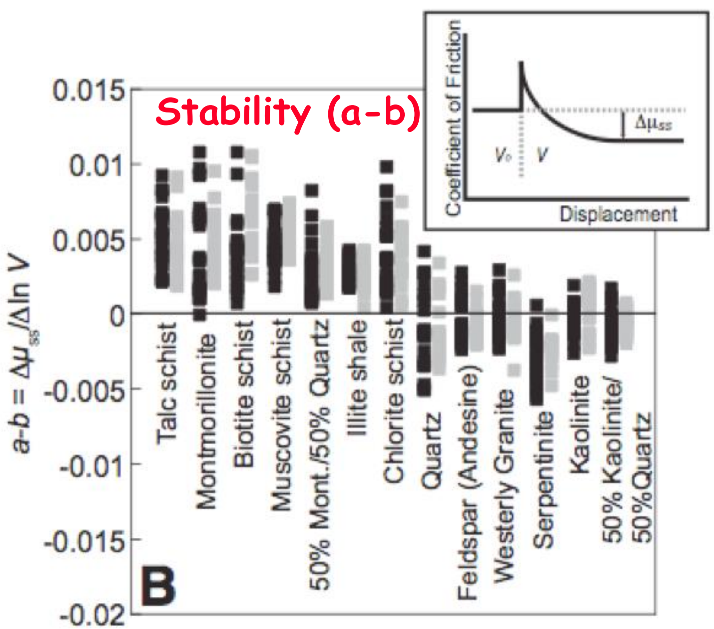
quaternary segmentation

Inputs for simulating friction-stability-permeability evolution & deriving constitutive relations

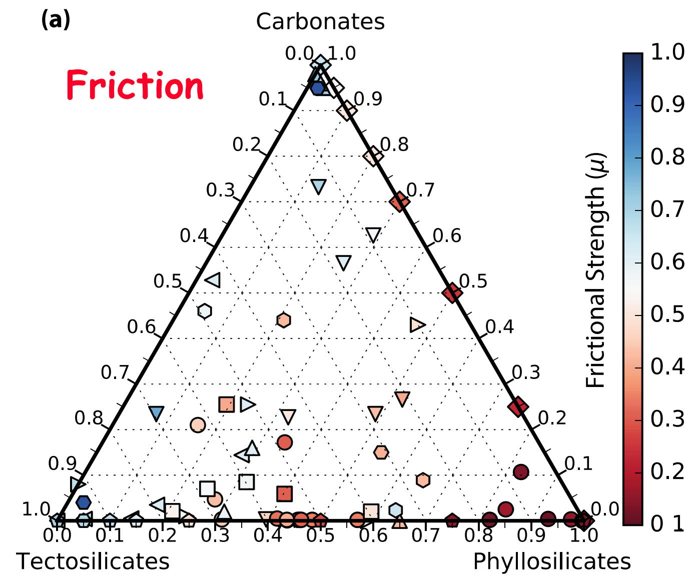
Stability-Permeability Relations in Composites/Mixtures

