# Seismicity-Permeability Coupling in the Breaching and Sealing of Reservoirs and Caprocks

Derek Elsworth (Penn State), Yi Fang (PSU), Chaoyi Wang (PSU), Takuya Ishibashi (AIST/PSU), Yves Guglielmi (LBNL/Aix-Marseille), Kyunjae Im (PSU), Yunzhong Jia (PSU/NTU), Brandon Schwartz (PSU), Ziyan Li (PSU), Elif Yildirim (PSU), Andre Niemeijer (UU), Thibault Candela (TNO), Ben Madara (PSU), Mengke An (Tongji), Fengshou Zhang (Tongji), Jacques Riviere (Grenoble/PSU), Parisa Shokouhi (PSU), Chris Marone (PSU)

**Some Key Issues in Energy Supply**

- Needs
- Constraints and Solutions

**$CO_2$ Sequestration - Linking Induced Seismicity to Permeability Evolution**

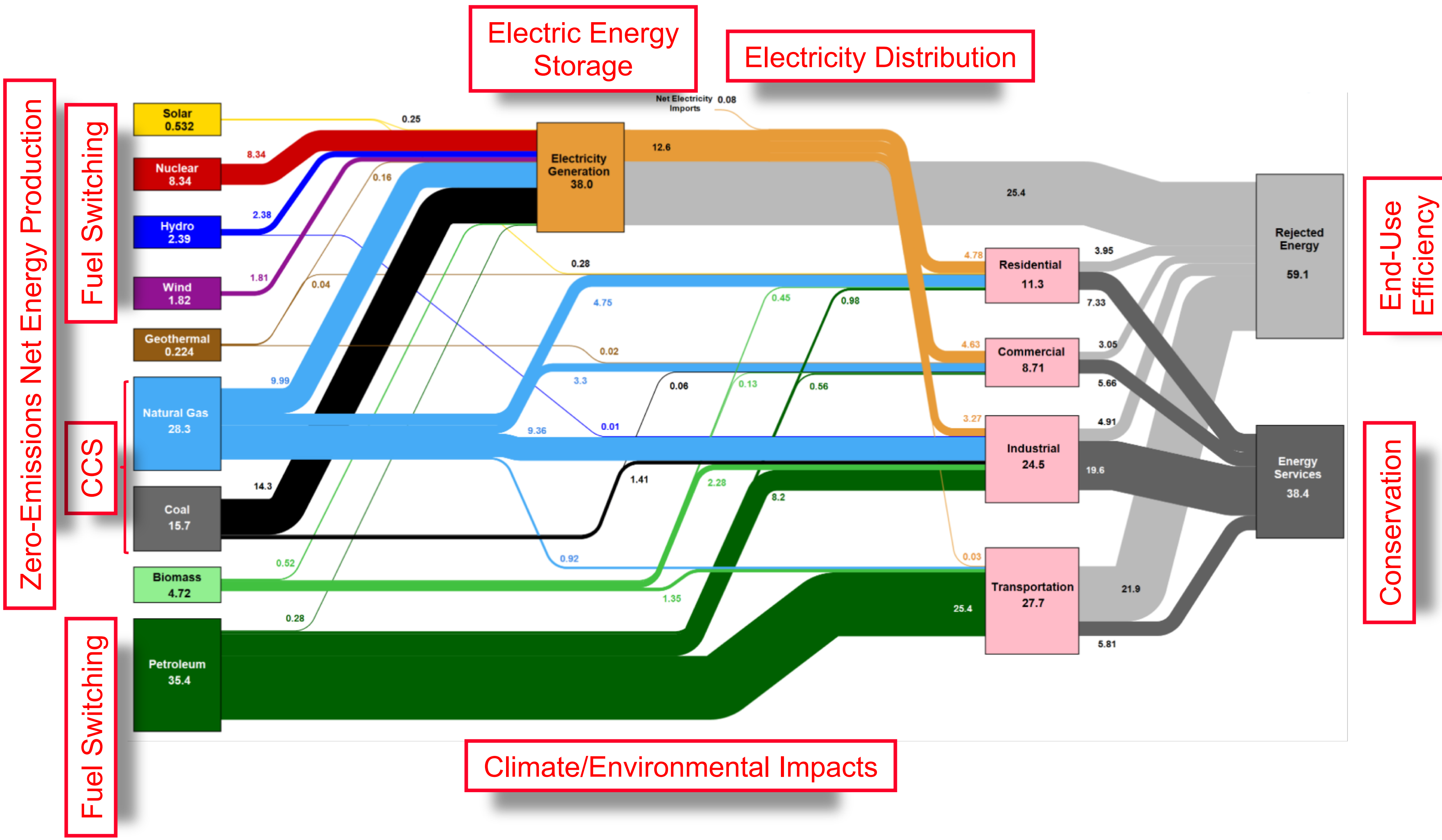
- Controls on seismicity – the aseismic-seismic transition
- Controls on maximum magnitude event
- RSF – for permeability evolution
- Controls on stability and permeability
  - Mineralogical & textural
  - Structural
- Healing and sealing and the seismic cycle

**Energy From Hot Rocks – EGS and SGRs**

- Anomalous seismicity – Newberry Demonstration Project
- Permeability scaling – Newberry Demonstration Project

**Summary**

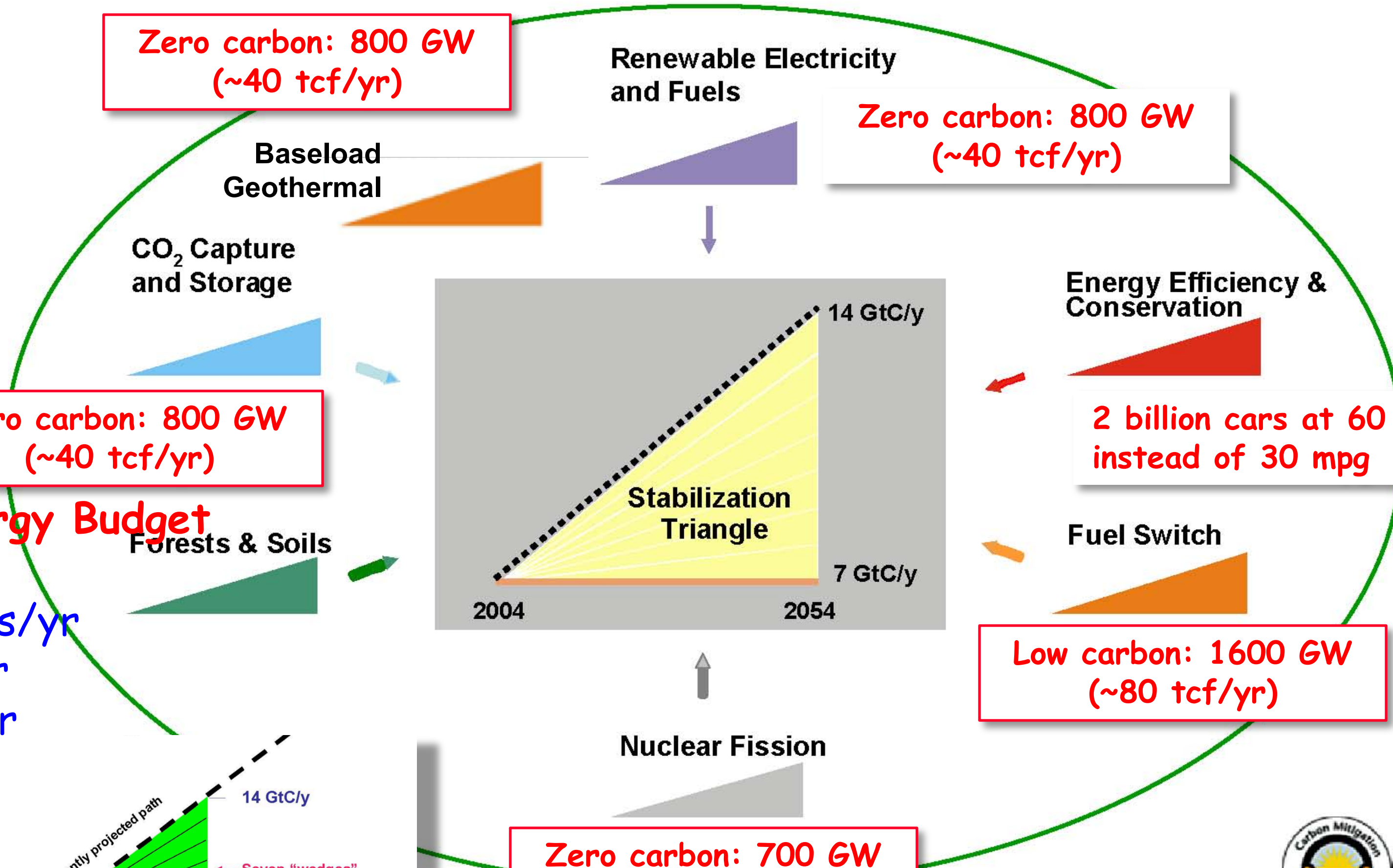
# US Energy Consumption 2015 – Key R&D Strategies
# ~100 Quads = 100 EJ = 100 tcf $CH_4$ (~20% of World)




[After Pat Dehmer, US DOE, Office of Science, 2009; Sankey Diagram from LLNL]

# Capacity Needs – Stabilization Wedges

## Fill the Stabilization Triangle with Seven Wedges




Zero carbon: 800 GW (~40 tcf/yr)

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2 billion cars at 60 mpg instead of 30 mpg

Low carbon: 1600 GW (~80 tcf/yr)

Zero carbon: 700 GW (~40 tcf/yr)

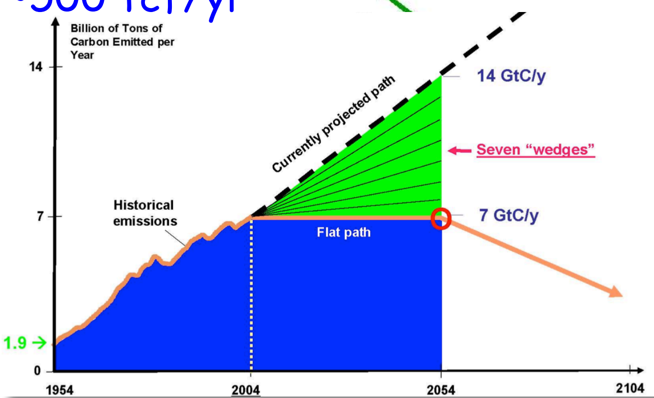
**Global Energy Budget**

~10-15TW

~500 Quads/yr

~500 EJ/yr

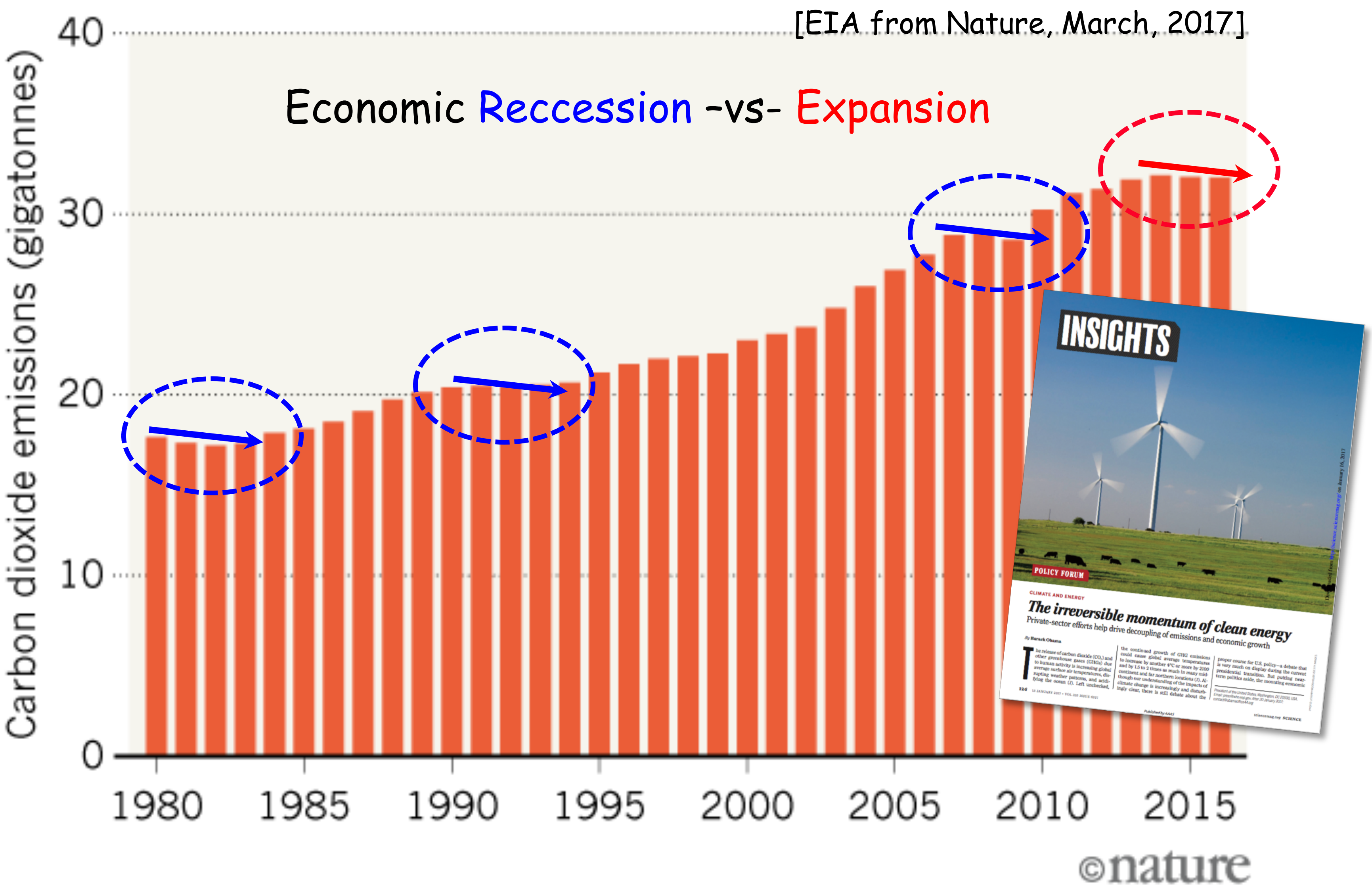
~500 tcf/yr




[**Rationale in:** Pacala & Socolow, *Science*, 2004, www.stabilisation2005.com/day3/**Socolow**.pdf]

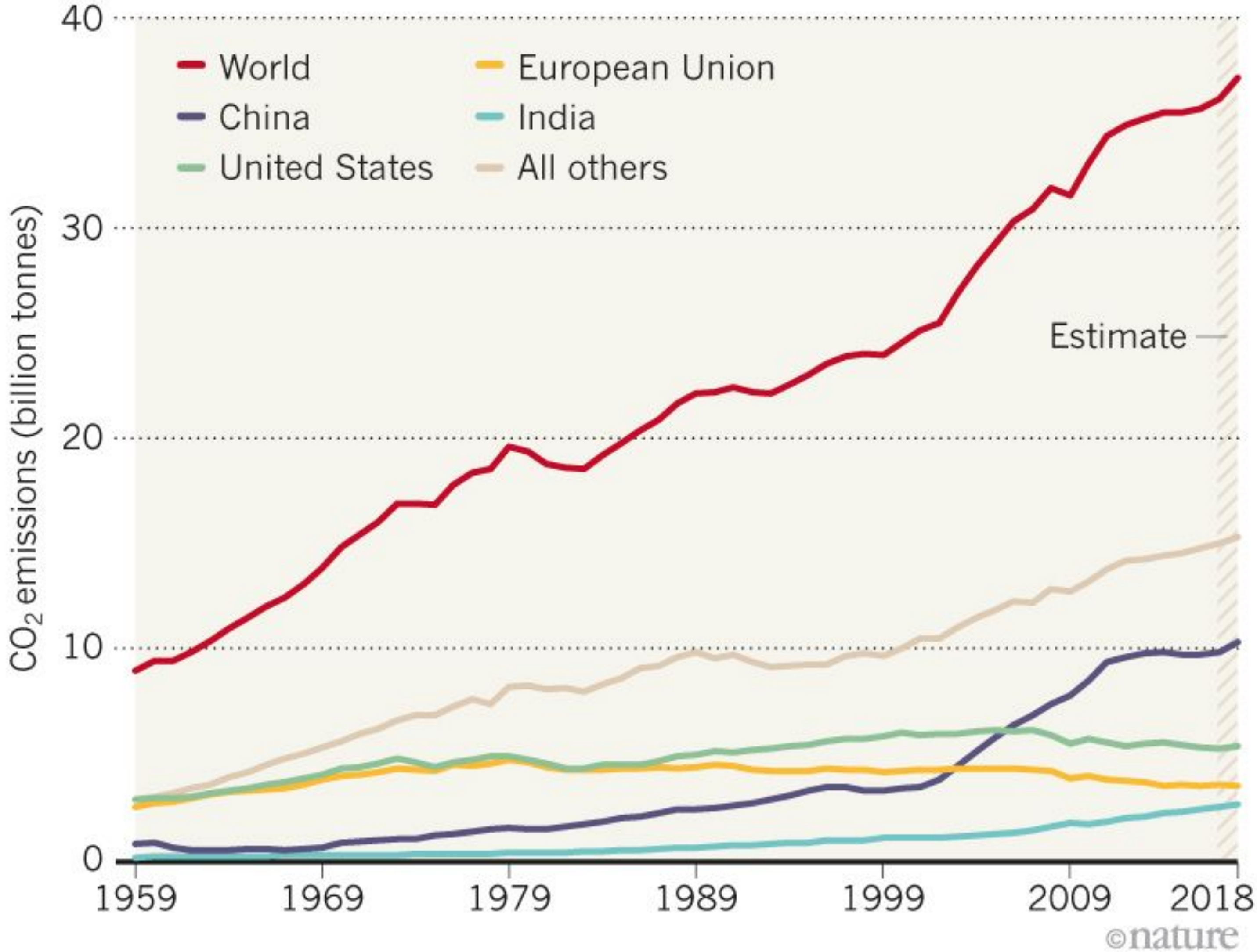
# CARBON DIOXIDE EMISSIONS FLAT FOR THIRD YEAR

Rising renewables use and improvements in energy efficiency have kept the world's carbon dioxide emissions stable.



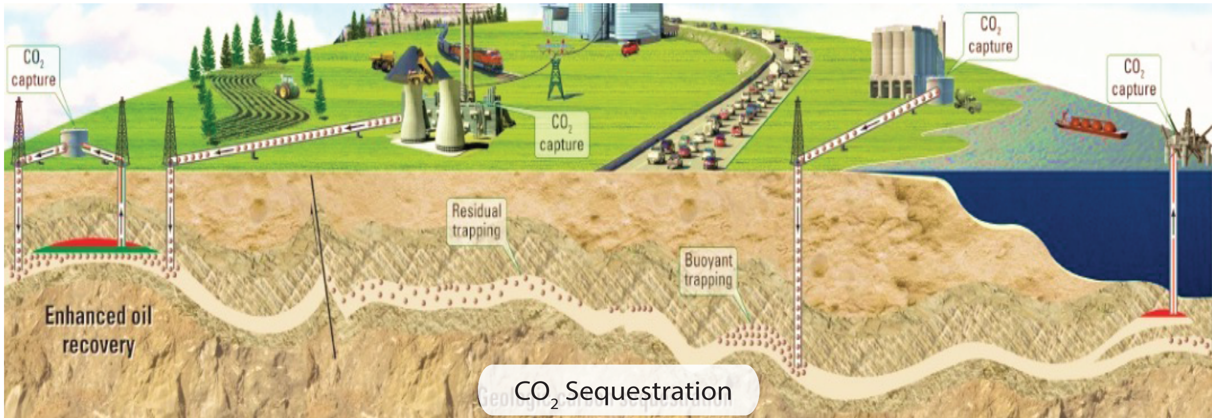
# $CO_2$ EMISSIONS KEEP ON RISING

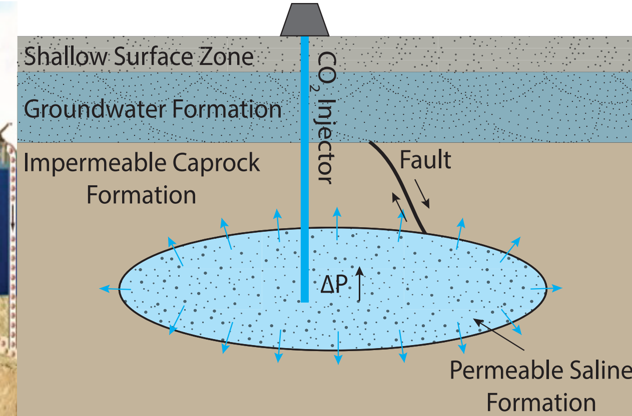
Industrial carbon-dioxide emissions are projected to rise again globally this year, even as individual countries' emissions look very different.

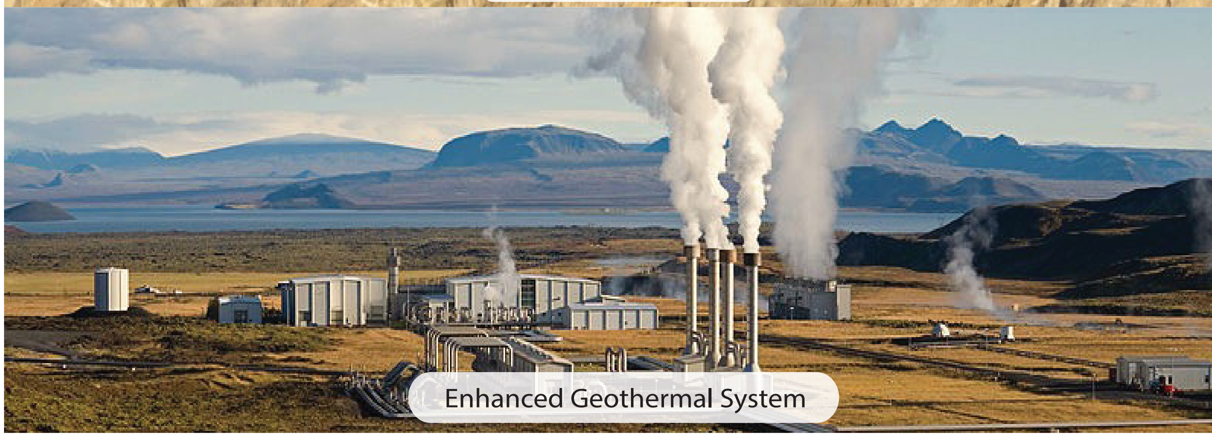


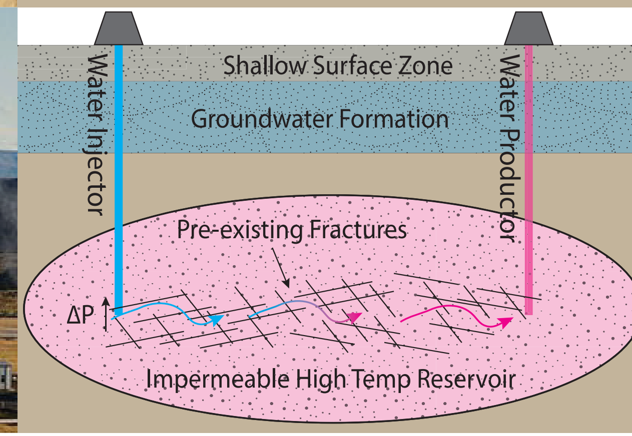

[From Nature, December, 2018]

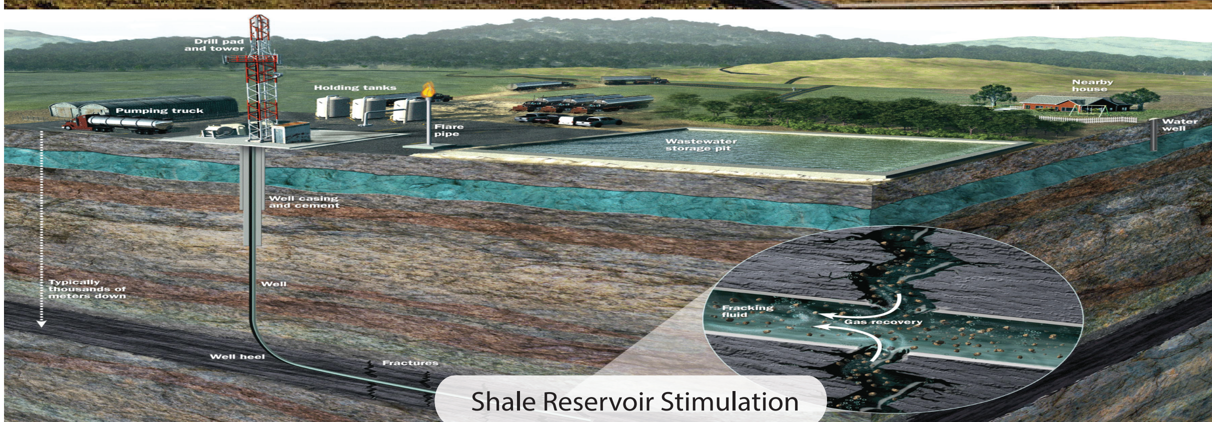
# Mechanical/Stability and Transport Properties of Fractured Rocks

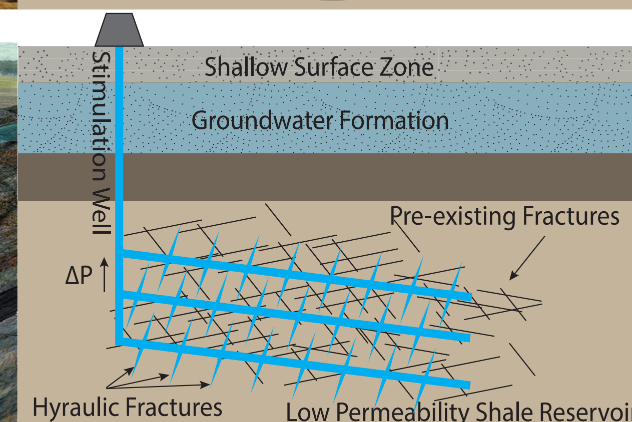


# Sub-Surface Geoengineering – Some Key Issues in Sustainable Recovery of Energy Resources

## "All-of-the-Above"

## Sequestration ($CO_2$/HLW)

- Permeability-seismicity coupling
  - Seismic-aseismic deformation and implications
  - Scale dependencies
  - Rational models for permeability-seismicity linkage

## Gas Shales – making permeability

- Making permeability - Gas fracturing
- Sustaining permeability in fracs/refracs
- Elevating long term permeability - dp, dc, dT

## EGS Geothermal Resources – controlling permeability

- Uniform sweep – permeability control
  - Complex coupled process interactions
  - Manifold approaches
  - Permeability-seismicity linkage for characterization
  - True control and engineering of reservoirs & migration of O/G technology

## Summary

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# Induced Seismicity

NEWSFOCUS

Ohio rumblings. Wastewater injected at this site in Youngstown triggered jolting earthquakes that prompted injection-well shutdowns and strong new regulations.

SEISMOLOGY

## Learning How to NOT Make Your Own Earthquakes

**As fluid injections into Earth's crust trigger quakes across the United States, researchers are scrambling to learn how to avoid making more**

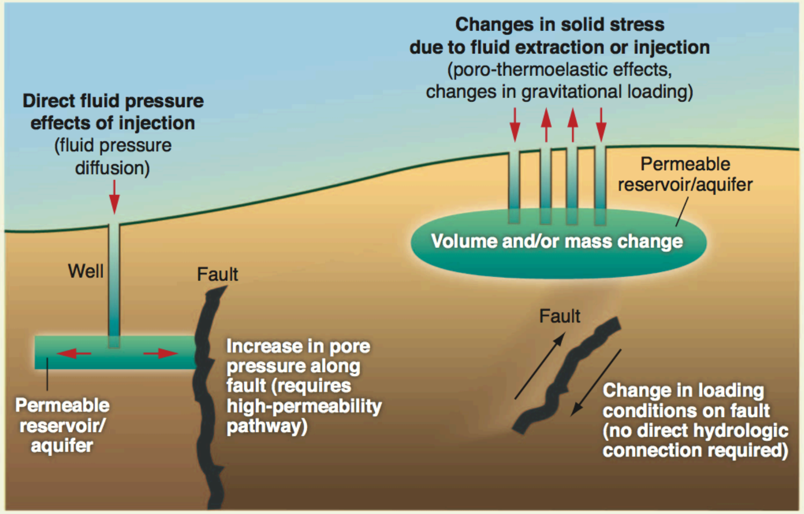
First off, fracking for shale gas is not touching off the earthquakes that have been shaking previously calm regions from New Mexico to Texas, Ohio, and Arkansas. But all manner of other energy-related fluid injection—including deep disposal of fracking's wastewater, seismicity, they are beginning to see a way ahead: learn as you go. Thorough preinjection studies followed by close monitoring of cautiously increasing injection offer to lower, although never eliminate, the risk of triggering intolerable earthquakes.

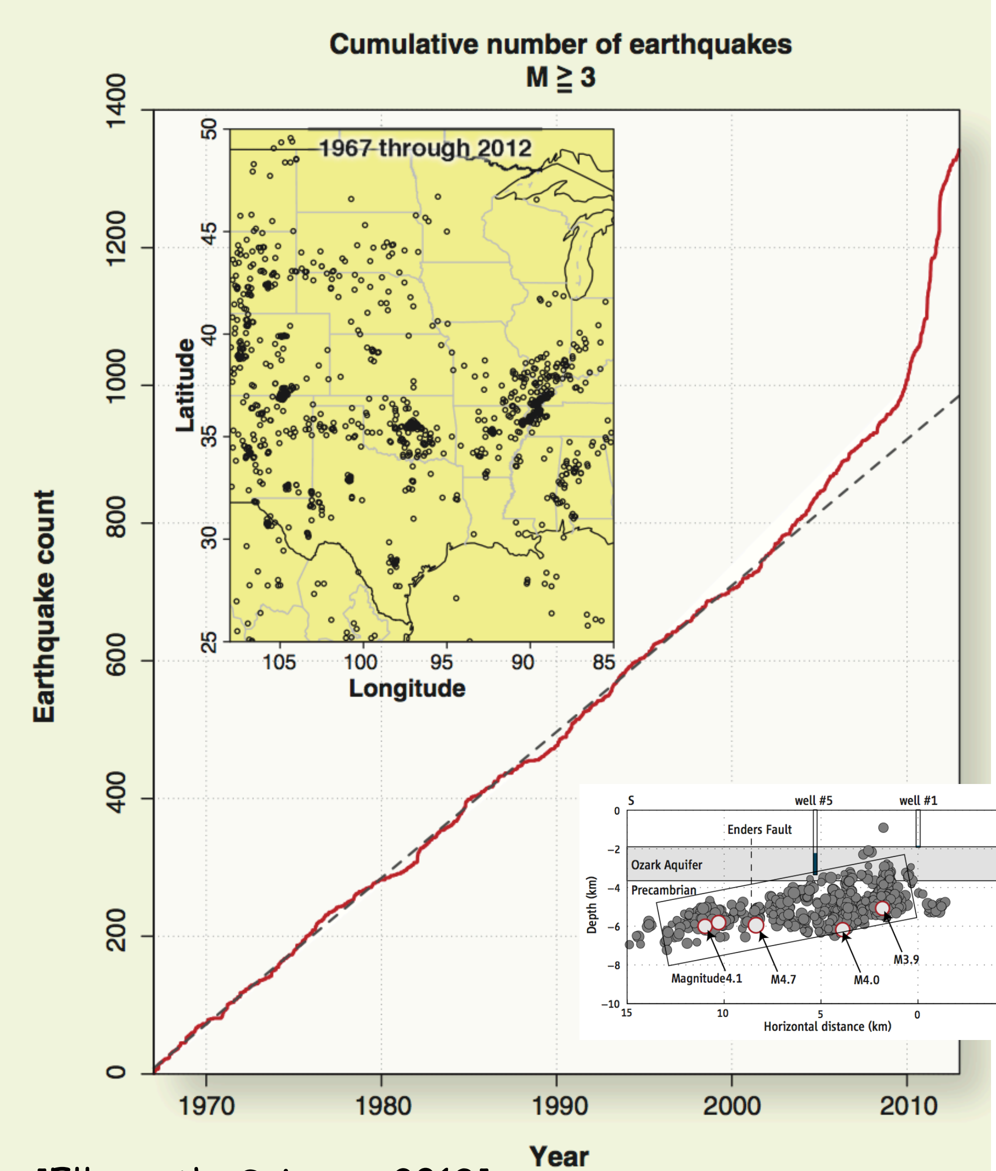
Arkansas. In the current March/April issue of *Seismological Research Letters*, the University of Memphis seismologist recounts his learn-as-you-go experience with injection-triggered quakes strong enough to seriously shake up the locals.

Fracking for natural gas, formally known as hydraulic fracturing, had come to Arkansas around 2009. Not that a seismologist in Memphis would have noticed. Injecting water into gas-bearing shale at high pressures does break the rock to free the gas—that's the point, after all. But the resulting tiny quakes rarely get above magnitude 0 (the logarithmic scale includes negative numbers), never mind to the magnitude-3 quakes that people might feel.

But shale gas drillers need to dispose of the millions of liters of water laden with natural brines and added chemicals that flow back up after a shale gas well has been fracked (*Science*, 25 June 2010, p. 1624). Injecting fracking wastewater into deep rock is a common solution, so starting in April 2009, 1- to 3-kilometer-deep disposal wells were sunk in the vicinity of Guy (population 706) and Greenbrier (population 4706), Arkansas.

