

Controls on Permeability and Seismicity in EGS Reservoirs

Derek Elsworth (Penn State), Quan Gan (PSU), Yi Fang (PSU/UT), Josh Taron (USGS), Ki-Bok Min (SNL), Hide Yasuhara (Ehime), Yves Guglielmi (LBNL/Aix-Marseille), Kyunjae Im (PSU/Caltech), Chaoyi Wang (PSU/Purdue), Takuya Ishibashi (AIST/PSU), Atsushi Sainoki (Kumamoto), Yunzhong Jia (NTU), Tim Kneafsey (LBNL), Joe Moore (Utah, EGI)

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

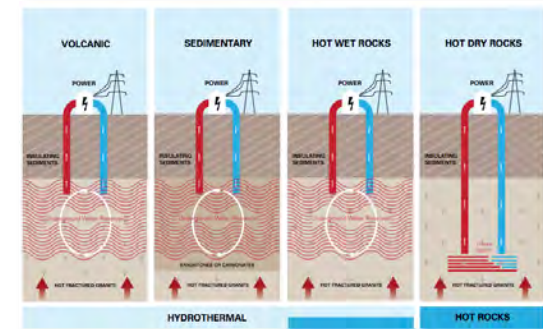
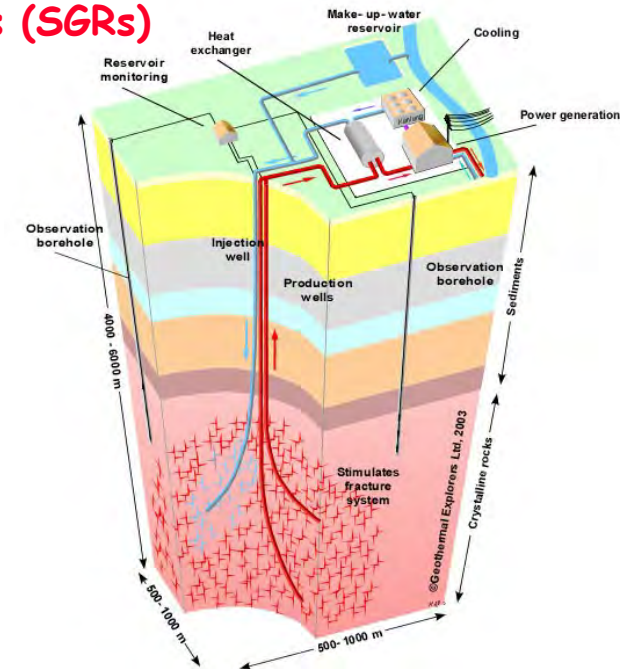
Reservoir Scale Response

Anomalous seismicity - Newberry Project

Permeability scaling - Newberry Project

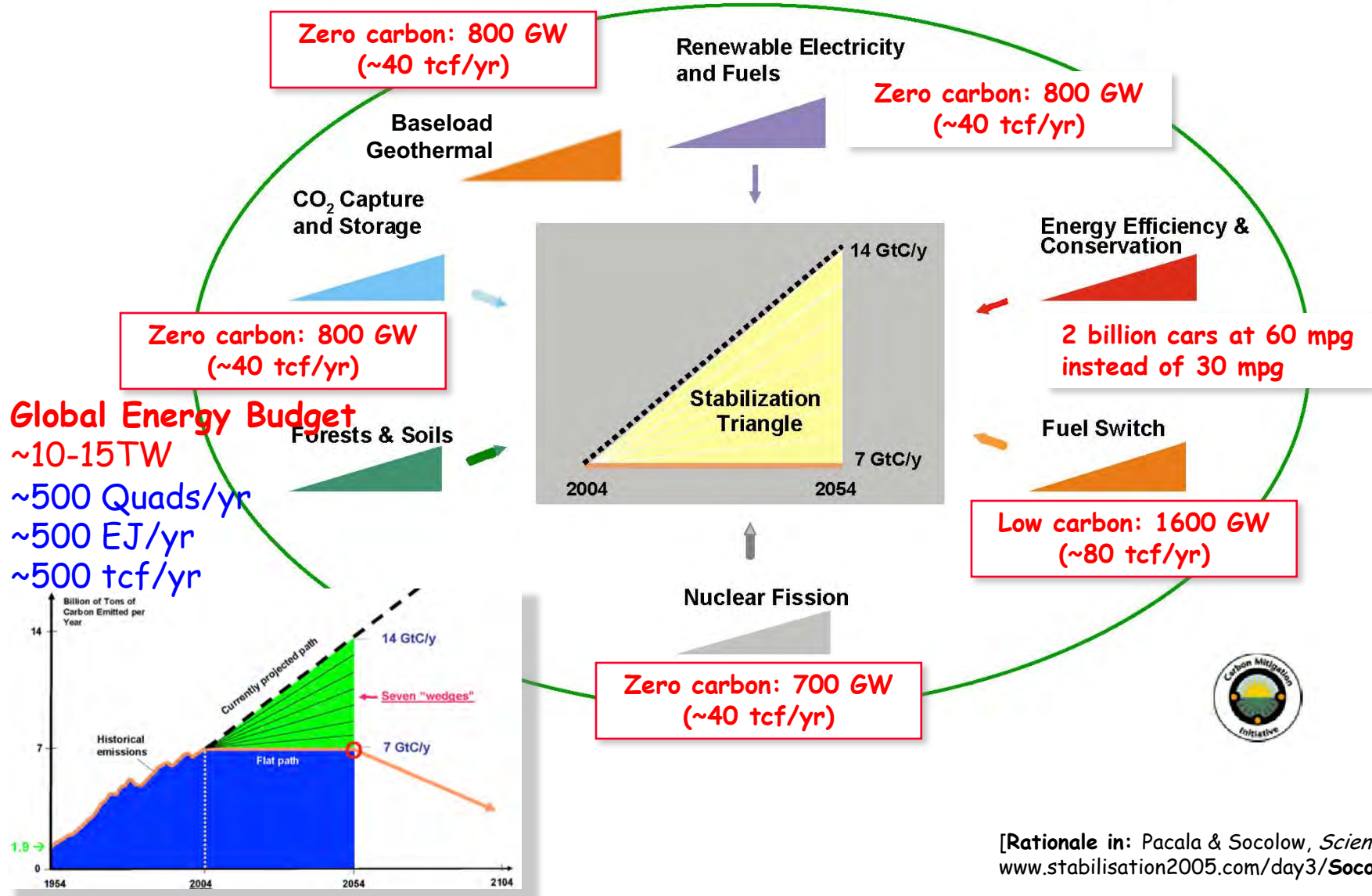
US (DoE) Road Map

Summary



Capacity Needs - Stabilization Wedges

Fill the Stabilization Triangle with Seven Wedges



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

Spectrum of Geothermal Reservoirs (SGRs)

SedHeat Initiative

<http://geothermal.tcu.edu>

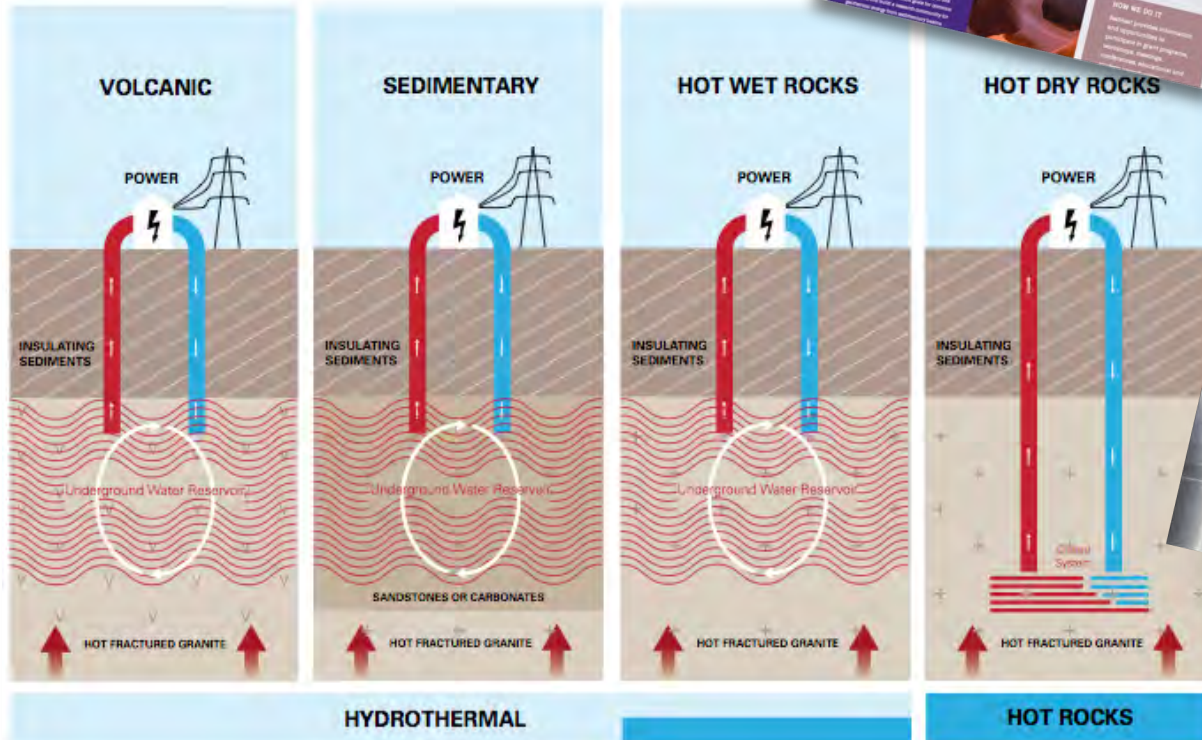
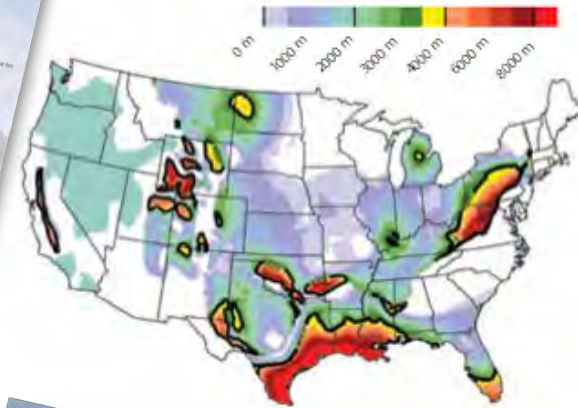
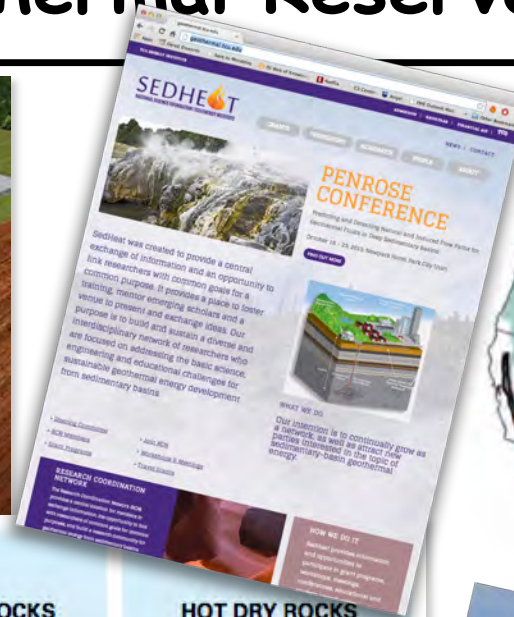
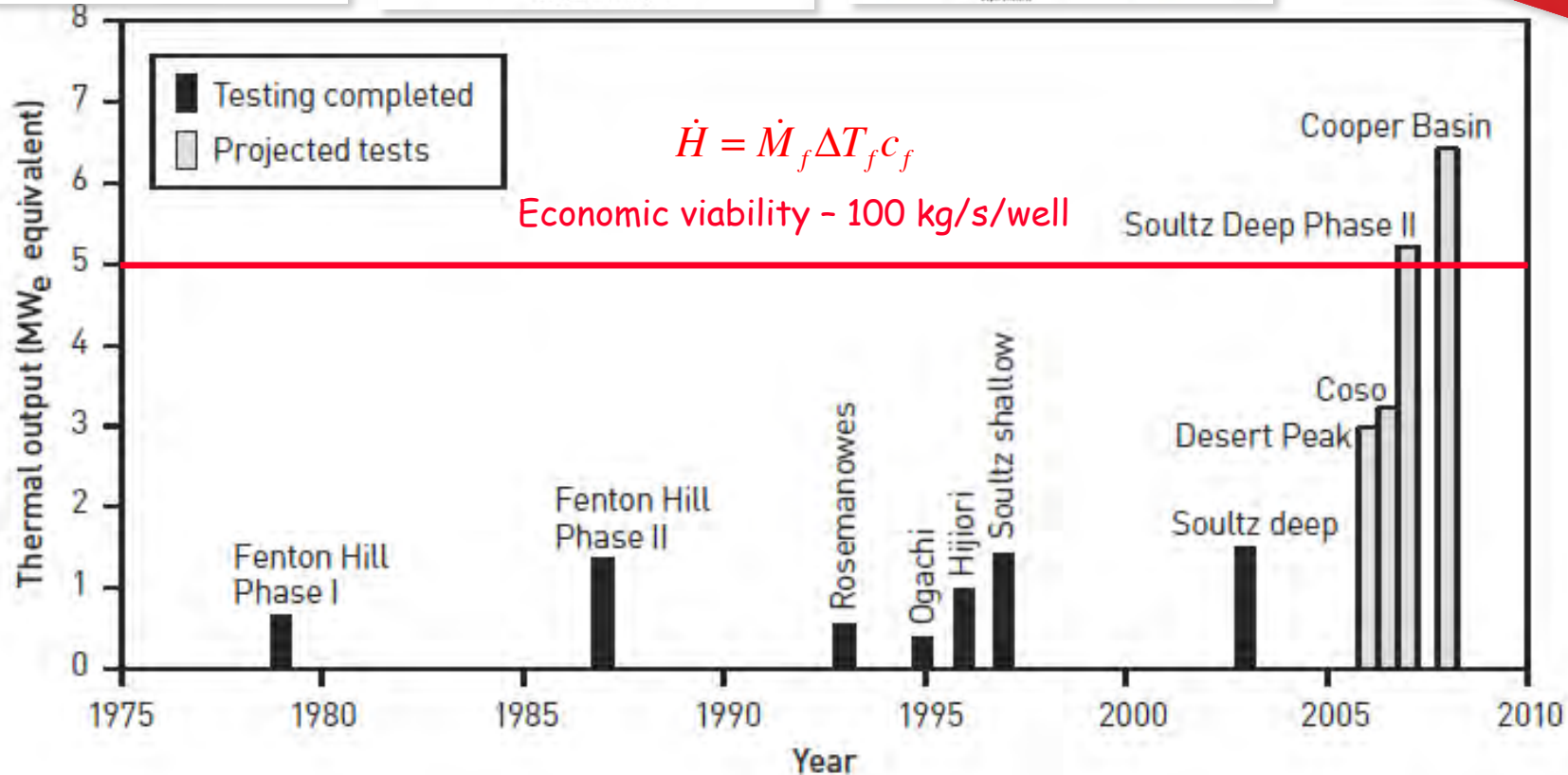
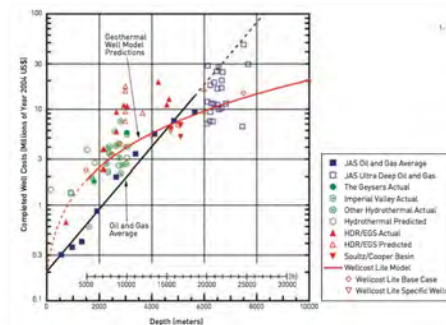
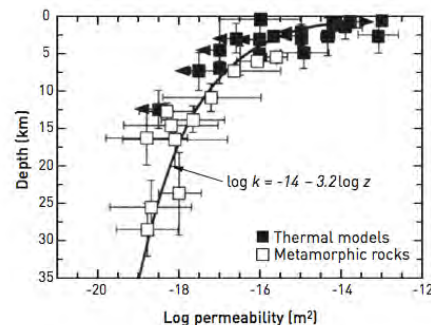
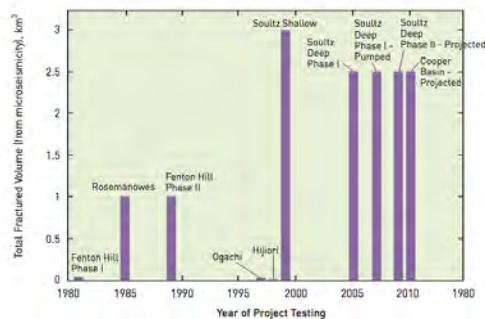


Figure 2: Average temperature at 4.5 km, conterminous United States. (Tester, et al., 2006, after Blackwell and Richards, 2004)

Can EGS ever be Viable?



Induced Seismicity

Quake Fears Stall Energy Extraction Project

By JAMES GLANZ

Published: July 13, 2009

The New York Times

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.

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SOUND OF MY VOICE
IN THEATRES 04.27.2012
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Basic Observations of Permeability Evolution and IS

Challenges

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

Observation

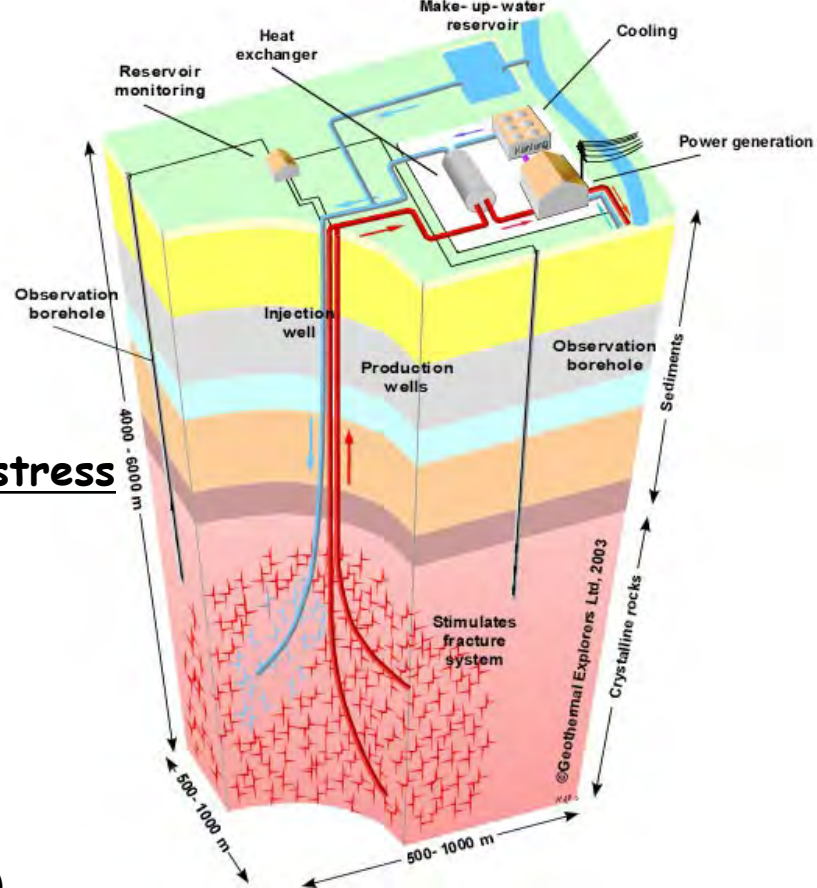
- Stress-sensitive reservoirs
- T H M C all influence via effective stress
- Effective stresses influence
 - Permeability
 - Reactive surface area
 - Induced seismicity

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

Resource

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



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
 - H₂O/CO₂ working fluids?
- **Fluid transmission**
 - Permeability microD to mD?
 - Distributed permeability
- **Thermal efficiency**
 - Large heat transfer area
 - Small conduction length
- **Long-lived**
 - Maintain mD and HT-area
 - Chemistry
- **Environment**
 - Induced seismicity
 - Fugitive fluids
- **Ubiquitous**

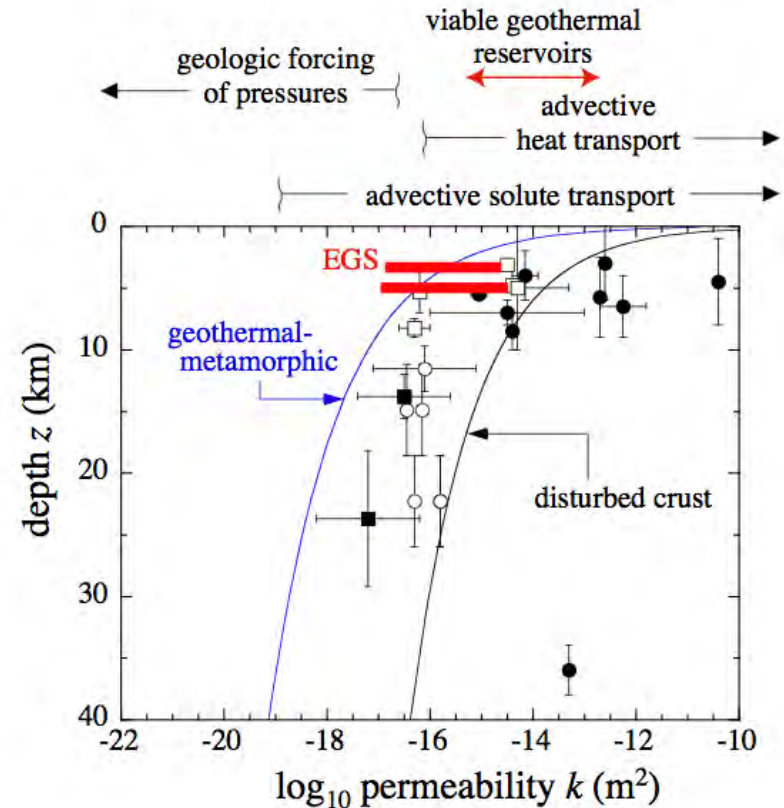
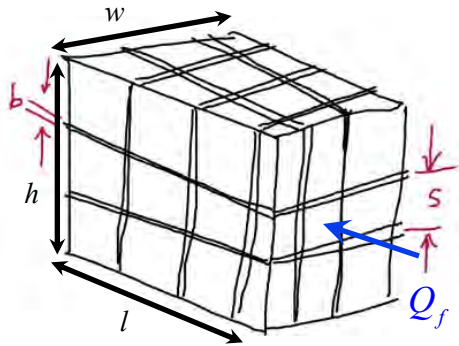


