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

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U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology, Innovation 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
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      - 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

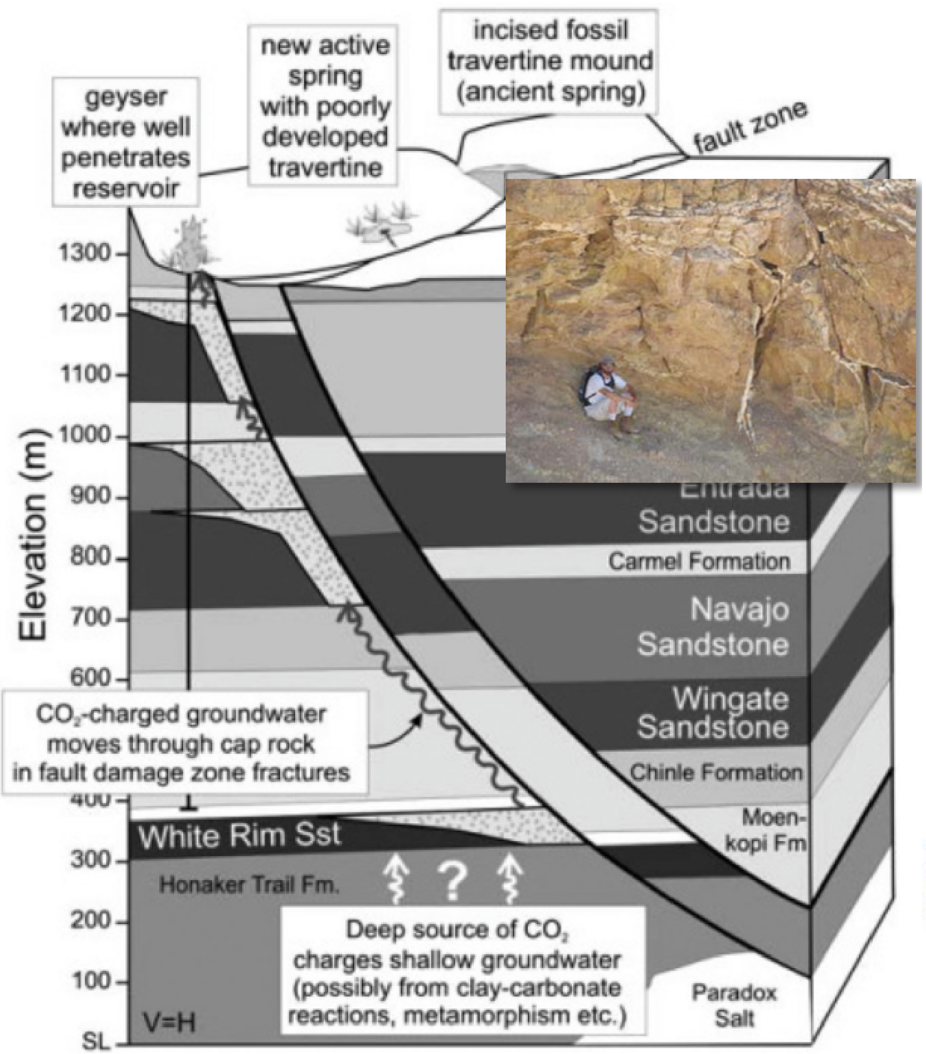
- Felt seismicity
  - Stable versus unstable slip
    - Mineralogical controls
    - Geometric (stiffness) controls
- Seal breaching
  - Evolution of permeability and capillarity characteristics

Methodology

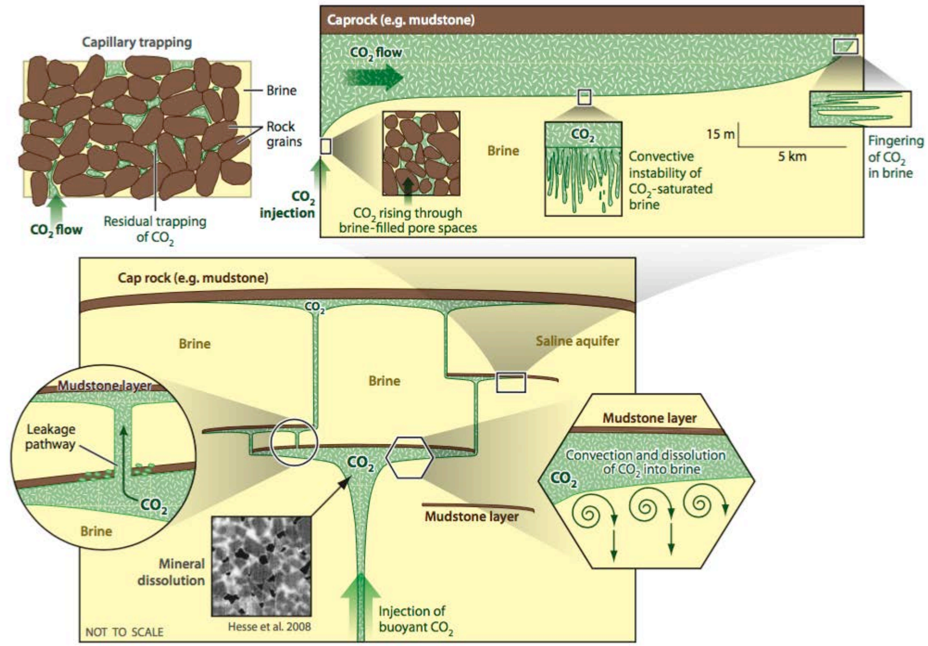
- **Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)**
  - Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)
  - Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)
  - Conduct Baseline Characterization of Natural and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

Fault Zones as Seals and Pathways

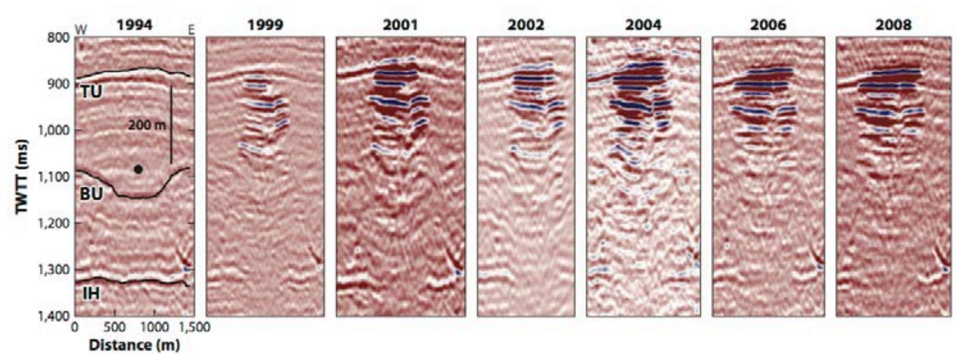
Little Grand Wash Fault, UT



[Patil et al., 2017; after Vrolijk et al., 2005]

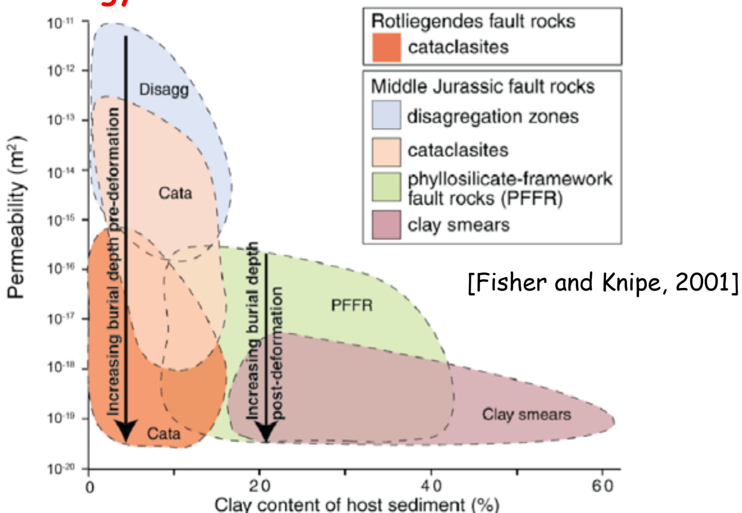


[Huppert and Neufeld, Ann. Rev. Fluid Mechs., 2014]



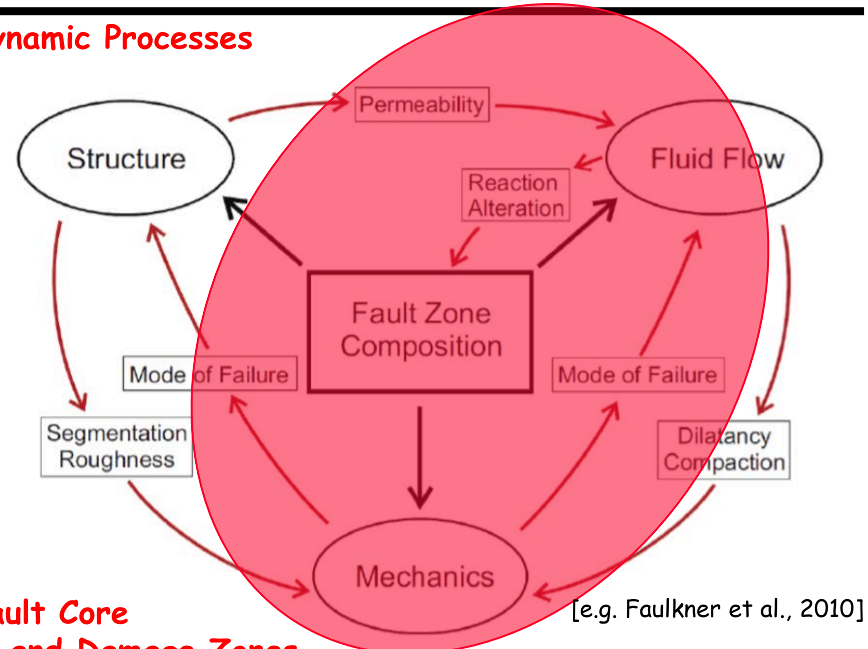
Controls on Permeability Structure

Mineralogy



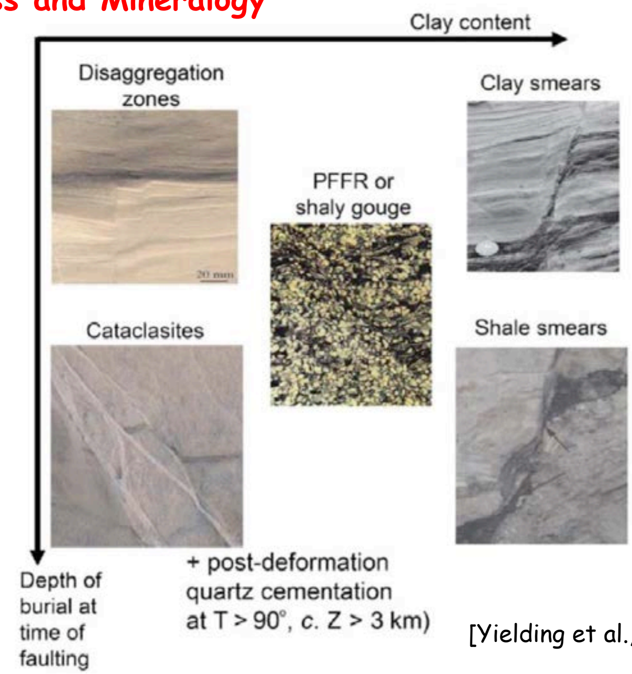
[Fisher and Knipe, 2001]

Dynamic Processes



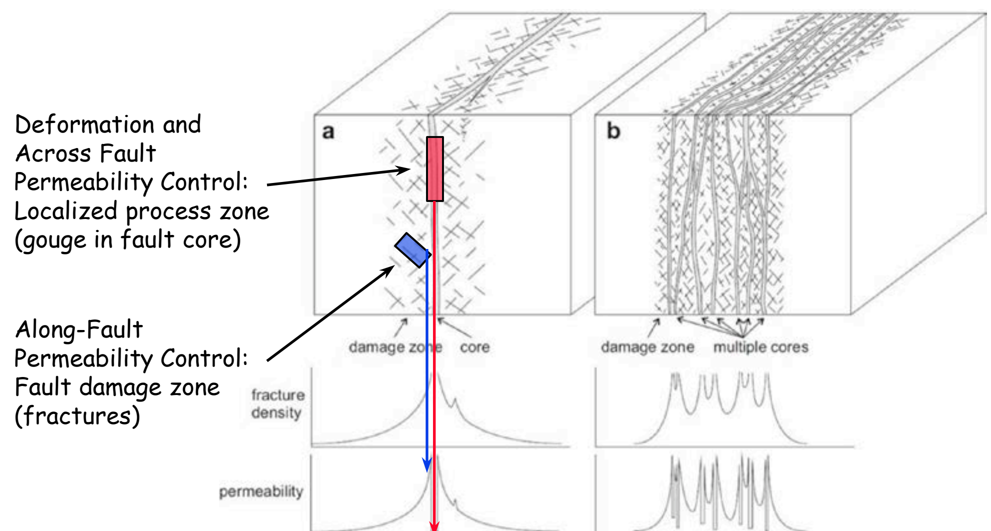
[e.g. Faulkner et al., 2010]

Stress and Mineralogy



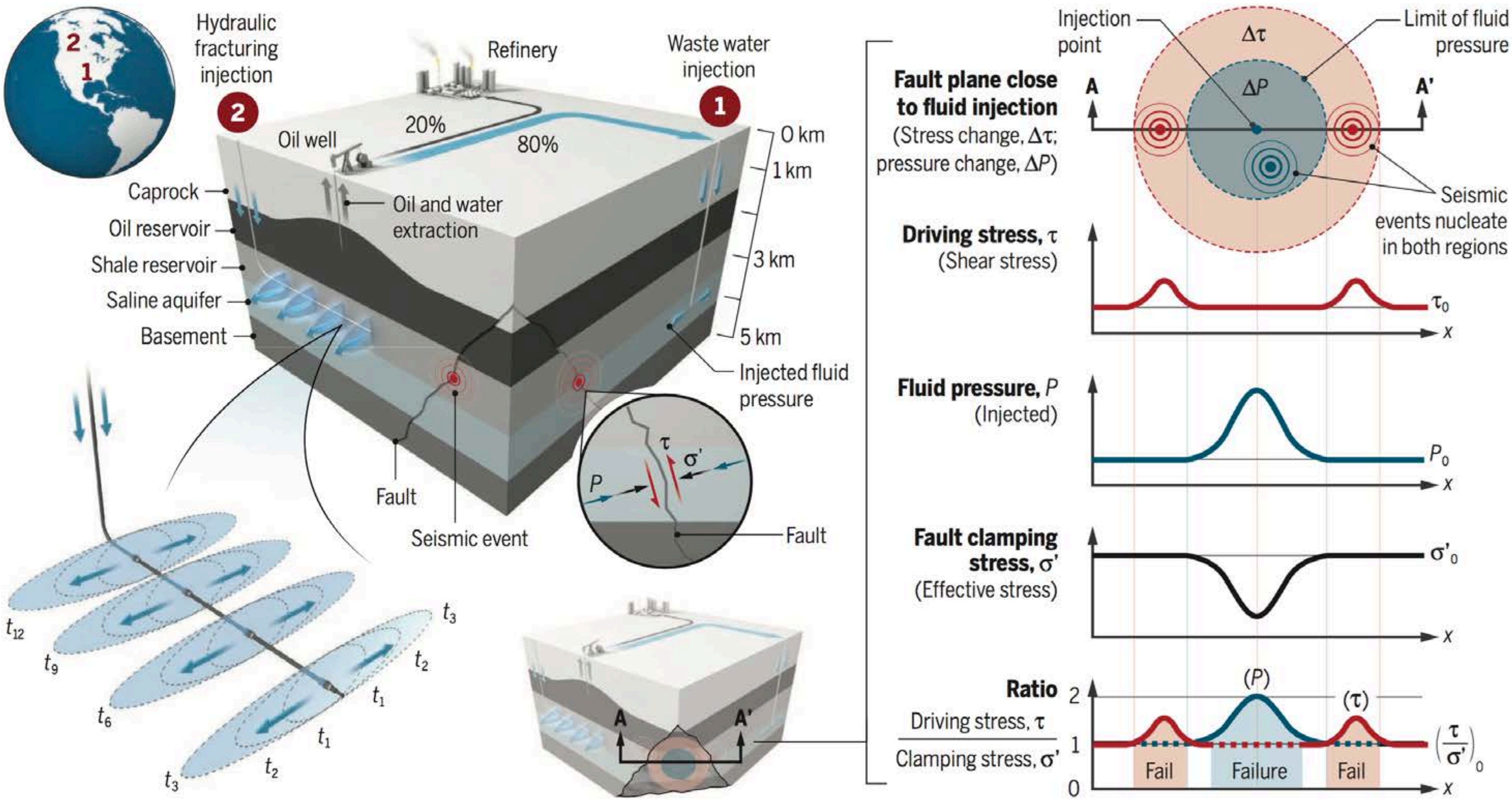
[Yielding et al., 2010]