That's when Horton and Scott Ausbrooks of the Arkansas Geological Survey took note of a curious cluster of earthquakes near Greenbrier. The Guy-Greenbrier area had had only one quake of magnitude 2.5 or greater in 2007 and two in 2008. But there were

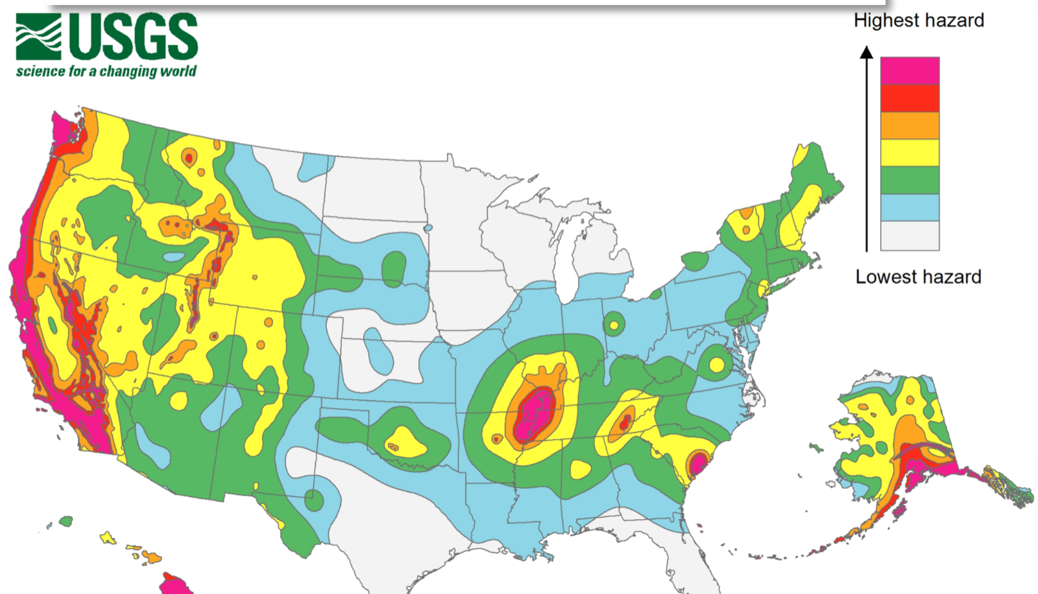


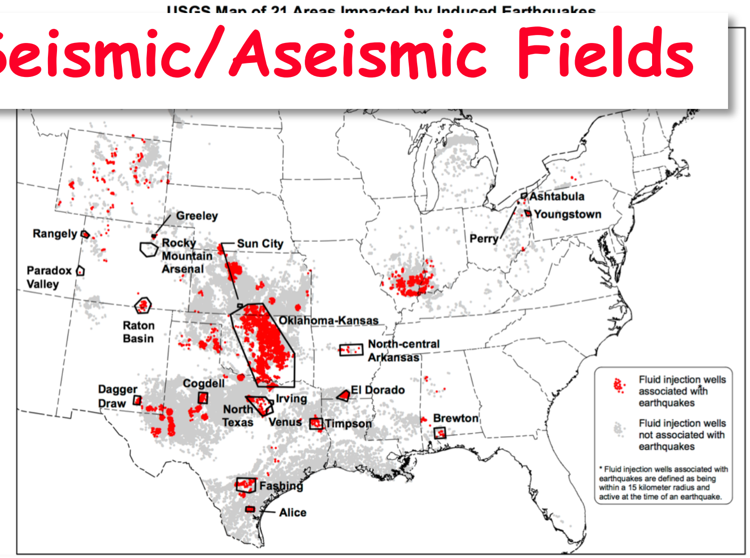

[Ellsworth, Science, 2013]

# Induced Seismicity

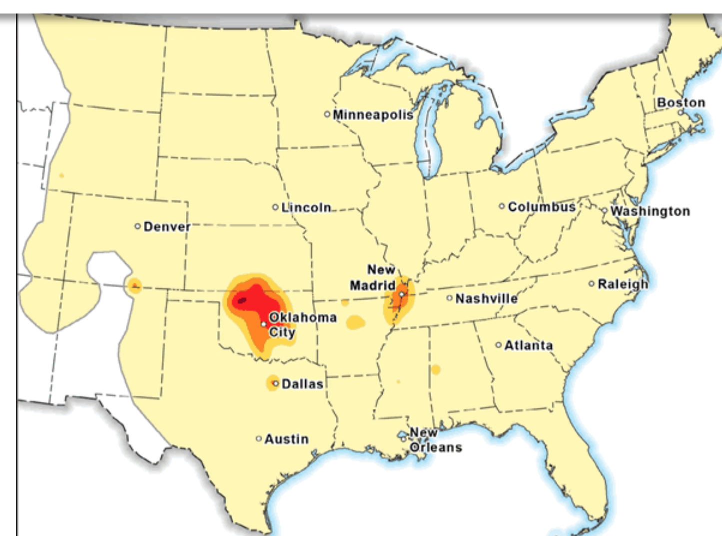
## US Seismic Hazard

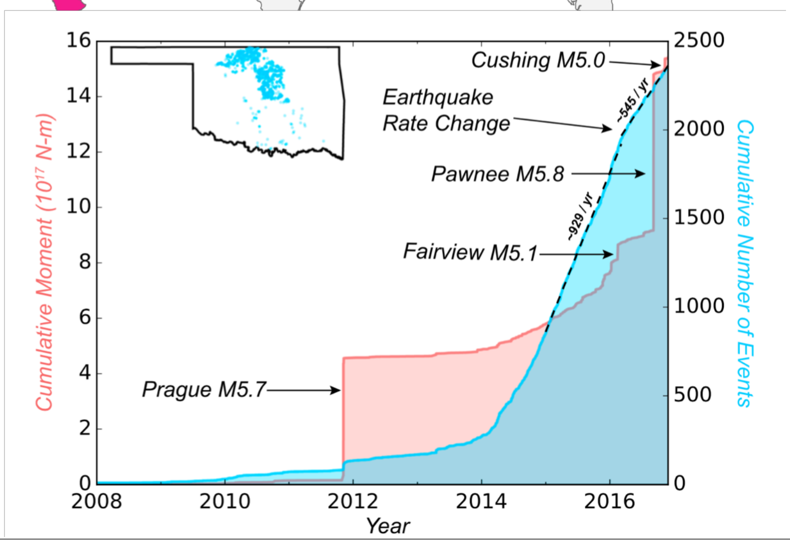



## Seismic/Aseismic Fields

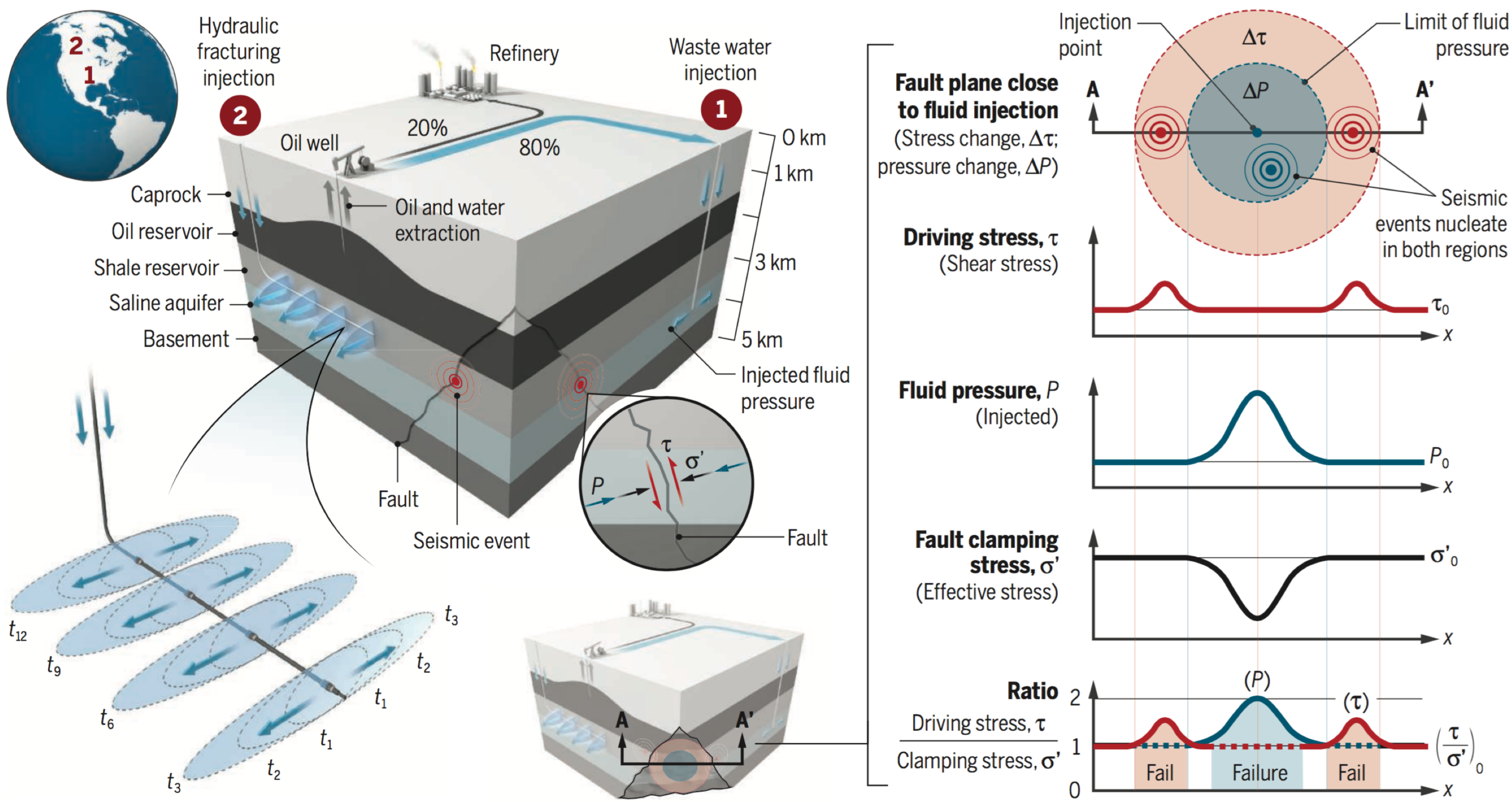



## Mid-west Seismic Hazard



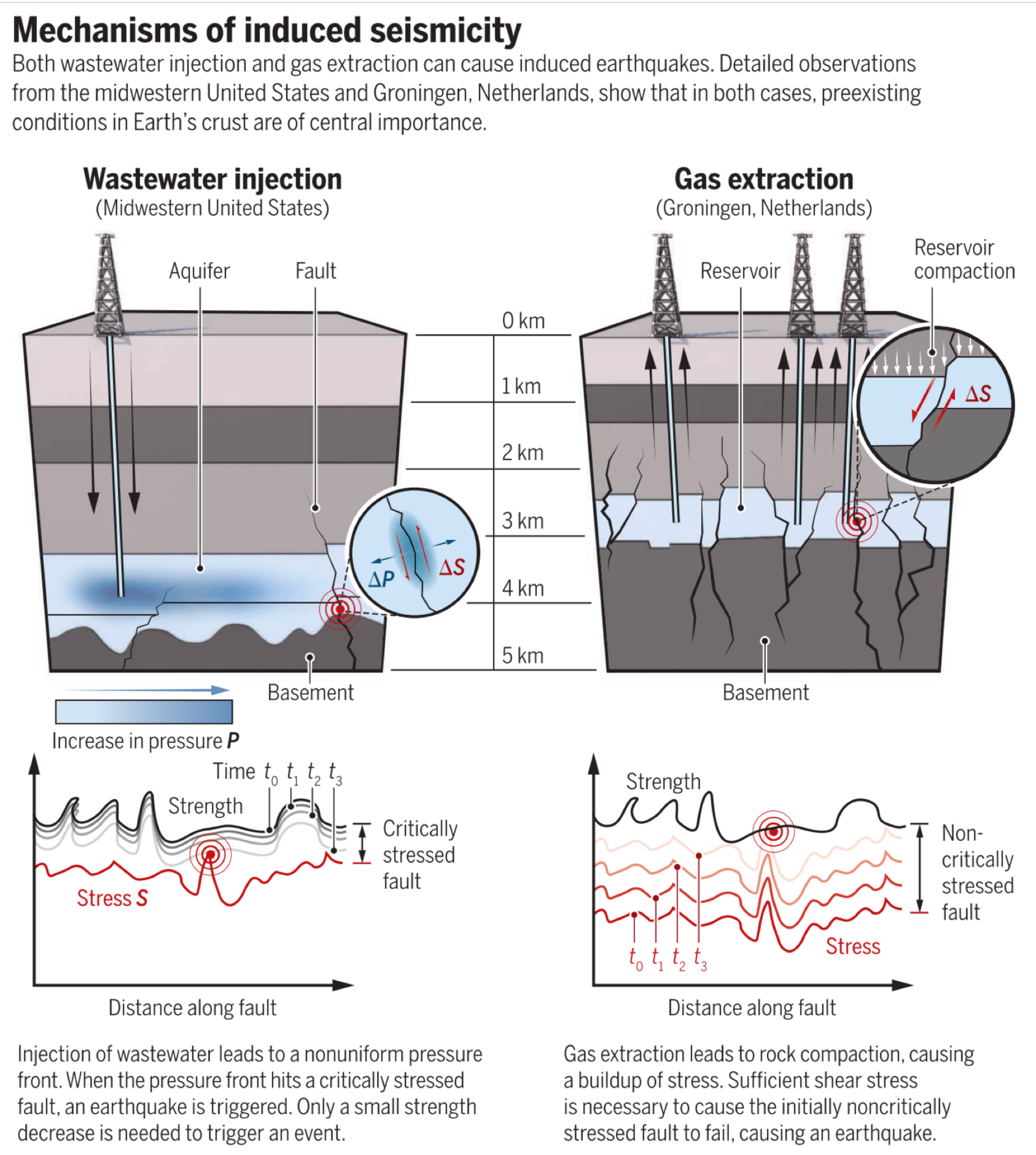



# Induced Seismicity




[Elsworth et al., Science, 2016]

# Mechanisms of Induced Seismicity

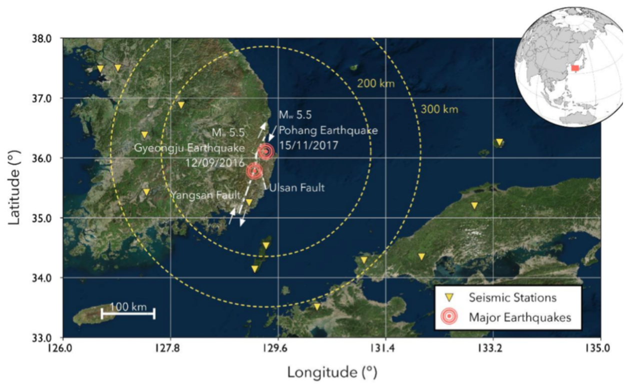


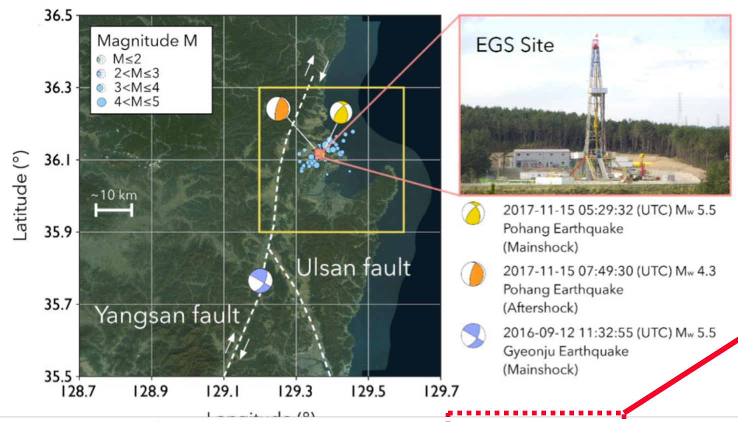


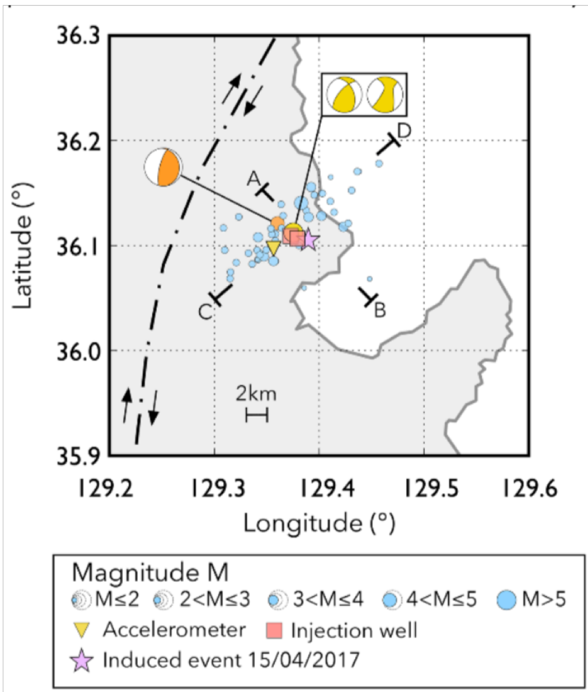
[Candela et al., Science, 2018]

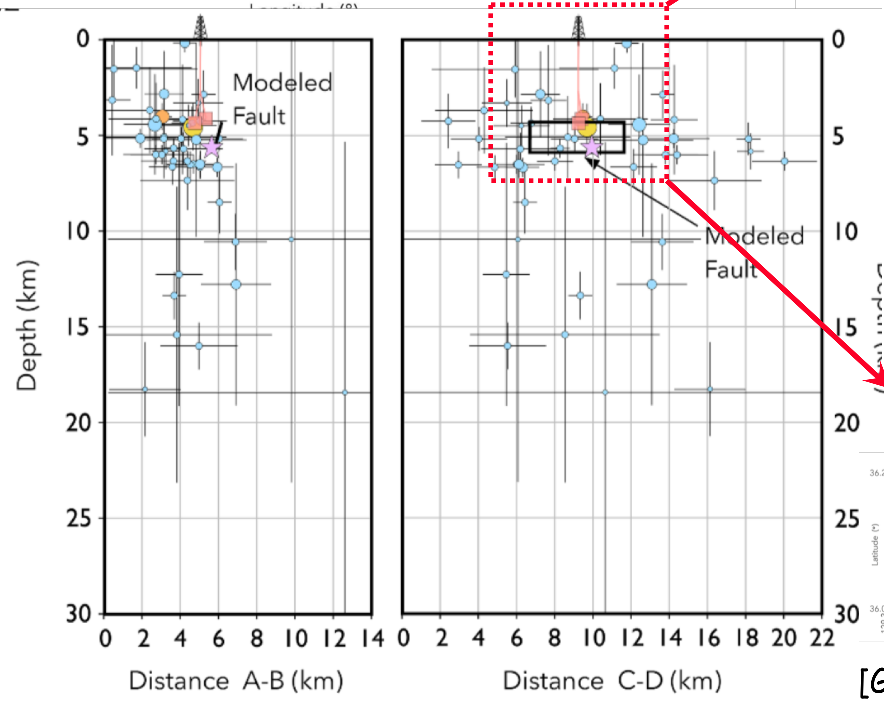
# Pohang (South Korea) Earthquake (2017) Mw~5.5

## EGS Stimulation Related?



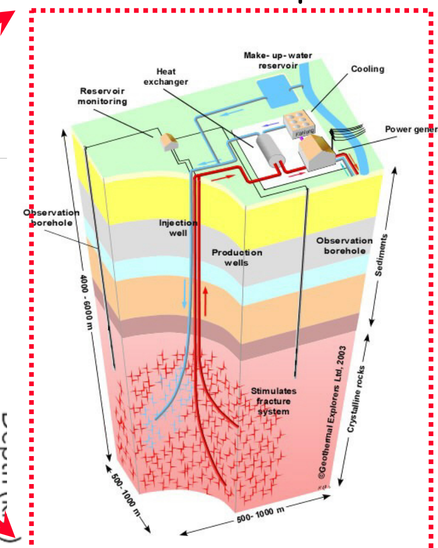



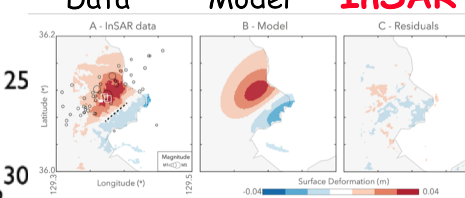




Anatomy of the EQ

- 15th century EQs Mw~7
- Mw<5 since instrumental recording in 1903
- Mw~5.5 ~30km south of EGS
- Mw~5.5 Pohang ~4km depth
- Same strike-slip fault

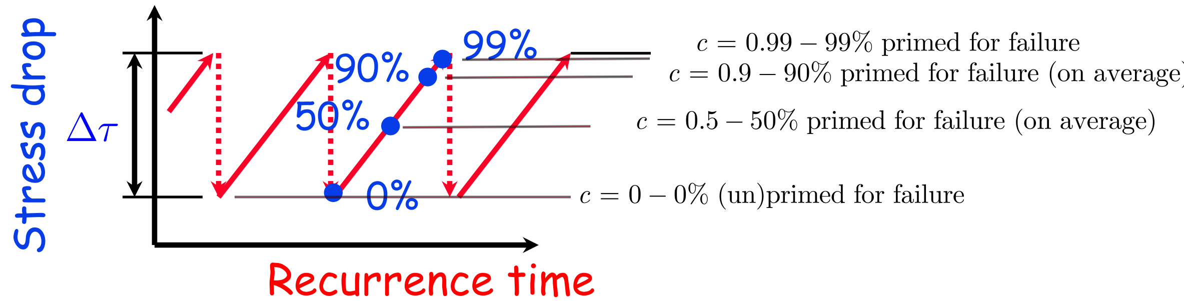



Data Model **InSAR**




[Grigoli et al., Science, 2018]

# Maximum Event Magnitude – Equivalent Porous Medium




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

## Moment Magnitude (Deviatoric)

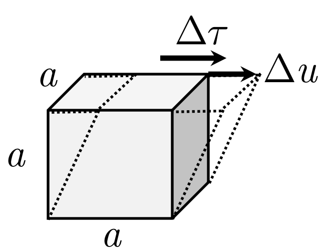
$$M = AG\Delta u$$

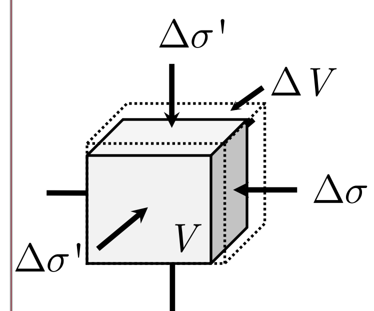
$$M = a^3 G \frac{\Delta u}{a}$$

$$M = VG\gamma$$

$$M = V\Delta\tau$$

$$\Delta\tau = \frac{M}{V}$$




## Stress-Strain (Spherical)

$$\Delta\sigma' = \Delta\sigma - \alpha\Delta p \; (\Delta\sigma = 0)$$

$$\alpha\Delta p = K \frac{\Delta V}{V}$$

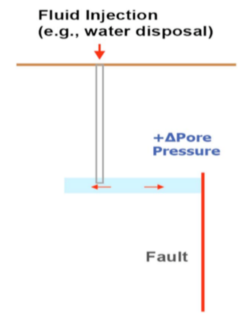
$$\alpha\Delta p = \frac{2}{3}\frac{(1+\nu)}{(1-2\nu)} G \frac{\Delta V}{V}$$

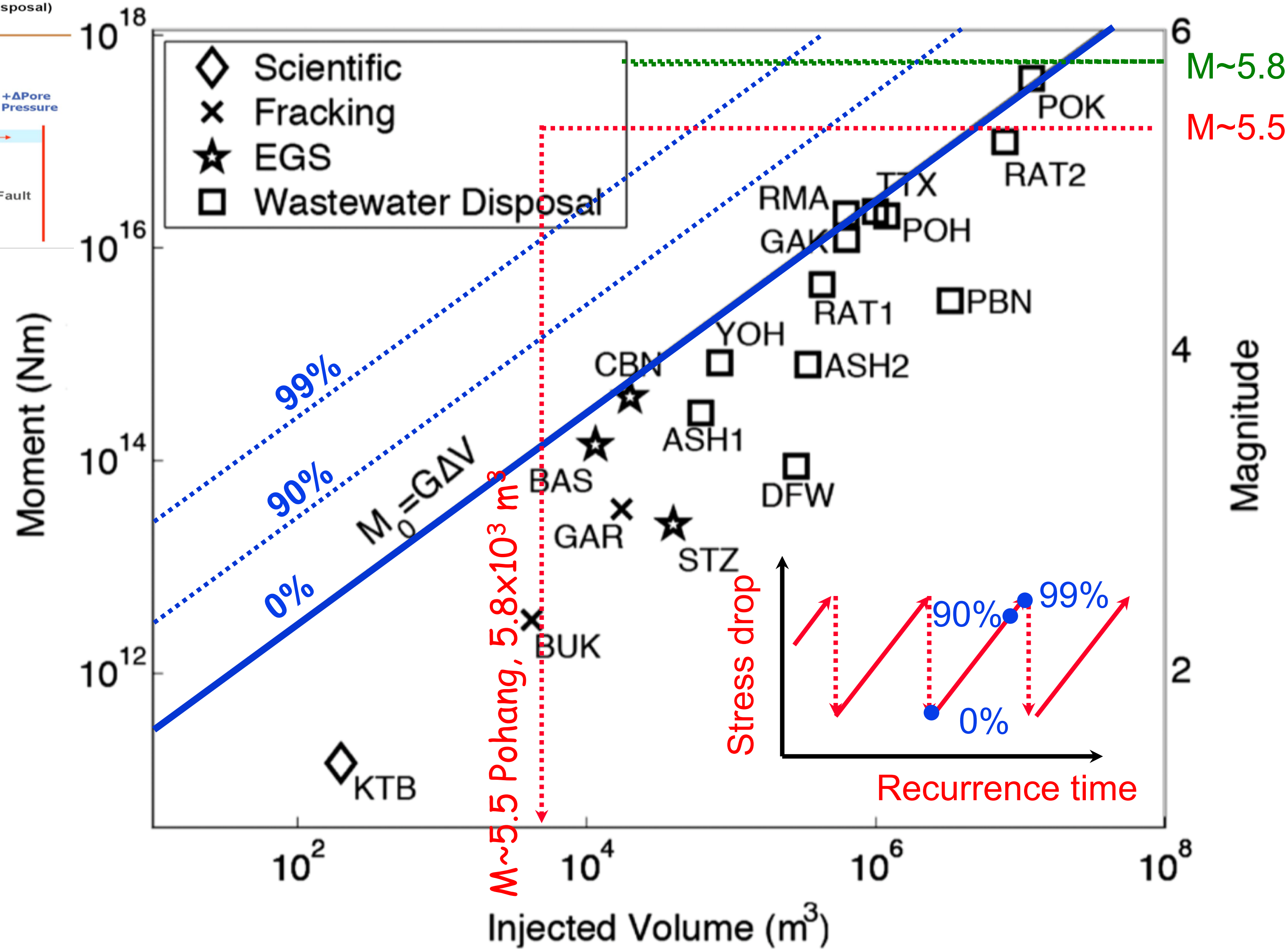
$$M = \frac{2}{3}\frac{(1+\nu)}{(1-2\nu)} \frac{1}{(1-c)} \mu G \Delta V$$

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

Modified from [McGarr, JGR, 1976 & 2014]

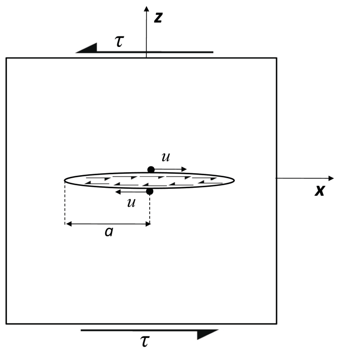
# Maximum Anticipated Moment Magnitude – M or M_dot? $M_{Gross}$ or $M_{Net}$? Triggered -vs- Induced?

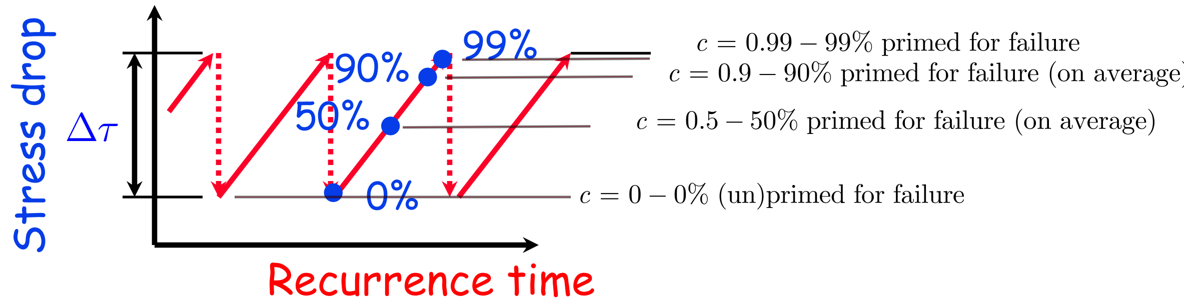



After [McGarr, JGR, 2014]

# Maximum Event Magnitude - Penny-Shaped Crack




## Moment Magnitude (Deviatoric)

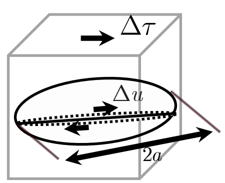
$$M = AG\Delta\bar{u}$$

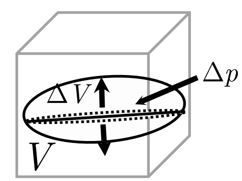
$$\Delta\bar{u} = \frac{8(1-\nu)}{3(2-\nu)}\frac{\Delta\tau a}{G\pi}$$

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

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

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




## Stress-Strain (Spherical)

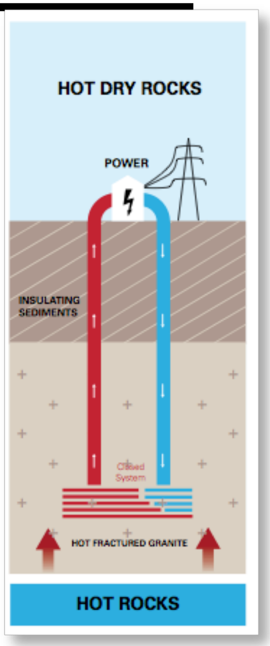
$$\frac{\Delta V}{A} = \frac{16(1-\nu^2)}{3\pi}\frac{\Delta p\, a}{E}$$

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

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

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

# Anticipated Thermal Stressing in EGS




**For a closed system in thermal equilibrium:**

Heat carried by water: $H = \Delta V \rho_f c_f \Delta T_f$

Heat in closed system: $H = V(n\rho_f c_f + (1-n)\rho_s c_s)\Delta T_{res}$

Volume*Temperature Product: $V\Delta T_{res} = \Delta V \Delta T_f \frac{1}{(n+(1-n)\frac{\rho_R c_R}{\rho_f c_f})}$

Event magnitude: $M = \frac{1}{(1-c)} G \alpha_T V \Delta T_{res} \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}$

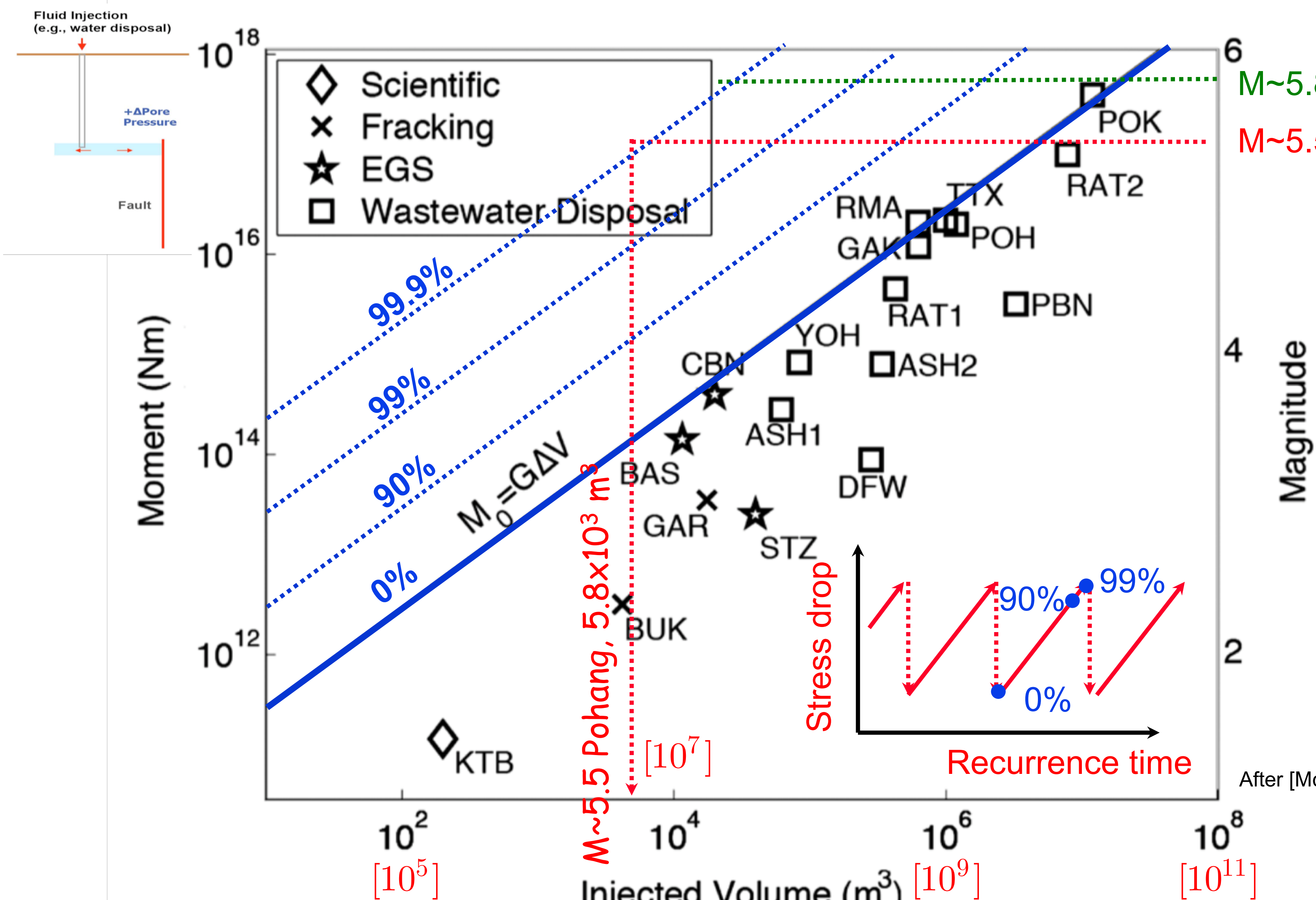
Injected volume: $M = \frac{1}{(1-c)} G \alpha_T \Delta V \Delta T_f \frac{1}{(n+(1-n)\frac{\rho_R c_R}{\rho_f c_f})} \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}$

**For an open and circulating system** (last term loses the preceding porosity):

$$M = \frac{1}{(1-c)} G \Delta V [\underbrace{\alpha_T \Delta T_f \frac{1}{(1-n)} \frac{\rho_f c_f}{\rho_R c_R}}_{postfactor}] \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}$$

$$postfactor = O[10^{-5}(1/K) \times 100(K) \times 1 \times 1/2] \sim 10^{-3}$$

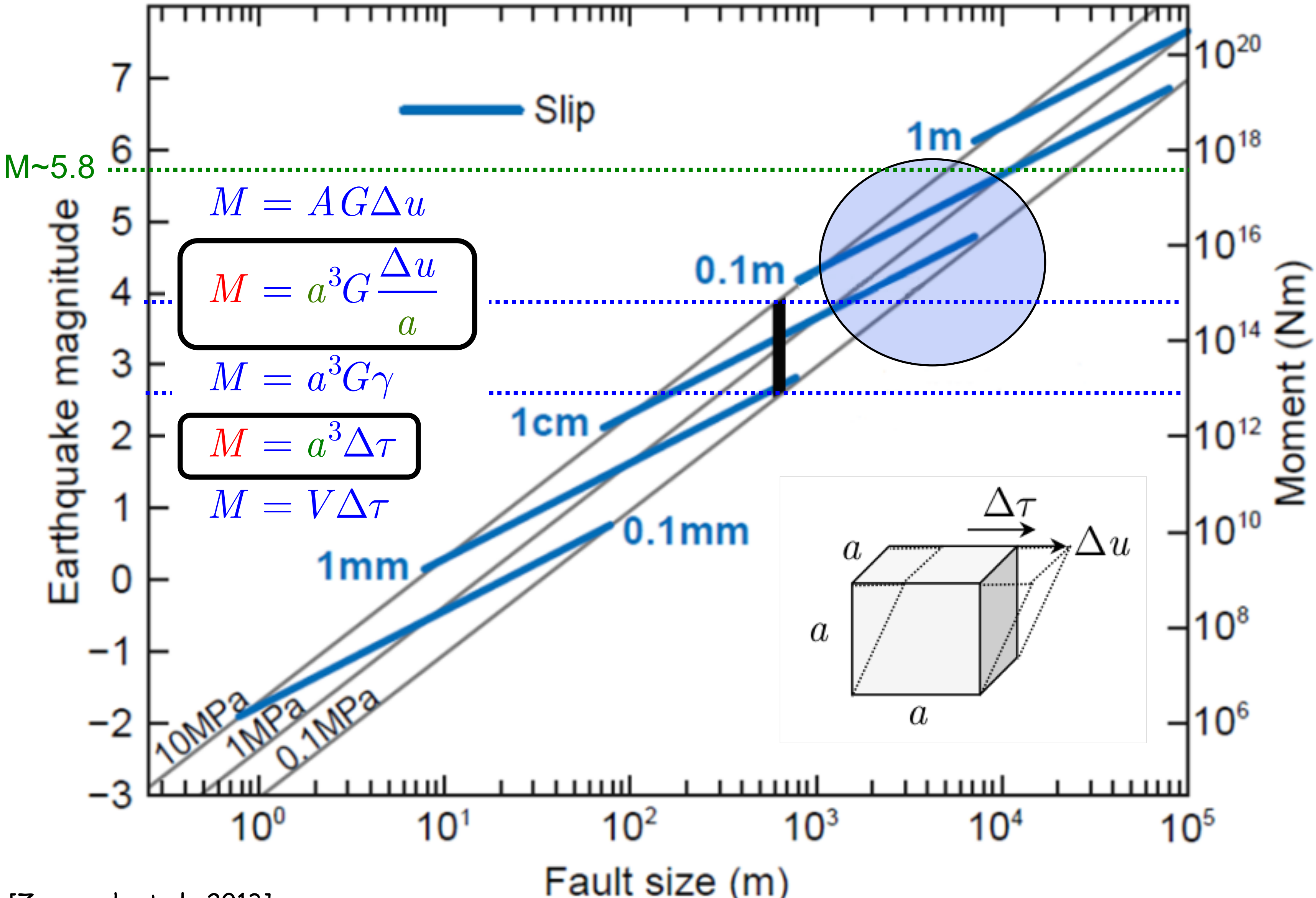
# Fluid Pressure –versus– Thermal Stressing-based Reactivation




After [McGarr, JGR, 2014]

Equivalent Throughflow Volume (m³) for Thermal Reactivation

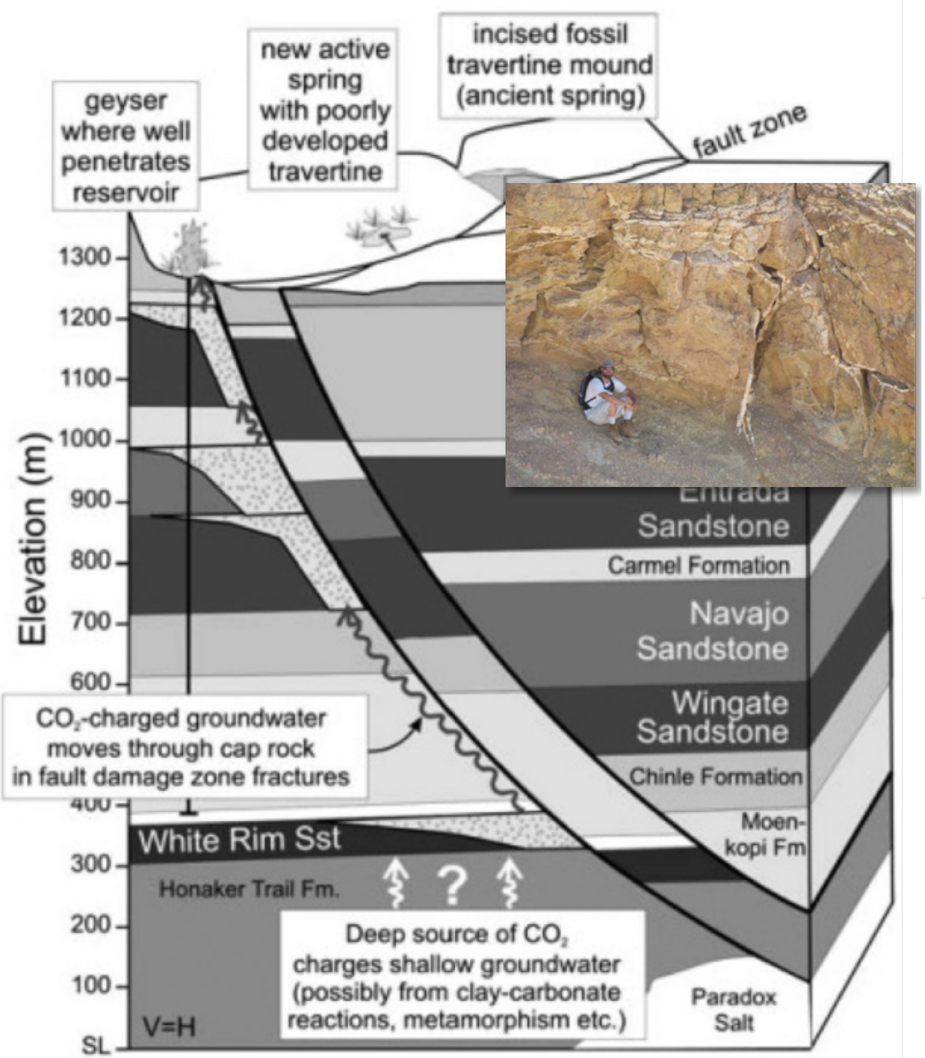
# Shear Offset Scaling - Seismic Only



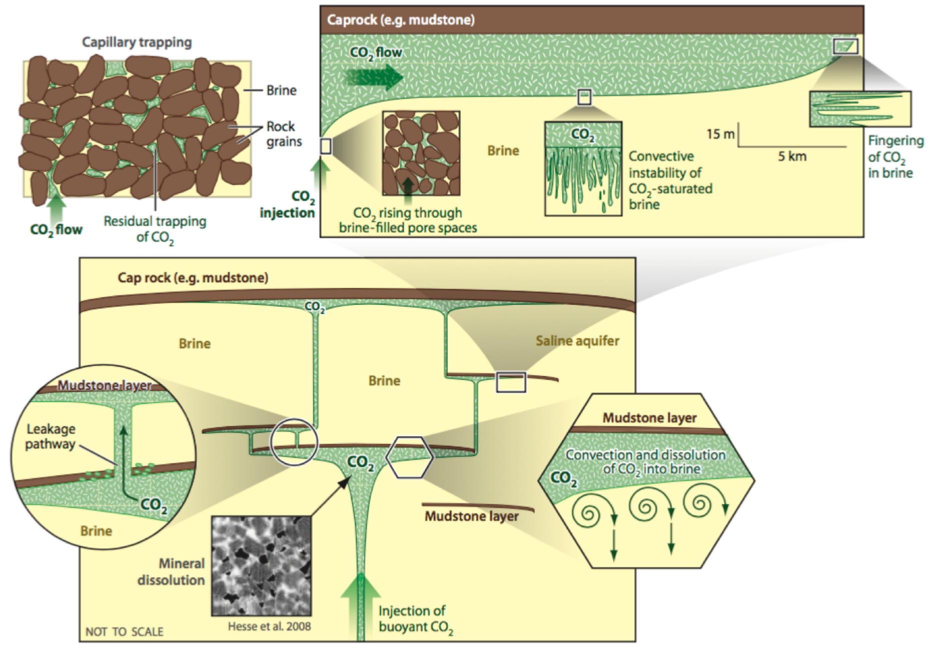

[Zangeneh et al., 2013]