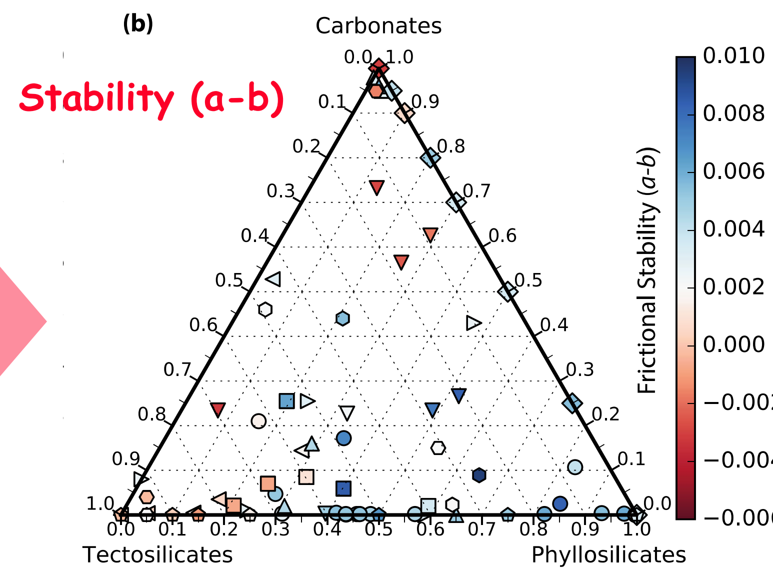
Mono-mineralic





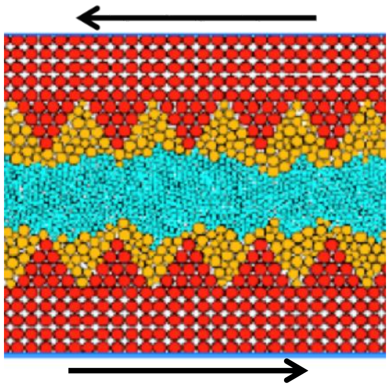
Multi-mineralic



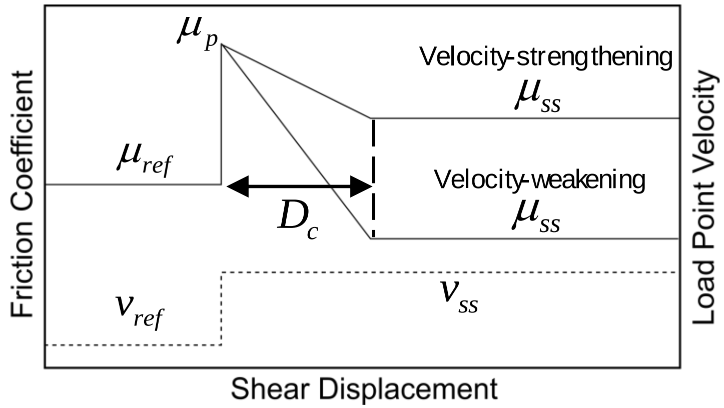


Multi-Mineral Frictional Strength

DEM Model



Particle-Particle Frictional



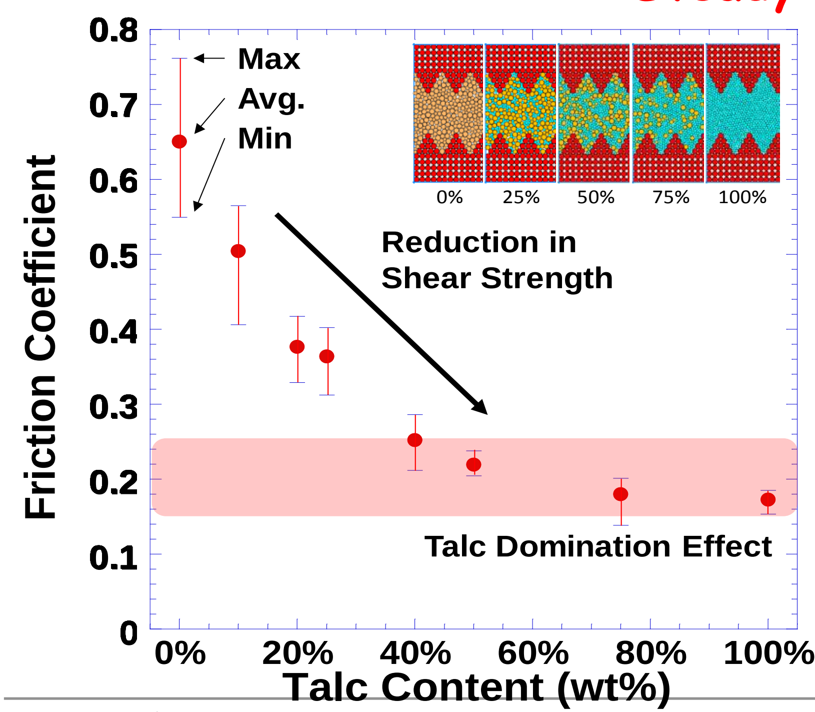
RSF Notation

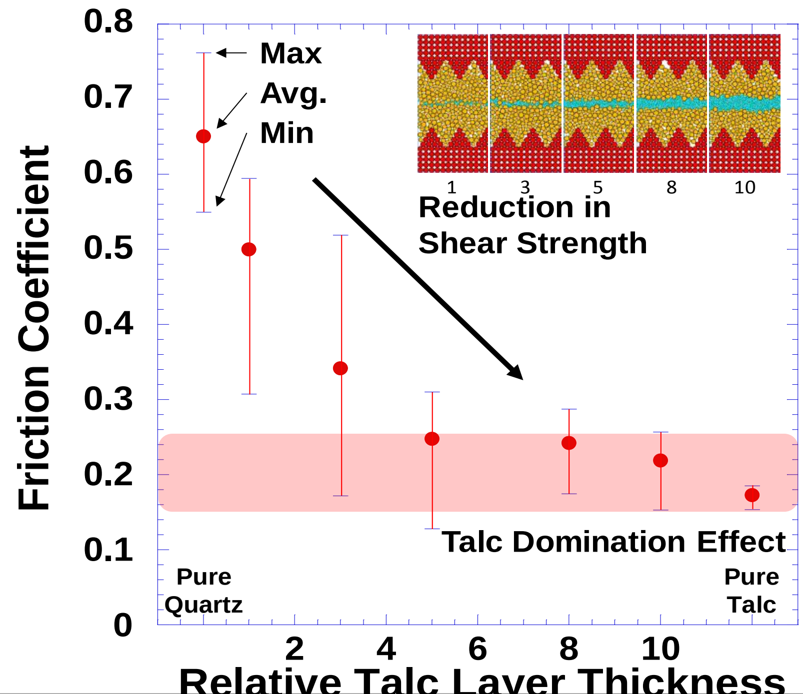
$$\mu_p = \mu_{ref} + a\ln\left(\frac{V_{ss}}{V_{ref}}\right)$$

