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

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Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

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Presentation Outline

- Technical Status
- Accomplishments
- Lesson Learned
- Synergistic Opportunities
- Summary [Repeat of *Lessons Learned*]

Technical Status & Methodology

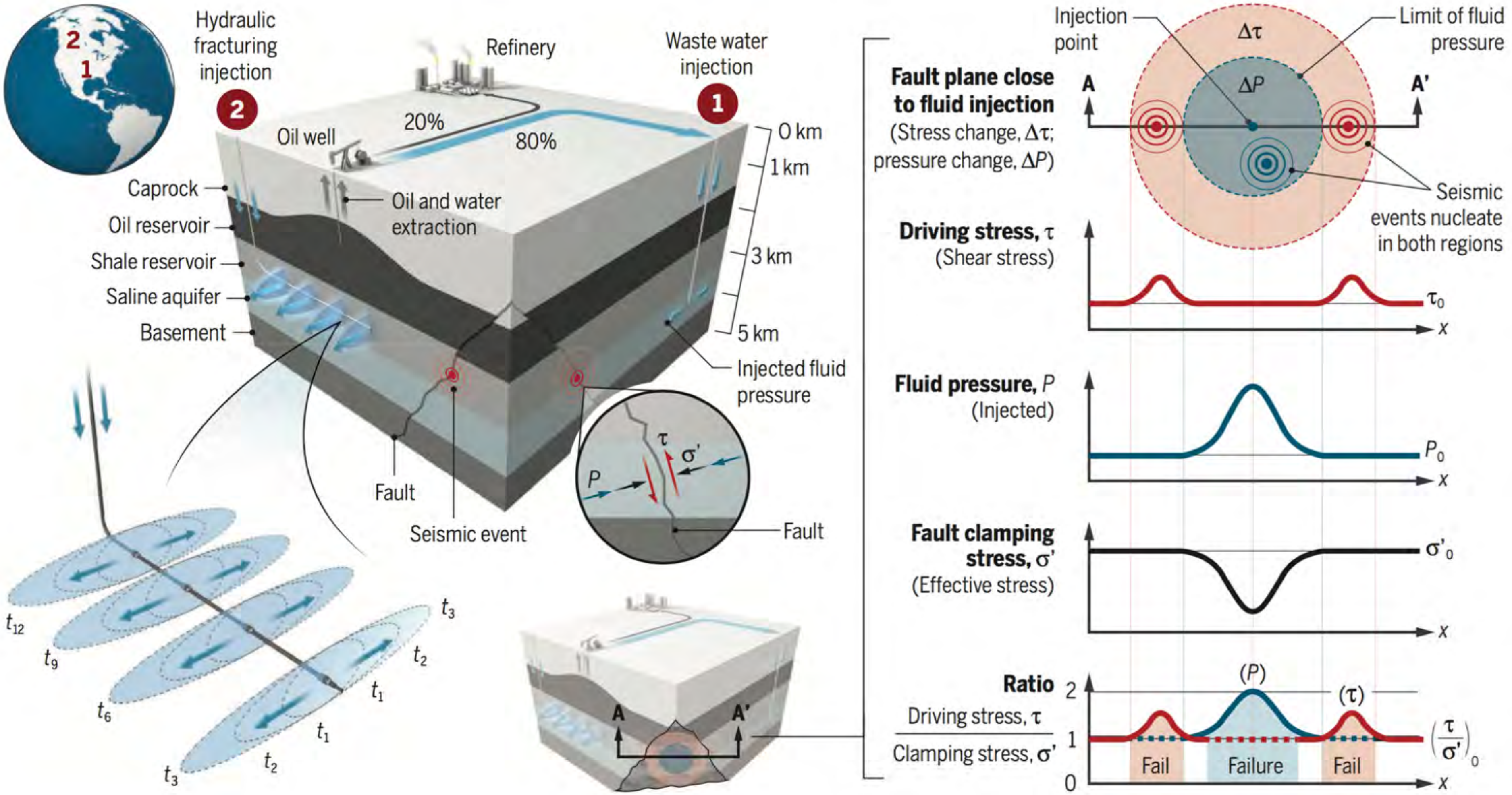
Background

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

Methodology

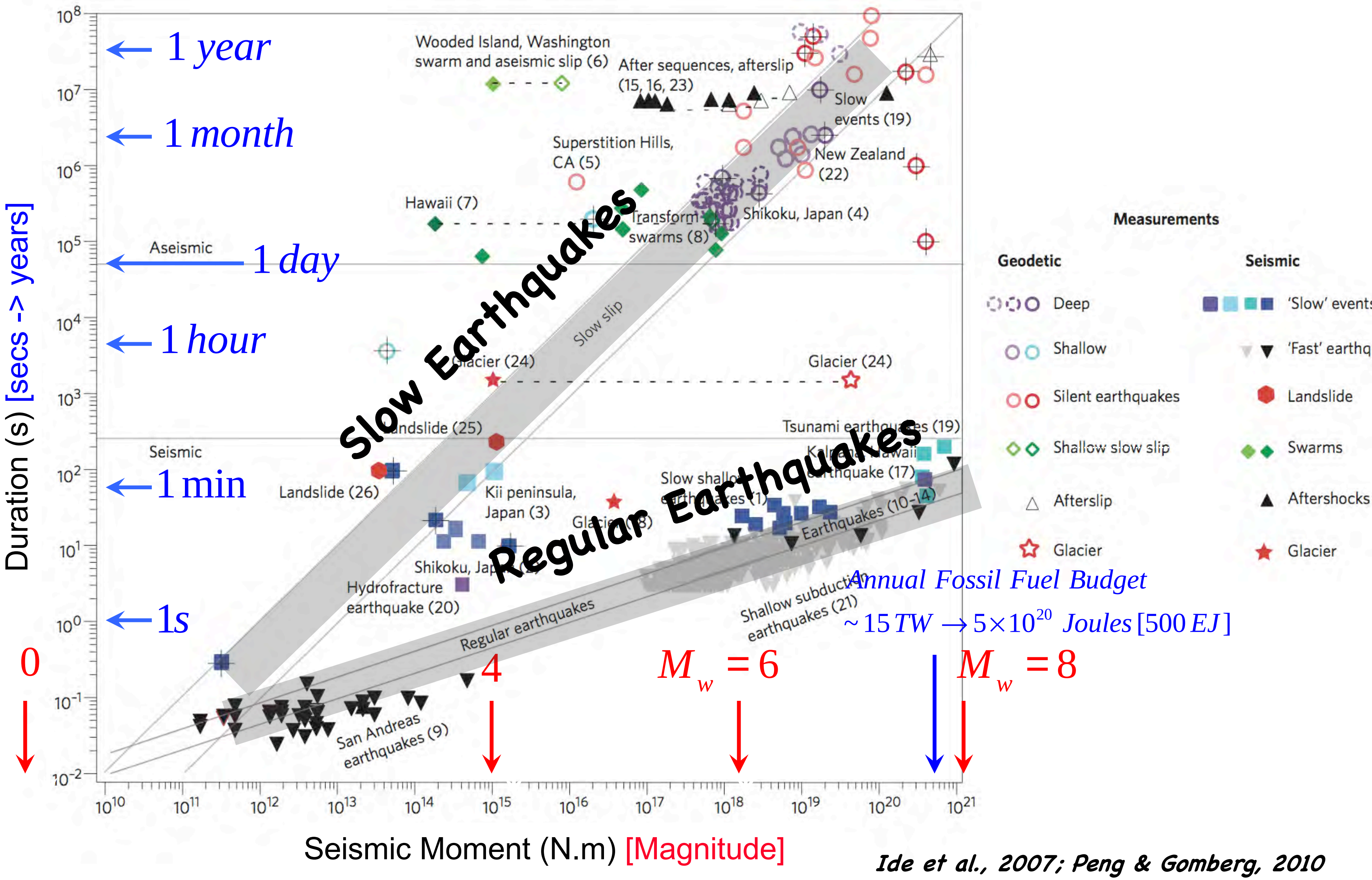
- **Collect, Synthesize and Characterize Sedimentary Formation Samples (Fitts, Lead)**
  - Collect Homogeneous and Mineralogically Complex Sedimentary Rocks (Peters)
  - Sinter Mineral Mixtures to Create Idealized Analogs of Sedimentary Rocks (Fitts)
  - Conduct Baseline Characterization of Natural and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

Induced Seismicity



[Elsworth et al., Science, 2016]

Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior

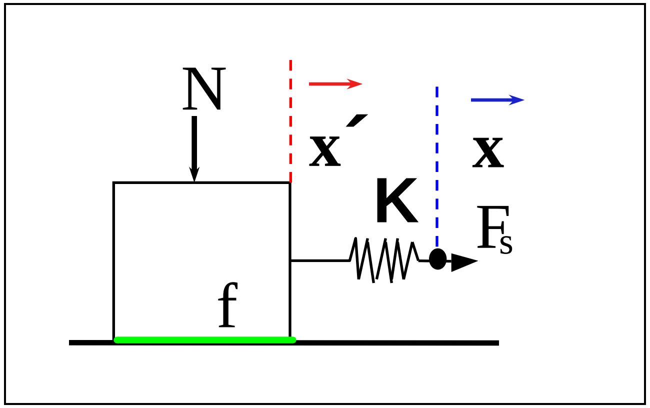


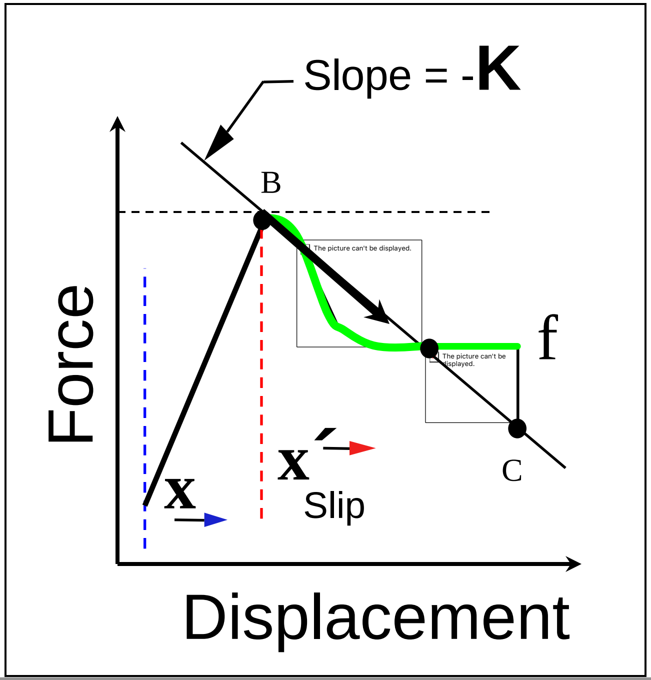
Annual Fossil Fuel Budget

$\sim 15\,TW \rightarrow 5\times10^{20}\ Joules\,[500\,EJ]$

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

Seismic – Aseismic Transition
Full Spectrum of Slip Behaviors





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

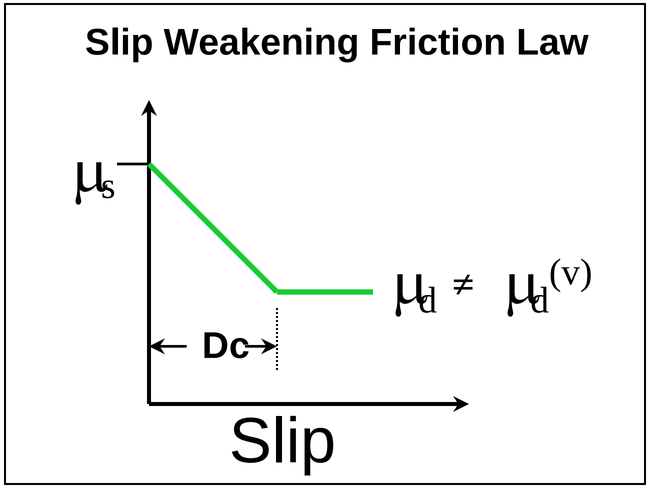
Promote Aseismic Response: $K_c < K$

Otherwise Seismic Slip if: $K_c > K$

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

Decrease: $D_c;G$

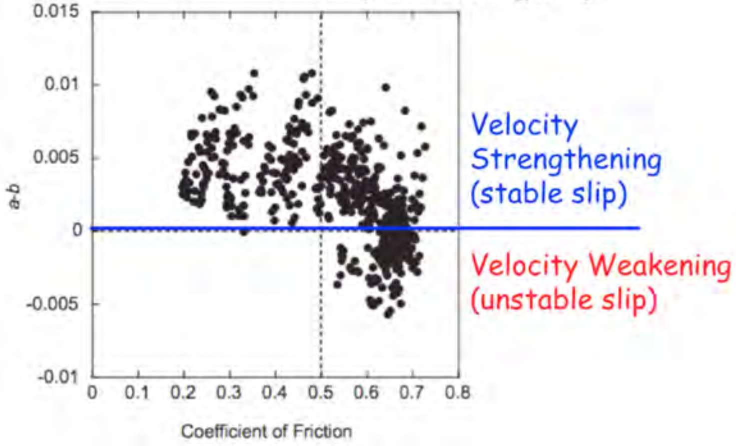
Recurrence Requires: *Healing*



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

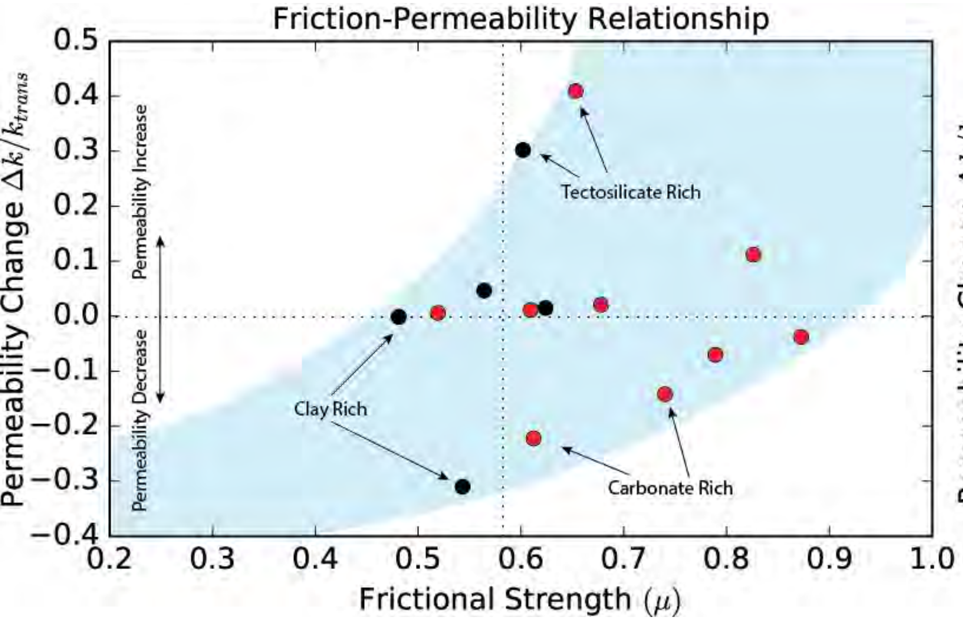
Nascent Friction-Stability-Permeability Relationships

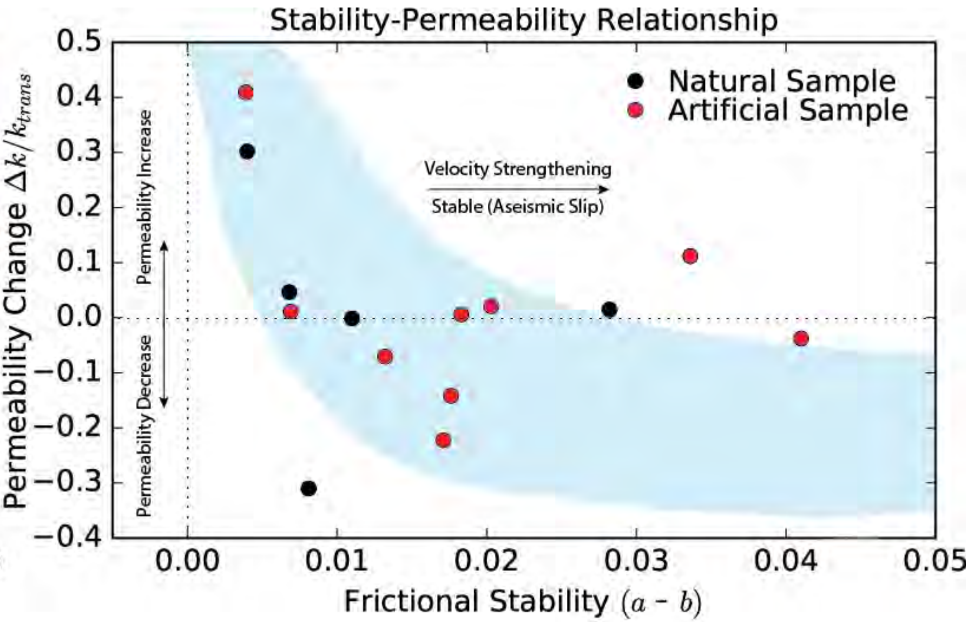
[Ikari et al., *Geology*, 2011]



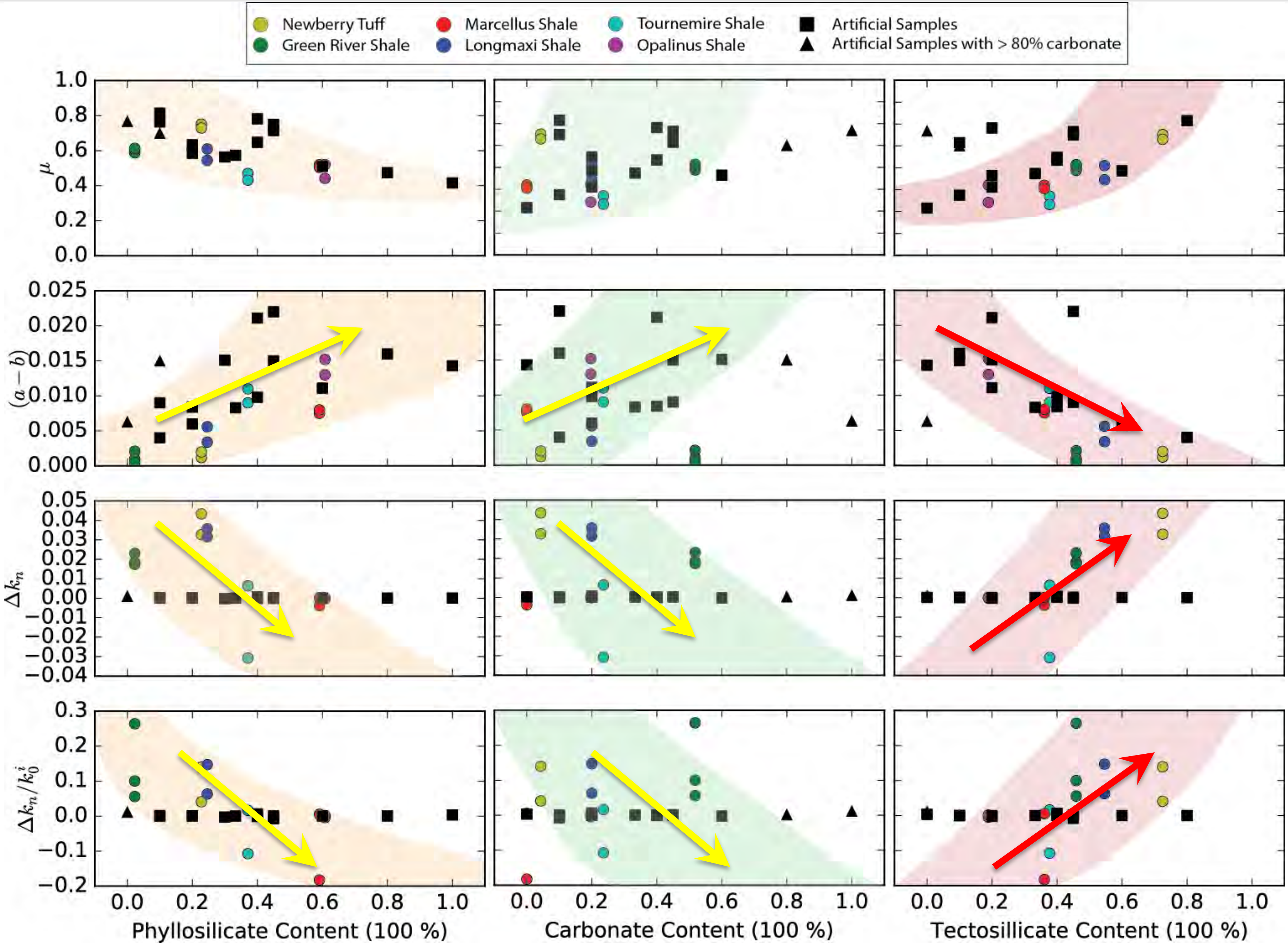
Observations

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





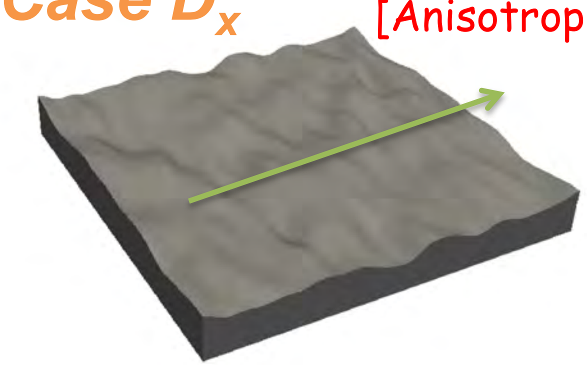
Seismicity-Permeability Linkages – Natural Samples

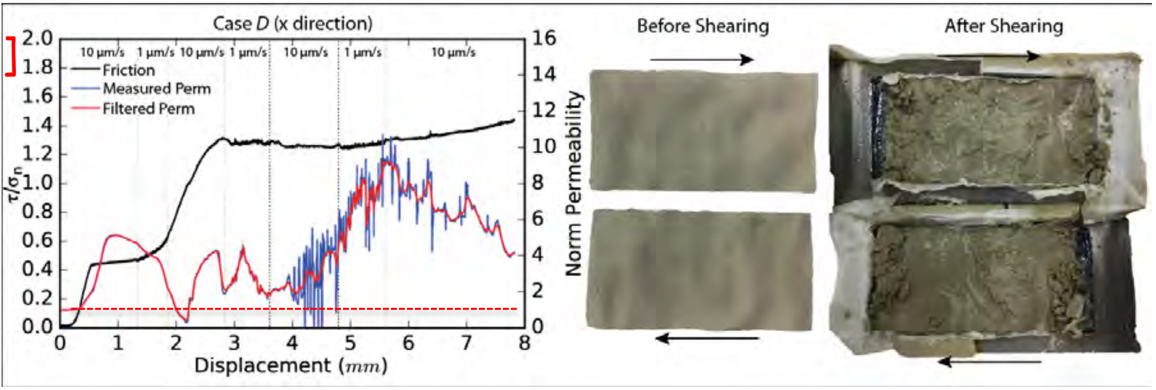


❖ Net Friction and Permeability Evolution

Case D_x

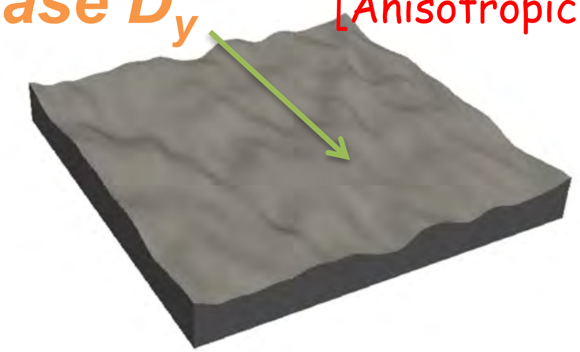
Full amplitude [Anisotropic – x]