# Fault Zones as Seals and Pathways

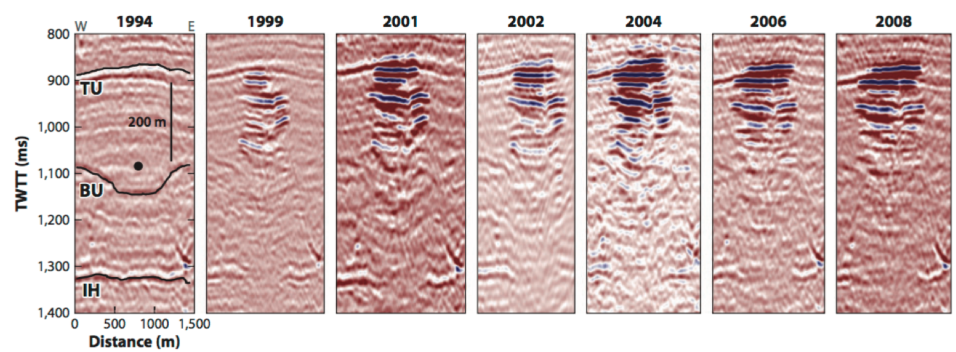
## Little Grand Wash Fault, UT




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

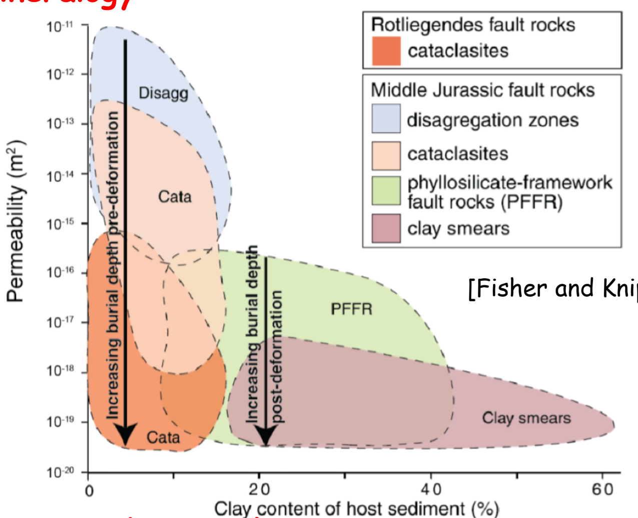



[Huppert and Neufeld, Ann. Rev. Fluid Mechs., 2014]



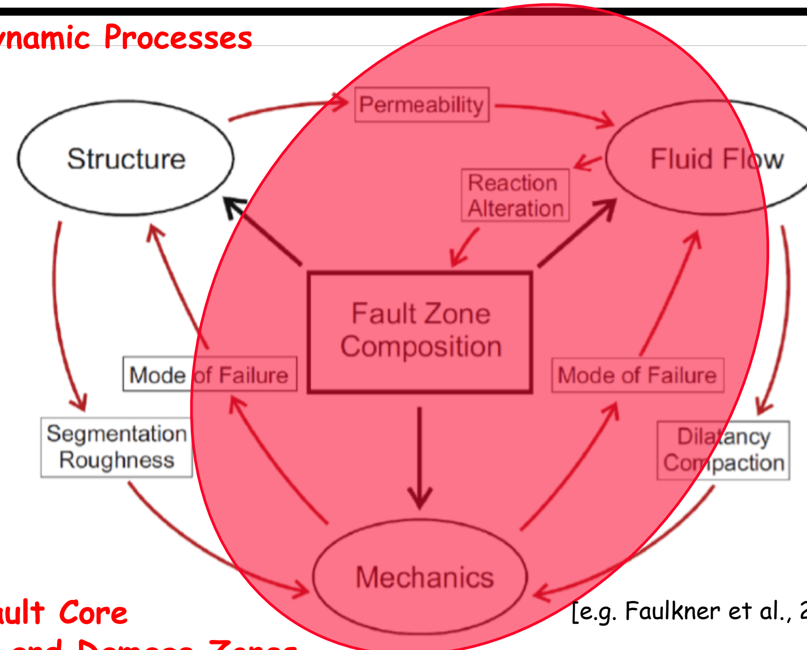
# Controls on Permeability Structure

## Mineralogy



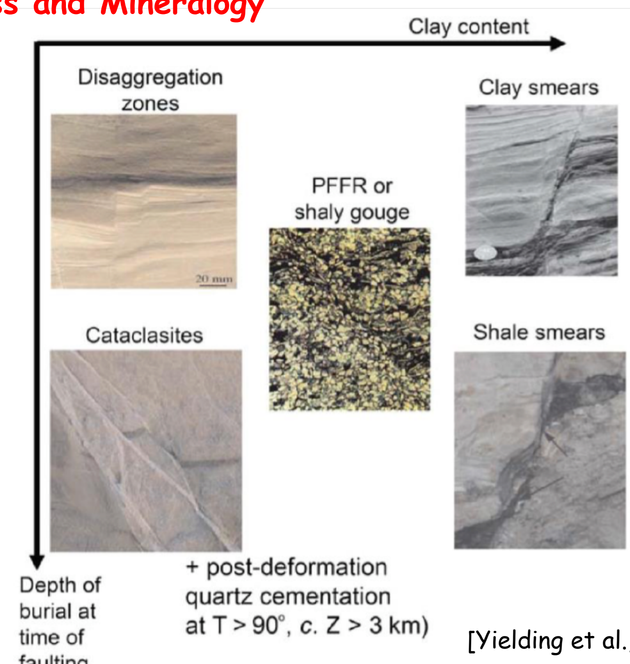

[Fisher and Knipe, 2001]

## Dynamic Processes




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

## Stress and Mineralogy

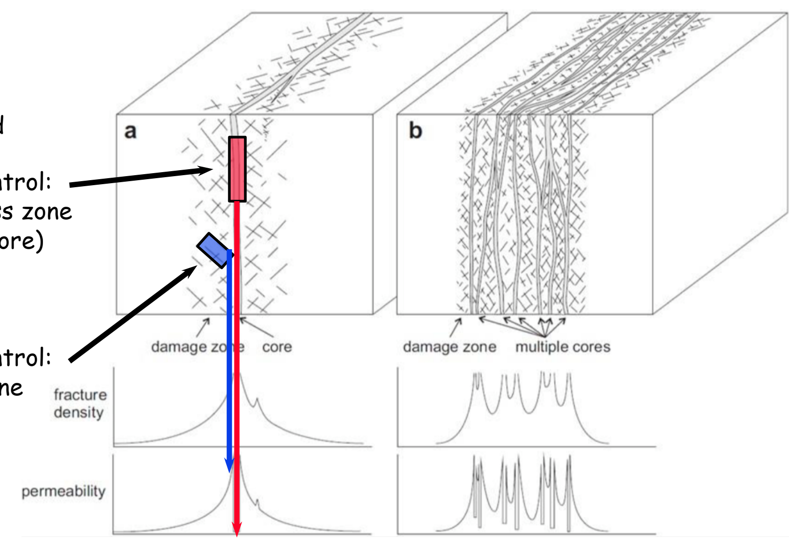



[Yielding et al., 2010]

## Fault Core and Damage Zones

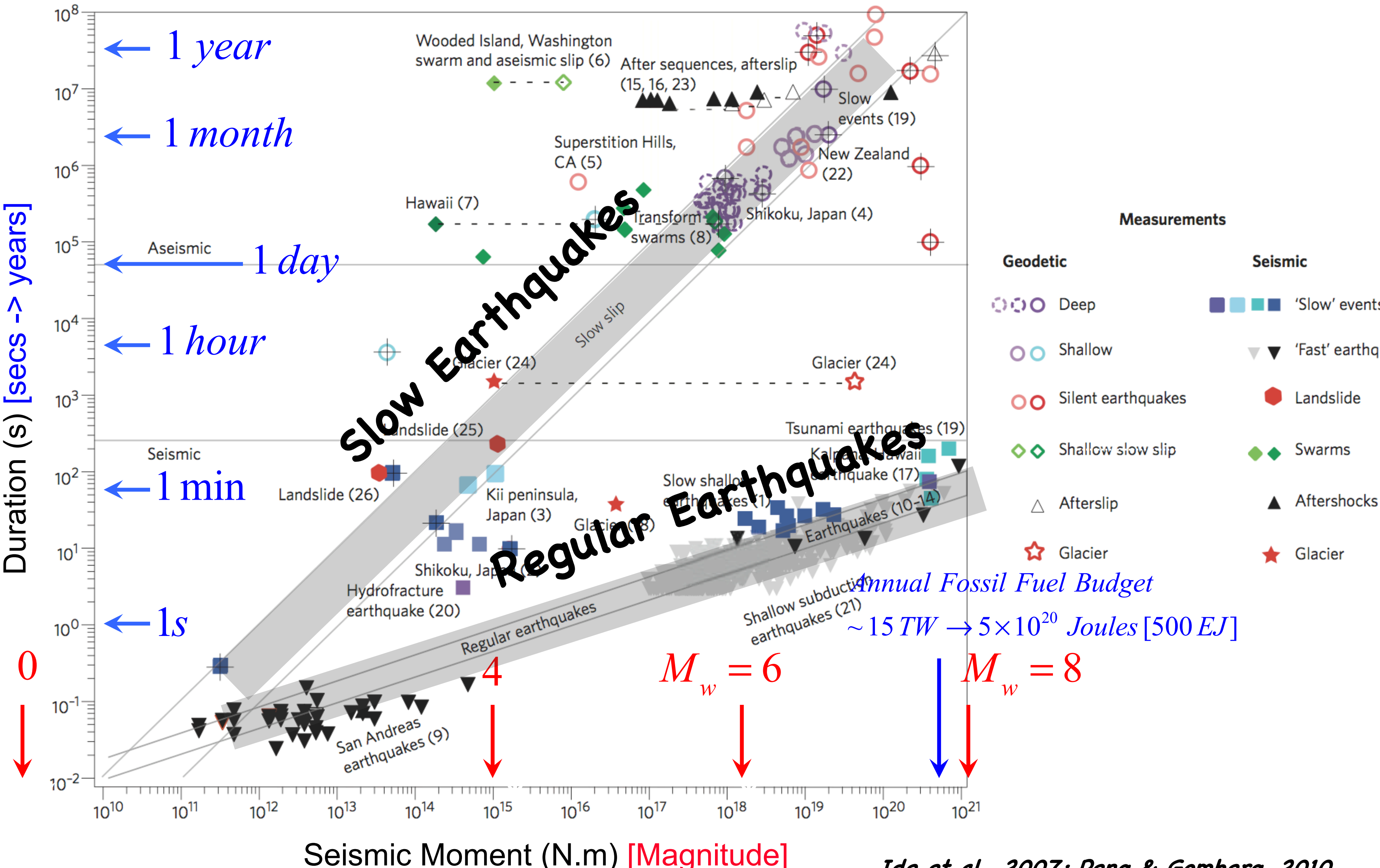
Deformation and Across Fault Permeability Control: Localized process zone (gouge in fault core)

Along-Fault Permeability Control: Fault damage zone (fractures)



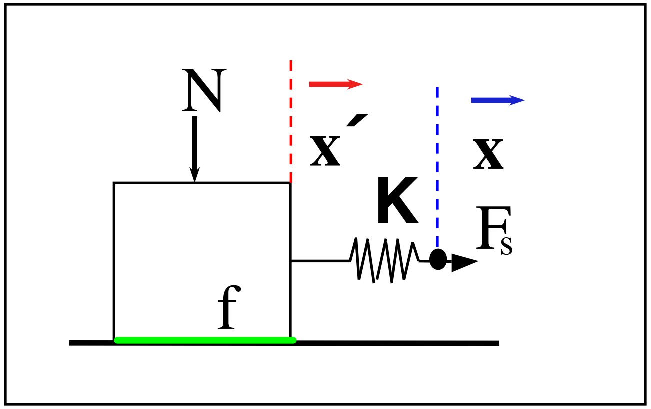

[IEAGHG, "Fault Permeability," 2016; after Faulkner et al., 2010]

# Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior




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

# Stick-slip (unstable) versus stable shear

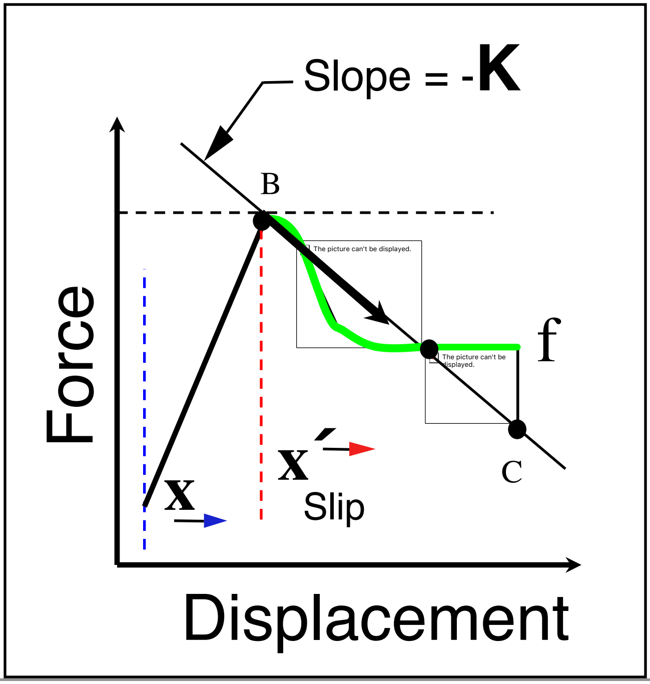


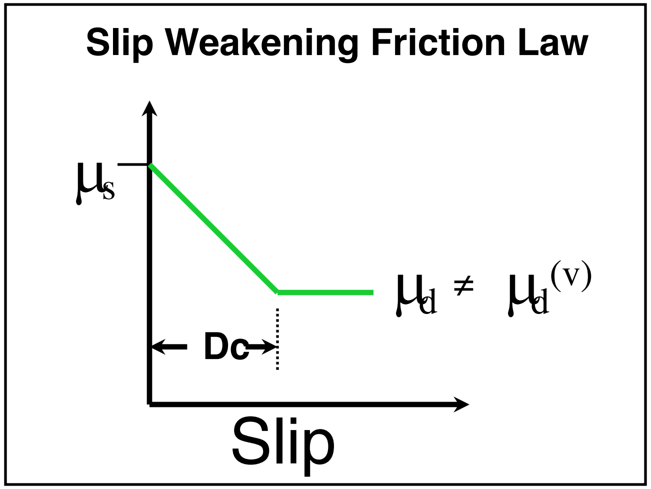

### Stick-slip dynamics

$$m\ddot{x}' + \Gamma\dot{x}' + f(\dot{x}', x', t, \theta) = F_s$$

$$m\ddot{x}' + \Gamma\dot{x}' + f(\dot{x}', x't, \theta) = K(v_{lp} - v)t$$

$$m\ddot{x}' + Fx' = K(v_{lp} - v)t$$



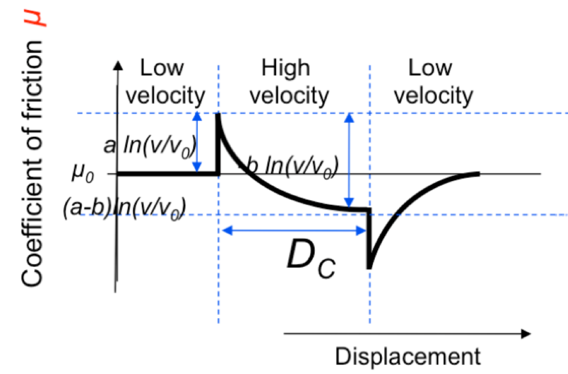




[After C.J. Marone, Pers. Comm., 2017]

# Requirements for Instability

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

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

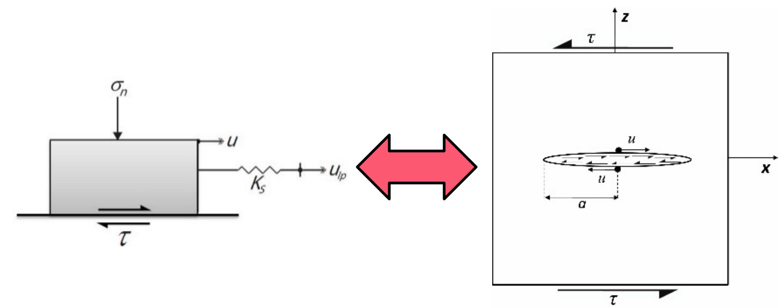



2. When failure occurs, strength is velocity (or strain) weakening - *i.e.*

$$a - b < 0$$

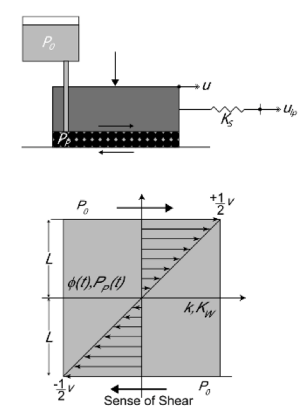
2. That the failure is capable of ejecting the stored strain energy adjacent to the fault (shear modulus and fault length ) - *i.e.*

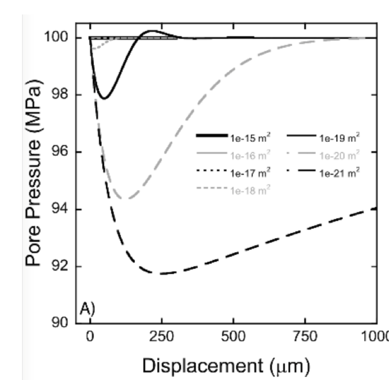
$$\frac{G}{l} < K_c = \frac{(b-a)\sigma_n'}{D_c}$$



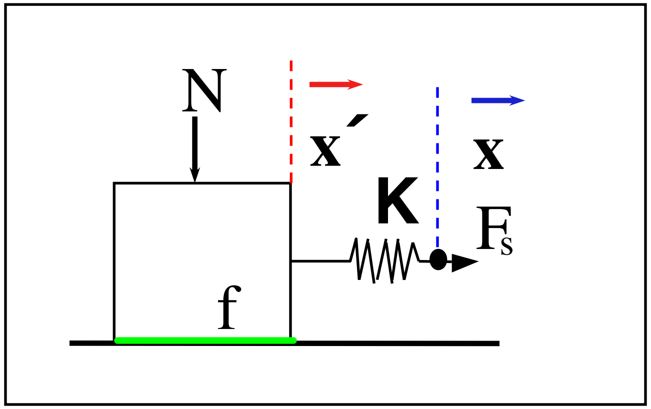

4. That effective normal stresses evolve that do not dilatantly harden the fault and arrest it via the failure criterion of #1 – *i.e.*

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



# Seismic – Aseismic Transition
# Full Spectrum of Slip Behaviors




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

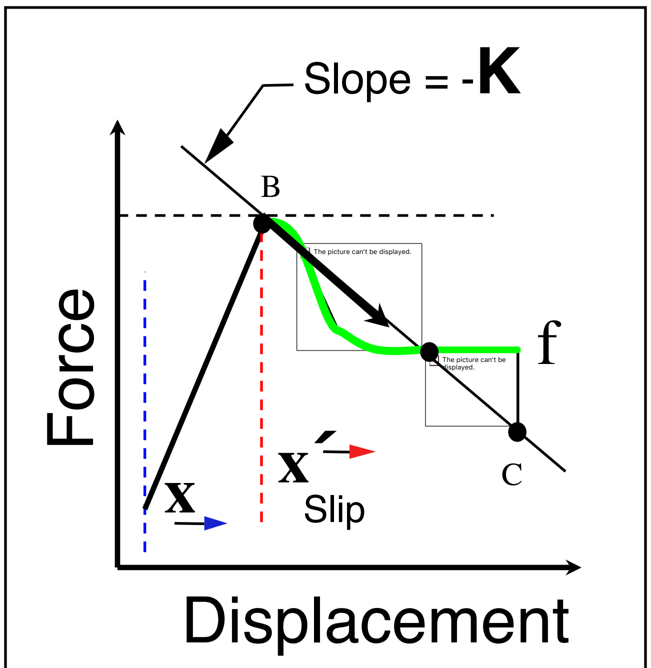
Promote Aseismic Response: $K_c < K$

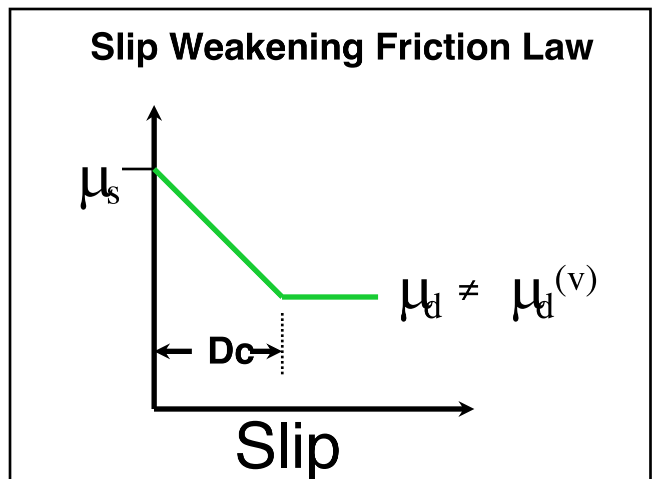
Otherwise Seismic Slip if: $K_c > K$

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

Decrease: $D_c; G$

Recurrence Requires: *Healing*

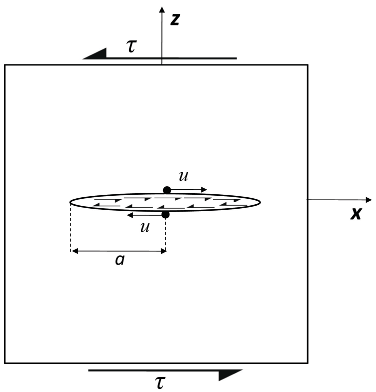


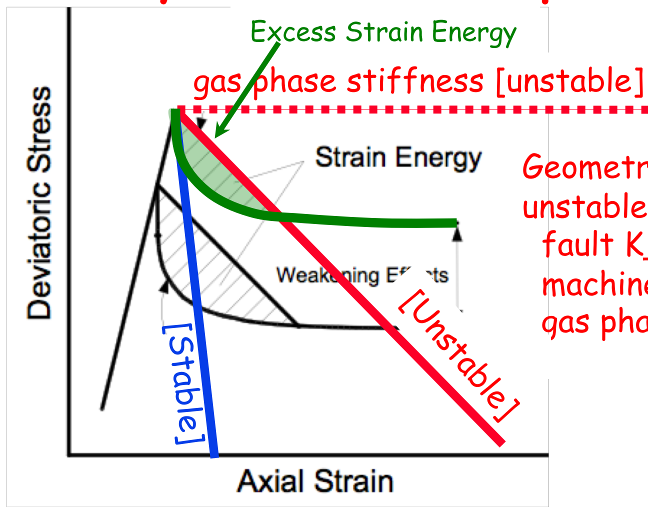

[Adapted from C.J. Marone, Pers. Comm., 2017]

# Instability Threshold - Penny-Shaped Crack

## System Stiffness



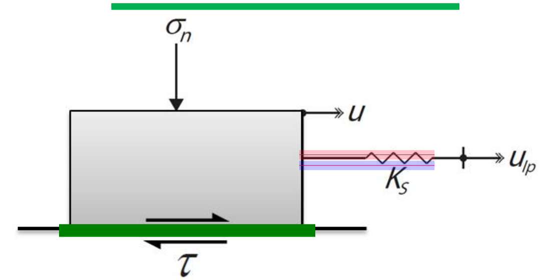

## System-Fault Response




Geometrically soft - unstable
- fault K_c
- machine/mine K_c
- gas phase K_c

Geometrically stiff - stable

## Fault Stiffness




$$\frac{\Delta\tau}{\Delta\bar{u}} = \frac{G}{a}\frac{3\pi(2-\nu)}{8(1-\nu)} < K_c = \frac{(b-a)\sigma'}{D_c}\left[1 + \frac{mv^2}{\sigma' a D_c}\right]$$

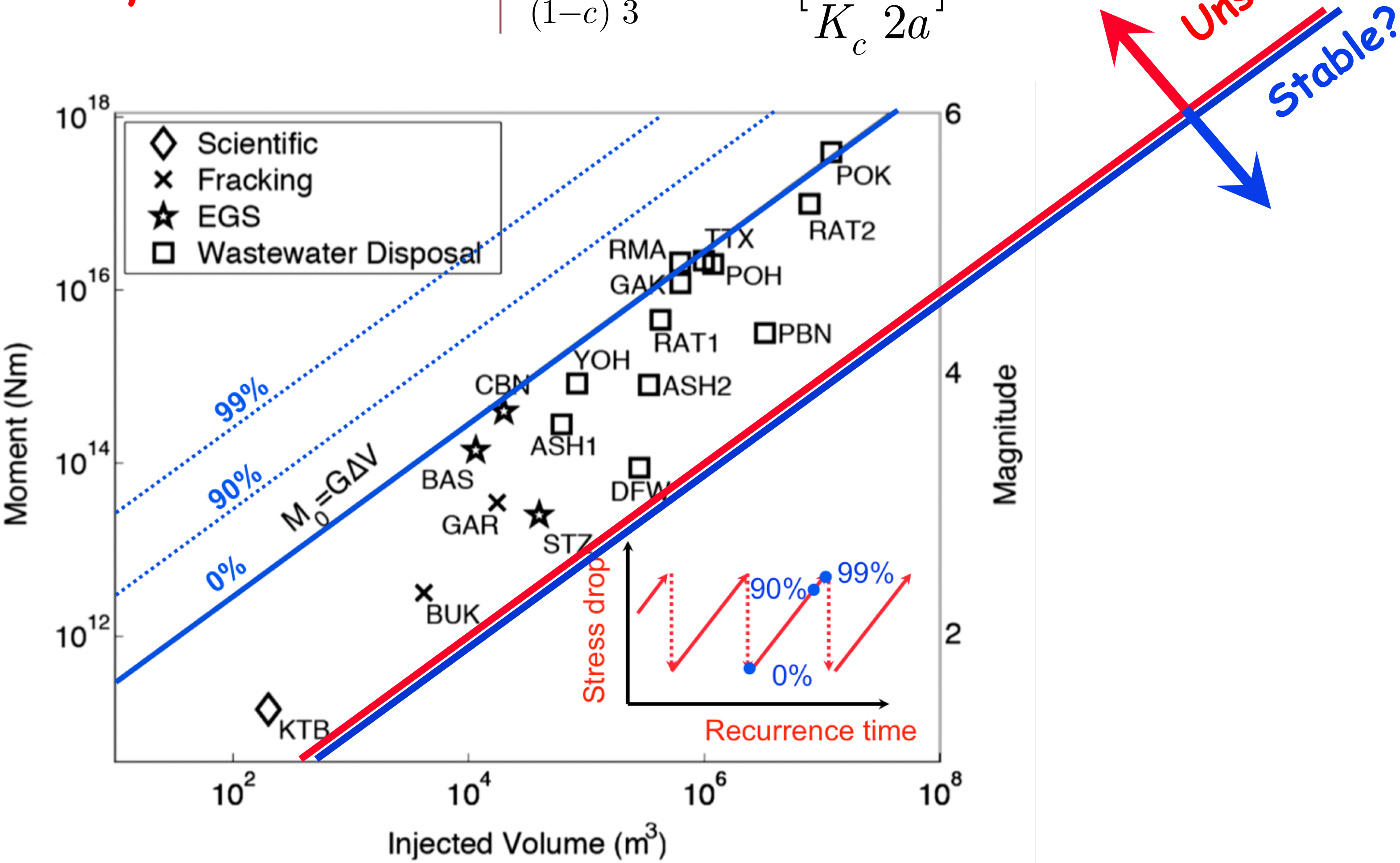
$$\sim 5\frac{G}{2a} < \frac{(b-a)\sigma'}{D_c} = K_c \begin{cases} \nu = 0.25 \\ \mu = 0.6 \\ \text{inertia negligible} \end{cases}$$

# Instability Threshold – Penny-Shaped Crack

**Stored strain energy:** $$M \sim \frac{1}{(1-c)}\frac{1}{3}G\Delta V$$

**Instability criterion:** $$M \sim \frac{1}{(1-c)}\frac{1}{3}G\Delta V \cdot [\frac{6}{K_c}\frac{G}{2a}]$$

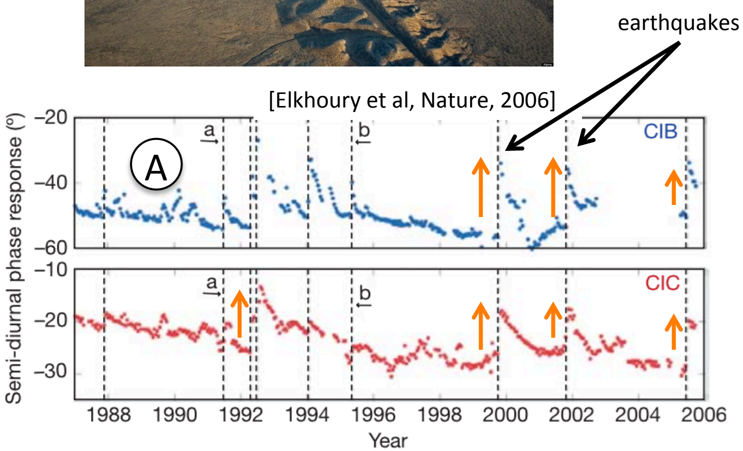
$$2a = 6\frac{G}{K_c}$$



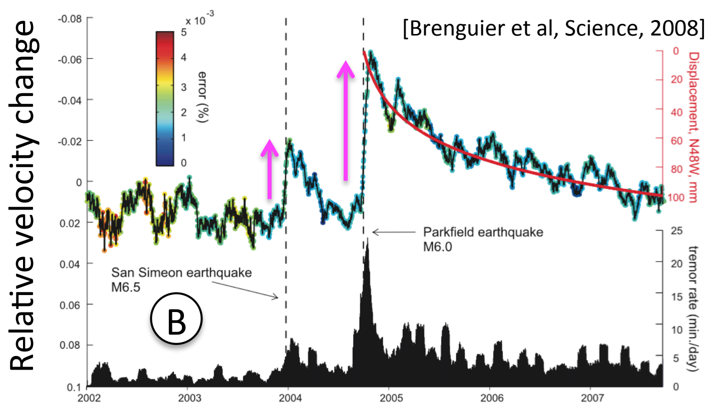
# Permeability and Elastic Softening

## Field-scale

Permeability

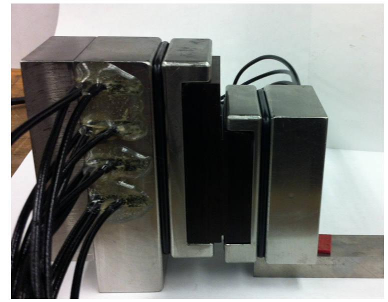


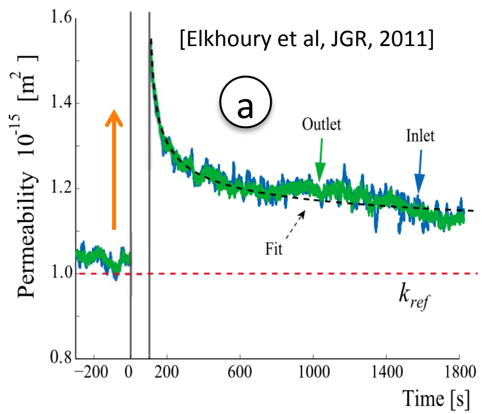

Elastic Softening

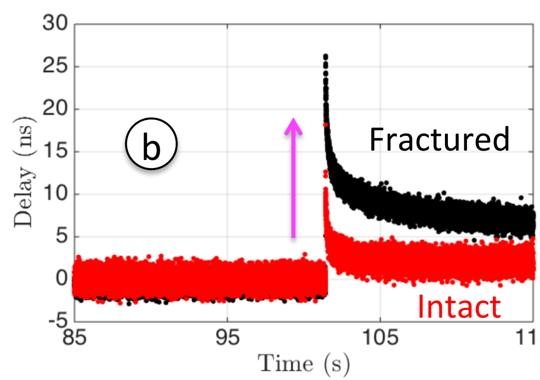



[Shokouhi, Pers. Comm. 2016]

## Laboratory-scale





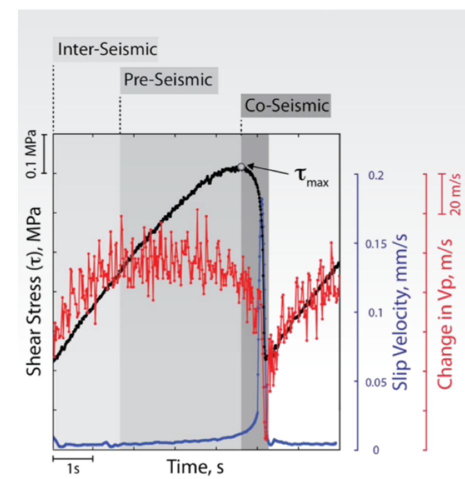




Permeability

Elastic Softening

**During the Seismic Cycle**

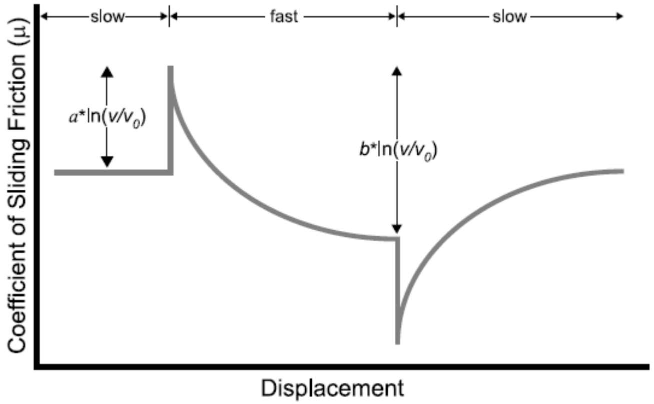
- Seismic waves trigger transient changes in elastic properties
- Elastic softening coincides with increased permeability
- Lab observations of precursors to earthquake-like failure (i.e., elastic wave speed)
- Monitoring to assess the critical stress-state in Earth's crust
- Potential for management of induced seismicity to maximize geothermal energy production




*[Scuderi et al., Nature Geosc, 2016]*

# Rate-State Friction [1]

## Velocity Steps




## R-S Friction

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

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

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

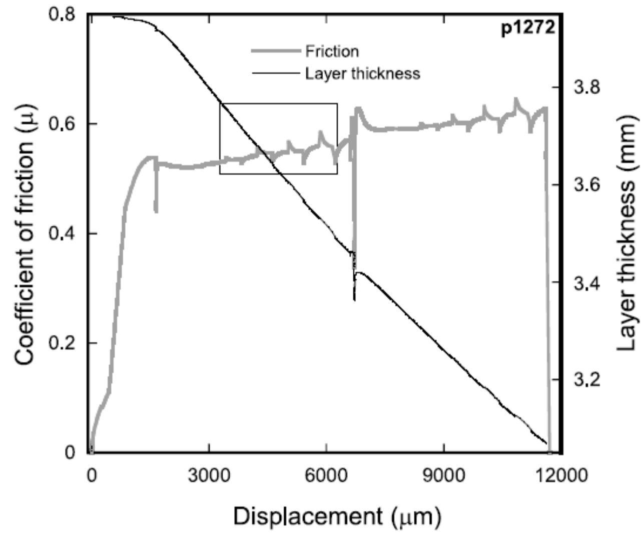
## Dilation

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

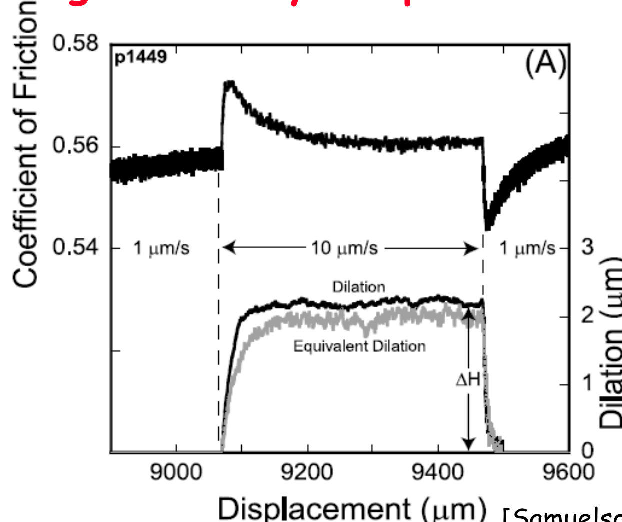
## Permeability Evolution

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

## Multiple Velocity Steps




## Single Velocity Step

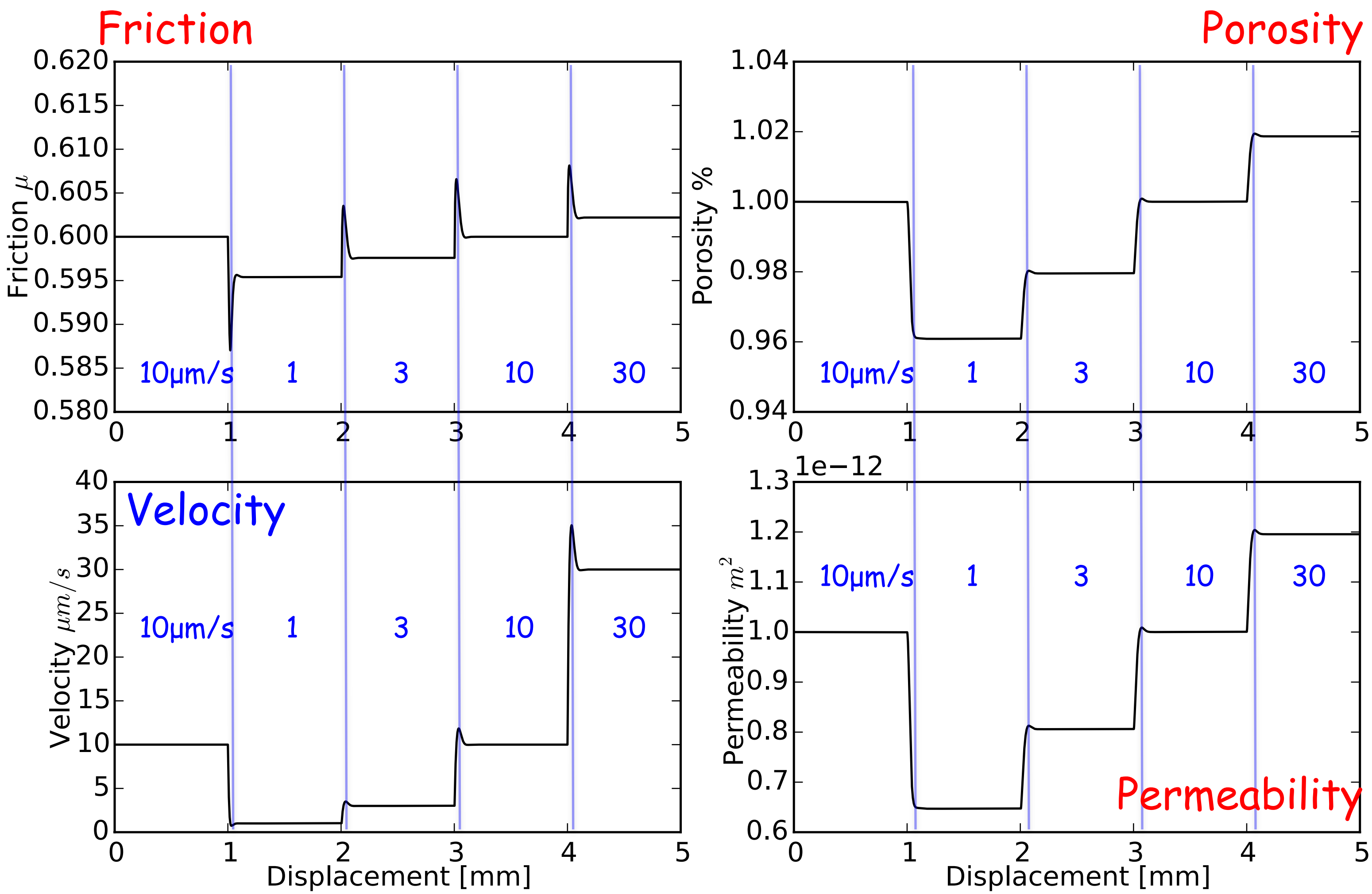



[Samuelson et al., 2009]