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

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

Steady-State Friction

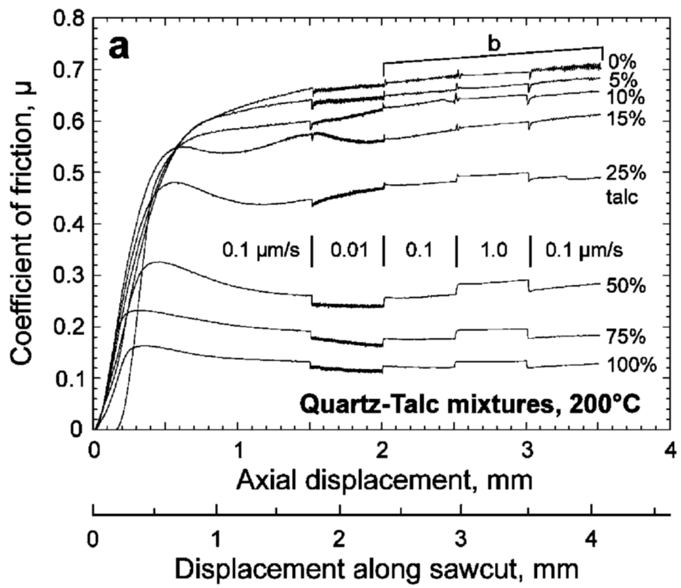


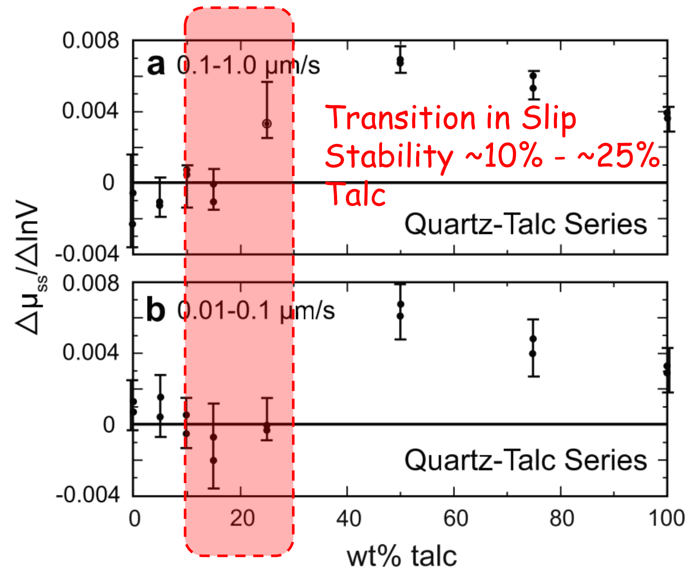


Mixture Controls of Frictional Instability

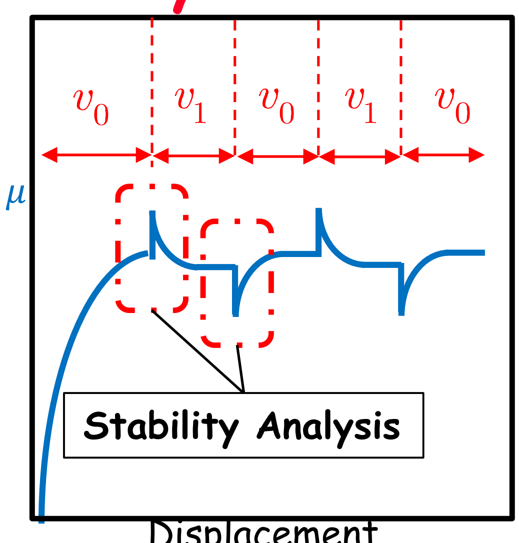
Observations

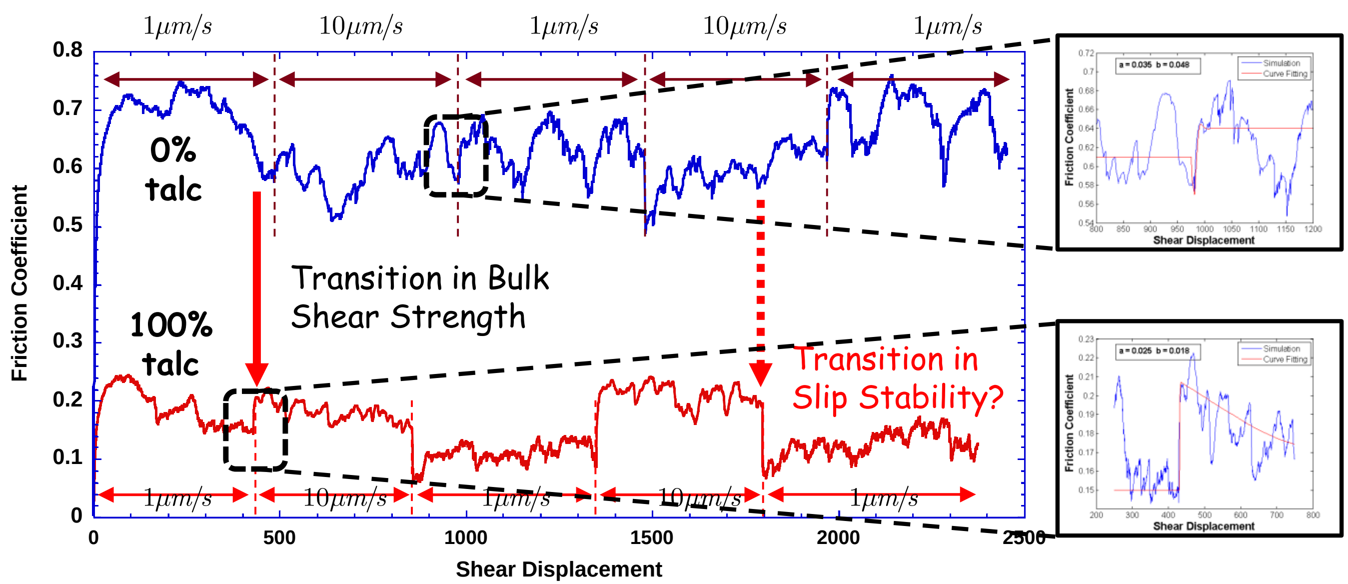
[Moore & Lockner 2011]