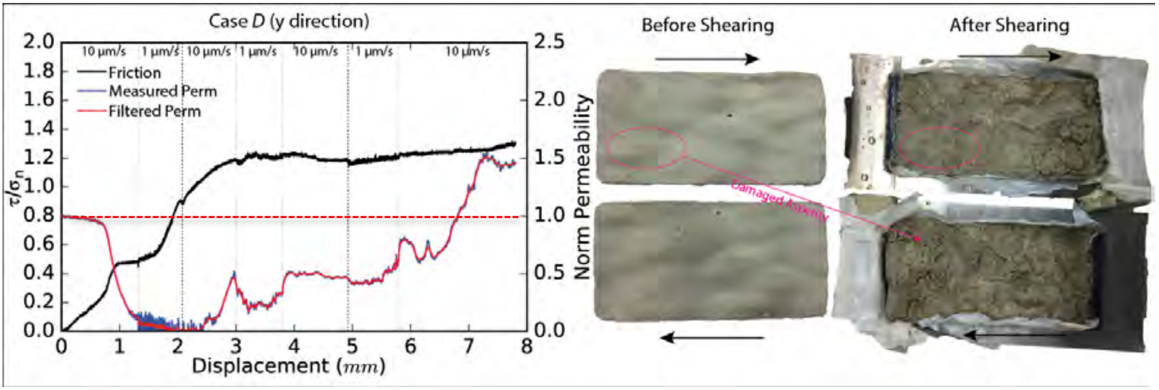




Case D_y

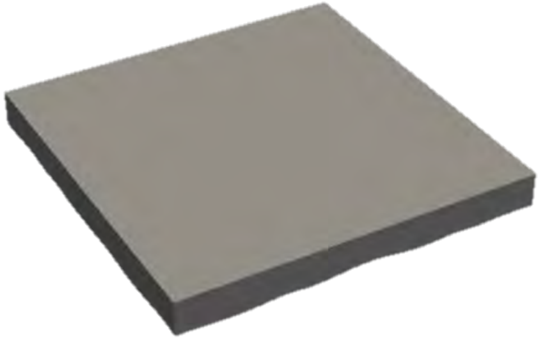
Full amplitude [Anisotropic –y]

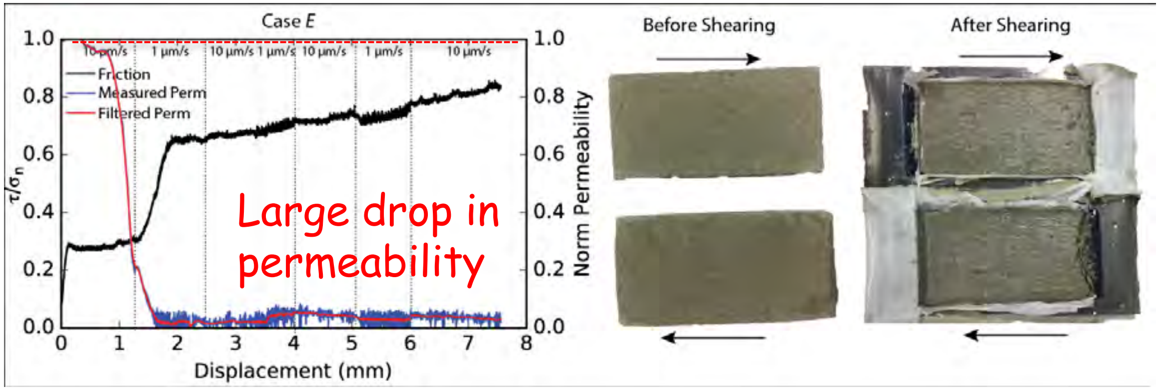




Case E

Smooth



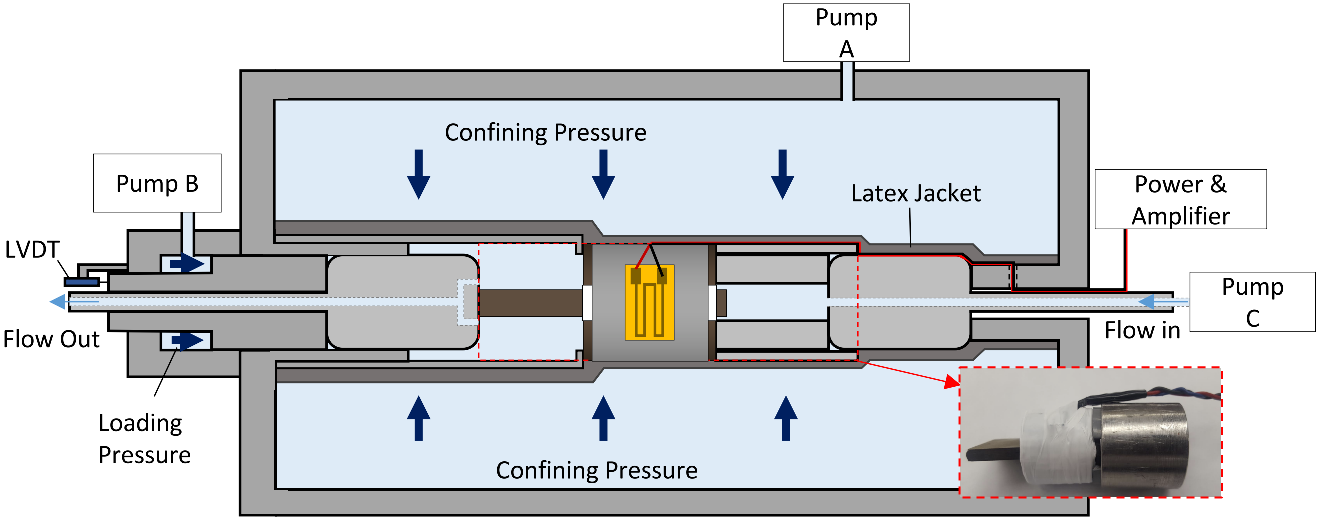


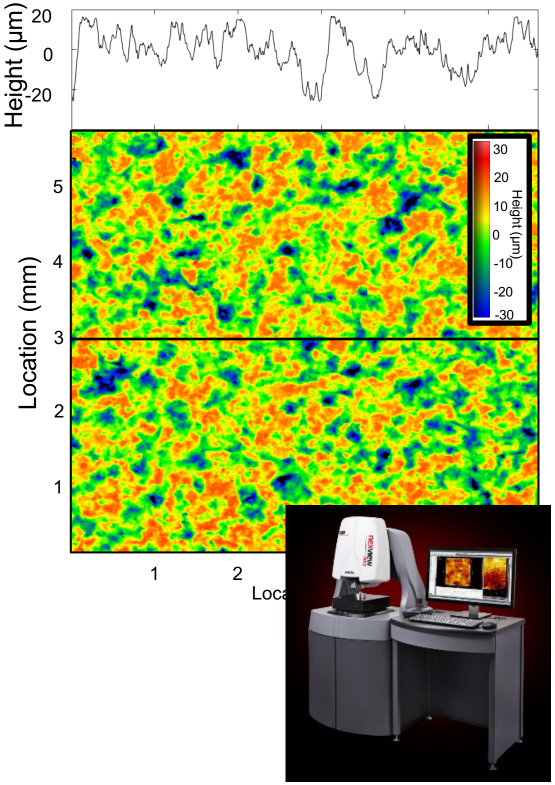
Large drop in permeability

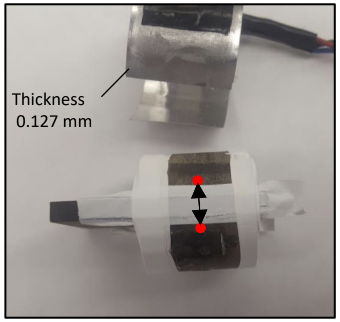
Cyclic Permeability Evolution and Normal Deformation

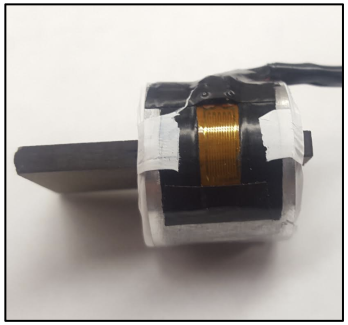
Experimental Method

- Slide-hold-slide with saw cut Green River shale (2 mm slide – 12 hours hold)
- Strain gage measures fault normal deformation
- Surface Profile measured by optical profilometry





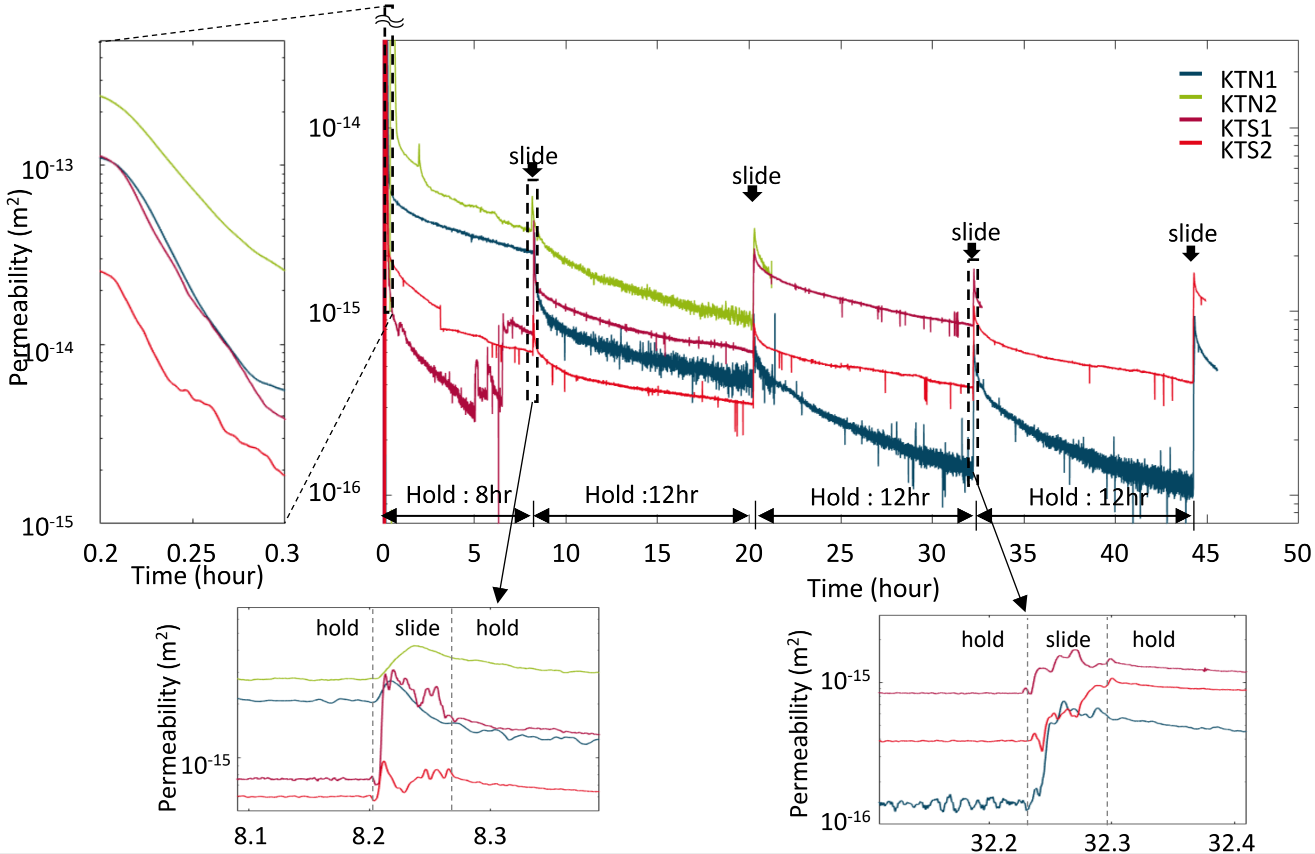




Cyclic Permeability Evolution and Normal Deformation

Result – Permeability Evolution

- Cyclic permeability evolution is apparent
- Strong permeability decline at initial shear-in
- Shear Permeability enhancement become more significant at later stage slips