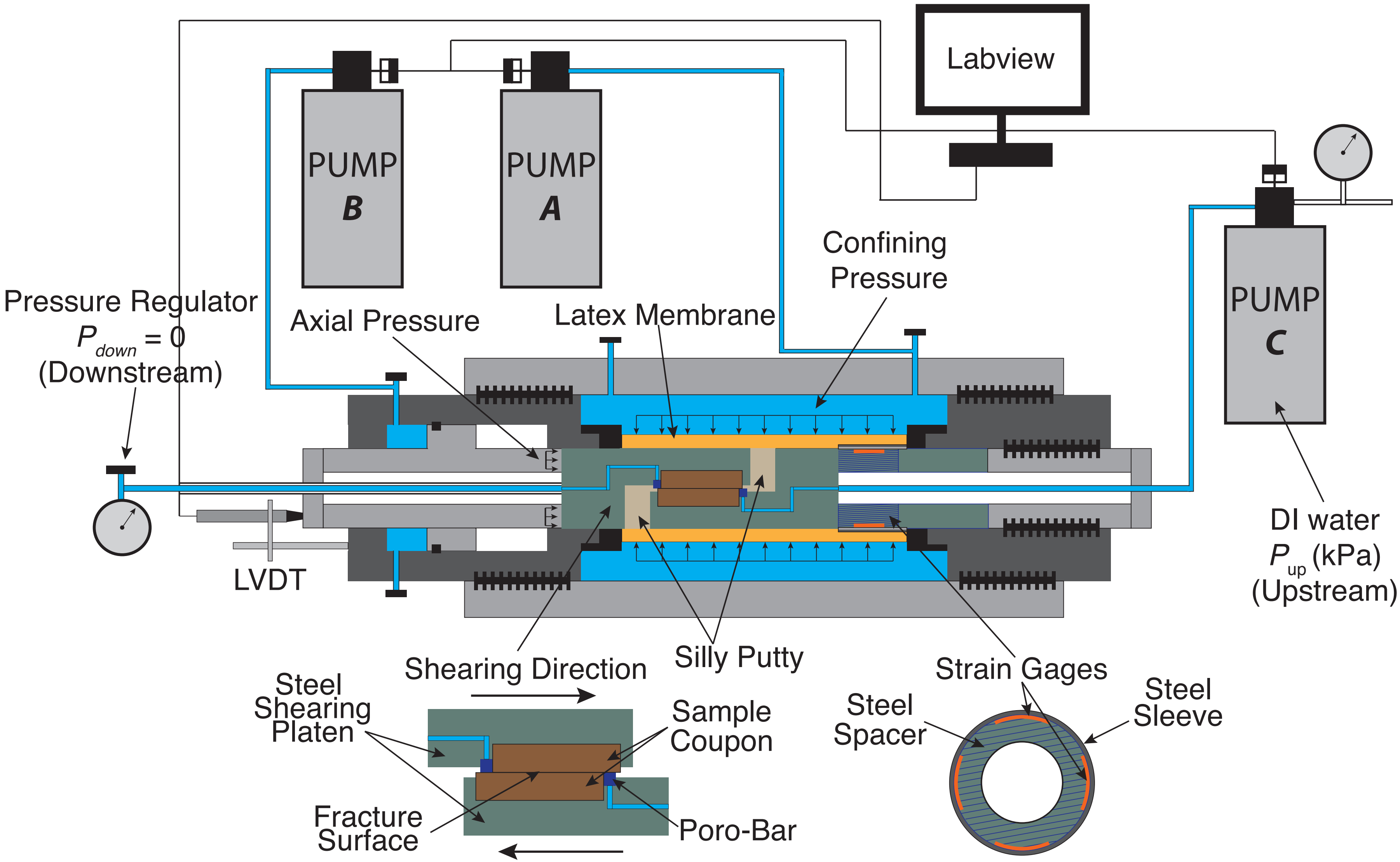
# Rational Linkages: Rate-State Friction, Porosity and Permeability

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

High Stiffness, positive dilatational coefficient

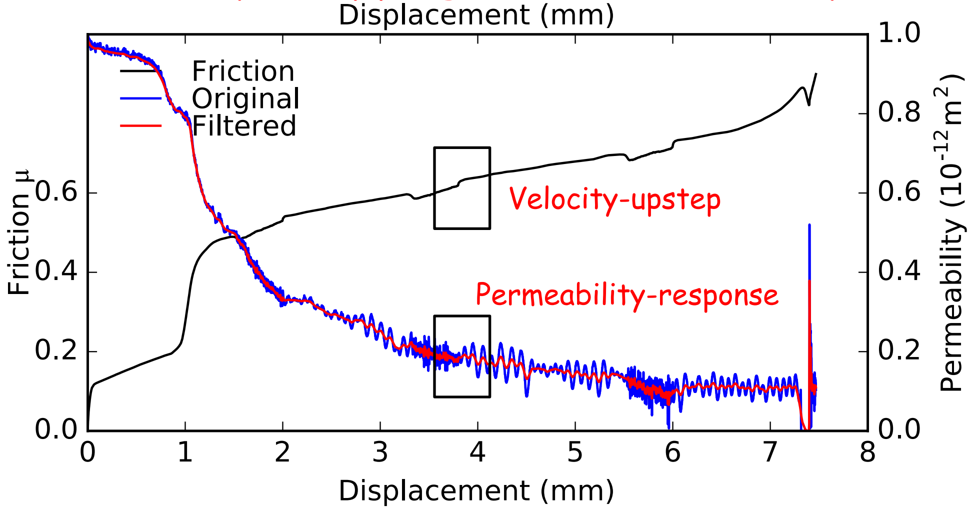


# Frictional Stability-Permeability Experiments

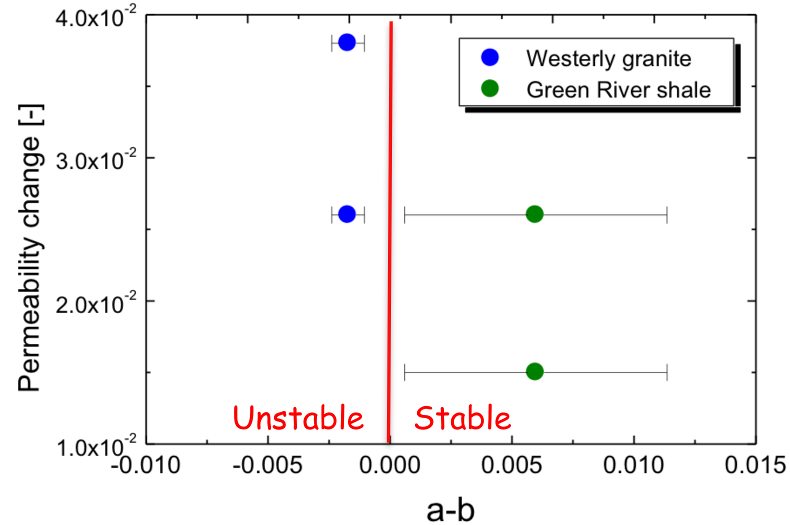


# Frictional Stability-Permeability Observations

## Velocity-stepping and Permeability

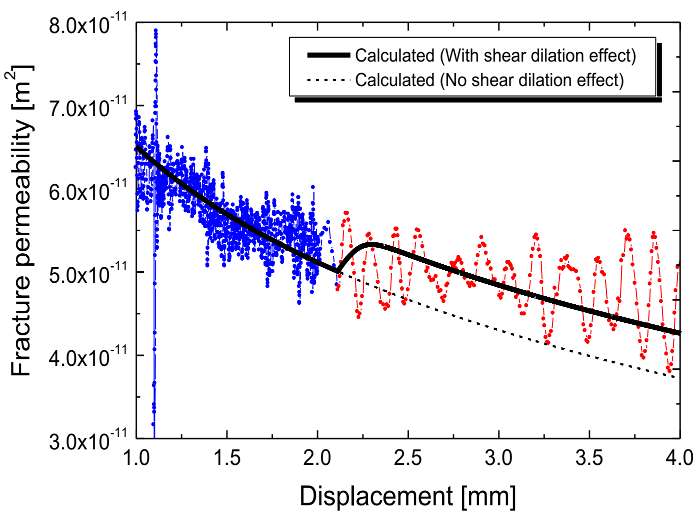



## Permeability-Frictional Stability

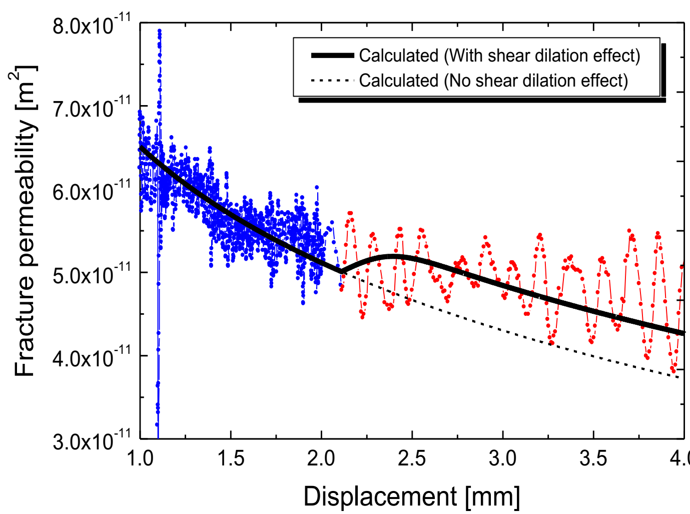



## Permeability Evolution

ε=0.0224 (n=2), Dc=50 [μm]



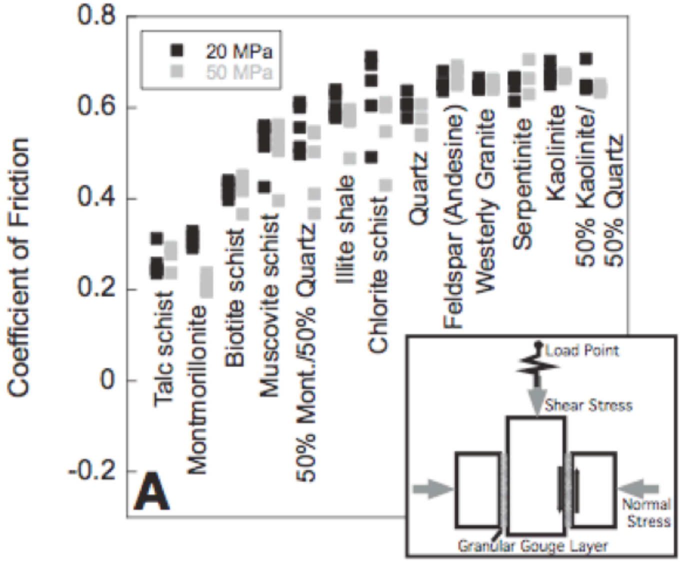

ε=0.0224 (n=2), Dc=100 [μm]

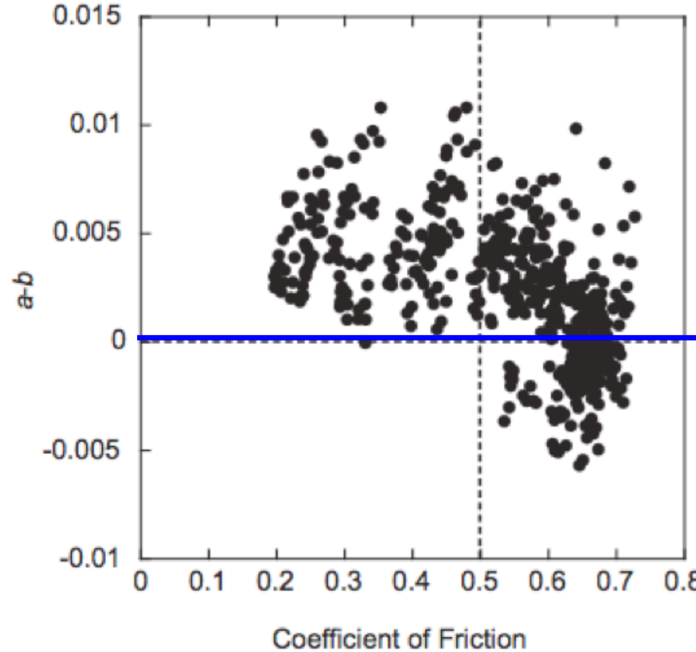


# Mineralogical Controls on Instability

## Friction

[Ikari et al., Geology, 2011]

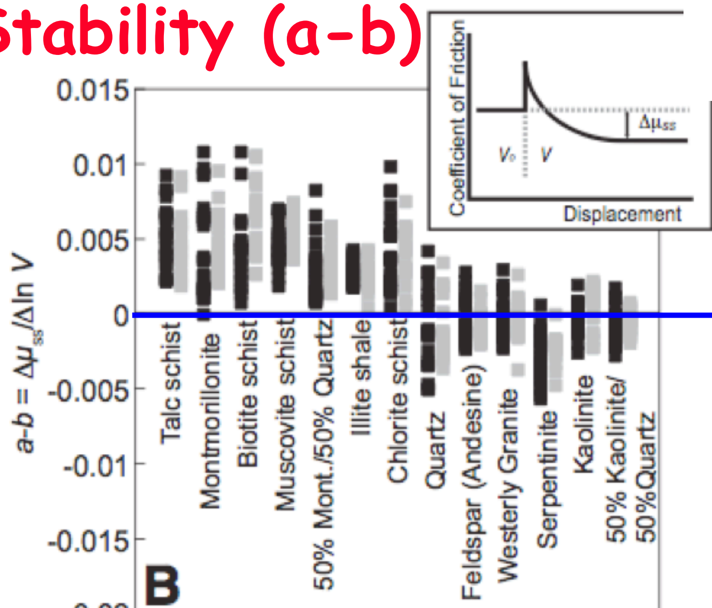



Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

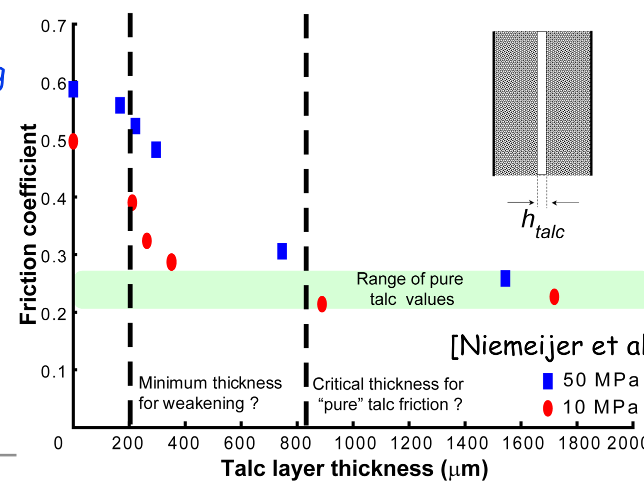
## Stability (a-b)




Velocity Strengthening (stable slip)

Velocity Weakening (unstable slip)

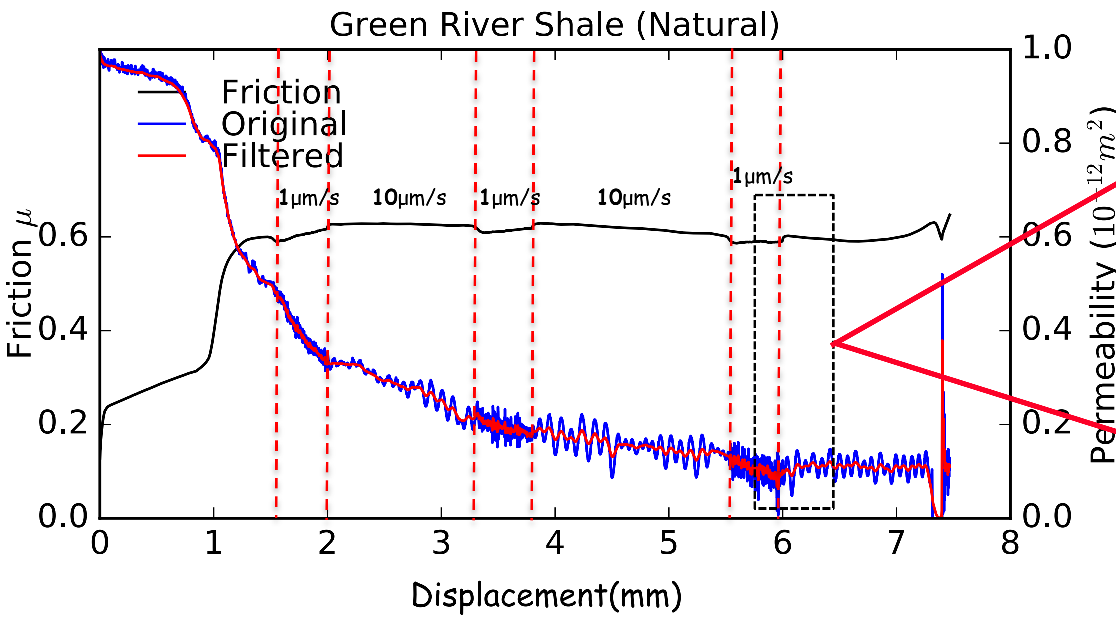
## Frictional Response of Mixtures

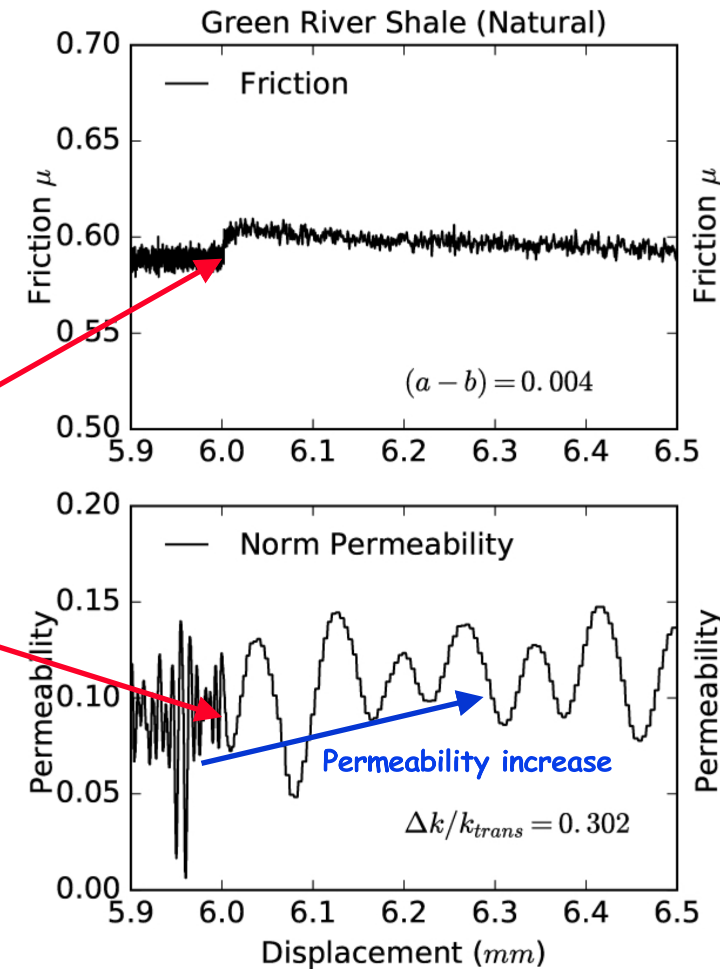


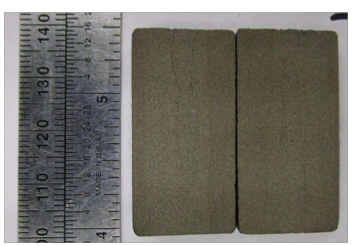

[Niemeijer et al., GRL, 2010]

# Green River Shale- Permeability Enhancement

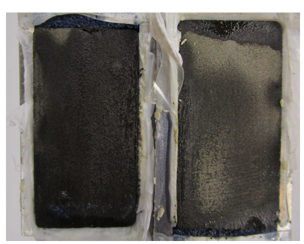
| | Tectosilicate | Carbonate | Phyllosilicate |
|---|---|---|---|
| Green River Shale | 45.44% | 51.96% | 2.60% |



Before



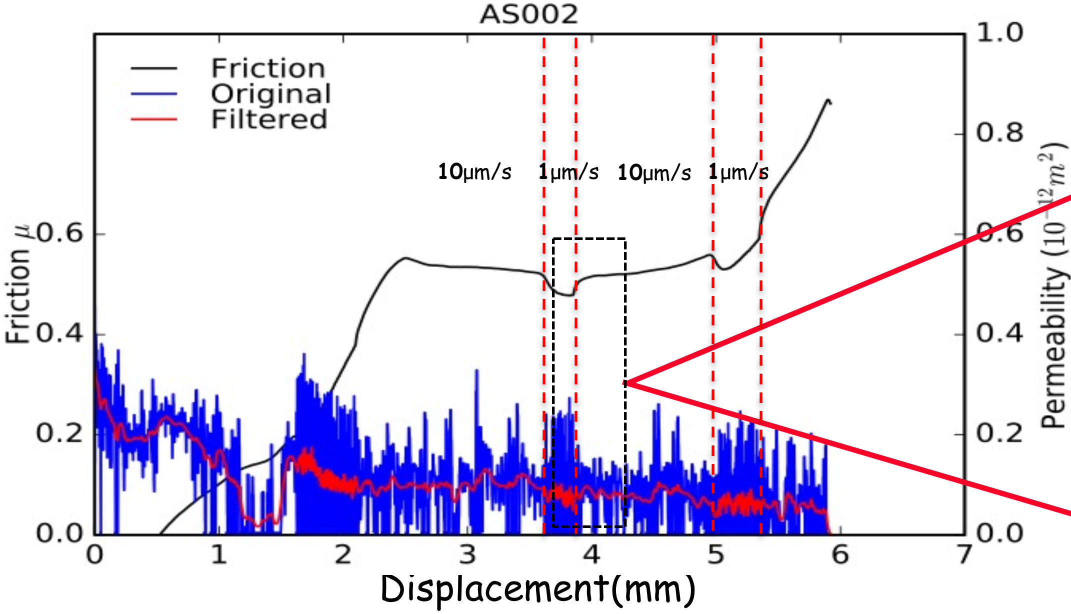
After

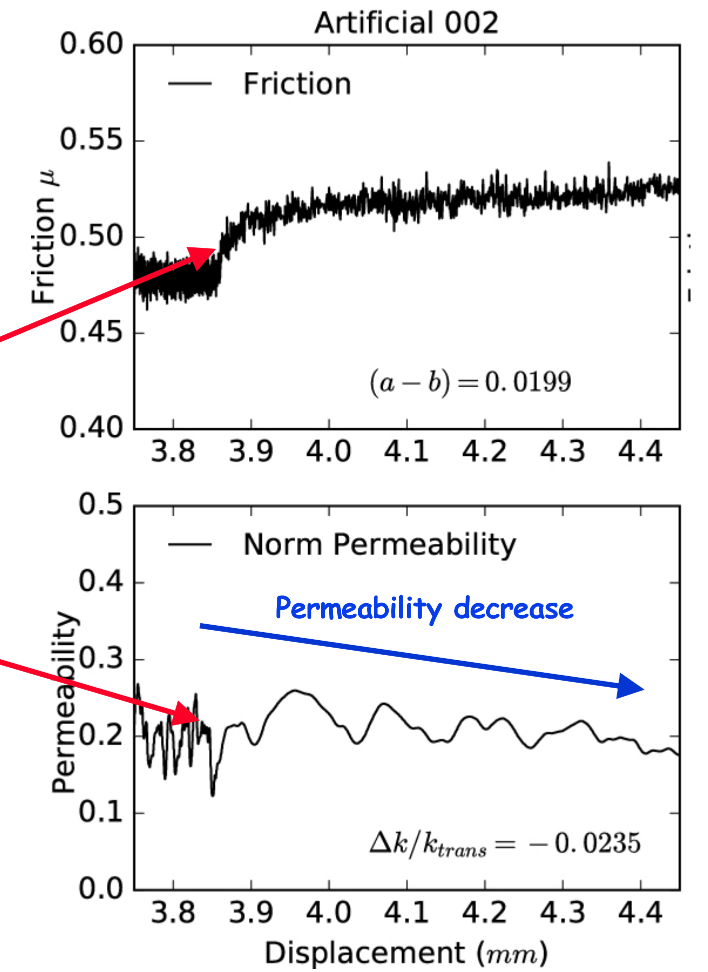
Wear products after slip

Velocity-upstep results in a permeability increase due to dilation

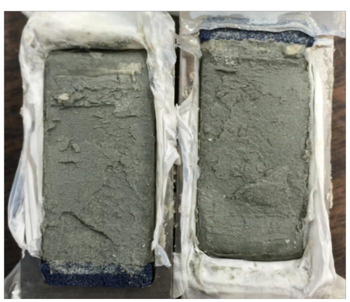
# Phyllosilicate-dominant Artificial Sample- Permeability Decrease

| | Tectosilicate | Carbonate | Phyllosilicate |
|---|---|---|---|
| AS002 | 10% | 10% | 80% |




Before

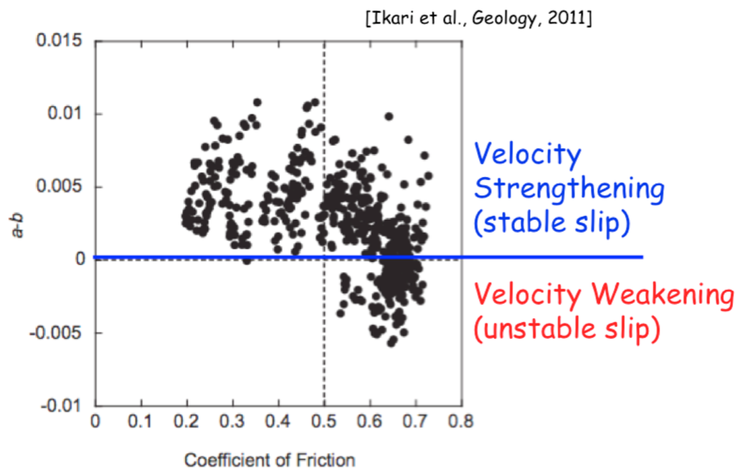


After

Clay swelling concurrent with shear damage

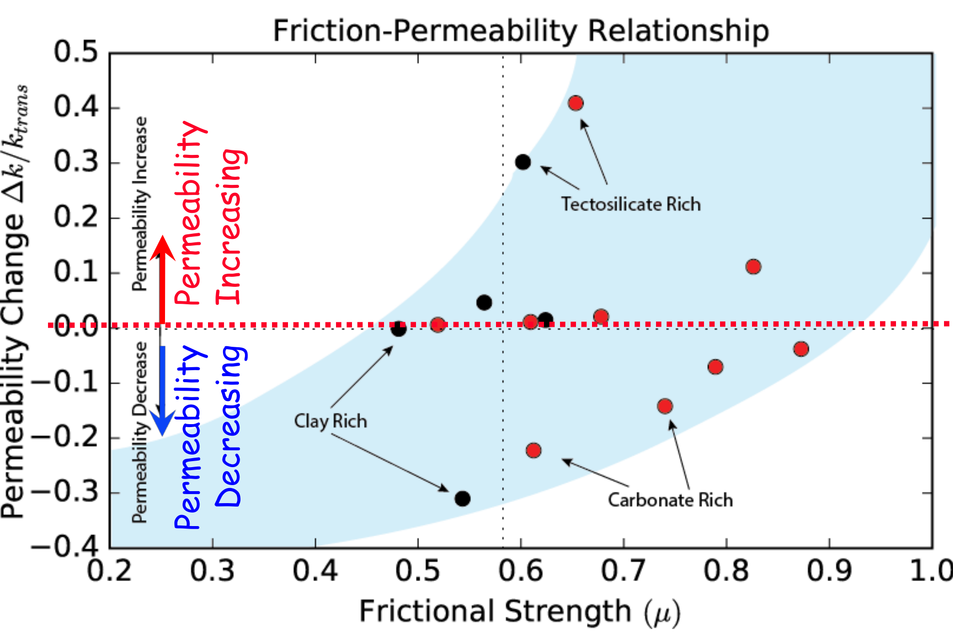
Velocity-upstep results in a permeability decrease due to wear products and swelling

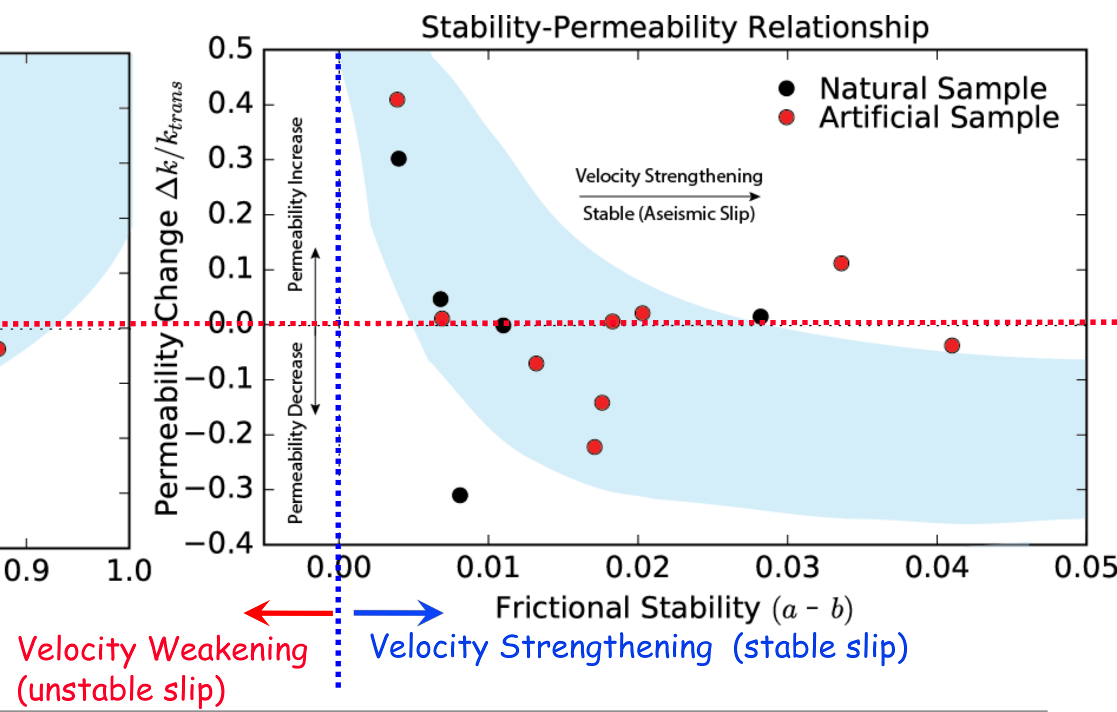
# Nascent Friction-Stability-Permeability Relationships



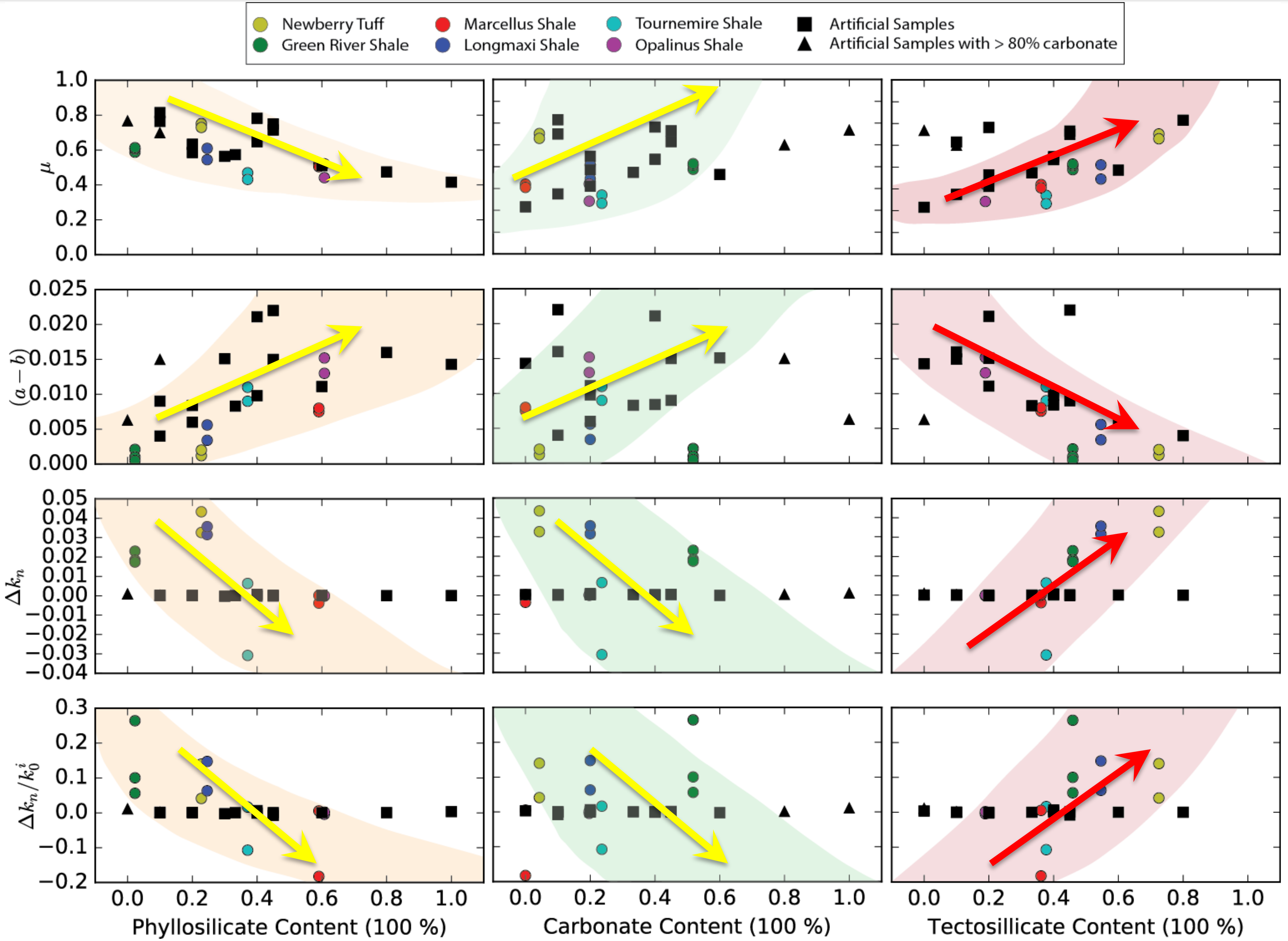

**Observations**

- $dk/k_0$ increases with increased brittleness (a-b)<0
- $dk/k_0$ increases with increased frictional strength
- Roles of mineralogy and surface roughness?