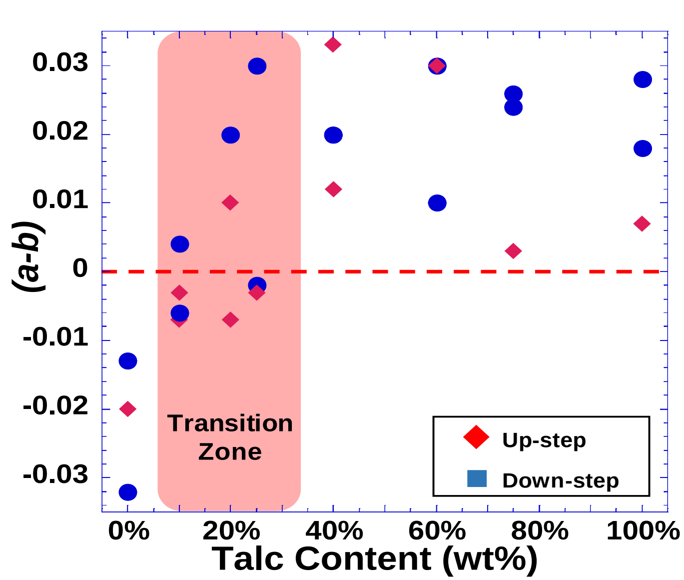


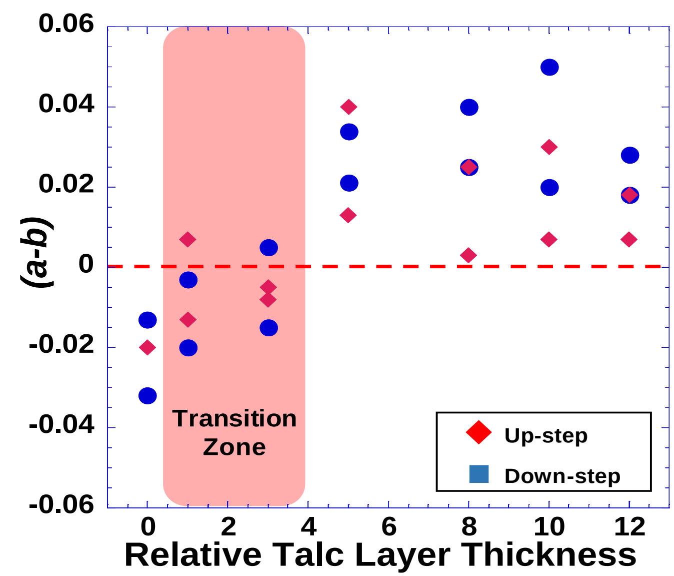
Analysis

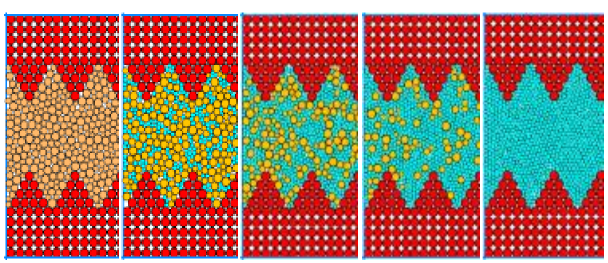




Multi-Mineral Frictional Stability

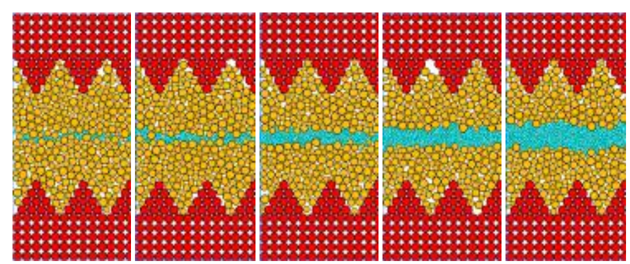






0% 25% 50% 75% 100%

Transition zone appears at ~10% to ~25% talc content

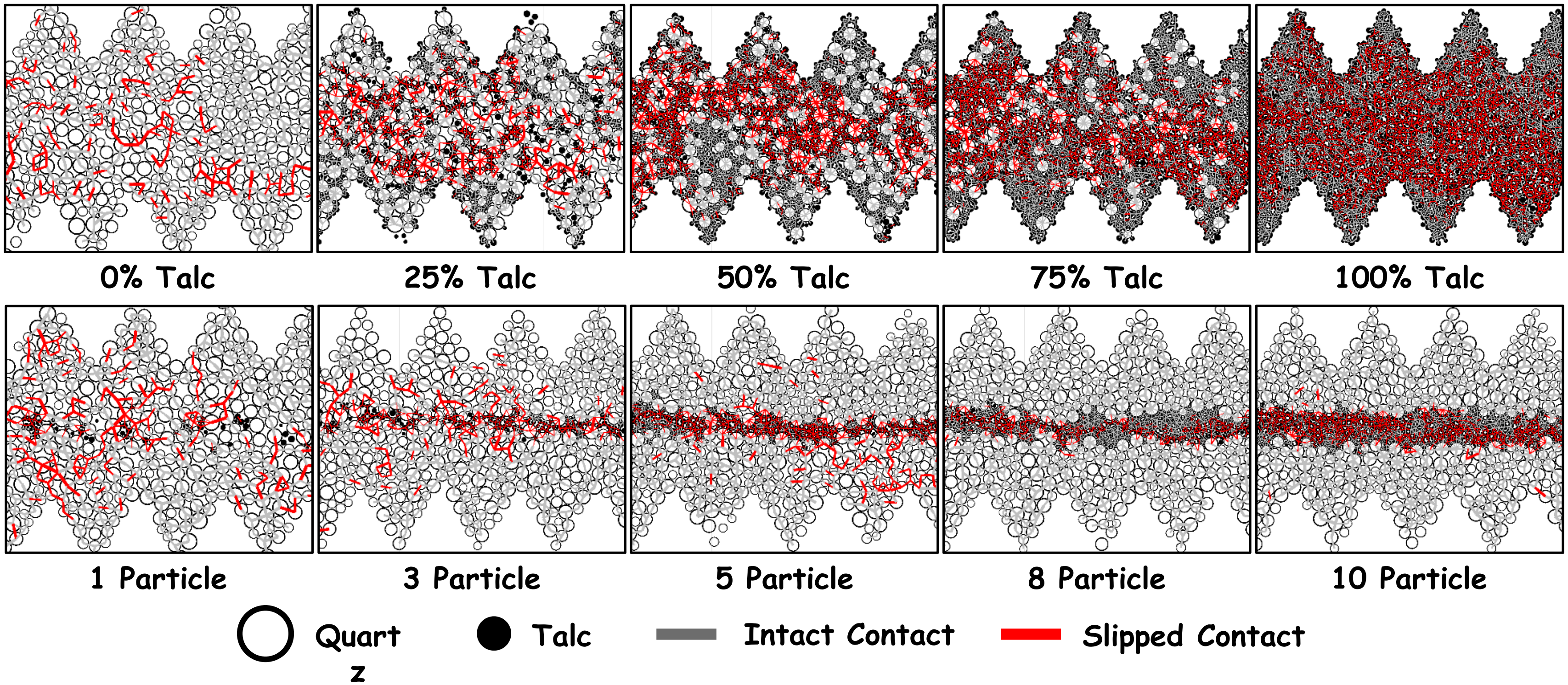


1 3 5 8 10

2% 3% 4% 10 % 13 %

Transition zone appears at ~2% to ~3% talc content

Texture-dependent Localization Effects



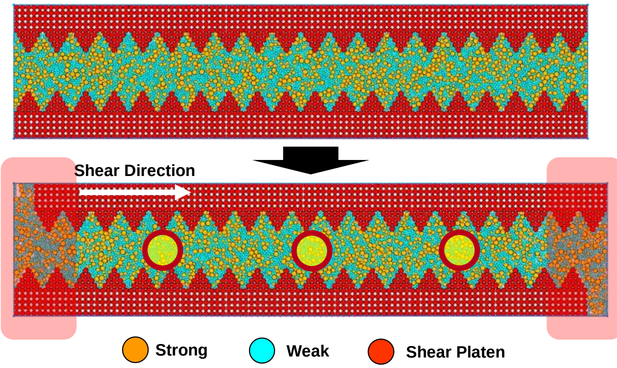
Distributed heterogeneity:

Slipped contacts are distributed homogeneously in the sample, following critical shear band directions.

Textured/layered:

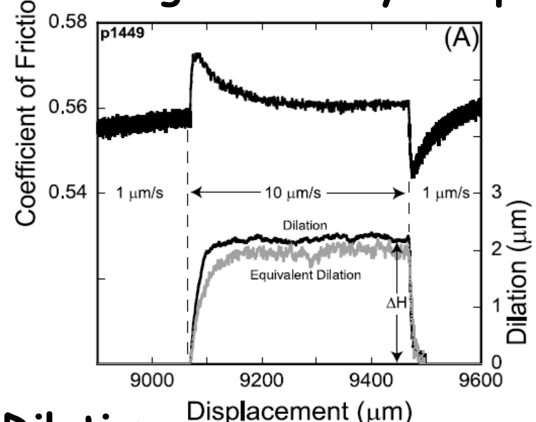
Slipped contacts are distributed inside talc/weak layer, forming a localized shear zone, forcing most slip to evolve within this zone.