Figure 12: Evidence for relatively high crustal-scale permeabilities showing power-law fit to data. Geothermal-metamorphic curve is the best-fit to geothermal-metamorphic data [Manga and Ingebritsen, 1999, 2002]. “Disturbed-crust” curve interpolates midpoints in reported ranges in k and z for a given 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



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

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

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

EGS:

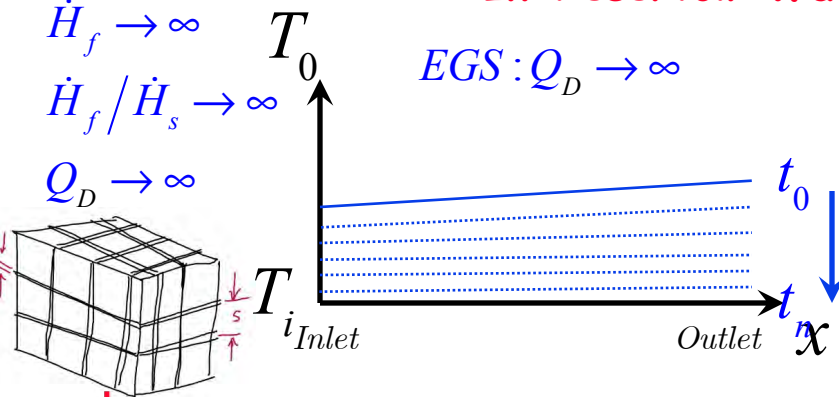
$$\dot{H}_f \rightarrow \infty$$

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

$$Q_D \rightarrow \infty$$

In-Reservoir Water Temperature Distributions:

$$EGS: Q_D \rightarrow \infty$$

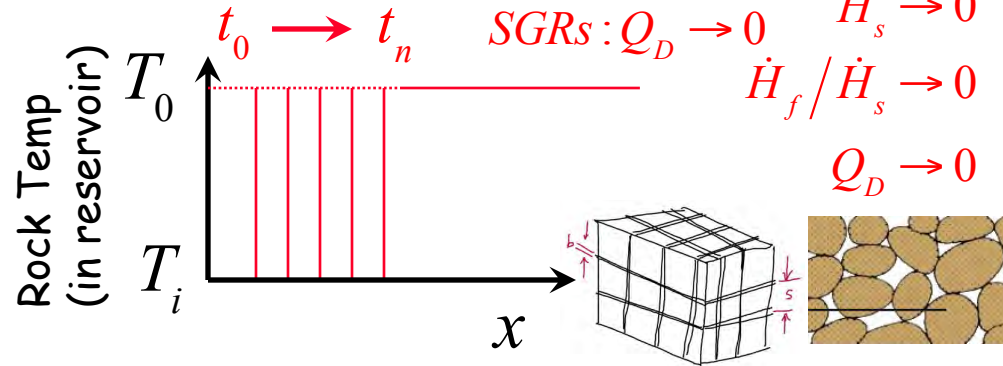


SGRs:

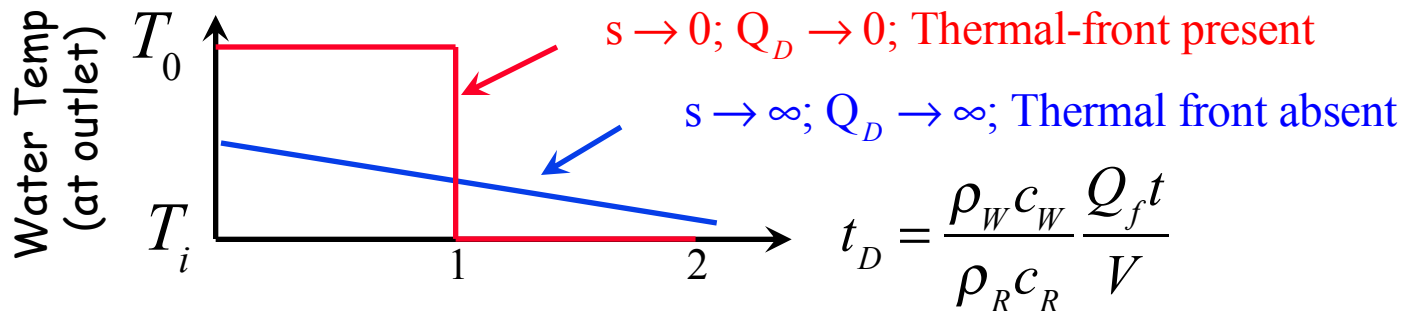
$$\dot{H}_s \rightarrow 0$$

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

$$Q_D \rightarrow 0$$

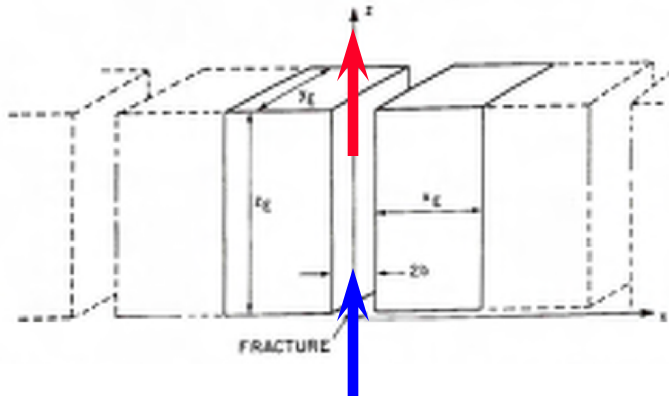


Thermal Output:



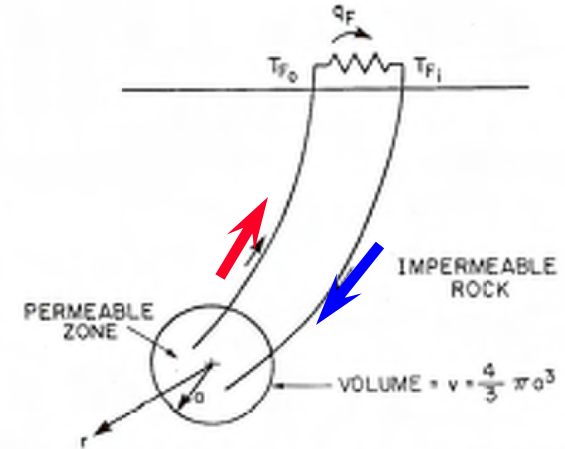
Thermal Recovery at Field Scale

Parallel Flow Model

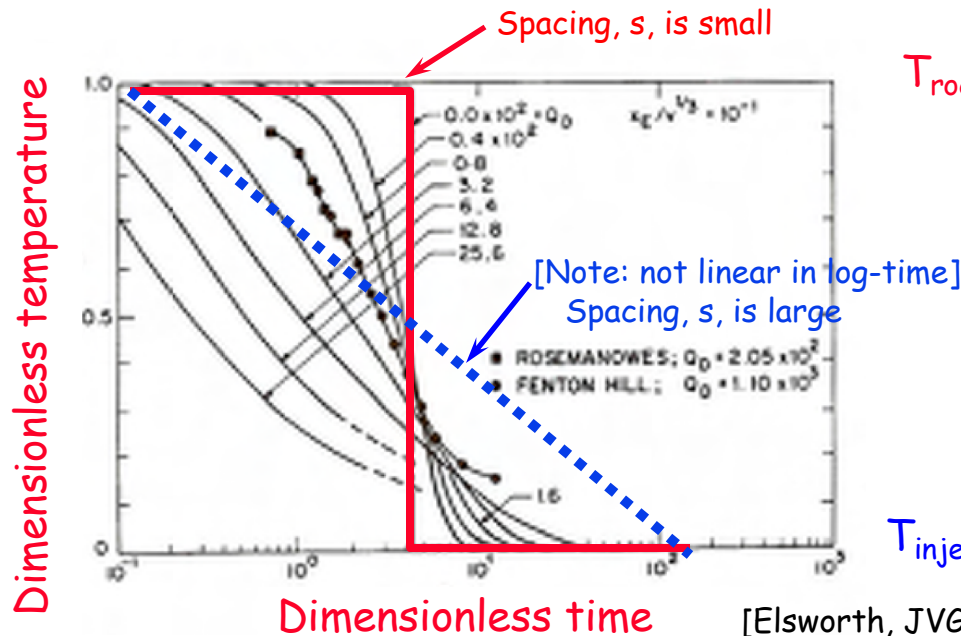


[Gringarten and Witherspoon, *Geothermics*, 1974]

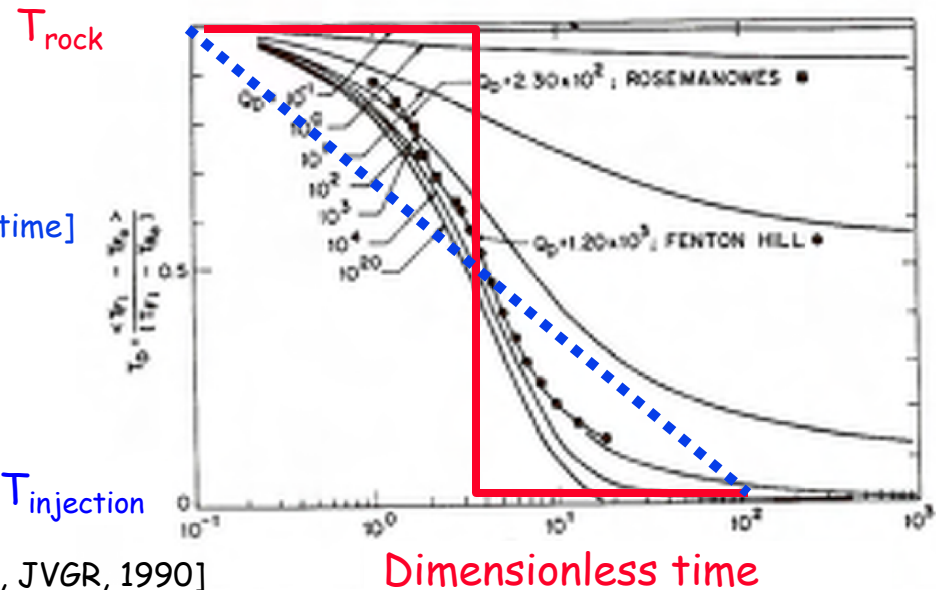
Spherical Reservoir Model



[Elsworth, *JGR*, 1989]



[Elsworth, *JVGR*, 1990]



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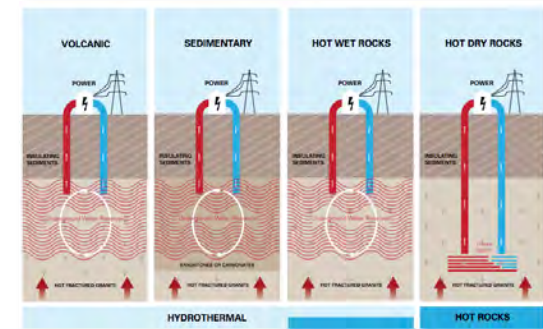
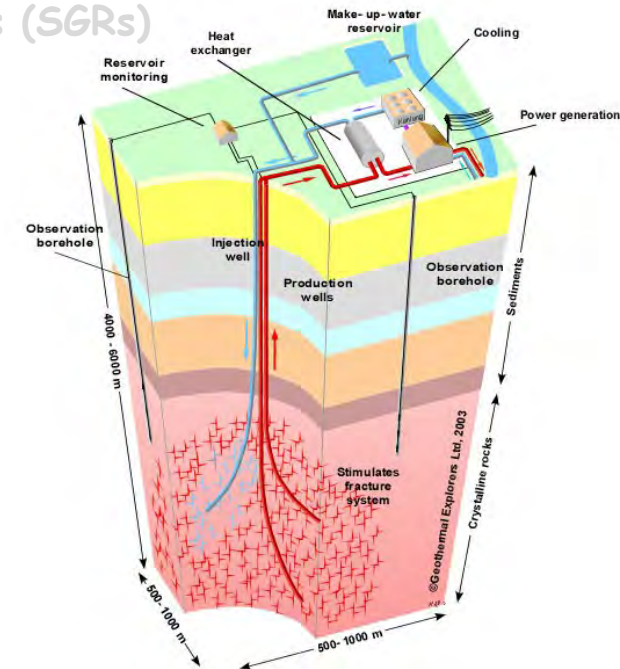
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US (DoE) Road Map

Summary



THMC Models - Rate-Limiting Processes

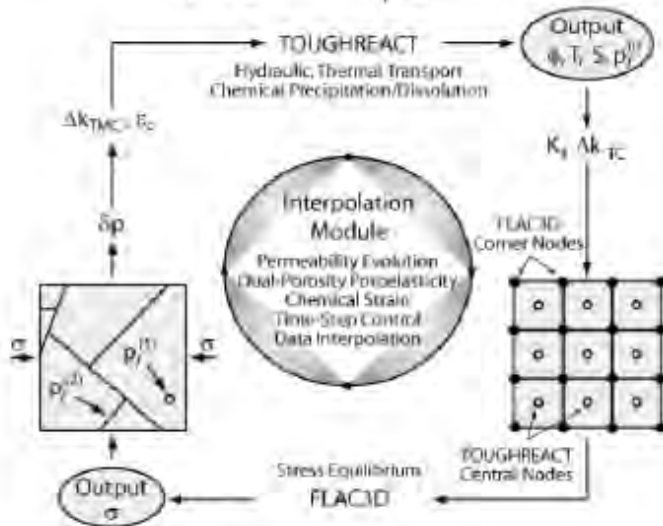
THMC-S - Linked codes

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

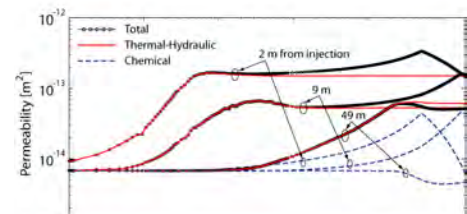
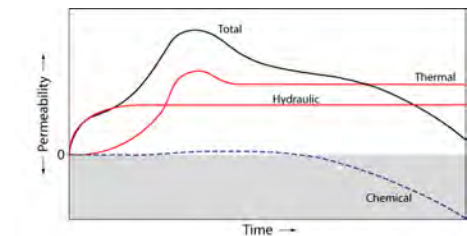
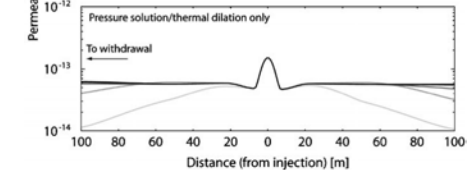
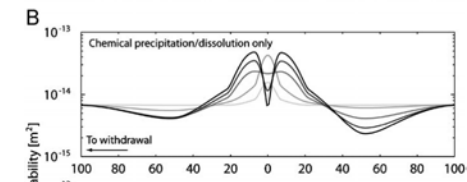
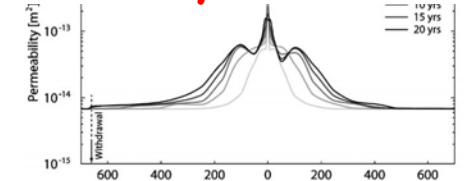
$$\frac{\partial M}{\partial t} = -\nabla \cdot \mathbf{F} + q$$

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

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

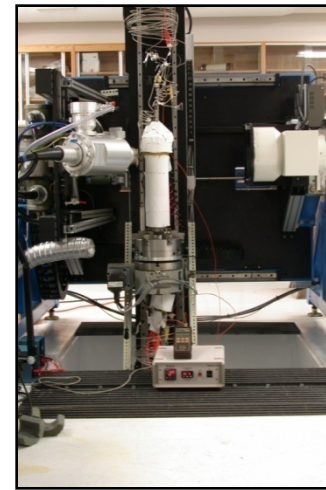
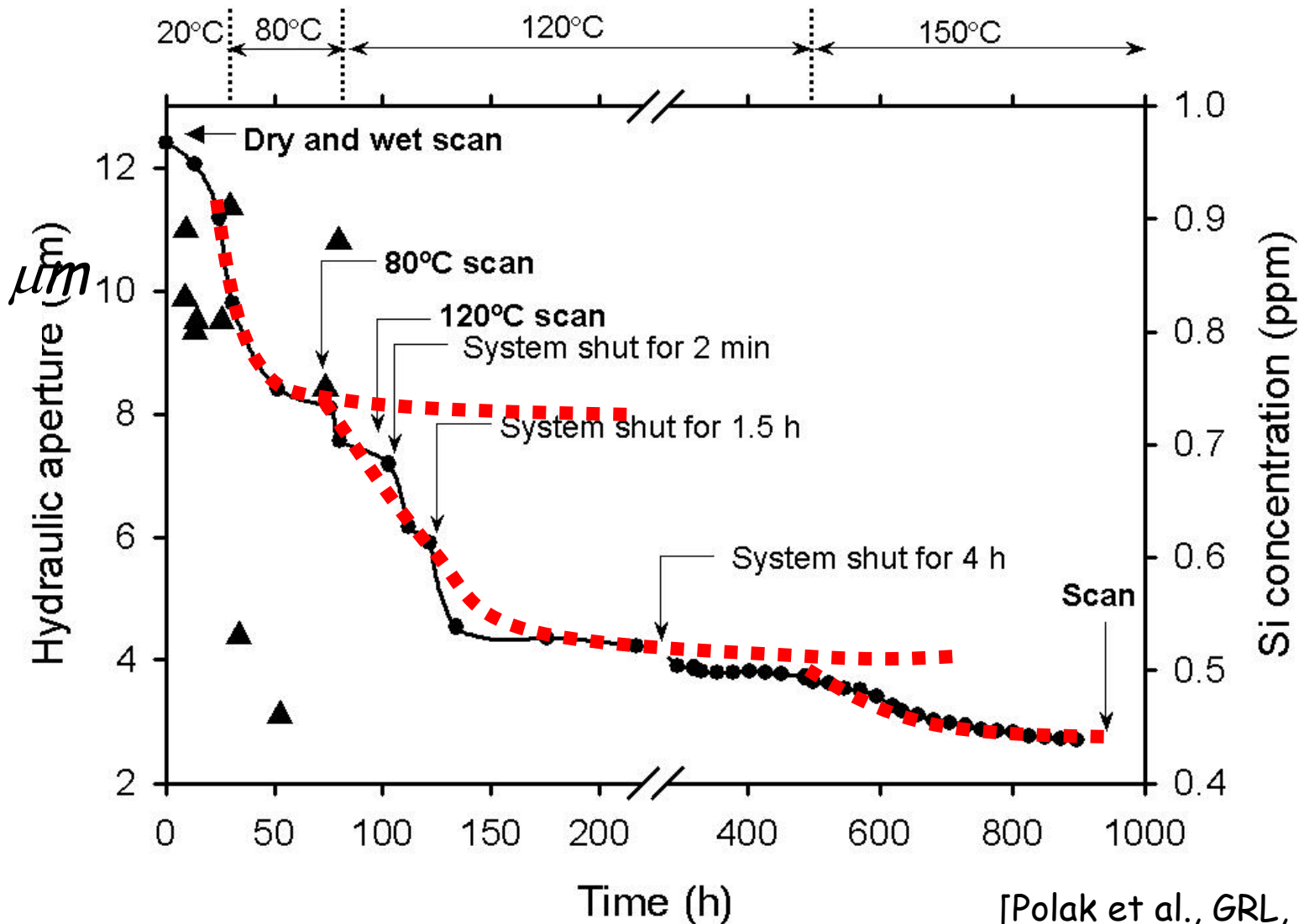


Spatial Permeability Evolution



Temporal Permeability Evolution

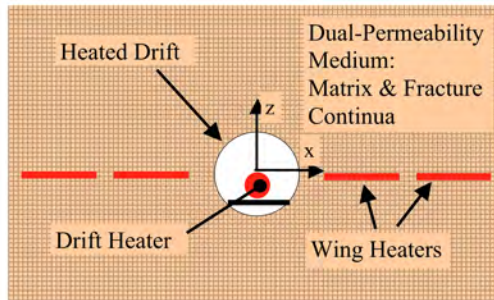
Enigmatic Response of Fractures - Present at Field Scale?