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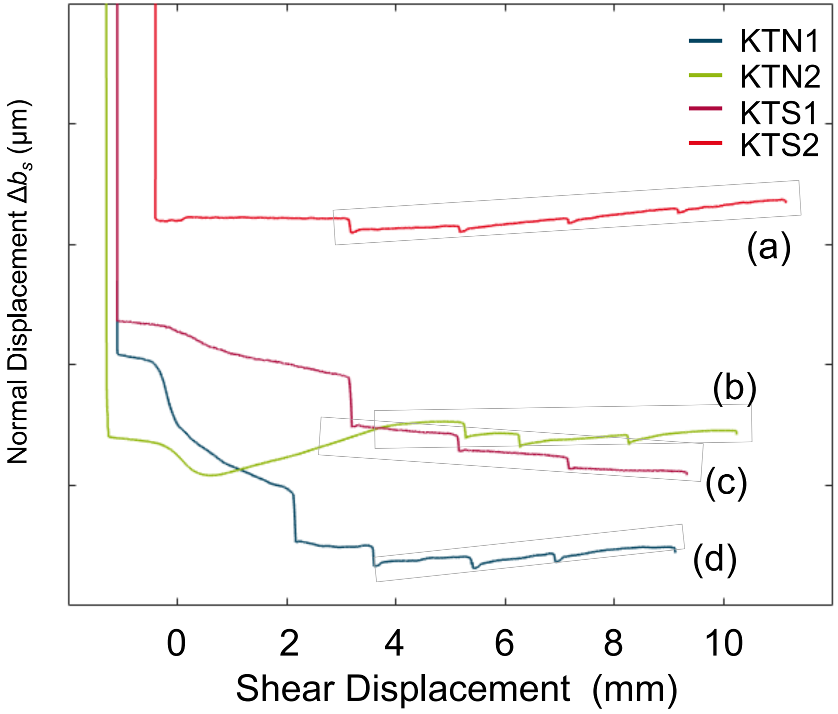
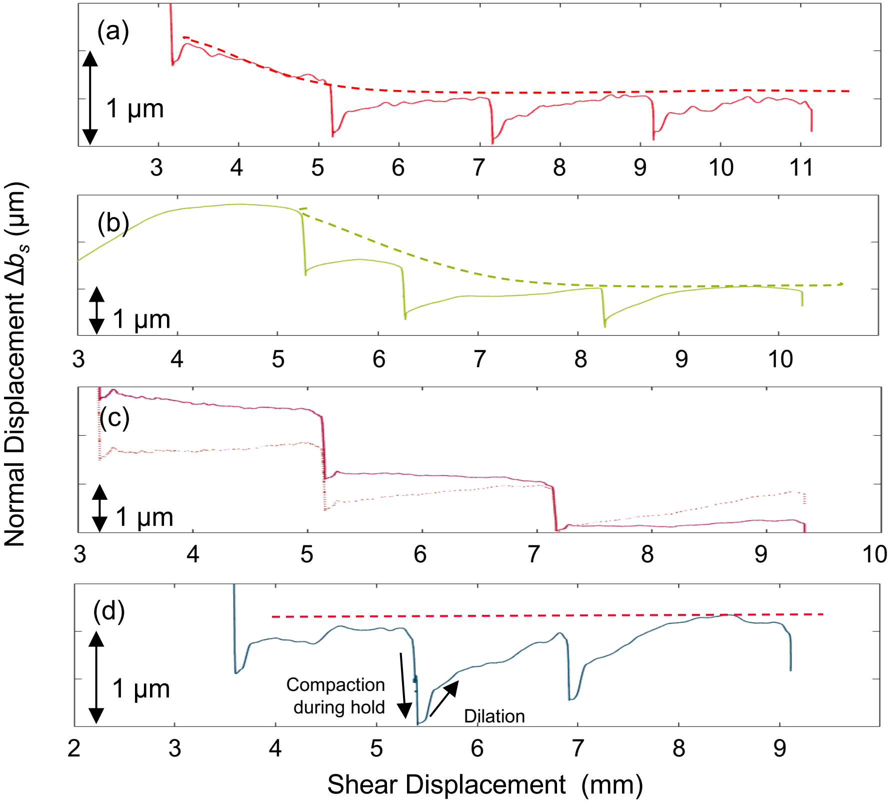
Cyclic Permeability Evolution and Normal Deformation

Result – Strain Gage Measurement

- Shear slips are associated with dilation but with one exceptional case – plot (c)
- Normal compaction is apparent during hold (without exception)
- Magnitude of cyclic compaction/dilation is ~1 micron

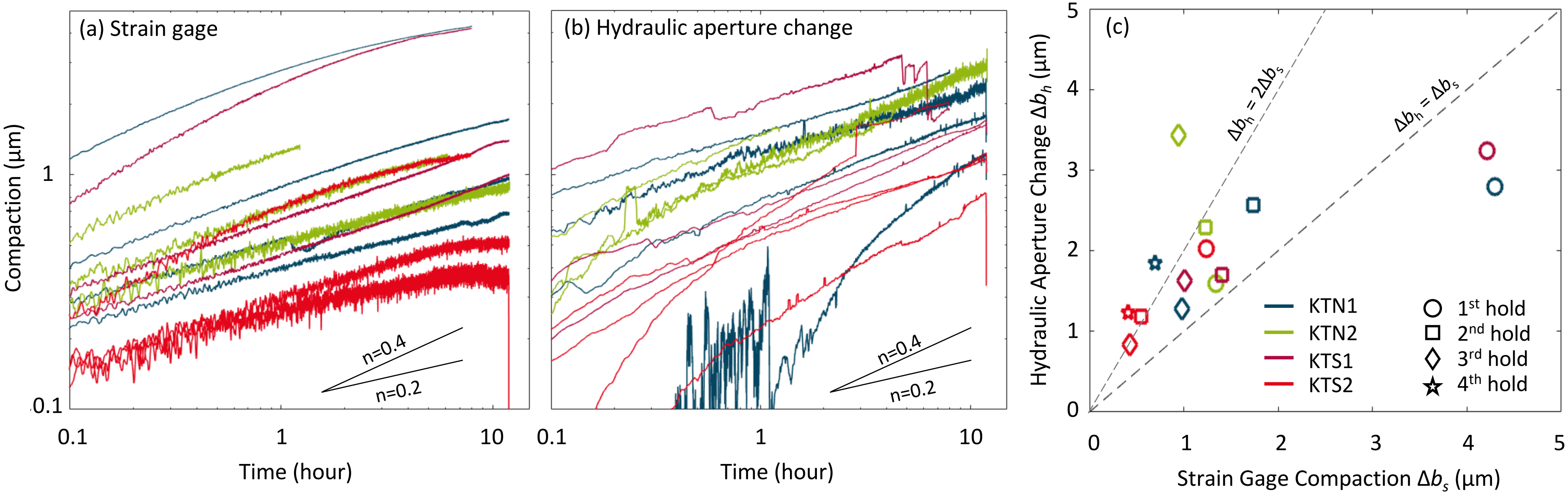




Cyclic Permeability Evolution and Normal Deformation

Time Dependent Static Compaction

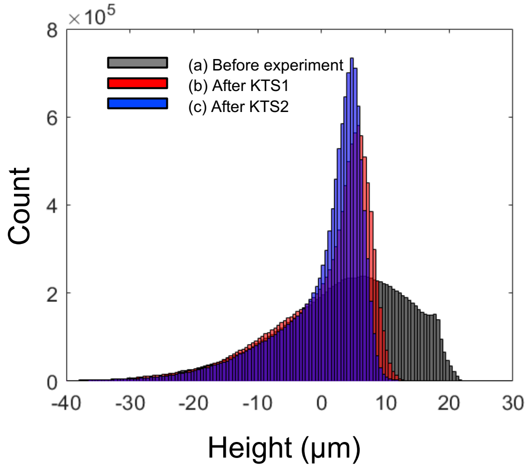
- Compaction approximately follows power law with power exponent ~0.2-0.4
- Compaction magnitude is a few microns (decreases during later stage holds)
- Magnitude of the mechanical and hydraulic compaction are similar but not identical
  - $\Delta b_s > \Delta b_h$ for first hold and $\Delta b_h > \Delta b_s$ for later hold

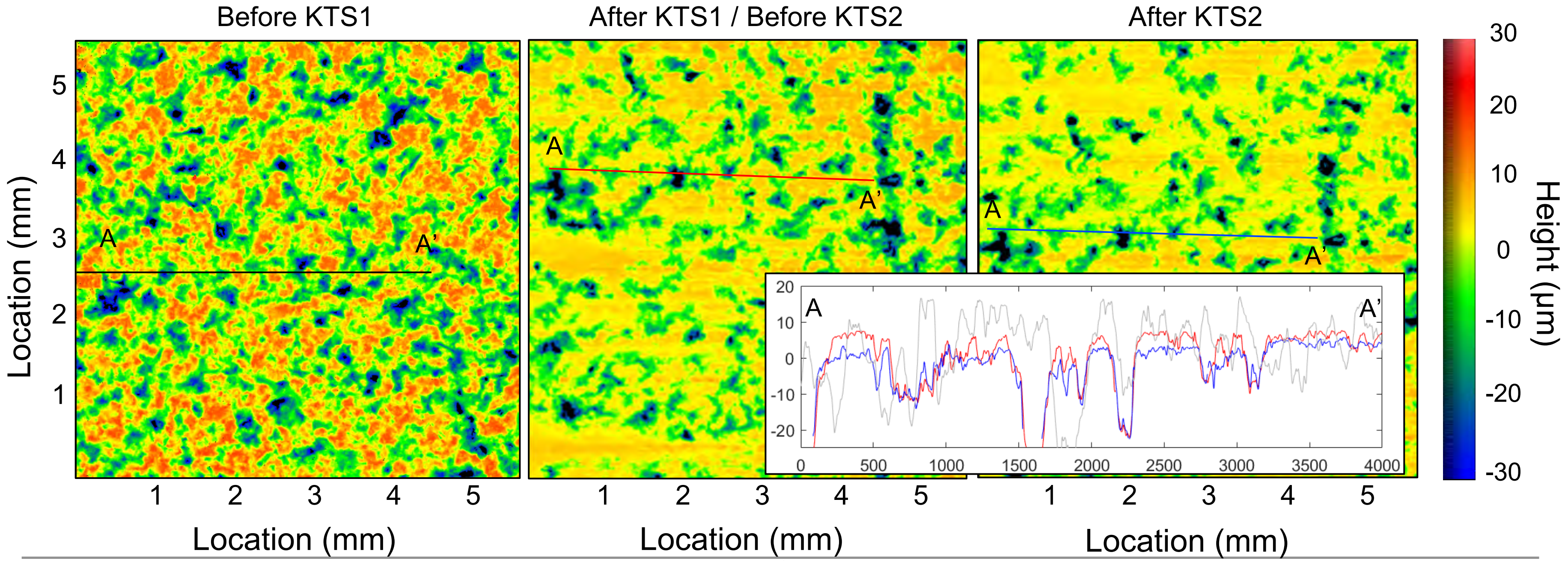


Cyclic Permeability Evolution and Normal Deformation

Surface Profile Evolution

- Strong comminution and flattening observed
- Comminution effect is significantly reduced at 2nd shear
- Small scale roughness develops on planed surface