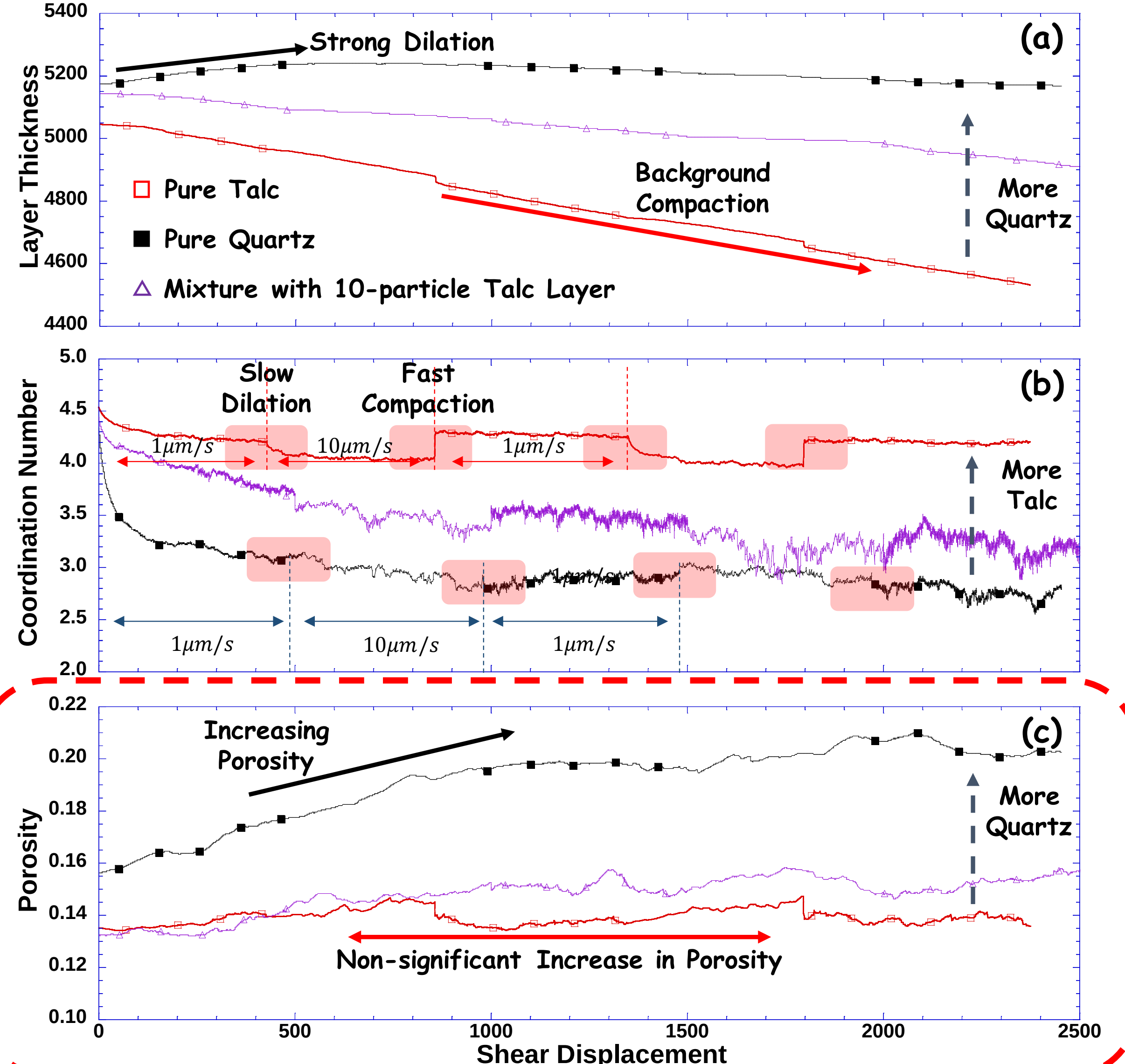
Evolution of Layer thickness, Coord. Num, and Porosity



Background Compaction

Single Velocity Step





Dilation

$$\frac{\Delta H}{H} \cong \Delta\phi = -\epsilon \ln(\frac{v}{v_0}) = -\epsilon \ln(\frac{v_0 \theta}{D_c})$$

Permeability Evolution

$$\frac{k}{k_0} = (1+\frac{\Delta b}{b_0})^3 = (1+\frac{\Delta H}{H})^3 \cong (1+\Delta\phi)^3$$

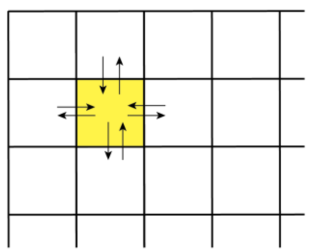
Coupling Reactive Transport and Mechanical Deformation

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

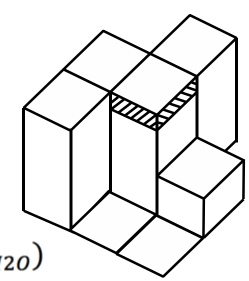


1. Transport

$$\frac{\partial}{\partial x}\left[b^3(x,y)\frac{\partial h(x,y)}{\partial x}\right]+\frac{\partial}{\partial y}\left[b^3(x,y)\frac{\partial h(x,y)}{\partial y}\right]=0$$

1. Speciation

$$CO_{2\,(aq)} + H_2O \leftrightarrow H_2CO_{3\,(aq)}$$
$$H_2CO_{3(aq)} \leftrightarrow H^+_{(aq)} + HCO^-_{3(aq)}$$
$$HCO^-_{3\,(aq)} \leftrightarrow H^+_{(aq)} + CO^{2-}_{3\,(aq)}$$
$$H_2O \leftrightarrow H^+_{(aq)} + OH^-_{(aq)}$$