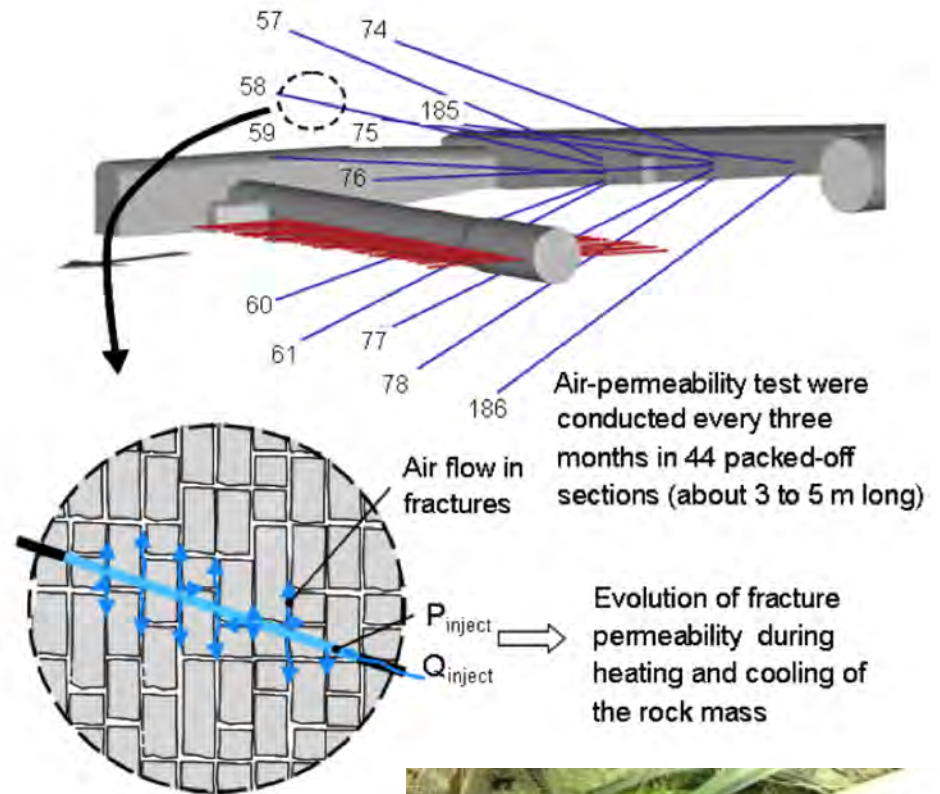
[Polak et al., GRL, 2003]

Radioactive Waste Disposal - Modeling Approach

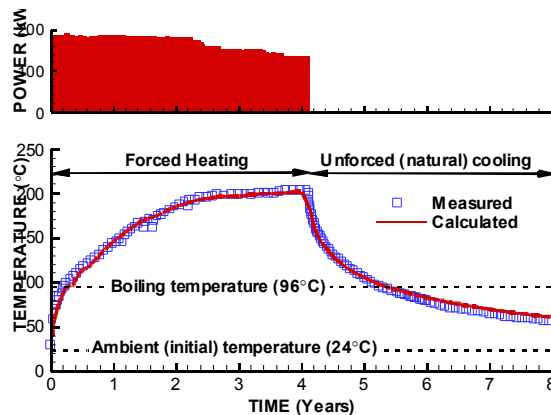
2-D Geometry



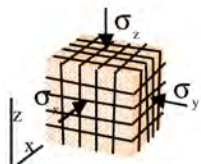
DST Geometry



Thermal Response



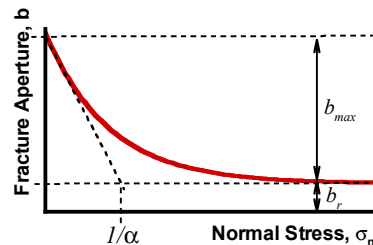
Fracture Constitutive Behavior



$$k_x = k_x(\sigma_y, \sigma_z)$$

$$k_y = k_y(\sigma_x, \sigma_z)$$

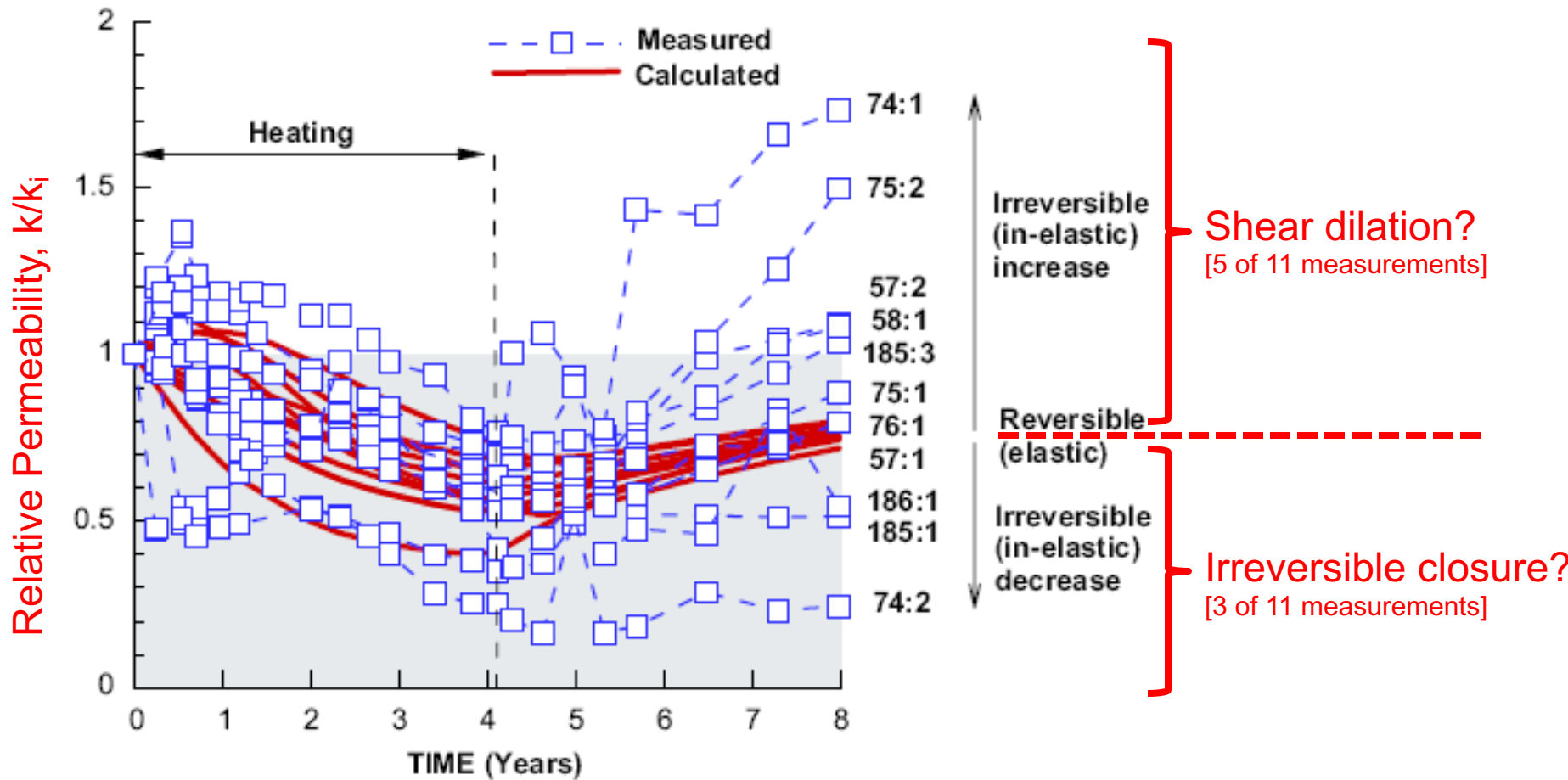
$$k_z = k_z(\sigma_x, \sigma_y)$$



[Rutqvist et al., 2008]



Ensemble Drift Scale Test Results



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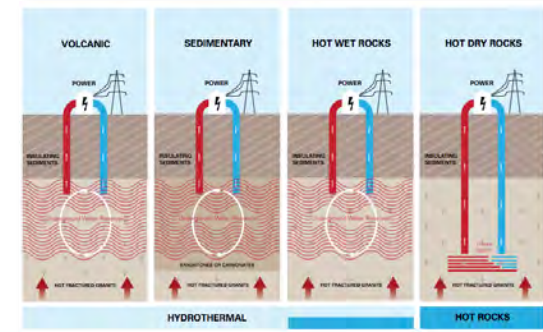
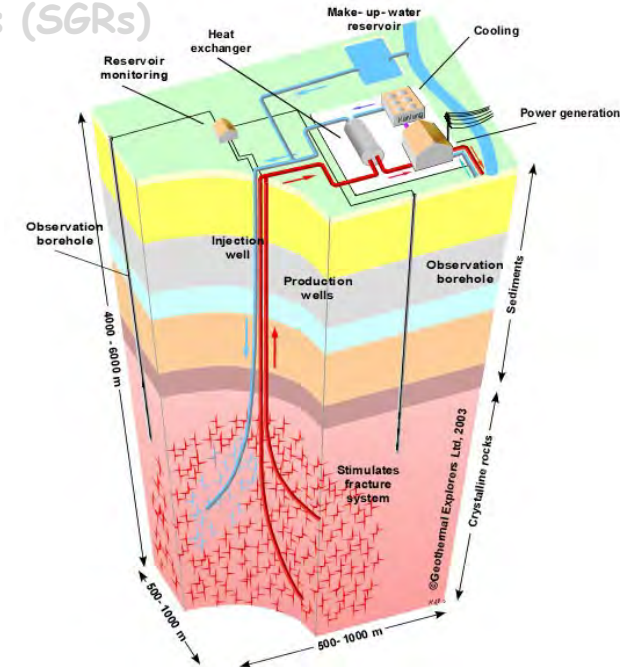
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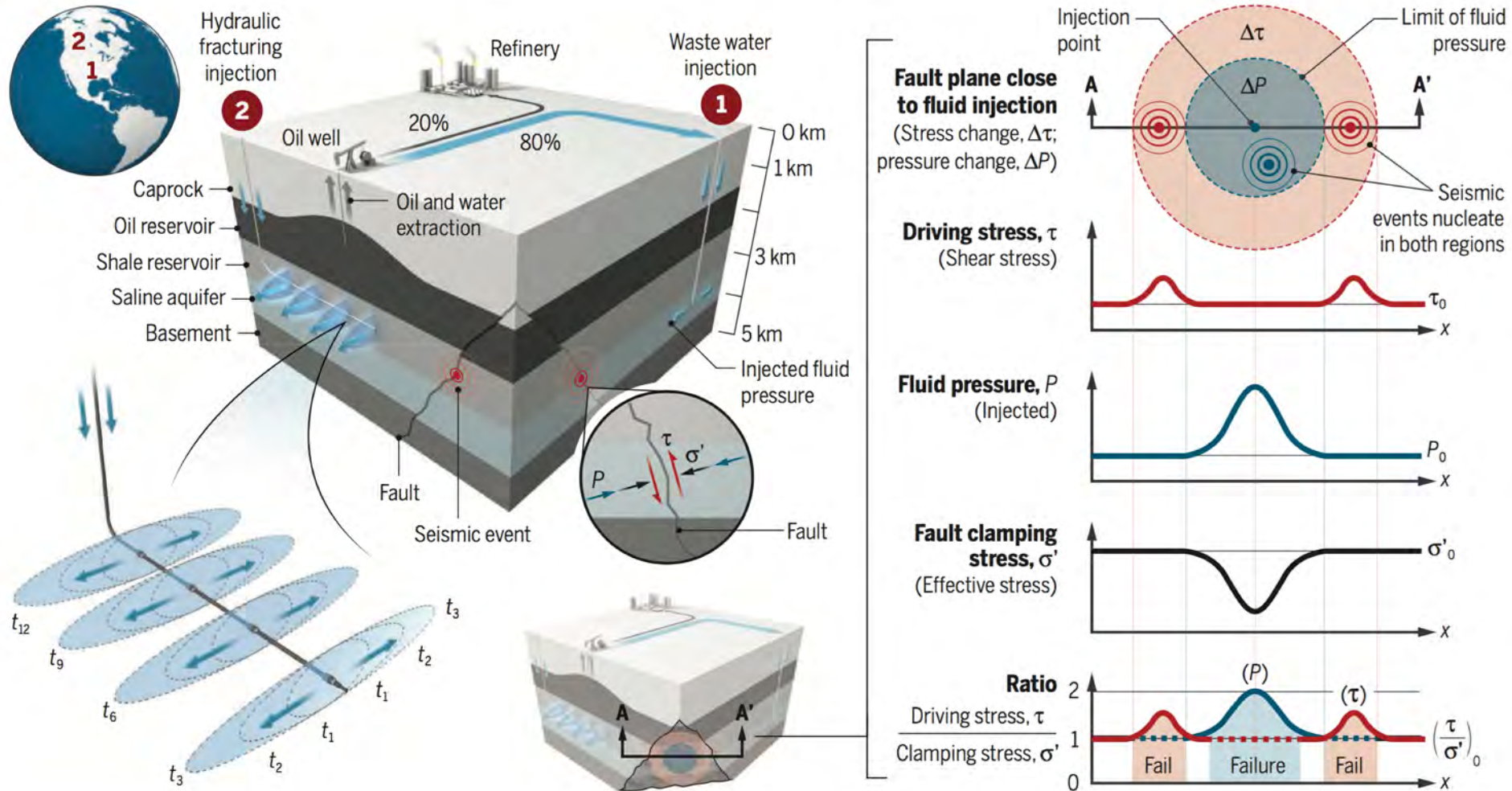
Permeability scaling - Newberry Project

US (DoE) Road Map

Summary



Induced Seismicity

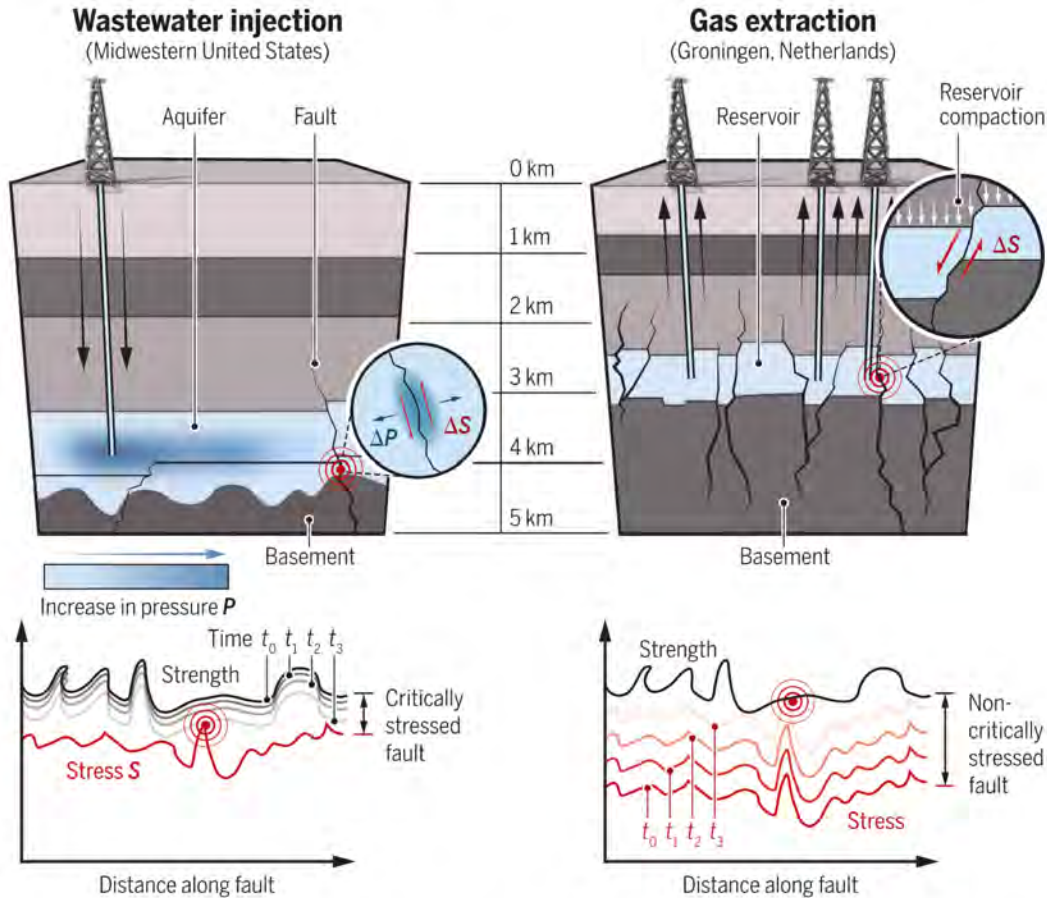


[Elsworth et al., Science, 2016]

Injection and Production Mechanisms of Induced Seismicity

Mechanisms of induced seismicity

Both wastewater injection and gas extraction can cause induced earthquakes. Detailed observations from the midwestern United States and Groningen, Netherlands, show that in both cases, preexisting conditions in Earth's crust are of central importance.



Injection of wastewater leads to a nonuniform pressure front. When the pressure front hits a critically stressed fault, an earthquake is triggered. Only a small strength decrease is needed to trigger an event.

Gas extraction leads to rock compaction, causing a buildup of stress. Sufficient shear stress is necessary to cause the initially noncritically stressed fault to fail, causing an earthquake.



[Candela et al., Science, 2018]

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

EGS Stimulation Related?

Anatomy of the EQ

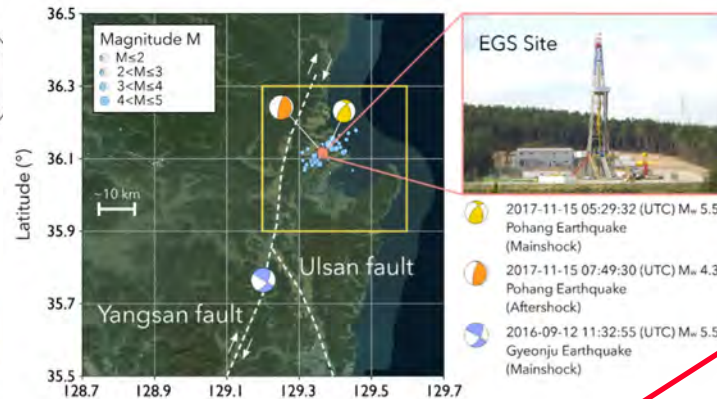
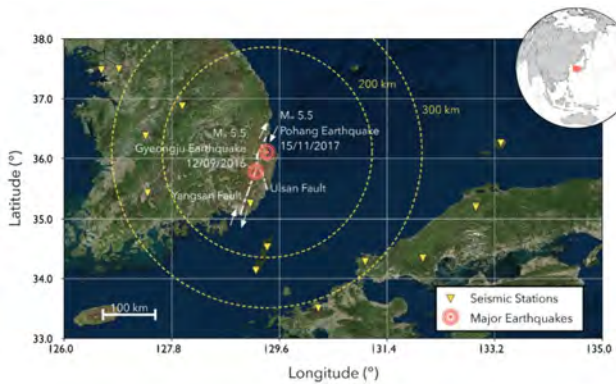
15th century EQs Mw~7

Mw<5 since instrumental recording in 1903

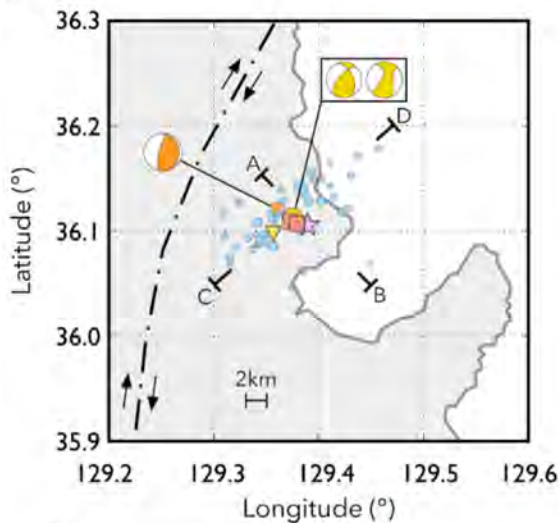
Mw~5.5 ~30km south of EGS

Mw~5.5 Pohang ~4km depth

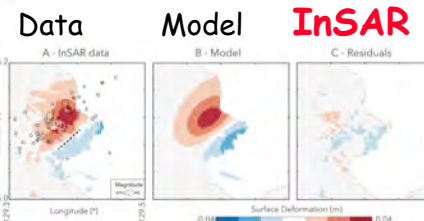
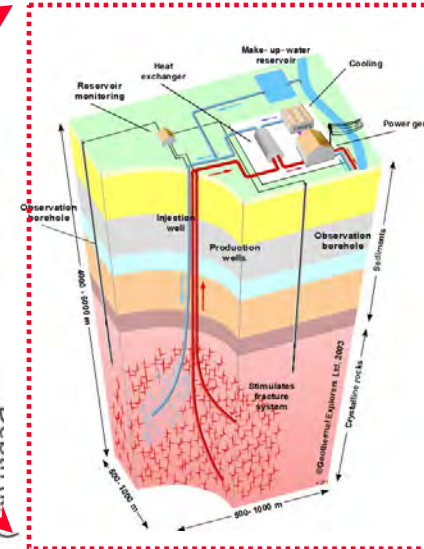
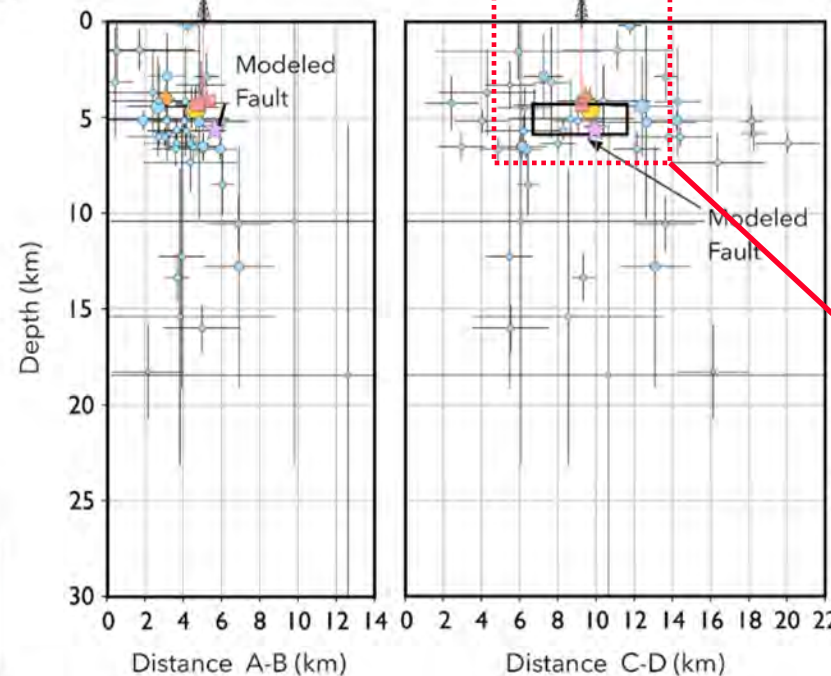
Same strike-slip fault



- 2017-11-15 05:29:32 (UTC) Mw 5.5 Pohang Earthquake (Mainshock)
- 2017-11-15 07:49:30 (UTC) Mw 4.3 Pohang Earthquake (Aftershock)
- 2016-09-12 11:32:55 (UTC) Mw 5.5 Gyeongju Earthquake (Mainshock)

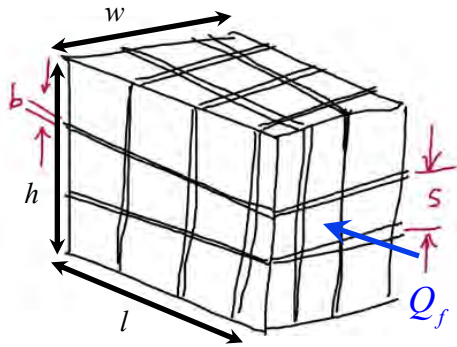


- Magnitude M
- M≤2
 - 2<M≤3
 - 3<M≤4
 - 4<M≤5
 - M>5
- Accelerometer
- Injection well
- Induced event 15/04/2017



[Grigoli et al., Science, 2018]

Thermal Drawdown and Late-Time Seismicity



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

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

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

EGS:

