Key Complex Process Couplings and Challenges in the Effective Recovery of Deep Geothermal Energy

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Key Issues in EGS and Sedimentary Geothermal Reservoirs (SGRs)

- Spectrum of Behaviors EGS to SGR
- Homogeneous Permeability Flow Modes

THMC Controls on Permeability Evolution

- Reinforcing feedbacks

Induced Seismicity

- Induced versus Triggered seismicity
- Late-time seismicity

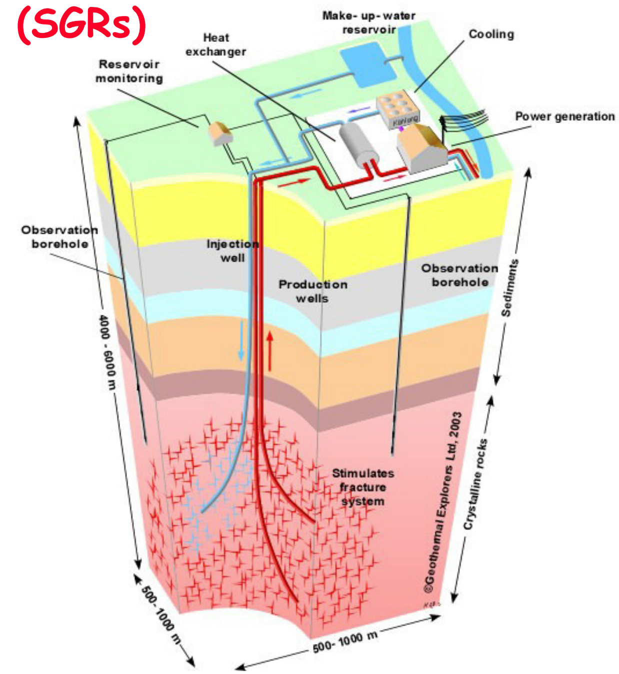
Linking Induced Seismicity to Permeability Evolution

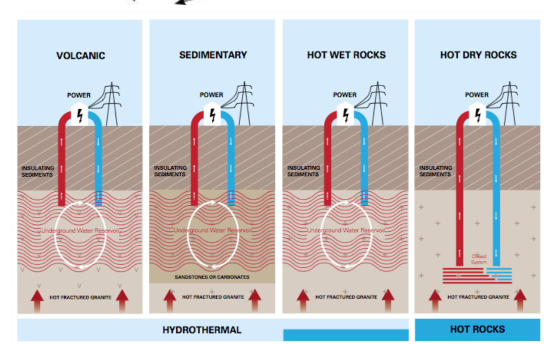
- Controls on seismicity – the aseismic-seismic transition
- RSF – for permeability evolution
- Controls on stability and permeability
- Dynamic stressing - permeability

Reservoir Scale Response

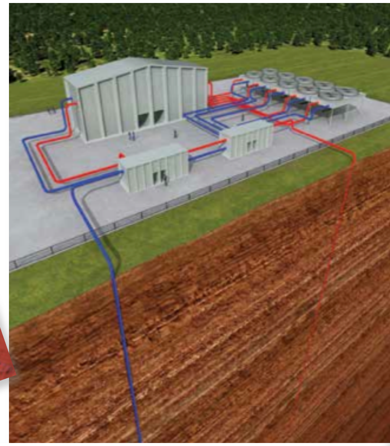
- Anomalous seismicity – Newberry Project
- Permeability scaling – Newberry Project

Summary





Spectrum of Behaviors: Hydrothermal => SGRs => EGS



SedHeat Initiative

http://geothermal.tcu.edu

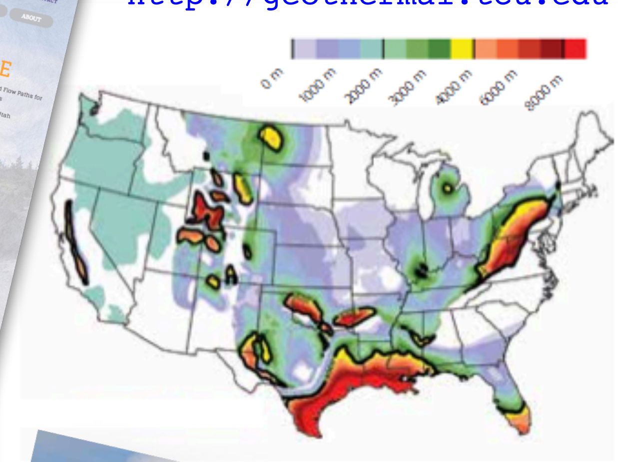
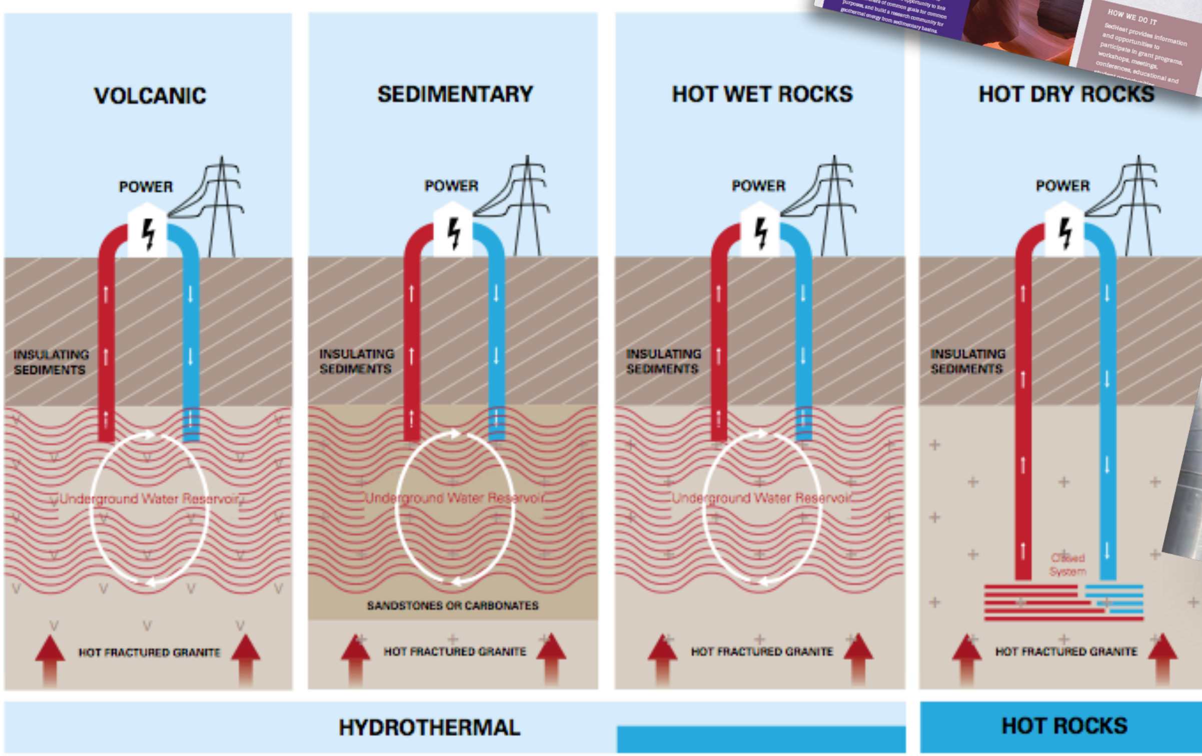
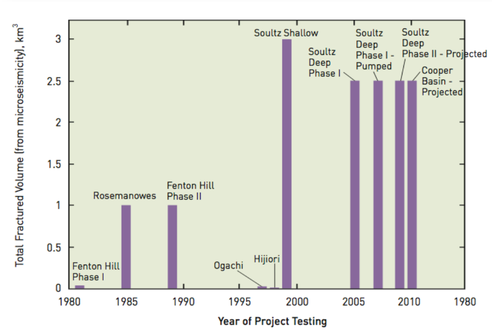
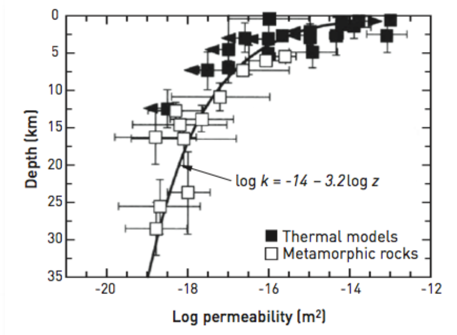


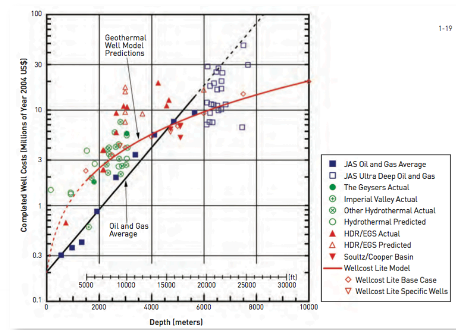
Figure 2: Average temperature at 4.5 km, conterminous United States. (Tester, et al., 2006, after Blackwell and Richards, 2004)

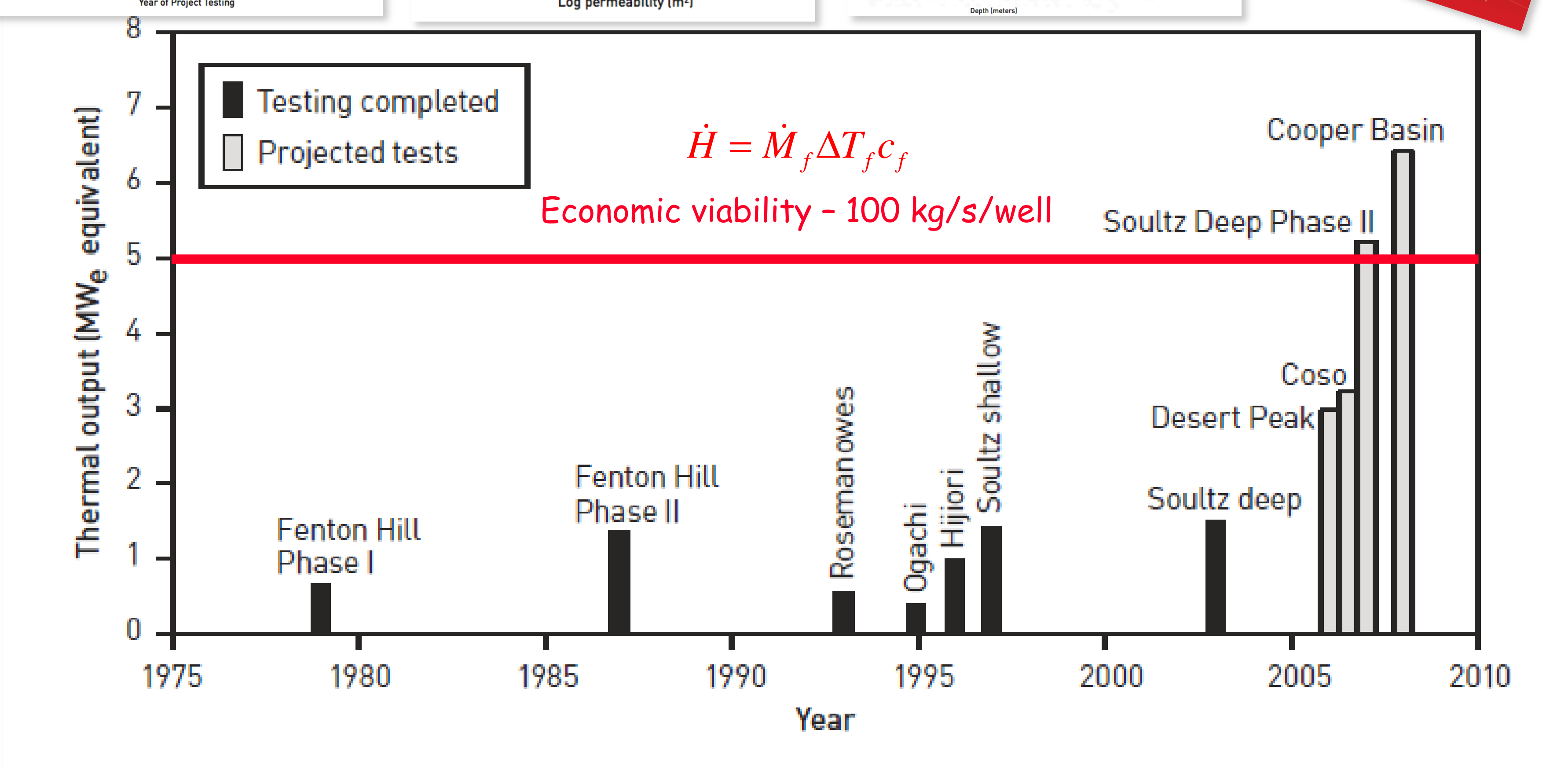


Can EGS ever be Viable?









Induced Seismicity

The New York Times

Quake Fears Stall Energy Extraction Project

By JAMES GLANZ
Published: July 13, 2009

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Two federal agencies are stopping a contentious California project from fracturing bedrock miles underground and extracting its geothermal energy until a scientific review determines whether the project could produce dangerous earthquakes, spokeswomen for the Energy and Interior Departments said on Monday.

Enlarge This Image

Jim Wilson/The New York Times

The project by AltaRock Energy, a start-up company with offices in Seattle and Sausalito, Calif., had won a grant of $6.25 million from the Energy Department, and officials at the Interior Department had indicated that it was likely to issue permits allowing the company to fracture bedrock on federal land in one of the most seismically active areas of the world, Northern California.

But when contacted last month by The New York Times for an article on the project, several federal officials said that AltaRock had not disclosed that a similar project in Basel, Switzerland, was shut down when it generated earthquakes that shook the city in 2006 and 2007.

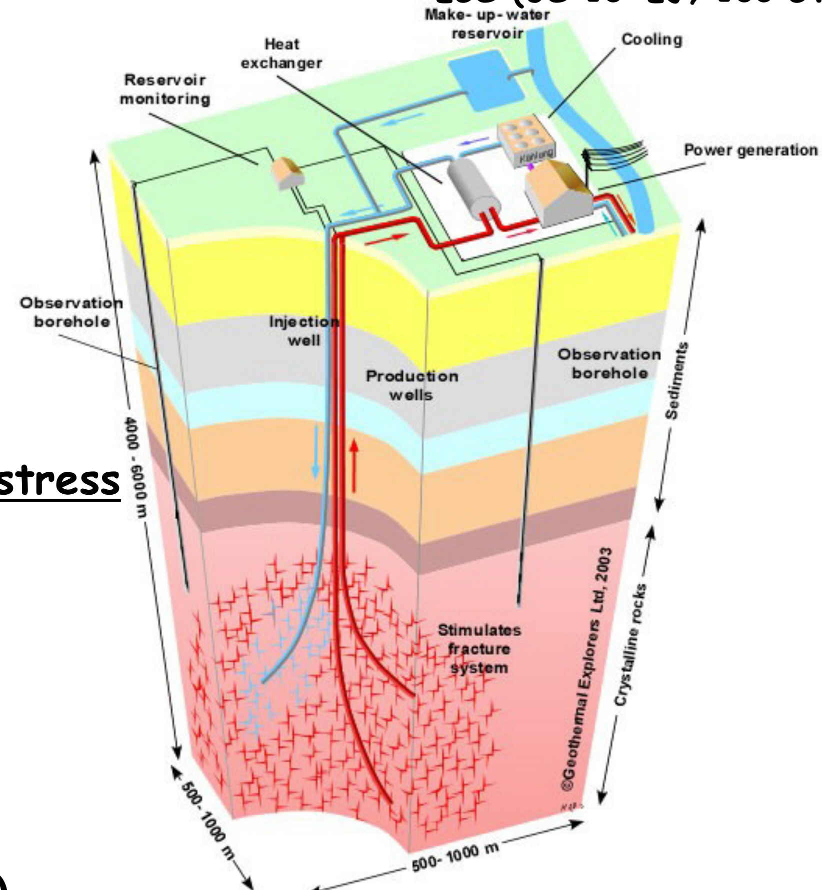
Basic Observations of Permeability Evolution and IS

Challenges

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

Resource

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



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

Key Questions in SGRs and EGS

Needs $\dot{H} = \dot{M}_f \Delta T_f c_f$

- **Fluid availability**
  - Native or introduced
  - H_2O/CO_2 working fluids?
- **Fluid transmission**
  - Permeability microD to mD?
  - <u>Distributed permeability</u>
- **Thermal efficiency**
  - Large heat transfer area
  - Small conduction length
- **Long-lived**
  - Maintain mD and HT-area
  - Chemistry
- **Environment**
  - Induced seismicity
  - Fugitive fluids
- **Ubiquitous**

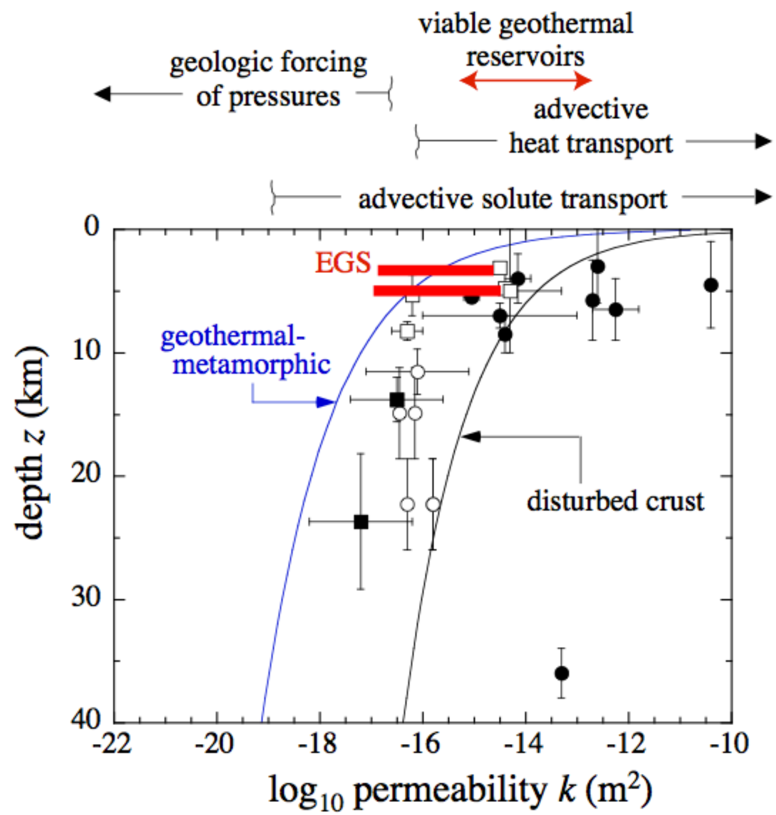
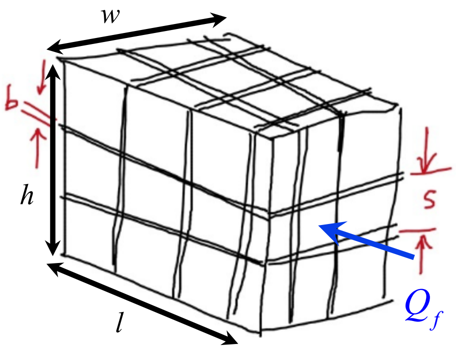


Figure 12: Evidence for relatively high crustal-scale permeabilities showing showing power-law fit to data. Geothermal-metamorphic curve is the best-fit to geothermal-metamorphic data [*Manga and Ingebritsen*, 1999, 2002]. "Disturbed-crust" curve interpolates midpoints in reported ranges in *k* and *z* for a given locality [*Manning and Ingebritsen*, 2010, their Table 1]; error bars depict the full permissible range for a plotted locality and are not Gaussian errors, and the Dobi (Afar) earthquake swarm is not shown on this plot (it is off-scale). Red lines indicate permeabilities before and after EGS reservoir stimulation at Soultz (upper line) and Basel (lower line) from *Evans et al.* [2005] and *Häring et al.* [2008], respectively. Arrows above the graph show the range of permeability in which different processes dominate.