Fault Core and Damage Zones



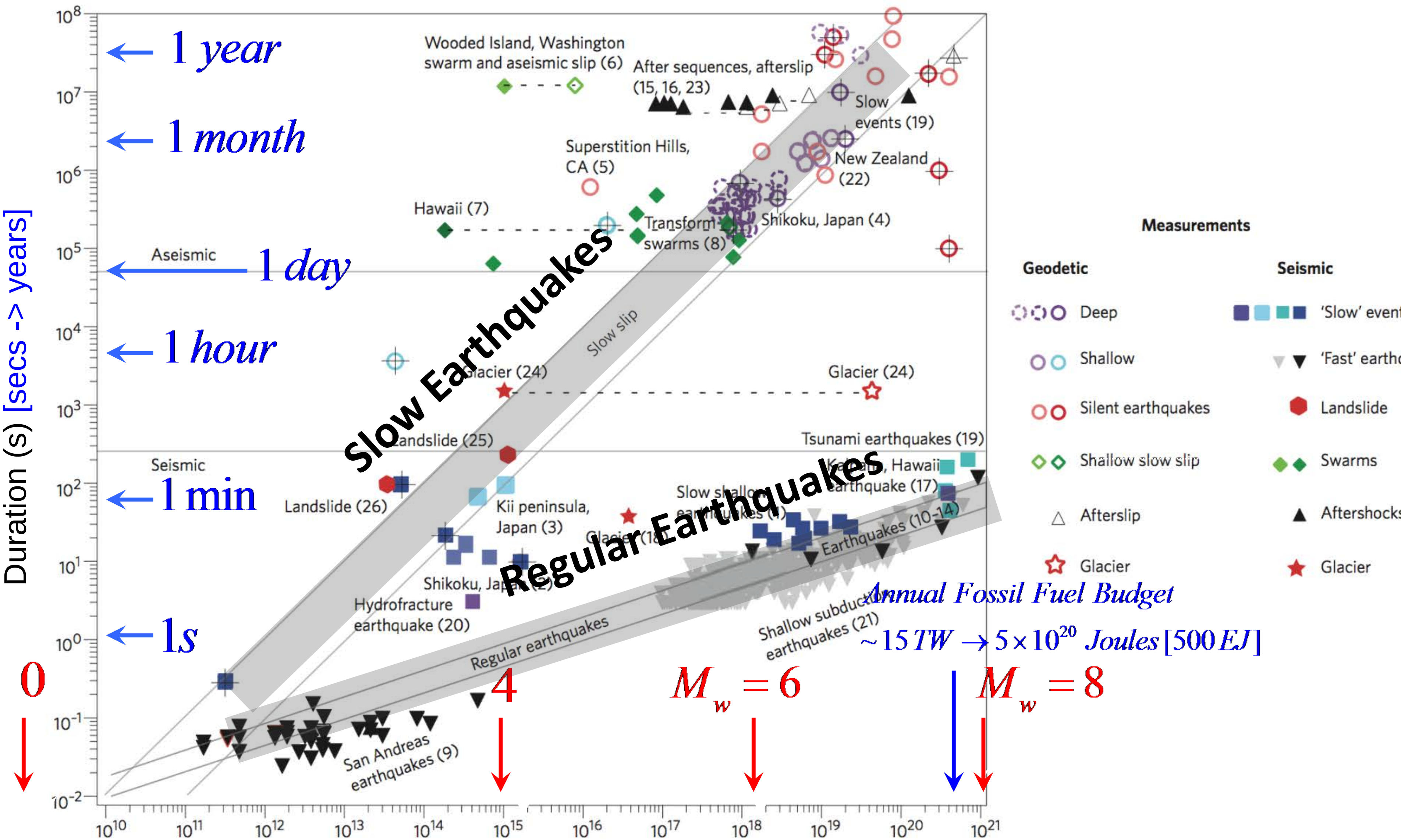
[IEAGHG, "Fault Permeability," 2016; after Faulkner et al., 2010]

Induced Seismicity



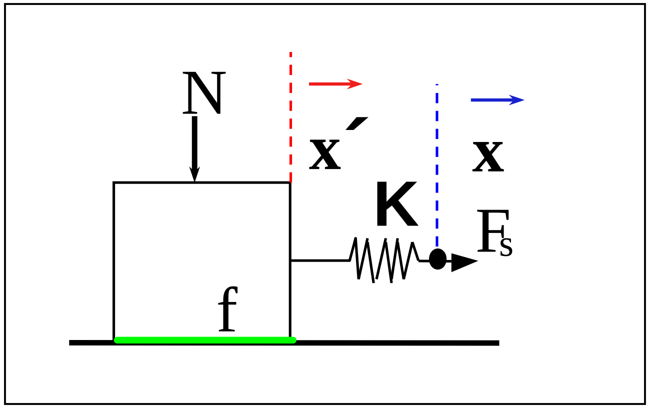
[Elsworth et al., Science, 2016]

Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior



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

Seismic – Aseismic Transition
Full Spectrum of Slip Behaviors



$$K_c = -\frac{(\sigma_n - p)(a-b)}{D_c} > \frac{G}{l} = K$$

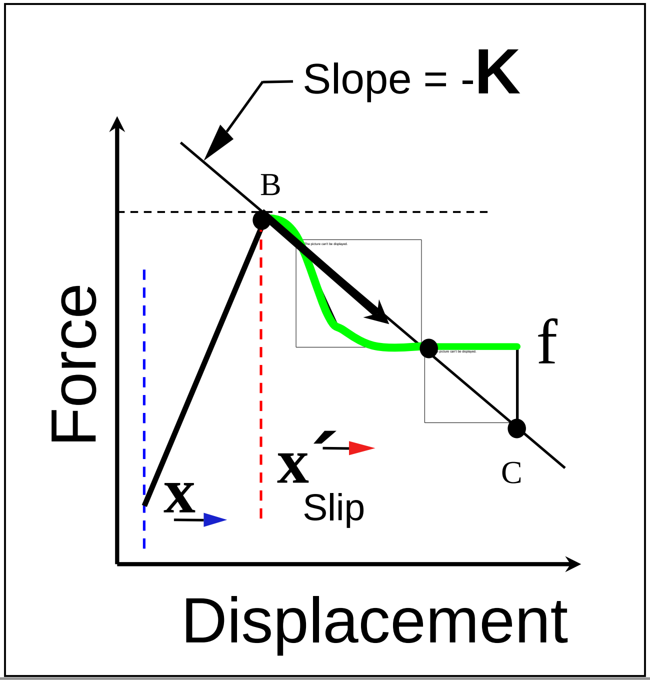
Promote Aseismic Response: $K_c < K$

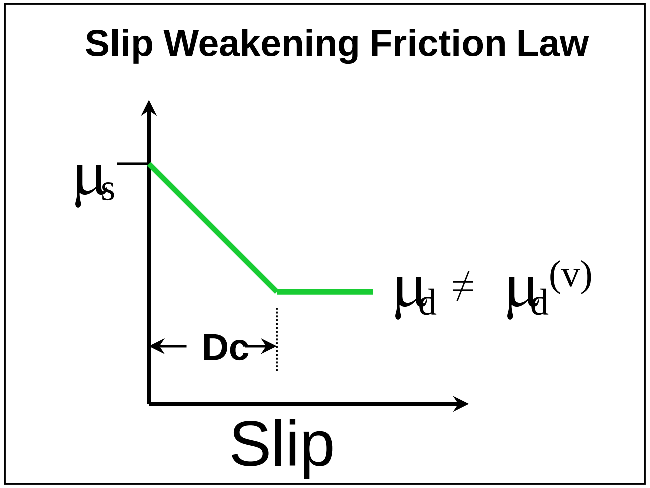
Otherwise Seismic Slip if: $K_c > K$

Increase: $K_c ; (\sigma_n - p) ; (a-b) ; l$

Decrease: $D_c ; G$

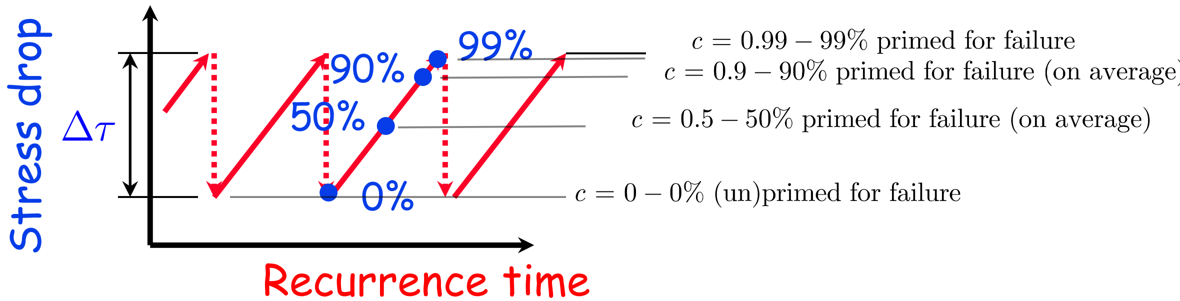
Recurrence Requires: *Healing*





[Adapted from C.J. Marone, Pers. Comm., 2017]

Maximum Event Magnitude – Equivalent Porous Medium

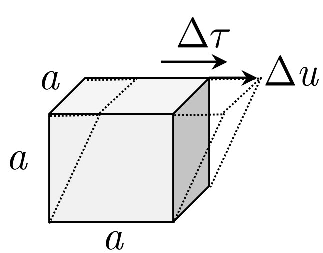


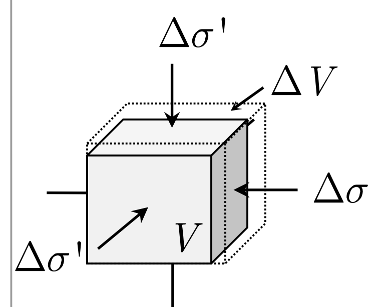
Moment Magnitude (Deviatoric)

$$\boxed{\Delta\tau \cdot (1-c) = \mu \cdot \Delta\sigma'}$$

Stress-Strain (Spherical)

$$\left.\begin{aligned} M &= AG\Delta u \\ M &= a^3 G \frac{\Delta u}{a} \\ M &= VG\gamma \\ M &= V\Delta\tau \\ \Delta\tau &= \frac{M}{V} \end{aligned}\right]$$





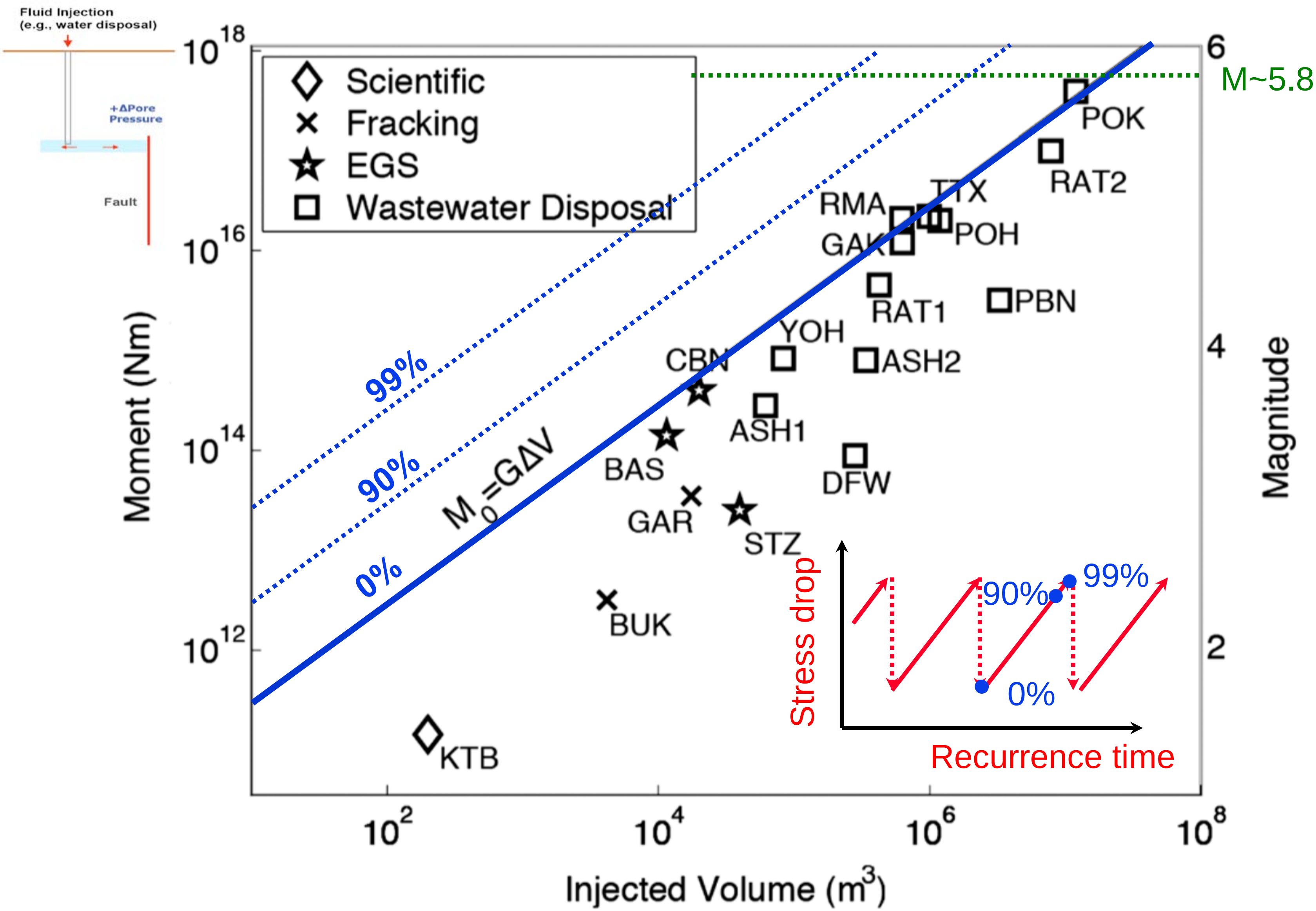
$$\left[\begin{aligned} \Delta\sigma' &= \Delta\sigma - \alpha\Delta p \; (\Delta\sigma = 0) \\ \alpha\Delta p &= K\frac{\Delta V}{V} \\ \alpha\Delta p &= \frac{2}{3}\frac{(1+\nu)}{(1-2\nu)} G \frac{\Delta V}{V} \end{aligned}\right.$$

$$M = \frac{2}{3}\frac{(1+\nu)}{(1-2\nu)}\frac{1}{(1-c)}\mu G\Delta V$$

$$\boxed{M = \frac{1}{(1-c)} G\Delta V \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}}$$