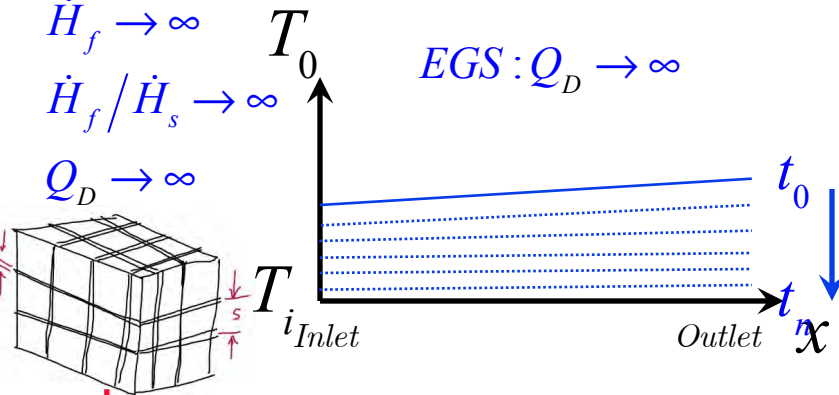
$$\dot{H}_f \rightarrow \infty$$

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

$$Q_D \rightarrow \infty$$

In-Reservoir Water Temperature Distributions:

$$EGS: Q_D \rightarrow \infty$$



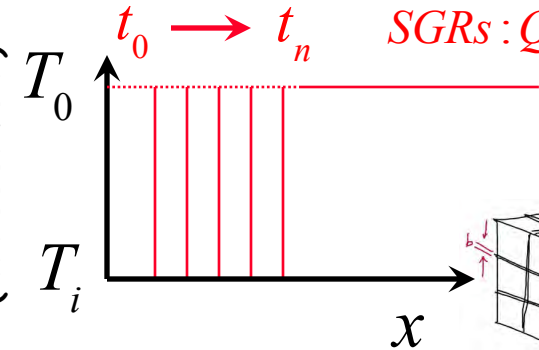
SGRs:

$$\dot{H}_s \rightarrow 0$$

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

$$Q_D \rightarrow 0$$

Rock Temp
(in reservoir)



Thermal Output:

Water Temp
(at outlet)



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

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

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

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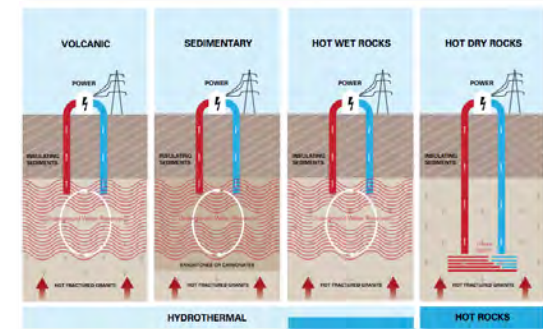
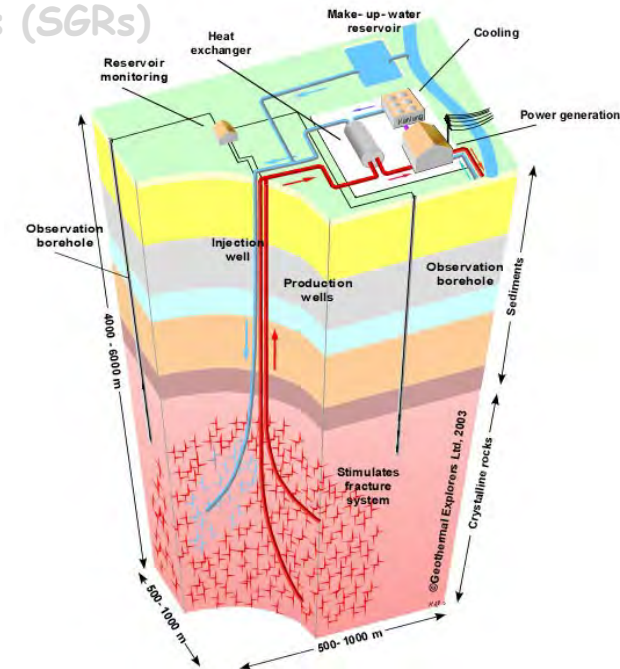
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US (DoE) Road Map

Summary

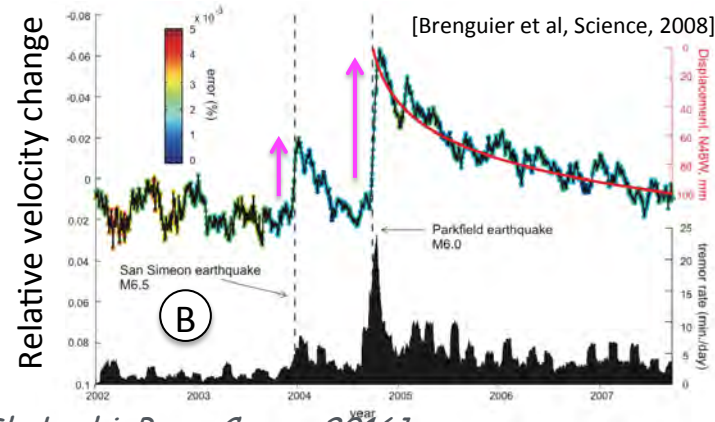
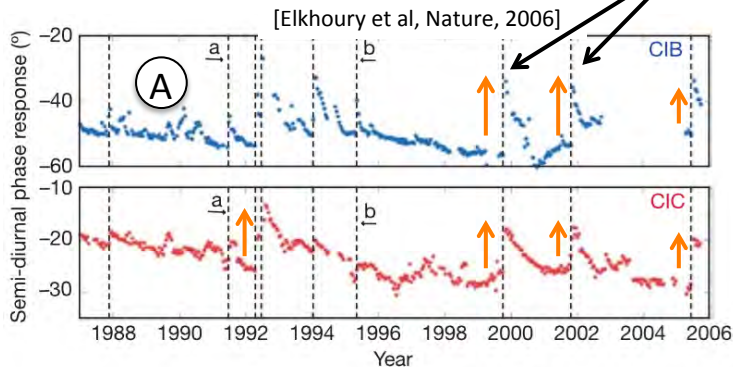


Permeability and Elastic Softening

Field-scale

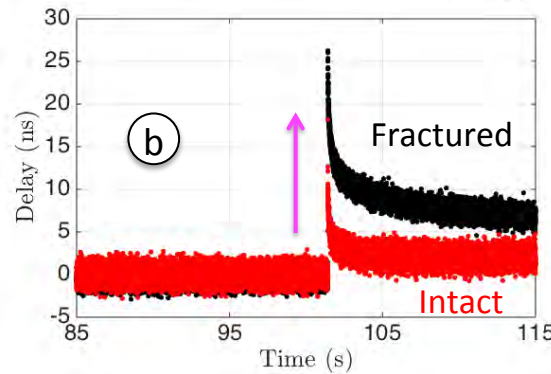
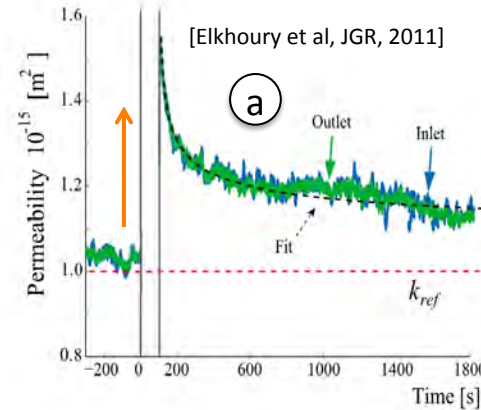


earthquakes



[Shokouhi, Pers. Comm. 2016]

Laboratory-scale



During the Seismic Cycle

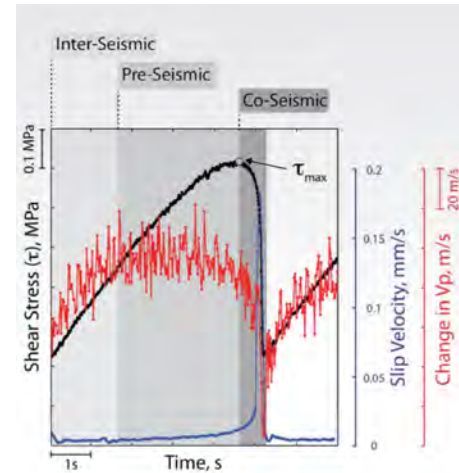
Seismic waves trigger transient changes in elastic properties

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]

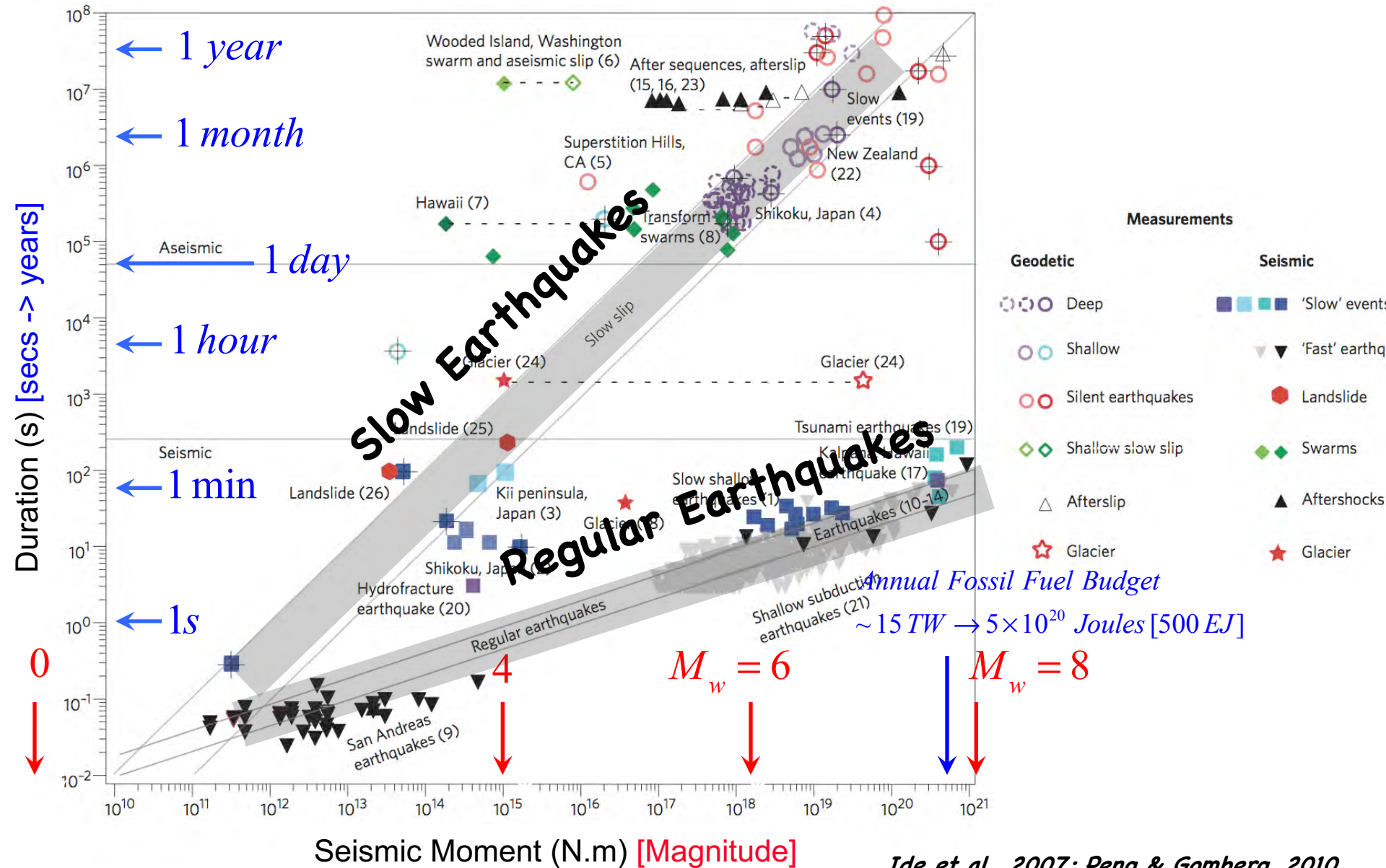
Permeability

Permeability

Elastic Softening

Elastic Softening

Subduction Zone Megathrusts and the Full Spectrum of Fault Slip Behavior



Brittle Friction Mechanics, Stick-slip

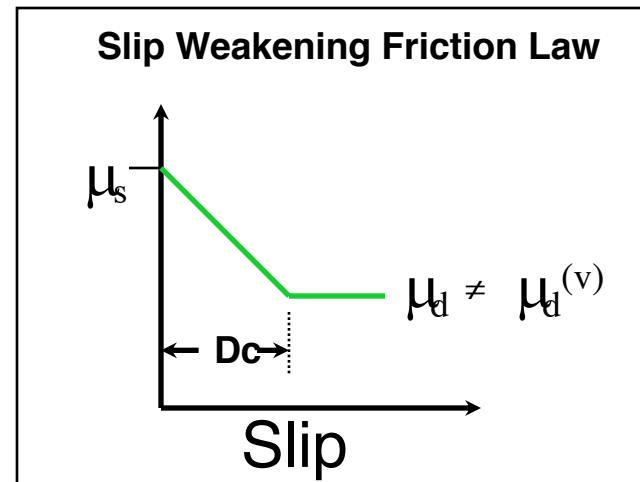
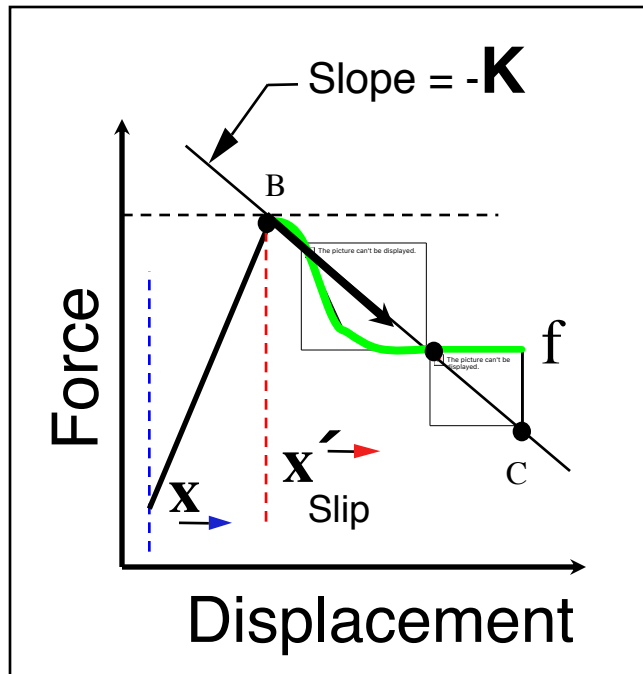
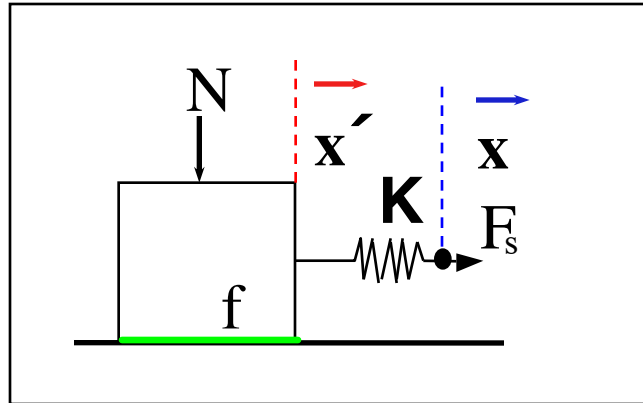
Stick-slip (unstable) versus stable shear

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.*

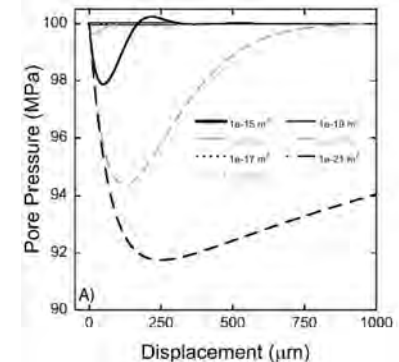
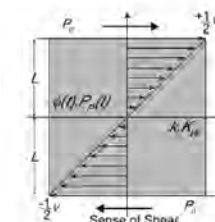
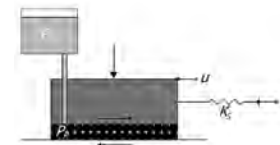
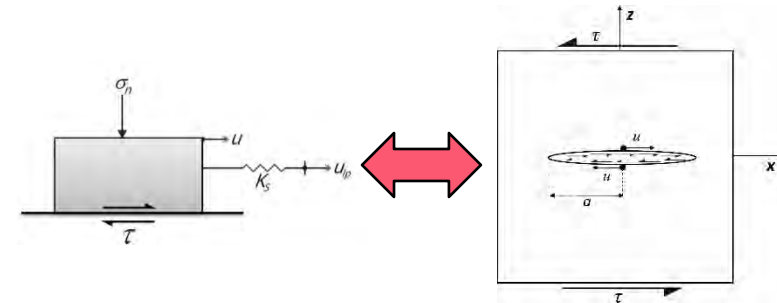
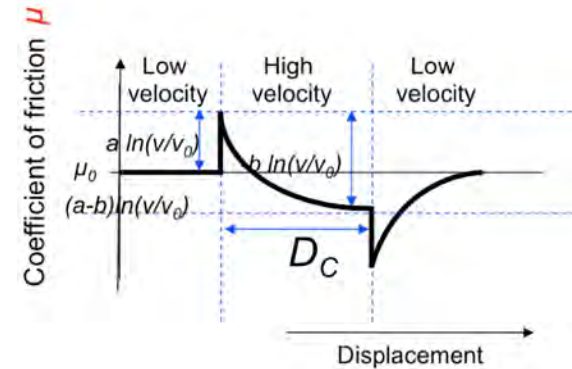
$$a - b < 0$$

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

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

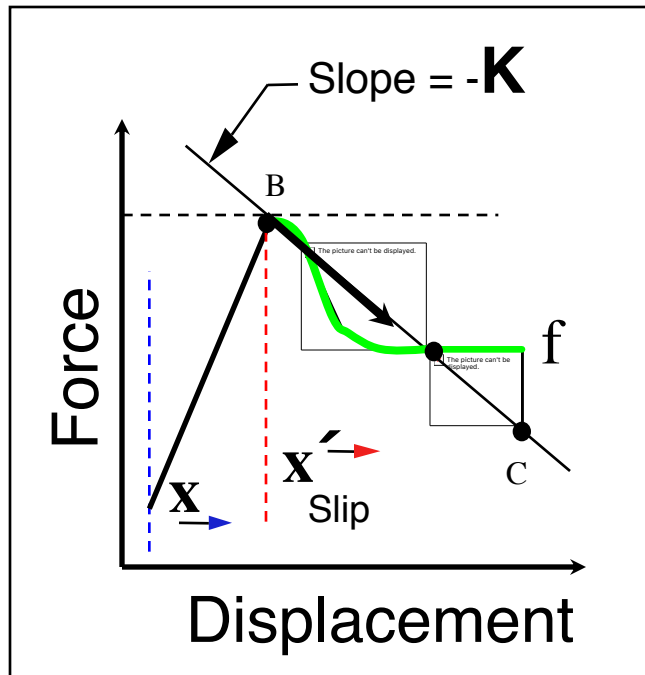
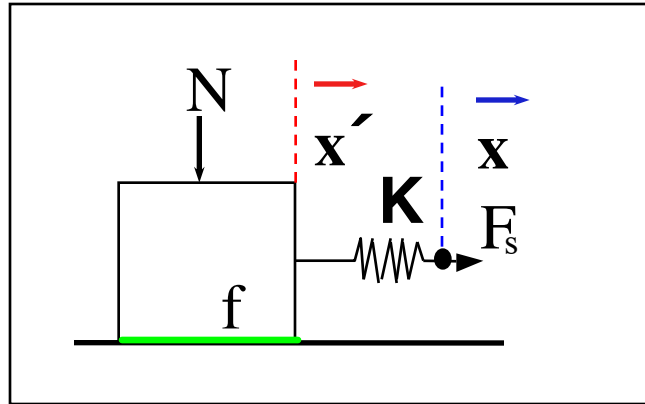
4. That effective normal stresses evolve that do not dilatantly harden the fault and arrest it via the failure criterion of #1 - *i.e.*

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



Seismic - Aseismic Transition

Full Spectrum of Slip Behaviors



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

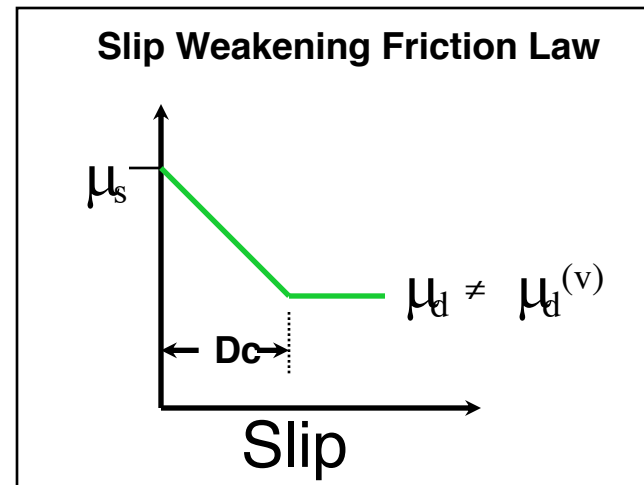
Promote Aseismic Response: $K_c < K$

Otherwise Seismic Slip if: $K_c > K$

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

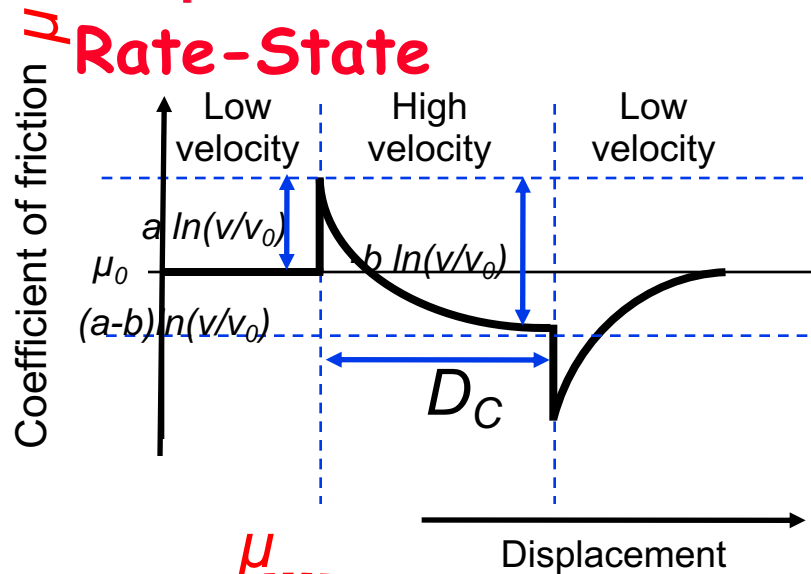
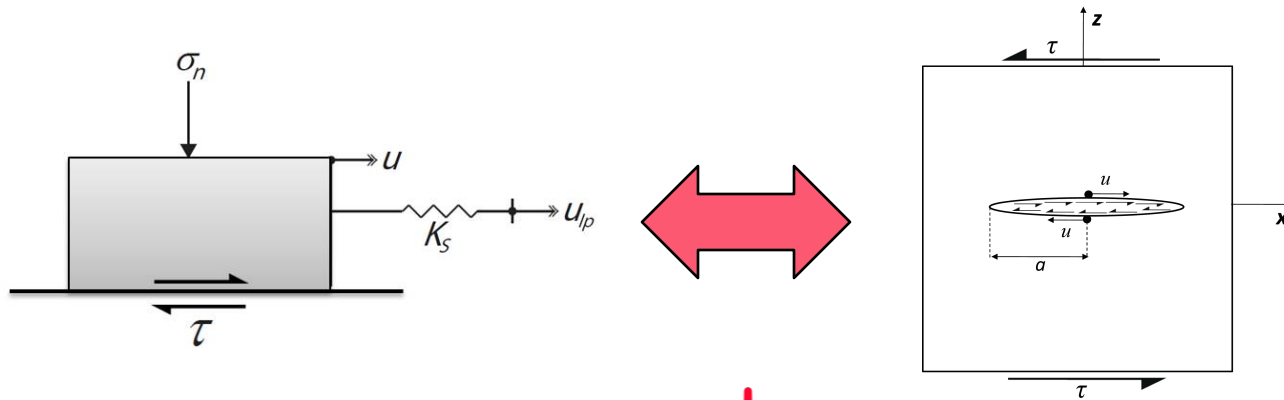
Decrease: $D_c; G$