Steve.ai [Ingebritsen and Manning, various, in Manga et al., 2012]

Thermal Drawdown EGS -vs- SGRs



$$\dot{H}_{solid} \sim A\lambda_R \frac{dT}{dx} \sim \frac{V\lambda_R \Delta T}{s^2}$$

$$\dot{H}_{fluid} \sim Q_f \rho_W c_W \Delta T$$

$$\frac{\dot{H}_f}{\dot{H}_s} \sim \frac{\rho_W c_W}{\lambda_R} \frac{Q_f s^2}{V} = Q_D$$

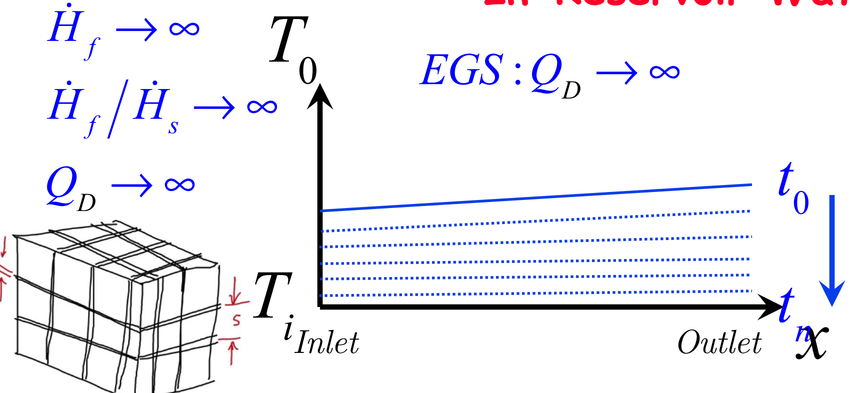
In-Reservoir Water Temperature Distributions:

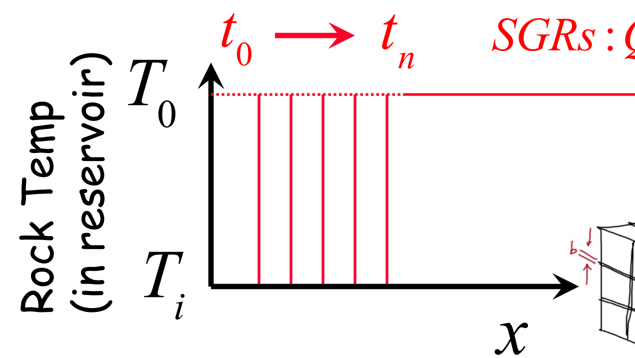
$EGS:$

$\dot{H}_f \to \infty$

$\dot{H}_f / \dot{H}_s \to \infty$

$Q_D \to \infty$



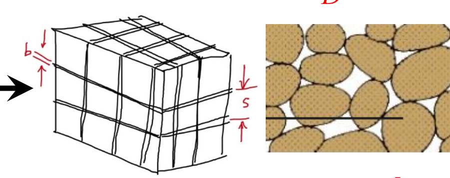


$SGRs:$

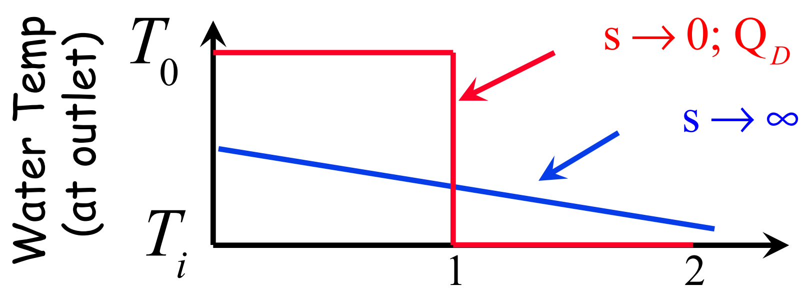
$\dot{H}_s \to 0$

$\dot{H}_f / \dot{H}_s \to 0$

$Q_D \to 0$



Thermal Output:



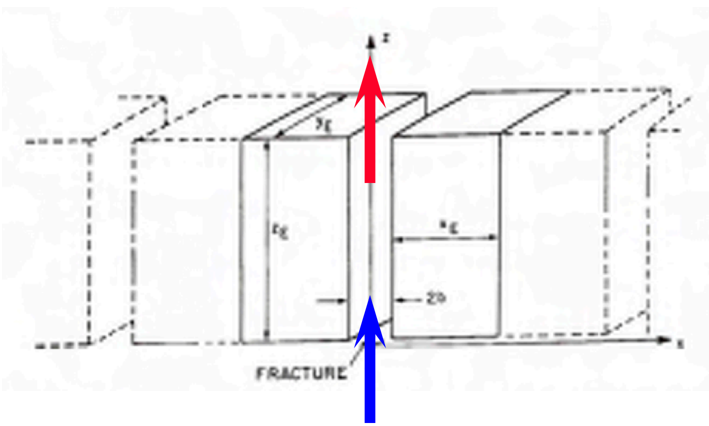
$s \to 0;\ Q_D \to 0;$ Thermal-front present

$s \to \infty;\ Q_D \to \infty;$ Thermal front absent

$$t_D = \frac{\rho_W c_W}{\rho_R c_R} \frac{Q_f t}{V}$$

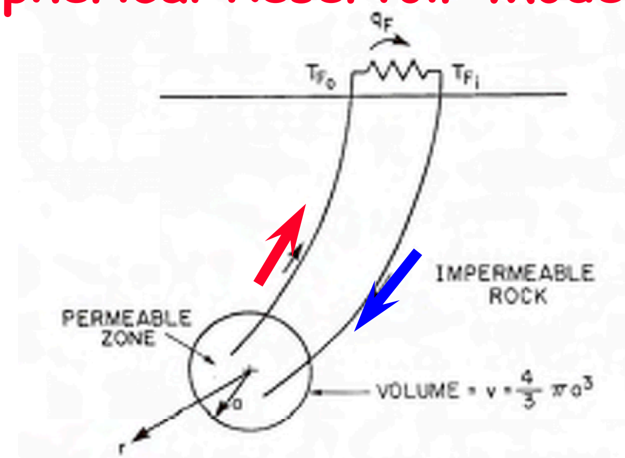
Thermal Recovery at Field Scale

Parallel Flow Model

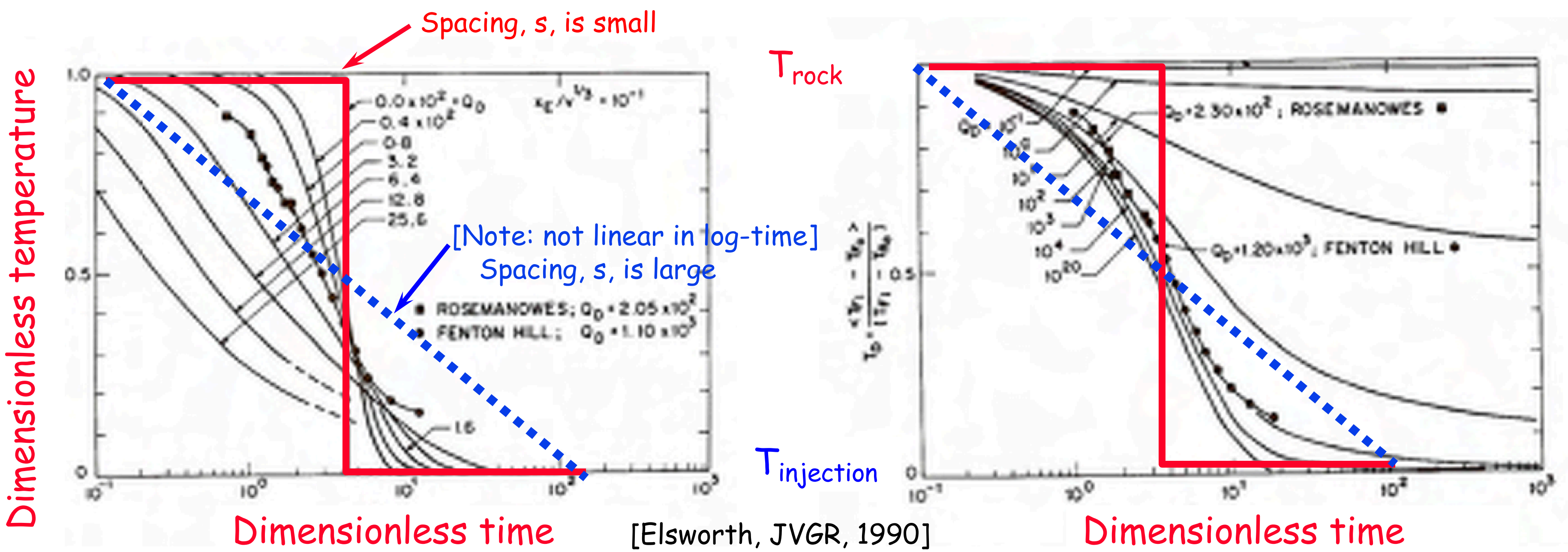


[Gringarten and Witherspoon, Geothermics,1974]

Spherical Reservoir Model



[Elsworth, JGR, 1989]



[Elsworth, JVGR, 1990]

derek.elsworth@psu.edu

Key Questions in EGS and SGRs

Needs

$$\dot{H} = \dot{M}_f \Delta T_f c_f$$

- **Fluid availability**
  - Native or introduced – fluid/geochemical compatibility
  - H_2O/CO_2 working fluids? – arid envts.
- **Fluid transmission**
  - Permeability microD to milliD? – high enough?
  - Distributed permeability
    - Characterizing location and magnitude
    - Defining mechanisms of perm evolution (chem/mech/thermal)
    - Well configurations for sweep efficiency and isolating short-circuits
- **Thermal efficiency**
  - Large heat transfer area – better for SGRs than EGS?
  - Small conduction length – better for SGRs than EGS?
- **Long-lived**
  - Maintain mD and HT-area – better understanding diagenetic effects?
  - Chemistry - complex
- **Environment**
  - Induced seismicity - Event size (max)/timing/processes (THMCB)
  - Fugitive fluids – Fluid loss on production and environment – seal integrity
- **Ubiquitous**

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- Permeability scaling – Newberry Project

US (DoE) Road Map

Summary

THMC Models - Rate-Limiting Processes

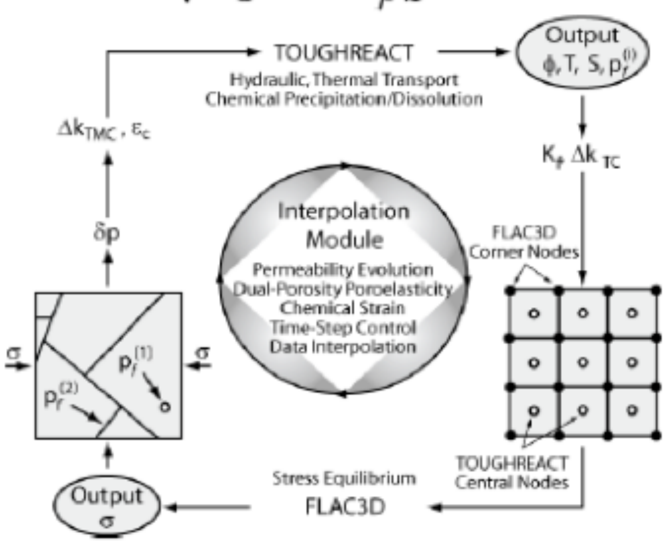
THMC-S – Linked codes

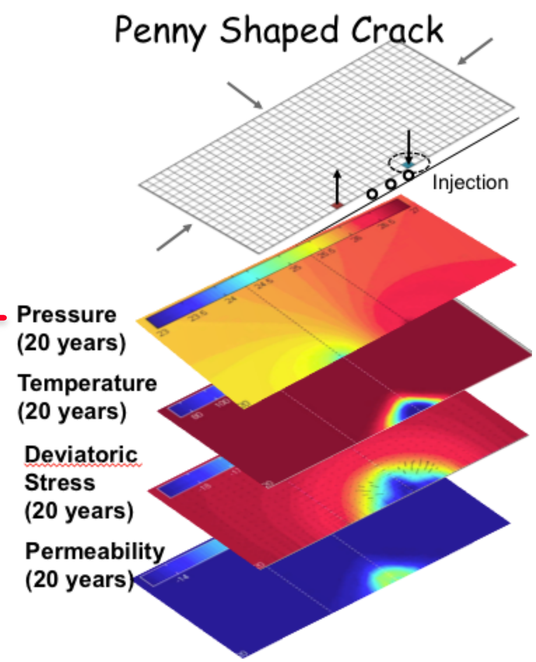
- **TOUGHREACT (THC)** – Accommodates non-isothermal, multi-component phase equilibria, pressure diffusion, multi-phase hydrologic transport, and chemical precipitation/dissolution (transient mass/energy balance)

$$\frac{\partial M}{\partial t} = -\nabla \cdot \mathbf{F} + q$$

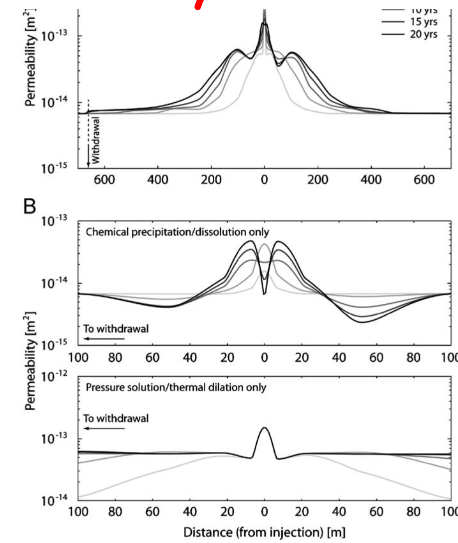
- **FLAC3D (M)** – Mechanical constitutive relations (force equilibrium, capable of THM)

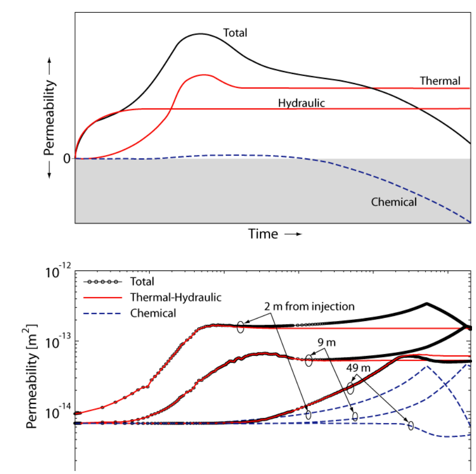
$$\nabla \cdot \boldsymbol{\sigma}^T = -\rho \mathbf{b}$$





Spatial Permeability Evolution





Temporal Permeability Evolution

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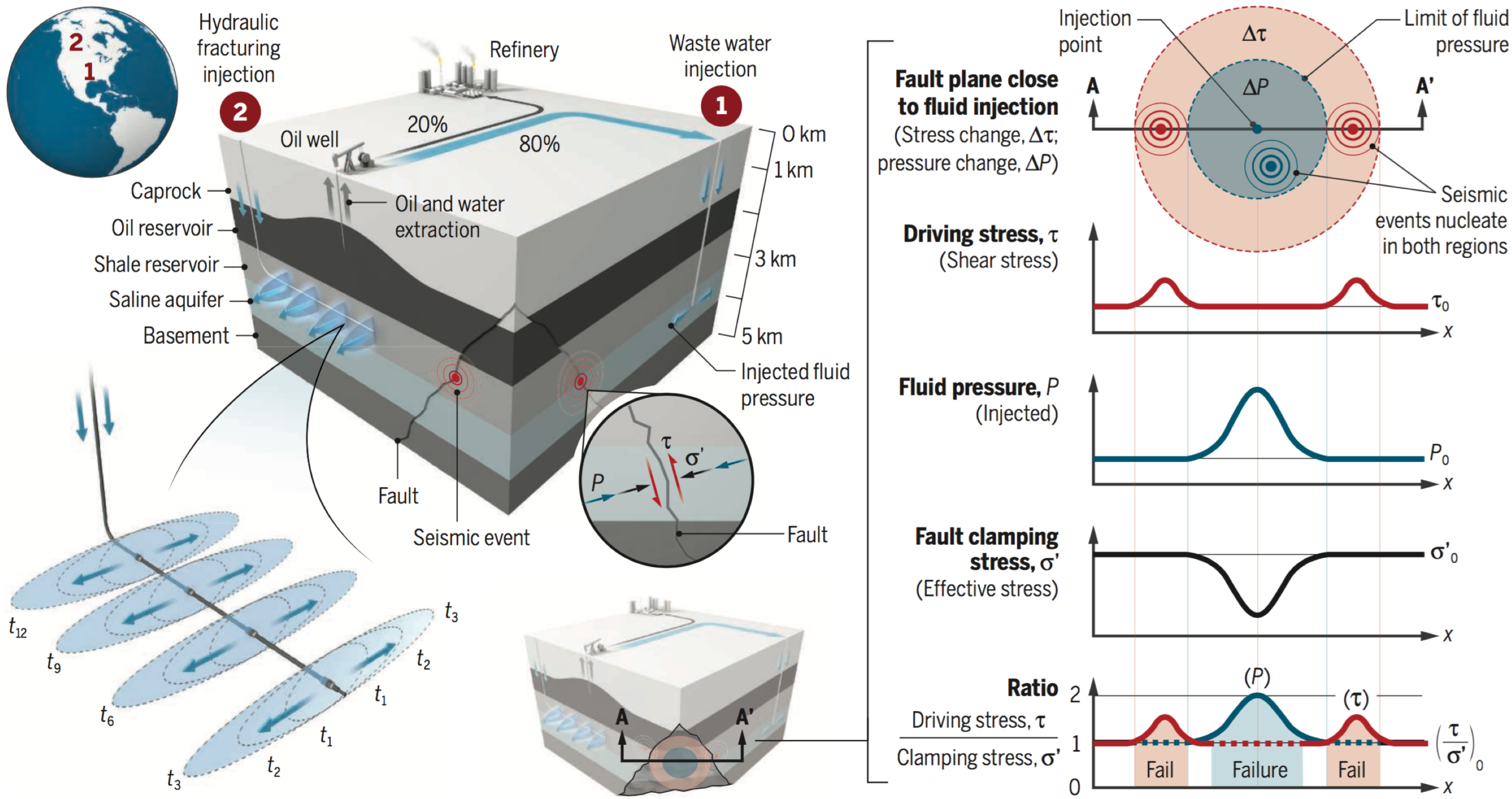
Induced Seismicity



[Elsworth et al., Science, 2016]

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

EGS Stimulation Related?