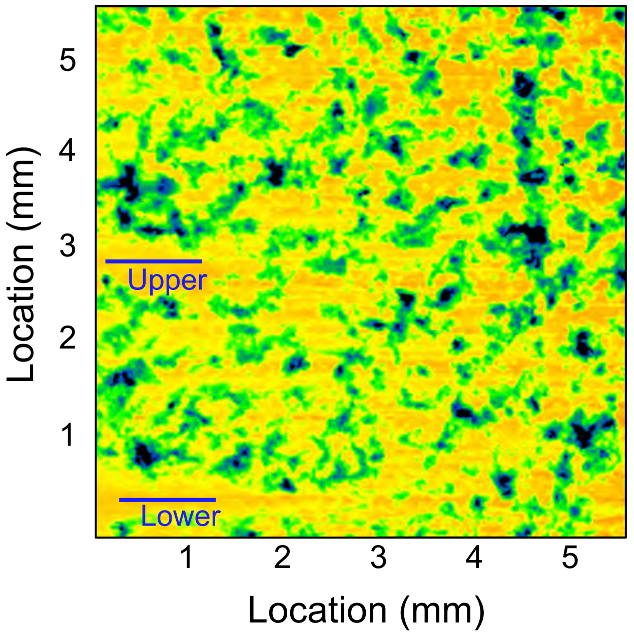


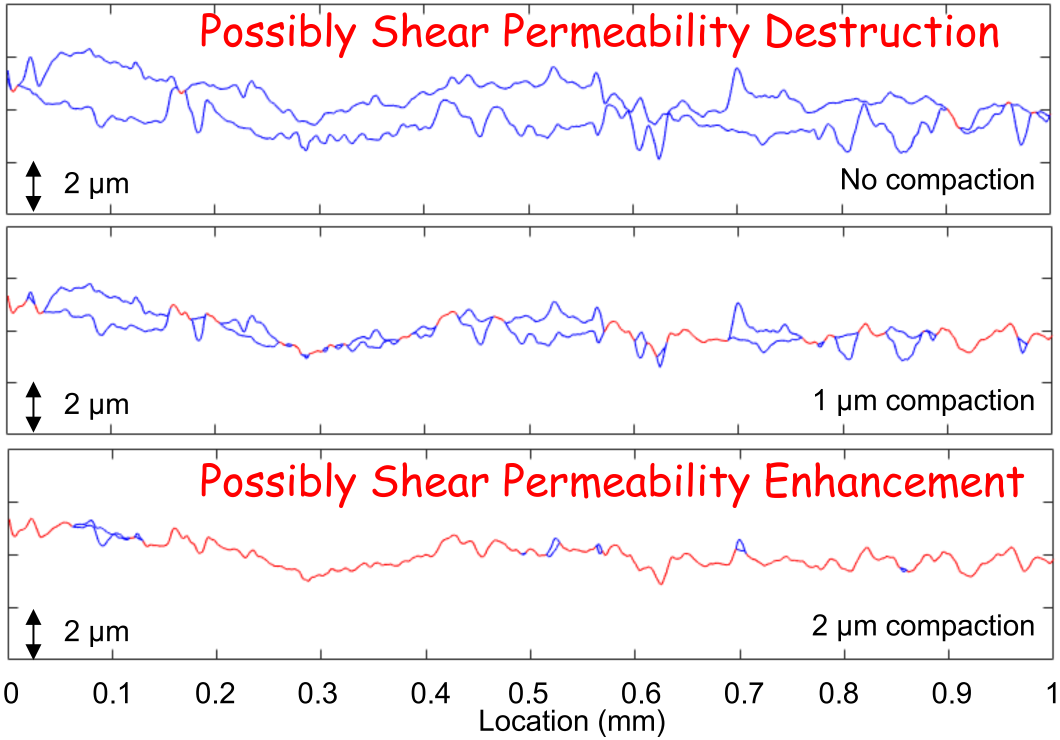


Cyclic Permeability Evolution and Normal Deformation

Discussion – Hypothetical Compaction and Matedness

- Two 1mm planed surface are hypothetically compacted assuming:
  - Mineral dissolution at real contact (pressure solution)
  - Dissolution rates are equal on upper and lower surfaces
- Pre-slip compaction likely determines the following shear permeability evolution



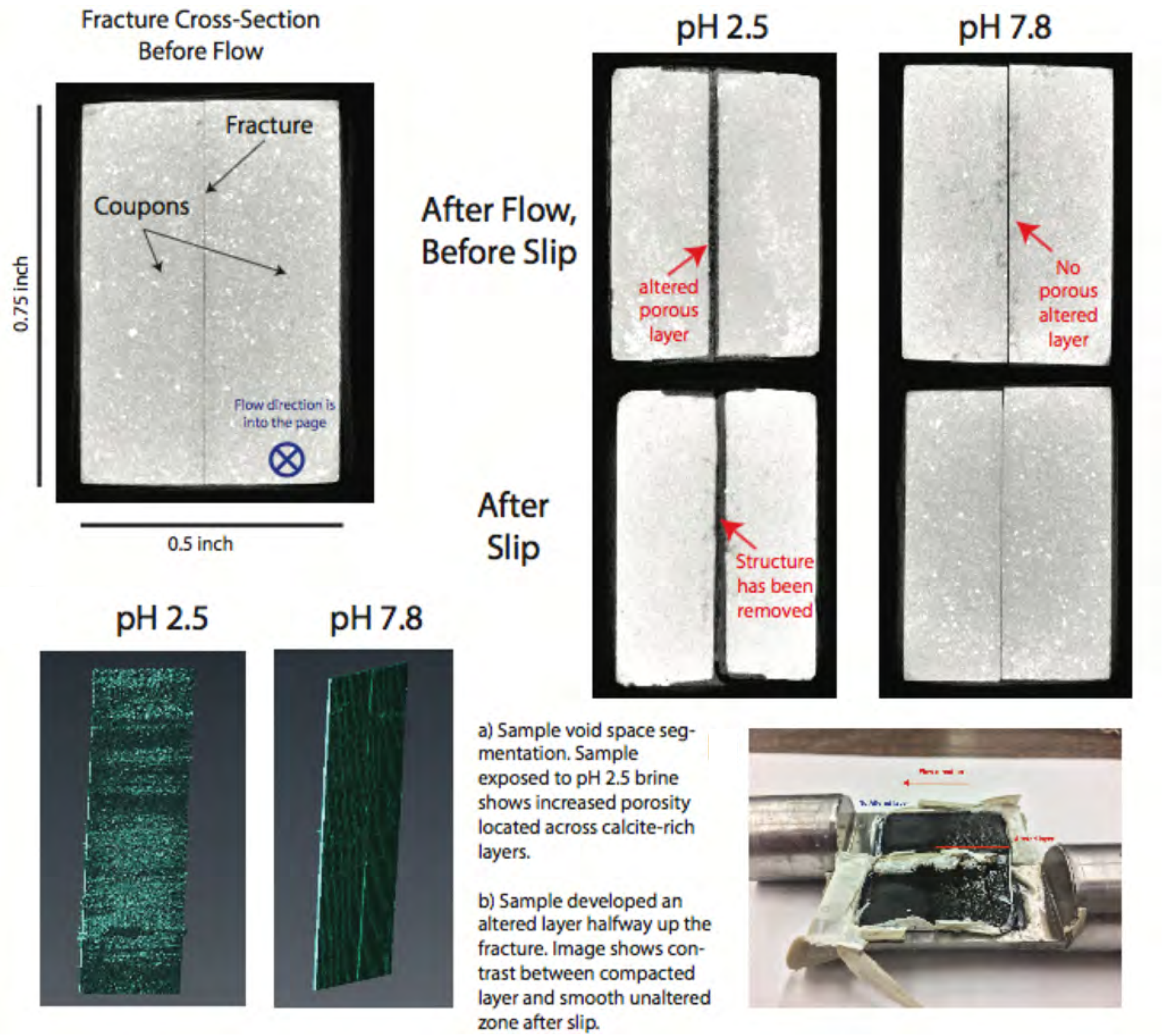

Possibly Shear Permeability Destruction

Possibly Shear Permeability Enhancement

Frictional-Stability-Permeability and Reaction

Experiments:

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



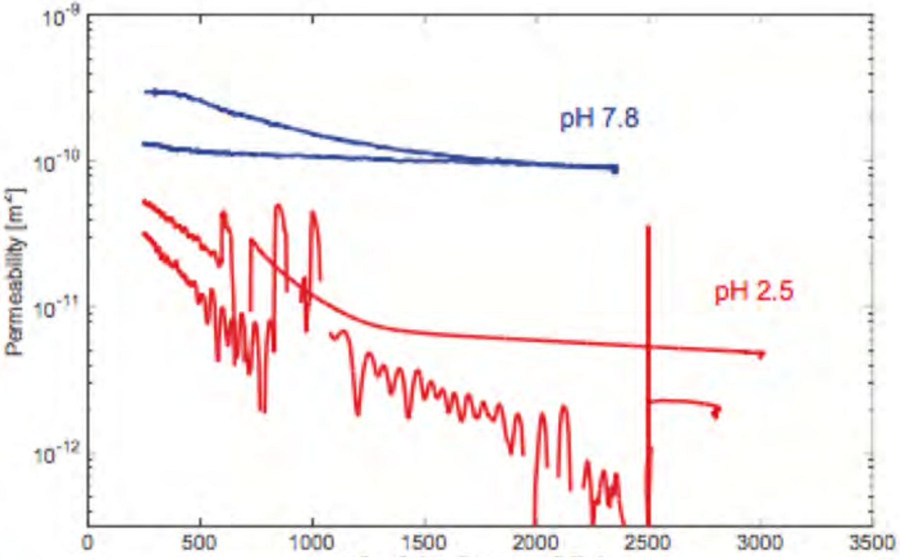
a) Sample void space segmentation. Sample exposed to pH 2.5 brine shows increased porosity located across calcite-rich layers.

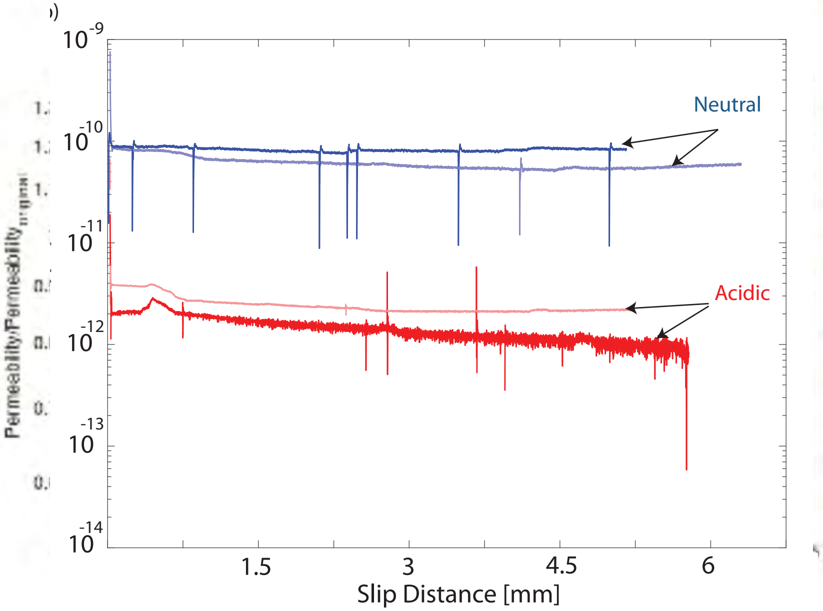
b) Sample developed an altered layer halfway up the fracture. Image shows contrast between compacted layer and smooth unaltered zone after slip.