Recurrence Requires: *Healing*

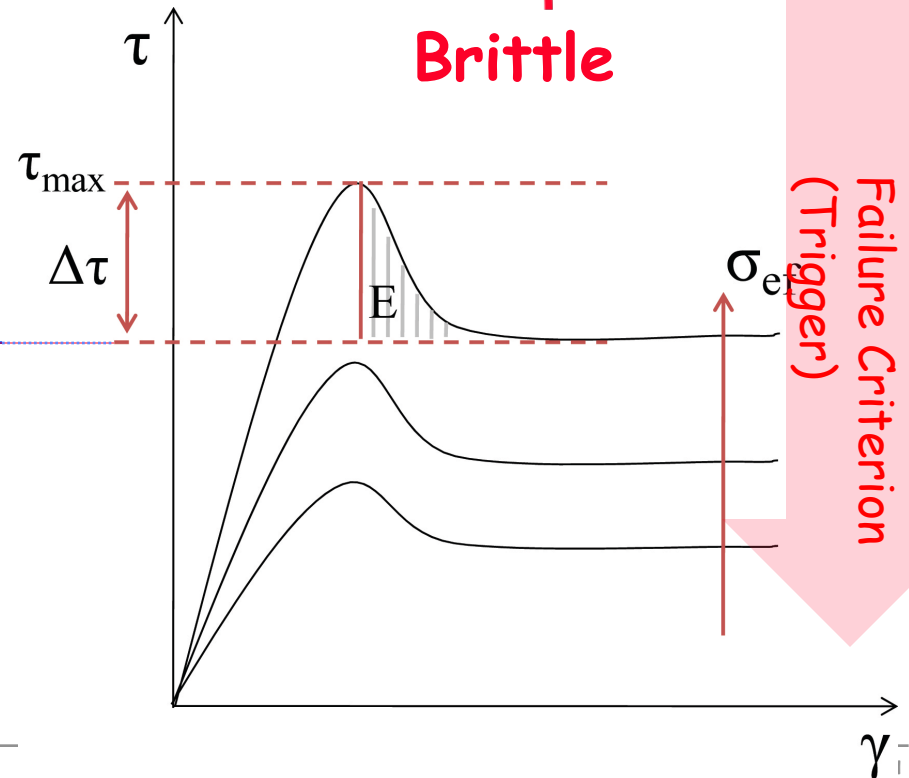


[Adapted from C.J. Marone, Pers. Comm., 2017]

Approaches - Rate-State versus Brittle Behavior

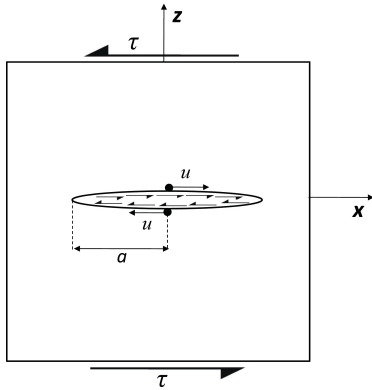


$$\tau = \left[\mu_0 + a \ln \left(\frac{v}{v_0} \right) + b \ln \left(\frac{v_0 \theta}{D_C} \right) \right] \sigma_{ef}$$

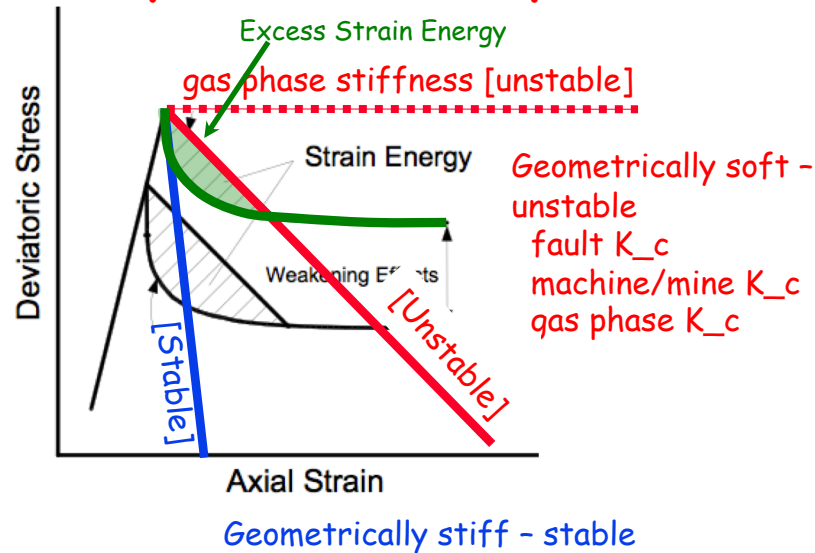


Instability Threshold - Penny-Shaped Crack

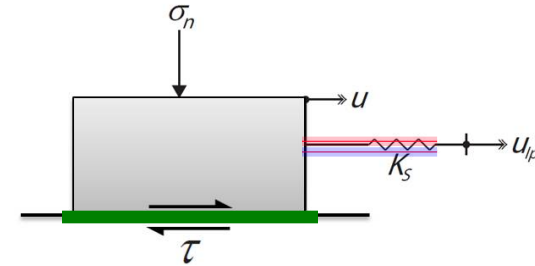
System Stiffness



System-Fault Response



Fault Stiffness



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

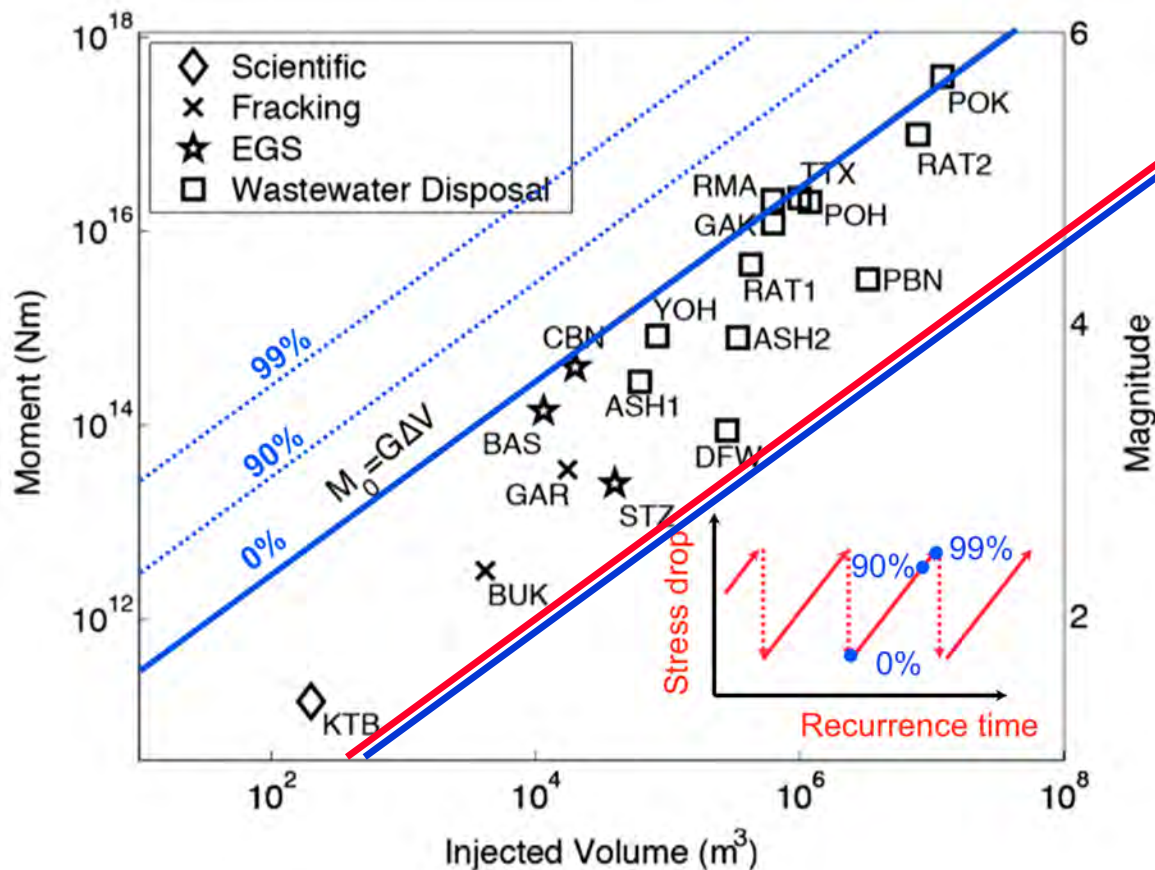
$$\sim 5 \frac{G}{2a} < \frac{(b-a)\sigma'}{D_c} = K_c \left\{ \begin{array}{l} \nu = 0.25 \\ \mu = 0.6 \\ \text{inertia negligible} \end{array} \right.$$

Instability Threshold - Penny-Shaped Crack

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

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

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

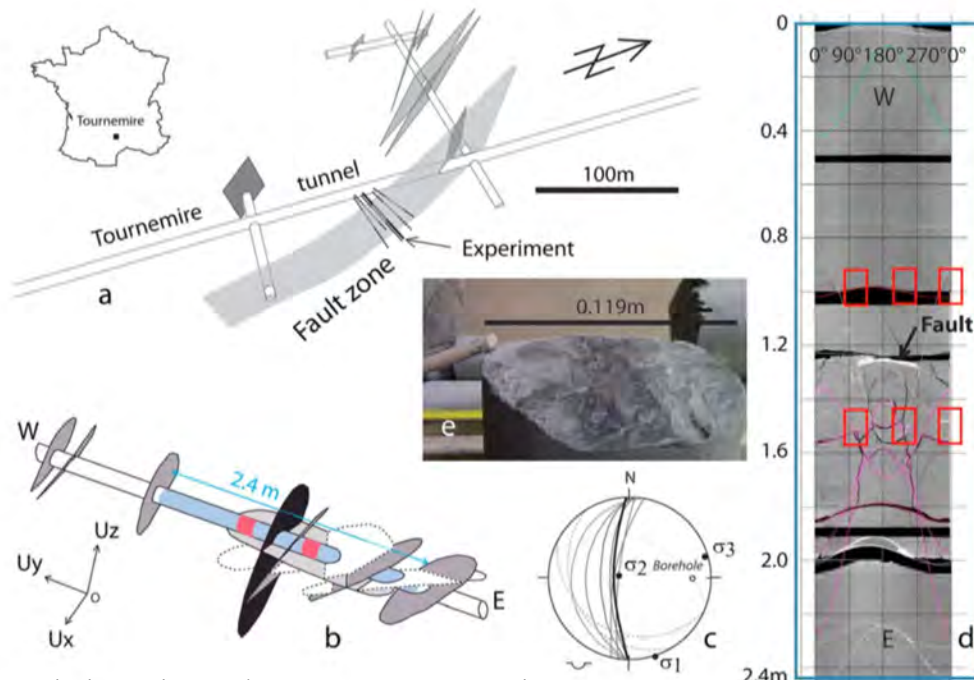


Unstable?
Stable?

Complex Episodic Response as Seals and Pathways

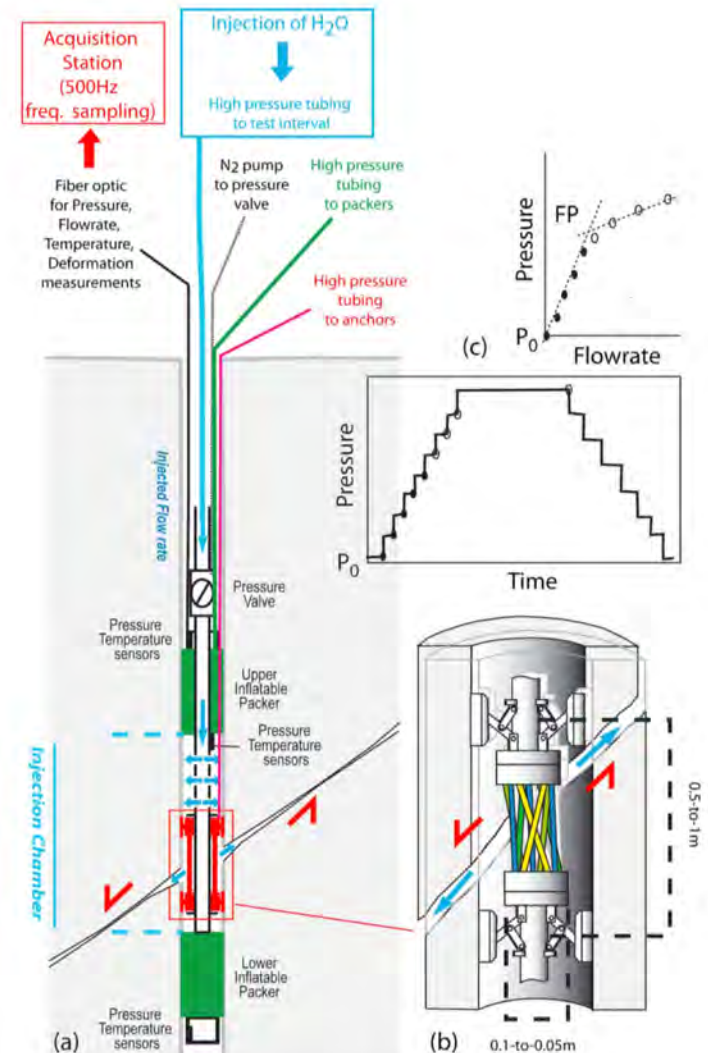
Mt. Terri Fault "Window"

Tournemire URL Fault "Window"

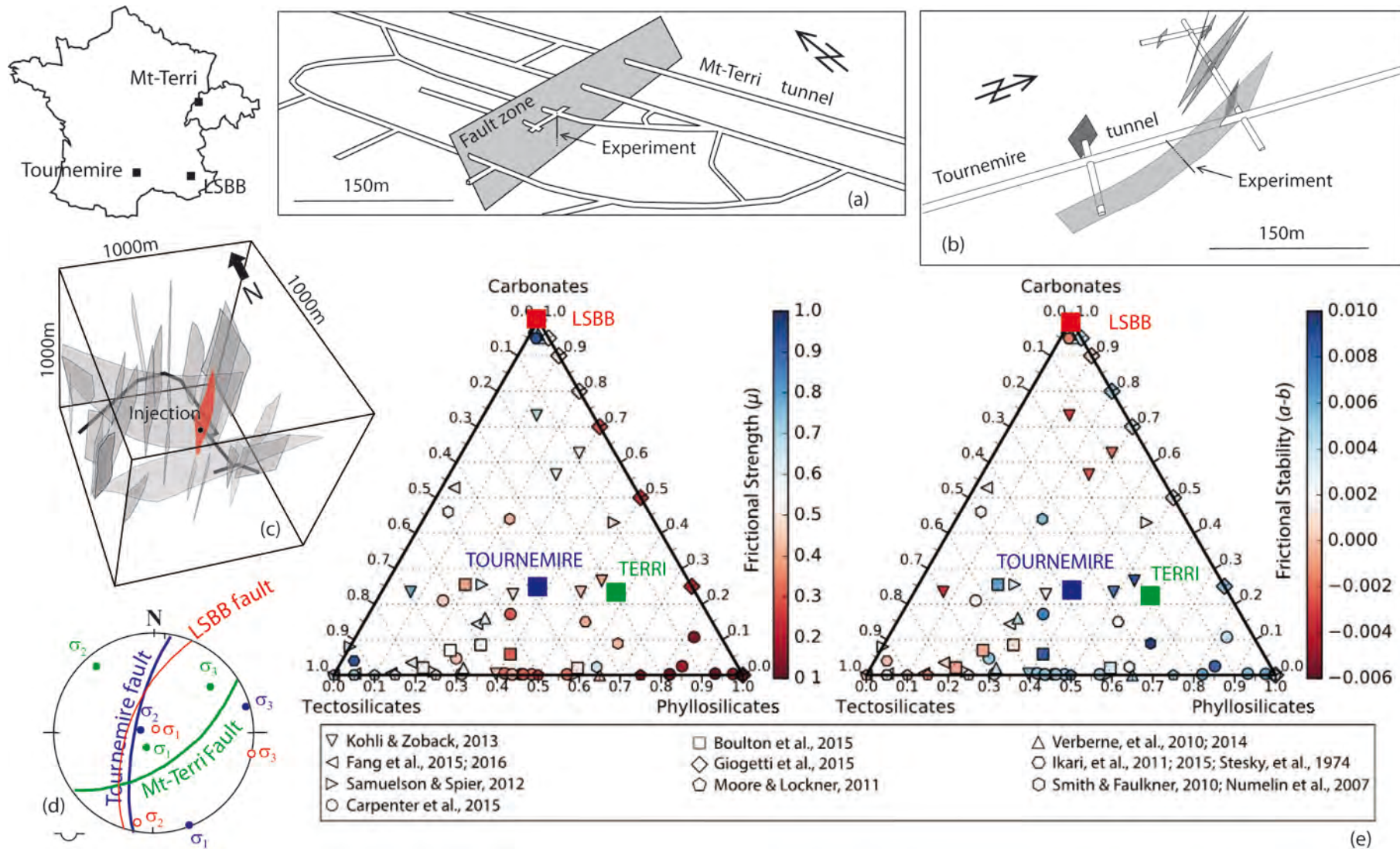


[e.g. Guglielmi, Elsworth, Cappa, Henri, et al., JGR, 2015]

HM Coupling



Mineralogical and Fault-Slip Style Controls



Aseismic-Seismic Transition



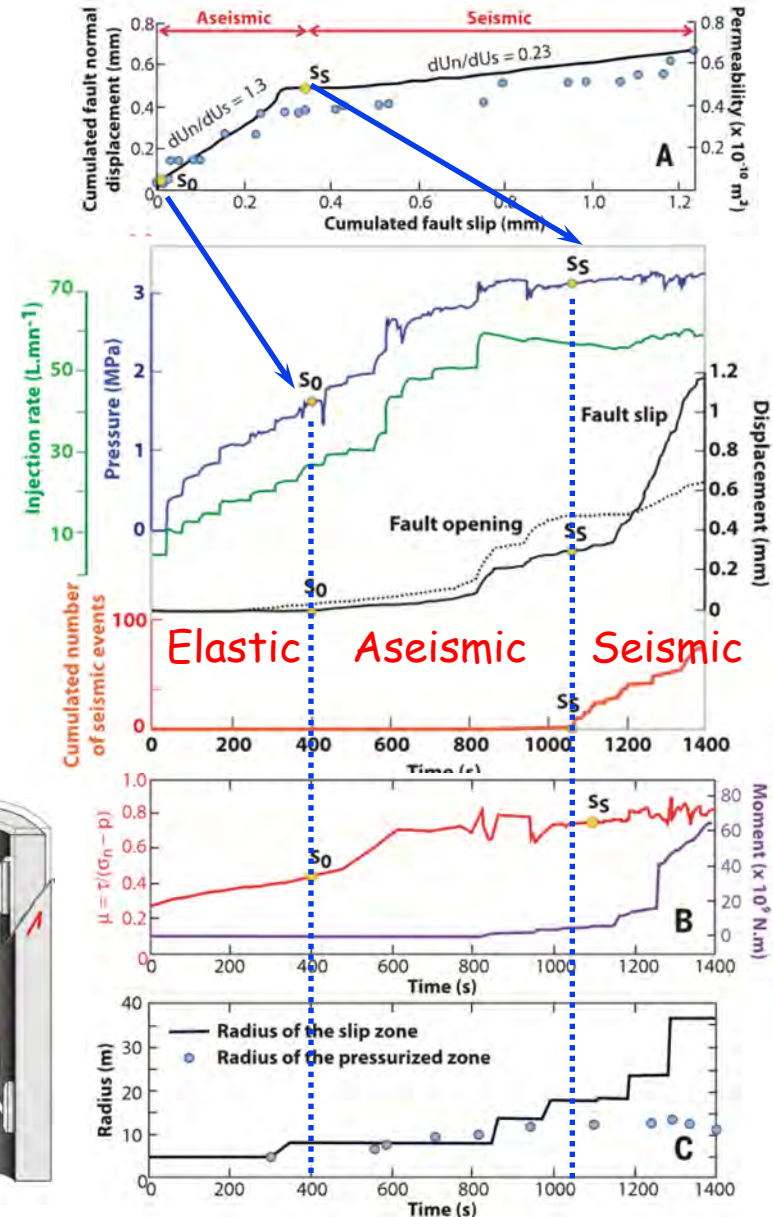
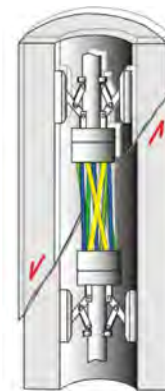
Scale Dependence - the need for URLS and constrained experimentation at meso scale.