Anatomy of the EQ

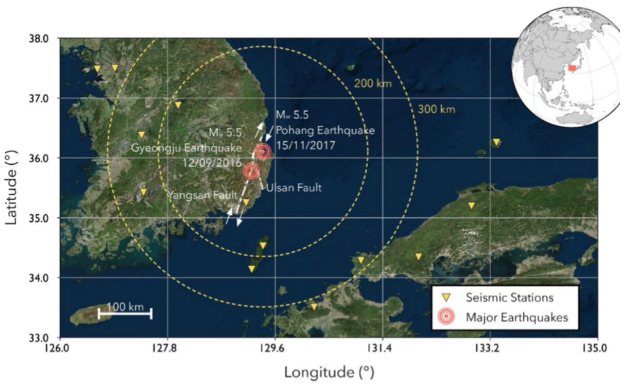
15th century EQs Mw~7

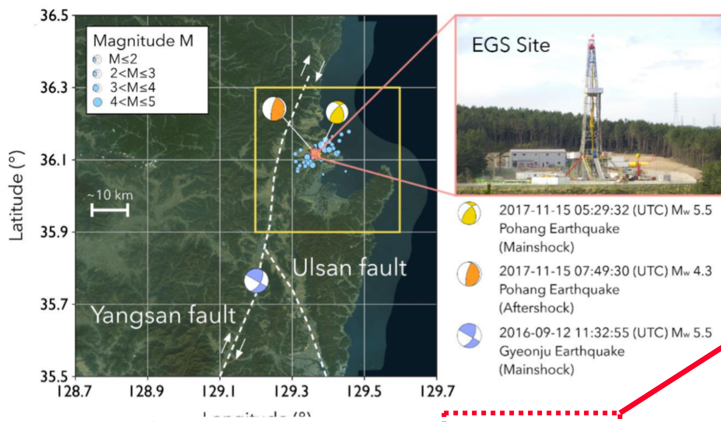
Mw<5 since instrumental recording in 1903

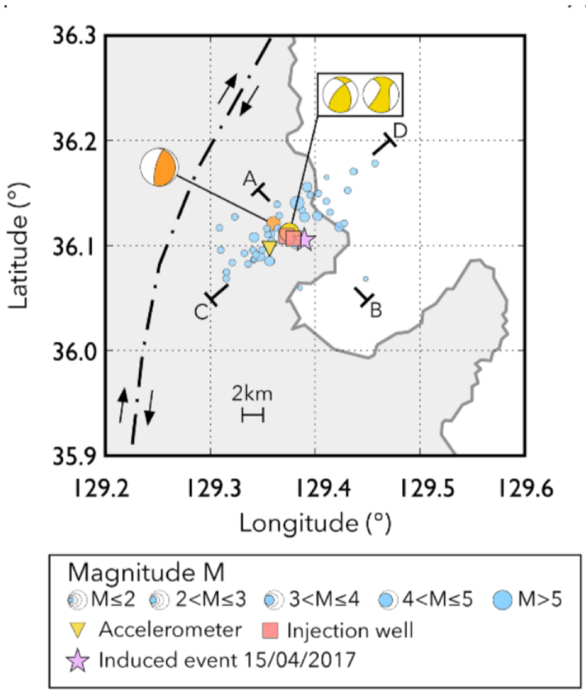
Mw~5.5 ~30km south of EGS

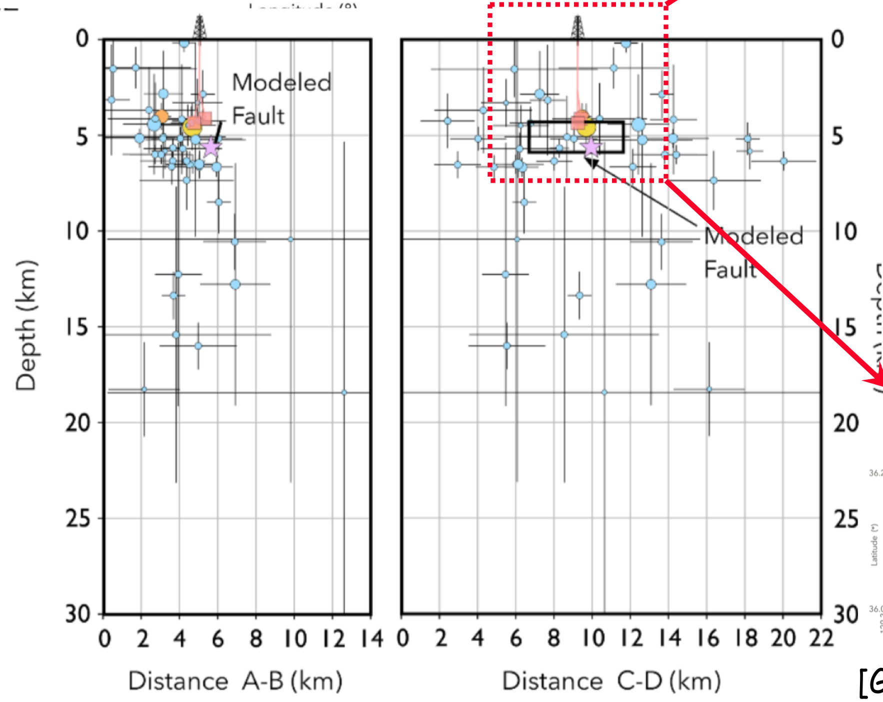
Mw~5.5 Pohang ~4km depth

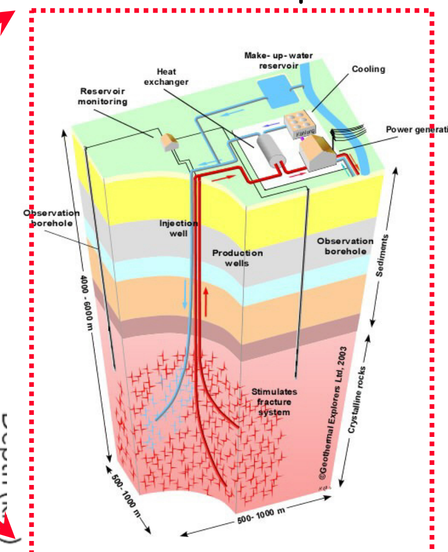
Same strike-slip fault



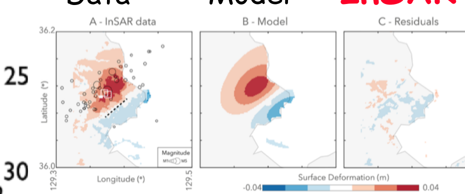






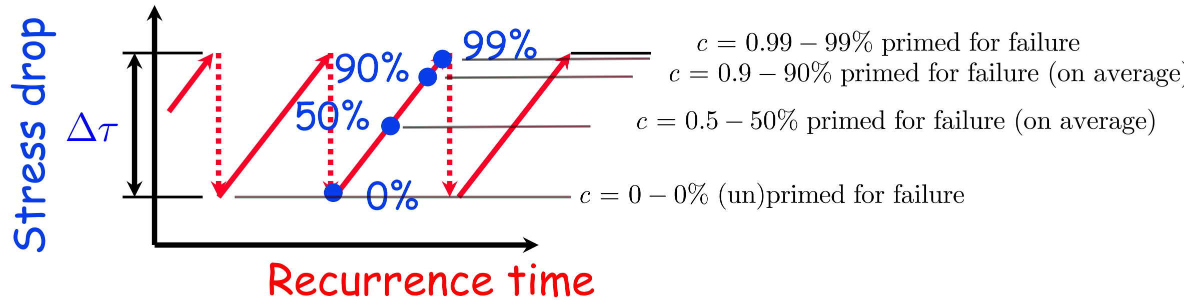


Data **Model** **InSAR**



[Grigoli et al., Science, 2018]

Maximum Event Magnitude – Equivalent Porous Medium



Moment Magnitude (Deviatoric)

$$M = AG\Delta u$$

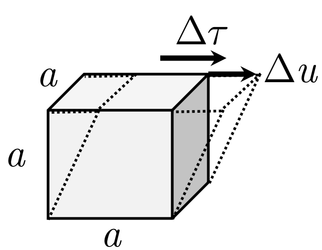
$$M = a^3 G \frac{\Delta u}{a}$$

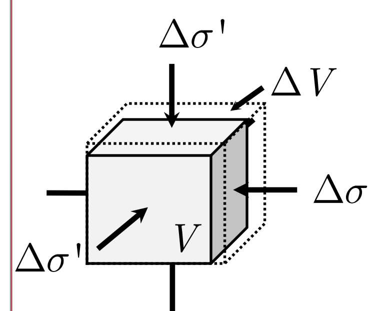
$$M = VG\gamma$$

$$M = V\Delta\tau$$

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

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





Stress-Strain (Spherical)

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

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

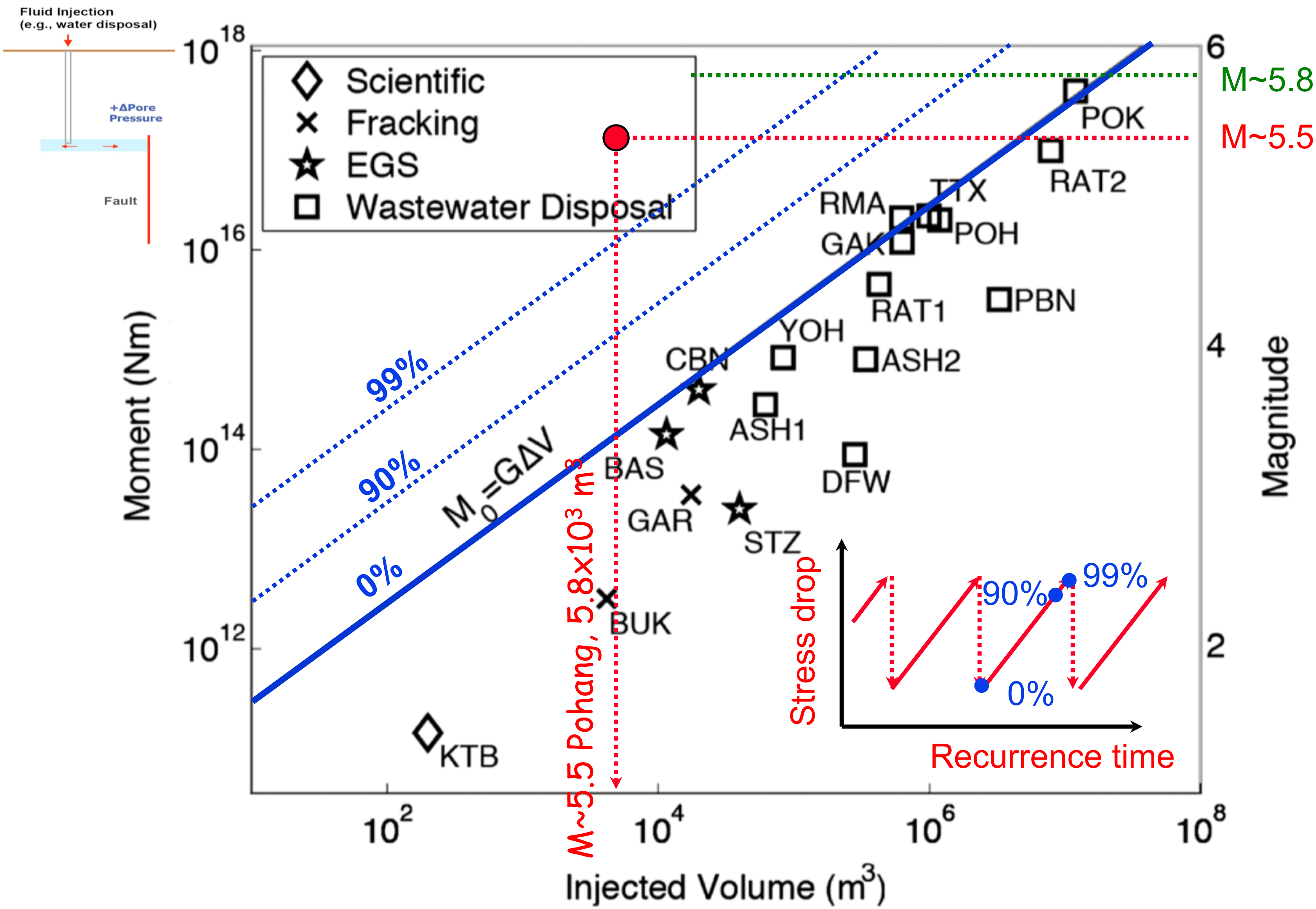
$$\alpha\Delta p = \frac{2}{3}\frac{(1+\nu)}{(1-2\nu)} G \frac{\Delta V}{V}$$

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

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

Modified from [McGarr, JGR, 1976 & 2014]

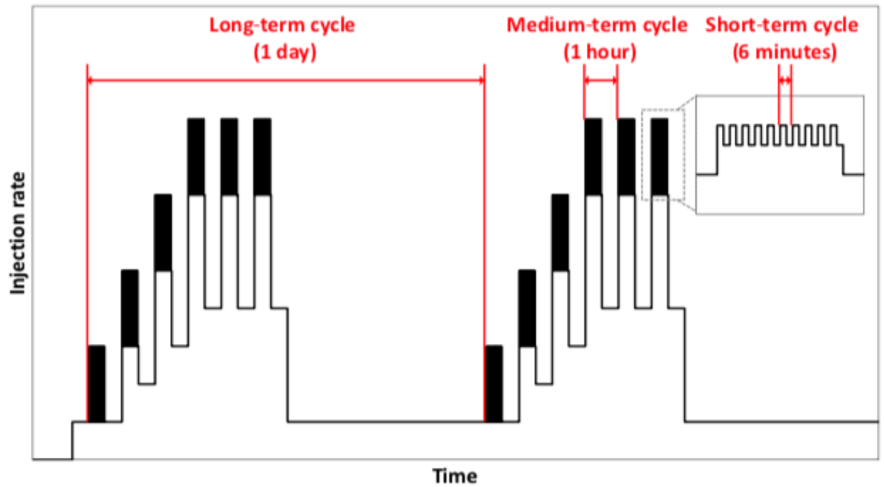
Maximum Anticipated Moment Magnitude – M or M_dot? M_{Gross} or M_{Net}? Triggered -vs- Induced?



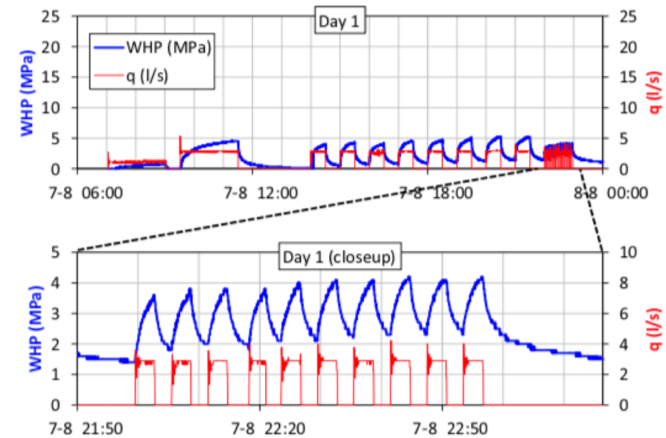
After [McGarr, JGR, 2014]

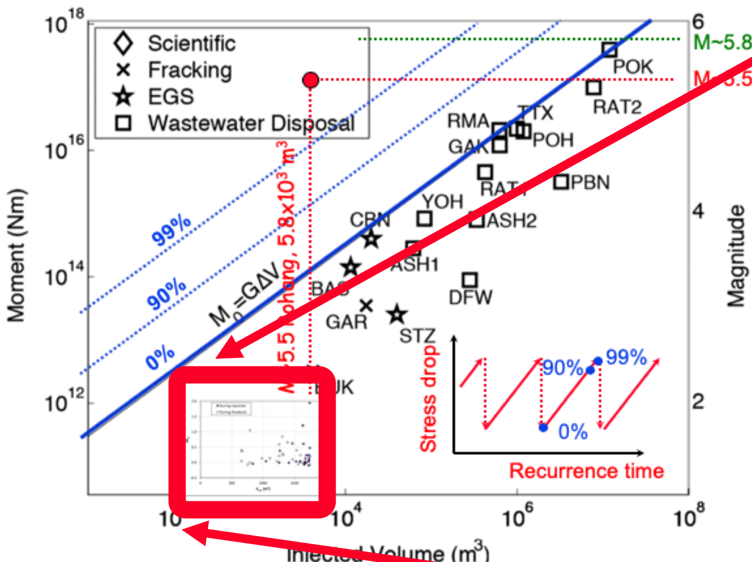
Possibility of Soft Stimulation (Pohang)?

Stepped and Oscillating Injection

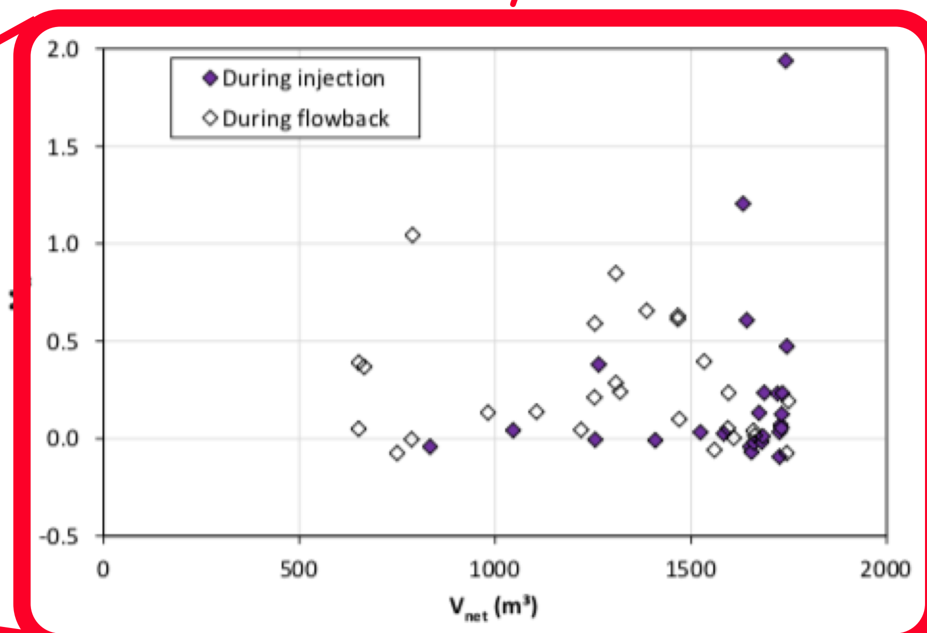


WHP and Flowrates



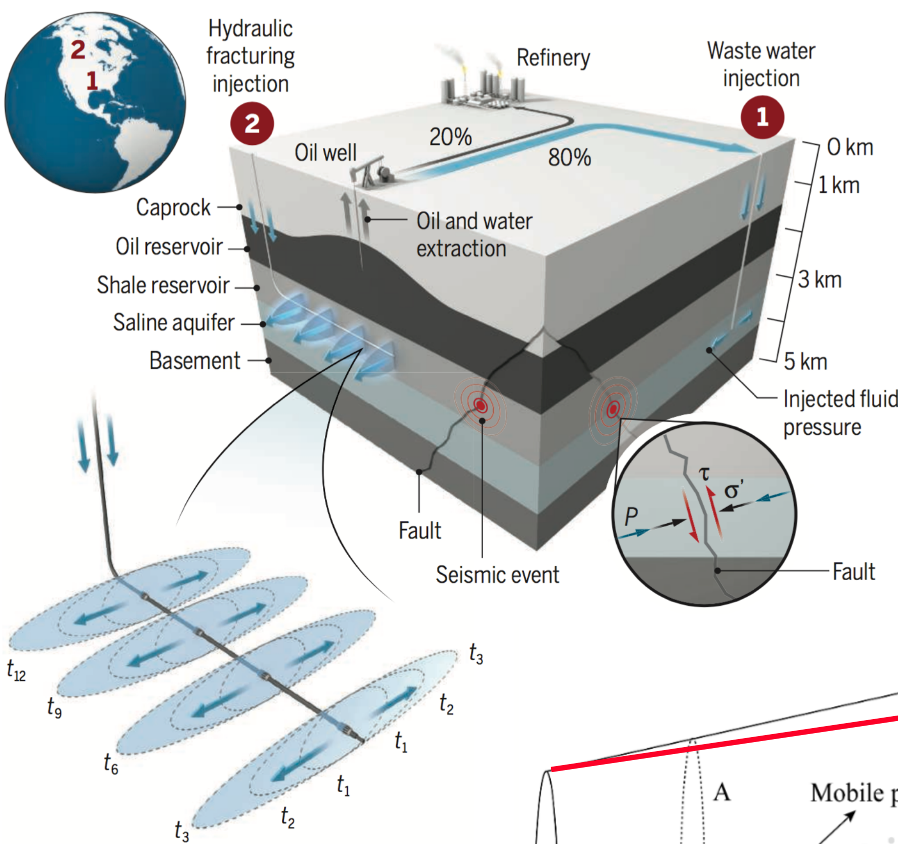


Observed Seismicity



[Hoffmann et al., GJI, 2019]

Some Key Issues in Hydraulic Fracturing



[Elsworth et al., Science, 2016]

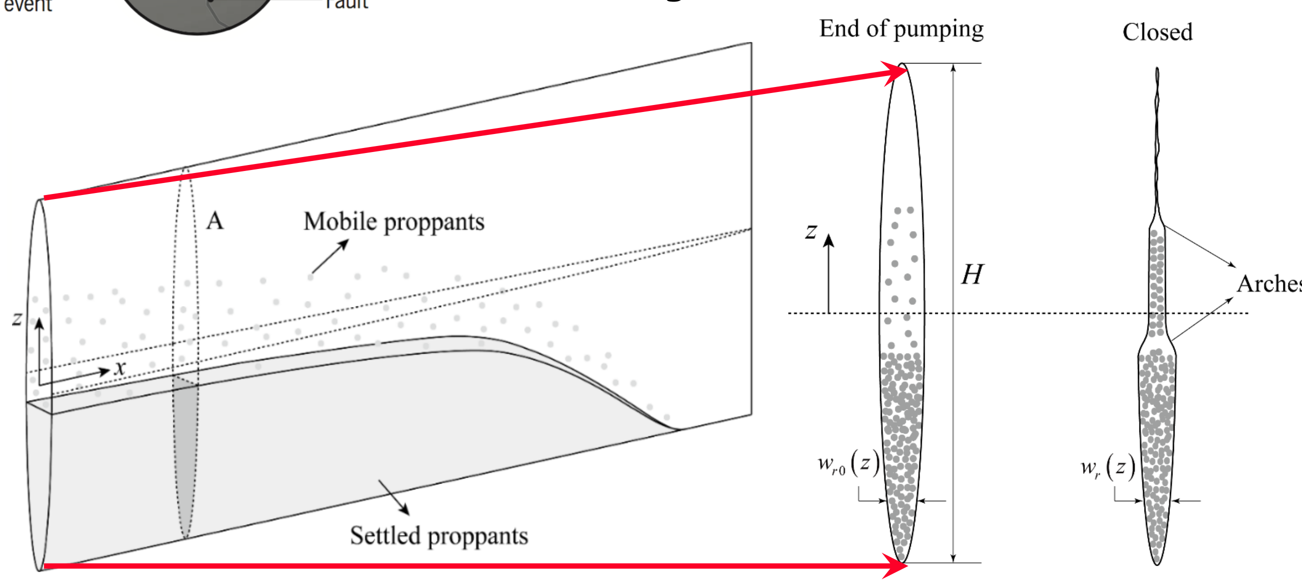
How Can We:

Maximize Recovery:

1. Longest/tallest/widest?
2. Highest proppant charge?
3. Most complex?
4. Best matched fluids?
5. Utilize natural natural fracture network?