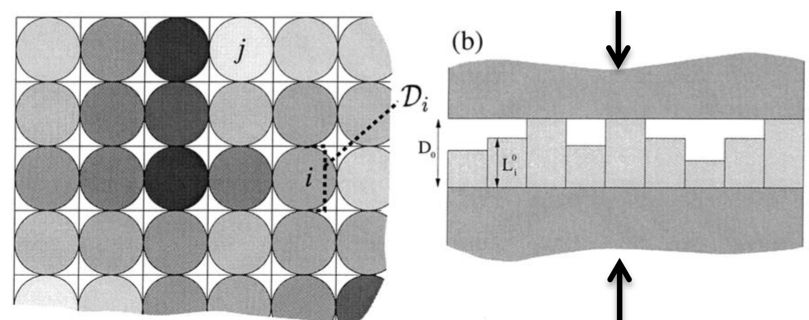


1. Reaction

$$R = A * k_f * \left(1 - \frac{IAP}{Ksp}\right)$$
$$k_f = k_1(a_{H+}) + k_2(a_{H2CO3}) + k_3(a_{H2O})$$

Hang Deng, PhD Dissertation, Princeton U., 2015

Mechanical Deformation Model



1. Elastic Column Compression (ΔLi)

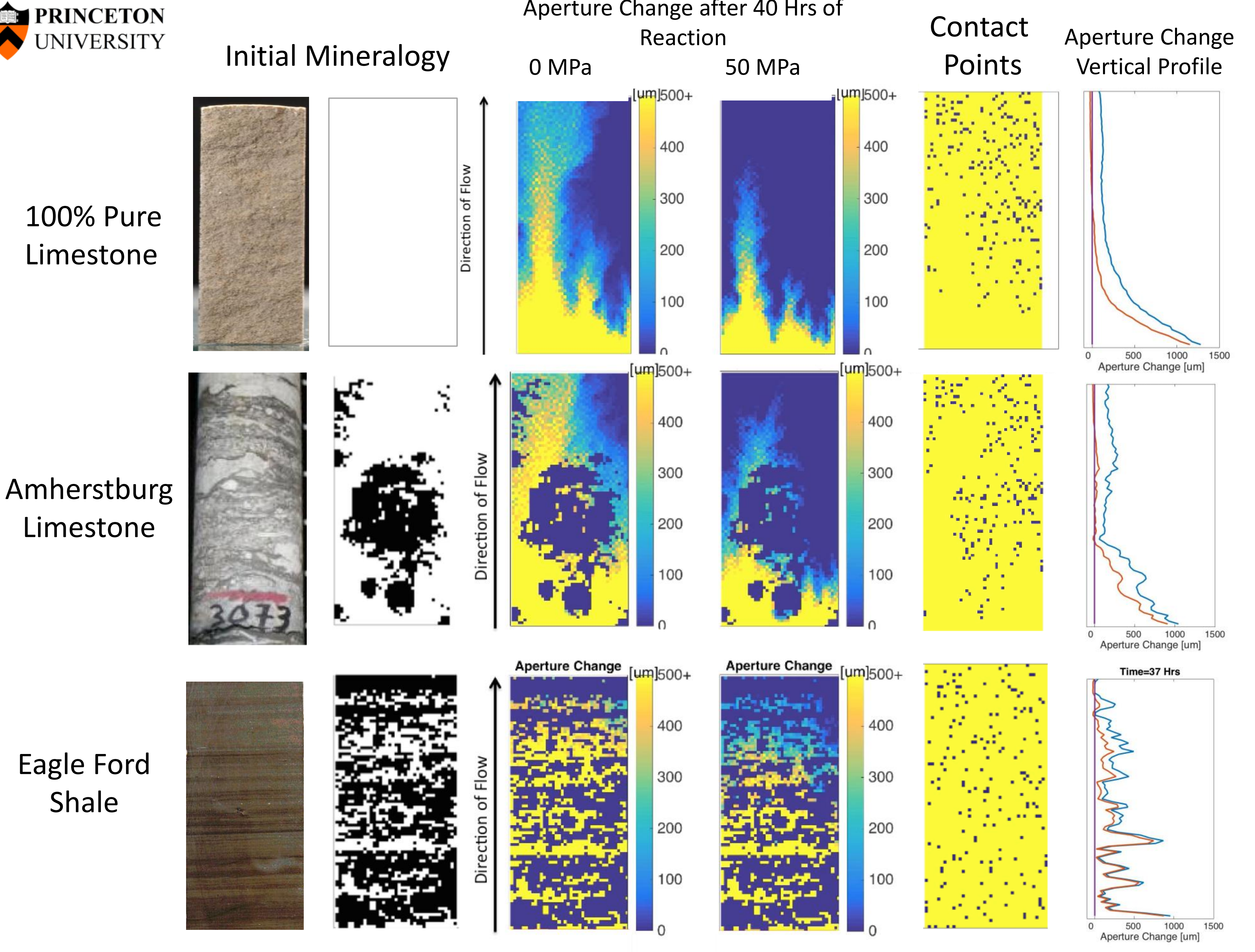
$$\Delta L_i = f_i \frac{L_i^0}{E\pi a^2}$$

1. Elastic half-wall deformation (W_i)

$$W_i = f_i * \frac{8(1-\nu^2)}{\pi^2 E a} I_4(a) + f_j * \frac{8(1-\nu^2)}{\pi^2 E a} I_3(r_{ij}, a)$$