Roles of:

Pressurization ($\sigma_n' \rightarrow 0$)

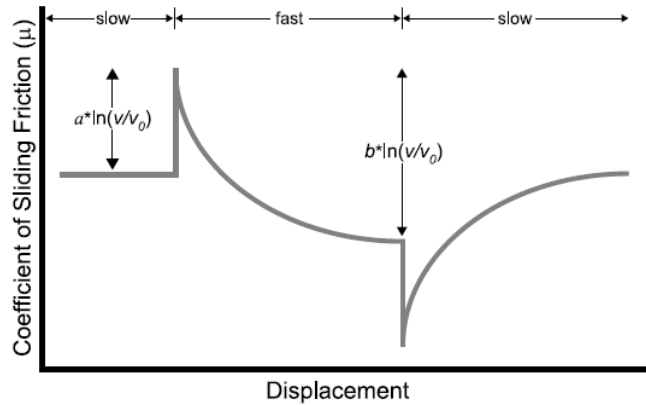
Deformation ahead of the fluid front
Mineralogical controls

[Guglielmi et al., Science, 2015]

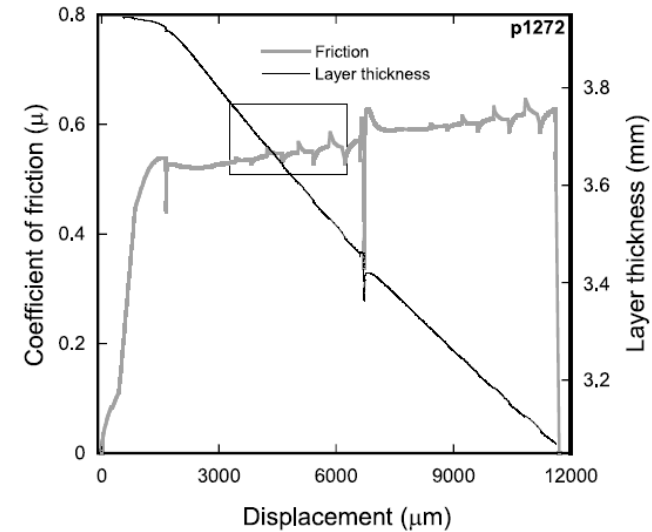


Rate-State Friction [1]

Velocity Steps



Multiple Velocity Steps



R-S Friction

$$\left. \begin{aligned} \mu &= \mu_0 + a \ln\left(\frac{v}{v_0}\right) + b \ln\left(\frac{v_0 \theta}{D_C}\right) \\ \frac{d\theta}{dt} &= 1 - \frac{v\theta}{D_C} \quad (\text{Dieterich Evolution}) \\ \frac{d\theta}{dt} &= \frac{-v\theta}{D_C} \ln\left(\frac{v\theta}{D_C}\right) \quad (\text{Ruina Evolution}) \end{aligned} \right\}$$

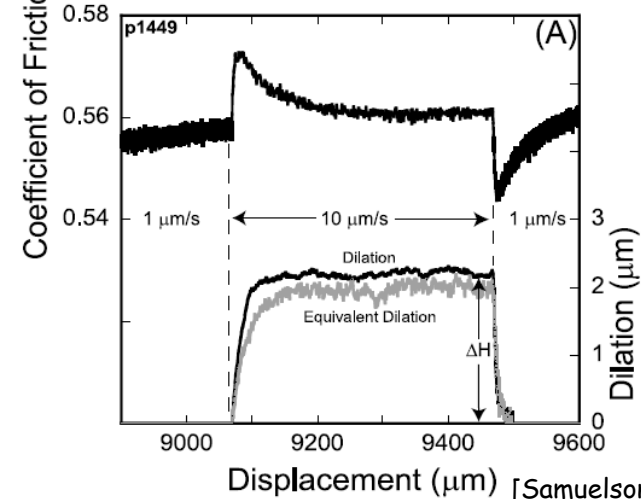
Dilation

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

Permeability Evolution

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

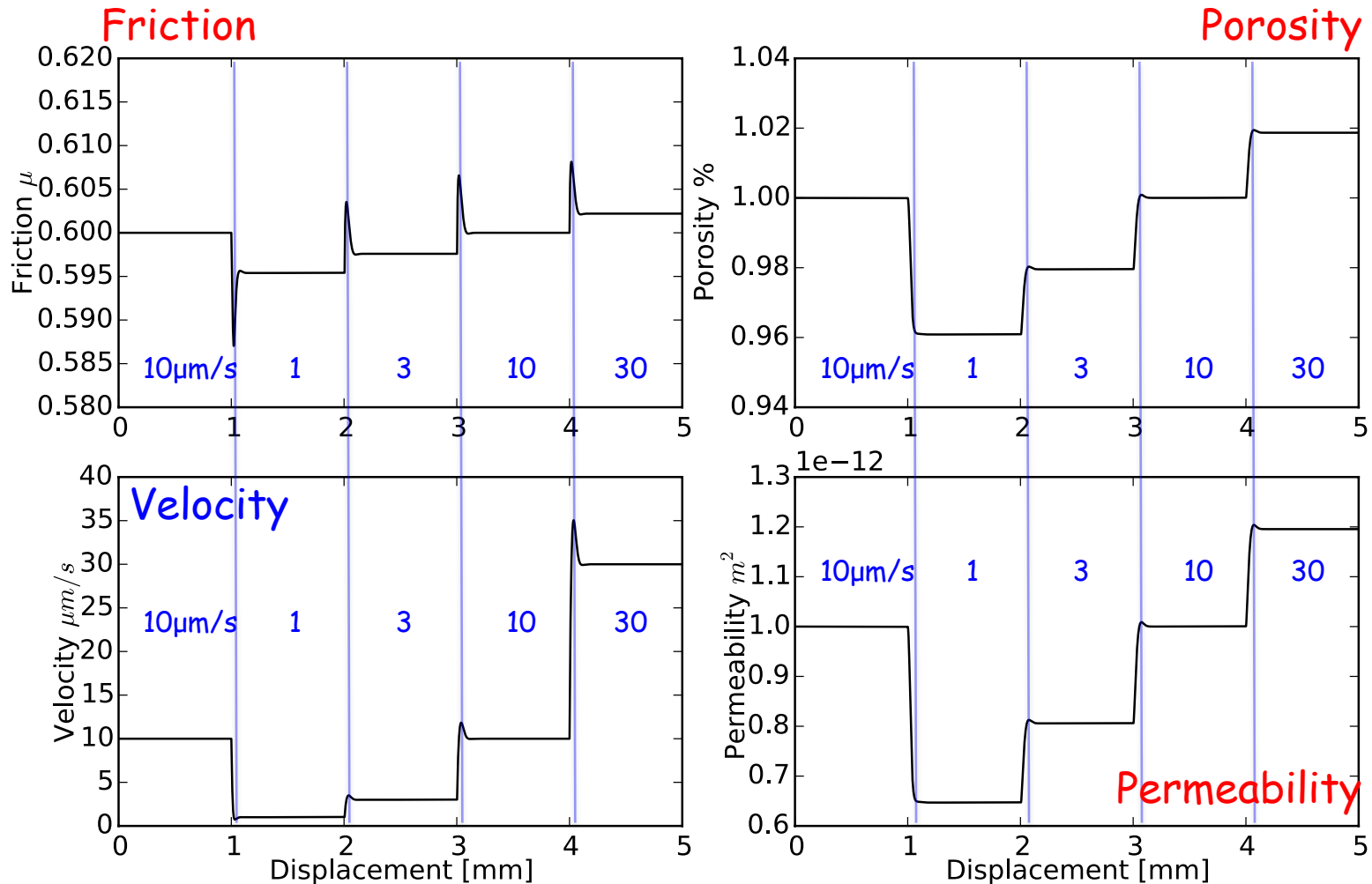
Single Velocity Step



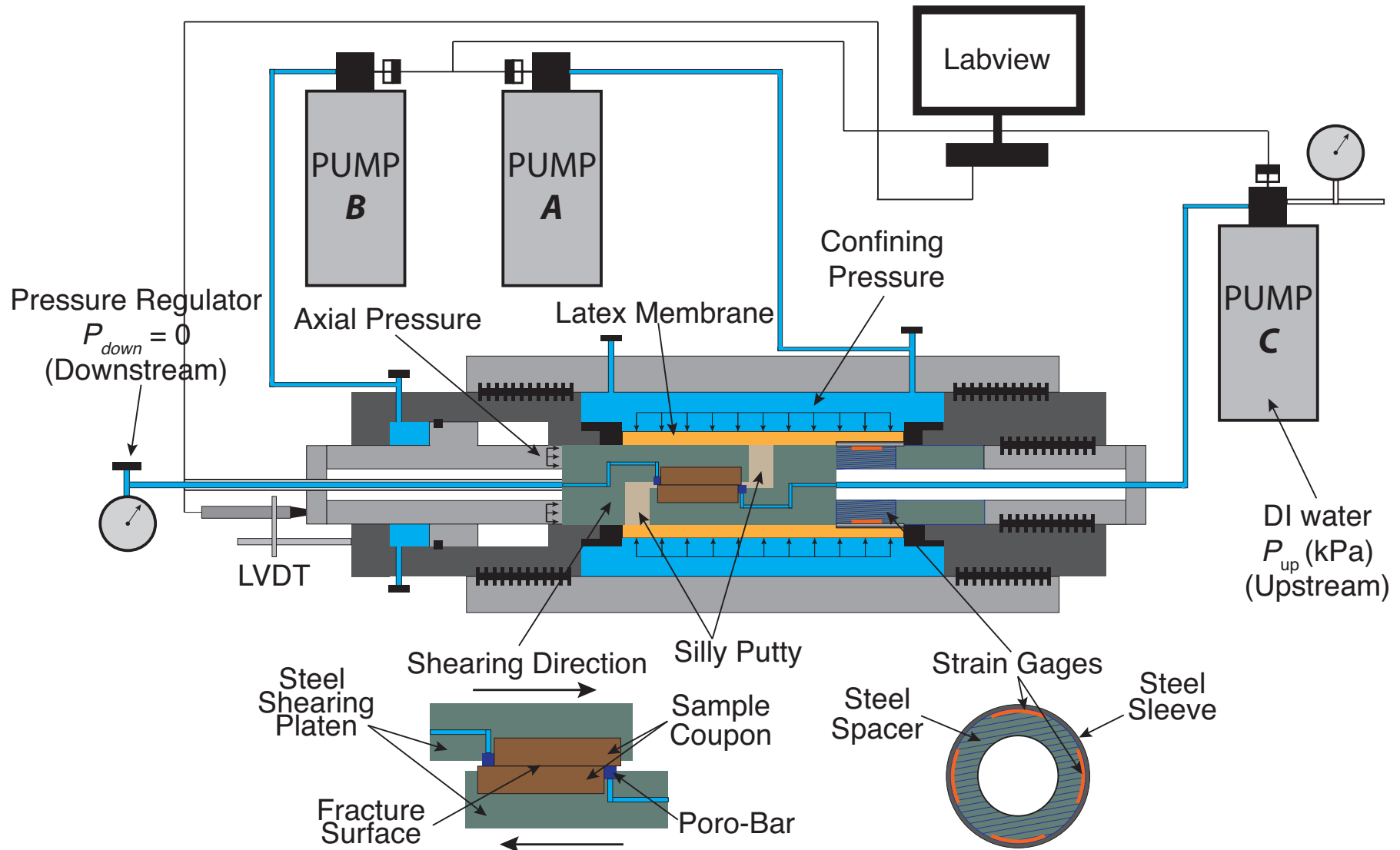
Rational Linkages: Rate-State Friction, Porosity and Permeability

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

High Stiffness, positive dilatational coefficient

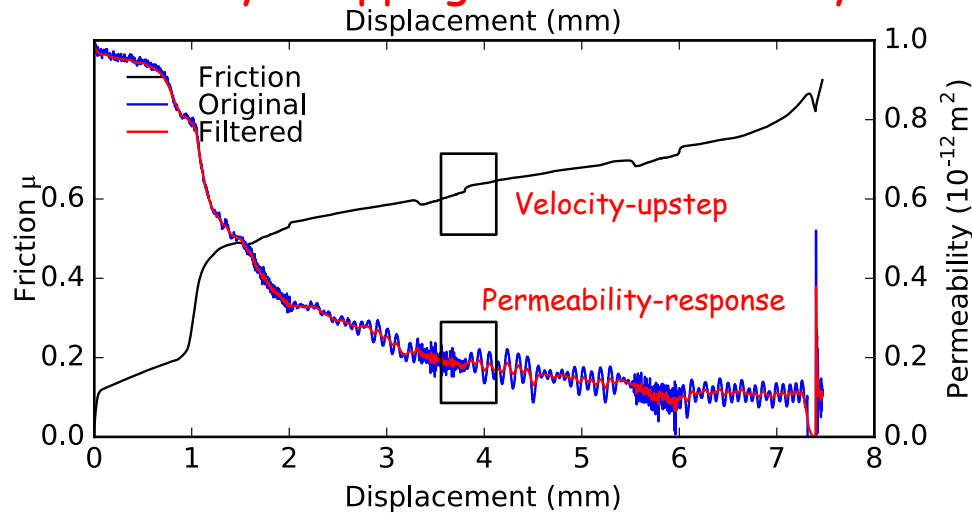


Frictional Stability-Permeability Experiments

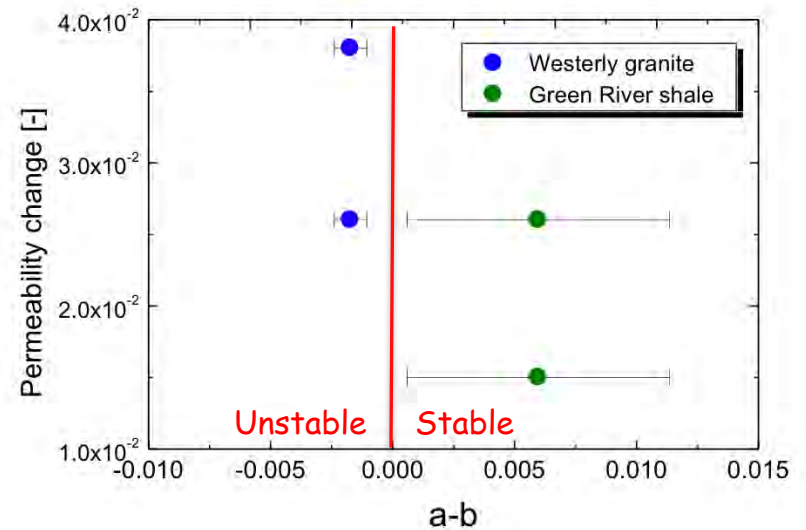


Frictional Stability-Permeability Observations

Velocity-stepping and Permeability

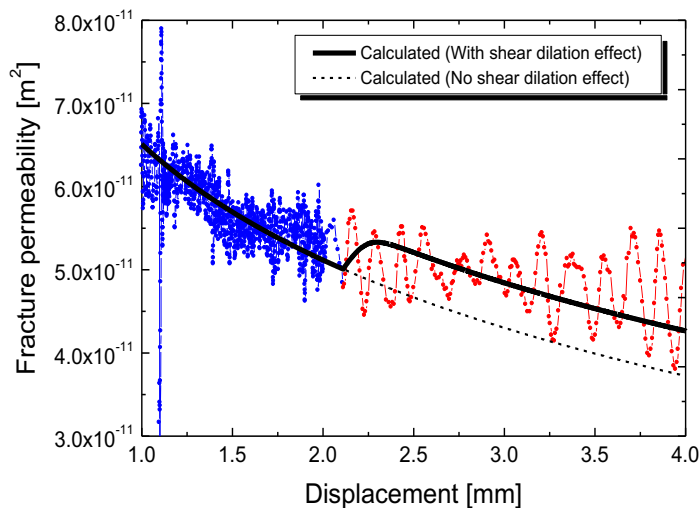


Permeability-Frictional Stability

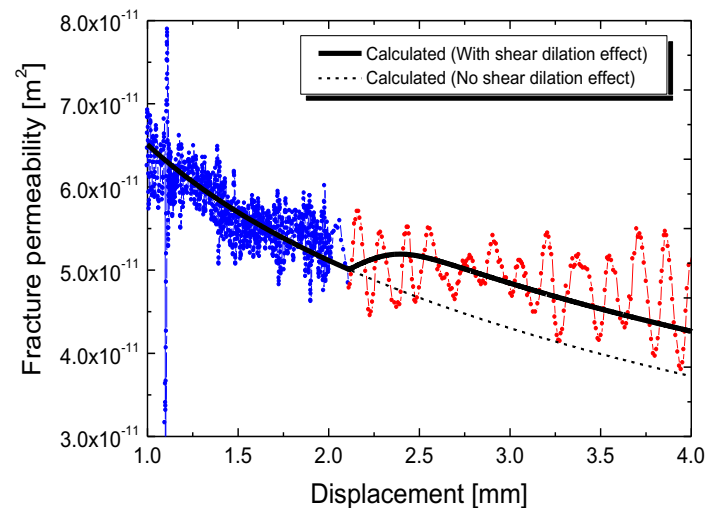


Permeability Evolution

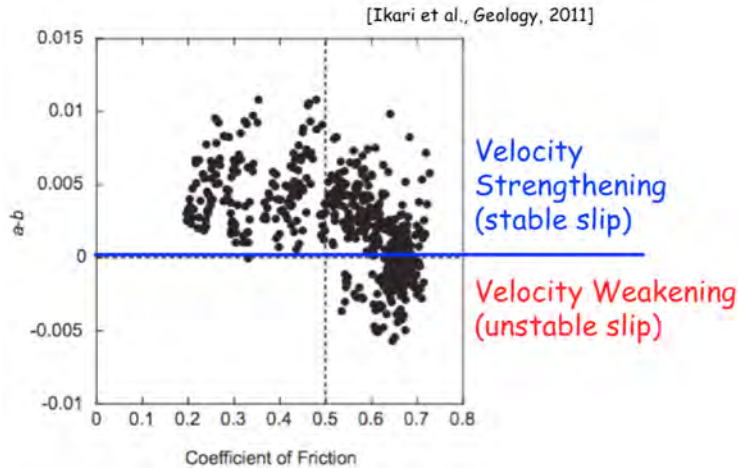
$\varepsilon=0.0224$ ($n=2$), $D_c=50$ [μm]



$\varepsilon=0.0224$ ($n=2$), $D_c=100$ [μm]