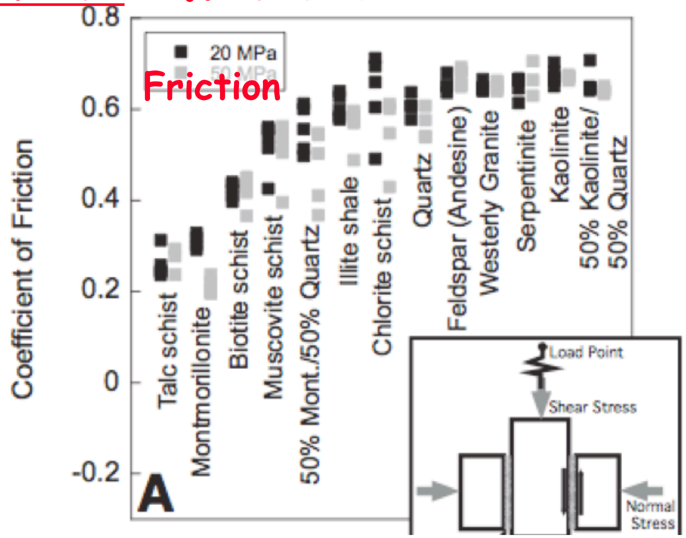



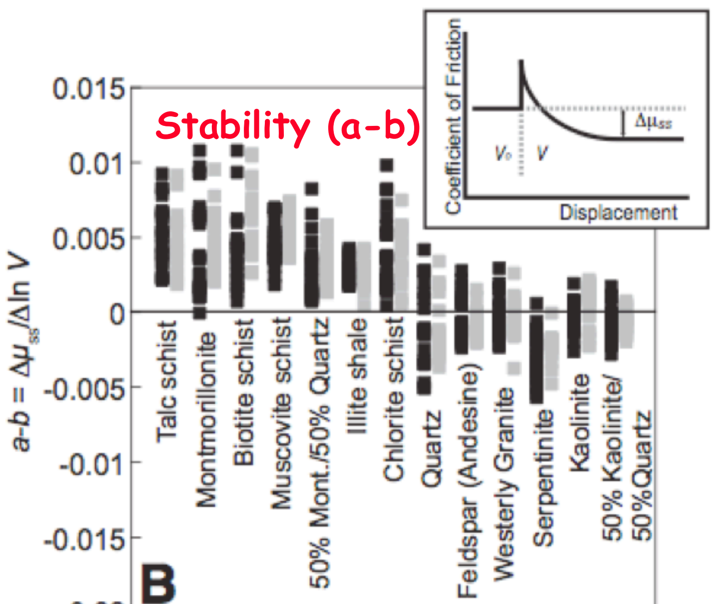
# Seismicity-Permeability Linkages – Natural Samples



# Stability-Permeability Relations in Composites/Mixtures

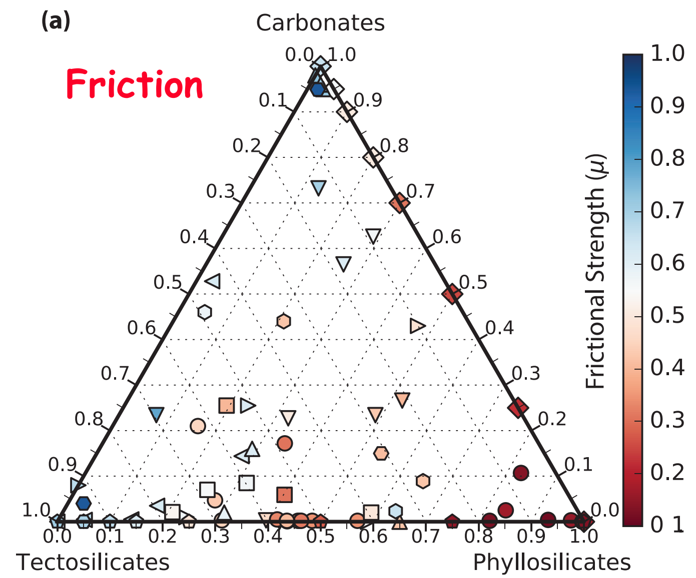
## Mono-mineralic

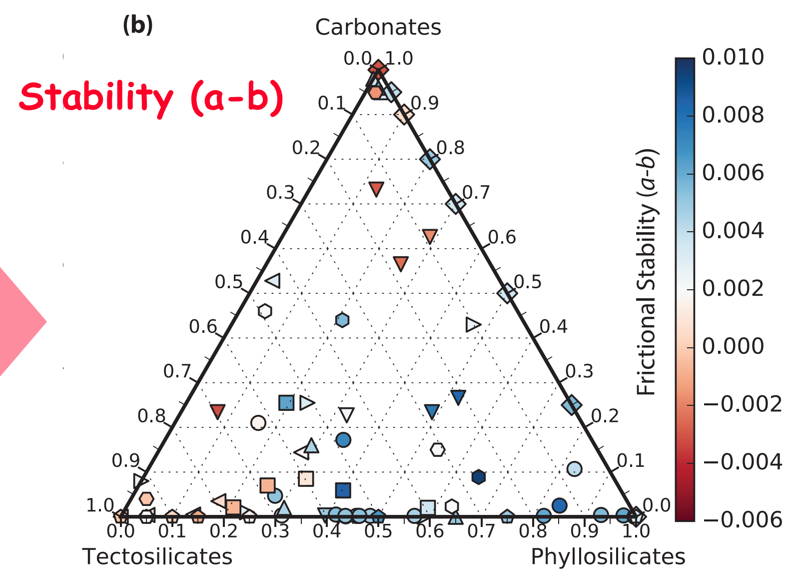



[Ikari et al., Geology, 2011]

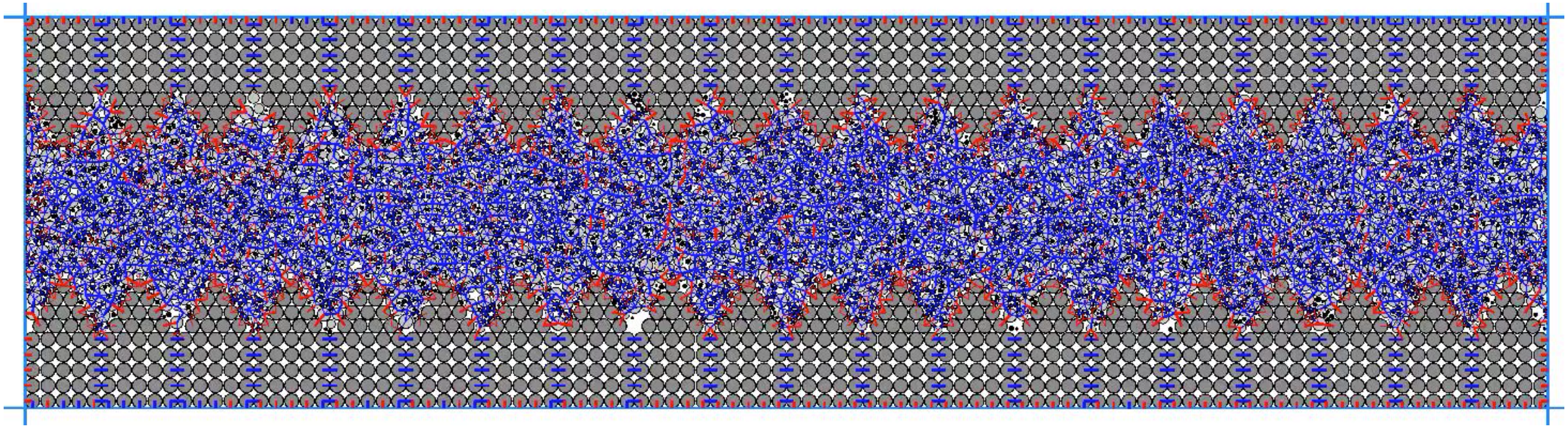
## Multi-mineralic



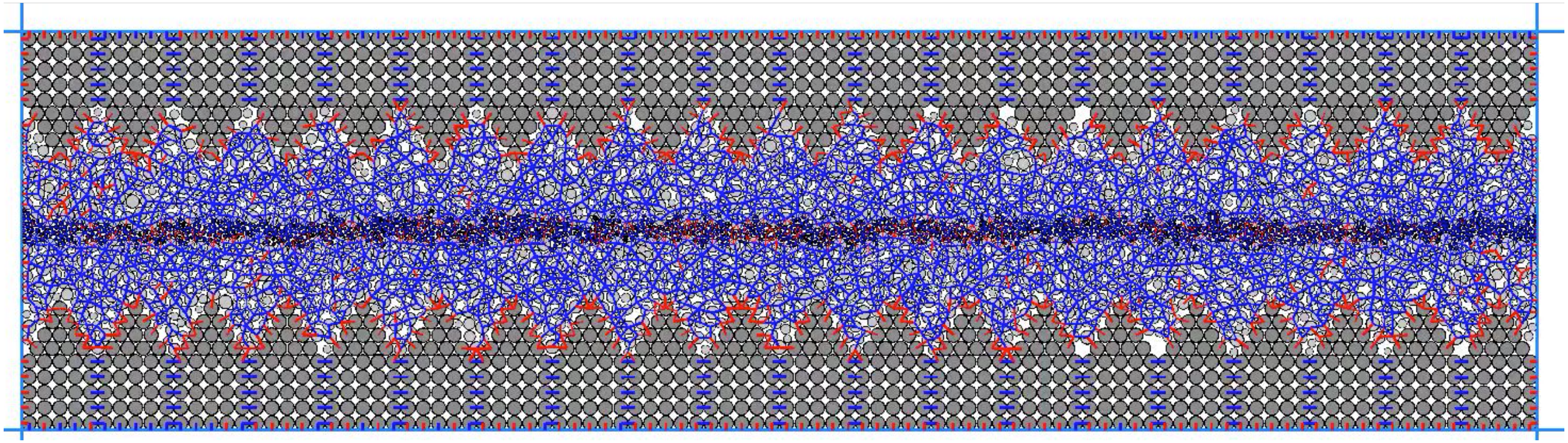



# Role of Texture in Friction-Stability-Permeability

**Heterogeneous Mixture**

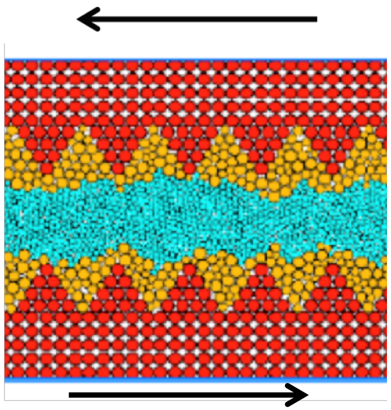


**Textured/Layered Mixture**

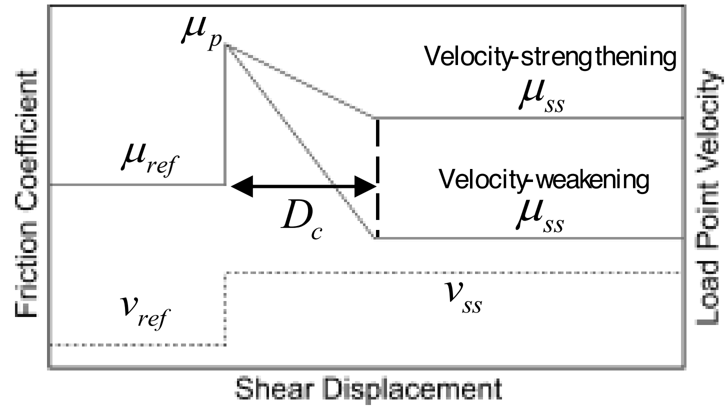


# Multi-Mineral Frictional Strength

## DEM Model



## Particle-Particle Friction



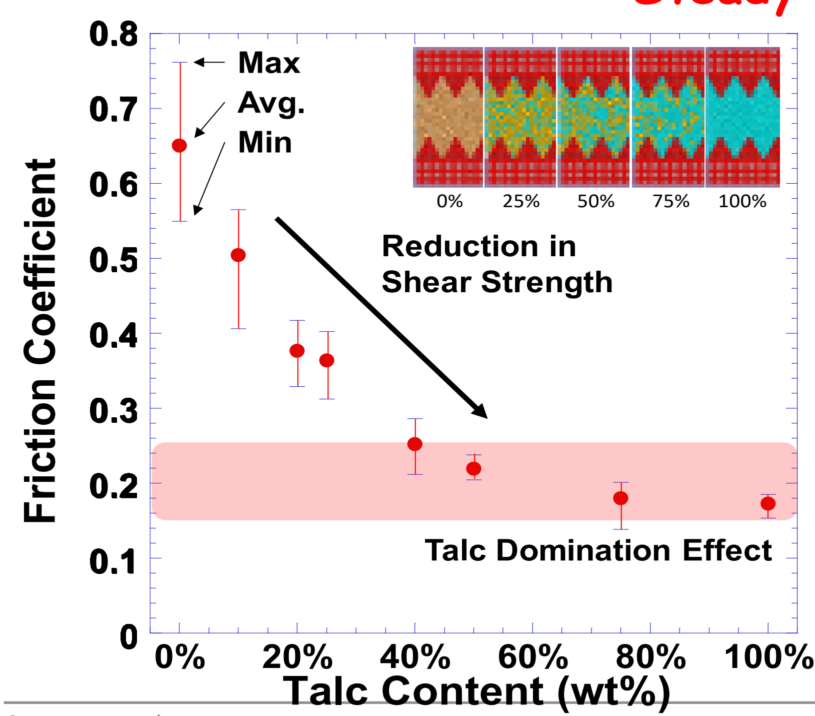

## RSF Notation

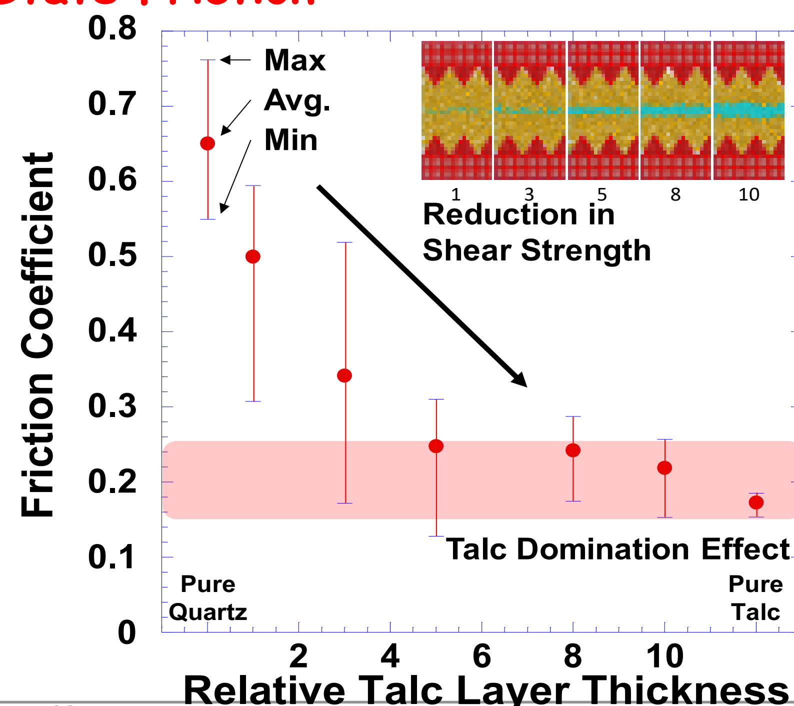
$$\mu_p = \mu_{ref} + a\ln\left(\frac{V_{ss}}{V_{ref}}\right)$$

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

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

## Steady-State Friction

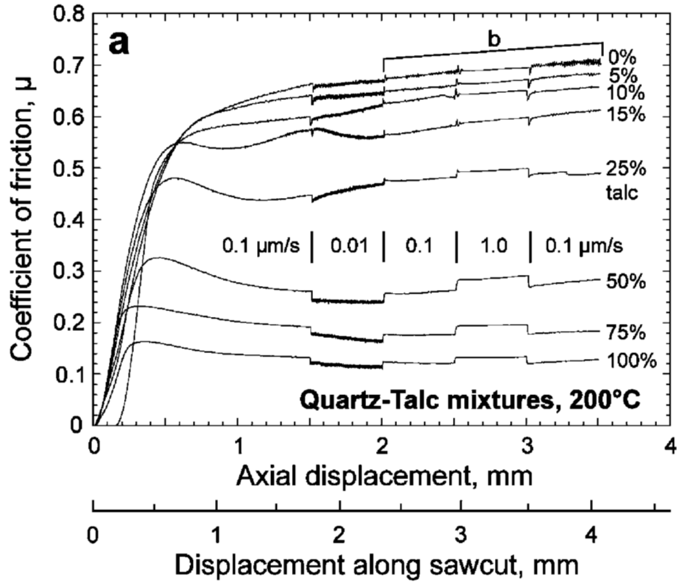


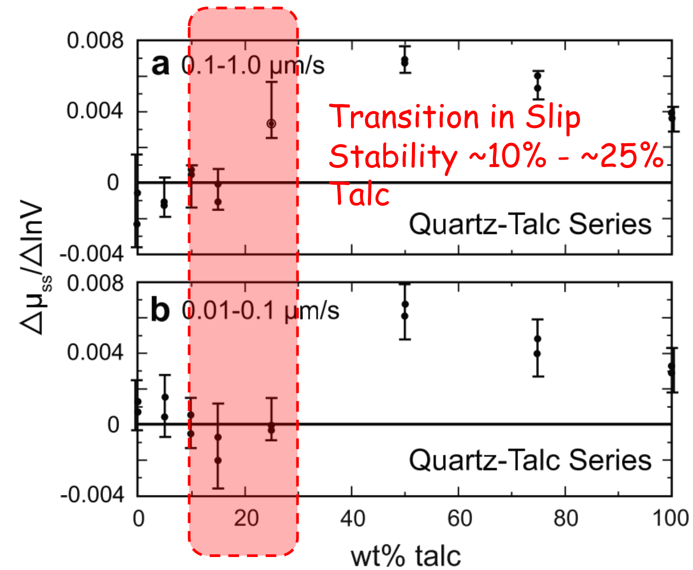



# Mixture Controls of Frictional Instability

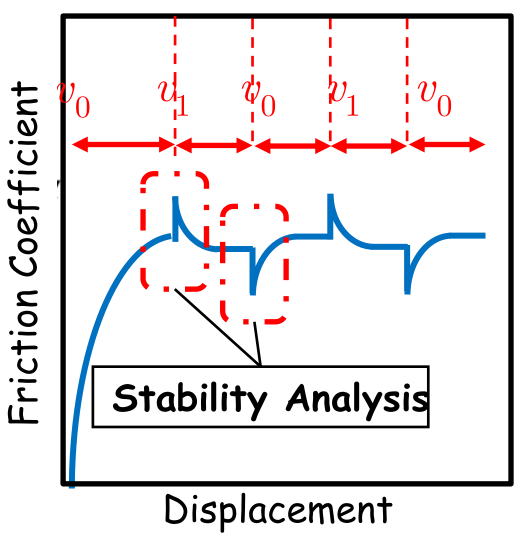
## Observations

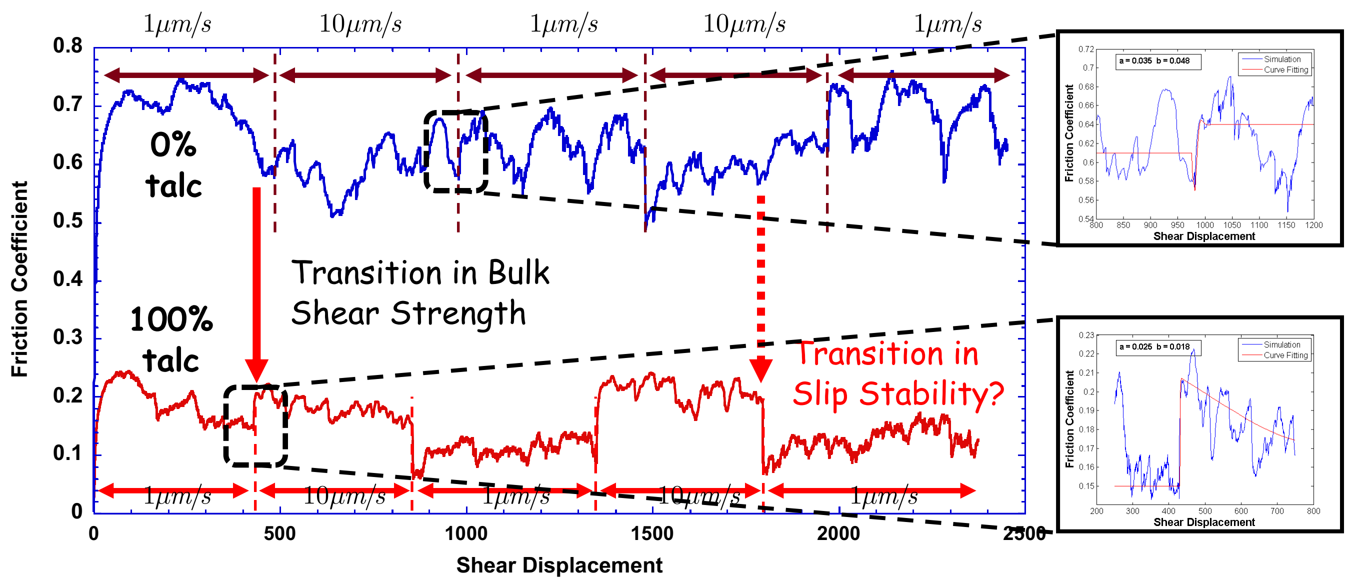
[Moore & Lockner 2011]



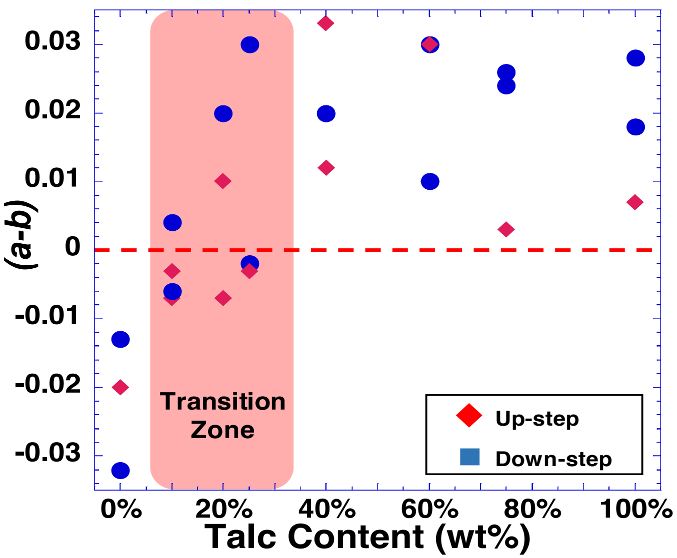



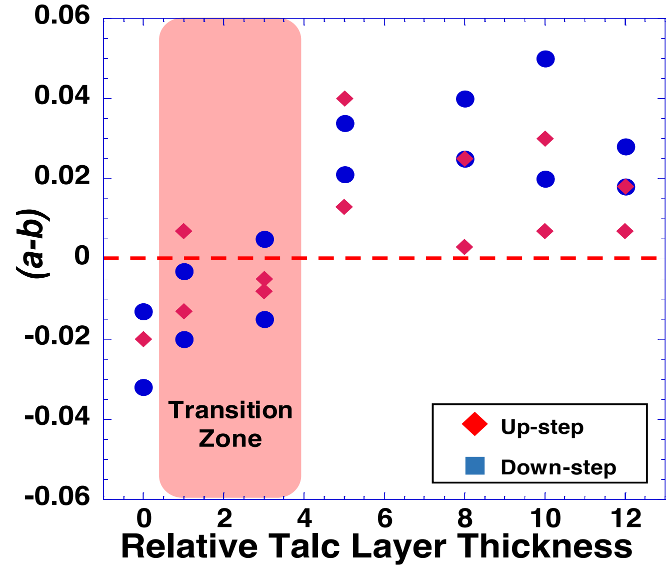

## Analysis

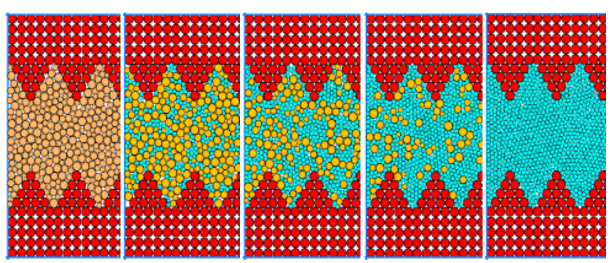


# Multi-Mineral Frictional Stability

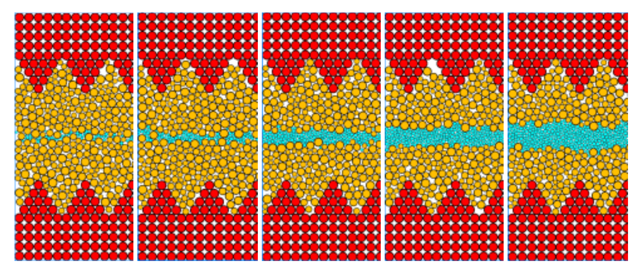


0% 25% 50% 75% 100%

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

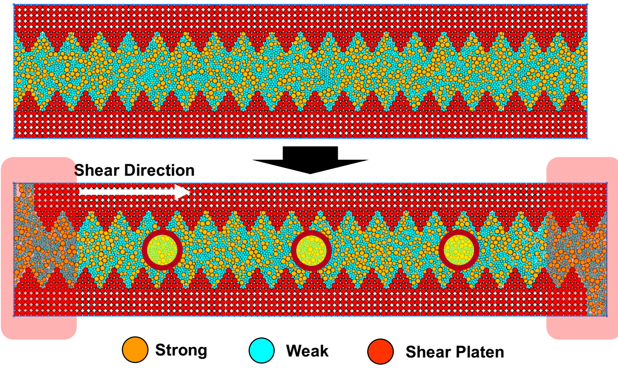


1 3 5 8 10

2% 3% 4% 10 % 13 %

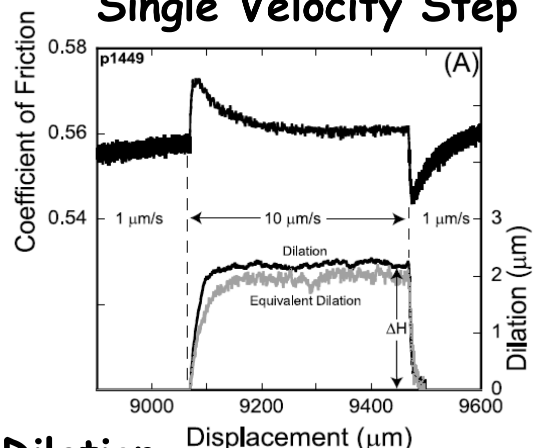
Transition zone appears at ~2% to ~3% talc content

# Evolution of Layer thickness, Coord. Num, and Porosity




## Background Compaction

## Single Velocity Step

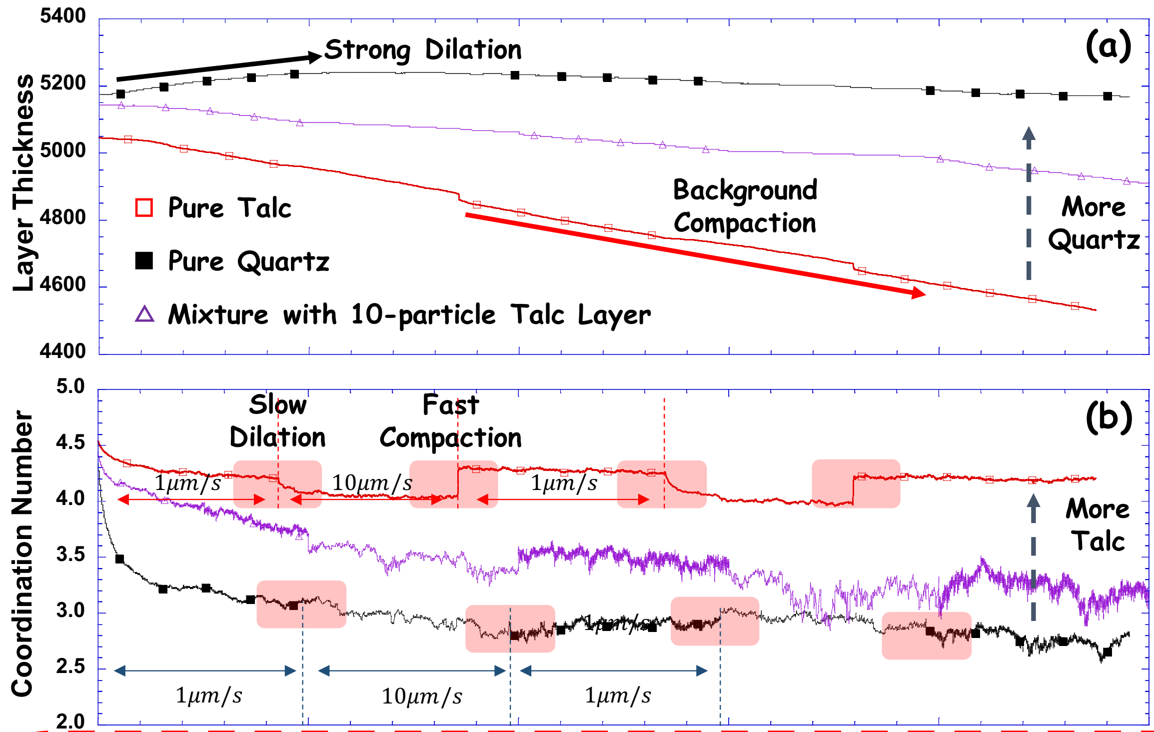


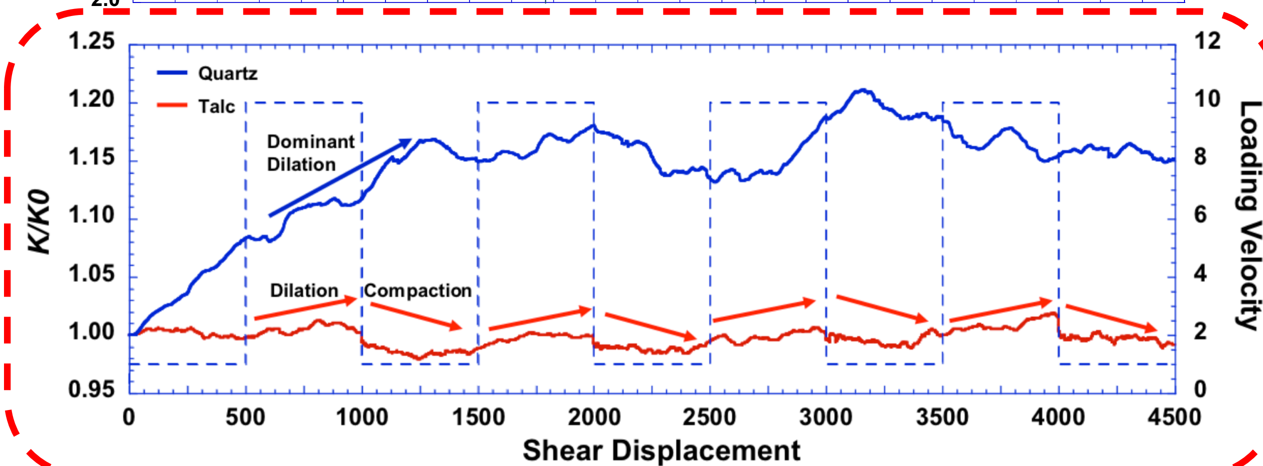

## Dilation

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

## Permeability Evolution

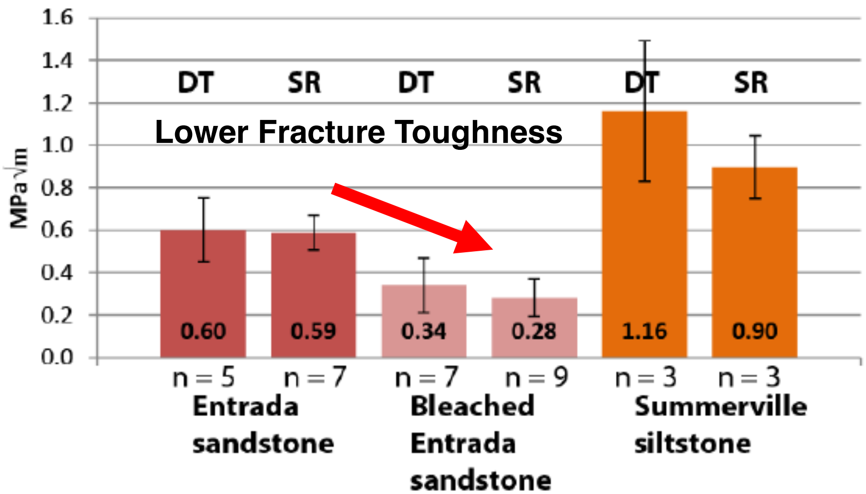
$$\frac{k}{k_0} = \left(1 + \frac{\Delta b}{b_0}\right)^3 = \left(1 + \frac{\Delta H}{H}\right)^3 \cong (1 + \Delta\phi)^3$$

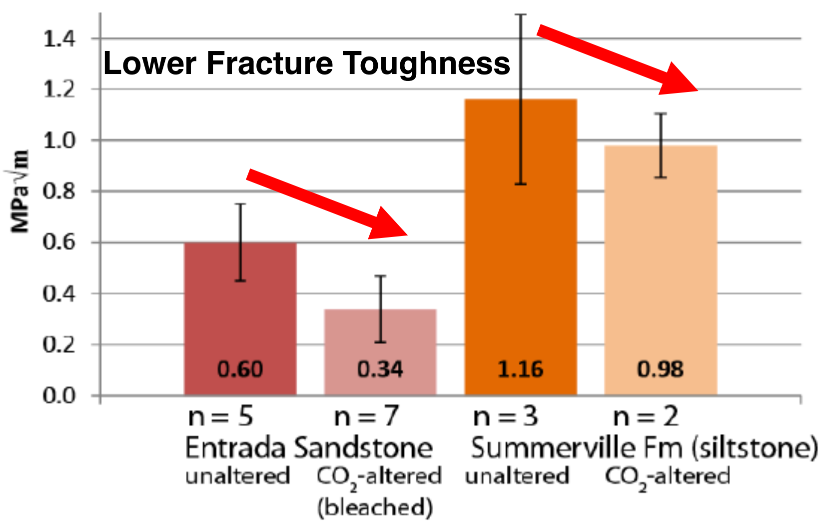


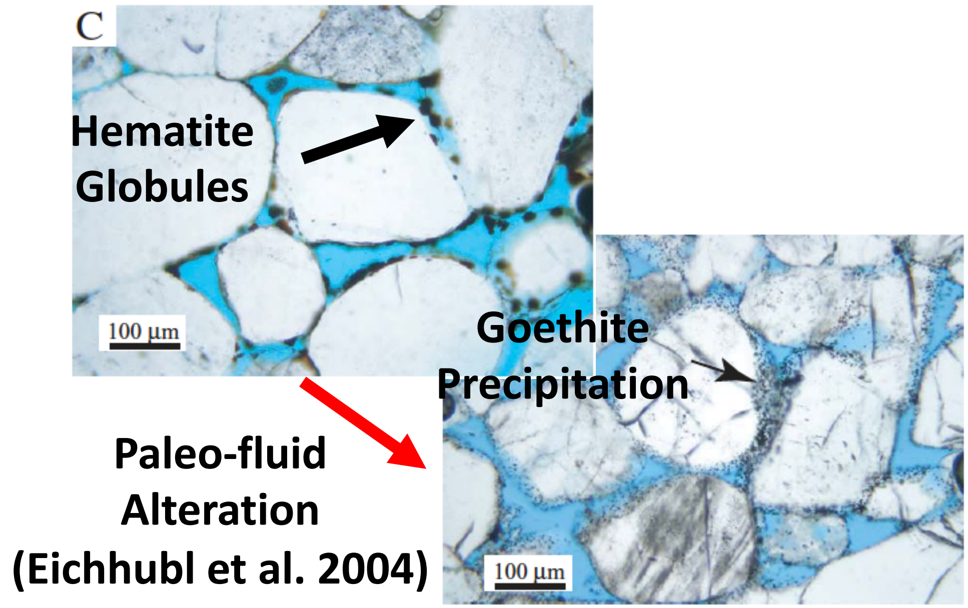



# Introduction & Motivation

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



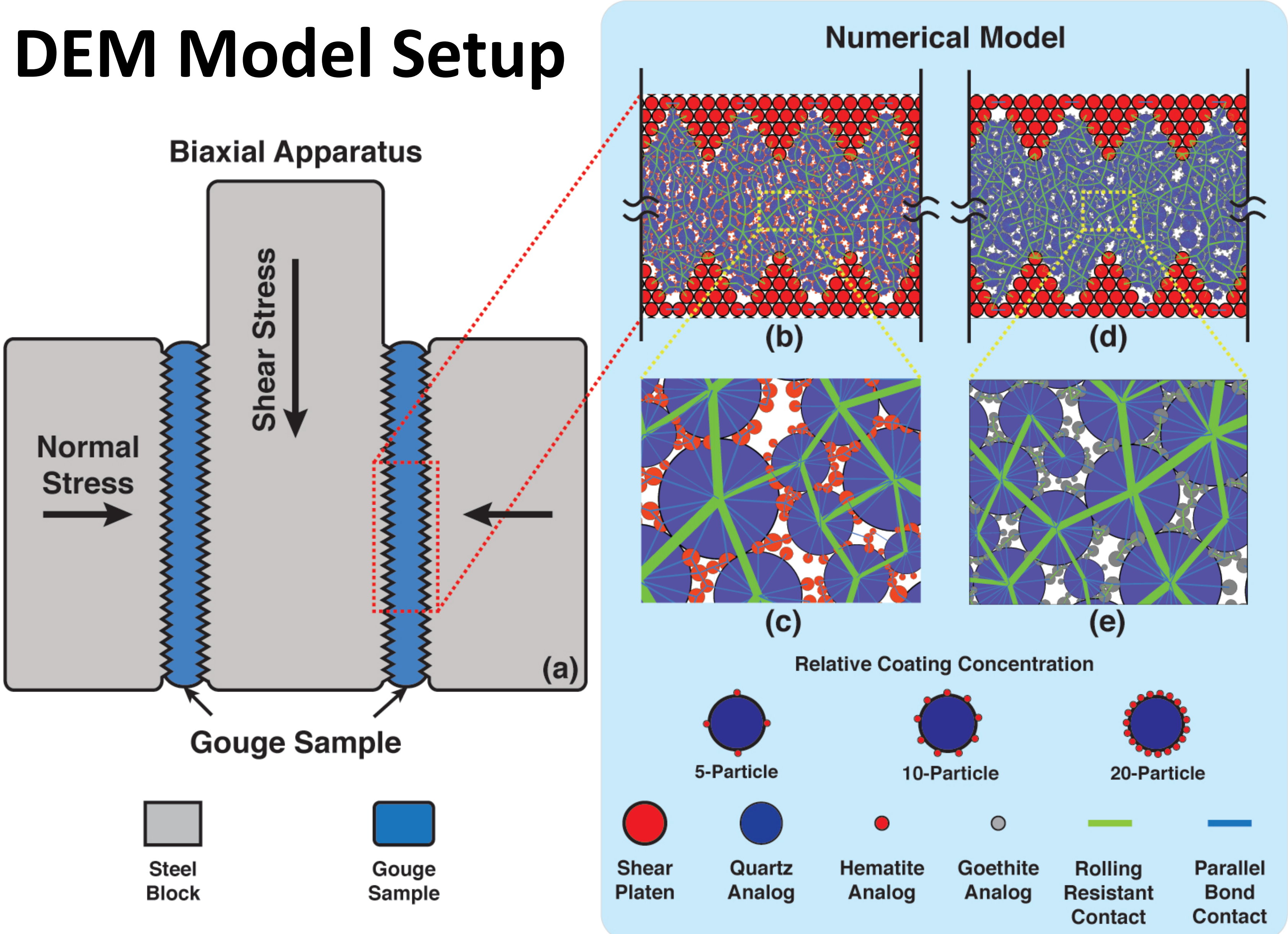




## Mineralogic Difference

**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)

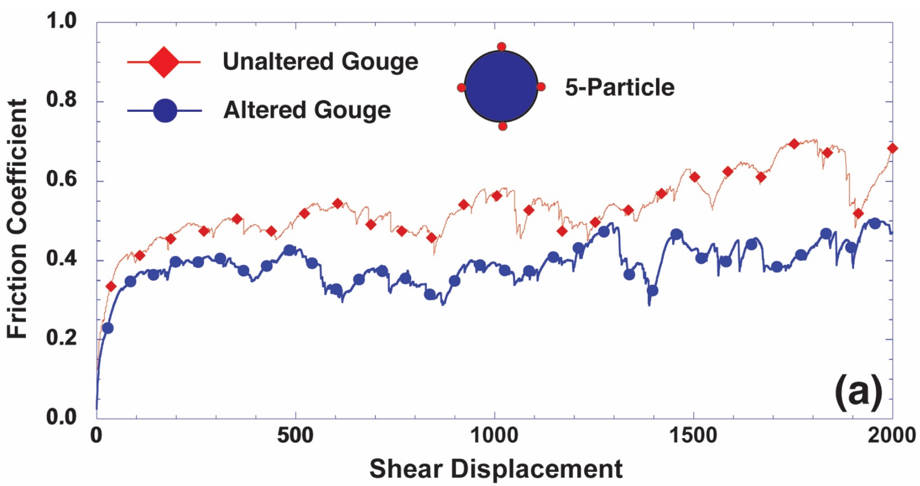
# DEM Model Setup

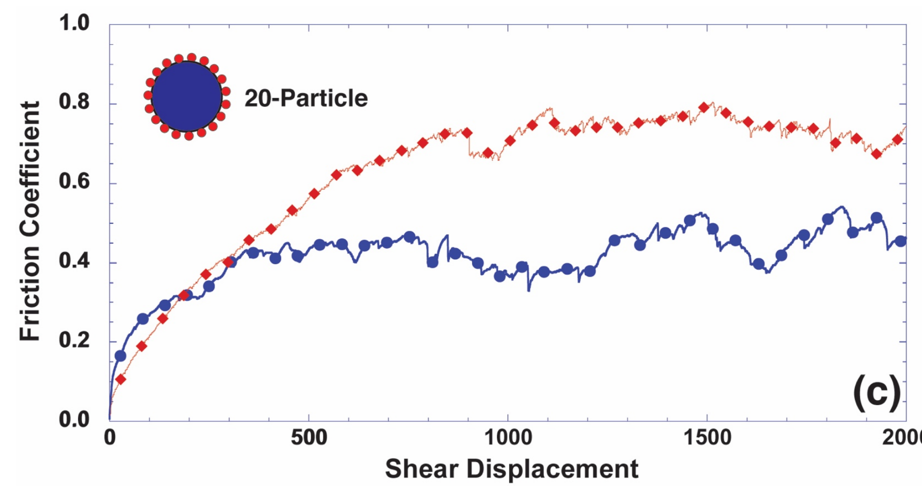


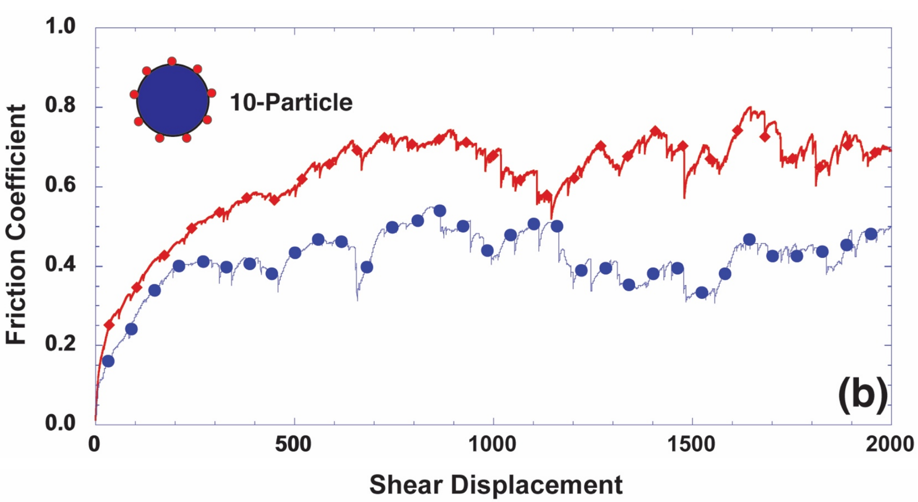

(Marone, 1999)