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

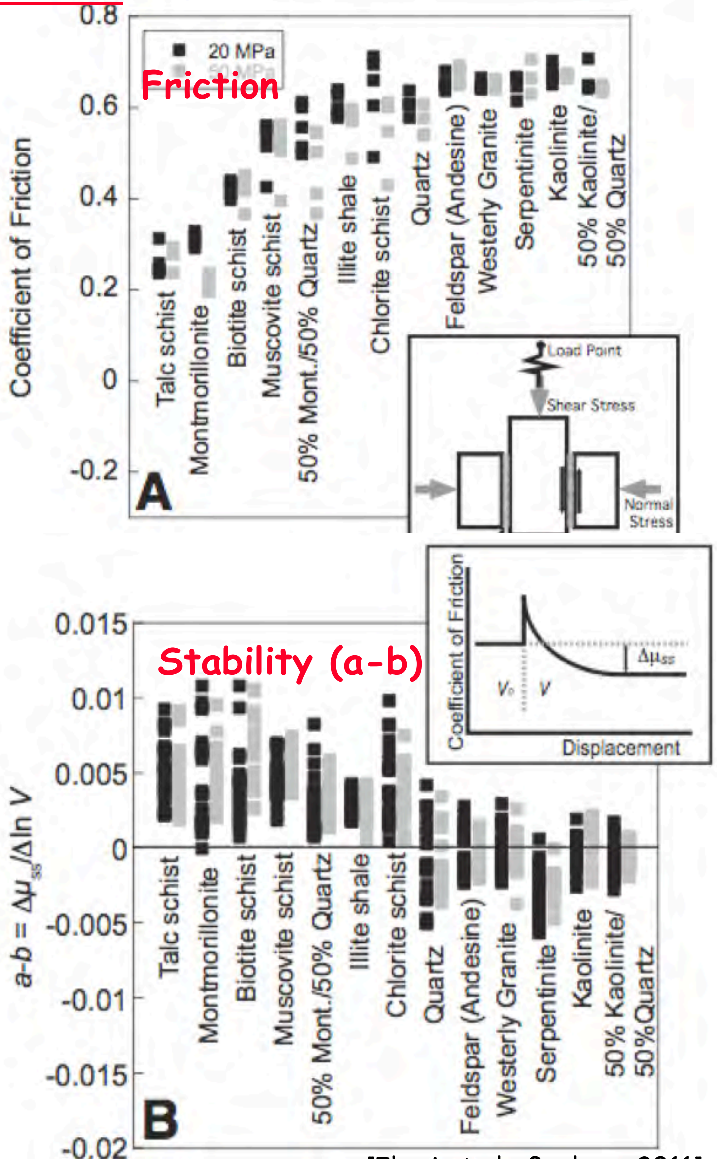
2. Permeability evolution during first 1.5mm of slip.
    - Permeability does not evolve systematically, likely controlled by unique sample geometries.
    - Maximum permeability increase observed for sample with altered layer and vice versa.





Stability-Permeability Relations in Composites/Mixtures

Mono-mineralic

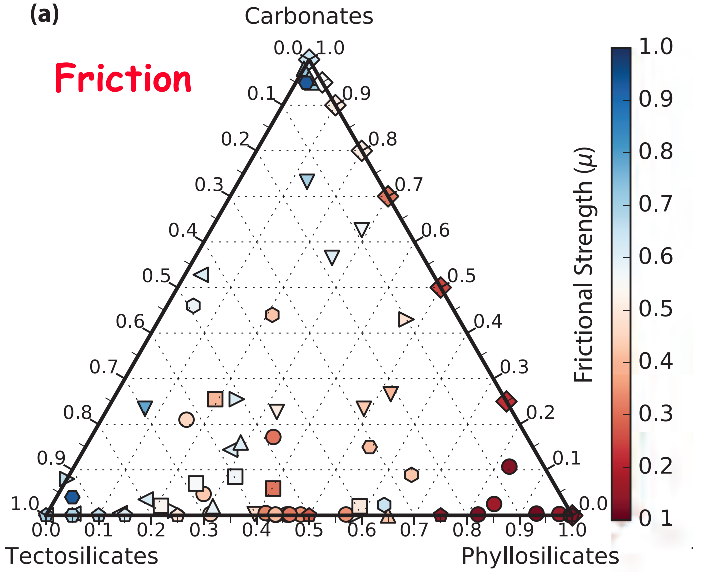


Friction

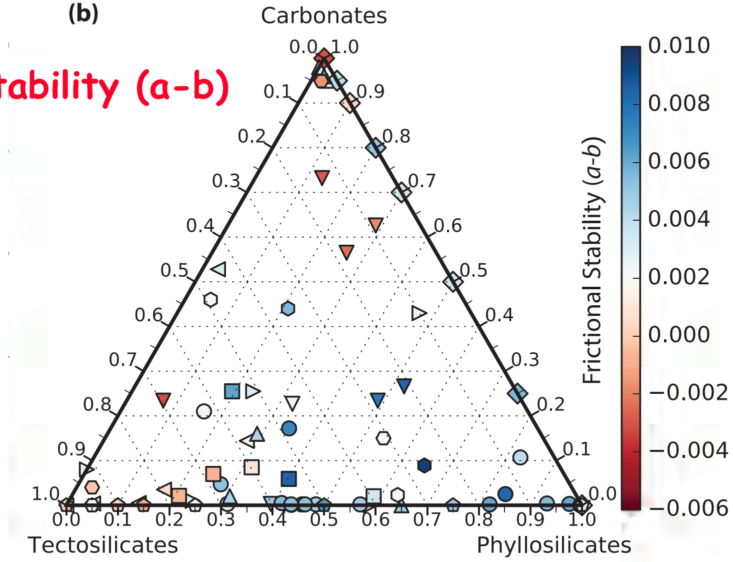
Stability (a-b)

[Ikari et al., Geology, 2011]

Multi-mineralic

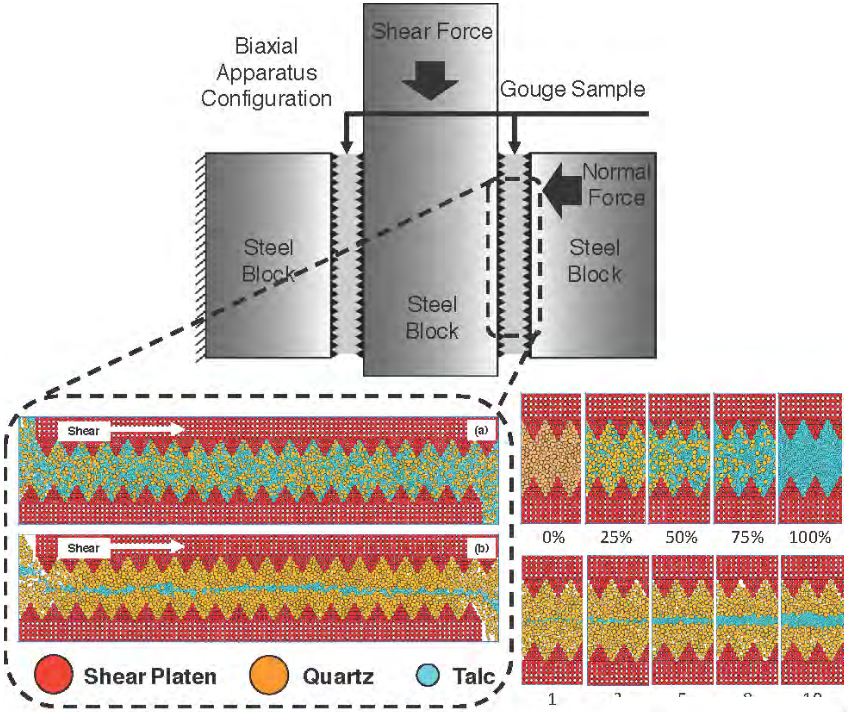


Friction



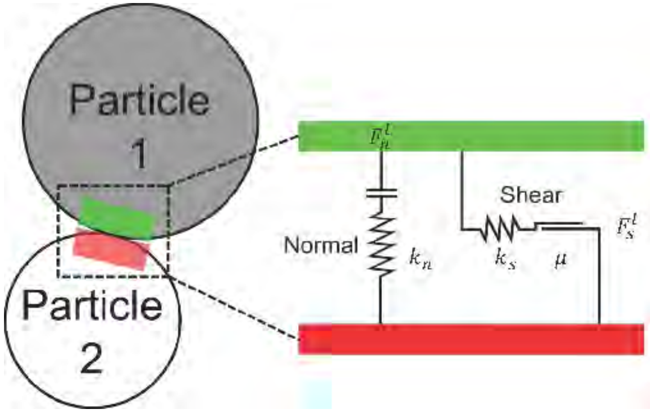
Stability (a-b)

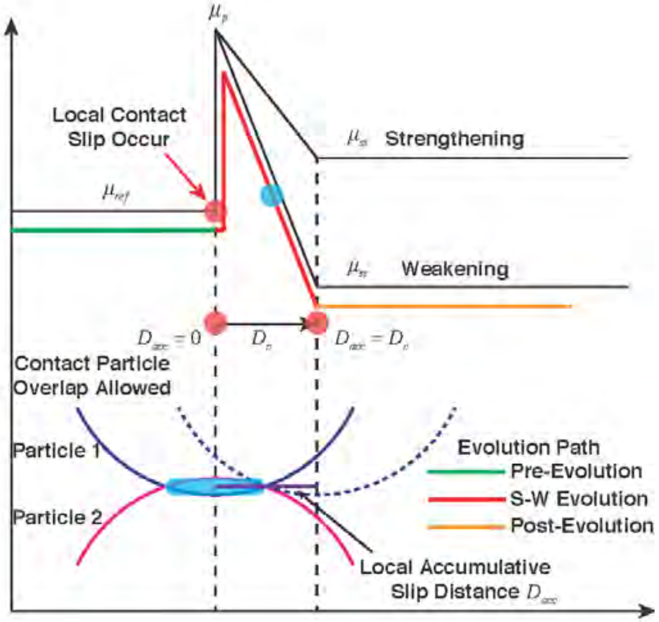
2D Model Configuration



DEM model configuration as a symmetric simplification of a double direct shear apparatus: (a) uniform mixtures; (b) textured (layered) mixtures; inset on the right-hand-side shows the variation of quartz (orange) to talc (blue) content/relative layer thickness in uniform/layered mixtures.