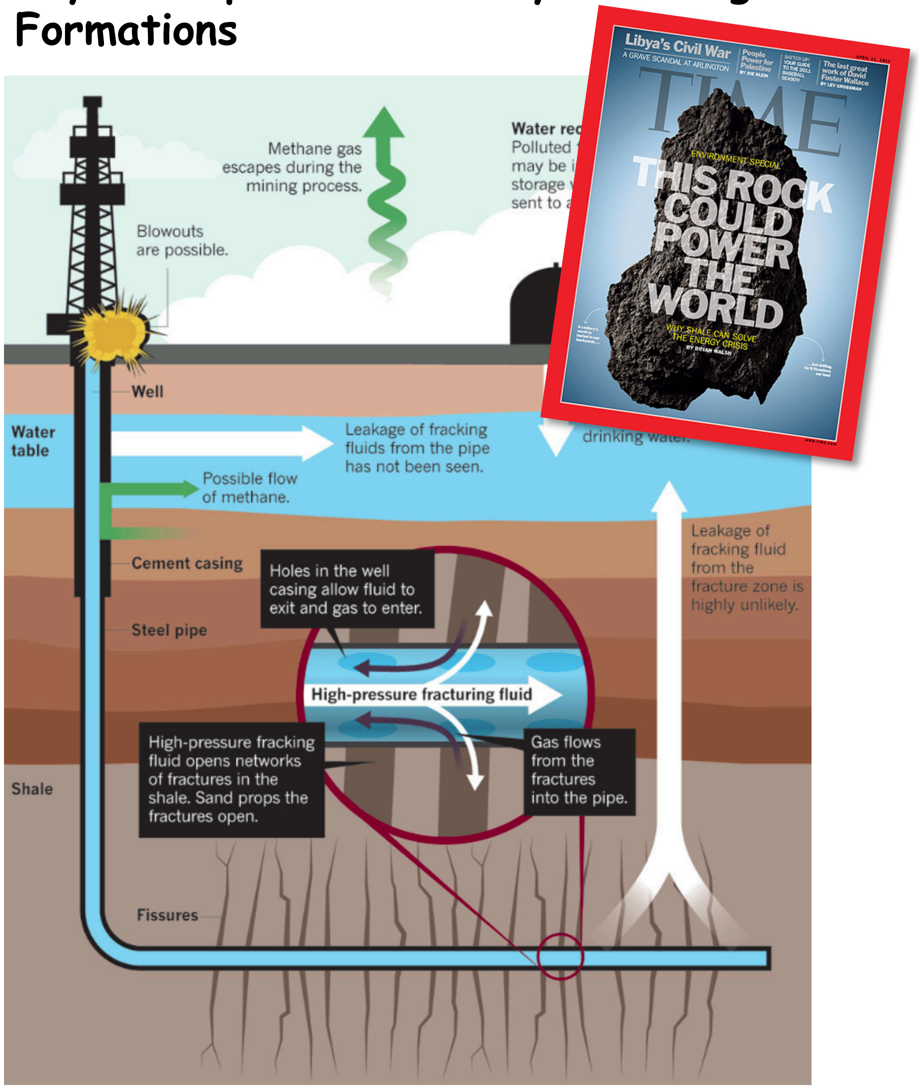
Key EGS Challenges:

1. Induced seismicity
2. High temperature (proppants/well-hardware)
3. Eliminating thermal short-circuits



Adaptation of HF to EGS?

Key Concepts of Recovery from Tight Formations



[Nature, 2011]

Key Need in EGS – relate to:

$$\dot{H} = \dot{M}_f \Delta T_f c_f$$

Constraints on Adapting Shale Revolution:

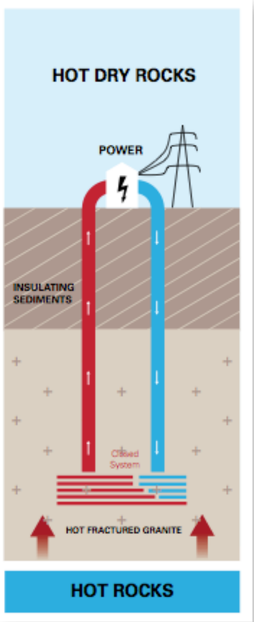
1. Open wells
2. High temperature
   1. Smart wells and casing
   2. Survivability of proppants
3. Hydraulic/thermal short-circuiting
4. ……..

Possible Contribution to EGS:

1. Horizontal/in-zone drilling
2. Hydraulic fracturing
3. Better hedge against IS?
4. ………

Potential use of HF and smart wells to maximize surface area and control short-circuiting

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

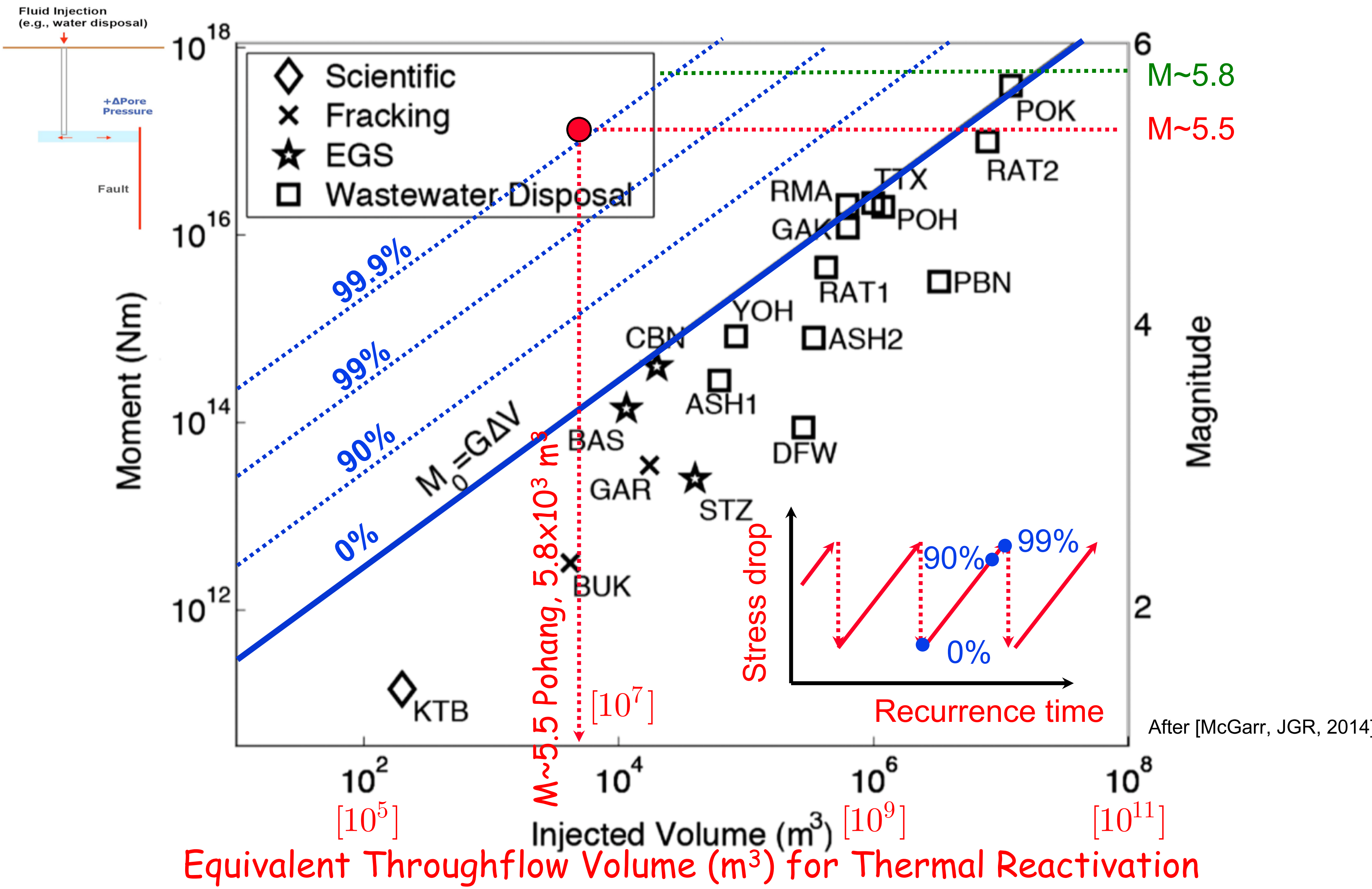
Injected volume: $$M = \frac{1}{(1-c)} G \alpha_T \Delta V \Delta T_f \frac{1}{(n + (1-n)\frac{\rho_R c_R}{\rho_f c_f})} \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}$$

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

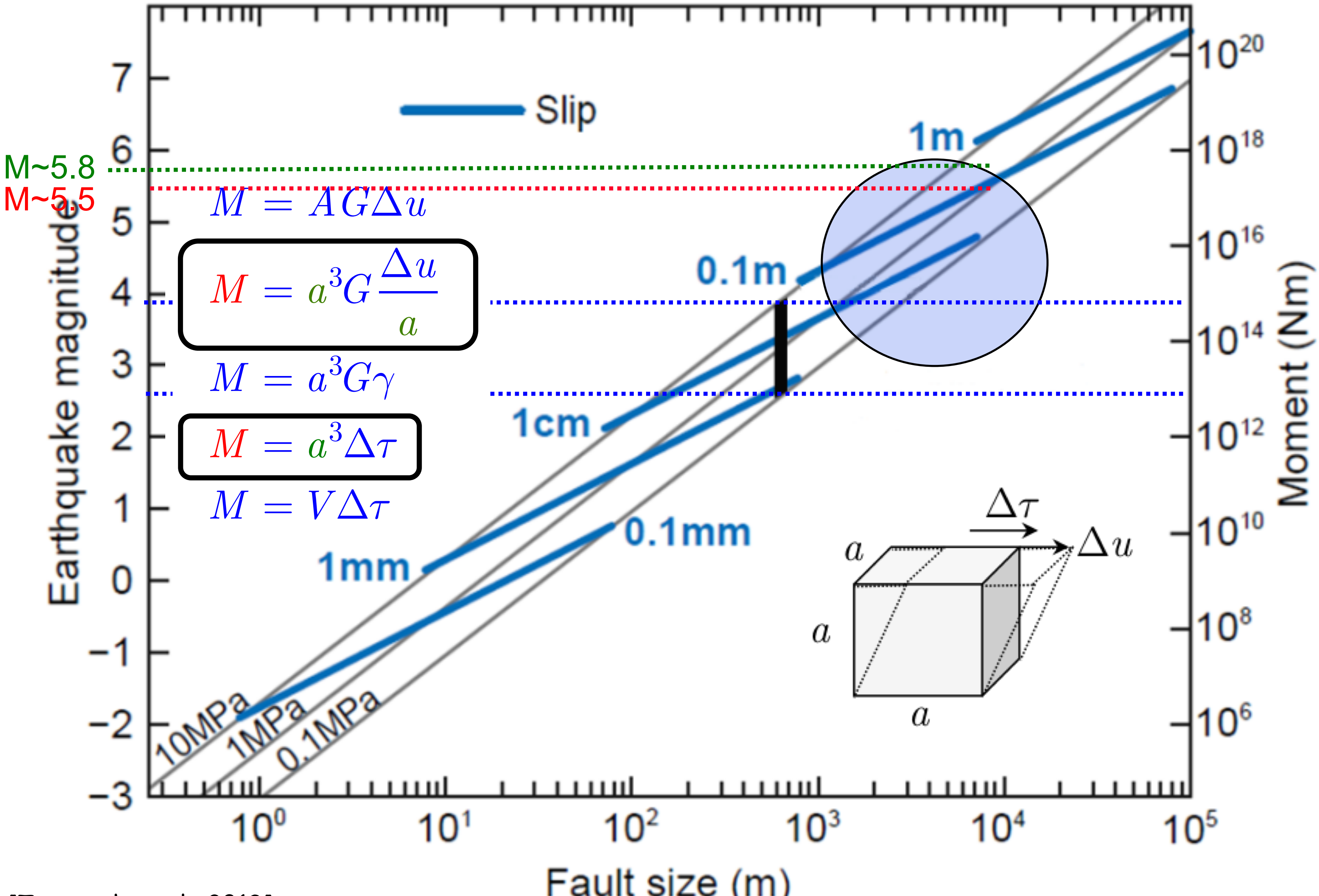
$$M = \frac{1}{(1-c)} G \Delta V [\underbrace{\alpha_T \Delta T_f \frac{1}{(1-n)} \frac{\rho_f c_f}{\rho_R c_R}}_{postfactor}] \begin{Bmatrix} \nu = 0.25 \\ \mu = 0.6 \end{Bmatrix}$$

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

Fluid Pressure –versus– Thermal Stressing-based Reactivation



Shear Offset Scaling - Seismic Only



[Zangeneh et al., 2013]

Key Complex Process Couplings and Challenges in the Effective Recovery of Deep Geothermal Energy

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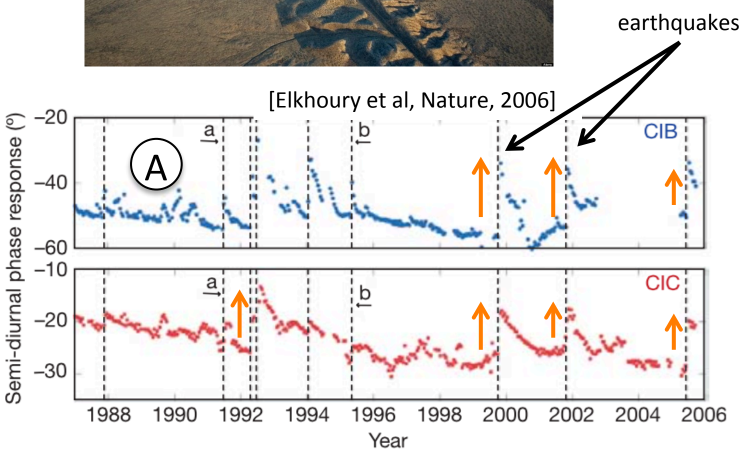
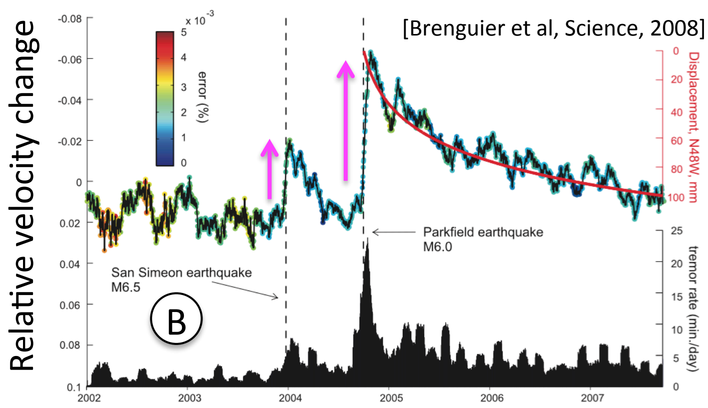
Permeability and Elastic Softening

Field-scale

Permeability

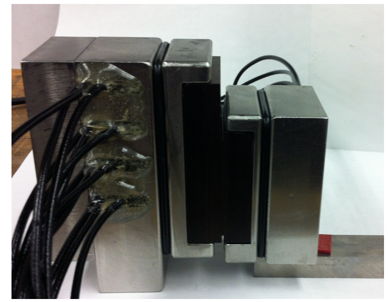


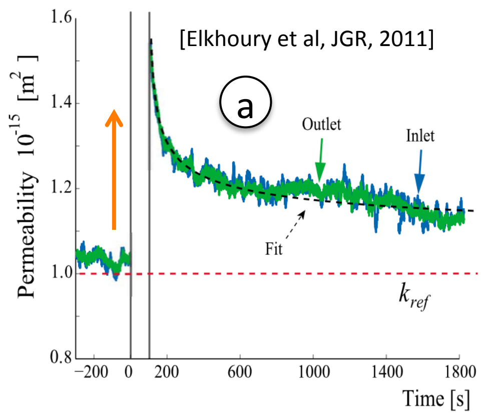
Elastic Softening

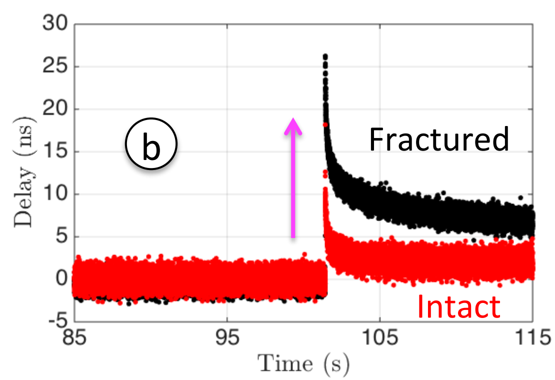


[Shokouhi, Pers. Comm. 2016]