# Shear Strength -- Unaltered vs Altered

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

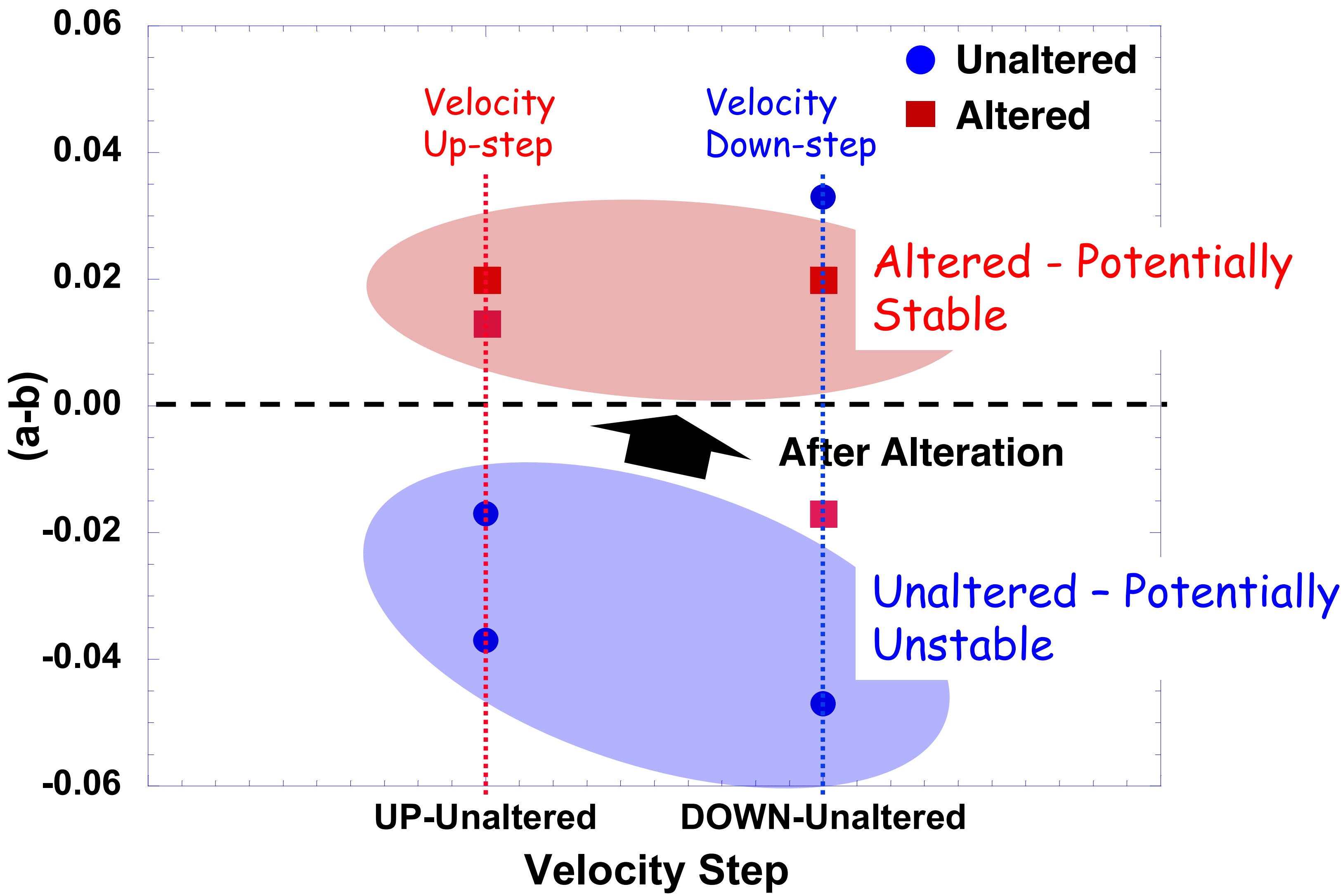


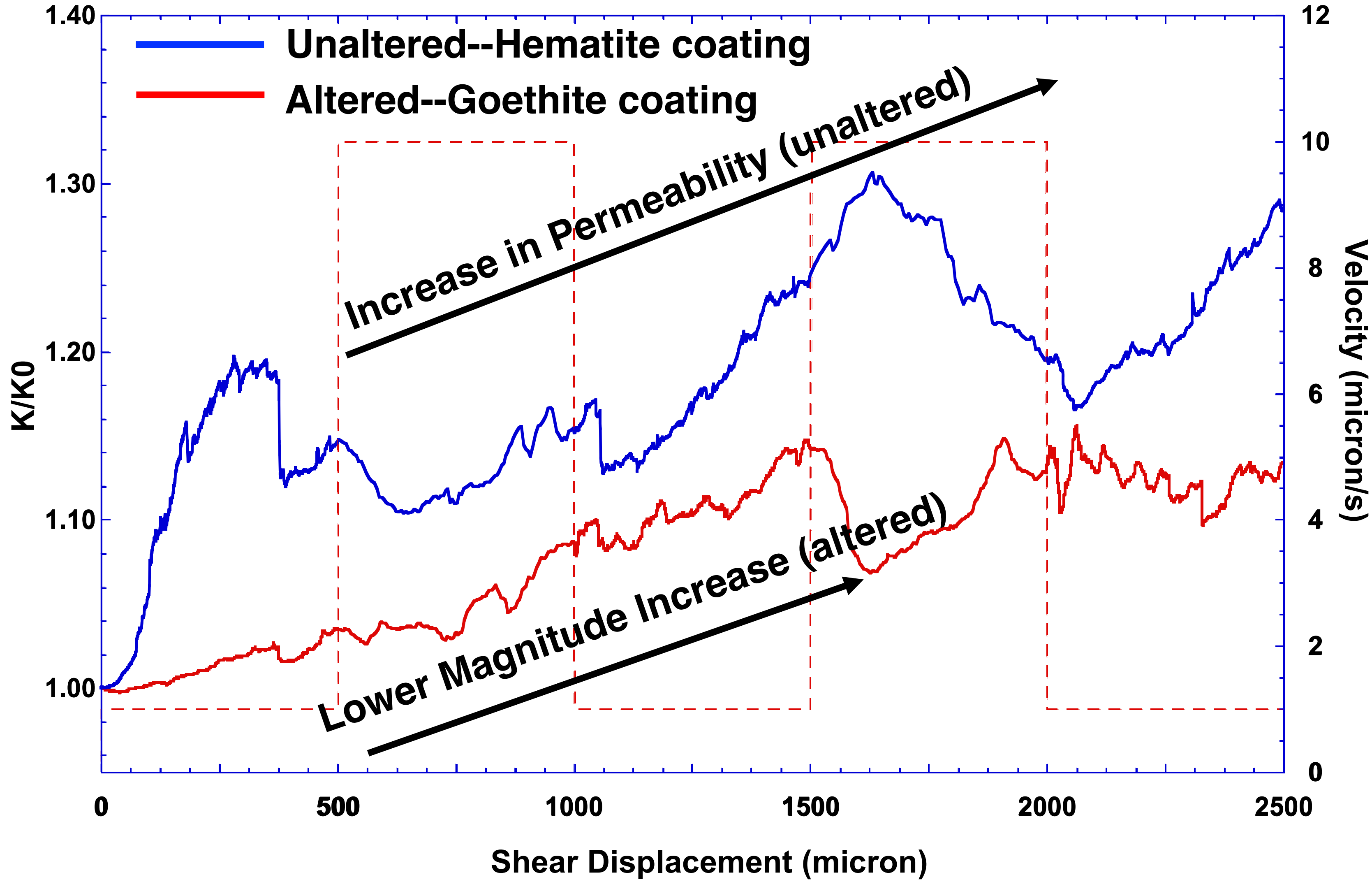




- $CO_2$ altered synthetic gouge shows **LOWER** frictional strength (shear strength) than unaltered synthetic gouge.
- Unaltered gouge shows **HIGHER** shear strength with more coating particles.

# Slip-Stability – Unaltered versus Altered

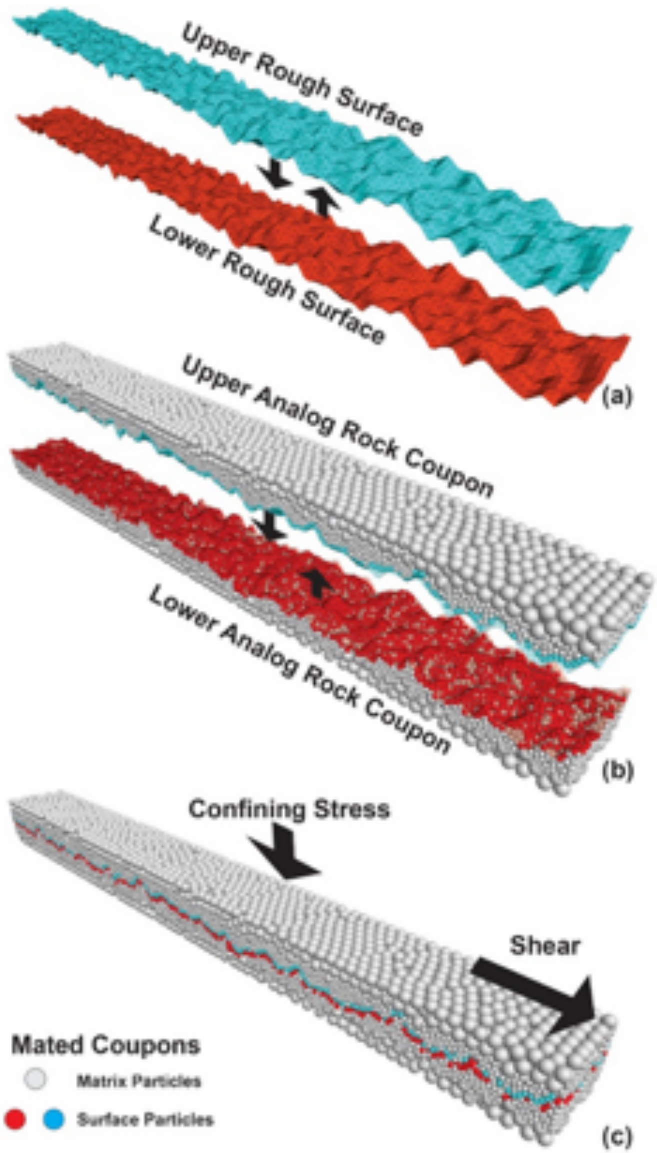


# Permeability Evolution

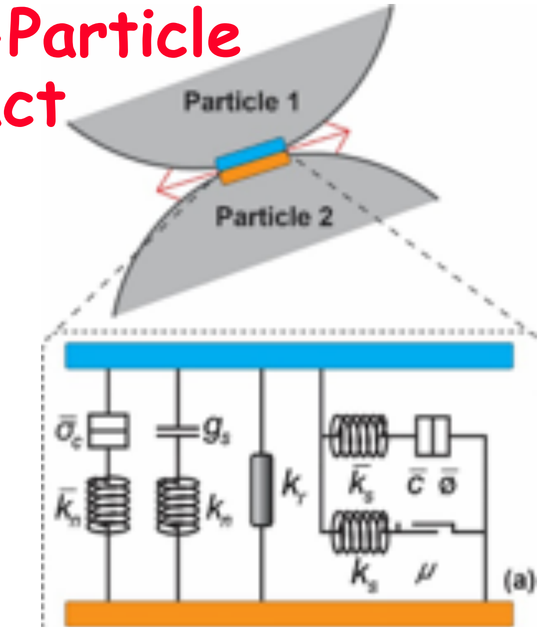


# Digital Fractures

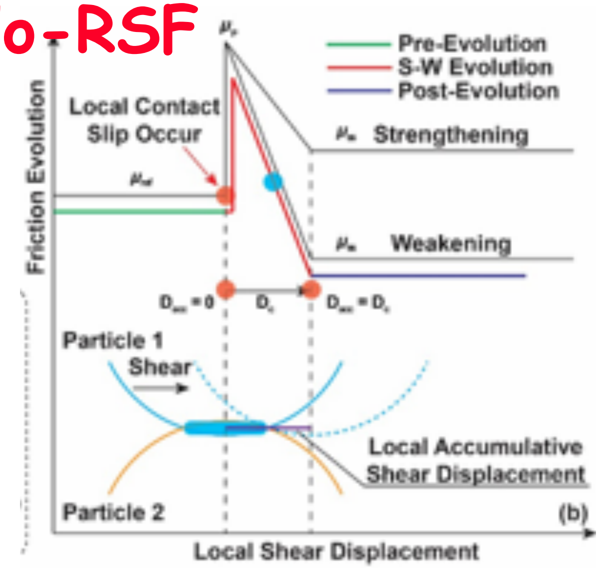
## Mated Fractures




## Particle-Particle Contact

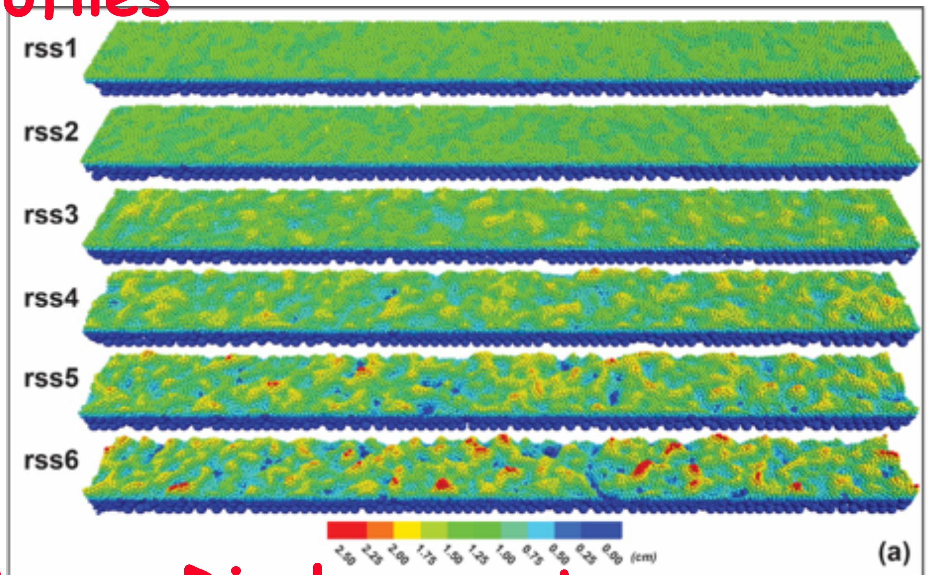



## Pseudo-RSF

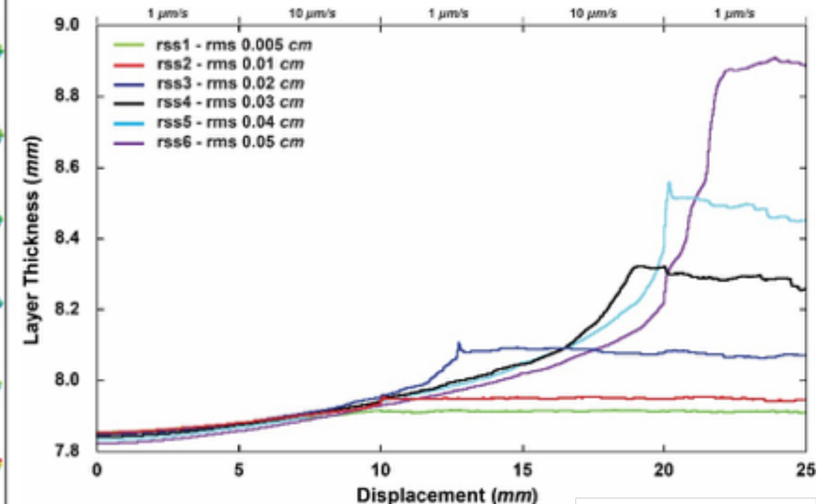


# DEM Modeling of Rough Fractures

Profiles

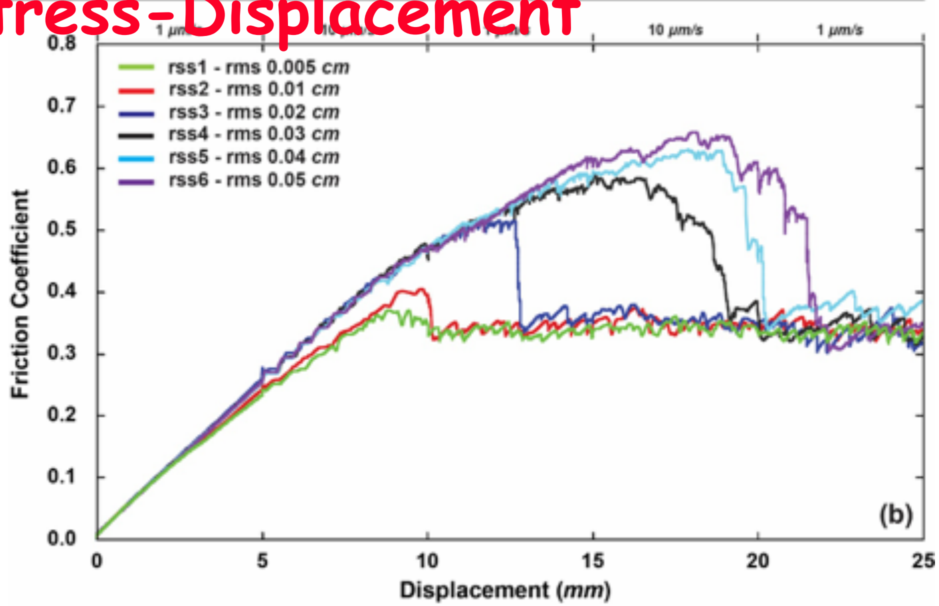



Dilation

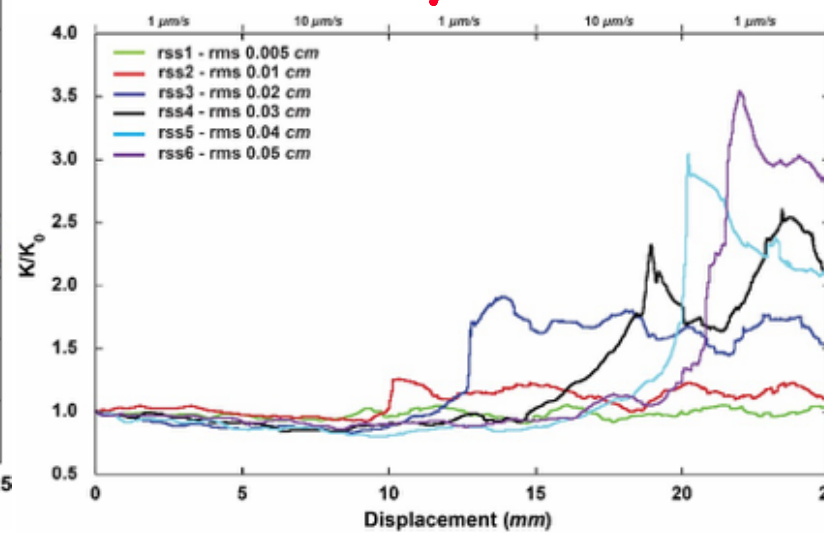



$$\frac{k}{k_0} \cong (1 + \Delta\phi)^3$$

Stress-Displacement

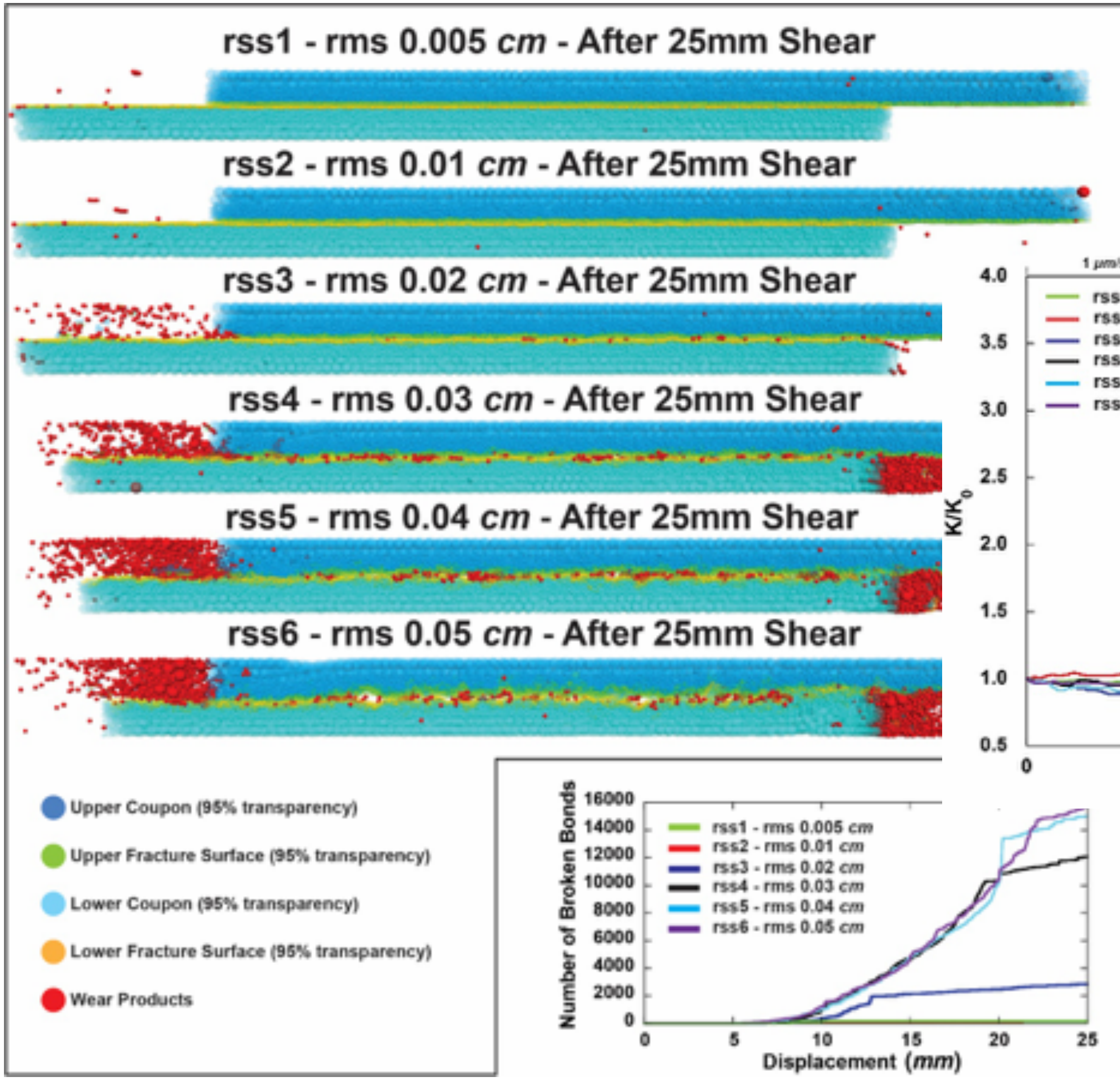



Permeability

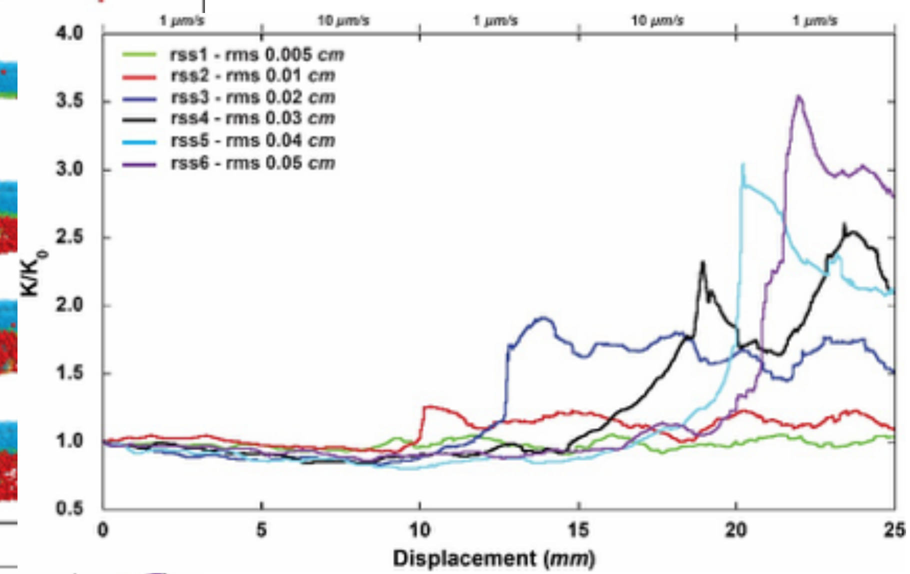


# Permeability Evolution - Role of Wear Products

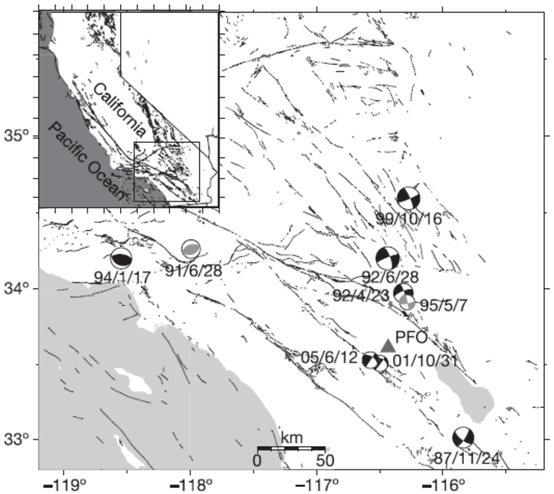
## Profiles – Variable RMS and Wear Products

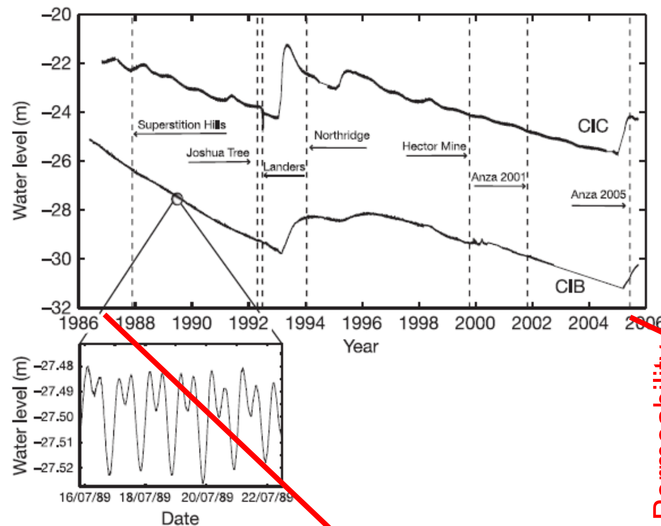


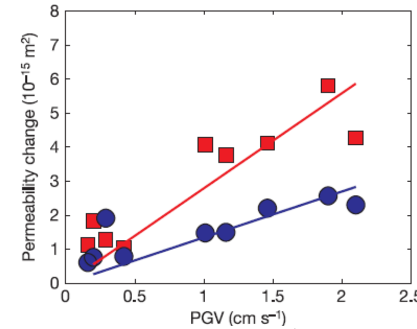

**Permeability Evolution**

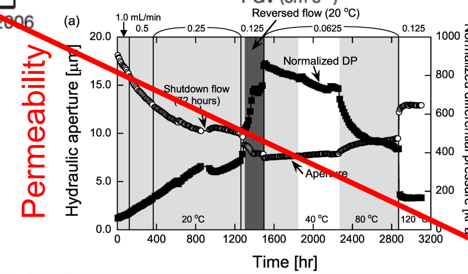


# Permeability Changes due to Dynamic Stressing




**<u>Remote</u> earthquakes trigger dynamic changes in permeability**

**Unusual record transits ~8y**

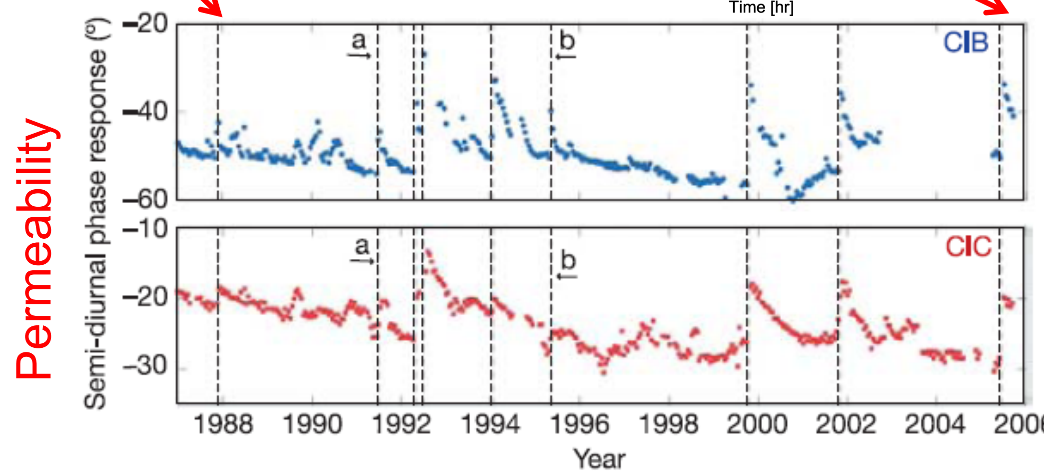
**Sharp rise in permeability followed by slow "healing" to background**

**Scales of observations:**

Field scale

Laboratory scale

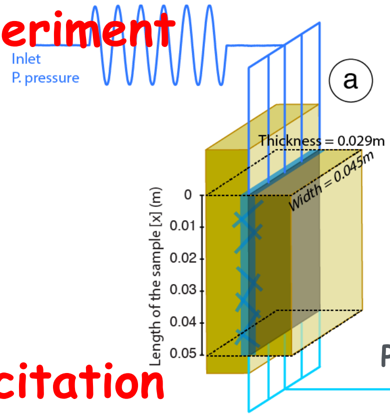
**<u>Mechanistic understanding and control</u>?**



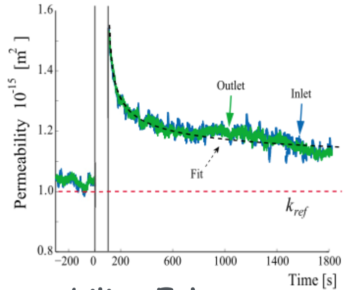

[Elkhoury et al., Nature, 2006]

# Dynamic Stressing - Mechanisms

## Experiment



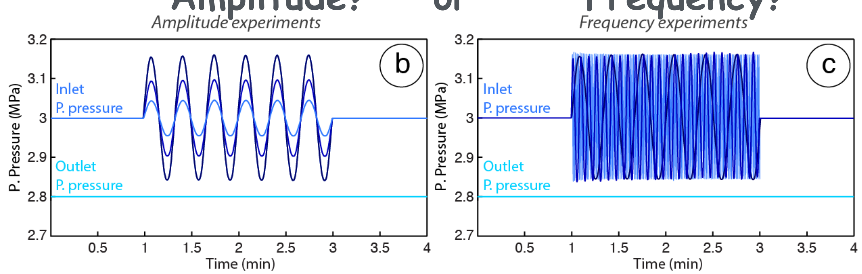

## Observation



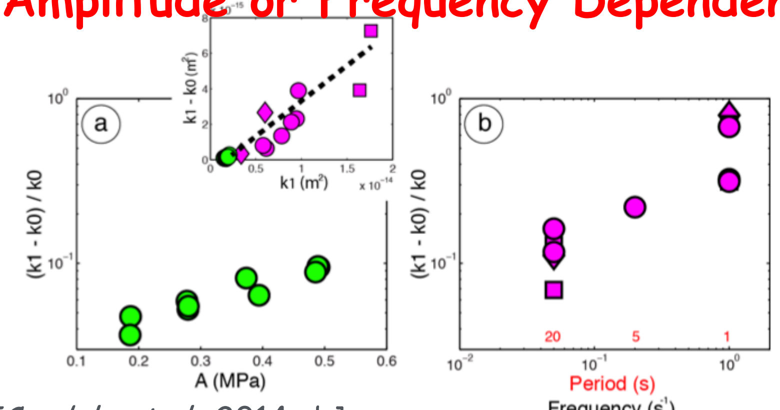

Permeability Enhancement via Dynamic Stressing

## Excitation

Amplitude? or Frequency?