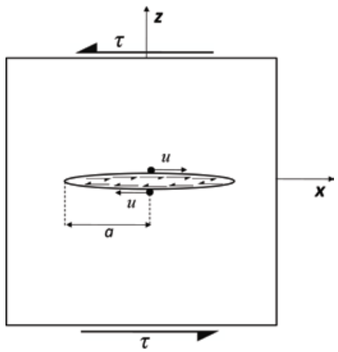
Modified from [McGarr, JGR, 1976 & 2014]

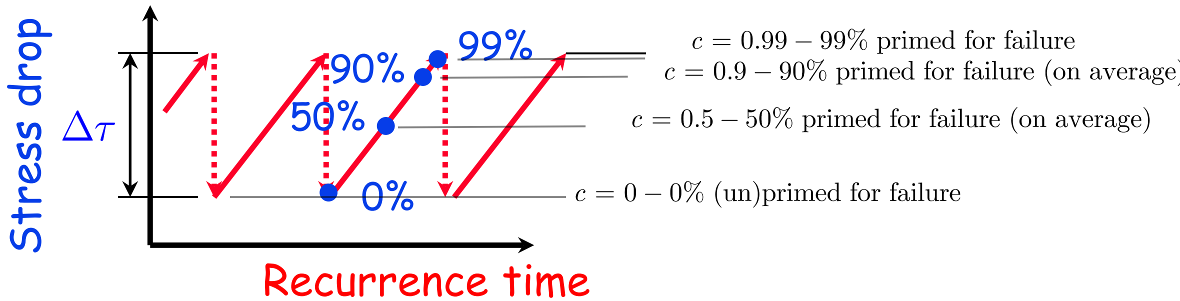
Maximum Anticipated Moment Magnitude – M or M_dot? M_{Gross} or M_{Net}? Triggered –vs- Induced?



After [McGarr, JGR, 2014]

Maximum Event Magnitude – Penny-Shaped Crack





Moment Magnitude (Deviatoric)

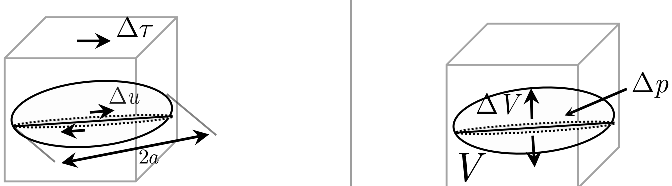
$$M = AG\Delta\bar{u}$$

$$\Delta\bar{u} = \frac{8(1-\nu)}{3(2-\nu)}\frac{\Delta\tau a}{G\pi}$$

$$M = AG\frac{8(1-\nu)}{3(2-\nu)}\frac{\Delta\tau a}{G\pi}$$

$$\Delta\tau = \frac{M\pi}{Aa}\frac{3(2-\nu)}{8(1-\nu)}$$

$$\boxed{\Delta\tau\cdot(1-c) = \mu\cdot\Delta p}$$



Stress-Strain (Spherical)

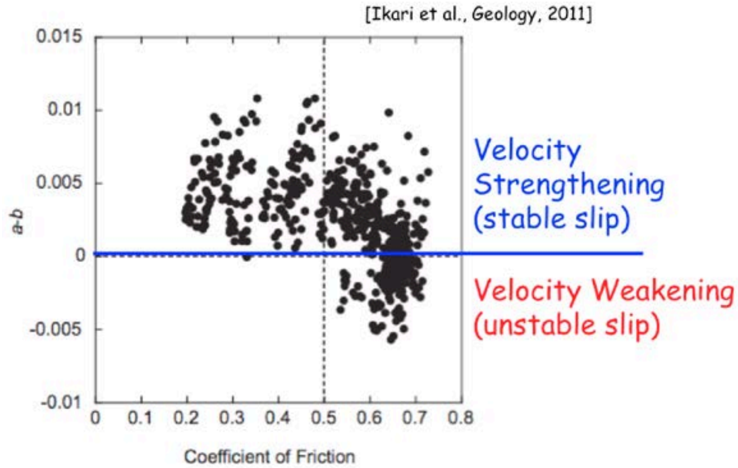
$$\frac{\Delta V}{A} = \frac{16(1-\nu^2)}{3\pi}\frac{\Delta p\, a}{E}$$

$$\Delta p = \frac{\Delta V}{Aa}\frac{3\pi}{16}\frac{E}{(1-\nu^2)}$$

$$M = \frac{1}{(2-\nu)}\frac{1}{(1-c)}\mu G\Delta V$$

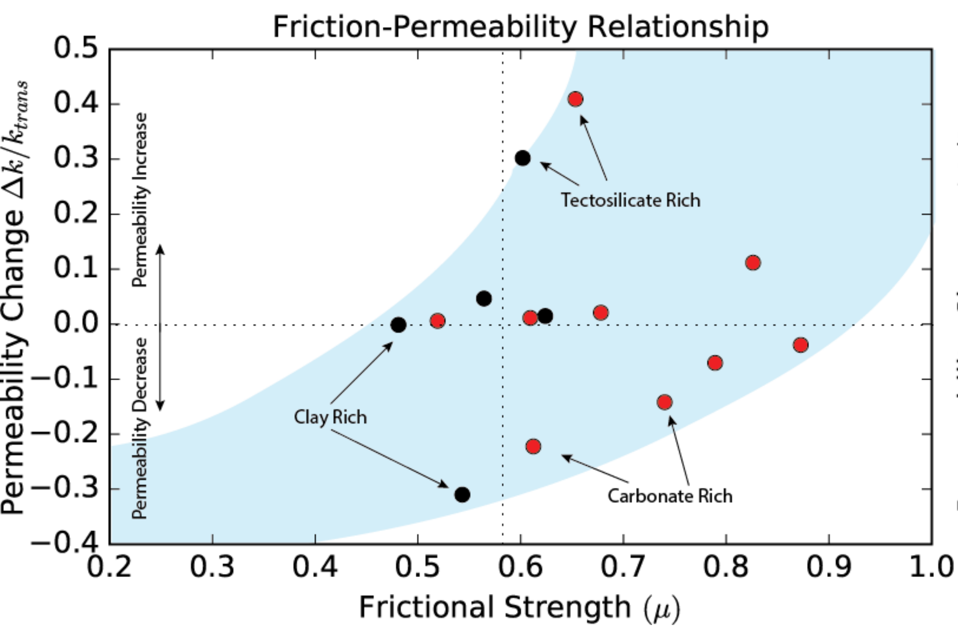
$$\boxed{M = \frac{1}{(1-c)}\frac{24}{70}G\Delta V \sim \frac{1}{(1-c)}\frac{1}{3}G\Delta V \left\{\begin{matrix}\nu = 0.25\\ \mu = 0.6\end{matrix}\right\}}$$

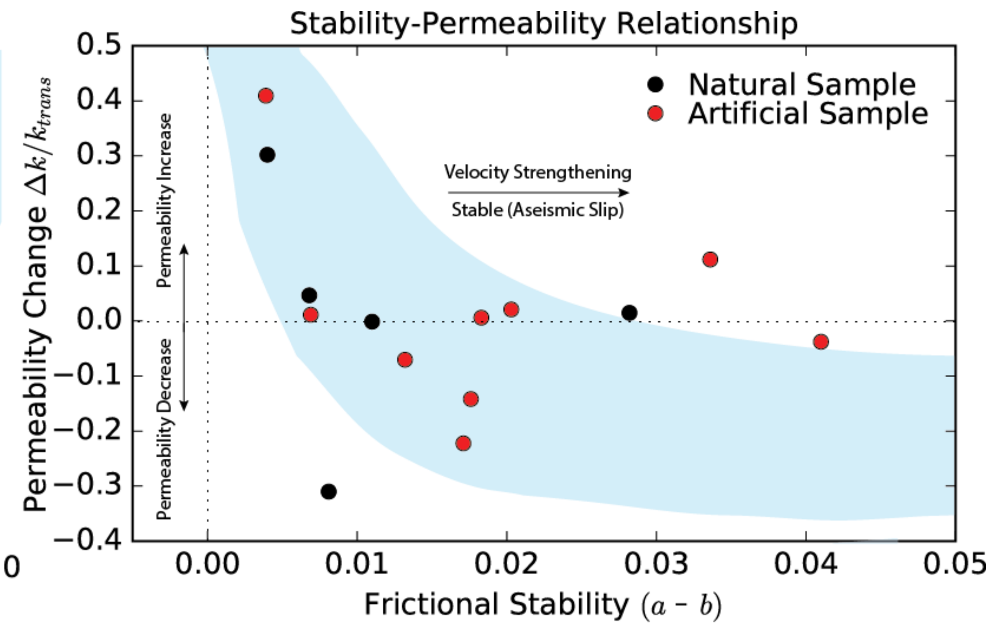
Nascent Friction-Stability-Permeability Relationships