Laboratory-scale





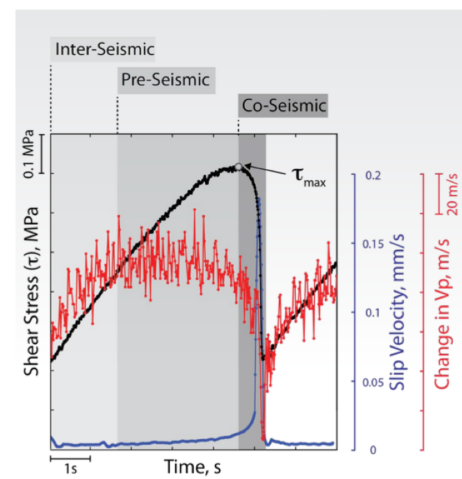


Permeability

Elastic Softening

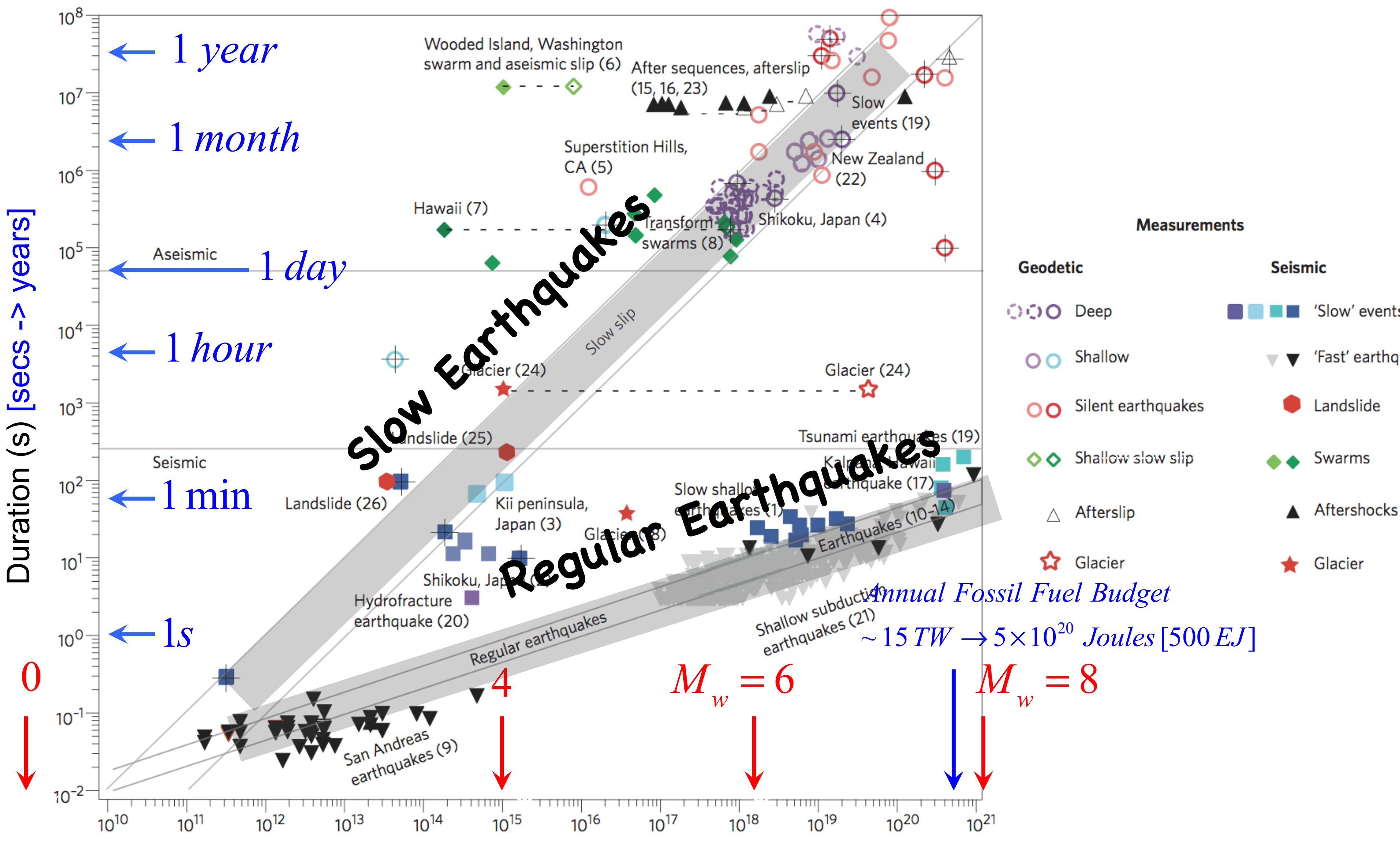
During the Seismic Cycle

- 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]

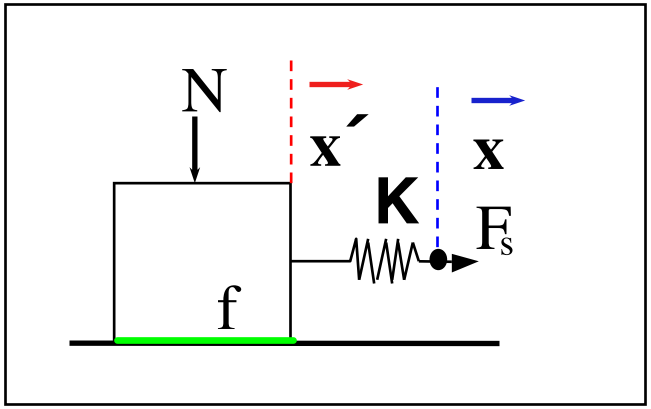
Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior



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

Brittle Friction Mechanics, Stick-slip

Stick-slip (unstable) versus stable shear

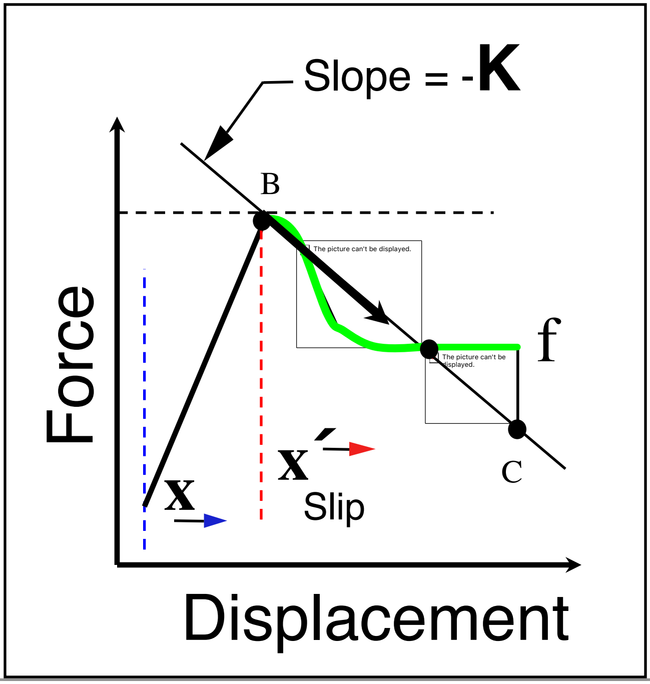


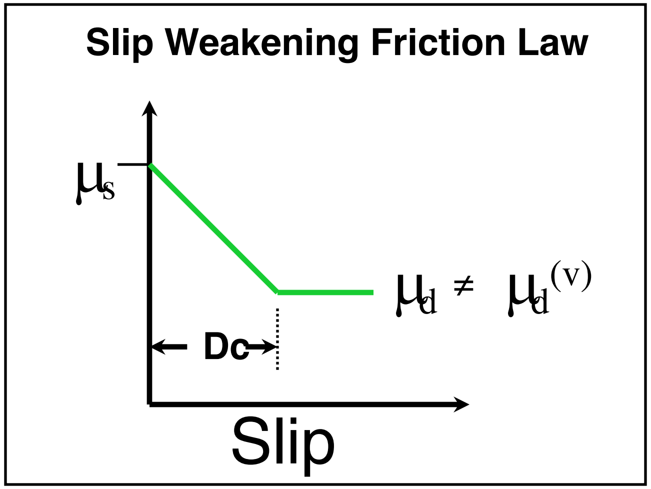
Stick-slip dynamics

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

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

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



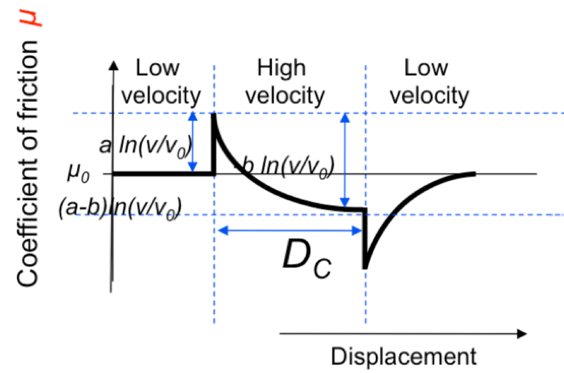


[After C.J. Marone, Pers. Comm., 2017]

Requirements for Instability

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

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

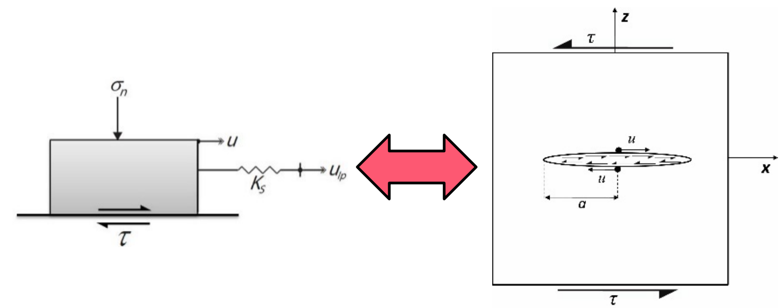


2. When failure occurs, strength is velocity (or strain) weakening - *i.e.*

$$a - b < 0$$

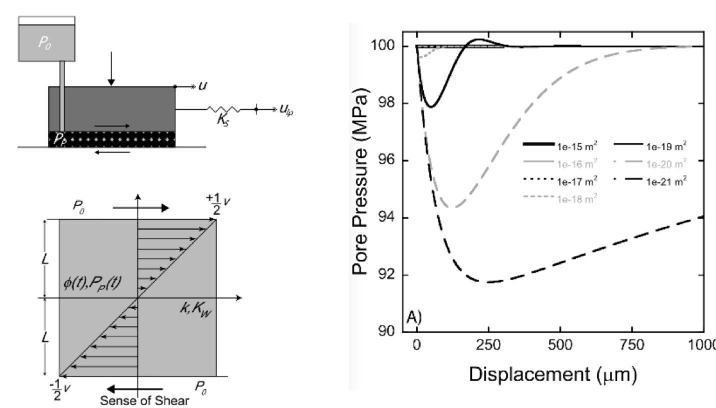
2. That the failure is capable of ejecting the stored strain energy adjacent to the fault (shear modulus and fault length) - *i.e.*

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

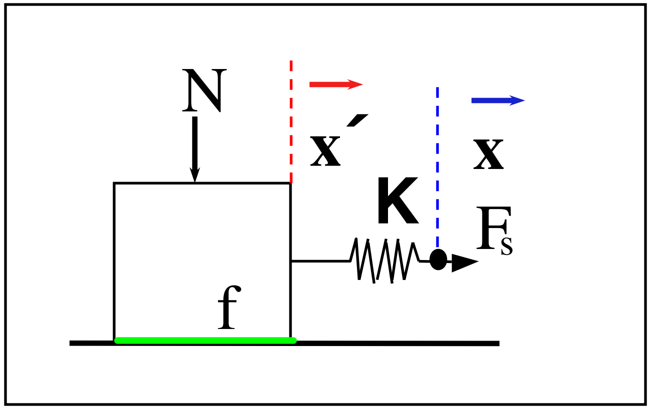


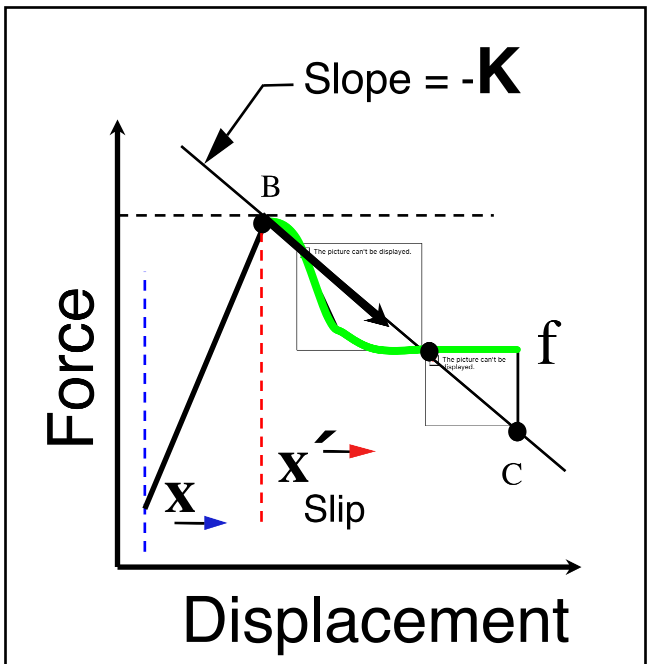
4. That effective normal stresses evolve that do not dilatantly harden the fault and arrest it via the failure criterion of #1 – *i.e.*

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



Seismic – Aseismic Transition
Full Spectrum of Slip Behaviors





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

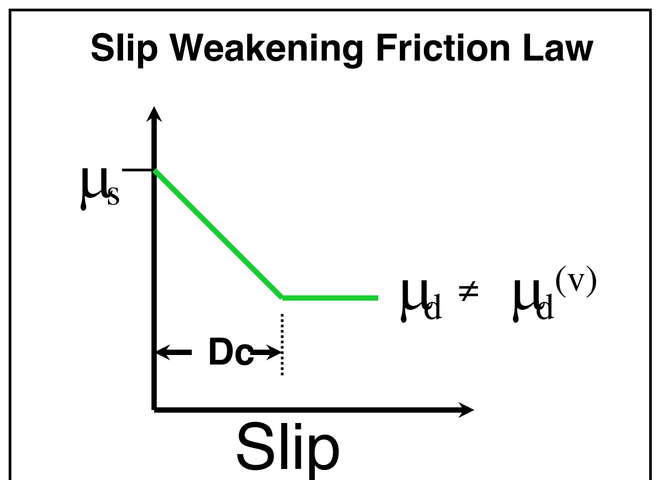
Promote Aseismic Response: $K_c < K$

Otherwise Seismic Slip if: $K_c > K$

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

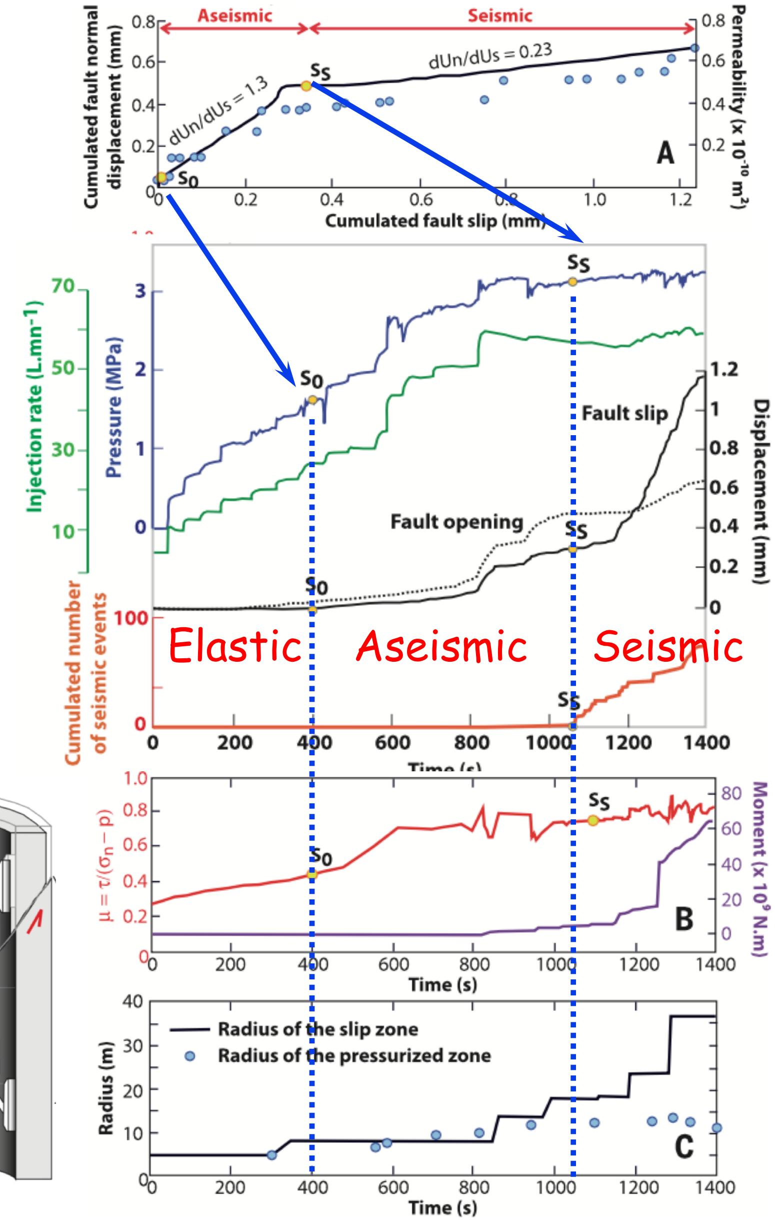
Decrease: $D_c;G$

Recurrence Requires: *Healing*



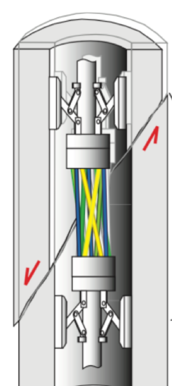
[Adapted from C.J. Marone, Pers. Comm., 2017]

Aseismic-Seismic Transition



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

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



Roles of:

Pressurization $(\sigma_n' \to 0)$

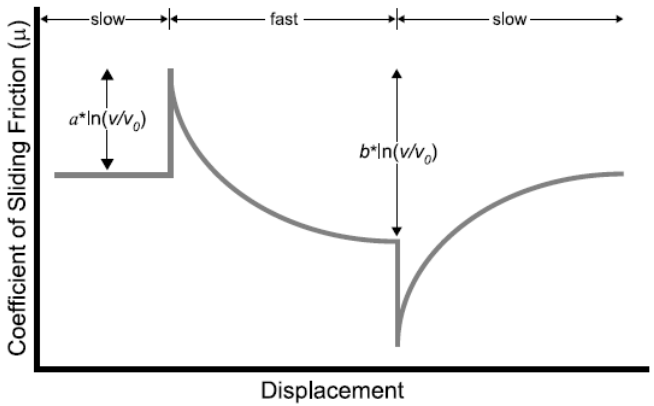
Deformation ahead of the fluid front

Mineralogical controls

[Guglielmi et al., Science, 2015]

Rate-State Friction [1]