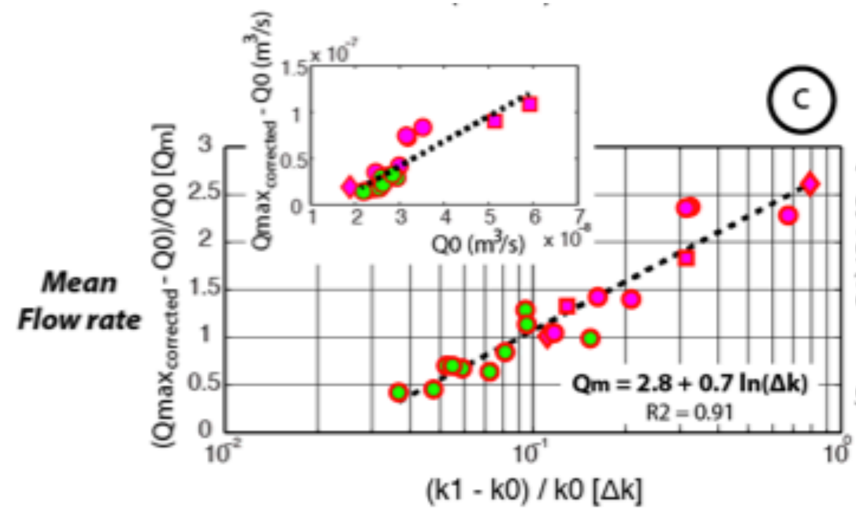



## Amplitude or Frequency Dependency

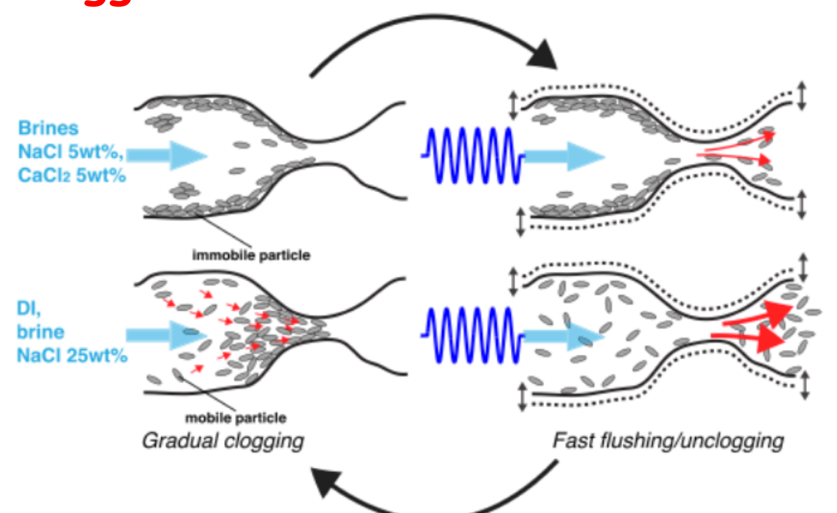



*[Candela et al.*, 2014a,b]

## Correlations with Flow Rate




## Suggested Mechanism

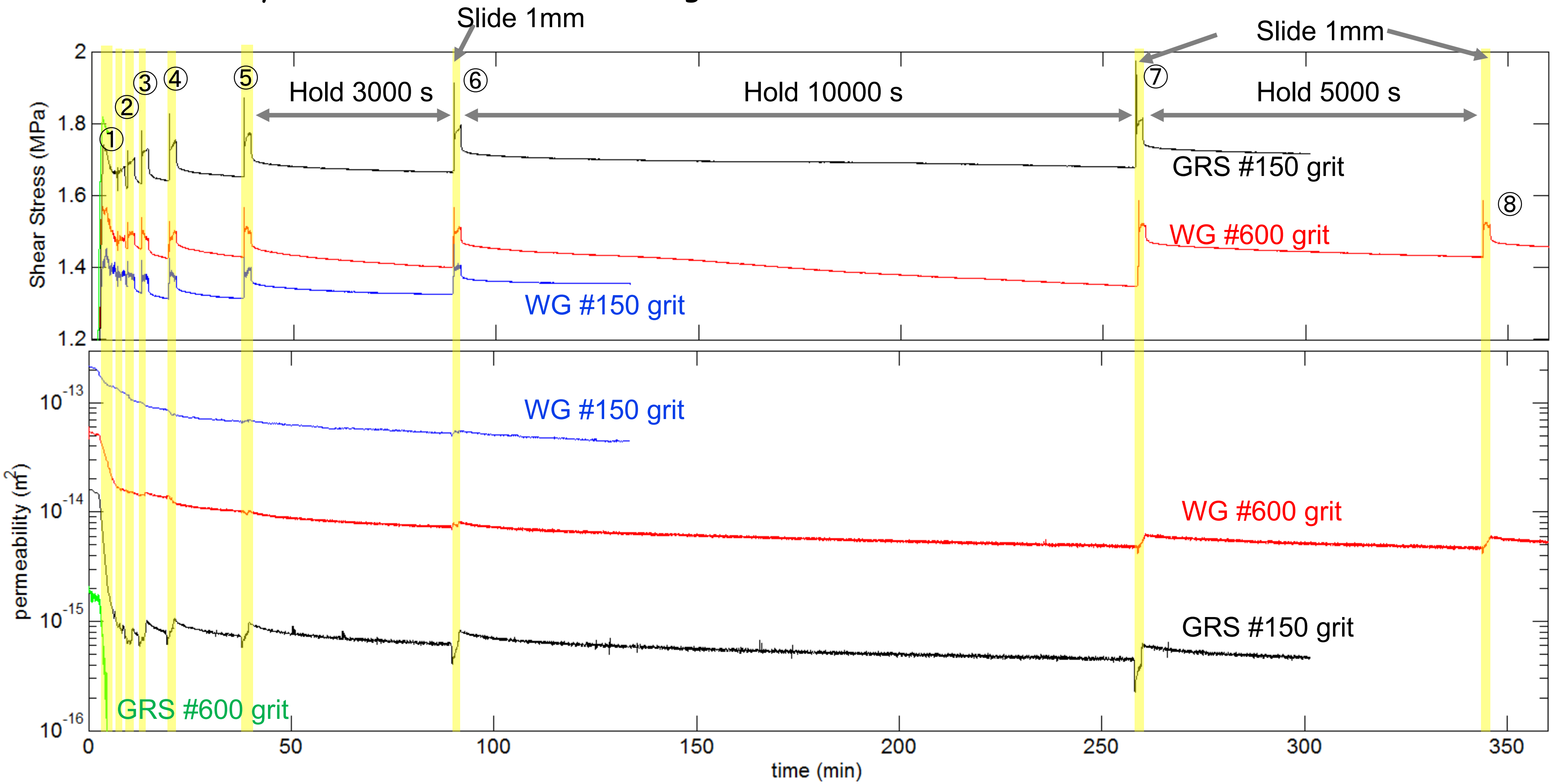


# Healing – Necessary Component of the Seismic Cycle

## 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

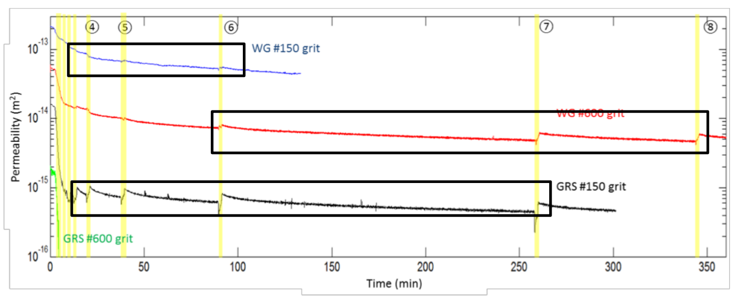
Experimental Notes
- Permeability of Green River shale #600 grit became unresolvable after initial shear
- Westerly granite #150 grit stopped at ~150 min due to limited pump capacity
- 8th shear applied to Westerly granite #600 grit after 5000 seconds

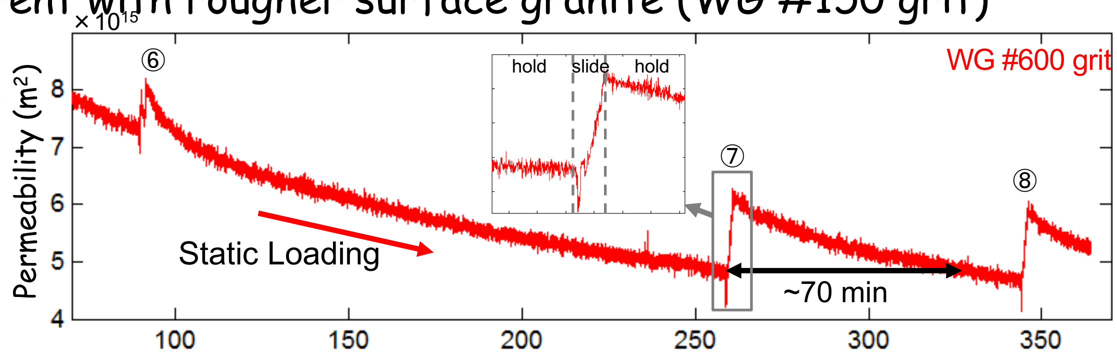


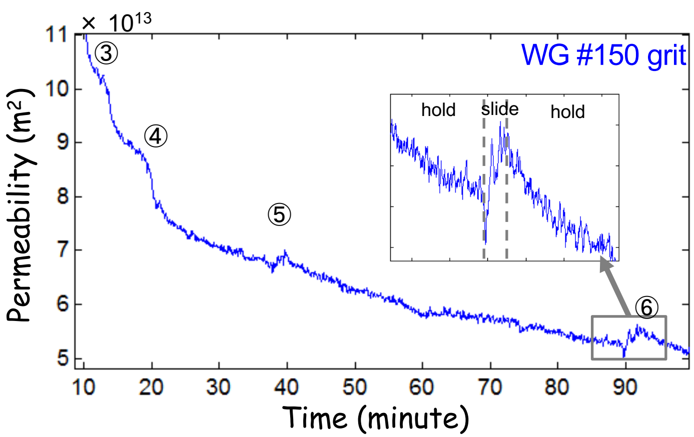
# Shear Permeability Enhancement

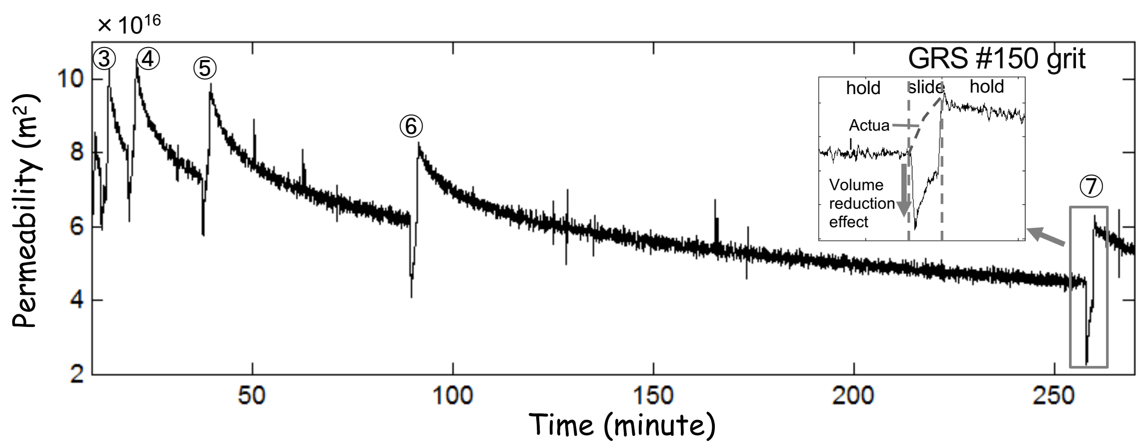
## Shear Induced Permeability Enhancement

- 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)



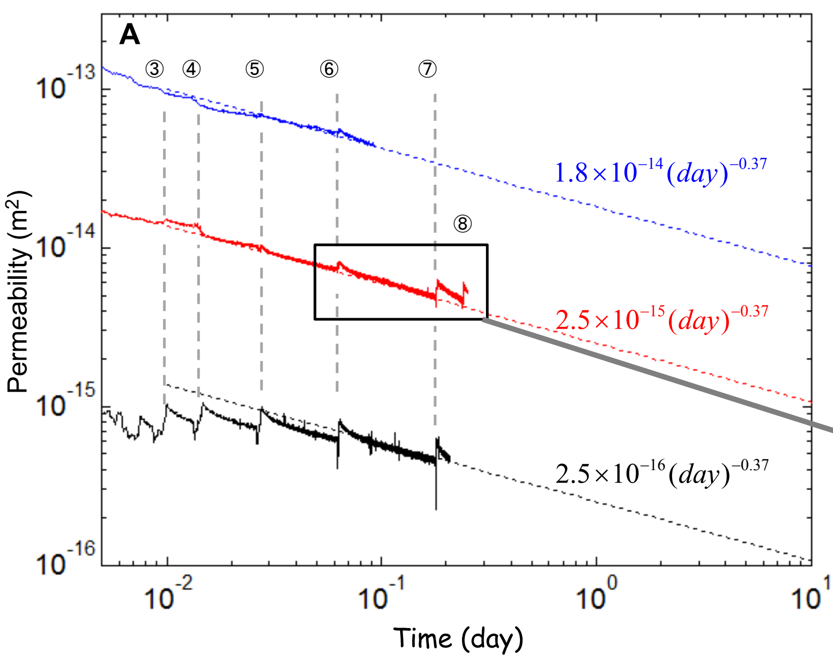



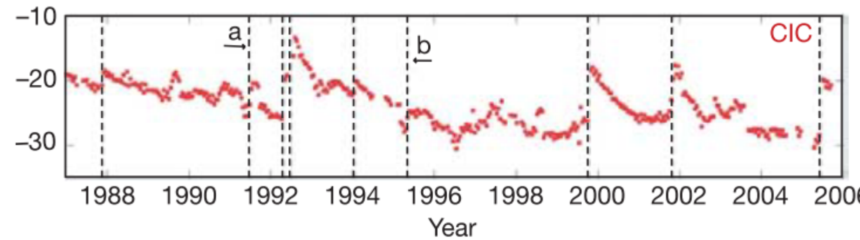



# Permeability Healing (Sealing) Law

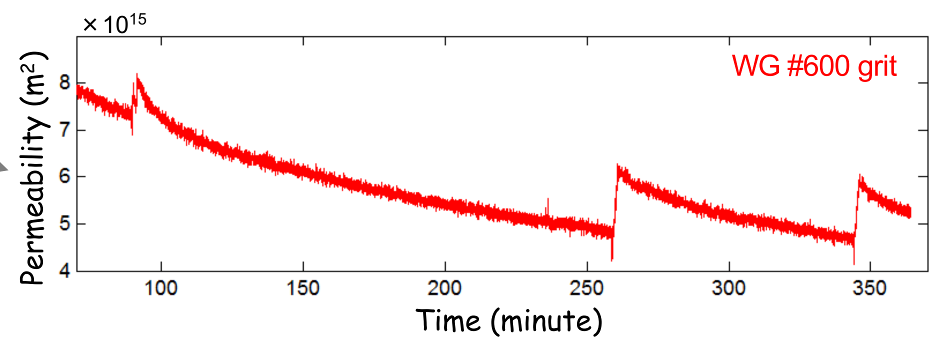
## Pressure solution

- 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?



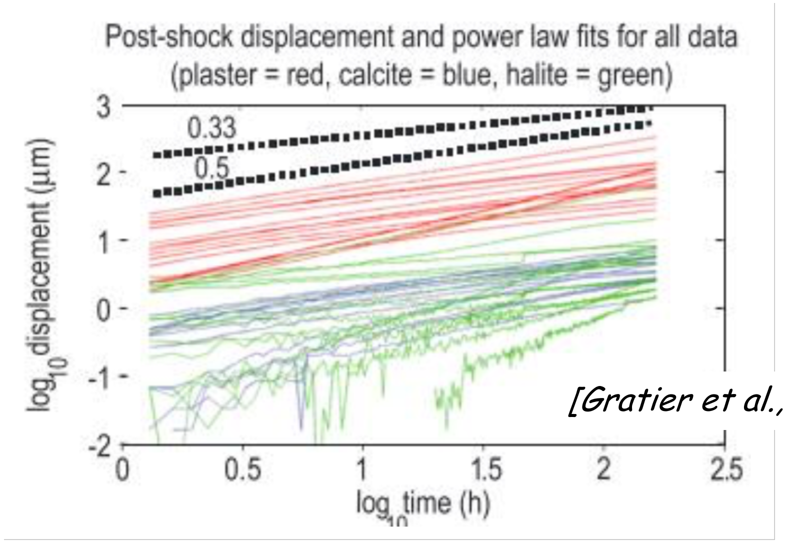

Permeability change and earthquake catalog ($M_L$>3) in southern California [Elkhoury et. al., 2006]



# Permeability Decay – Role of Pressure Solution

Power-law dependence

Rigid indenter, Pressure solution



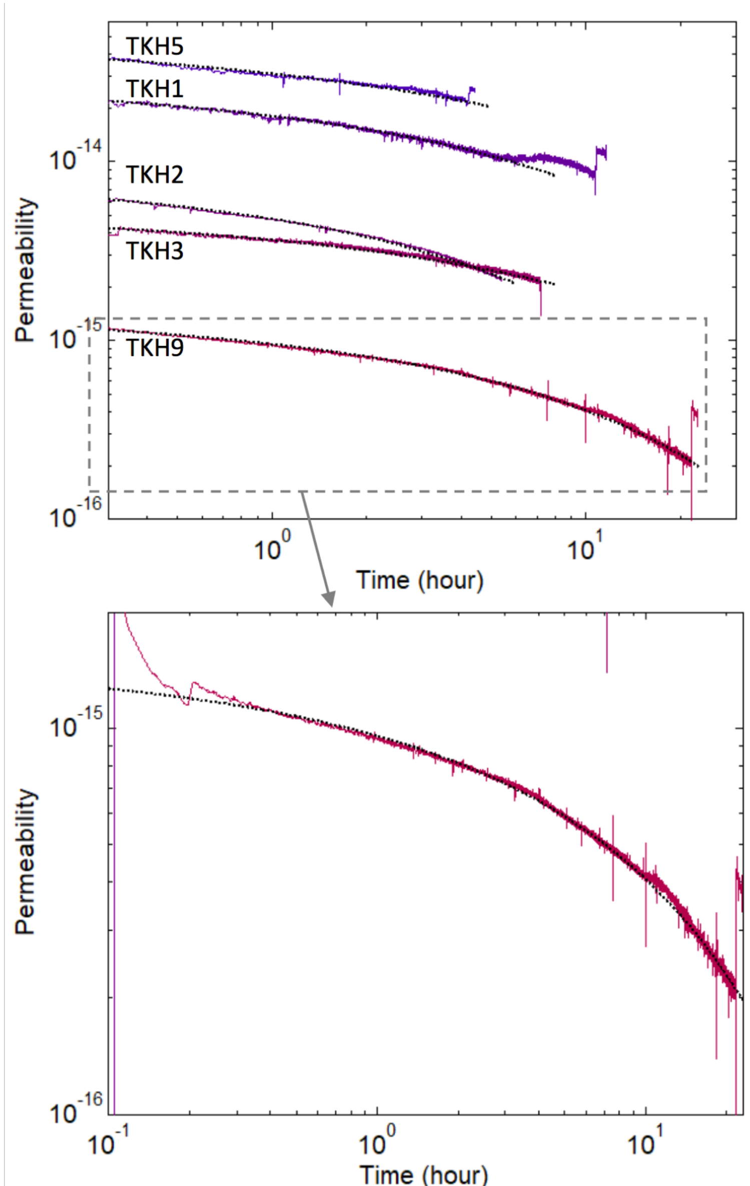

[Gratier et al., 2014]

Indentation rate:

$$\Delta b = \alpha t^{\beta}$$

Permeability change:

$$k = k_0[1 - \frac{\Delta b}{b_0}]^3 \rightarrow k = k_0[1 - \frac{\alpha}{b_0} t^{\beta}]^3$$



# Shear Permeability Enhancement

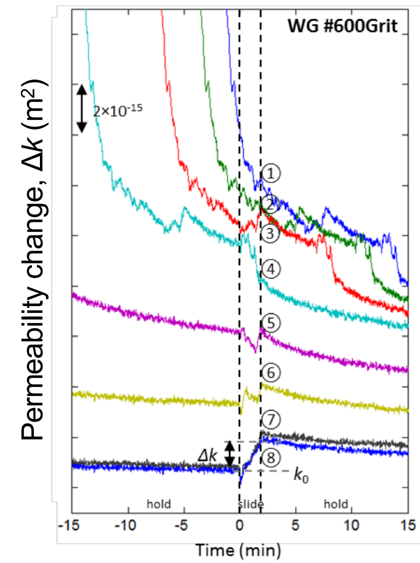
## Magnitude of Permeability Enhancement

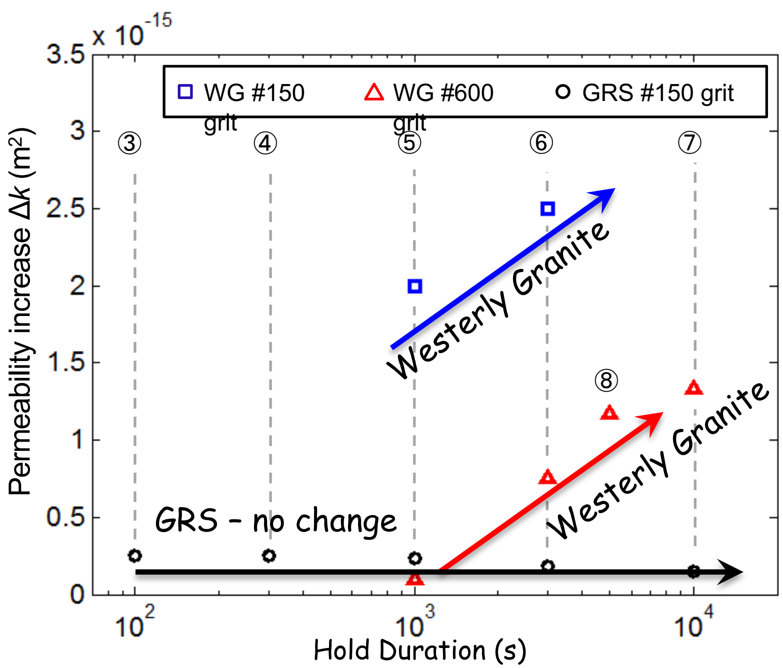
Absolute perm increase: rougher granite > smoother granite > shale

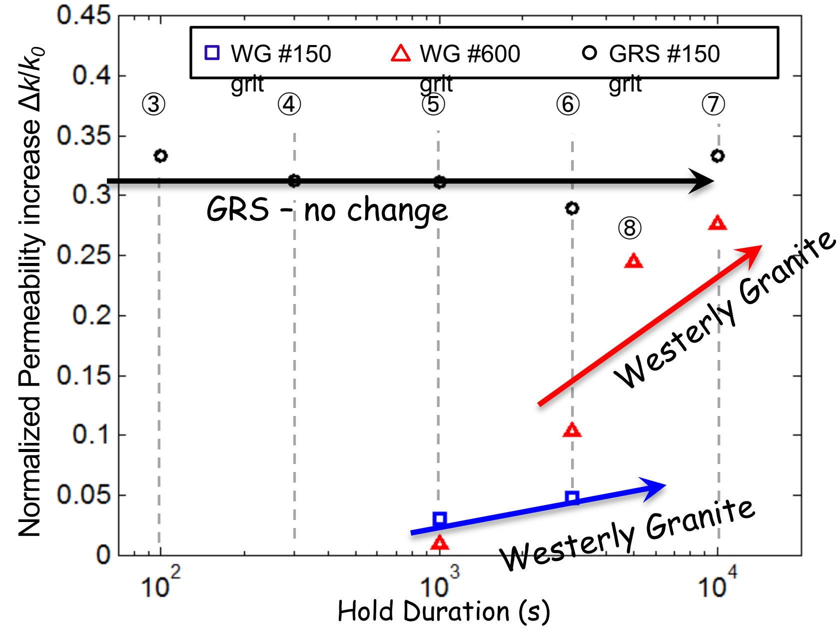
Normalized perm increase: shale > smoother granite > rougher granite

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

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

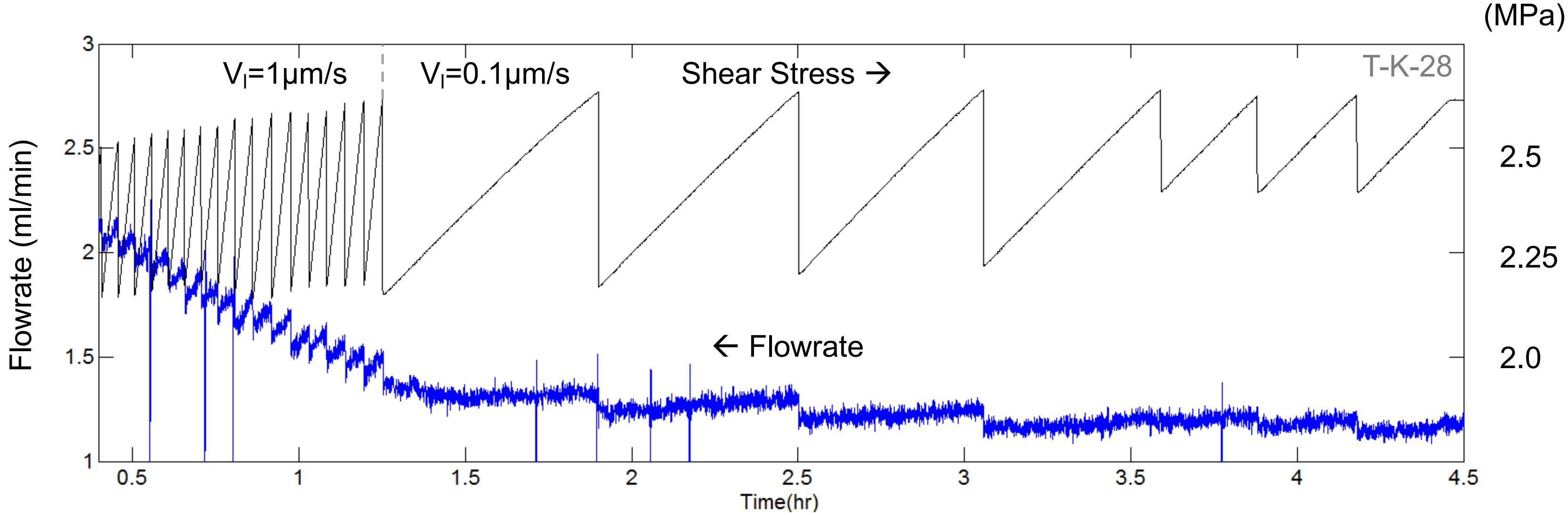


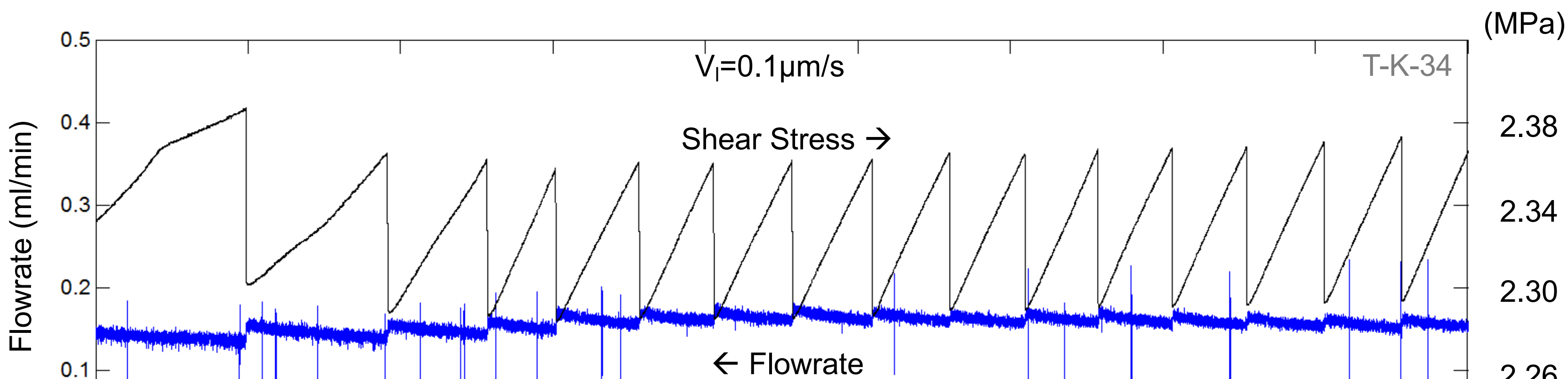



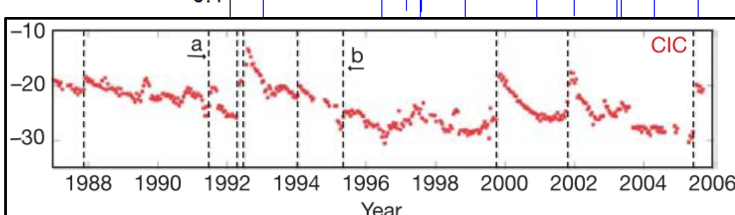



# Stick-Slip Response

## Response to Laboratory Earthquakes (Stick Slip)



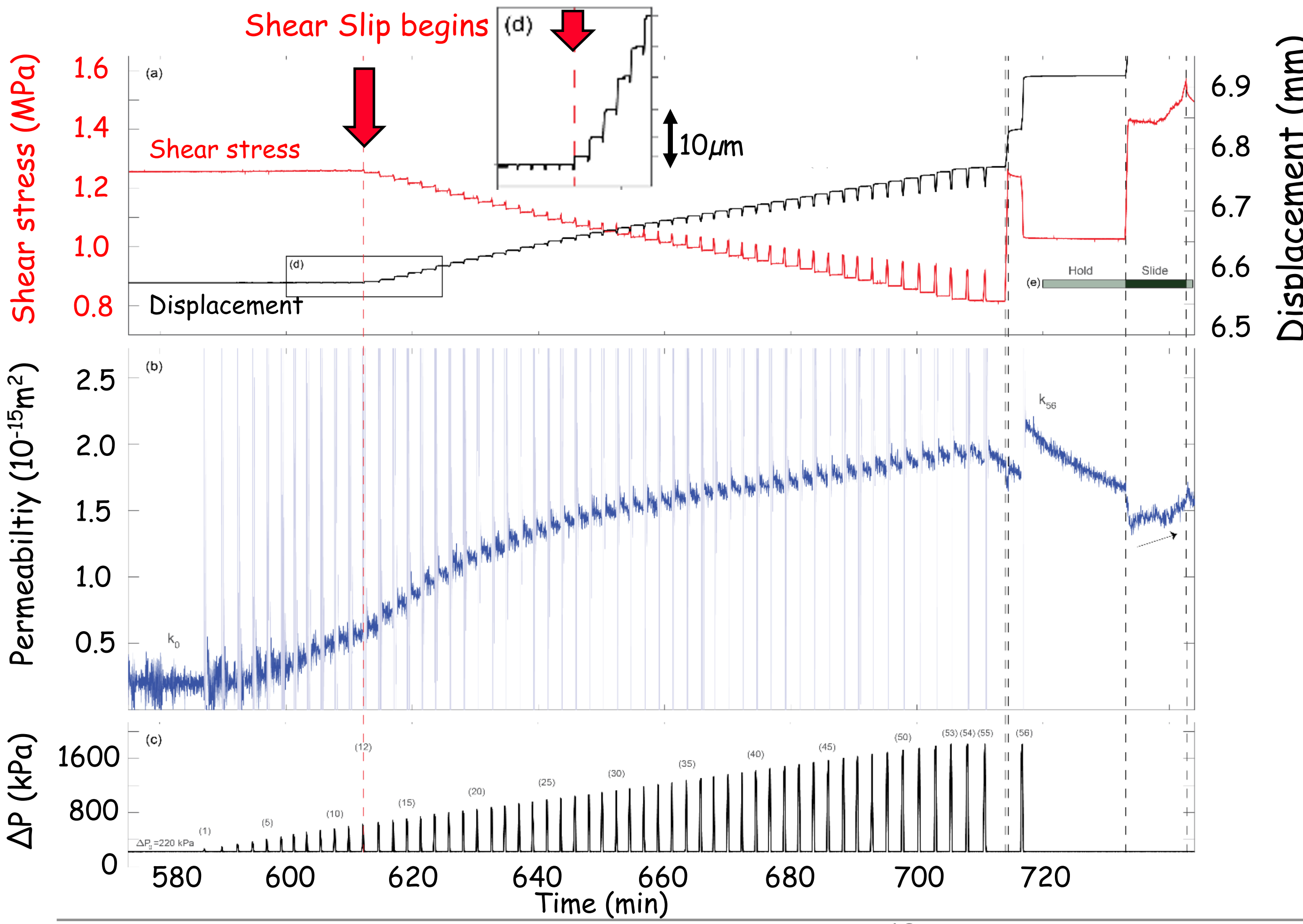


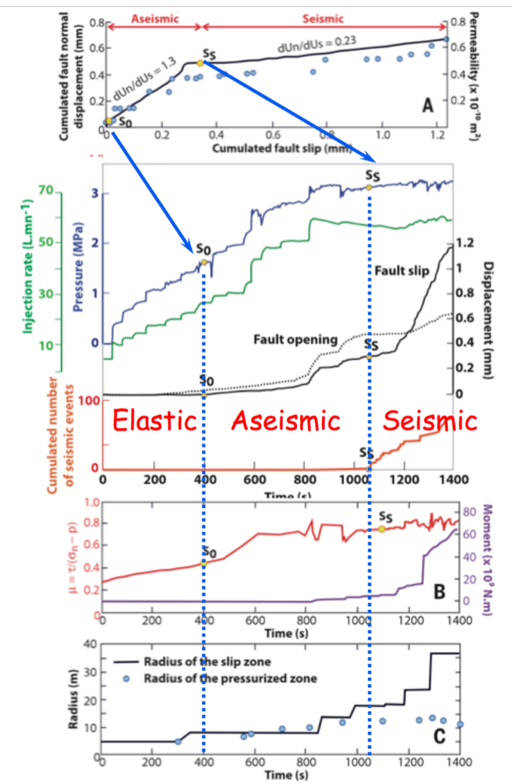

derek.elsworth@psu.edu

# Pore Pressure Perturbation

## Permeability response to pore pressure steps and induced shear slip

- Address question of relative impact of normal and shear stress incremental contributions
- Stepwise incremented pressure pulse – to cross critically-(shear)-stressed threshold
- Permeability increases with magnitude of pressure pulse
- Induced shear slip begins at fluid pressure ~600 kPa → Permeability increment becomes larger

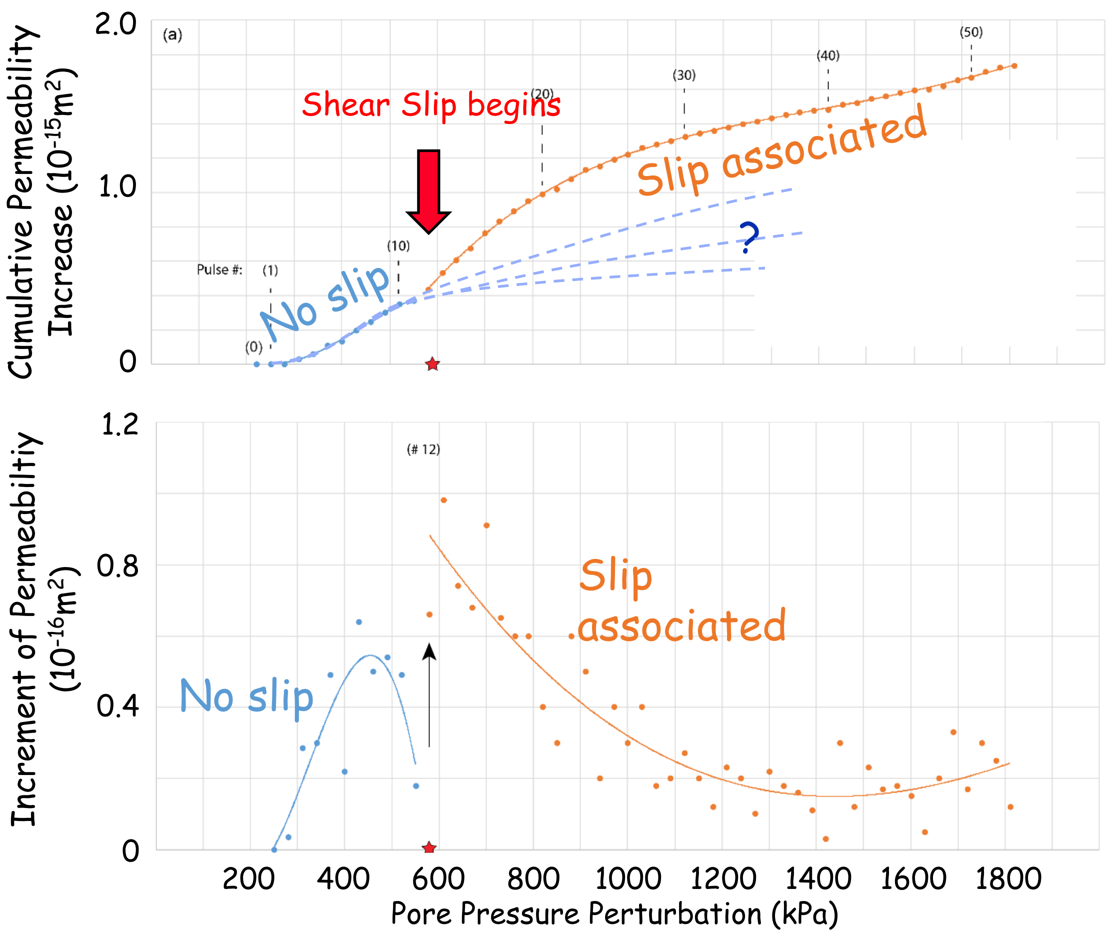


# Pore Pressure Perturbation

## Effect of induced shear slip

- Slope of permeability increment curve changes at initiation of shear slip
- Permeability increment suddenly increases when shear slip initiates (stress threshold)



# Seismicity-Permeability Coupling in the Breaching and Sealing of Reservoirs and Caprocks

Derek Elsworth (Penn State), Yi Fang (PSU), Chaoyi Wang (PSU), Takuya Ishibashi (AIST/PSU), Yves Guglielmi (LBNL/Aix-Marseille), Kyunjae Im (PSU), Yunzhong Jia (PSU/NTU), Brandon Schwartz (PSU), Ziyan Li (PSU), Elif Yildirim (PSU), Andre Niemeijer (UU), Thibault Candela (TNO), Ben Madara (PSU), Mengke An (Tongji), Fengshou Zhang (Tongji), Jacques Riviere (Grenoble/PSU), Parisa Shokouhi (PSU), Chris Marone (PSU)

**Some Key Issues in Energy Supply**

- Needs
- Constraints and Solutions

**$CO_2$ Sequestration – Linking Induced Seismicity to Permeability Evolution**

- Controls on seismicity – the aseismic-seismic transition
- Controls on maximum magnitude event
- RSF – for permeability evolution
- Controls on stability and permeability
  - Mineralogical & textural
  - Structural
- Healing and sealing and the seismic cycle

**Energy From Hot Rocks – EGS and SGRs**

- Anomalous seismicity – Newberry Demonstration Project
- Permeability scaling – Newberry Demonstration Project

**Summary**

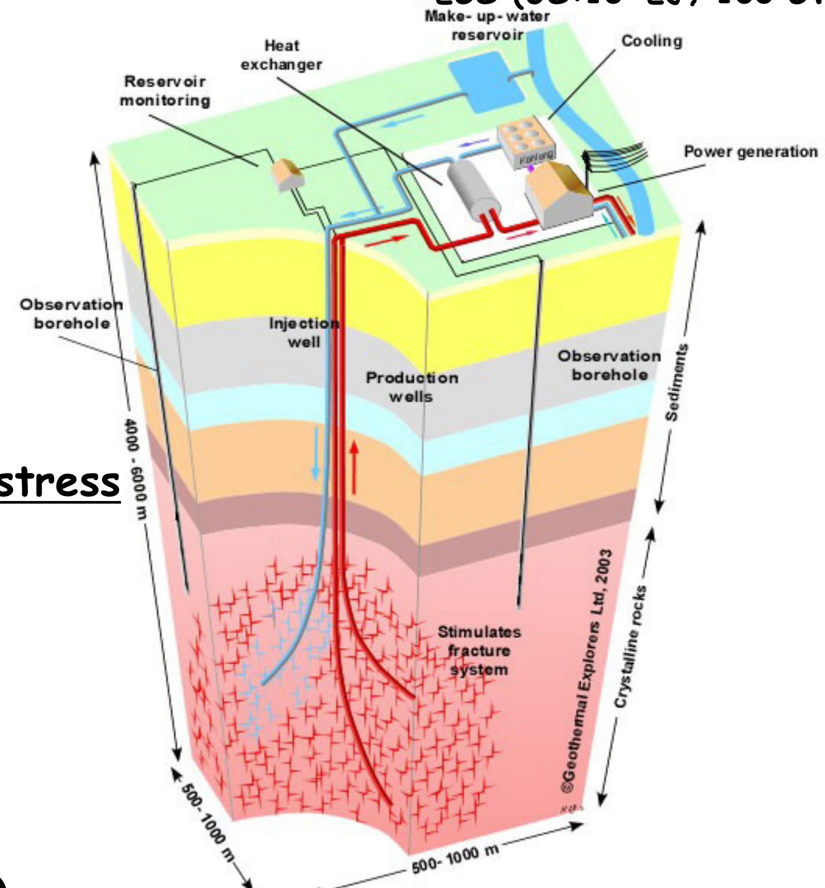
# Basic Observations of Permeability Evolution and IS

**Resource**

- Hydrothermal (US:$10^4$ EJ)
- EGS (US:$10^7$ EJ; 100 GW in 50y)

**Challenges**

- Prospecting (characterization)
- Accessing (drilling)
- Creating reservoir
- Sustaining reservoir
- Environmental issues




**Observation**

- Stress-sensitive reservoirs
- T H M C all influence via effective stress
- Effective stresses influence
    - Permeability
    - Reactive surface area
    - Induced seismicity

**Understanding T H M C is key:**

- Size of relative effects of THMC(B)
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

{ Permeability
Reactive surface area
Induced seismicity

# Anomalous Seismicity – The Missing Zone

*Questions:*

- What is the mechanism of this anomalous distribution of MEQs?
- What does the anomalous distribution of MEQs imply?