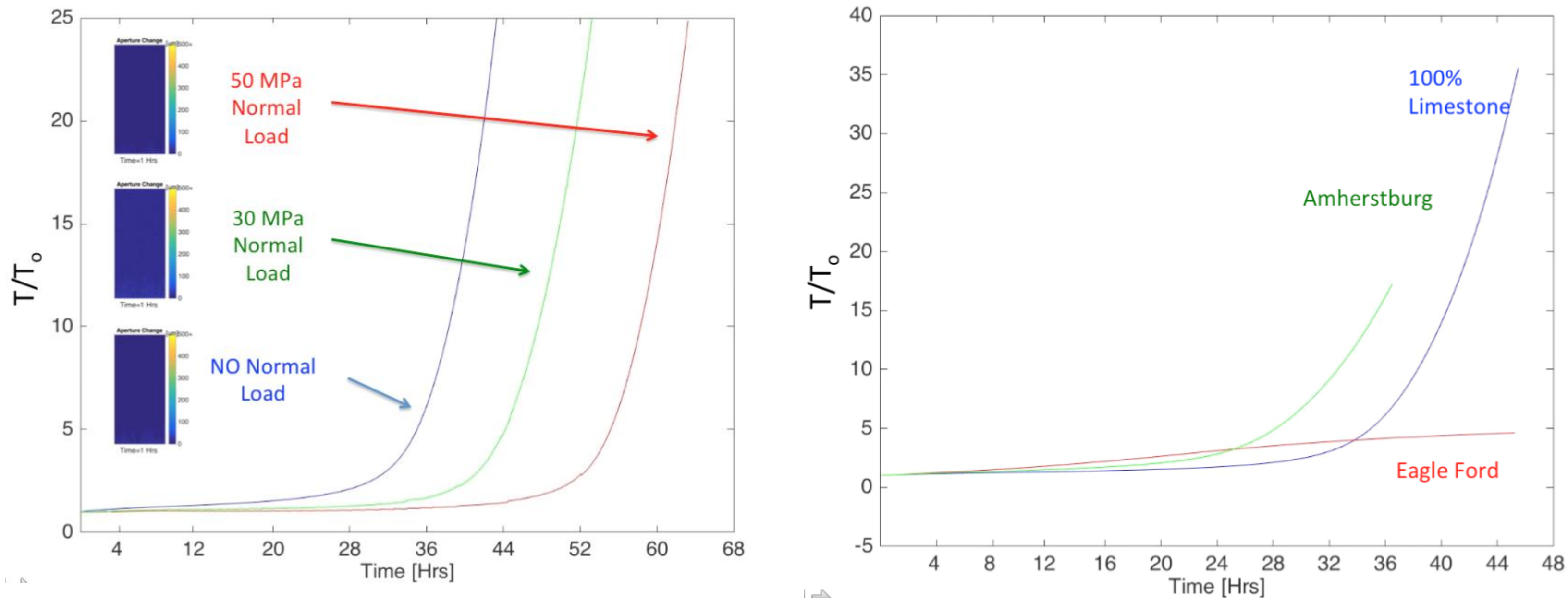
Pyrak-Nolte & Morris, 2000

PRINCETON UNIVERSITY



PRINCETON UNIVERSITY
Initial Mineralogy
Aperture Change after 40 Hrs of Reaction
0 MPa
50 MPa
Contact Points
Aperture Change Vertical Profile
100% Pure Limestone
Amherstburg Limestone
Eagle Ford Shale
3073
Direction of Flow
Aperture Change
[um]
500+
400
300
200
100
0
Time=37 Hrs
0
500
1000
1500
Aperture Change [um]

Transmissivity Change over Time



- When the rock is spatially <u>homogenous</u> mineralogically, transmissivity remains controlled by unreacted downstream apertures
- When the rock includes areas of <u>nonreactive minerals</u>, 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, <u>fracture closure delays transmissivity increase</u>

- Future Projects:
  – Effect of reactive transport along fracture interfaces on fracture frictional properties

PRINCETON UNIVERSITY

Accomplishments to Date

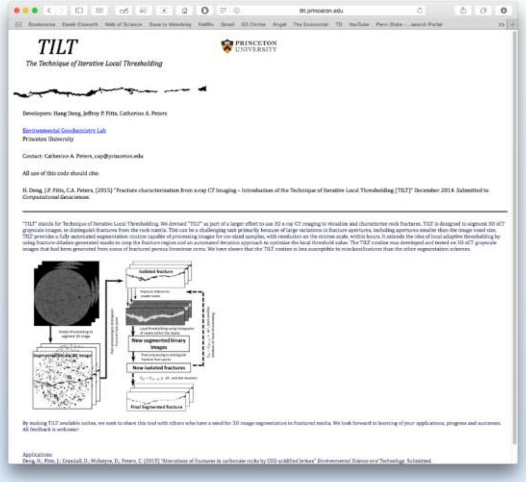
ACCOMPLISHMENTS

- 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 dk)
- 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

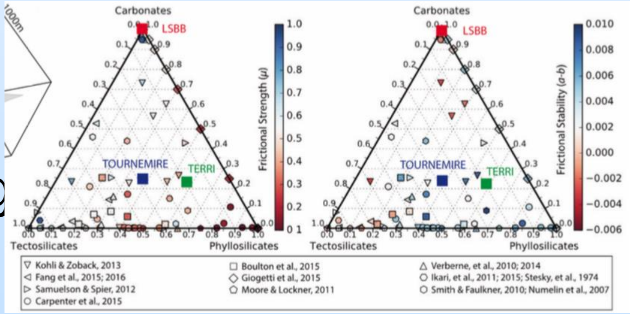
ONGOING

- 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 deply 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