Velocity Steps



R-S Friction

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

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

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

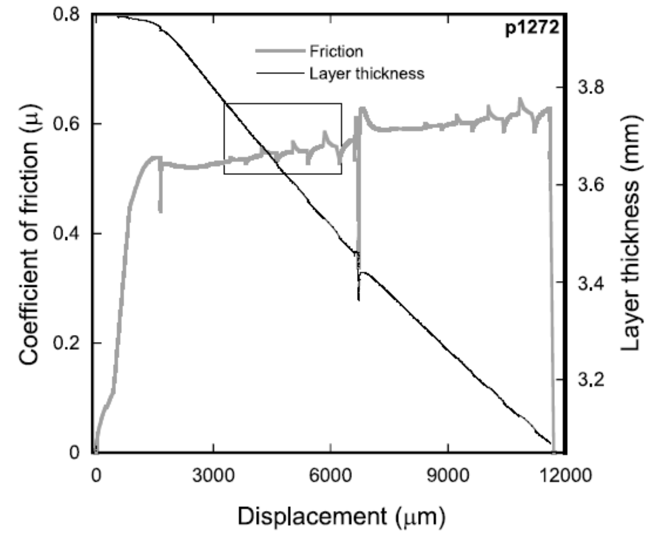
Dilation

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

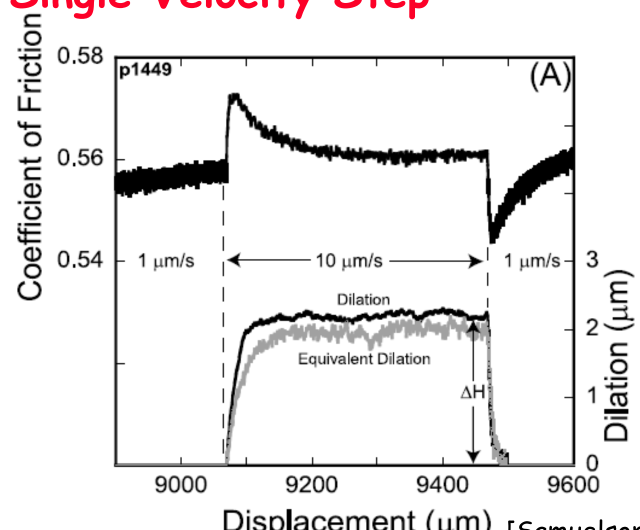
Permeability Evolution

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

Multiple Velocity Steps



Single Velocity Step

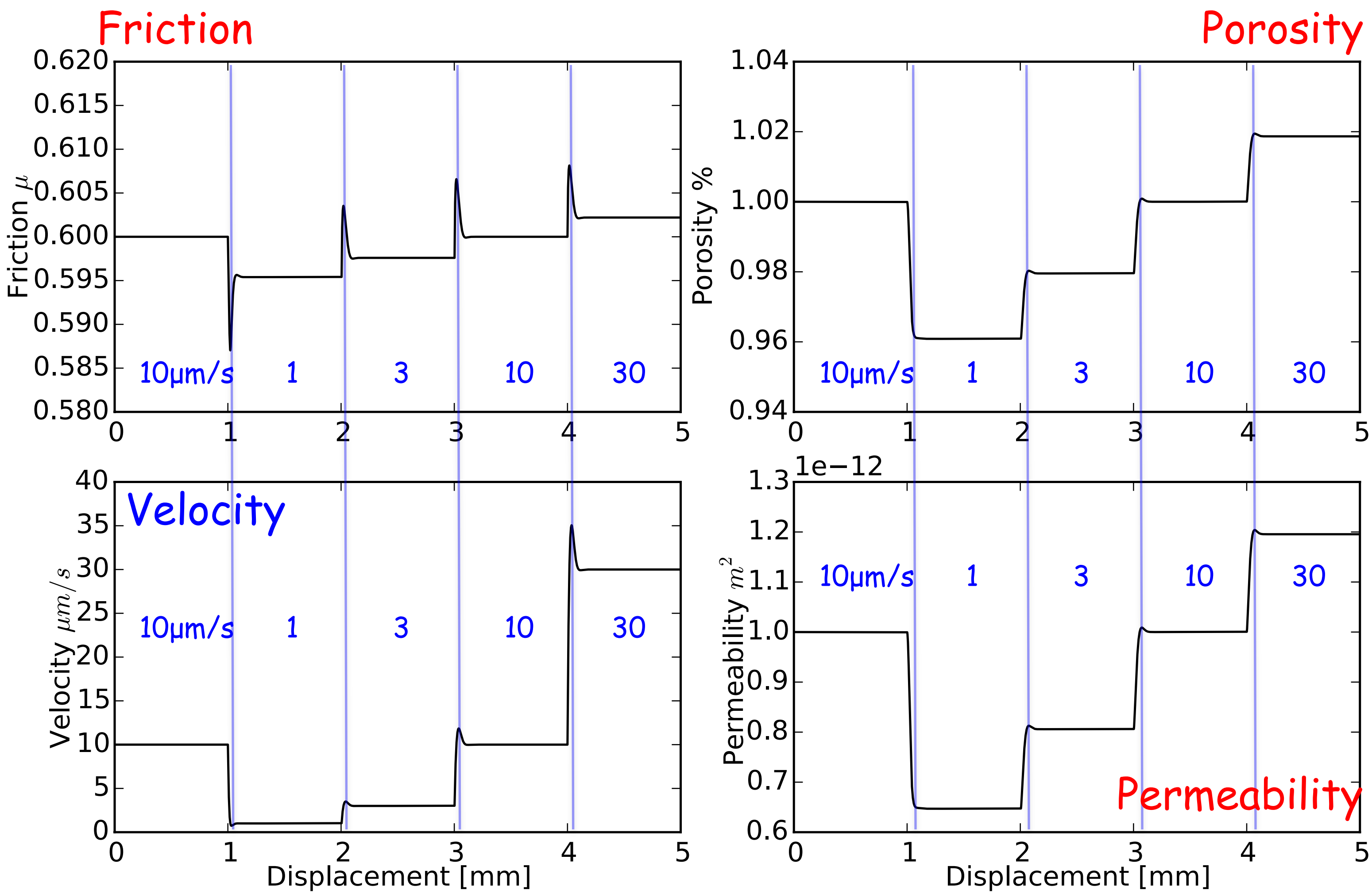


[Samuelson et al., 2009]

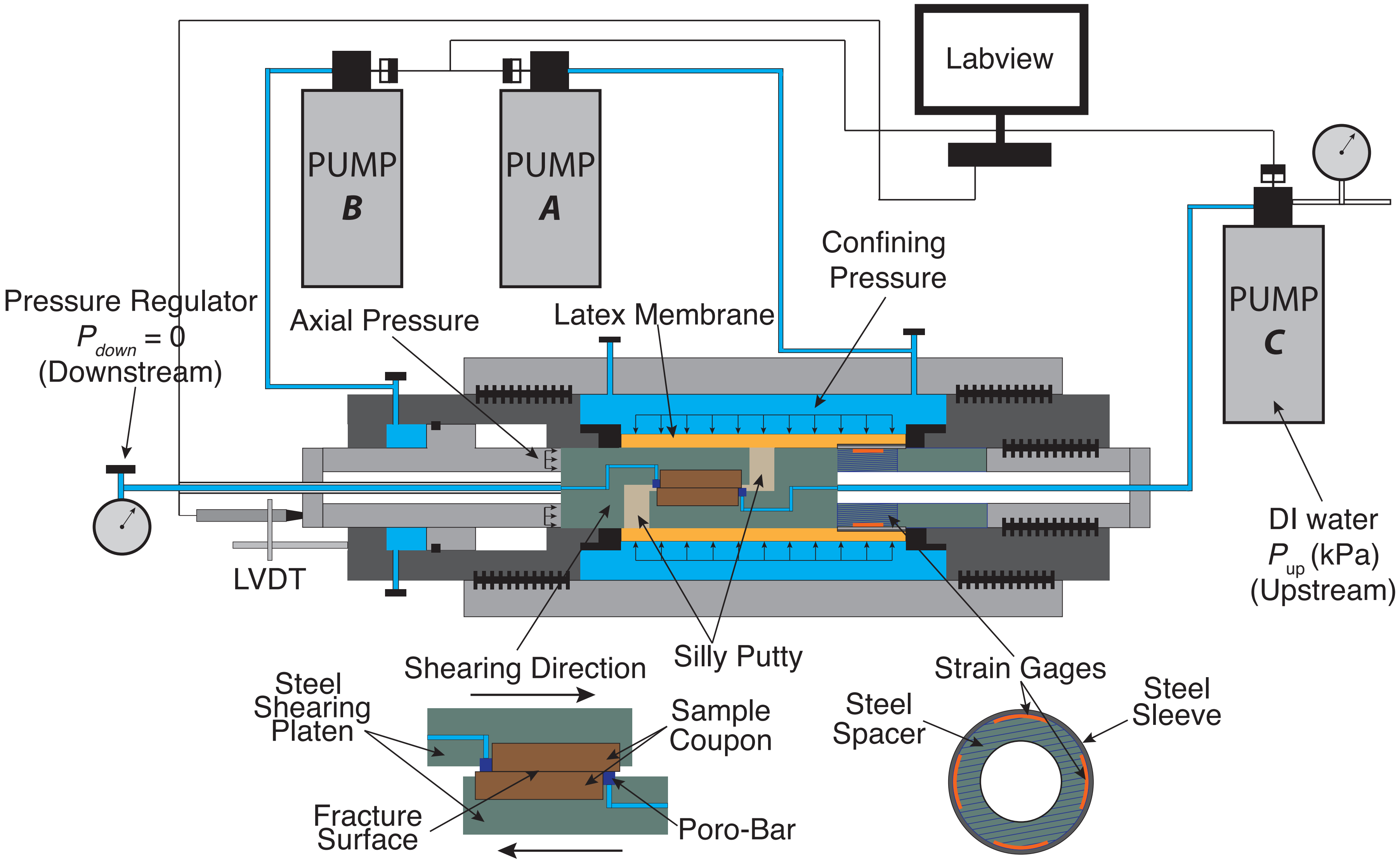
Rational Linkages: Rate-State Friction, Porosity and Permeability

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

High Stiffness, positive dilatational coefficient

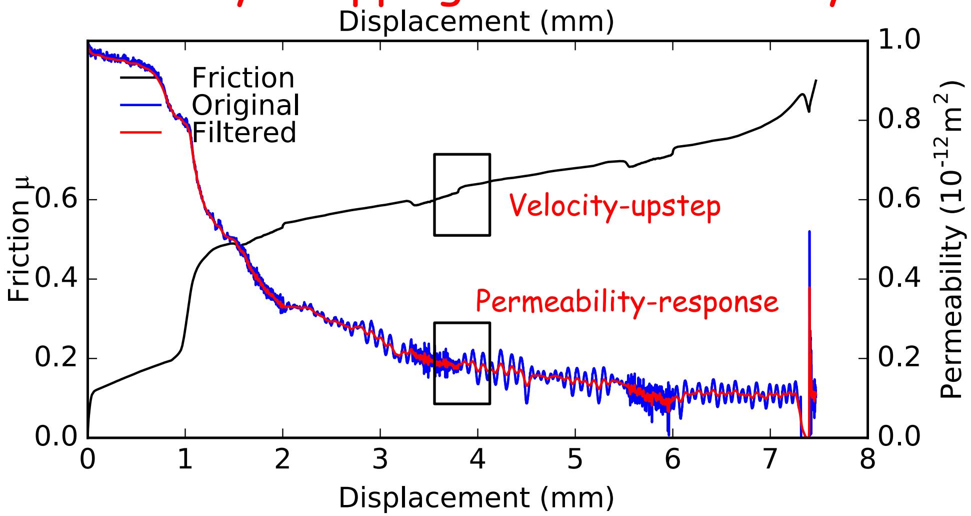


Frictional Stability-Permeability Experiments

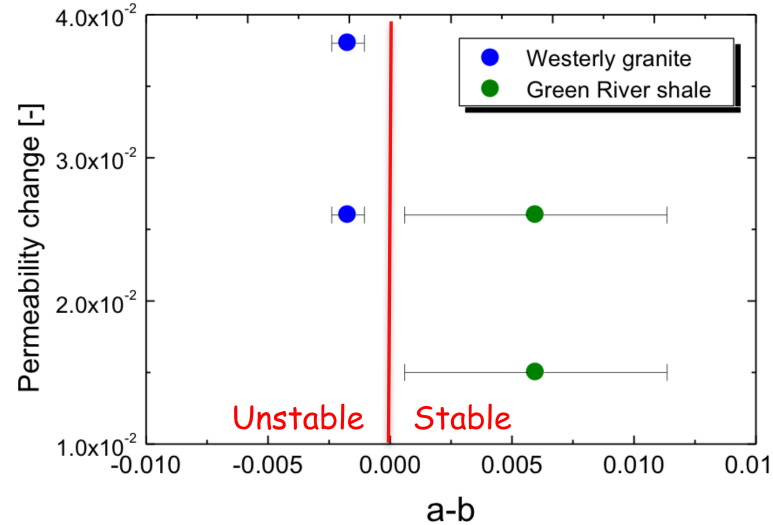


Frictional Stability-Permeability Observations

Velocity-stepping and Permeability

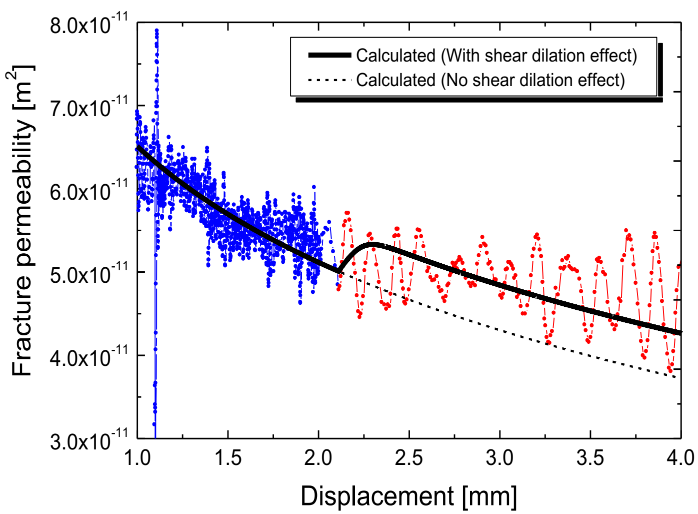


Permeability-Frictional Stability

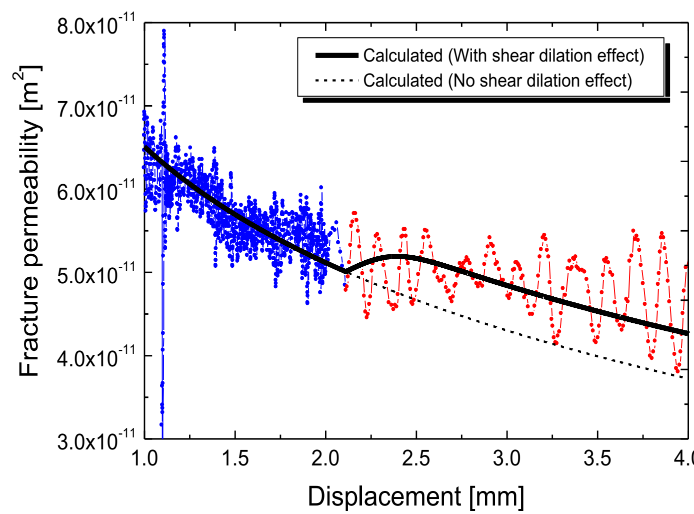


Permeability Evolution

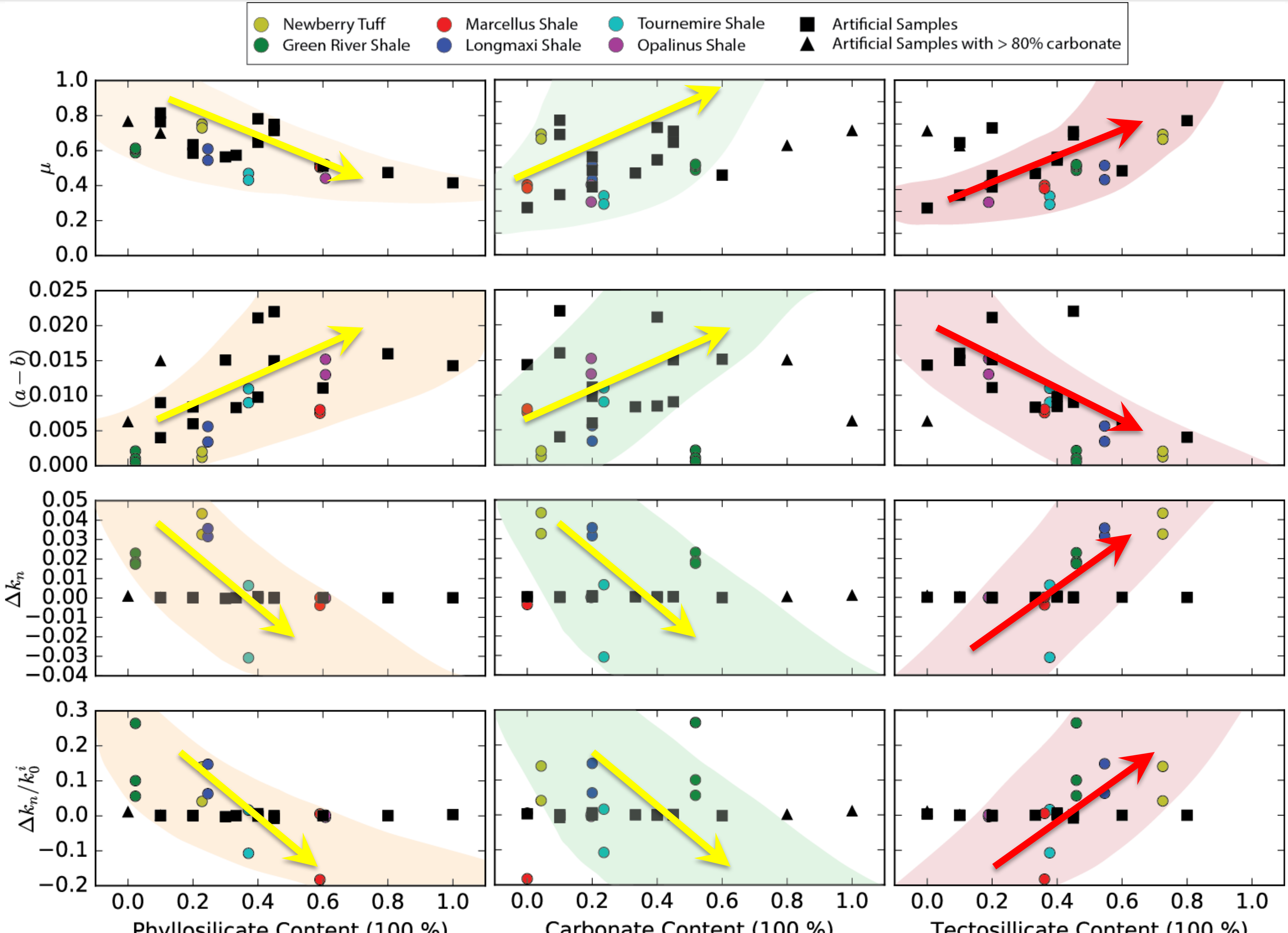
ε=0.0224 (n=2), Dc=50 [μm]



ε=0.0224 (n=2), Dc=100 [μm]



Seismicity-Permeability Linkages – Natural Samples

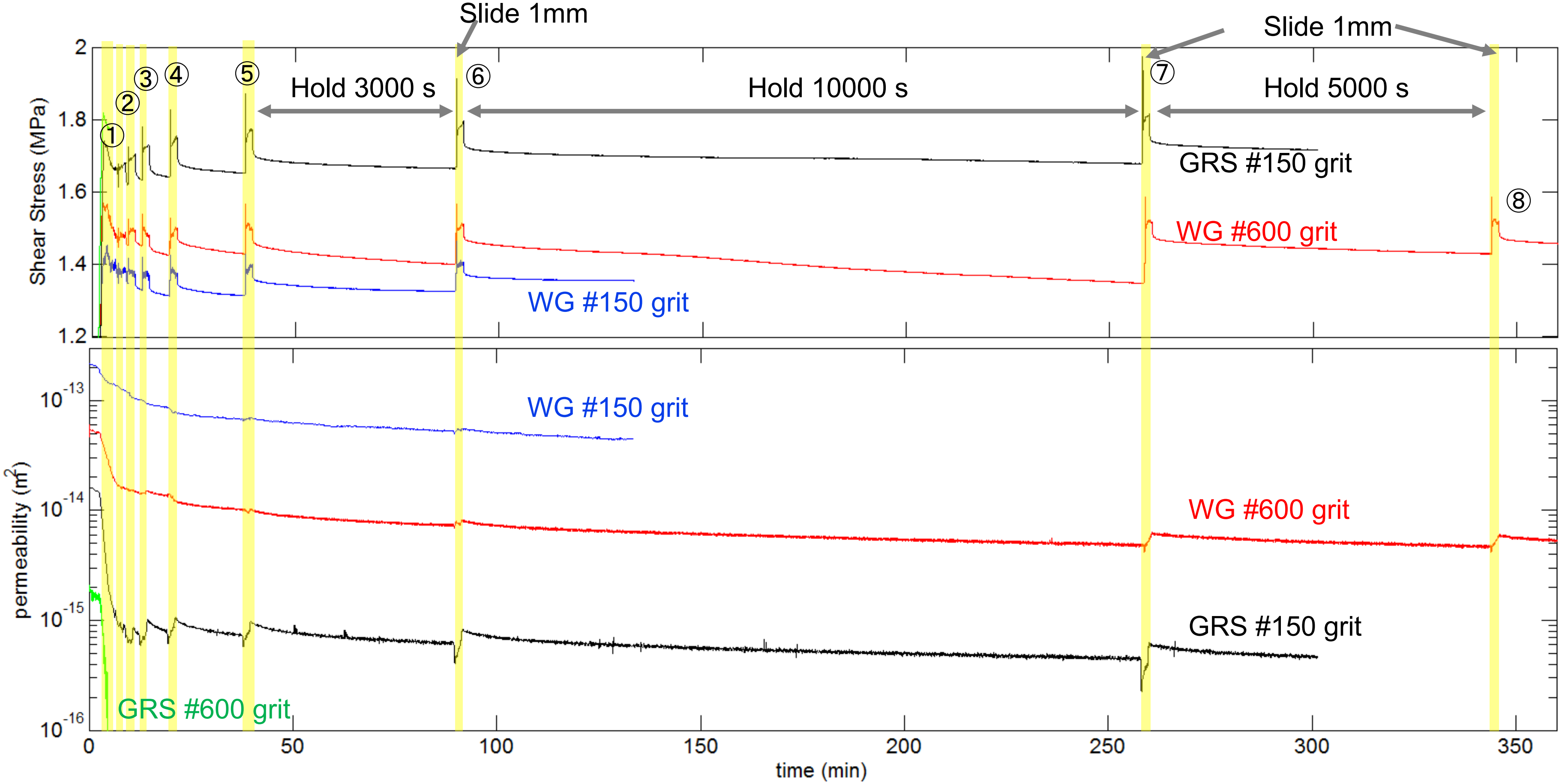


Healing – Necessary Component of the Seismic Cycle

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

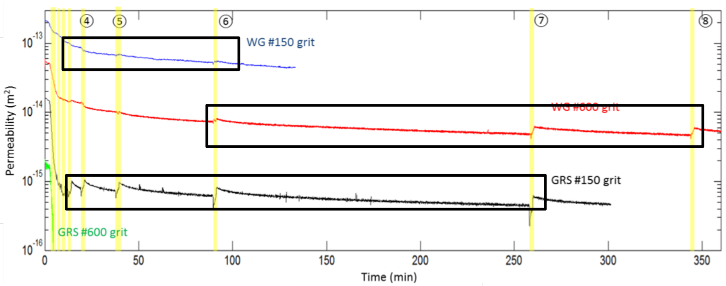
Experimental Notes
- Permeability of Green River shale #600 grit became unresolvable after initial shear
- Westerly granite #150 grit stopped at ~150 min due to limited pump capacity
- 8th shear applied to Westerly granite #600 grit after 5000 seconds