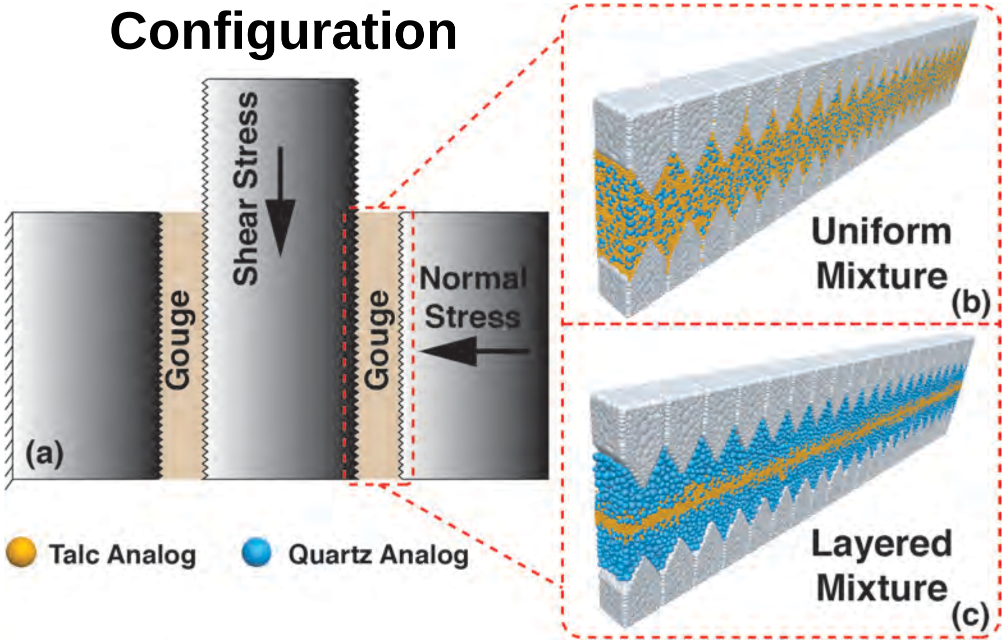
Linear Elastic Contact Model





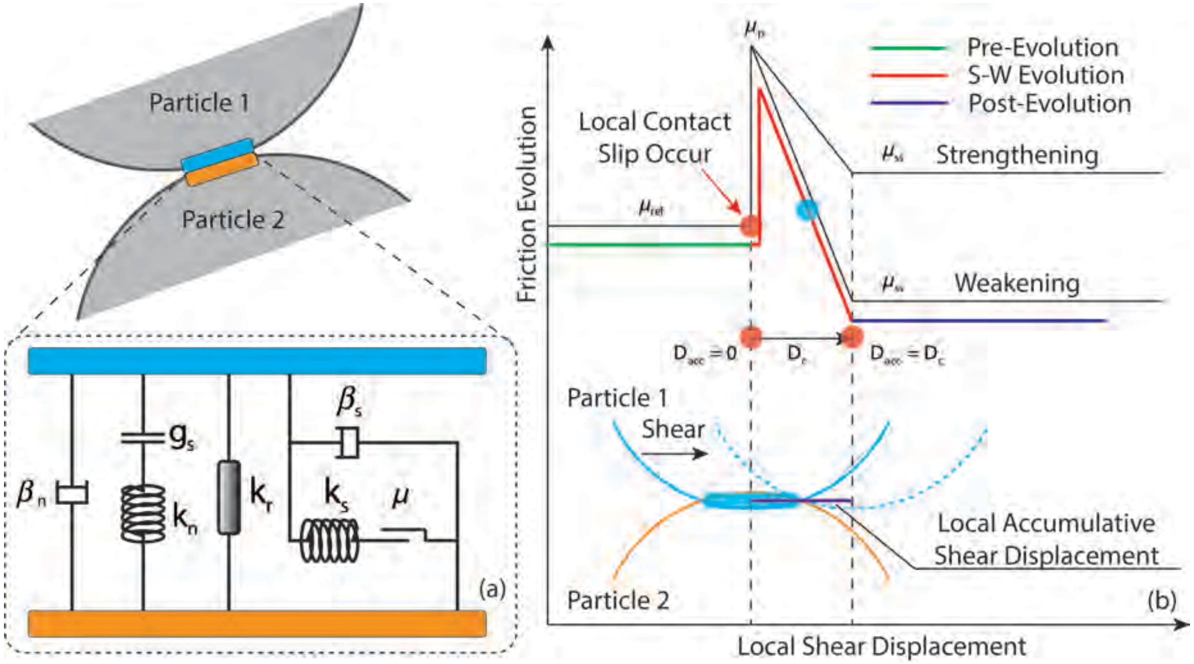
Schematic of the contact model: the friction coefficient of a local contact starts to evolve upon a slip event together with a difference between global load point velocity and stored global reference velocity friction will reach a peak and continue to evolve to its steady state if local slip persists according to either velocity-strengthening or velocity-weakening; if slip halted before reaching steady state, the friction coefficient will state as-is; friction evolution of newly formed contact will be reset and evolve from the beginning (left to right).

3D Model Configuration

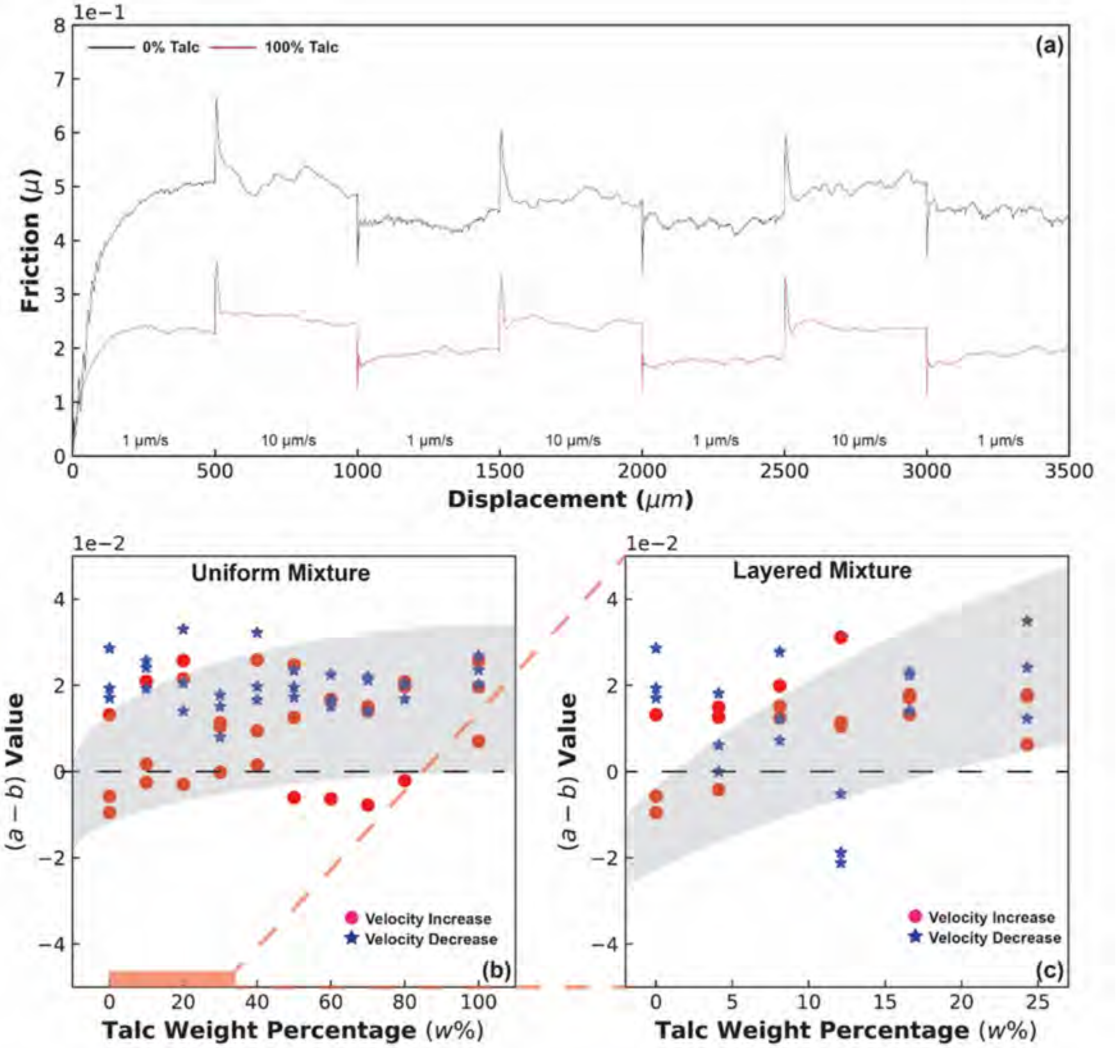


Model configuration represents one half of the double direct shear configuration (Mair & Marone, 1999). (a) Double direct shear configuration; (b) DEM model for homogeneous mixtures; (c) Layered/textured mixture.

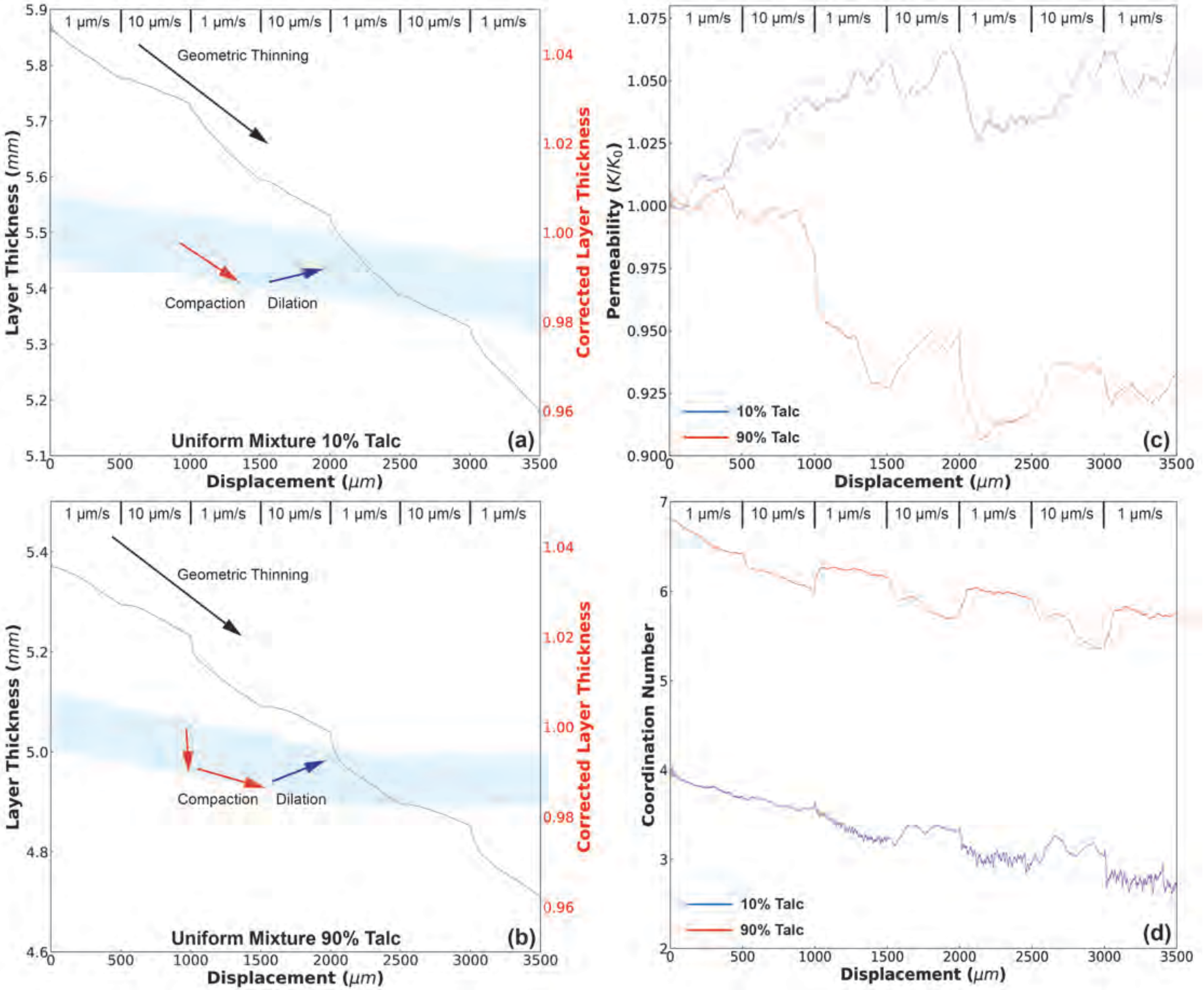
Rotation Resistant Contact Model



(a) Contact model between two particles comprises linear elastic components in the local shear and normal directions with a moment-based rolling resistant component (k_r); (b) modified slip-weakening constitutive relation acting at each particle-particle contact.



(a) Typical friction evolution curve of a uniform mixture of talc and quartz (0% talc and 100% talc are shown); (b) (a-b) of uniform mixture plotted against talc weight percentage, shaded area indicates trend; (c) (a-b) of layered mixture plotted against talc weight percentage, zoom-in view shows a comparison of the weight scale with the uniform mixture, shaded area indicates increasing trend of (a-b)



Uncorrected/corrected evolution of sample layer thickness with shear displacement for (a) a 10% talc-quartz mixture; (b) a 90% talc-quartz mixture; (c) local normalized permeability evolution of 10% and 90% talc-quartz mixtures estimated from local porosity evolution; (d) evolution of average coordination number of 10% and 90% talc-quartz mixtures.