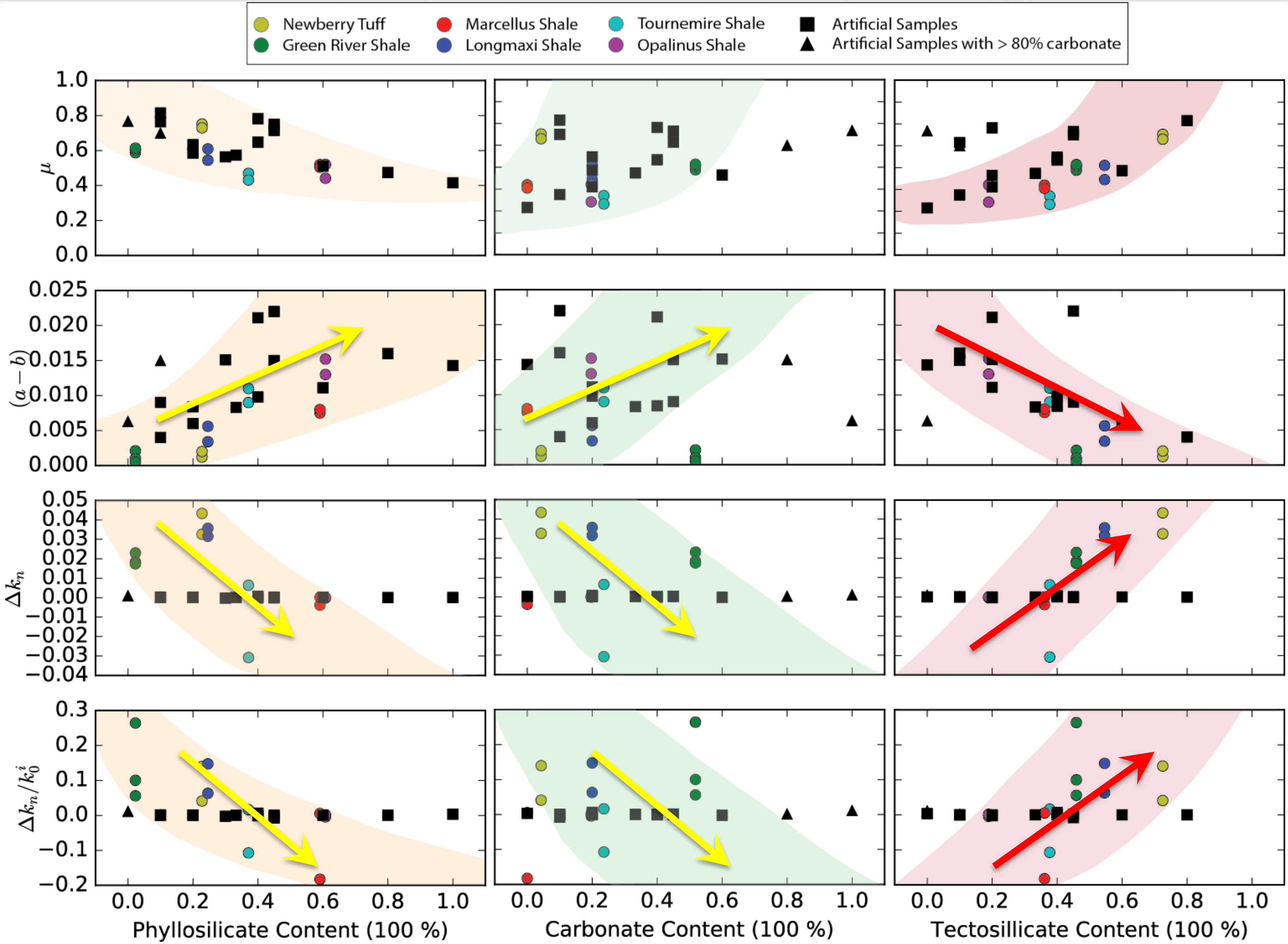
Observations

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

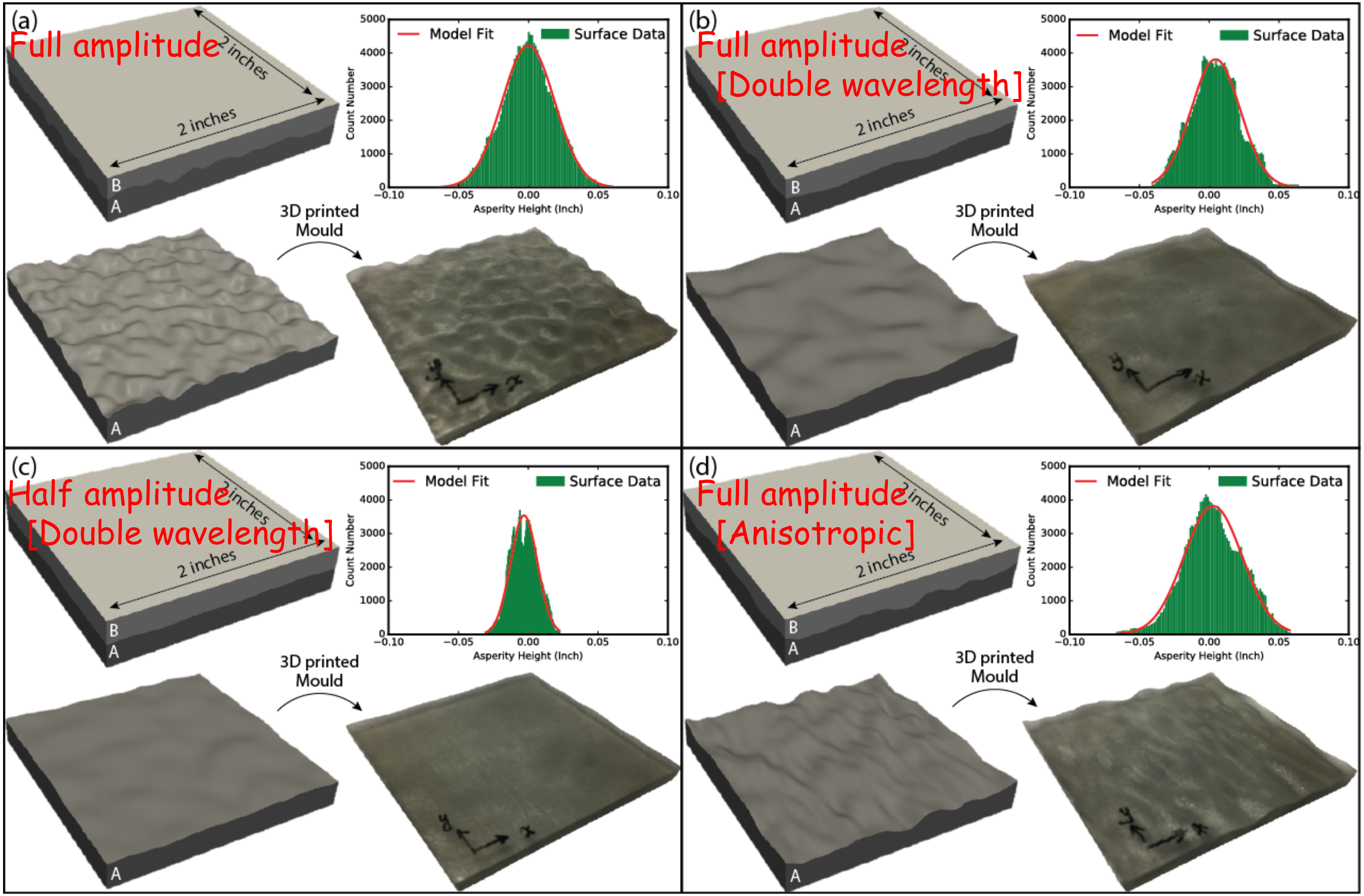




Seismicity-Permeability Linkages – Natural Samples



❖ Role of Roughness - Fabricated Fracture Surfaces

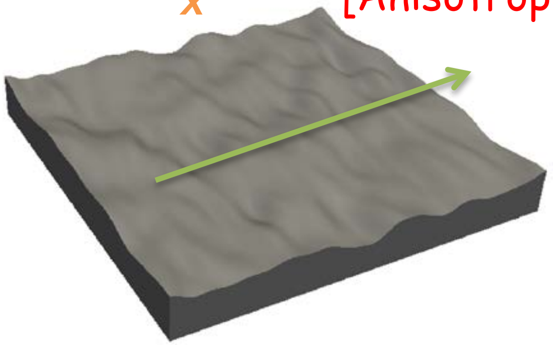


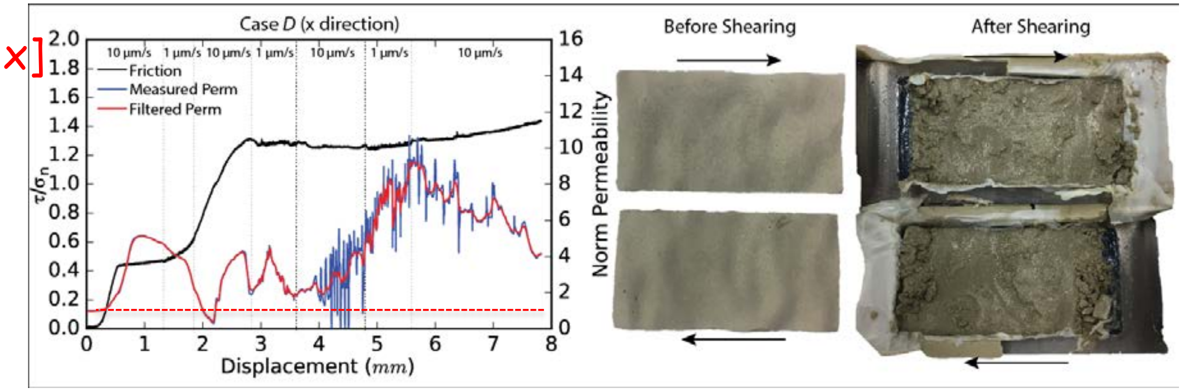
- **3D printed fracture casts with different geometric features**

❖ Net Friction and Permeability Evolution

Case D_x

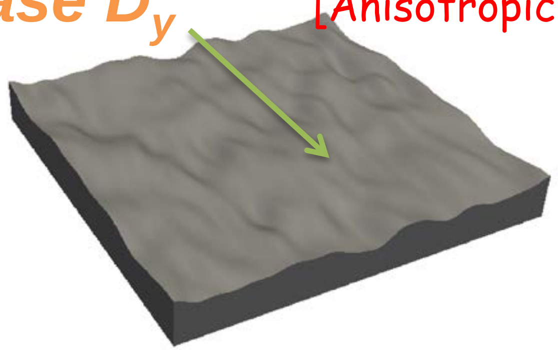
Full amplitude [Anisotropic – x]

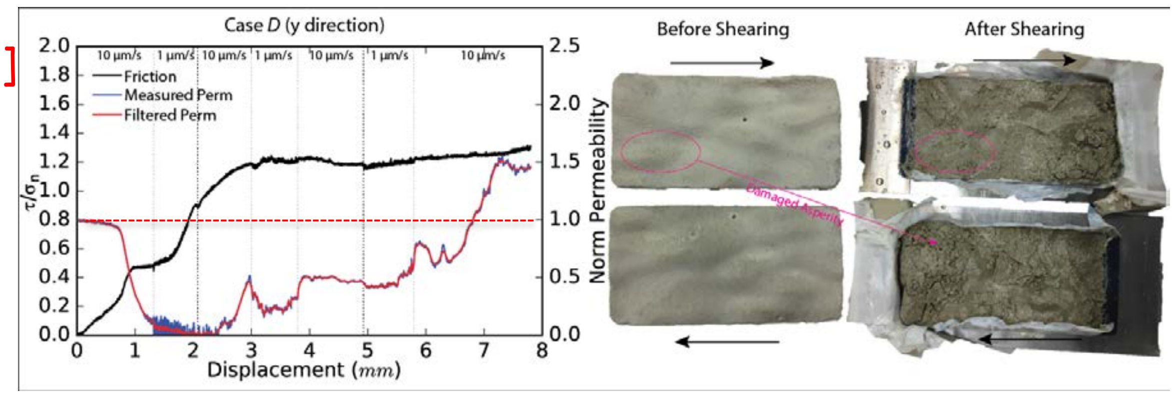




Case D_y

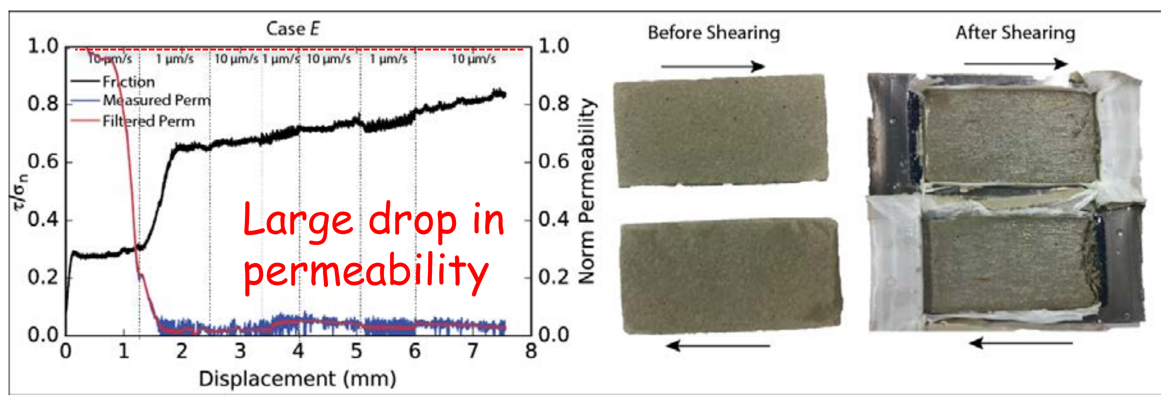
Full amplitude [Anisotropic –y]





Case E

Smooth

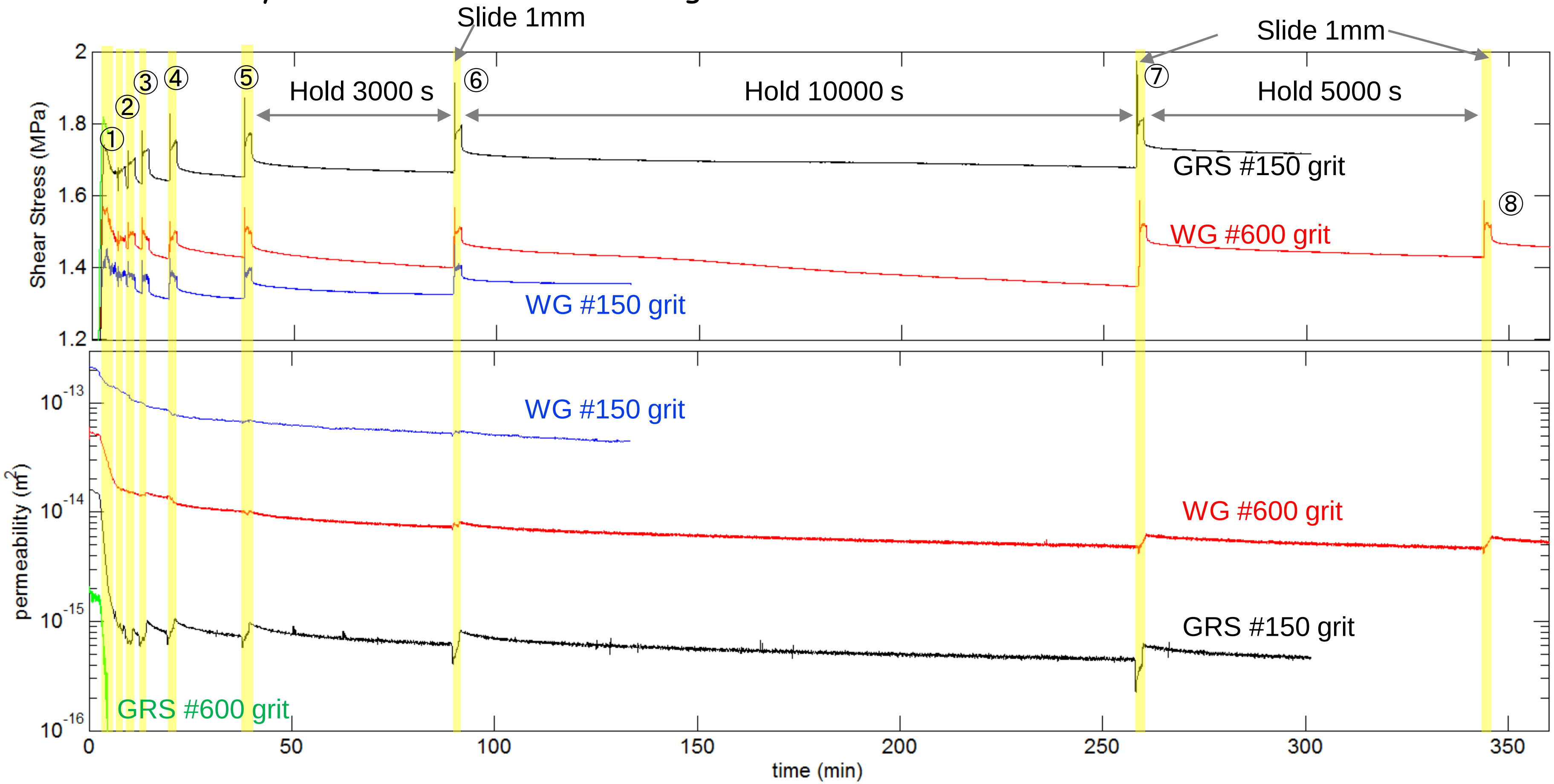


Healing – Necessary Component of the Seismic Cycle

Shear Stress and Permeability Evolution

- Increasing shear stress peak is observed with increasing hold time (Frictional Healing)
- Permeability declines overall with temporal response to shear events
- Permeability decline is fast at initial stage then become slower

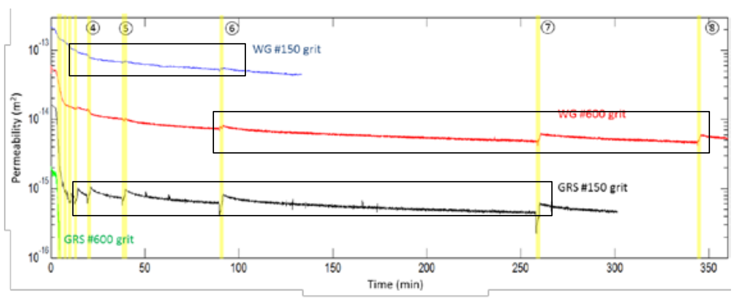
Experimental Notes
- Permeability of Green River shale #600 grit became unresolvable after initial shear
- Westerly granite #150 grit stopped at ~150 min due to limited pump capacity
- 8th shear applied to Westerly granite #600 grit after 5000 seconds

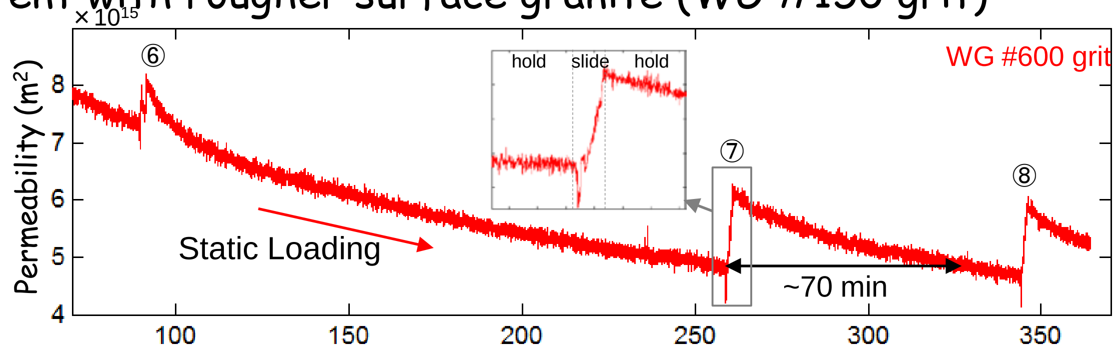


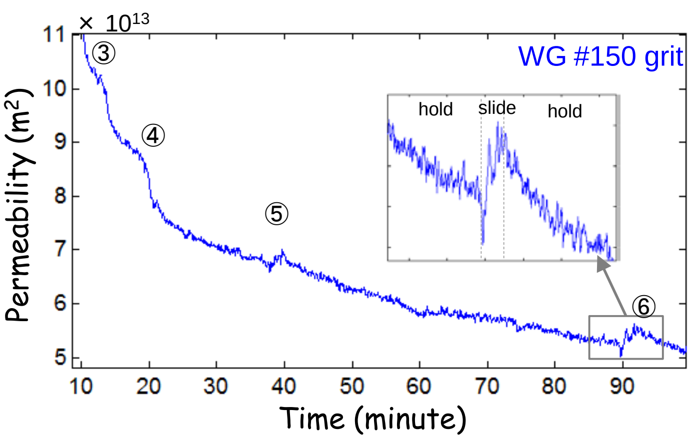
Shear Permeability Enhancement

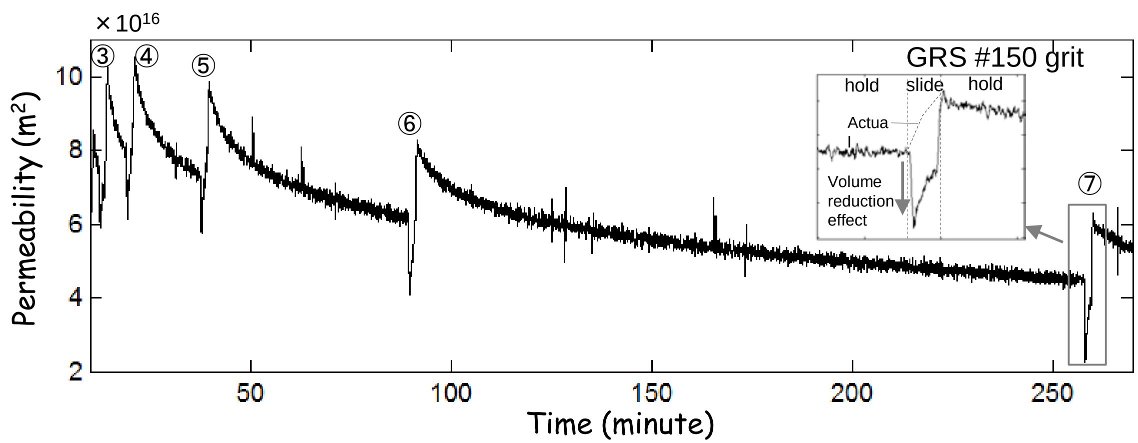
Shear Induced Permeability Enhancement

- Later stage shear slip + Incremented duration of prior slip → Significant permeability enhancement
- Permeability continuously decreases during hold (Pressure solution?)
- Prior slip permeability recovery took 70 minute after slip ⑦, WG #600 grit case
- Permeability increase appears to be linear to slip distance
- The enhancement is least apparent with rougher surface granite (WG #150 grit)