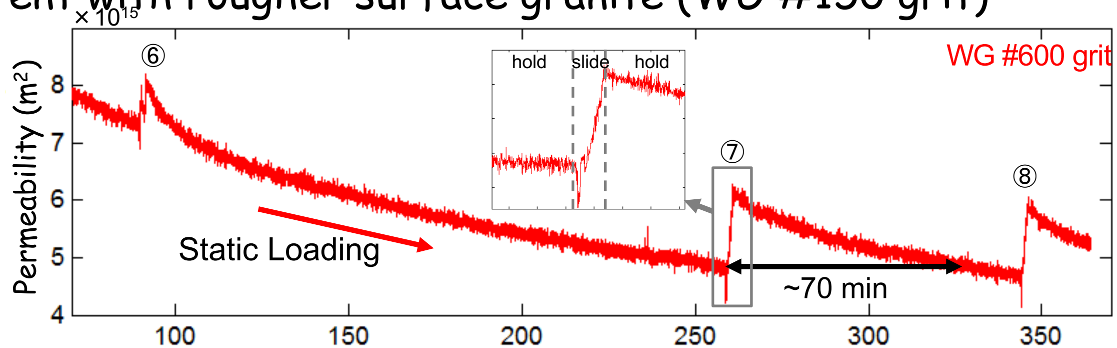


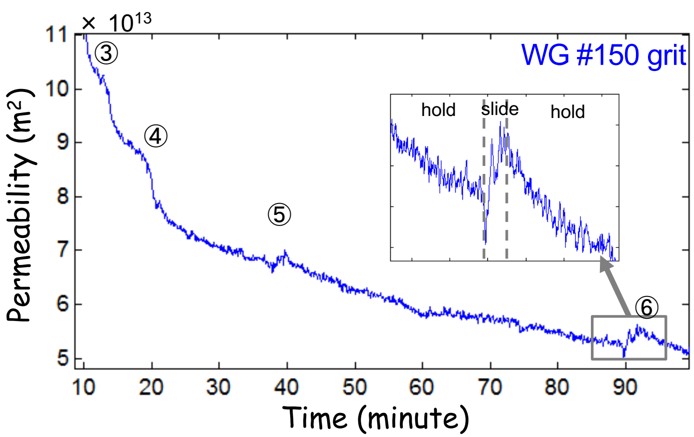
Shear Permeability Enhancement

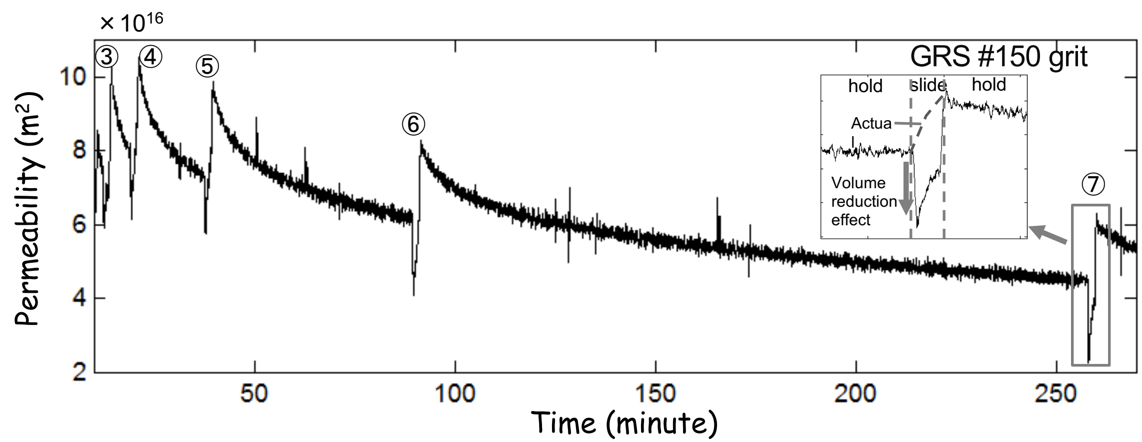
Shear Induced Permeability Enhancement

- 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)





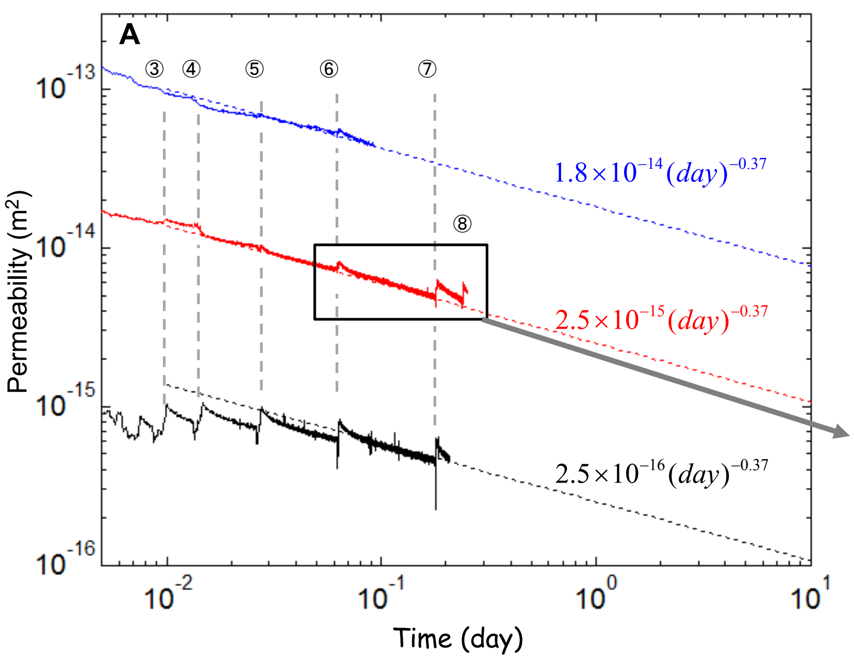


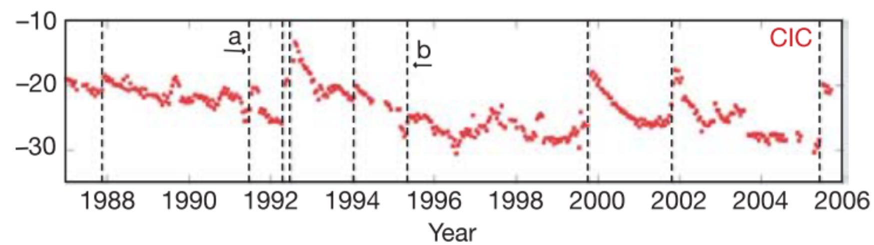


Permeability Healing (Sealing) Law

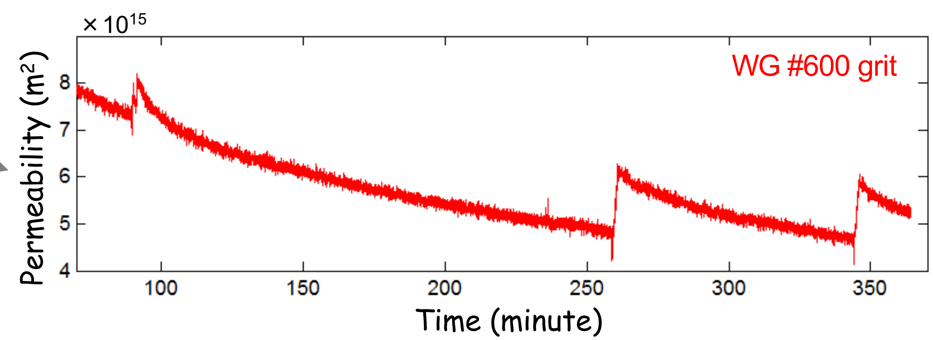
Pressure solution

- 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

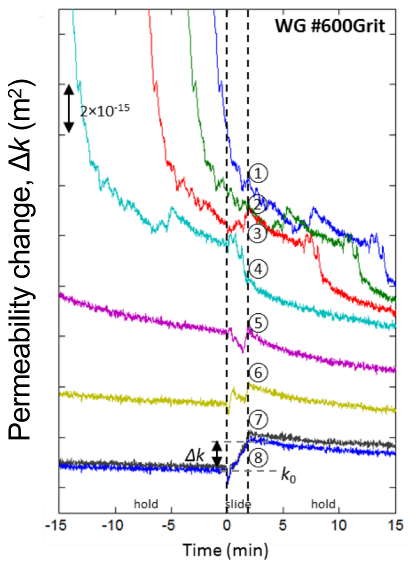
Magnitude of Permeability Enhancement

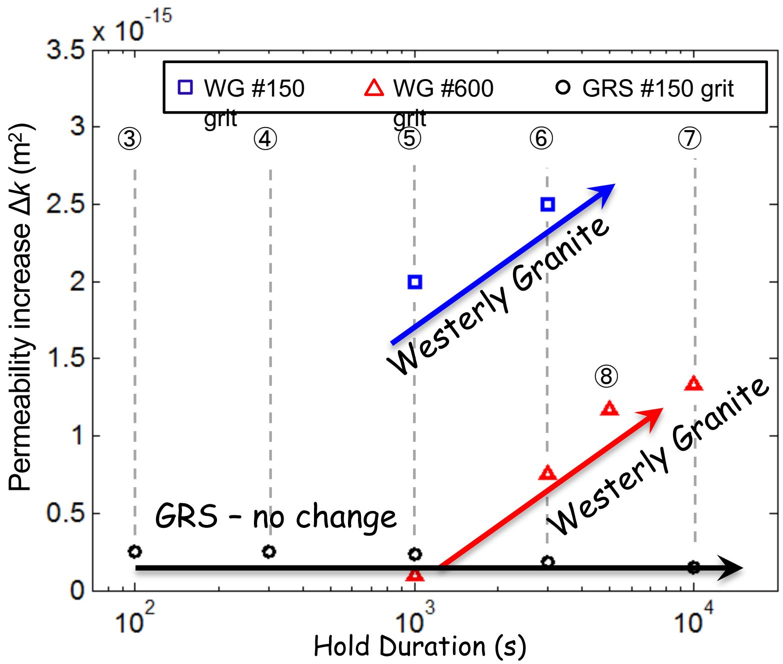
<ins>Absolute</ins> perm increase: rougher granite > smoother granite > shale

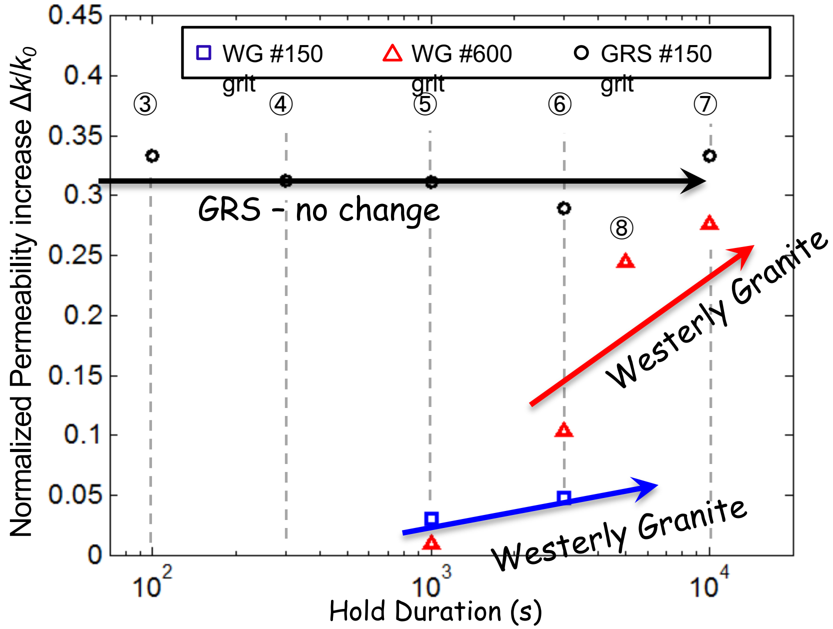
<ins>Normalized</ins> perm increase: shale > smoother granite > rougher granite

<ins>Shear</ins> permeability increase with duration of prior hold time for Westerly granites

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







Key Complex Process Couplings and Challenges in the Effective Recovery of Deep Geothermal Energy

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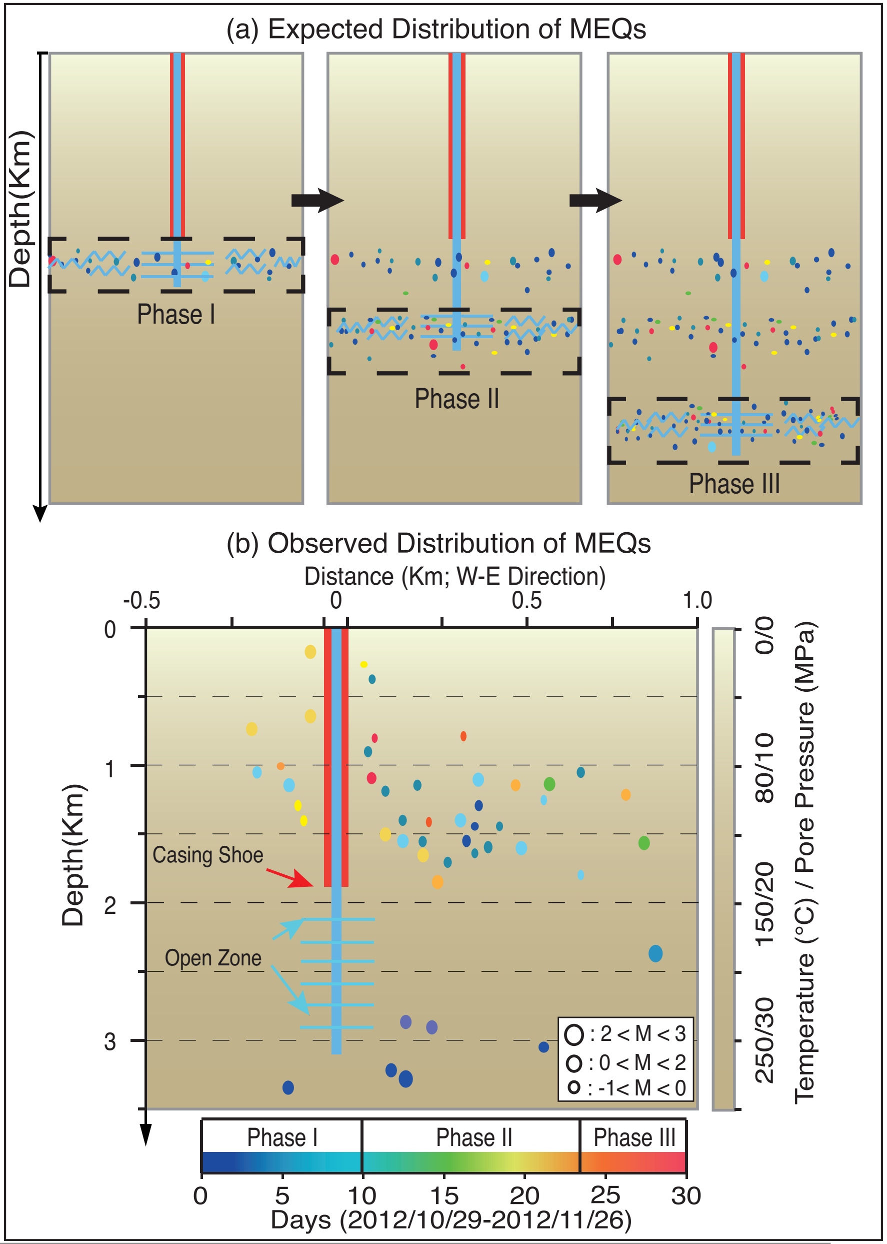
Anomalous Seismicity – The Missing Zone

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

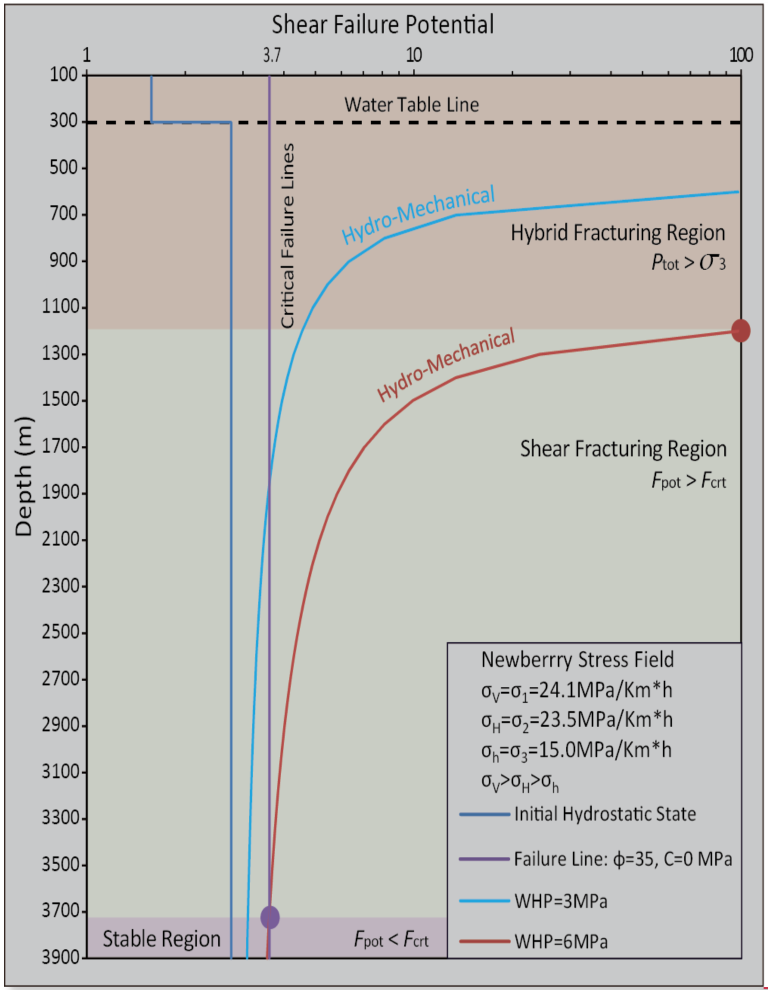
Spatial Anomaly
- Bimodal depth distribution
- Below 1950 m, only a few MEQs occurred.
- Between 500m and 1800m, 90% MEQs occurred adjacent to the cased part.