Accomplishments to Date

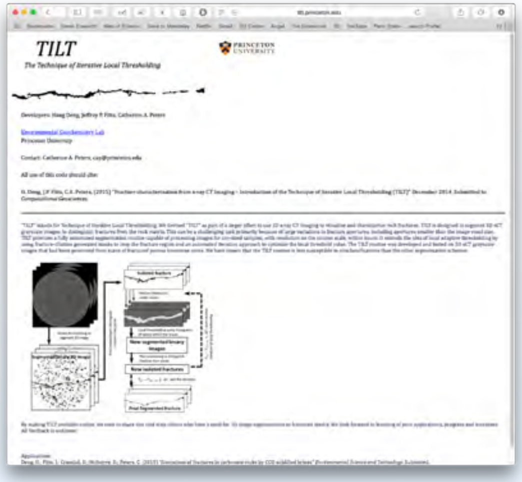
- **VS and SHS Experiments**
  - Mechanisms-based seismicity-permeability evolution RSF-k
  - VS experiments on broad suite of natural and artificial samples
  - Stability-permeability relations (indicate larger stability smaller dk)
  - Important role of healing on perm-cycle and seismicity defined
  - Important role of reactive transport on perm-evolution and friction/stability
- **Imaging**
  - Frozen post-test fractures
  - Completed 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

Lessons Learned/Summary

- **Friction-Stability-Healing Behavior – Related to Permeability**
  - RSF-k is a viable method to link permeability-response
    - Linkage correct when strength to stress ratio is high
    - Linkage incorrect where wear products predominate response
  - Stability-permeability relations (indicate increasing stability -> smaller dk)
  - Friction-instability follows observed norms on mineralogy
    - Quartz – predominantly unstable – permeability increase
    - Carbonates and Clays – predominantly stable – permeability decrease
  - Important role of healing on perm-cycle and seismicity defined
    - Short hold times/repose then compactive deformation and small permeability increase or drop
    - Long hold times/repose then dilation and increased permeability increase
  - Important role of reactive transport on perm-evolution in fracture walls
    - High porosity zone in Eagle Ford shale where carbonate leached
      - » But compaction and reactivation results in collapse and loss of permeability
    - Mineralogic transformation Hematite-> Goethite results in changes in stability and permeability (conforms)
- **Modeling**
  - DRP models for friction and stability – gouge - compared with mixtures data
    - Local contact models confirm laboratory data for stability and permeability

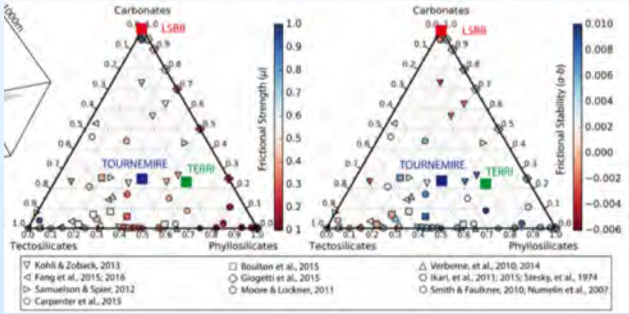
Synergistic Opportunities

- 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)
    - EGS Collab
  - Imaging *in vivo* (Dustin Crandall)



TILT

The Technique of Iterative Local Thresholding



Lessons Learned/Summary [Repeated]

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  - RSF-k is a viable method to link permeability-response
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- **Modeling**
  - DRP models for friction and stability – gouge - compared with mixtures data
    - Local contact models confirm laboratory data for stability and permeability

Appendix Following

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

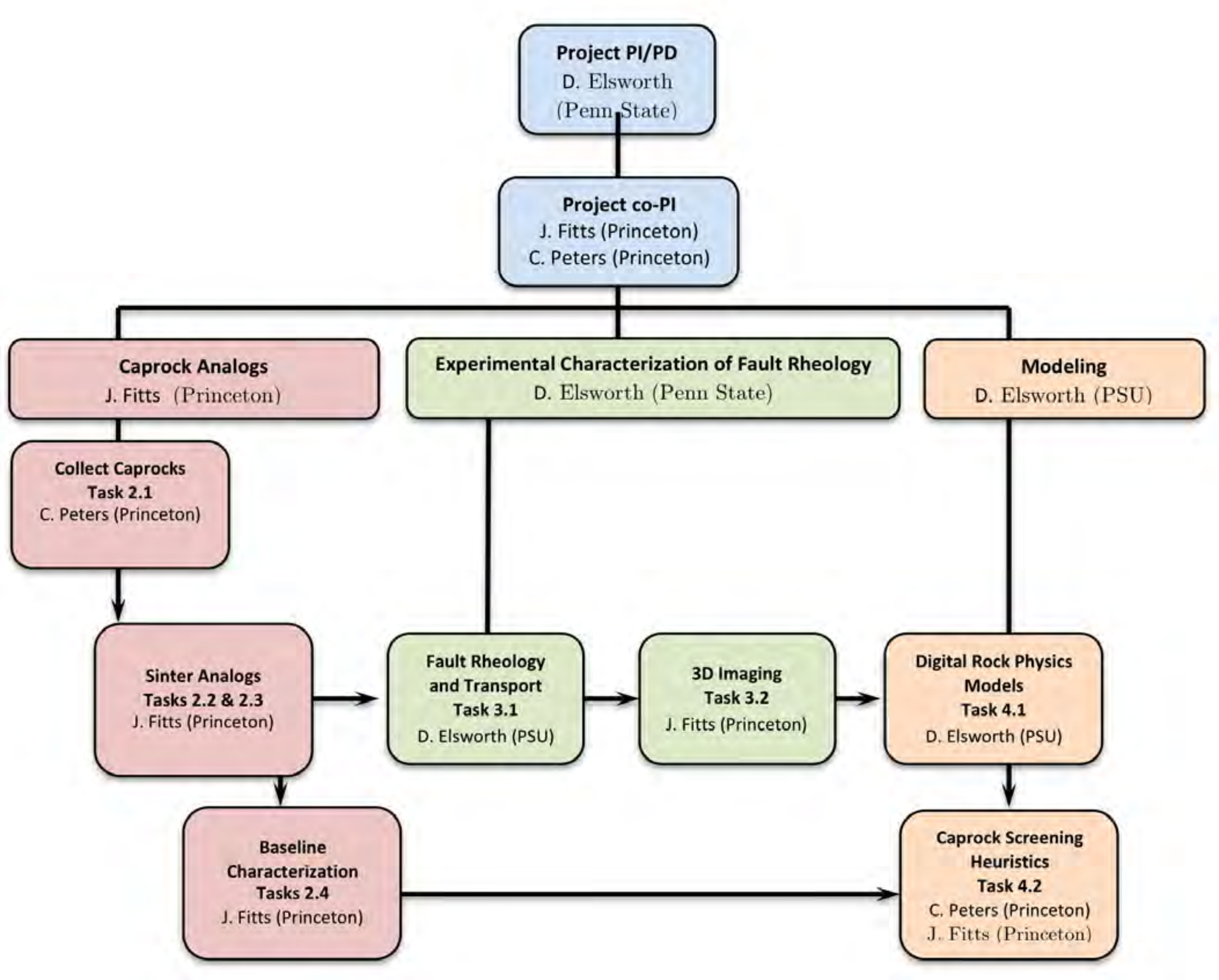
Examine geophysical and mineralogical controls of caprocks on:

- **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.

Organization Chart/ Communication Plan



Project PI/PD
D. Elsworth
(Penn State)

Project co-PI
J. Fitts (Princeton)
C. Peters (Princeton)

Caprock Analogs
J. Fitts (Princeton)

Experimental Characterization of Fault Rheology
D. Elsworth (Penn State)

Modeling
D. Elsworth (PSU)

Collect Caprocks
Task 2.1
C. Peters (Princeton)

Sinter Analogs
Tasks 2.2 & 2.3
J. Fitts (Princeton)

Fault Rheology and Transport
Task 3.1
D. Elsworth (PSU)

3D Imaging
Task 3.2
J. Fitts (Princeton)

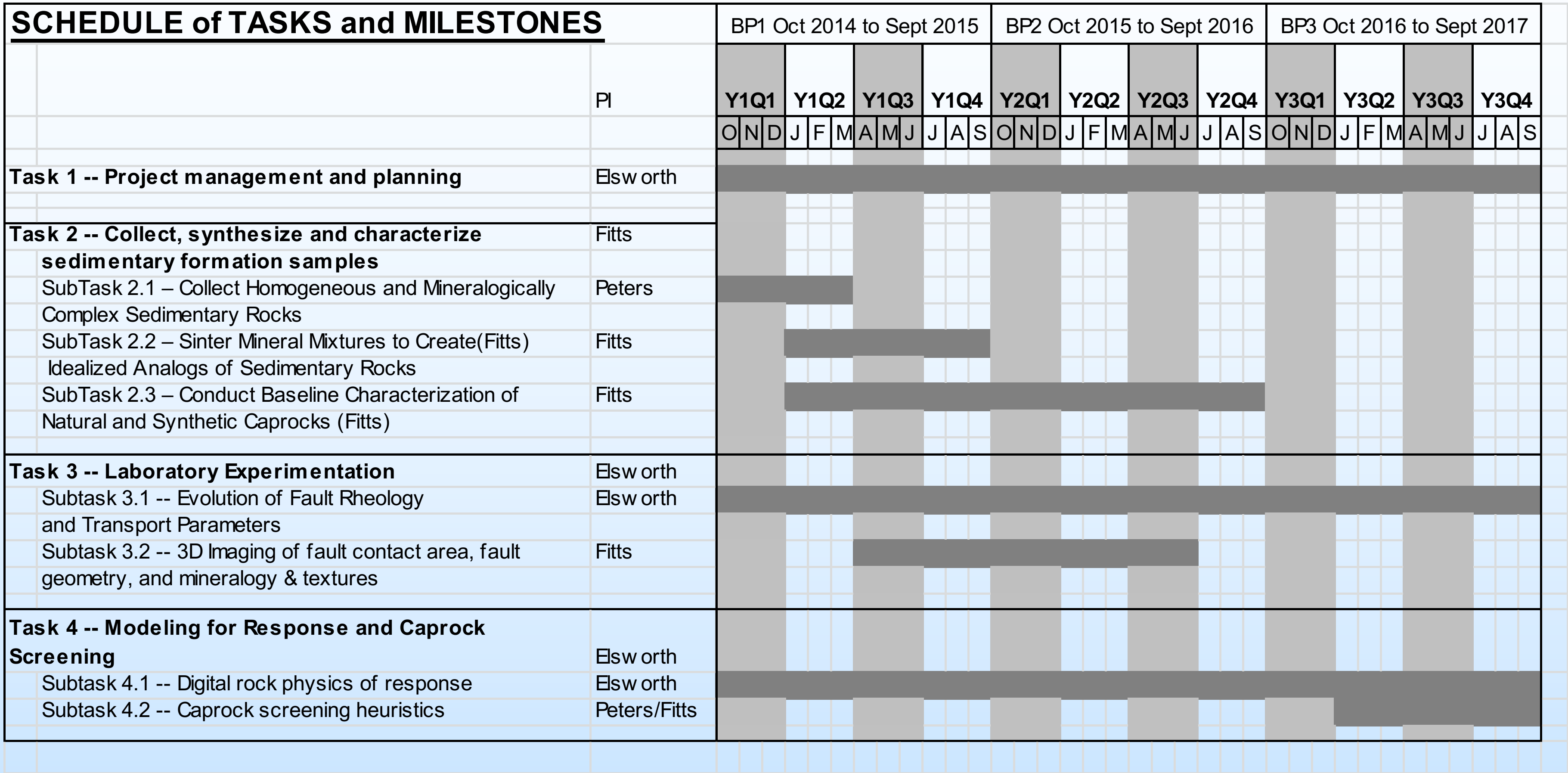
Digital Rock Physics Models
Task 4.1
D. Elsworth (PSU)

Baseline Characterization
Tasks 2.4
J. Fitts (Princeton)

Caprock Screening Heuristics
Task 4.2
C. Peters (Princeton)
J. Fitts (Princeton)

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			
	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										■	■	■

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