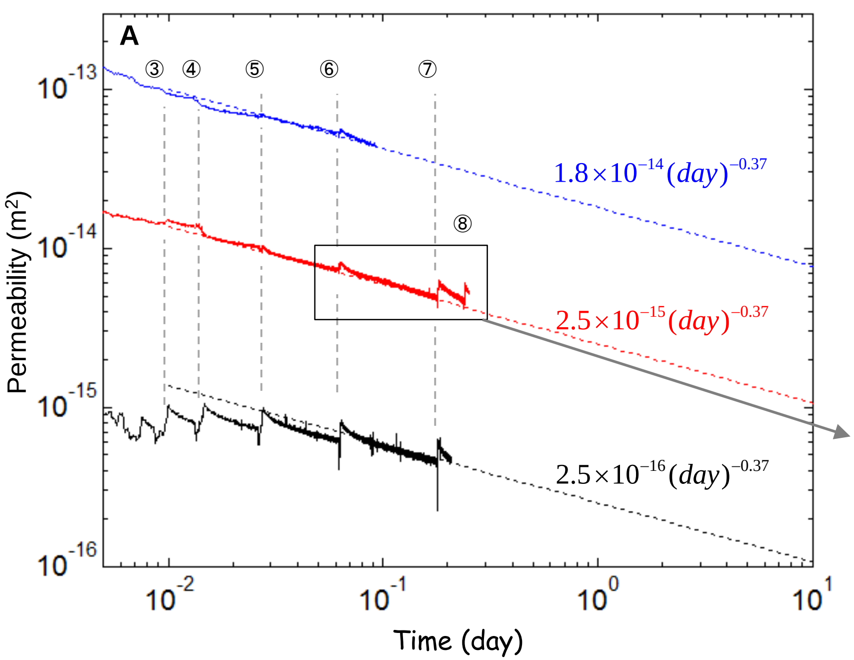


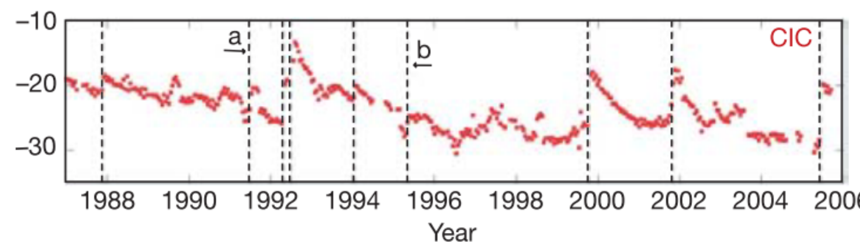


Permeability Healing (Sealing) Law

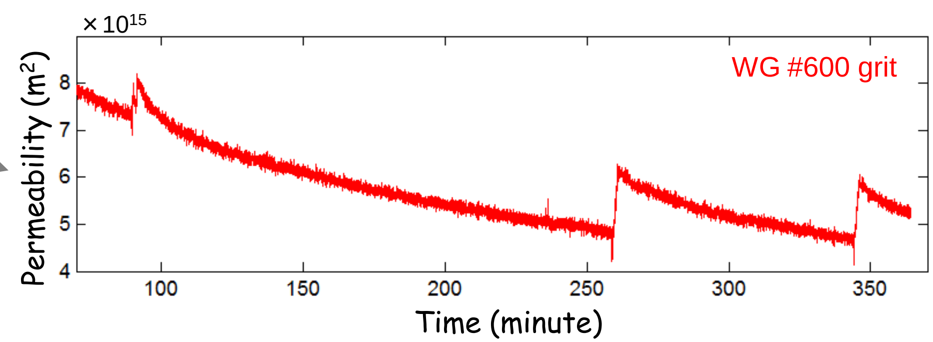
Pressure solution

- Permeability reduction due to pressure solution in all cases seems to follow power law decay $k = k_0 t^{-p}$ with power *p* =-0.37
- The enhancement can be significant after extremely long (natural scale) holds
- Can this be applied to natural hydraulic systems?





Permeability change and earthquake catalog (M_L>3) in southern California [Elkhoury et. al., 2006]



Shear Permeability Enhancement

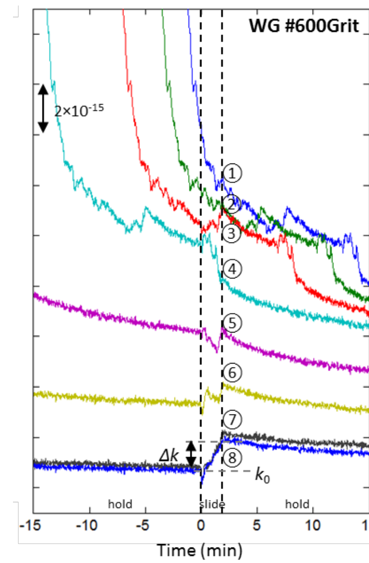
Magnitude of Permeability Enhancement

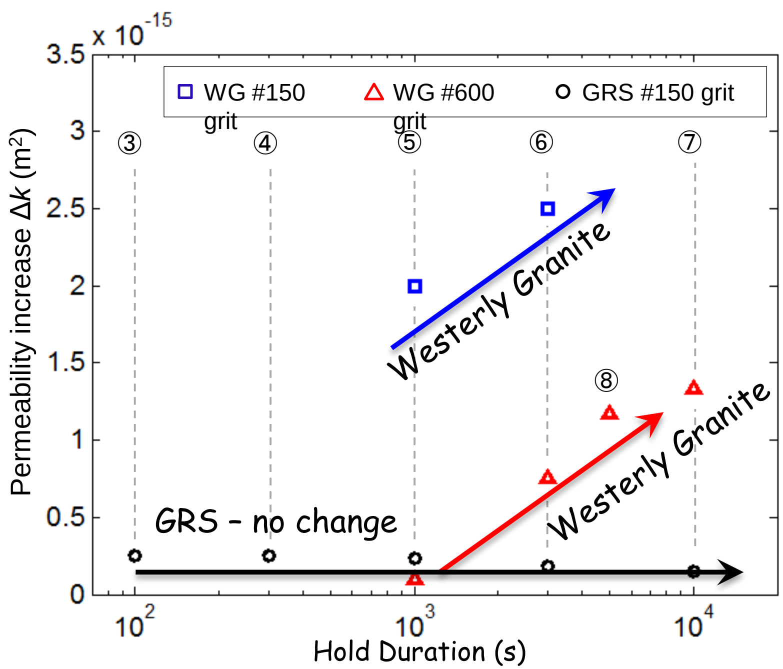
Absolute perm increase: rougher granite > smoother granite > shale

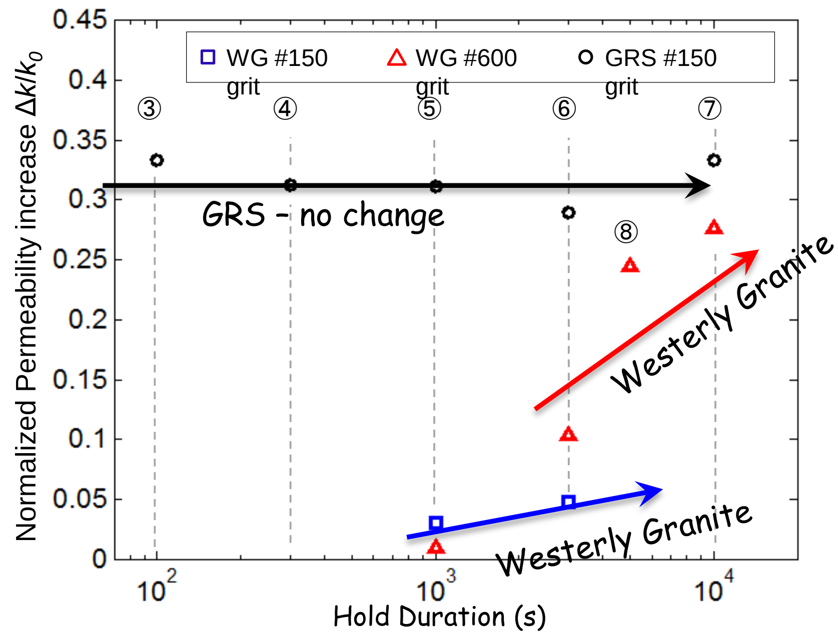
Normalized perm increase: shale > smoother granite > rougher granite

Shear permeability increase with duration of prior hold time for Westerly granites

Shear permeability slightly decreases with prior hold time for Green River shale

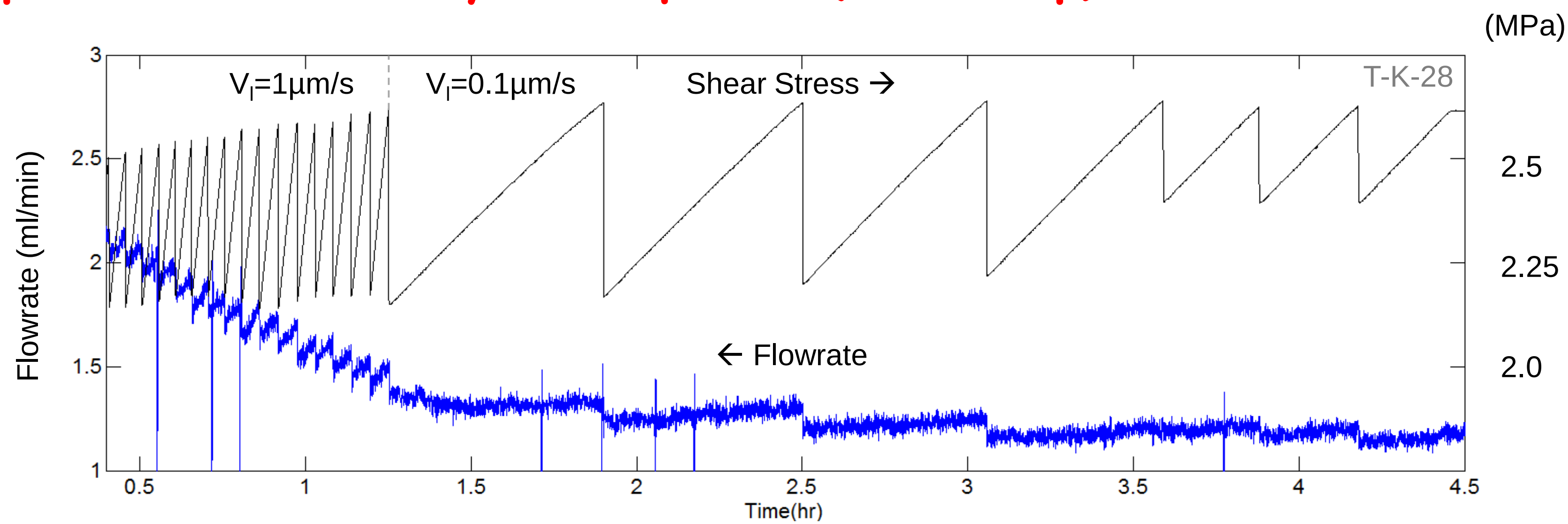


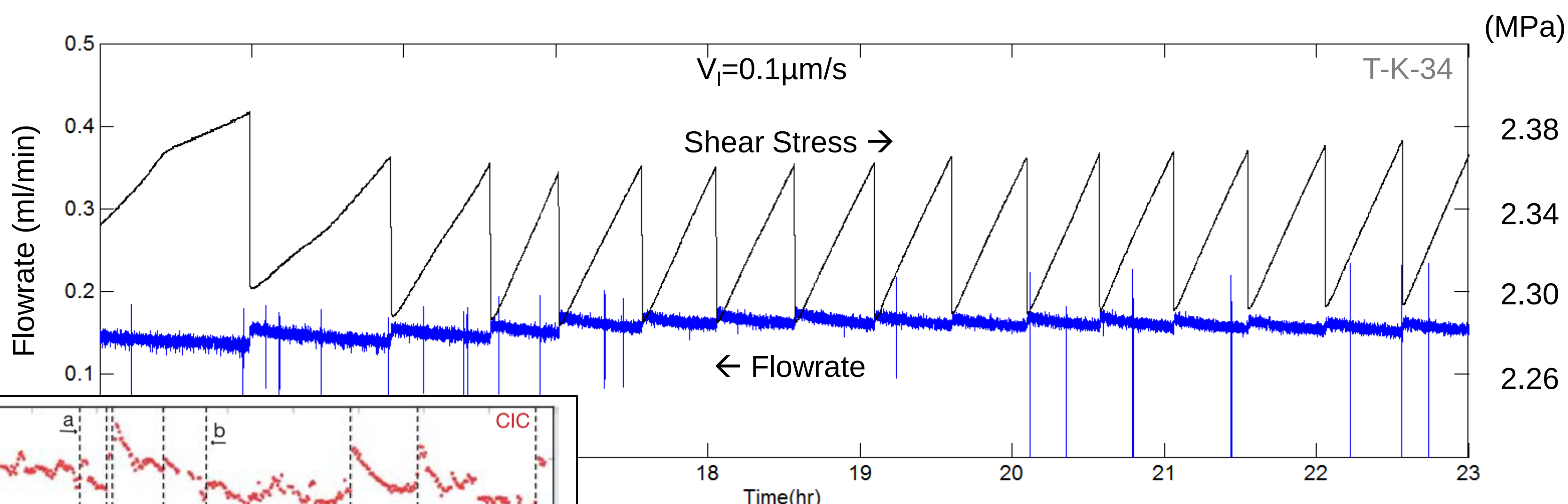


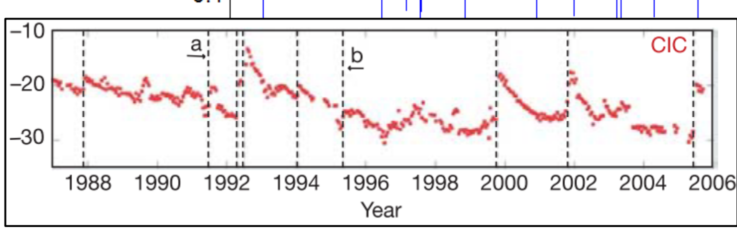


Stick-Slip Response

Response to Laboratory Earthquakes (Stick Slip)