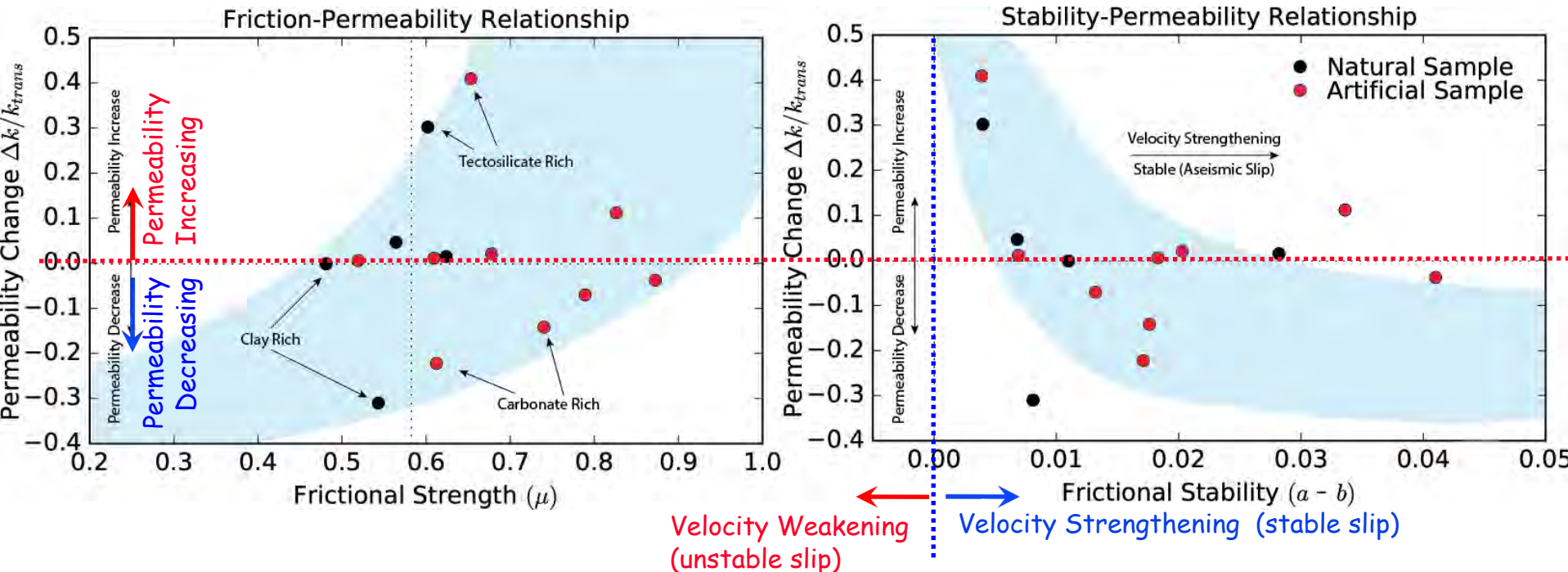


Nascent Friction-Stability-Permeability Relationships



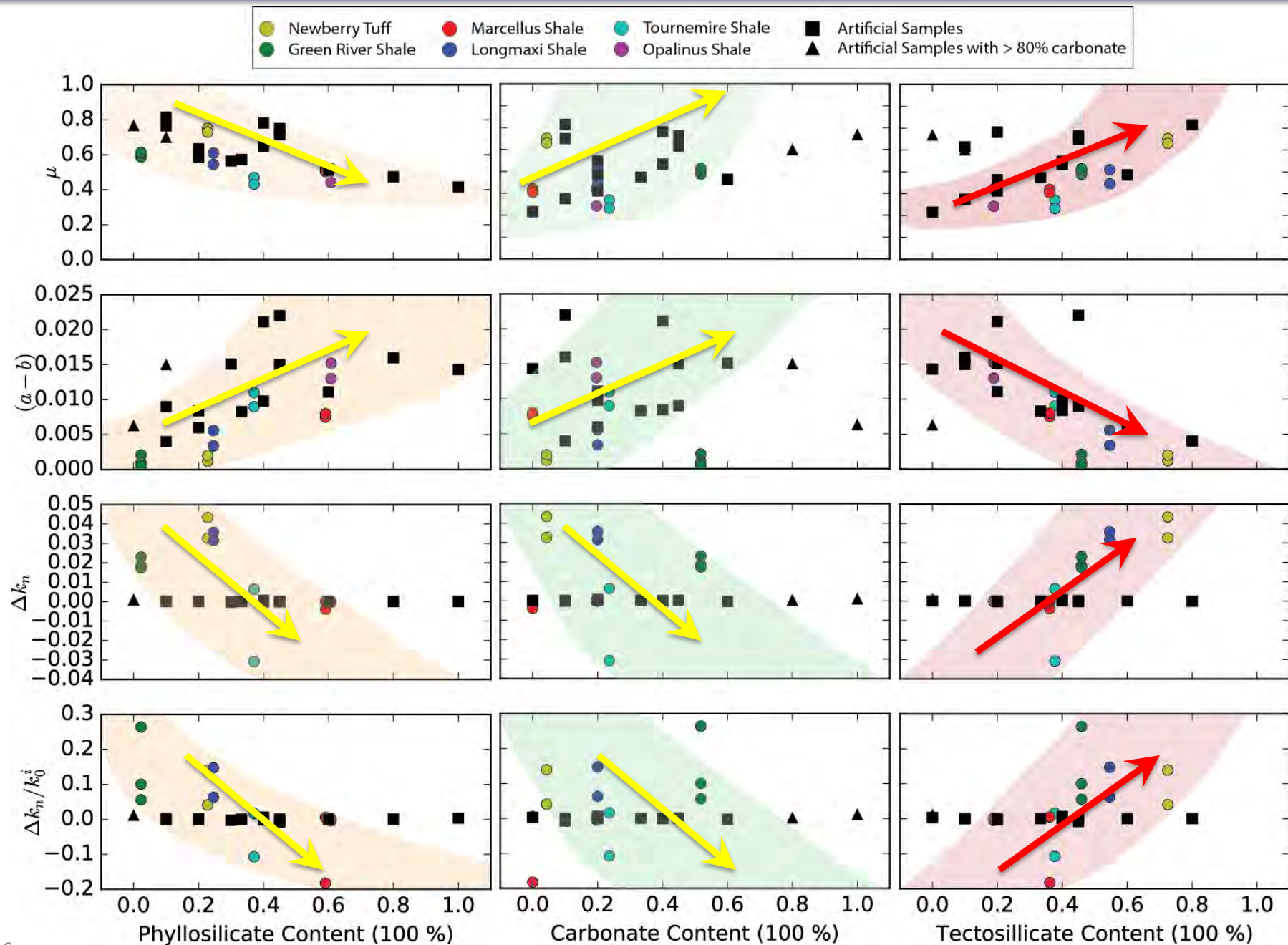
Observations

- 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



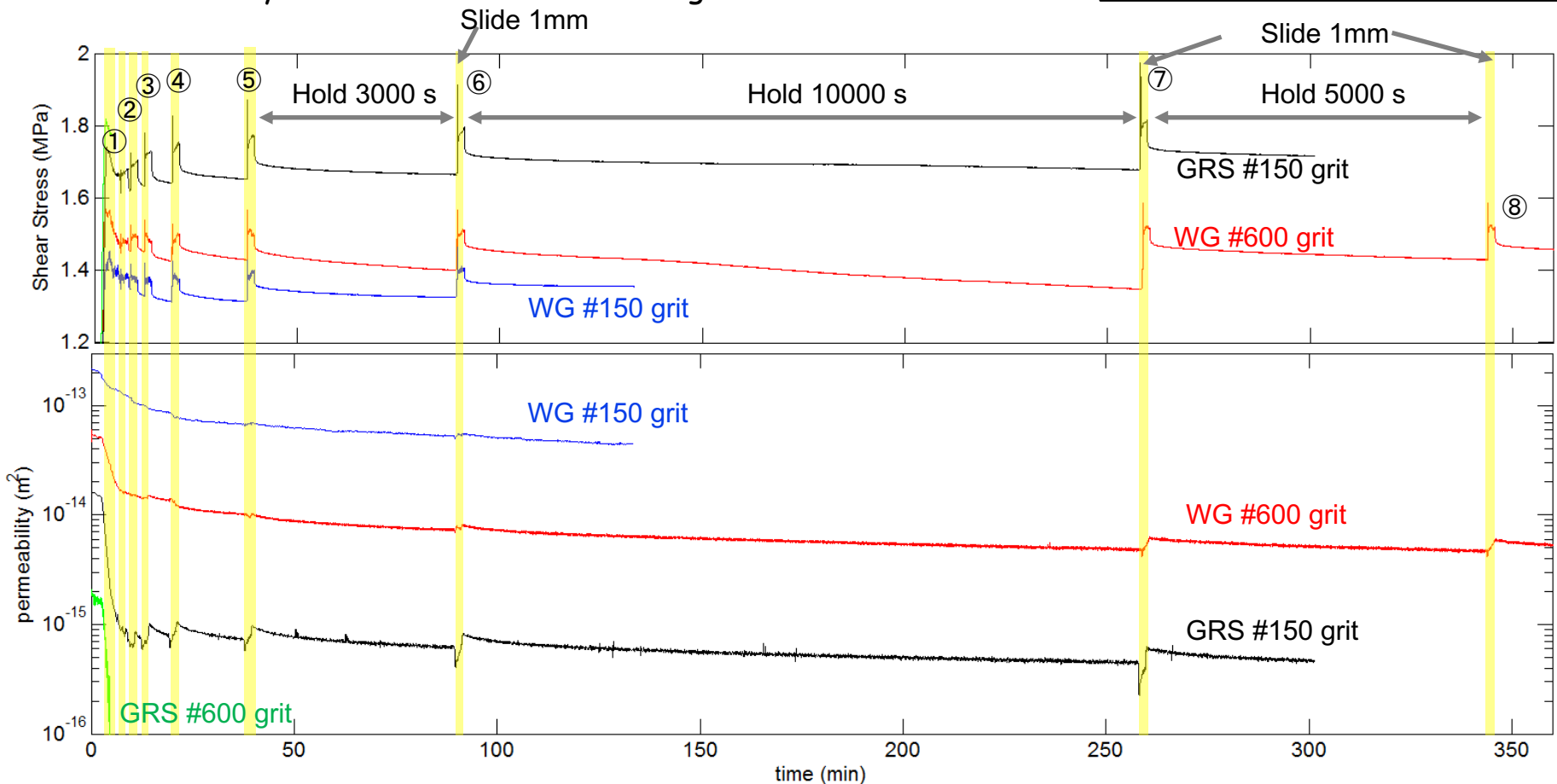
Healing - Necessary Component of the Seismic Cycle

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

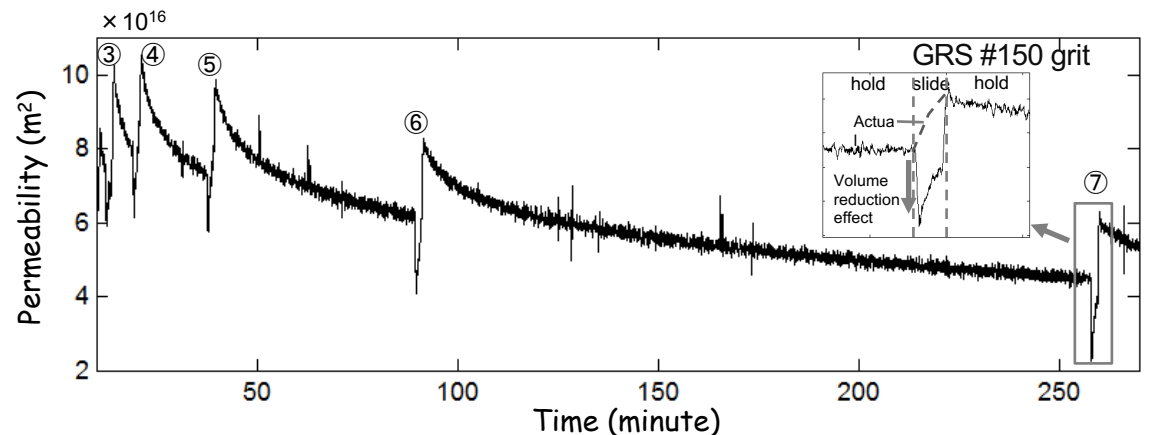
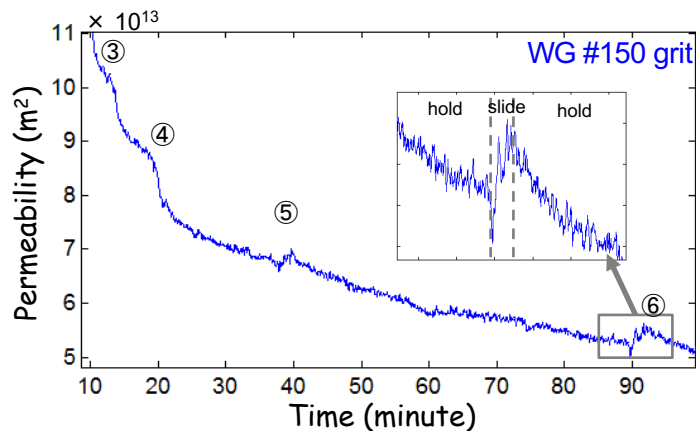
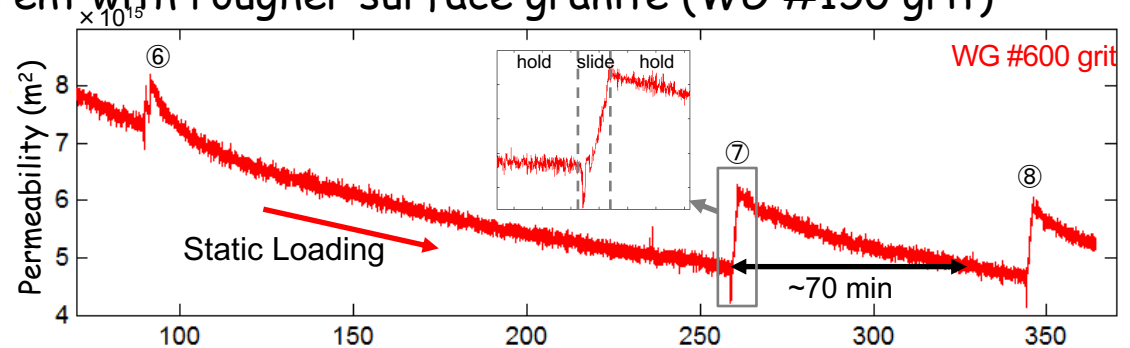
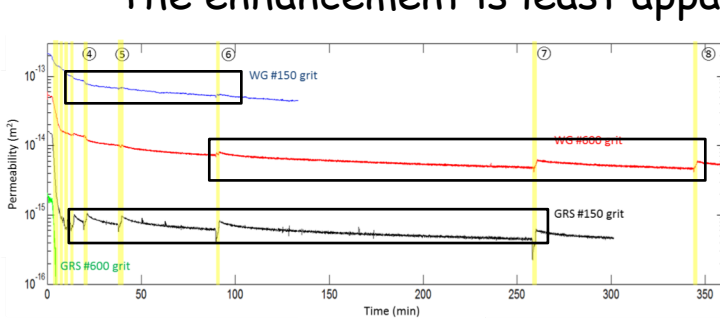
- Permeability of Green River shale #600 grit became unresolvable after initial shear
- Westerly granite #150 grit stopped at ~150 min due to limited pump capacity
- 8th shear applied to Westerly granite #600 grit after 5000 seconds



Shear Permeability Enhancement

Shear Induced Permeability Enhancement

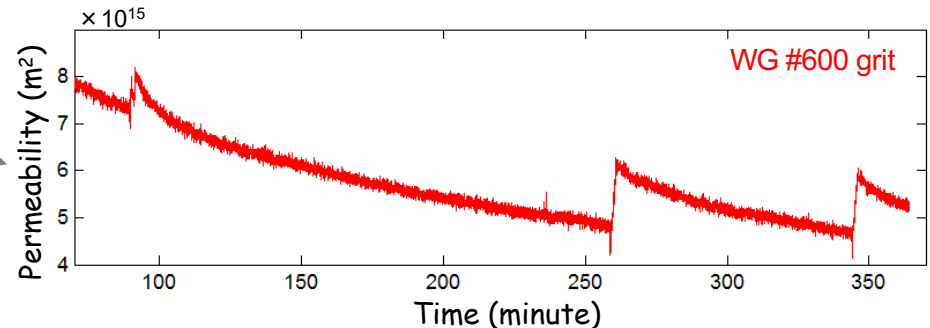
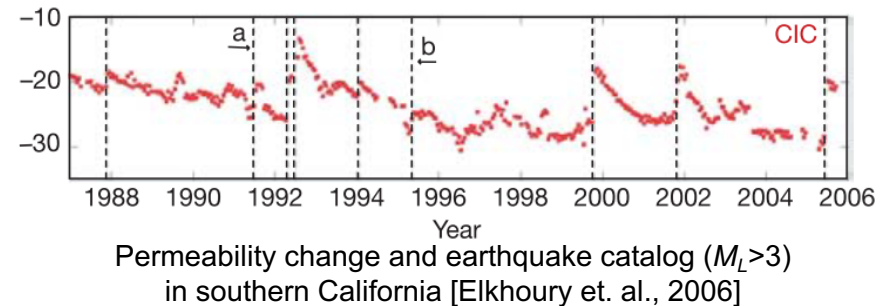
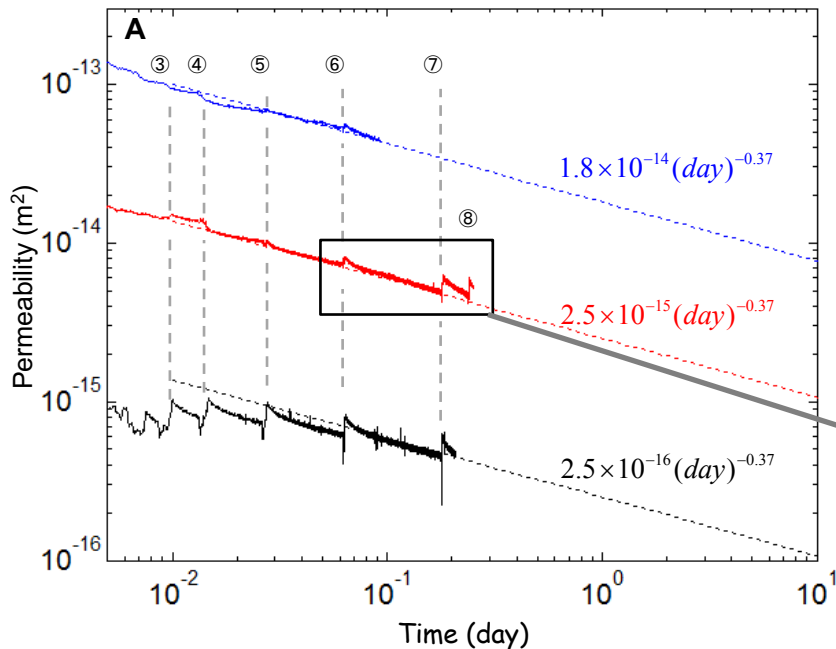
- Later stage shear slip + Incremented duration of prior slip → Significant permeability enhancement
- Permeability continuously decreases during hold (Pressure solution?)
- Prior slip permeability recovery took 70 minute after slip ⑦, WG #600 grit case
- Permeability increase appears to be linear to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



Permeability Healing (Sealing) Law

Pressure solution

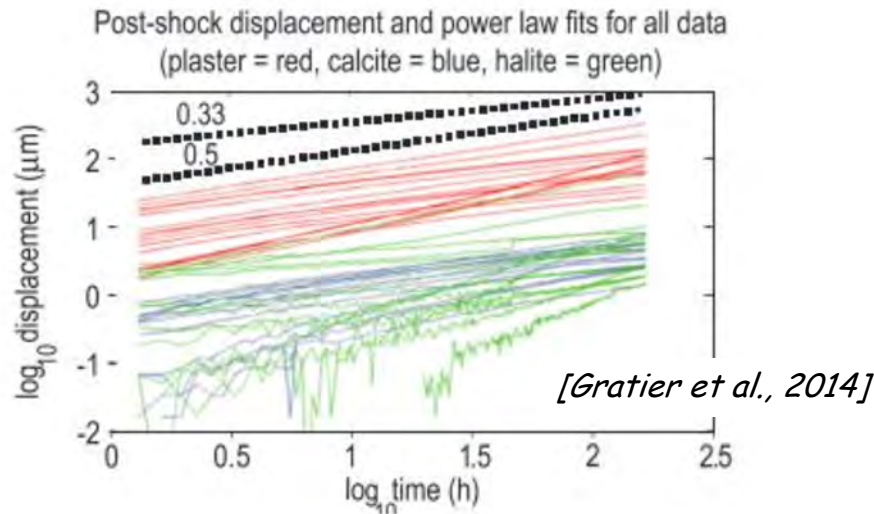
- Permeability reduction due to pressure solution in all cases seems to follow power law decay $k = k_0 t^{-p}$ with power $p = -0.37$
- The enhancement can be significant after extremely long (natural scale) holds
- Can this be applied to natural hydraulic systems?



Permeability Decay - Role of Pressure Solution

Power-law dependence

Rigid indenter, Pressure solution

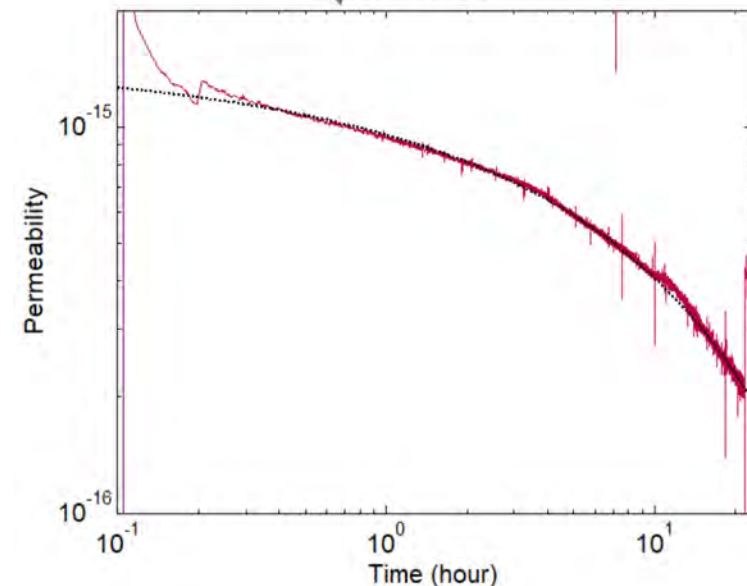
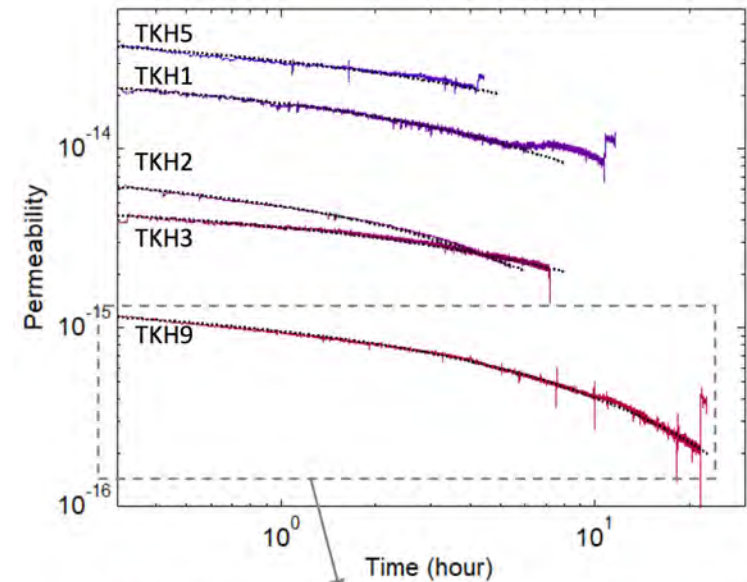


Indentation rate:

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

Permeability change:

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



Shear Permeability Enhancement

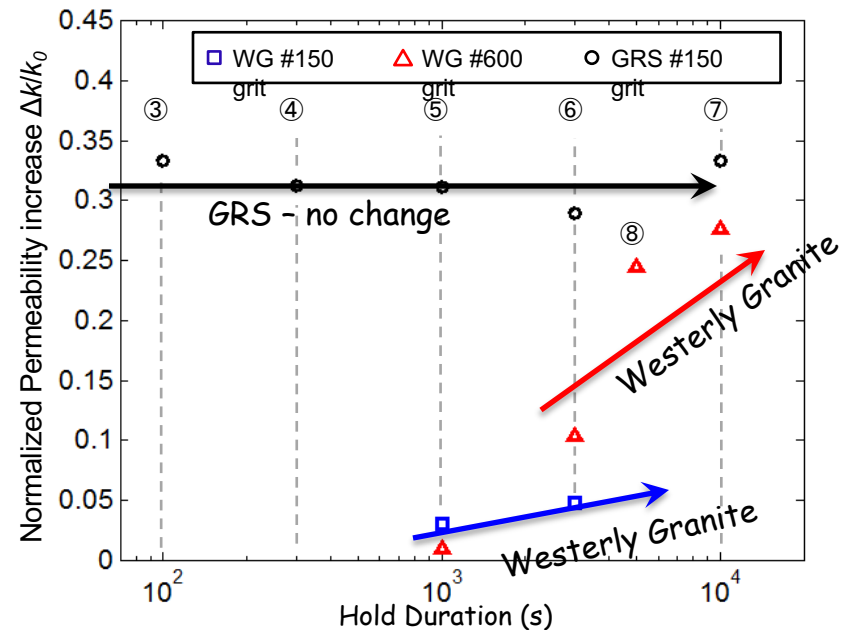
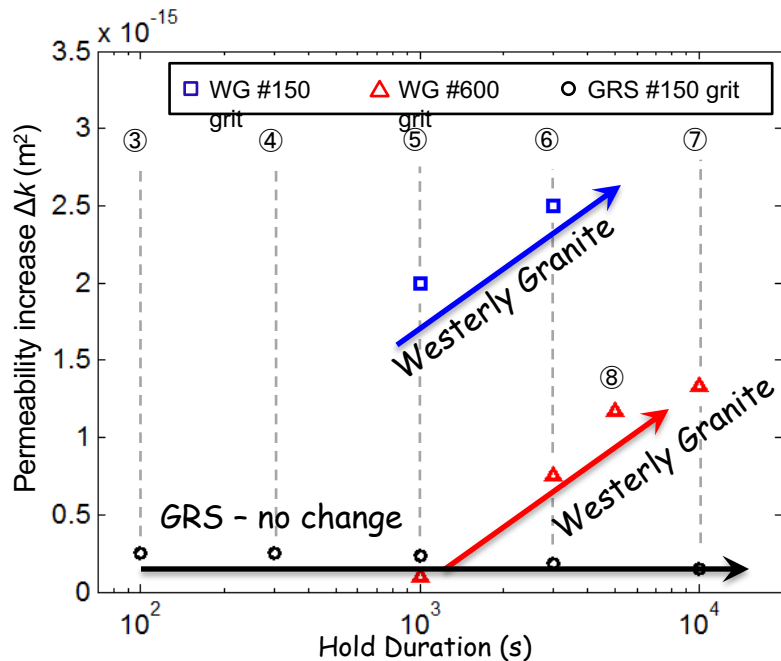
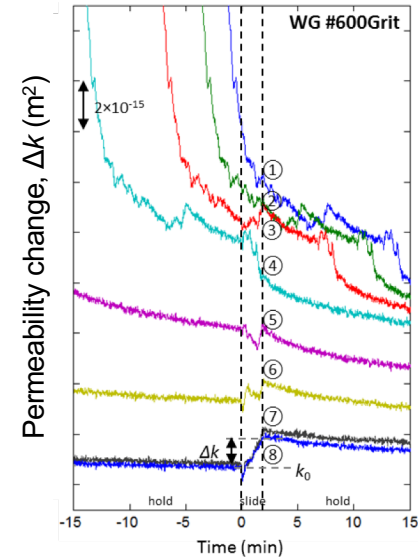
Magnitude of Permeability Enhancement