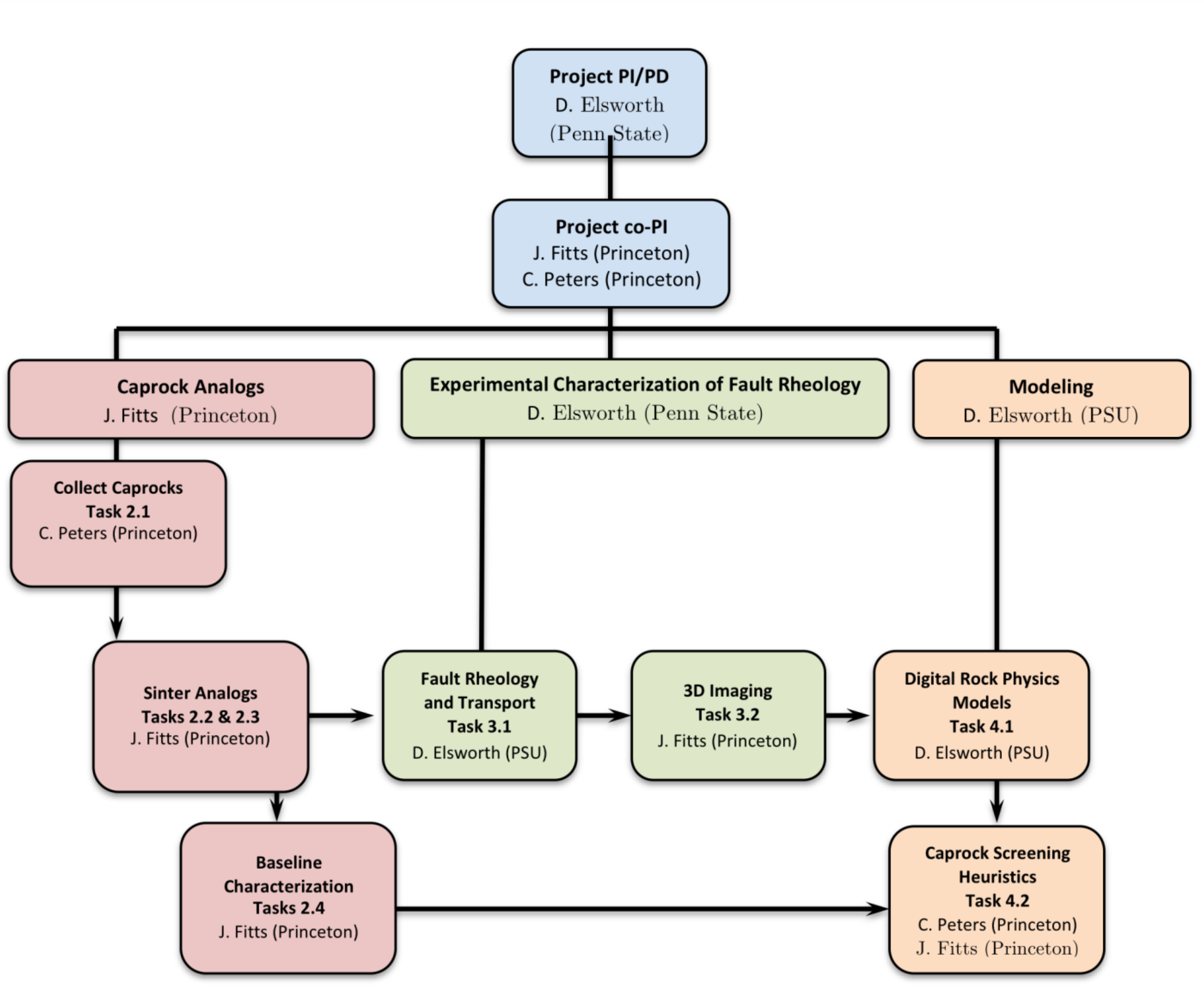
- Rupture of caprocks is a potentially important issue in CCS where:
  - Large overpressures may result from CO_2 injection
  - May result in seismic (felt) or aseismic rupture
  - May result in loss of inventory
- Absent and needed are data/information to constrain:
  - Seismic and aseismic reactivation 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 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

Appendix

Following

Organization Chart/ Communication Plan



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

Biannual meeting

Gantt Chart

SCHEDULE of TASKS and MILESTONES

BP1 Oct 2014 to Sept 2015 | BP2 Oct 2015 to Sept 2016 | BP3 Oct 2016 to Sept 2017

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

	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. (2016) Evolution of strength and permeability in stressed fractures with fluid-rock interactions. Pure and Applied Geophys., Vol. 173, No. 2, pp. 525-536. http://dx.doi.org/10.1007/s00024-015-1099-5

Zhong, Z., Elsworth, D., Hu, Y.J. (2015) Frictional properties of the stressed limestone fracture. Proc. ISRM Congress, Montreal, Canada. May 10-13. ISBN: 978-1-926872-25-4

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.

Fang, Y., Elsworth, D., Wang, C., Ishibashi, T., Fitts, J.P. (2016) Friction-Stability-Permeability relationships for fractures in shale. In review.

Wang, C., Elsworth, D. (2016) Influence of weakening minerals on the ensemble strength and slip stability of faults. In review.

Fang, Y., Wang, C., Elsworth, D., Ishibashi, T. (2016) Friction-permeability relationships for reservoir caprocks. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Wang, C., Elsworth, D. (2016) Numerical investigation of the effect of frictionally weak minerals on the shear strength of faults. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Ishibashi, T., Asanuma, H., Fang, Y., Wang, C., Elsworth, D. (2016) Exploring the link between permeability and strength during fracture shearing. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Bibliography - Presentations

Fang, Y., Wang, C., Elsworth, D., Ishibashi, T. (2016) Friction-permeability relationships for reservoir caprocks. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Wang, C., Elsworth, D. (2016) Numerical investigation of the effect of frictionally weak minerals on the shear strength of faults. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Ishibashi, T., Asanuma, H., Fang, Y., Wang, C., Elsworth, D. (2016) Exploring the link between permeability and strength during fracture shearing. Proc. 50th US Symposium on Rock Mechanics and Geomechanics. Houston. June 26-29.

Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Wang, C., Ishibashi, T., Niemeijer, A., Candela, T. 2016. Induced seismicity and permeability evolution in EGS reservoirs – The good, the bad and the ugly. ARMA Workshop on Microseismic Geomechanics from Laboratory to Field Scale across all Industries. June 26. [Invited]

Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Wang, C., Ishibashi, T., Niemeijer, A., Candela, T. 2016. Induced seismicity and permeability evolution in EGS reservoirs – The good, the bad and the ugly. First Annual Darcy Center Symposium. *Mastering the Complexity of Fracture Networks.* Technical University of Eindhoven, Netherlands. June 2. [Keynote]

Elsworth, D., Zhi, S., Wang, S., Liu, J. 2016. The role of gas desorption on the energetic failure of coal. Northeastern University, Shenyang, China. May 26. [Invited]

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

Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Wang, C., Ishibashi, T. 2016. Induced seismicity and permeability evolution in EGS reservoirs – The good, the bad and the ugly. Second Int. Conf. on Rock Dyn. and App., Suzhou. May 19. [Keynote]

Elsworth, D., Gan, Q., Fang, Y., Pogacnik, J., Taron, J., Izadi, G., Guglielmi, Y., Im, K.J., Wang, C., Ishibashi, T. 2016. Control of permeability and seismicity in EGS reservoirs – The good, the bad and the ugly. China University of Mining and Technology, Beijing. May 16. [Invited]

Spokas, K., Peters, C.A. (2016) Coupling Stress and Reactive Transport in Fractures: Effects of Mineralogy on the Evolution of Contacting Asperities and Fracture Permeability. XXI International Conference of Computational Methods in Water Resources. Toronto, Canada. June 20-24.

Spokas, K., Peters, C.A., Pyrak-Nolte, L.J. (2016). Modeling Geomechanical Deformation in Reactive Fractures. 26th Goldschmidt Conference. Yokohama, Japan. June 26-July 1.