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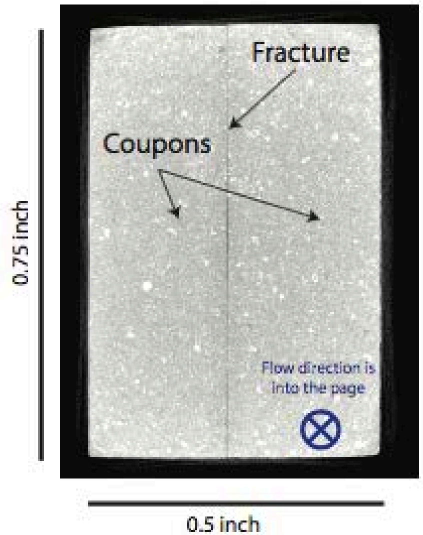
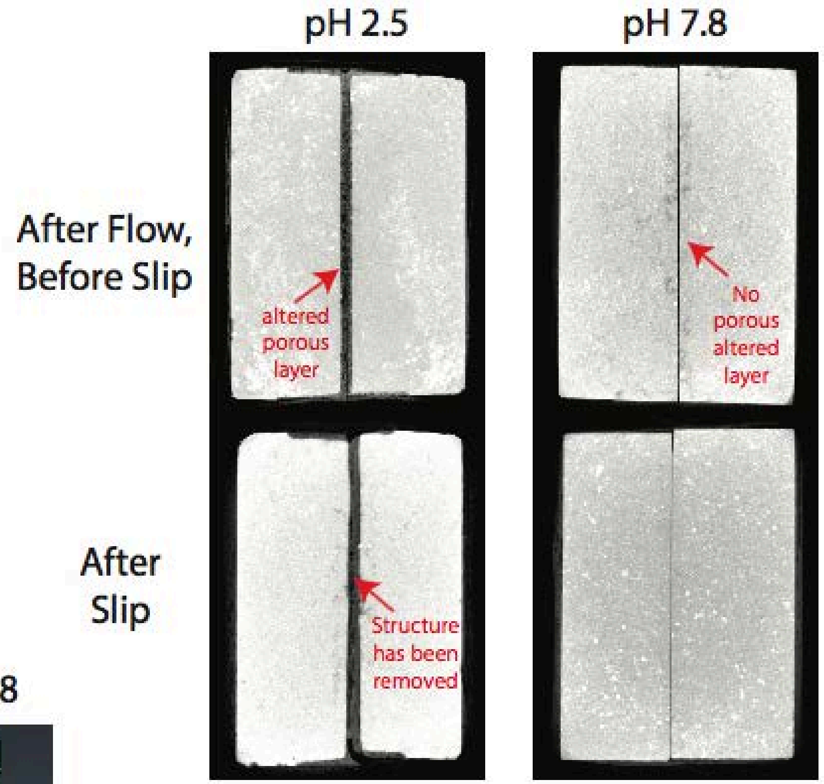
Frictional-Stability-Permeability and Reaction

Experiments:

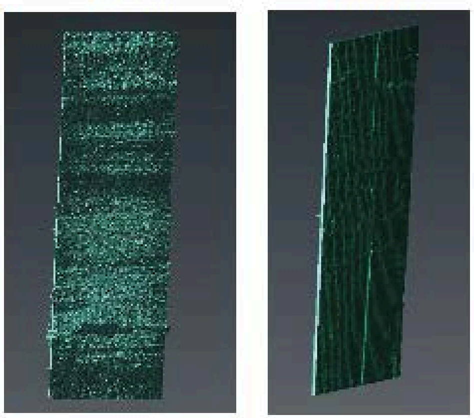
- Eagle Ford Shale
- Two fluids:
  - pH 2.5
  - pH 7.8
- xCT Imaging before and after flow

Fracture Cross-Section
Before Flow





pH 2.5 pH 7.8

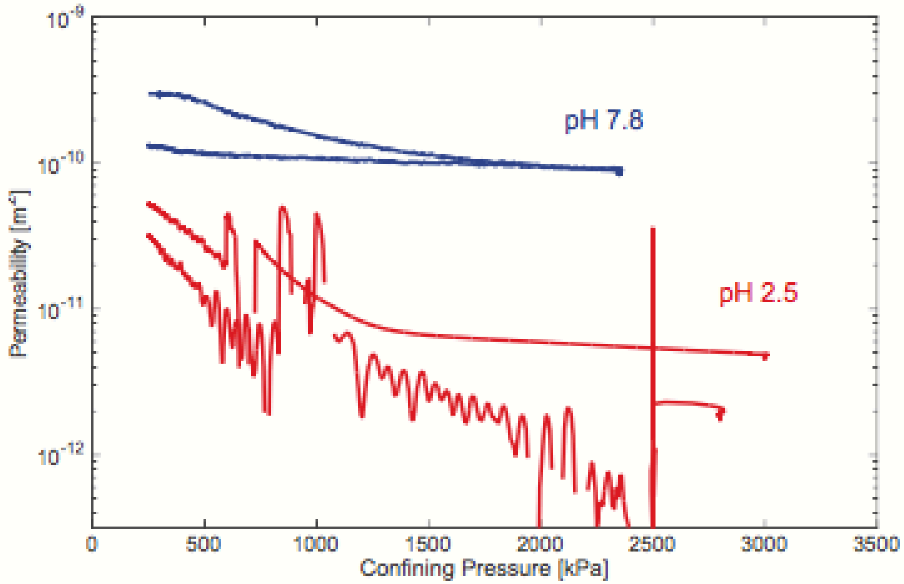


a) Sample void space segmentation. Sample exposed to pH 2.5 brine shows increased porosity located across calcite-rich layers.

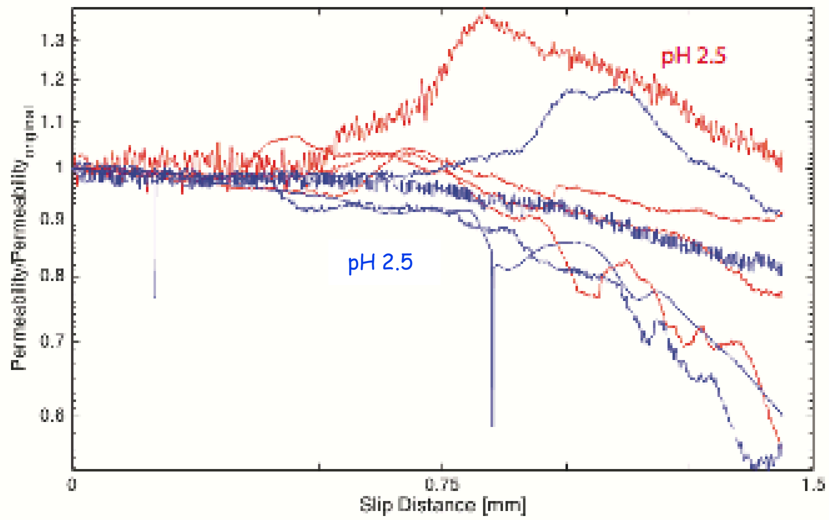
b) Sample developed an altered layer halfway up the fracture. Image shows contrast between compacted layer and smooth unaltered zone after slip.

Frictional-Stability-Permeability and Reaction

1. Permeability change during compression of fracture coupons.
   - From 250 kPa to 2500-3000 kPa confining pressure.
   - Compression of porous altered layer leads to lower permeability, likely to due compaction/creation of gauge

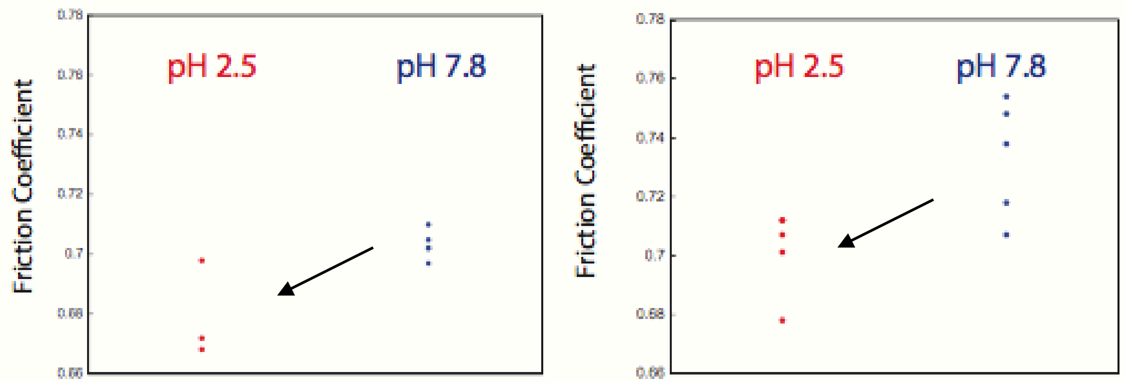


2. Permeability evolution during first 1.5mm of slip.
   - Permeability does not evolve systematically, likely controlled by unique sample geometries.
   - Maximum permeability increase observed for sample with altered layer and vice versa.



Frictional-Stability-Permeability and Reaction

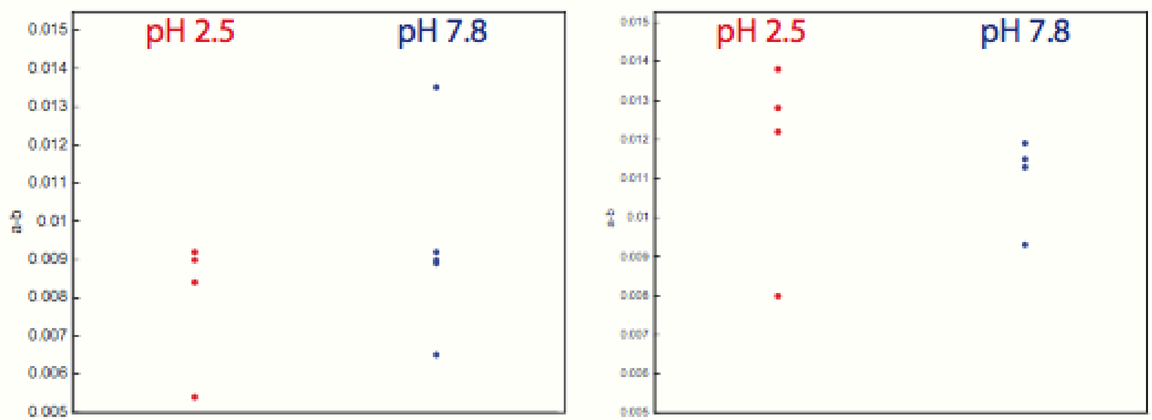
Friction Before Velocity Step



- Results suggest samples exposed to a pH 2.5 brine that formed an altered layer have a lower coefficient of friction relative to samples exposed to a pH 7.8 brine. We hypothesize this is due to the formation of a gouge layer due to the compaction of the altered layer.

Rate-State Friction: $u=u_i+(a-b)\ln(V/V_i)$ (Dieterich, 1981)

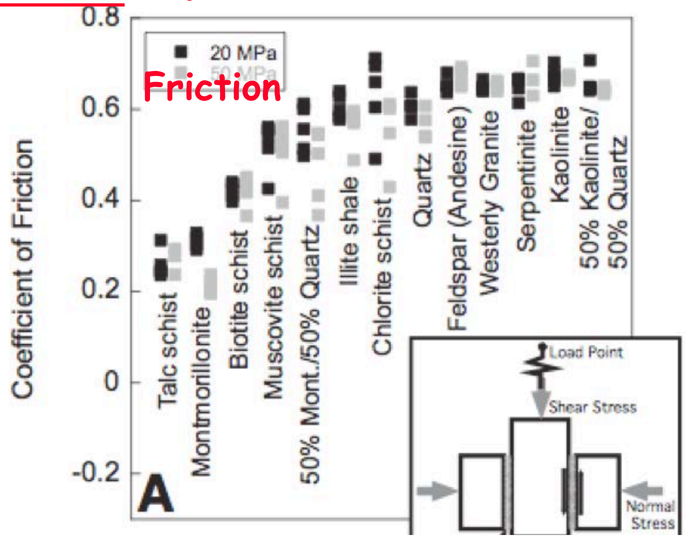
Rate State Friction Behavior

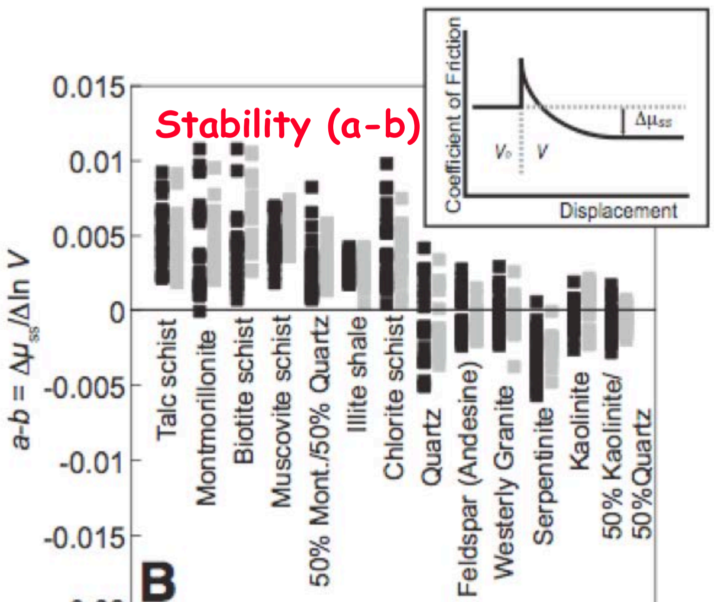


- Results suggest no clear trend for changes in rate-state friction due to the formation of an altered layer/gouge. This may be due to apparatus resistance influence or unique sample geometries.