*Wellbore Characteristics*

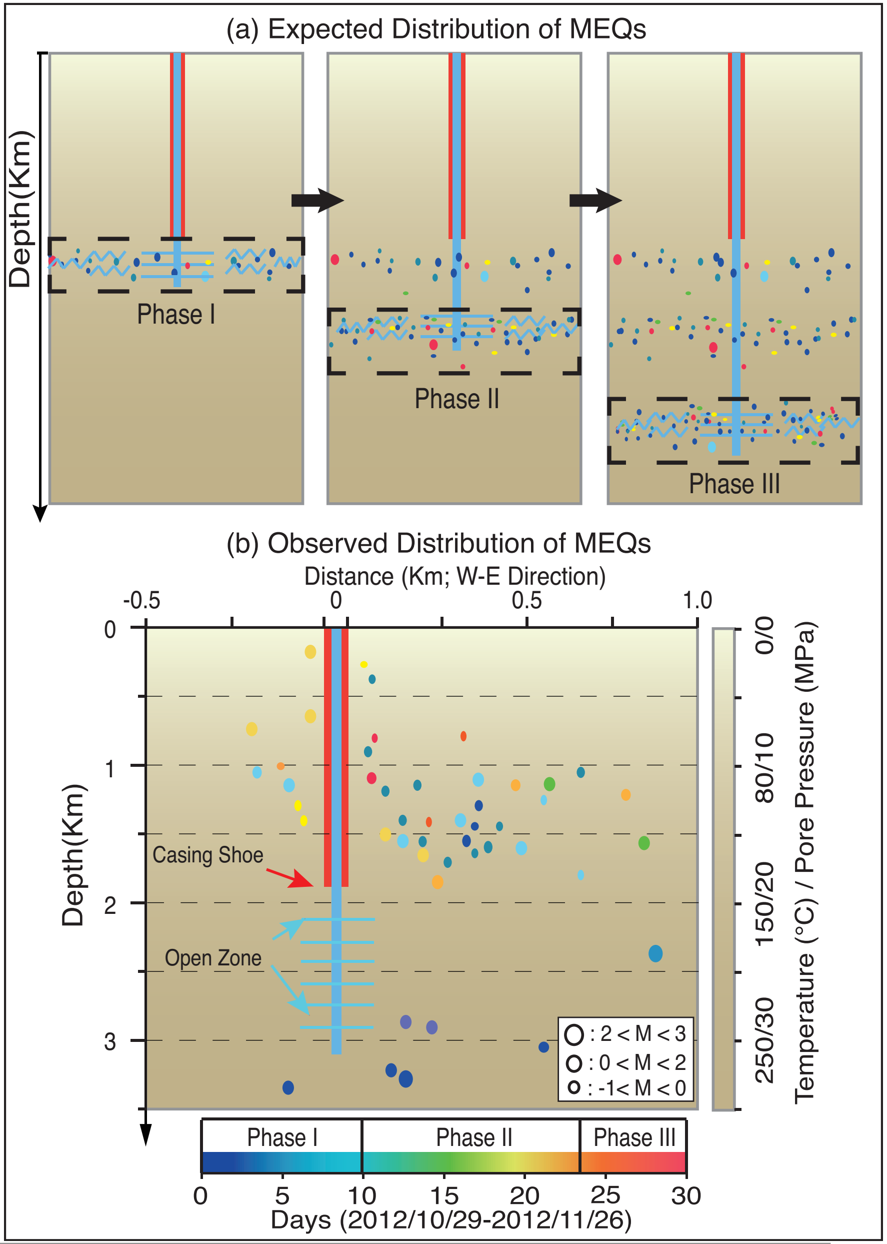
- 0-2000m: Casing shoe
- 2000m-3000m: open zone

*Spatial Anomaly*

- Bimodal depth distribution
- Below 1950 m, only a few MEQs occurred.
- Between 500m and 1800m, 90% MEQs occurred adjacent to the cased part.

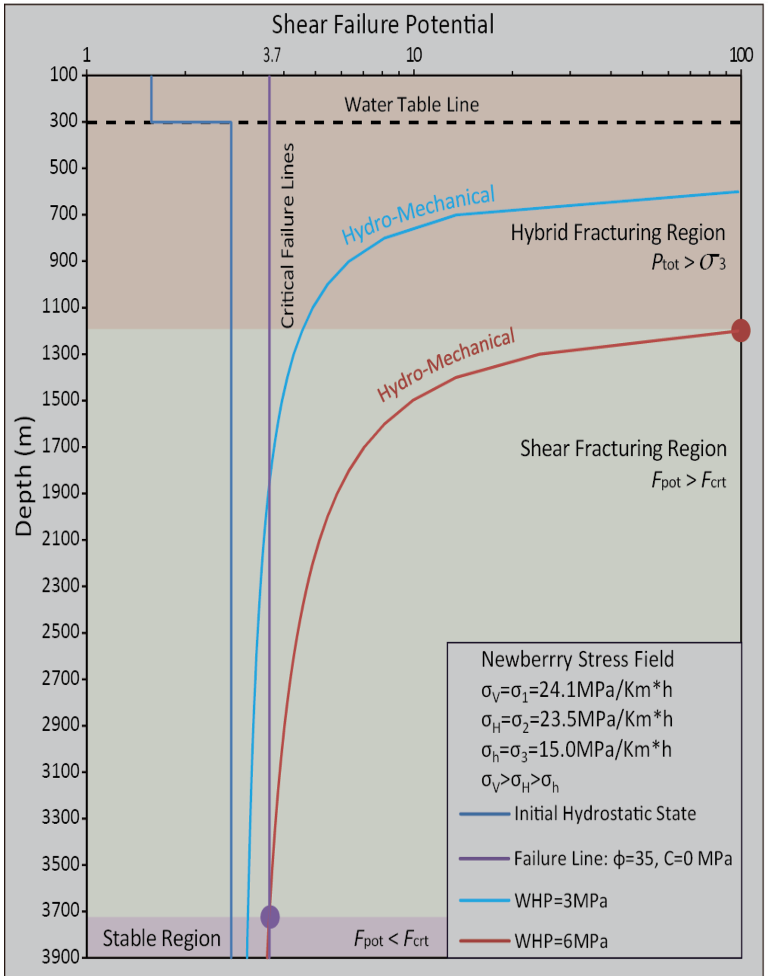
*Temporal Anomaly*

- Deep MEQs occurred within 4 days and diminished after that time.
- Shallow MEQs occurred since the 4th day.



# Constraints on Frictional Slip

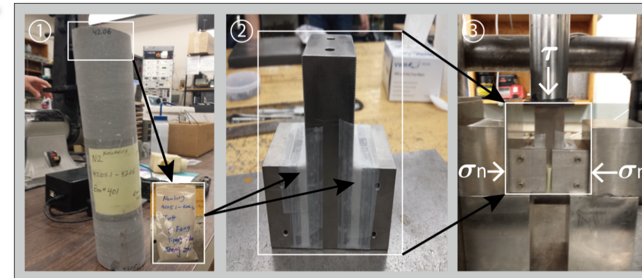
## 1. Shear Failure Analysis

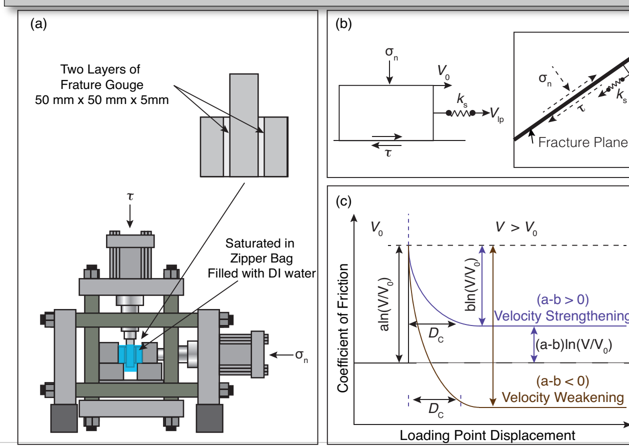


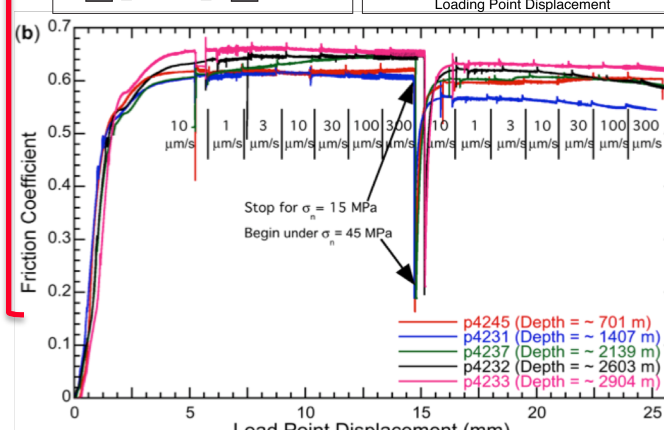

1. Shear Failure Analysis suggests that if seismicity occurs at great depth, it should occur continuously up the rock column, and not with a gap.

2. Frictional Experiments are performed to explore the frictional stability with depth and to explore the mechanisms of the unexplained seismic gap.

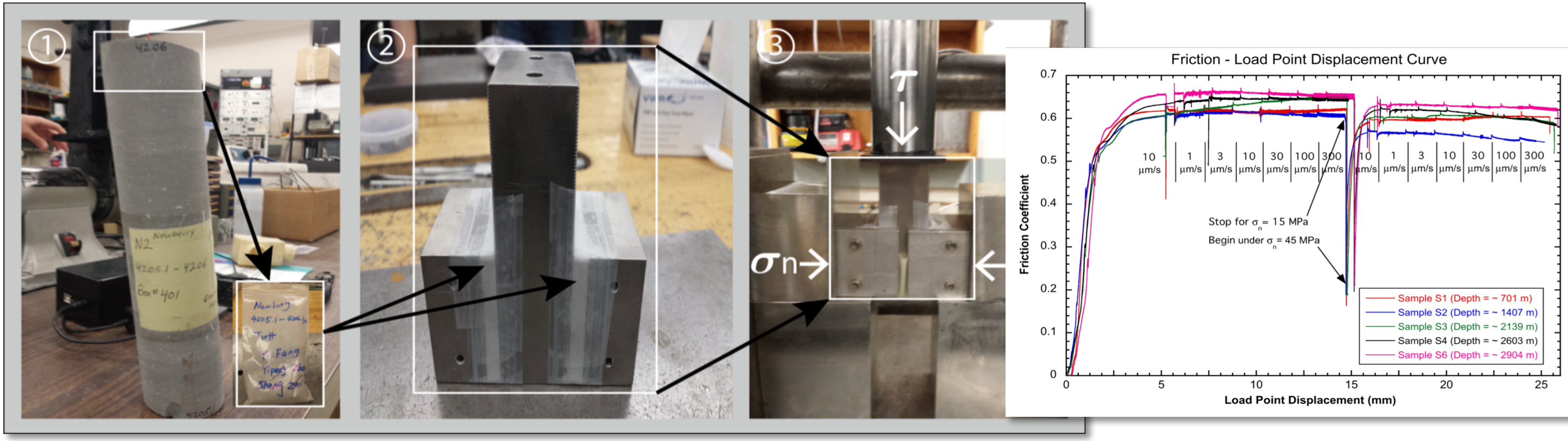
## 2. Friction Experiments

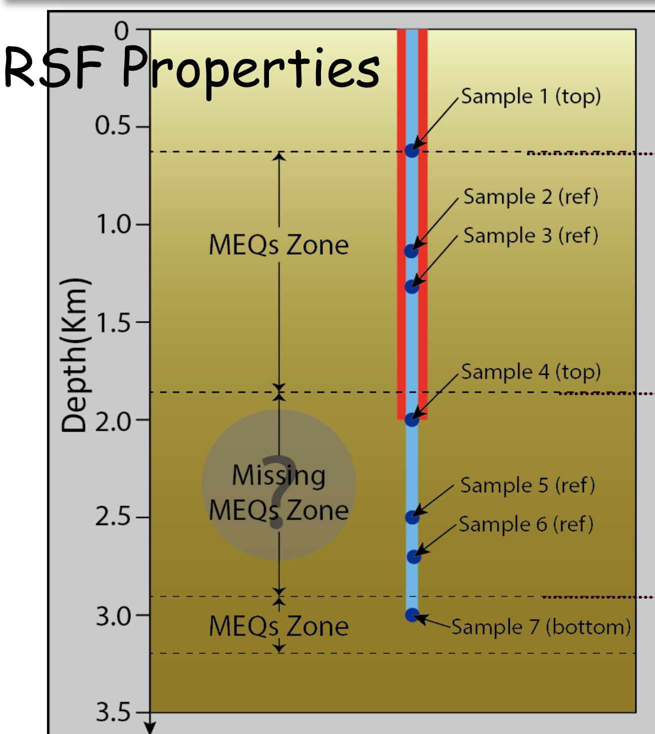


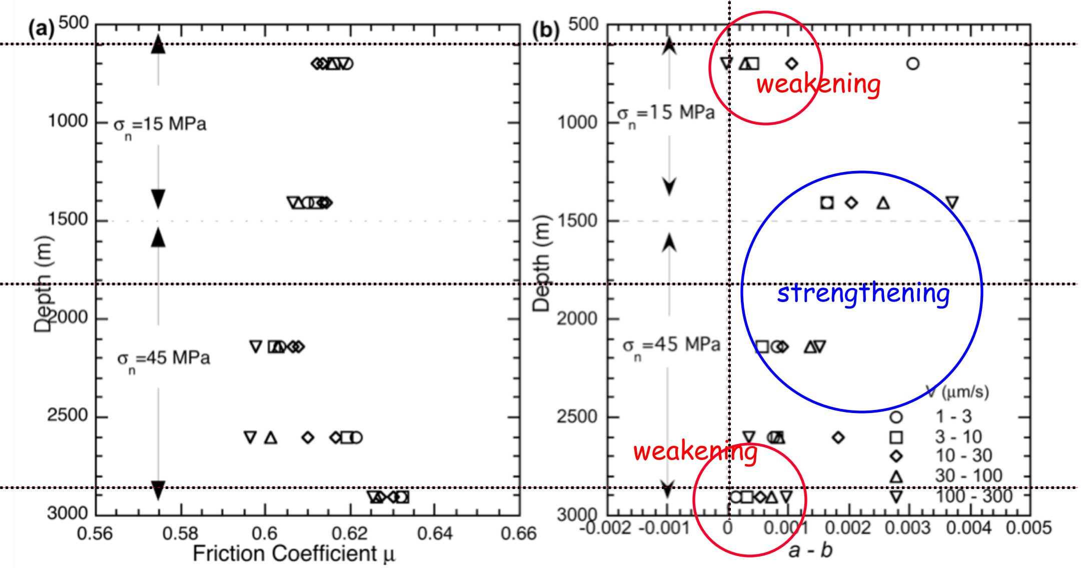
# RSF Properties




Friction

(a-b) at 15-45 MPa



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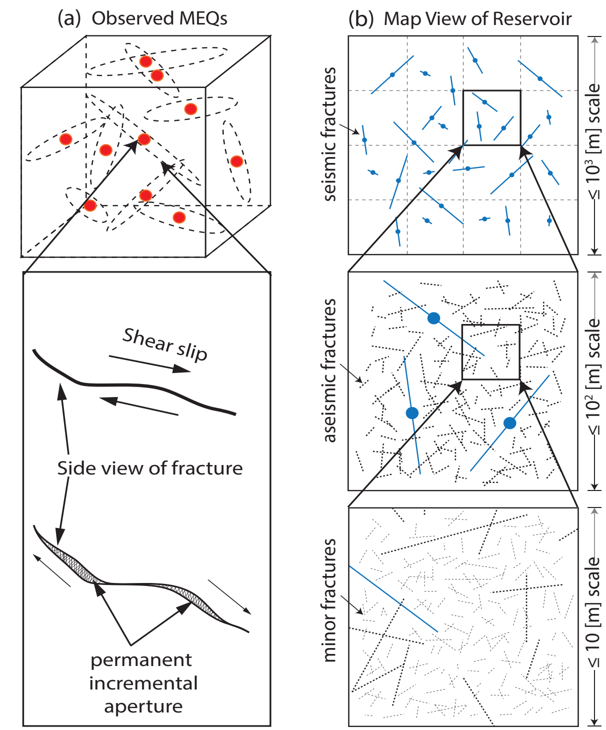
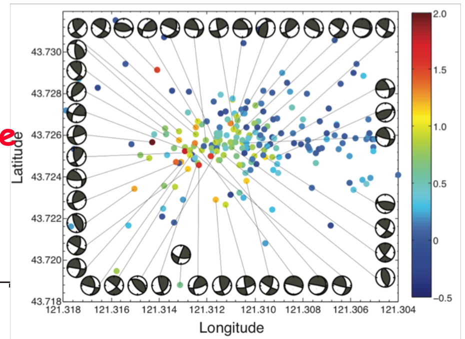
# Linking MEQs to Permeability Evolution

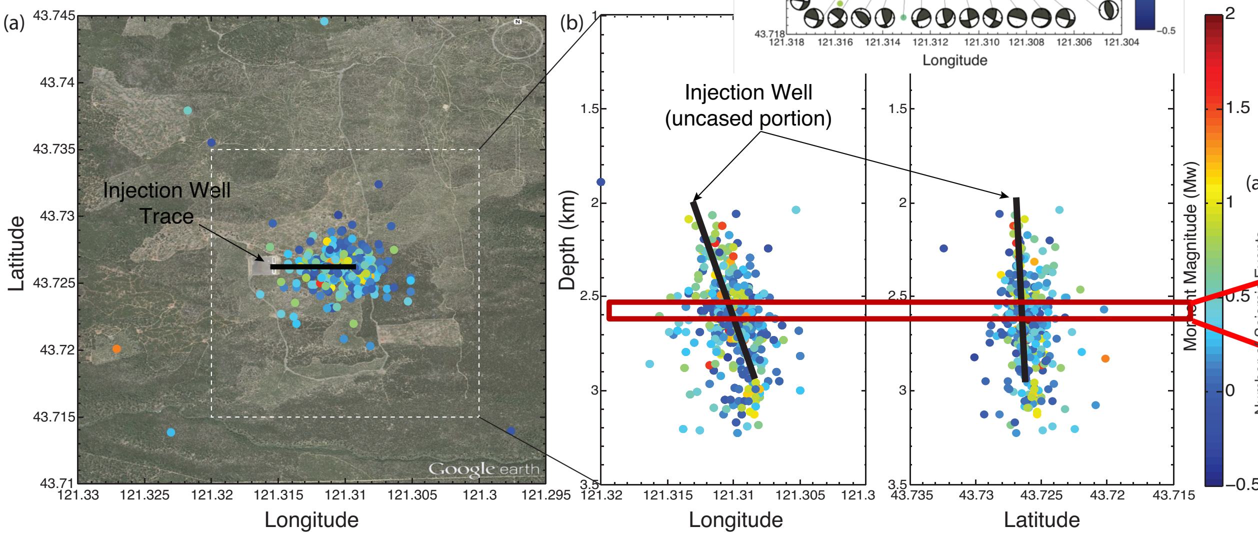
1. Seismicity induced by hydroshearing is controlled by the Mohr-Coulomb shear criterion.
2. The frictional coefficient evolves during seismic slip.
3. Two types of fractures:
   - Velocity-weakening/seismic fractures and,
   - Velocity-strengthening/aseismic fractures (fracture size smaller than the critical length).
4. Fracture interaction is ignored – consequently variations in the orientations of principal stresses are negligible



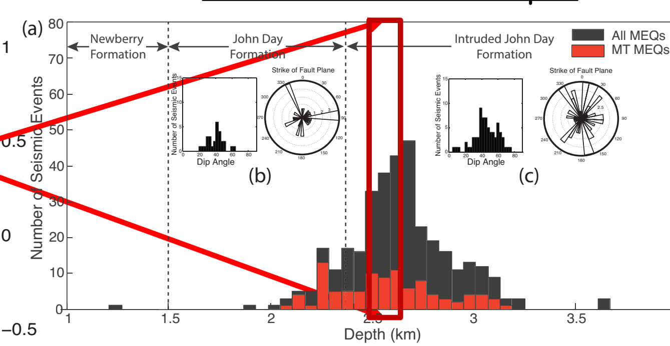

**Workflow:**

1. MT -> Orientation, mode of disp.
2. Magnitude, stress drop -> fracture size
3. Size -> roughness and dilation
4. Dilation/mode -> permeability evolution



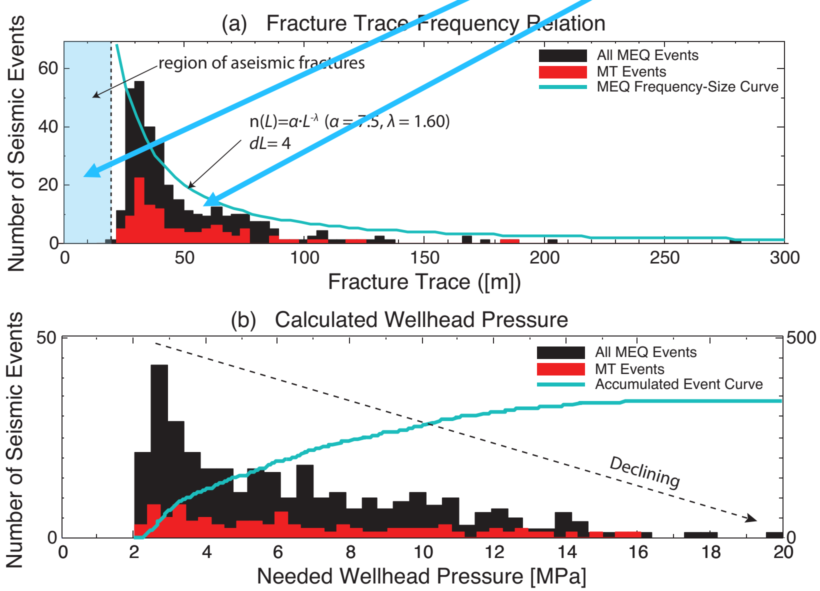

## Seismic Events vs. Depth



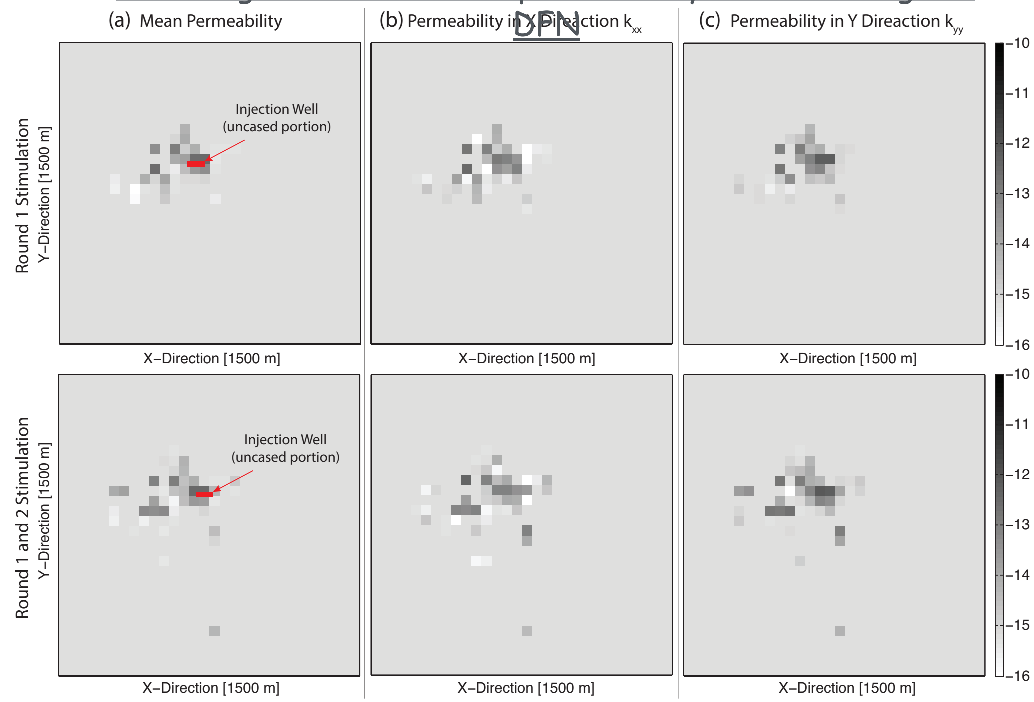
# Seismicity-Permeability Validation

$$n_{tot} = n_{aseis} + n_{seis} = \boxed{n_{aseis}} + \boxed{n_f} + n_{uf}$$

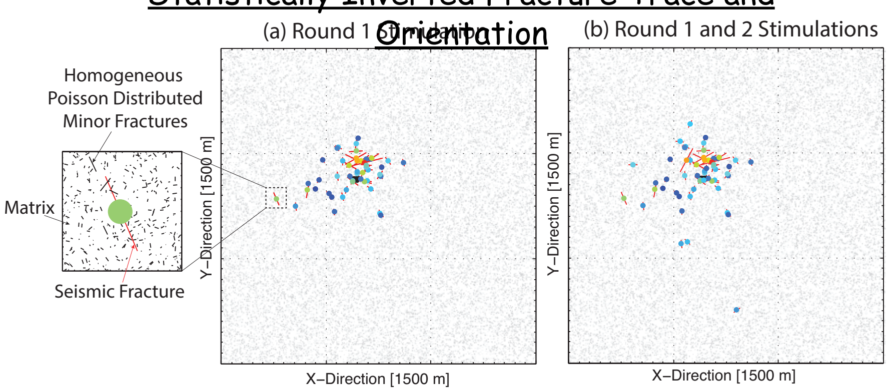
max  0



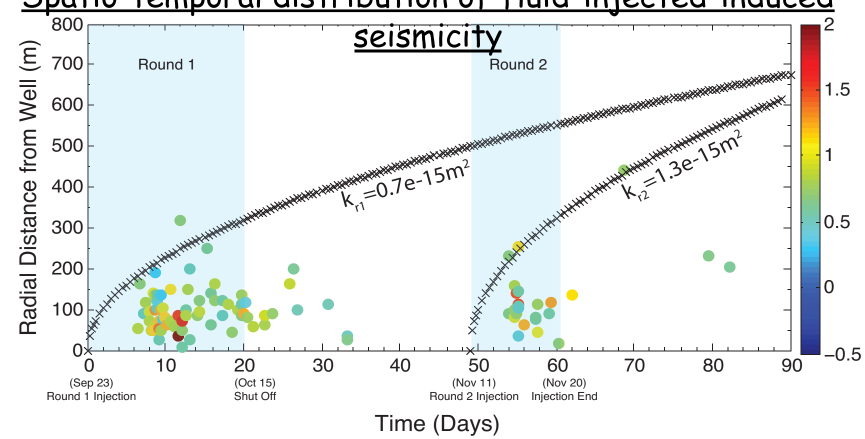

## Cellular grid of stimulated permeability created using the DFN



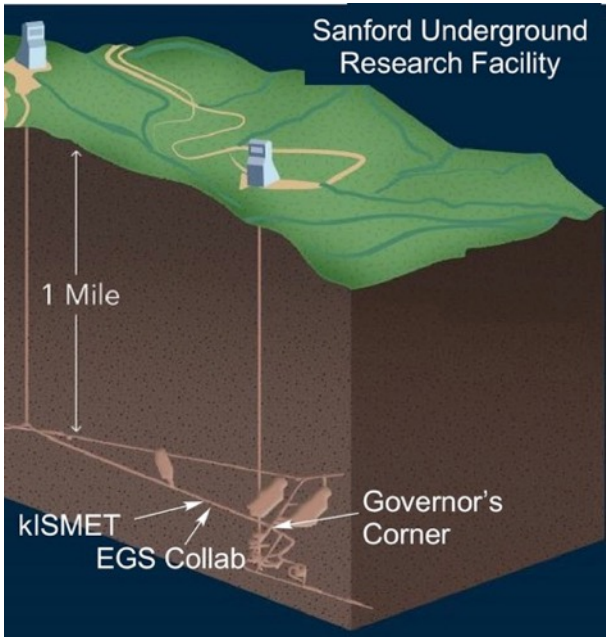

## Statistically Inverted Fracture Trace and Orientation




## Spatio-temporal distribution of fluid-injected-induced seismicity



# DoE EGS Collab(oration) Project

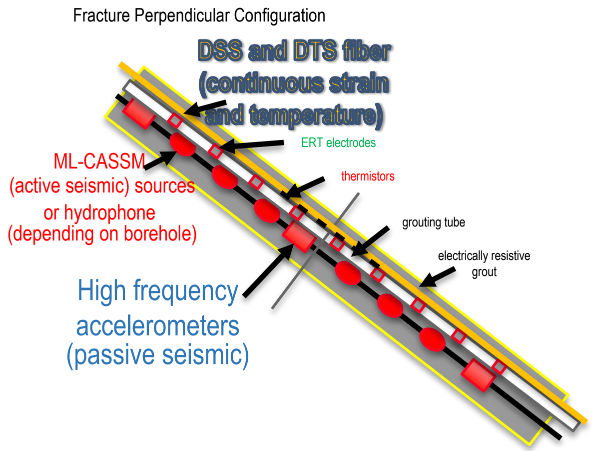


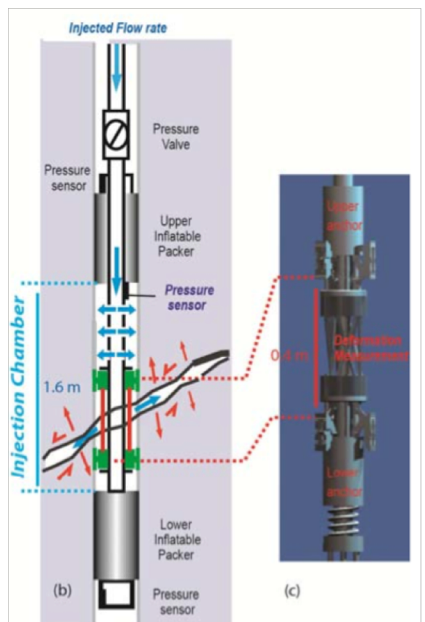

At Sanford Underground Research Facility (SURF-DUSEL) – 1500m

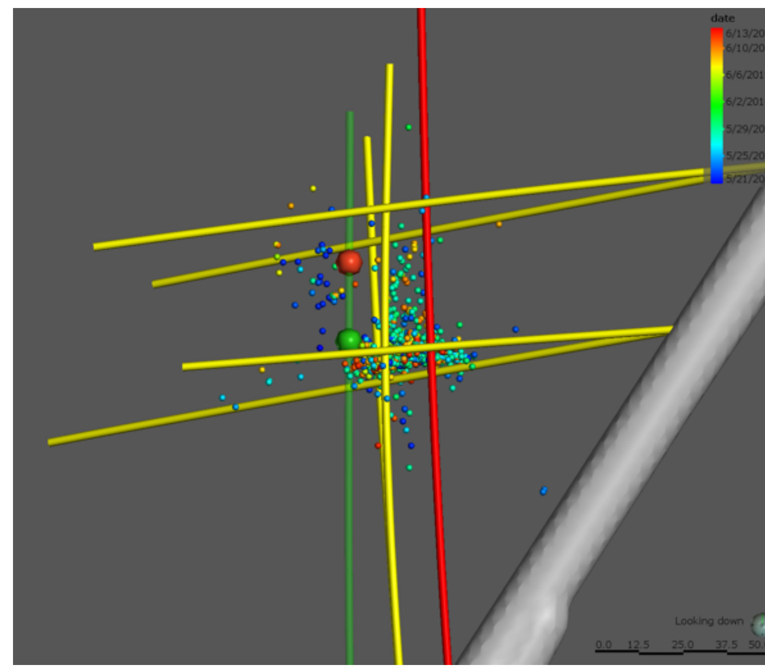
Experiment 1, intended to investigate hydraulic fracturing*, in situ

Experiment 2 designed to investigate shear stimulation*.

Experiment 3 will investigate changes in fracturing strategies – TBD.

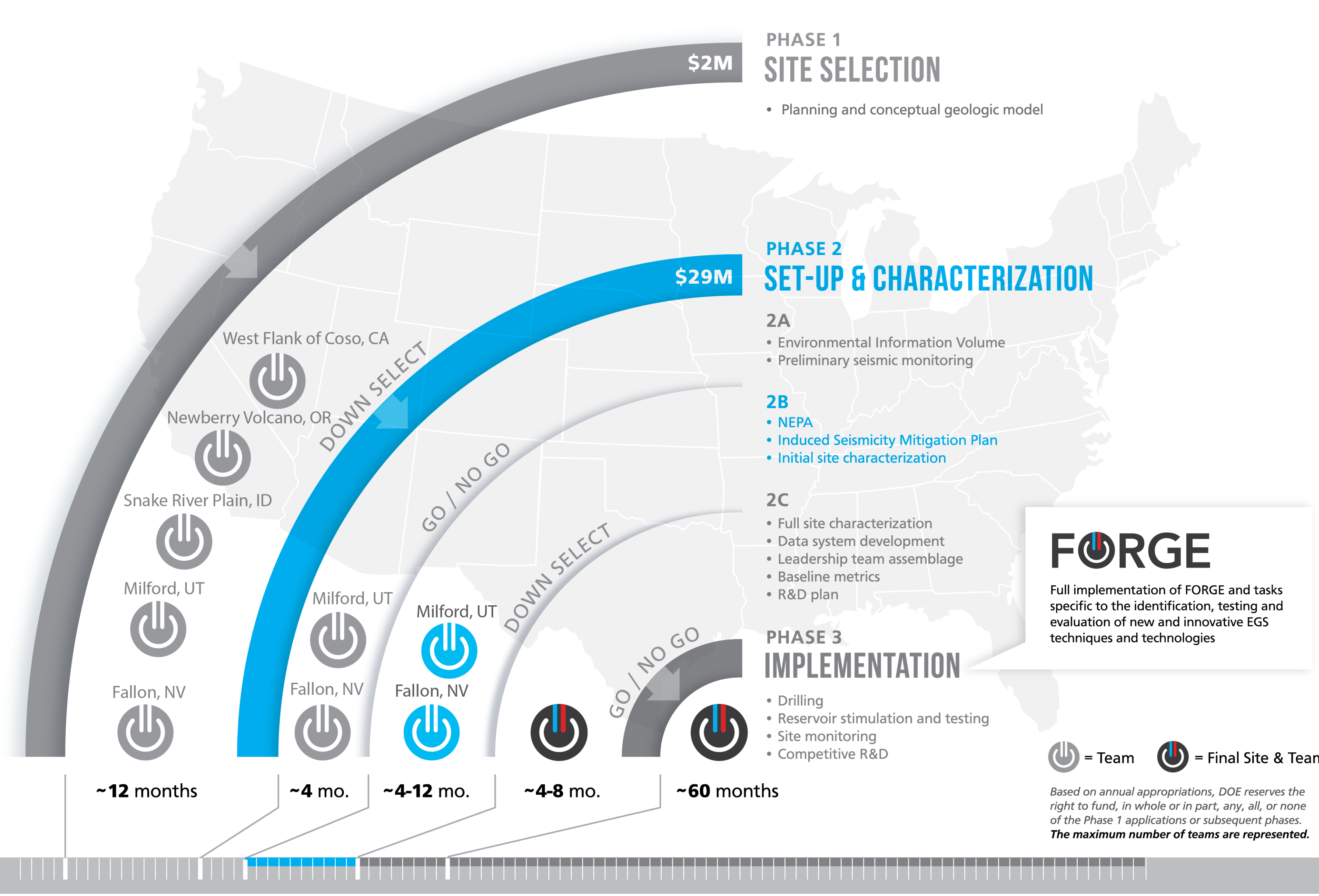



Courtesy: Tim Kneafsey (LBNL), Tim Johnson (PNNL), Hunter Knox (SNL), Jonathan Ajo-Franklin (LBNL), Paul Cook (LBNL), Yves Guglielmi (LBNL), Martin Schoenball (LBNL), Hari Neupane (INL) & EGS Collab.

# Frontier Observatory for Research in Geothermal Energy



# Summary

**Sub-Surface Science/Engineering is a Key Component to a Sustainable Future**

- Deep geothermal, unconventional resources and sequestration are examples
- Access to, and the ability to create and control the "reservoir" is key

**Complex Process Interactions Influence Reservoir Evolution**

- Permeability/Seismicity evolution is strongly influenced by these processes
- These interactions can be complex and involve:
  - Mineralogy
  - Structure, texture and heterogeneity
  - Evolving patch dimension
  - Brittlemess (a-b) and pore-pressure or effective stress level
  - Role of Fault Core (FC) and Damage Zone (FDZ)

**Interseismic Behavior**

- Necessary to reset permeability for brittle failure
- Consistent with observations with far-field reactivation of faults/fractures

**Prospects for Permeability-Seismicity Linkage**

- Observed seismicity is a certifiable predictor of permeability evolution
- Possible despite potential for aseismic slip
  - possibility that aseismic slip -> creep -> no dilation & wear products