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



Constraints on Frictional Slip

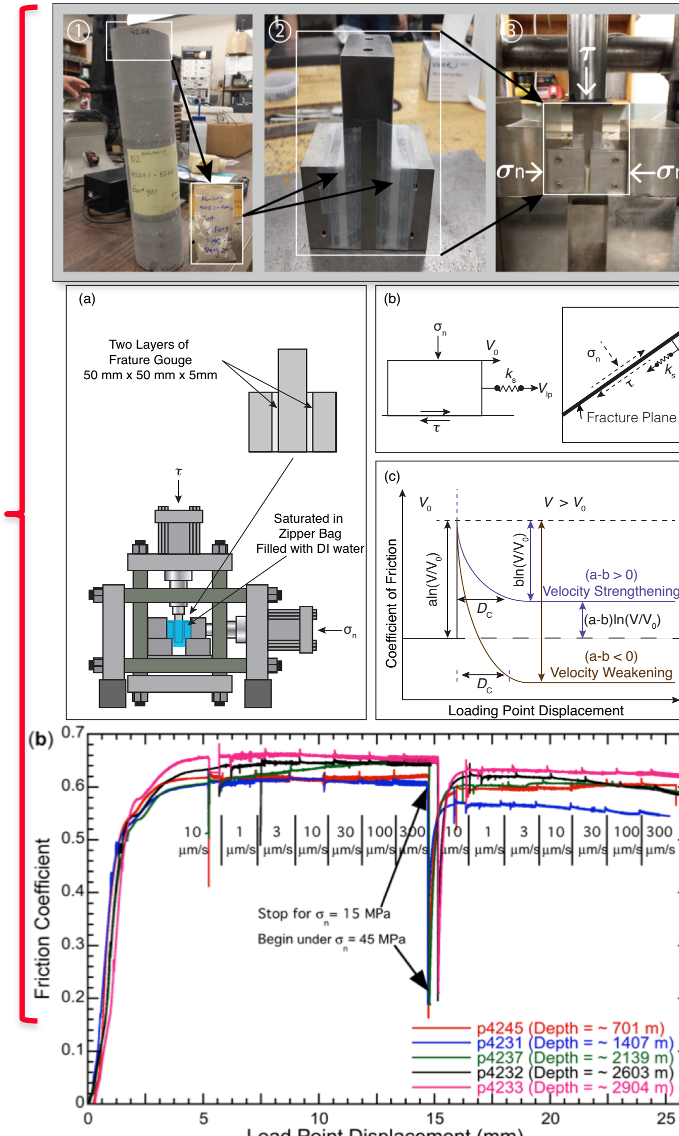
1. Shear Failure Analysis



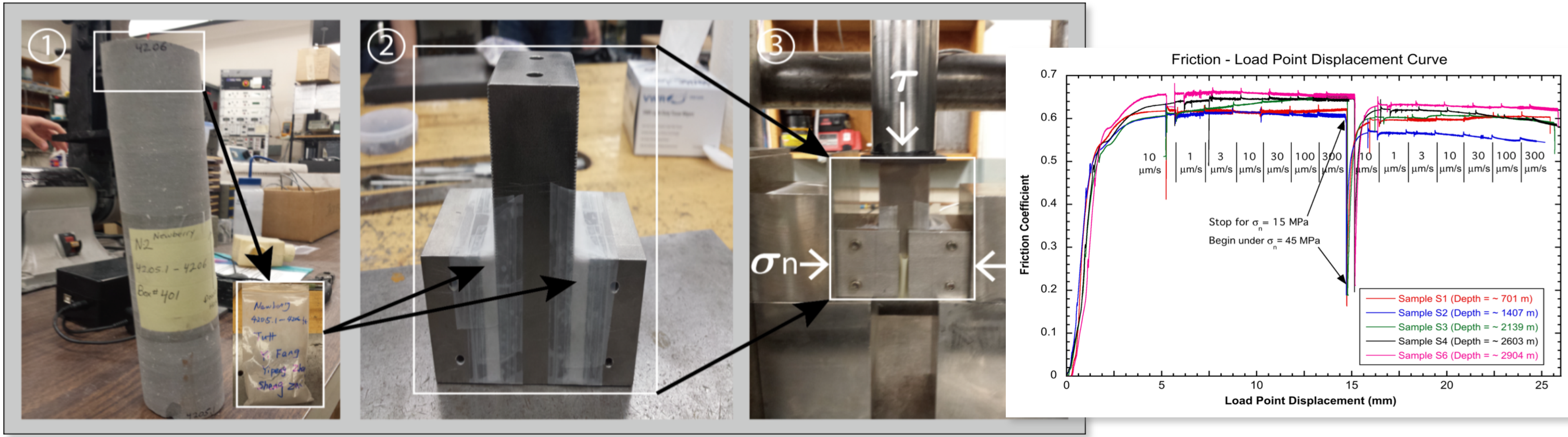
1. Shear Failure Analysis suggests that if seismicity occurs at great depth, it should occur continuously up the rock column, and not with a gap.

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

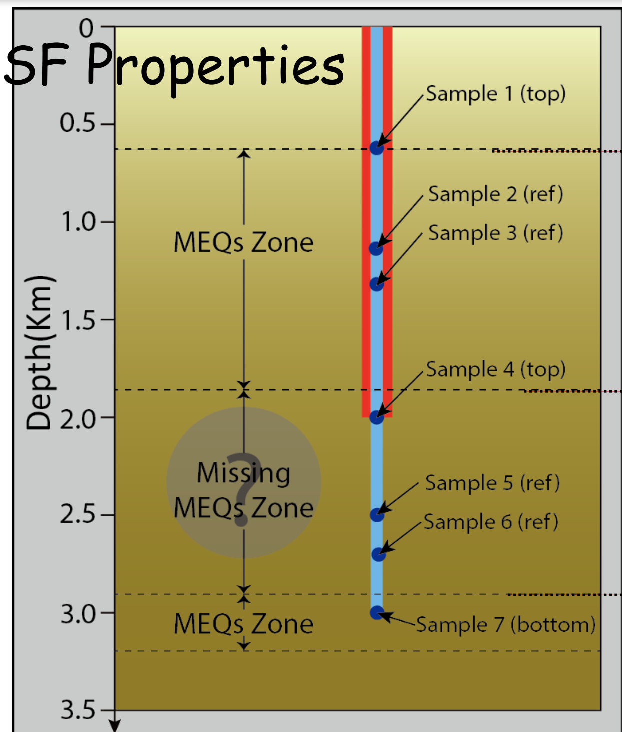
2. Friction Experiments



RSF Properties

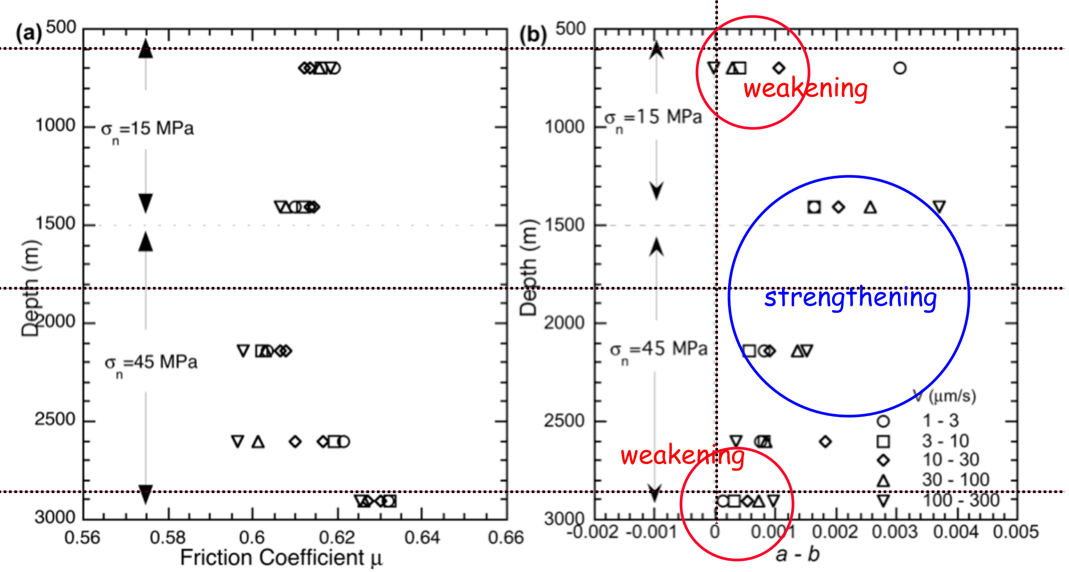


RSF Properties



Friction

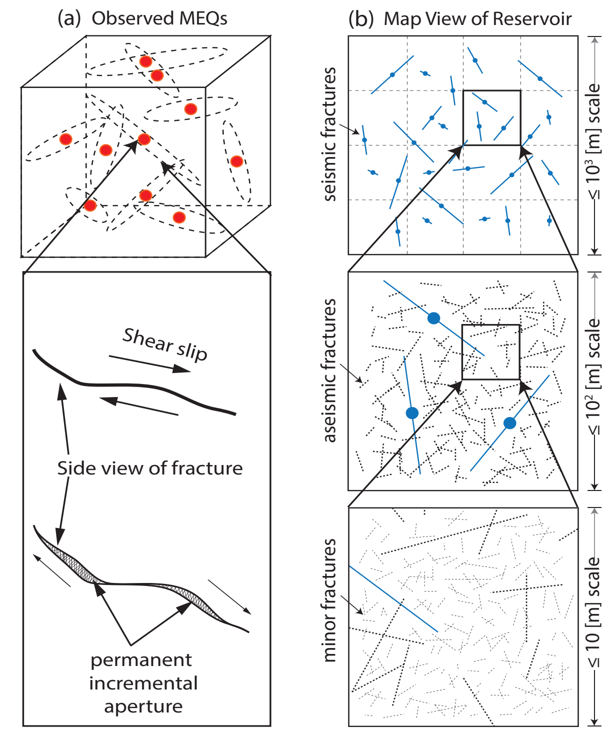
(a-b) at 15-45 MPa



derek.elsworth@psu.edu

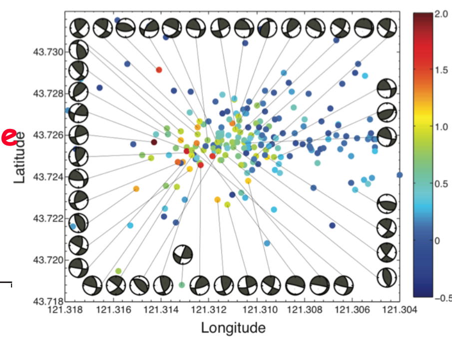
Linking MEQs to Permeability Evolution

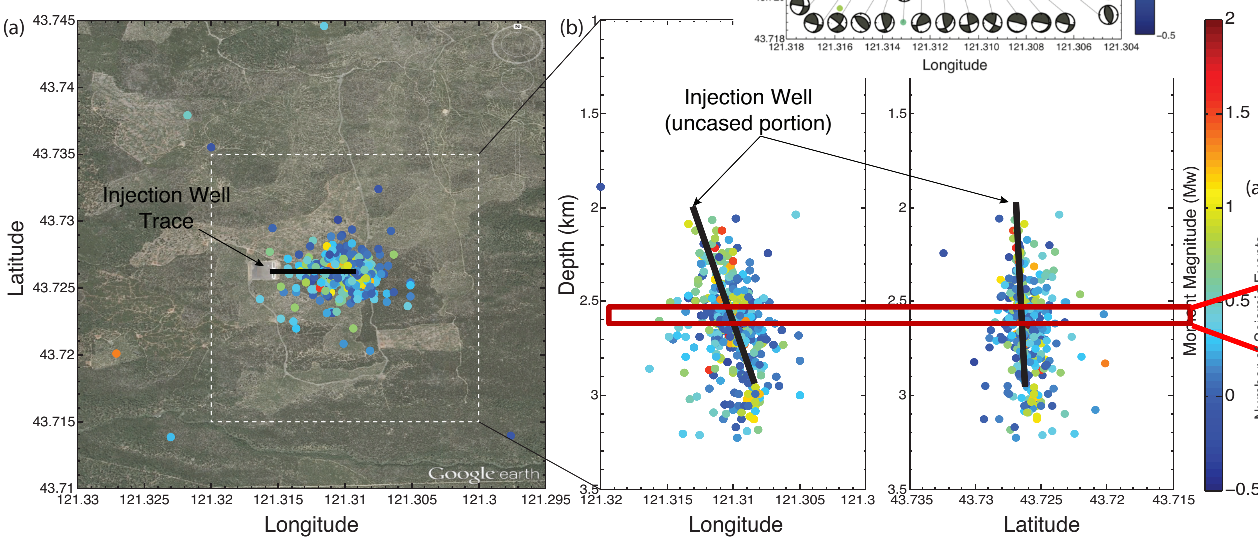
1. Seismicity induced by hydroshearing is controlled by the Mohr-Coulomb shear criterion.
2. The frictional coefficient evolves during seismic slip.
3. Two types of fractures:
   - Velocity-weakening/seismic fractures and,
   - Velocity-strengthening/aseismic fractures (fracture size smaller than the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



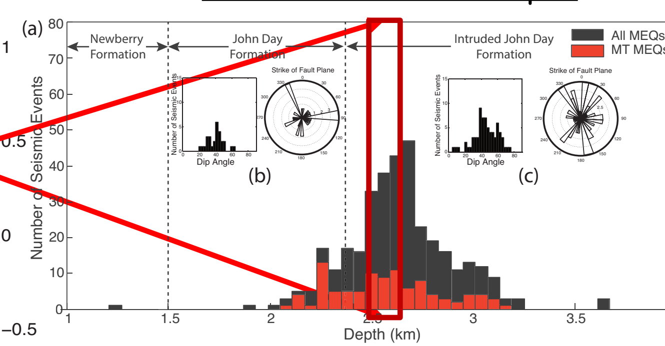
Workflow:

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





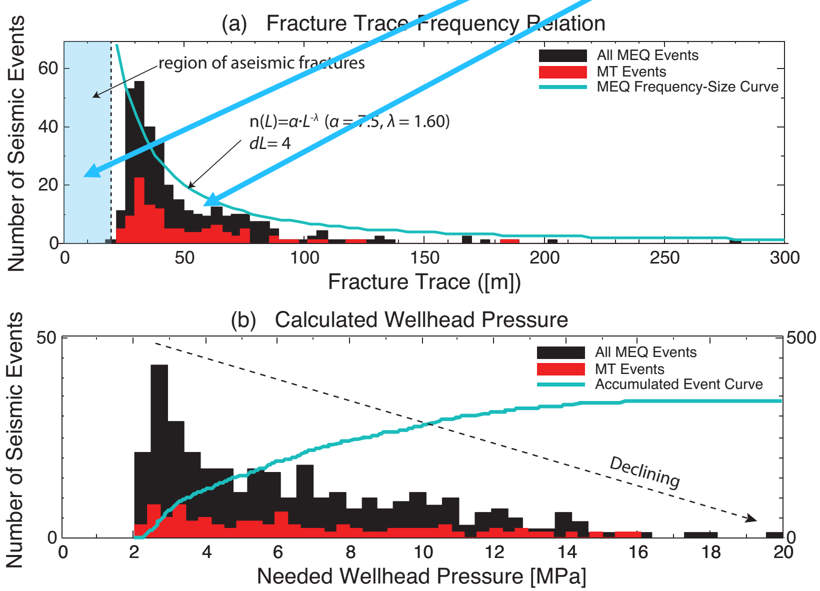
Seismic Events vs. Depth



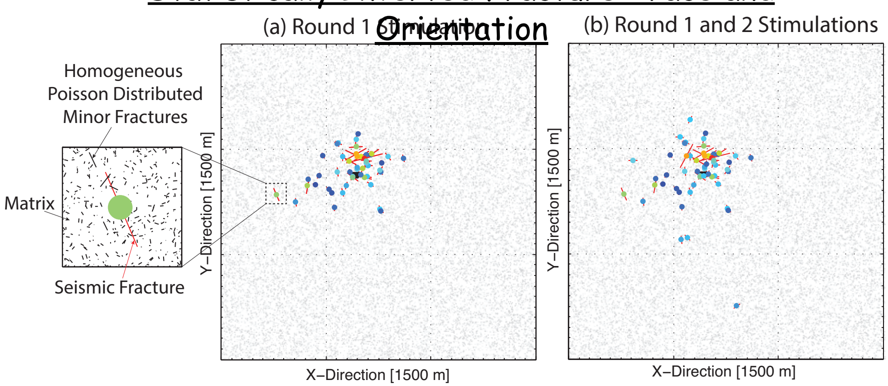
Seismicity-Permeability Validation

max 0

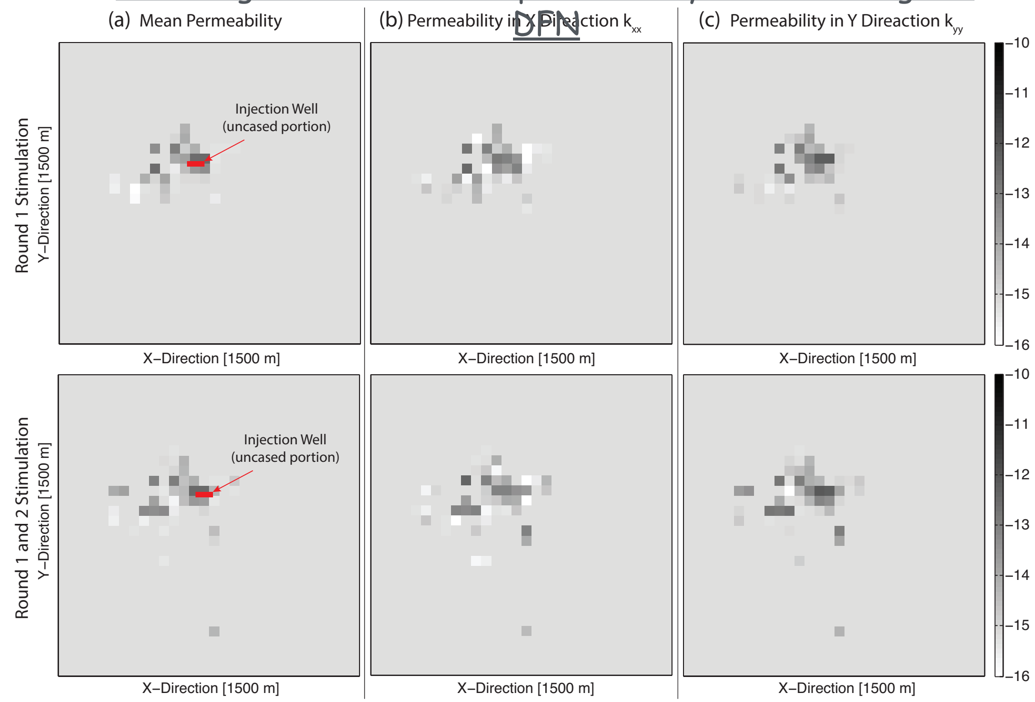
$$n_{tot} = n_{aseis} + n_{seis} = \boxed{n_{aseis}} + \boxed{n_f} + n_{uf}$$



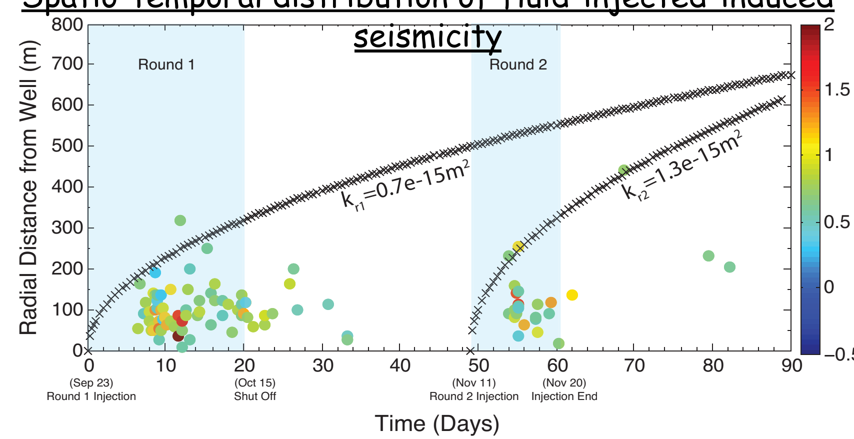
Statistically Inverted Fracture Trace and Orientation



Cellular grid of stimulated permeability created using the DFN



Spatio-temporal distribution of fluid-injected-induced seismicity



Conclusions

Heat/Energy Recovery is a/the Key Parameter Defining Viability

Indexed via: $\dot{H} = \dot{M}_f \Delta T_f c_f$

Sensitivity spectrum of response: Hydrothermal->SGR->EGS

Key Challenges - Complex THMC Interactions Influence Reservoir Evolution

1. Induced/Triggered Seismicity
2. Permeability evolution (also heat-transfer area)

Seismicity

Events can be large

Driven by both dp and dT (and dC?)

Triggered –vs- Induced events control M_w

Permeability

Evolution linked to seismicity via RSF

Implies key controls on permeability, e.g. –

mineralogy, dynamic stressing, sealing/healing

Seismicity-Permeability Linkage

Deciphering anomalous responses

Potential for reservoir creation, management and control