Stability-Permeability Relations in Composites/Mixtures

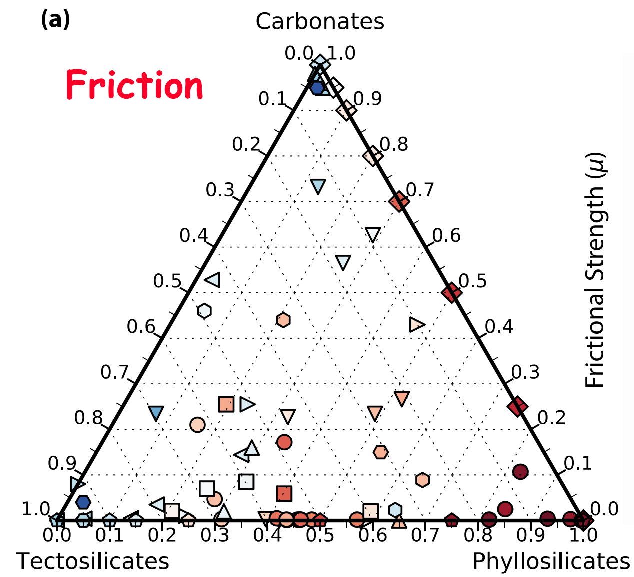
Mono-mineralic





[Ikari et al., Geology, 2011]

Multi-mineralic



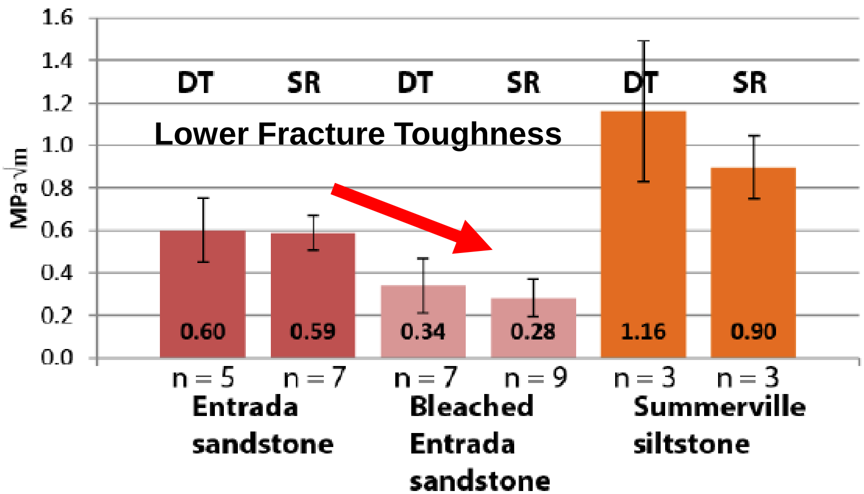
(b)

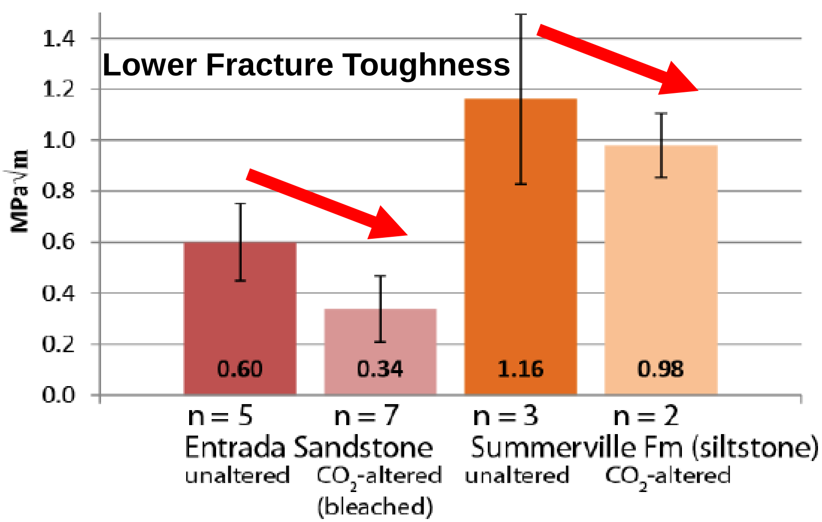
Stability (a-b)

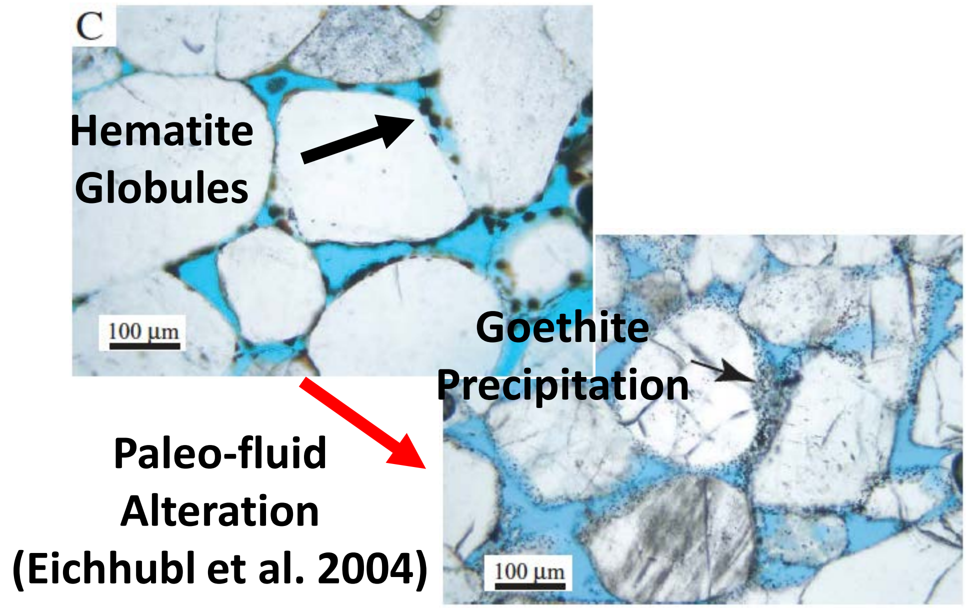
Frictional Stability (a-b)

Introduction & Motivation

CO_2 bleached sand stone and silt stone showed lower fracture toughness
(Major et al. 2014)





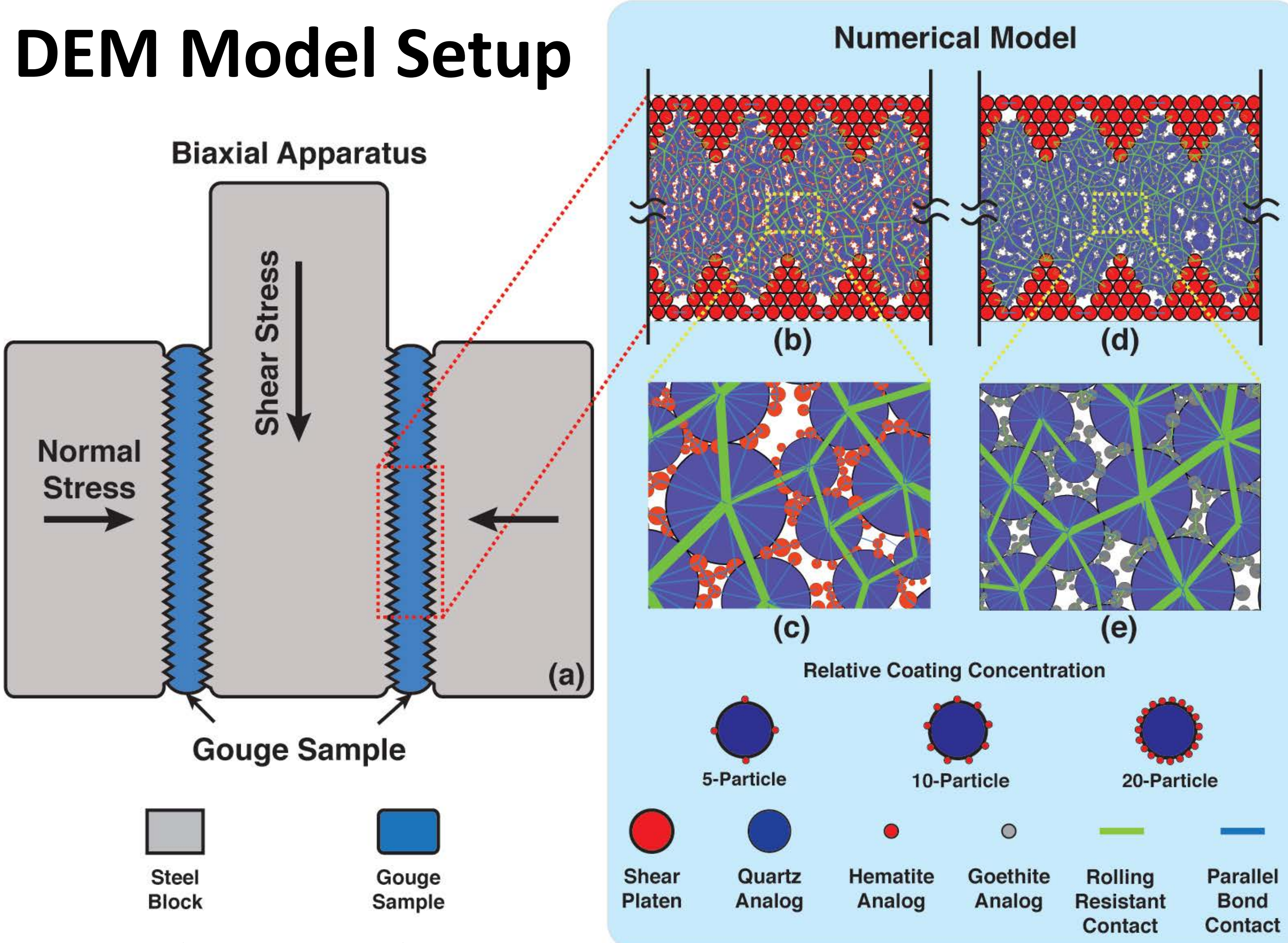


Mineralogy Difference

Unaltered Entrada Sand Stone: quartz rich, minor feldspar and calcite, with hematite coating.

Altered Entrada Sand Stone: hematite coating is dissolved, replaced by goethite, no significant change in quartz, feldspar, and calcite.
(Major et al. 2014)

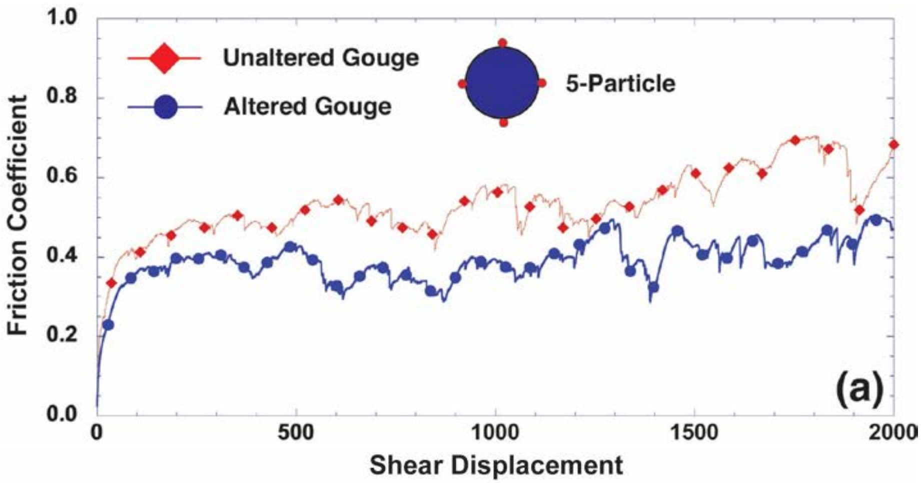
DEM Model Setup

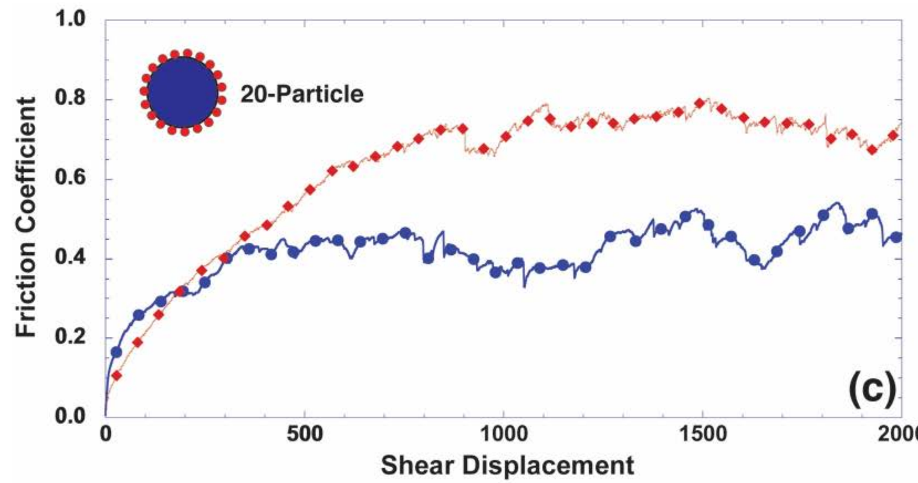


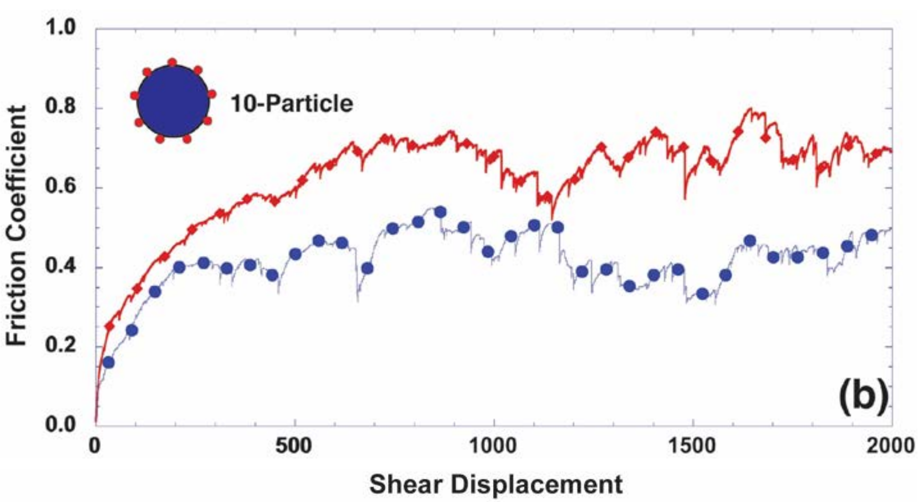
(Marone, 1999)

Shear Strength -- Unaltered vs Altered

Evolution of friction at 10 MPa normal stress [other normal stresses (5, 15 MPa) show similar trend].

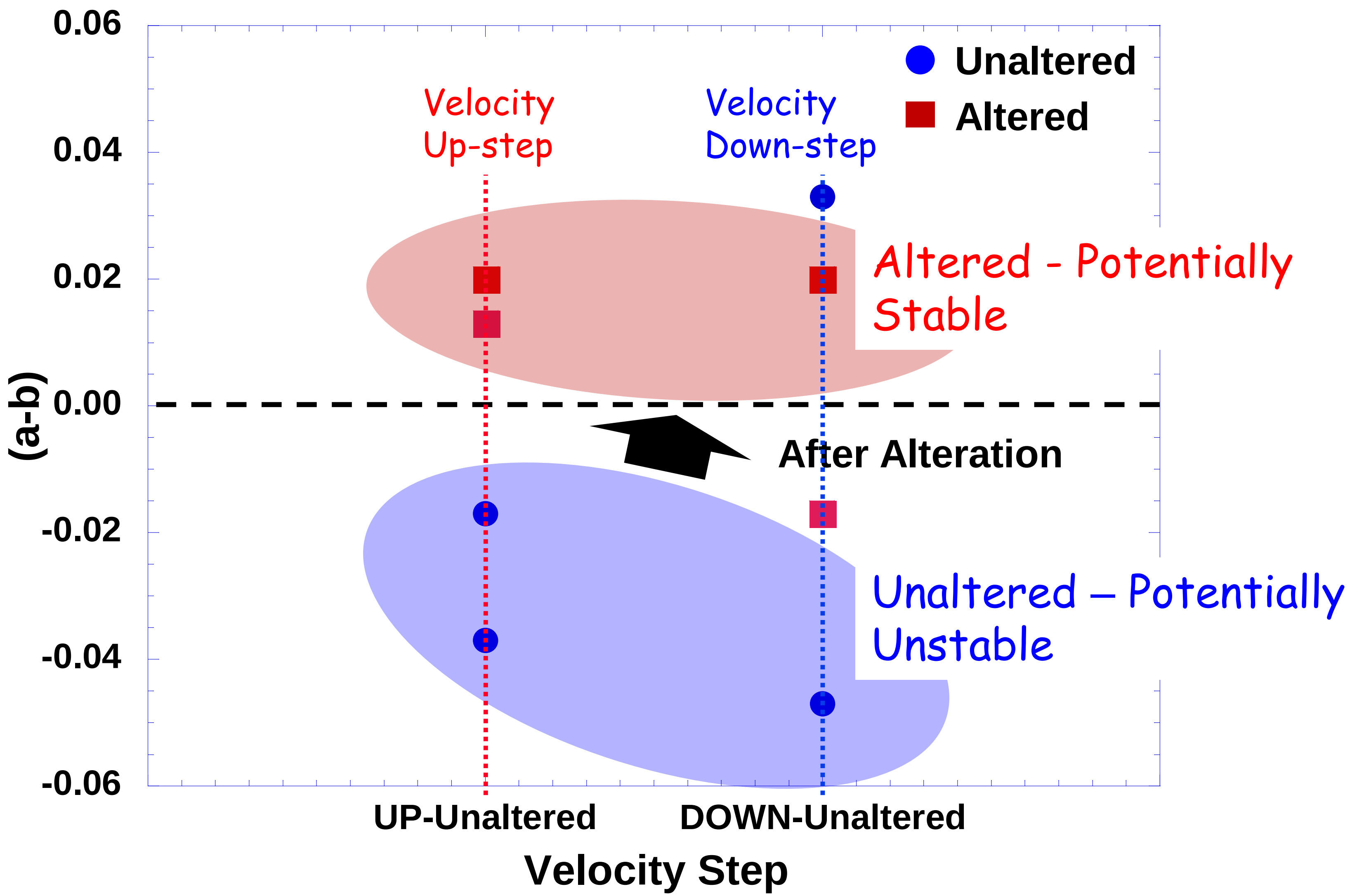




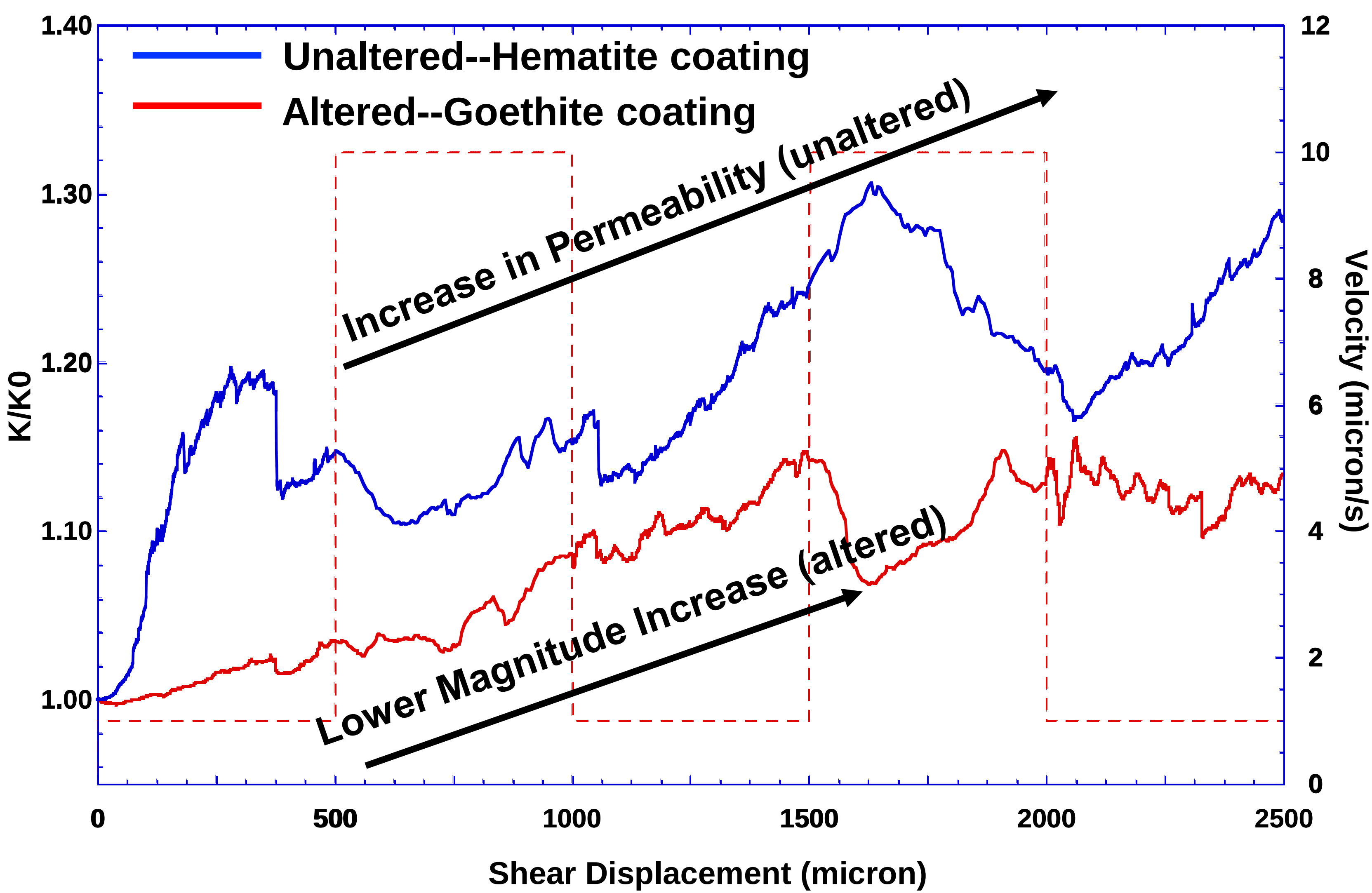


- CO_2 altered synthetic gouge shows **LOWER** frictional strength (shear strength) than unaltered synthetic gouge.
- Unaltered gouge shows **HIGHER** shear strength with more coating particles.

Slip-Stability – Unaltered versus Altered



Permeability Evolution



Accomplishments to Date

ACCOMPLISHMENTS

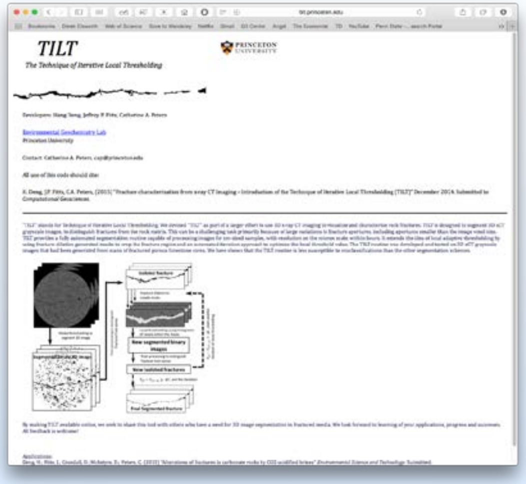
- VS and SHS Experiments
  - Mechanisms-based seismicity-permeability evolution RSF-k
  - VS experiments on broad suite of natural and artificial samples
  - Nascent stability-permeability relations (indicate larger stability smaller dk)
  - Important role of healing on perm-cycle confirmed
  - Important role of reactive transport on perm-evolution and potentially on stability
- 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
    - Extended to CO_2 altered samples
  - Developed RT models for stiffness and permeability evolution of fractures

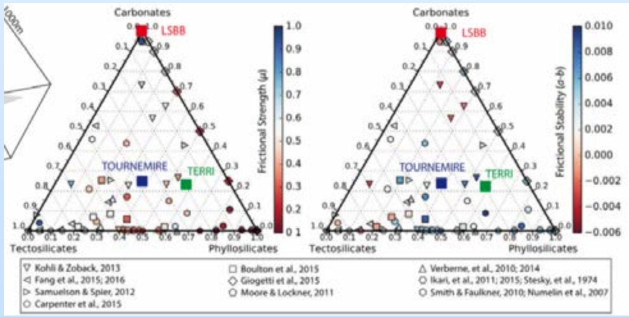
ONGOING

- 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
- Integrating modeling and experiments and imaging

Synergistic Opportunities

- TILT.princeton.edu
- Linkages with:
  - Explored broad suite of mineralogies that are applicable to various CO_2 demonstration projects and others
  - 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

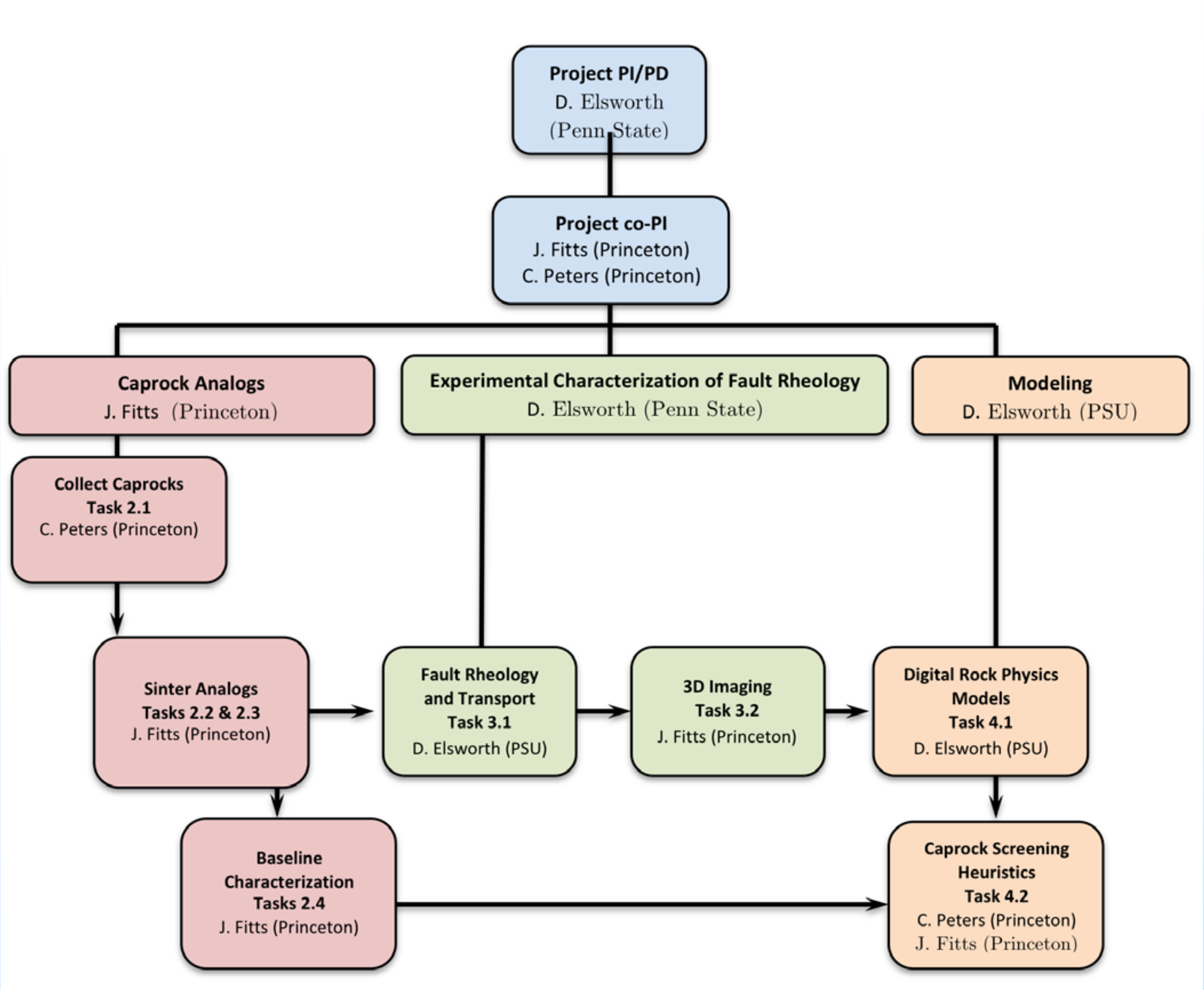
- Rupture of caprocks is a potentially important issue in CCS where:
  - Large overpressures may result from CO_2 injection
  - May result in seismic (felt) or aseismic rupture
  - May result in loss of inventory
- Absent and needed are data/information to constrain:
  - Seismic and aseismic reactivation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

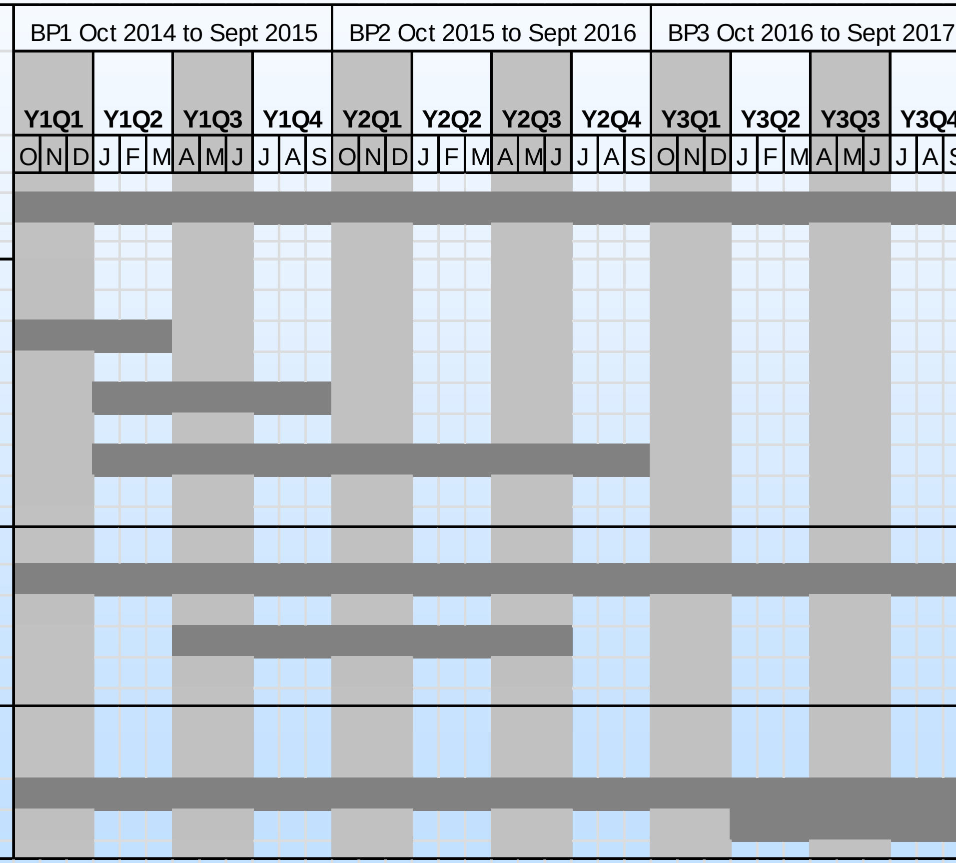


Communication plan: Biweekly Skype [Oct 23; Nov 6, ….]

Biannual meeting

Gantt Chart

SCHEDULE of TASKS and MILESTONES	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



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