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

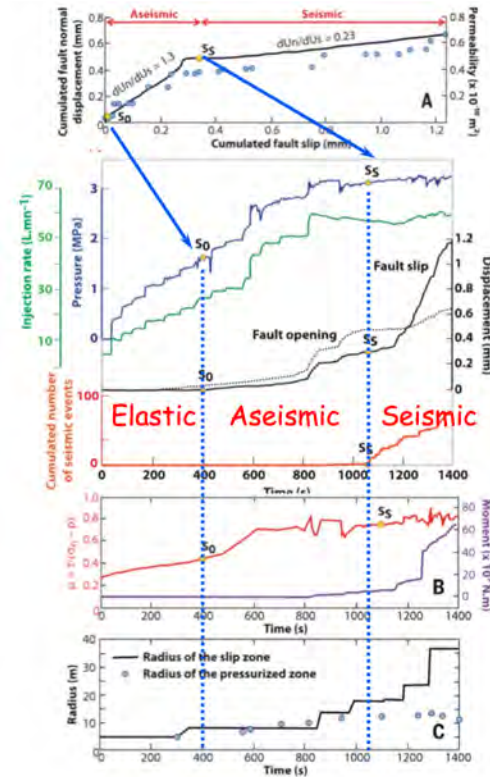
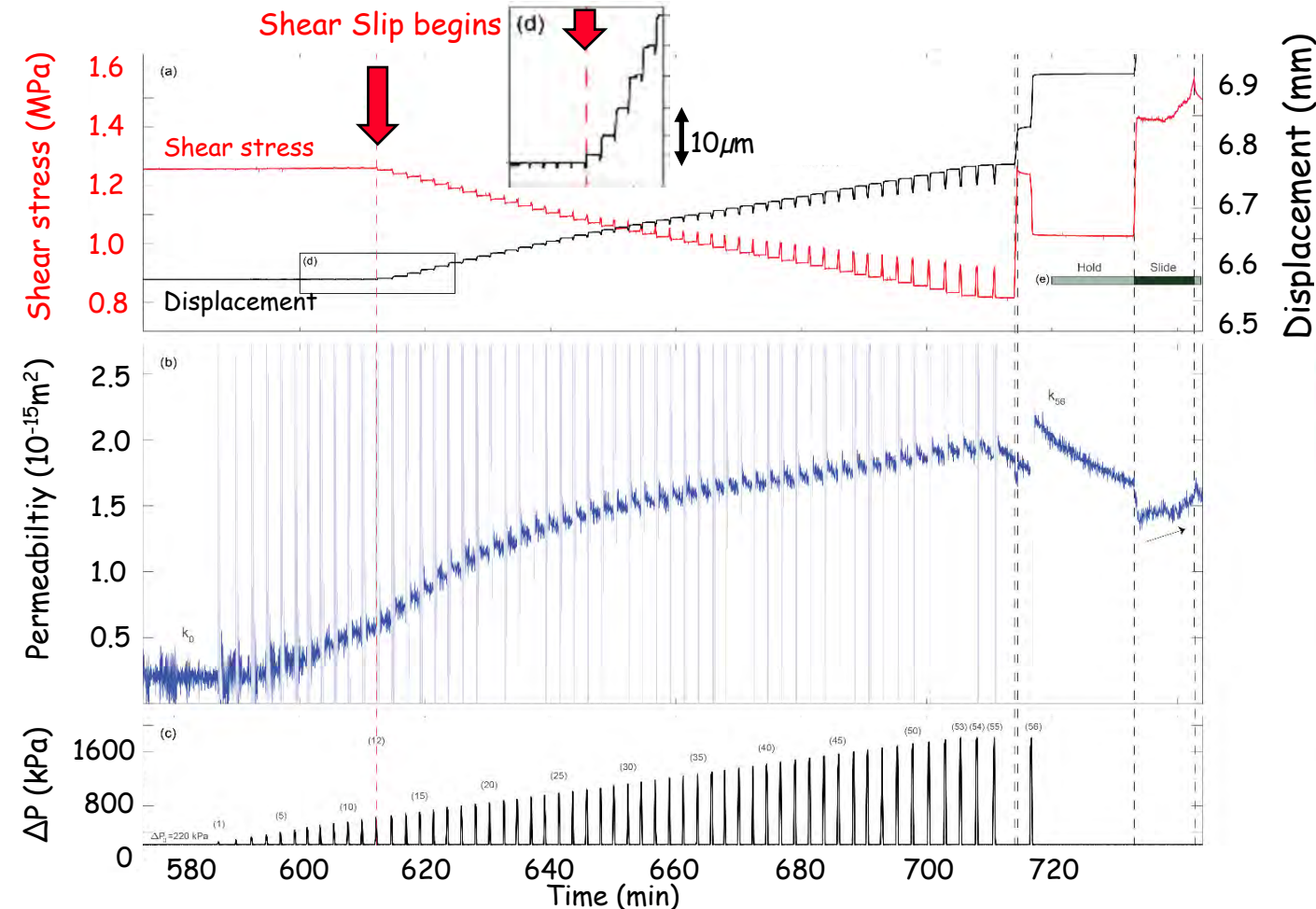
Shear permeability slightly decreases with prior hold time for Green River shale



Pore Pressure Perturbation

Permeability response to pore pressure steps and induced shear slip

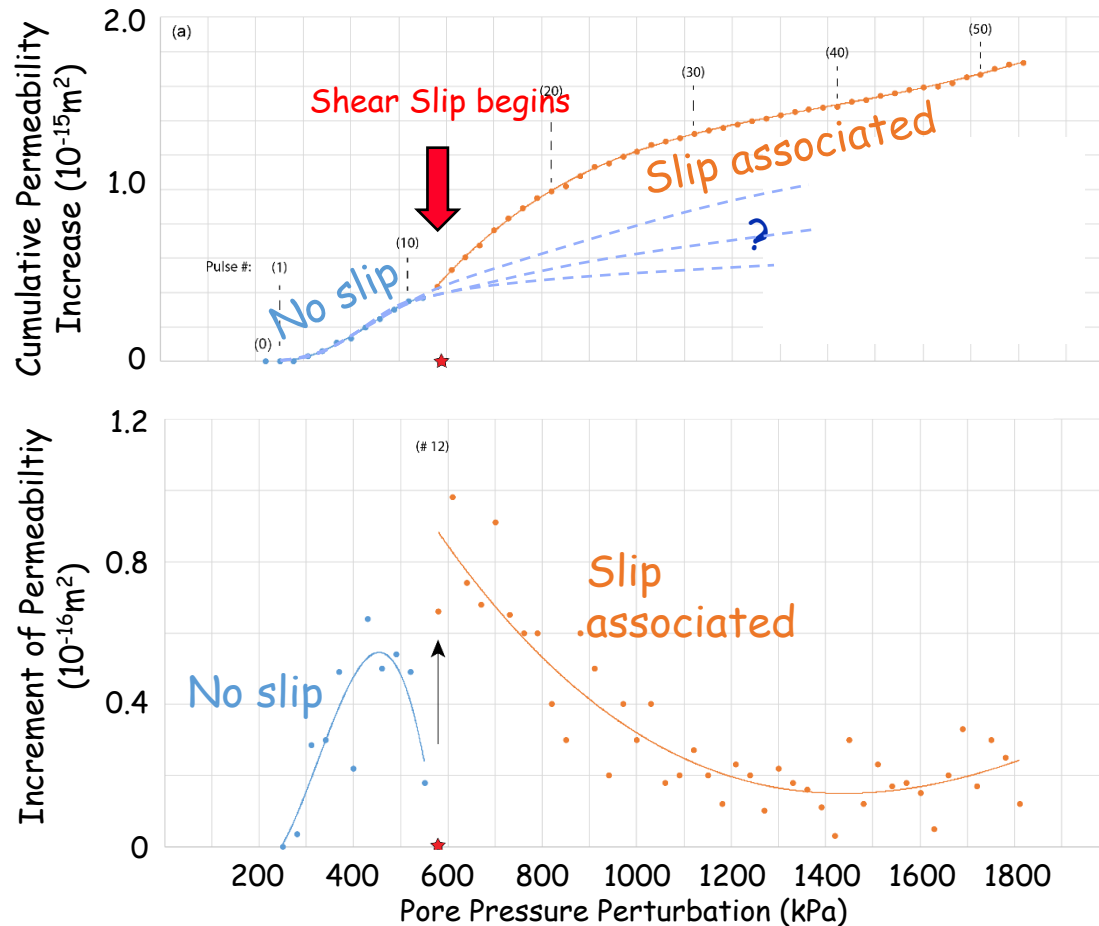
- Address question of relative impact of normal and shear stress incremental contributions
- Stepwise incremented pressure pulse - to cross critically-(shear)-stressed threshold
- Permeability increases with magnitude of pressure pulse
- Induced shear slip begins at fluid pressure ~ 600 kPa $\rightarrow$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



Controls on Permeability and Seismicity in EGS Reservoirs

Derek Elsworth (Penn State), Quan Gan (PSU), Yi Fang (PSU/UT), Josh Taron (USGS), Ki-Bok Min (SNL), Hide Yasuhara (Ehime), Yves Guglielmi (LBNL/Aix-Marseille), Kyunjae Im (PSU/Caltech), Chaoyi Wang (PSU/Purdue), Takuya Ishibashi (AIST/PSU), Atsushi Sainoki (Kumamoto), Yunzhong Jia (NTU), Tim Kneafsey (LBNL), Joe Moore (Utah, EGI)

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

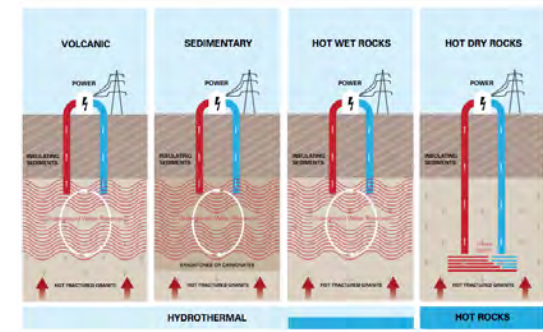
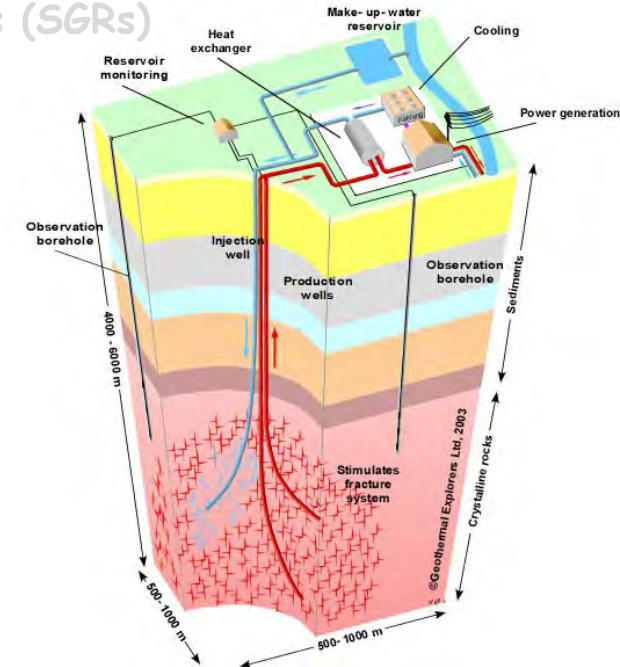
Reservoir Scale Response

Anomalous seismicity - Newberry Project

Permeability scaling - Newberry Project

US (DoE) Road Map

Summary



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

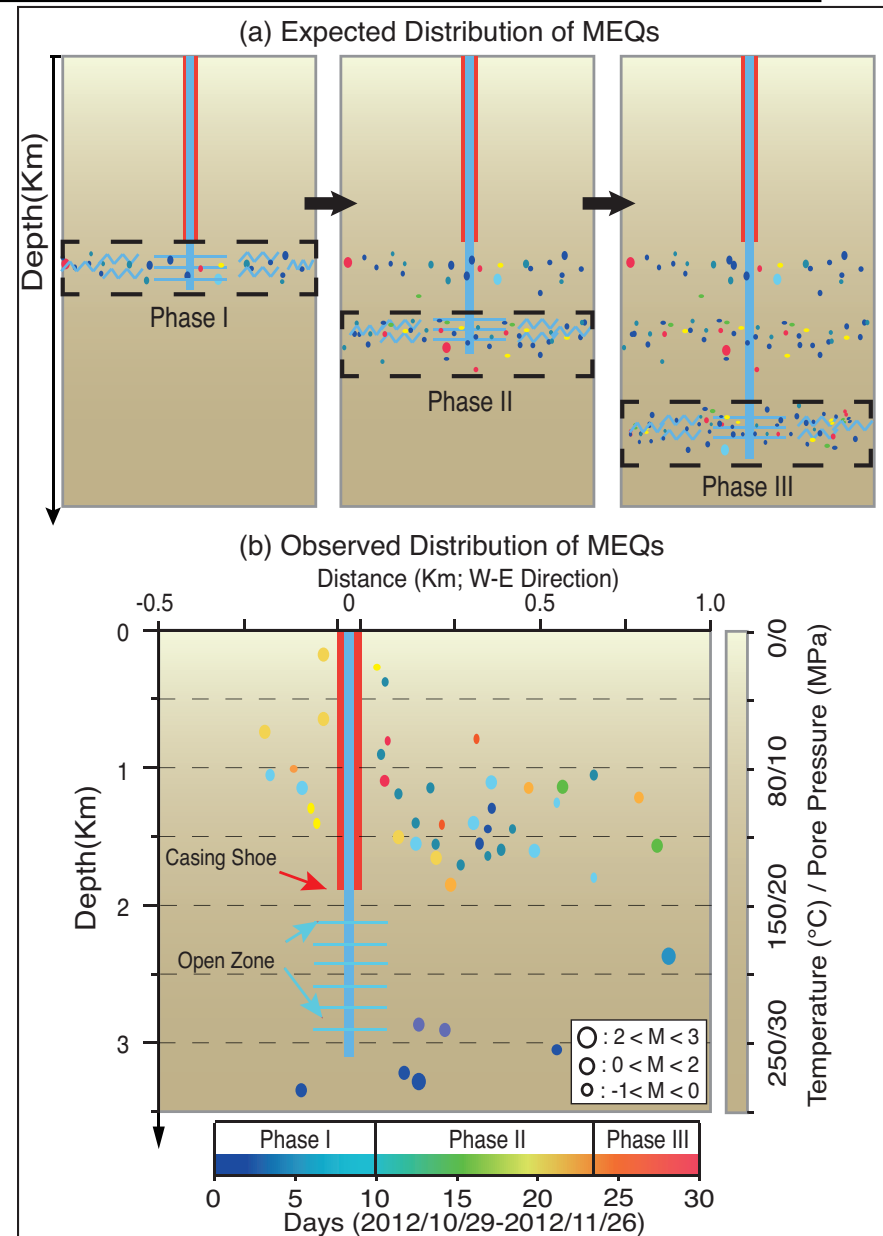
- 0-2000m: Casing shoe
- 2000m-3000m: open zone

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.

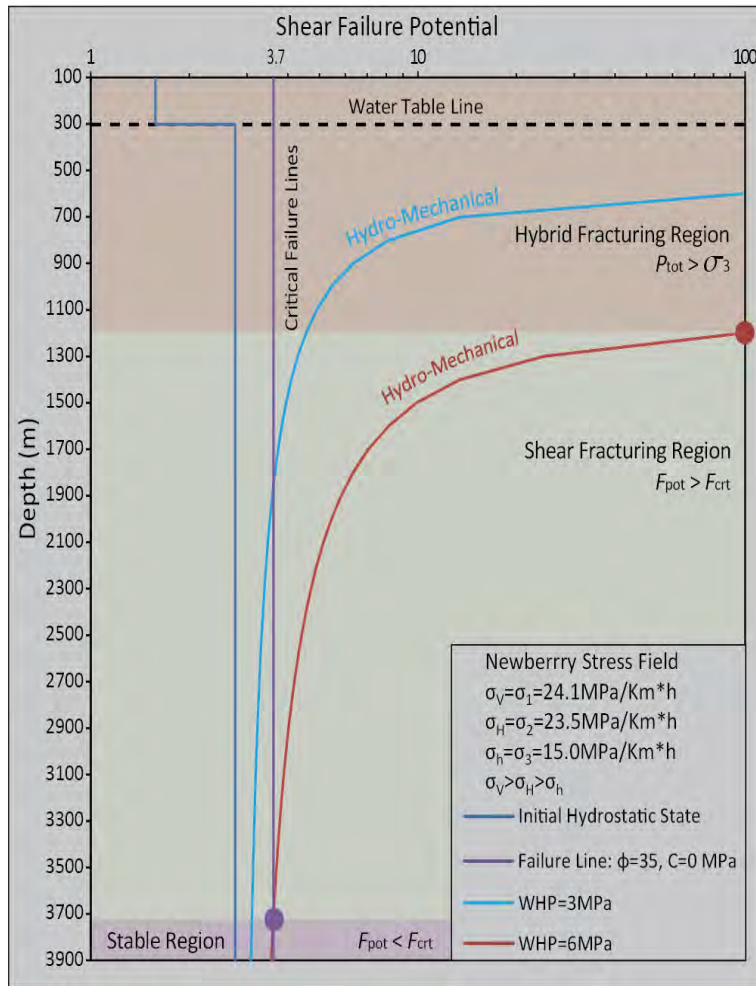
Temporal Anomaly

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



Constraints on Frictional Slip

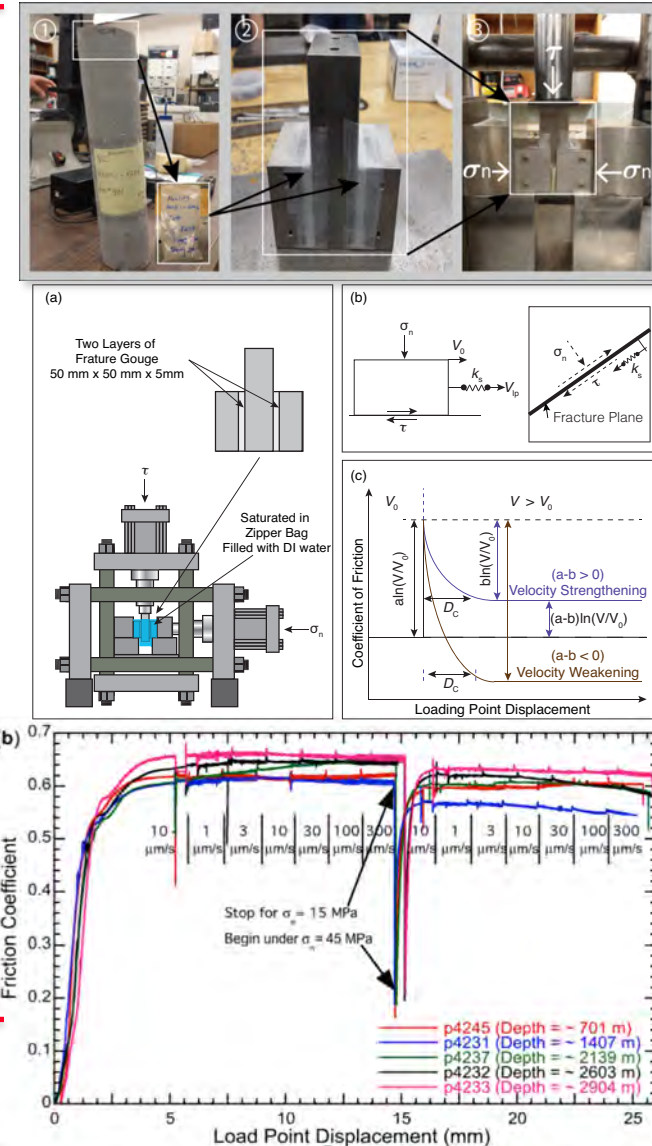
1. Shear Failure Analysis



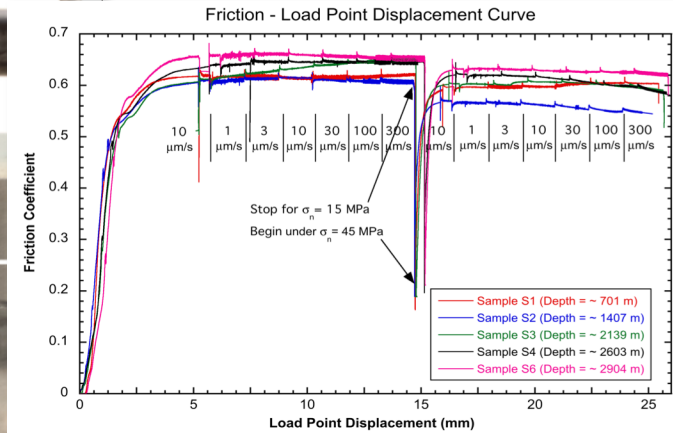
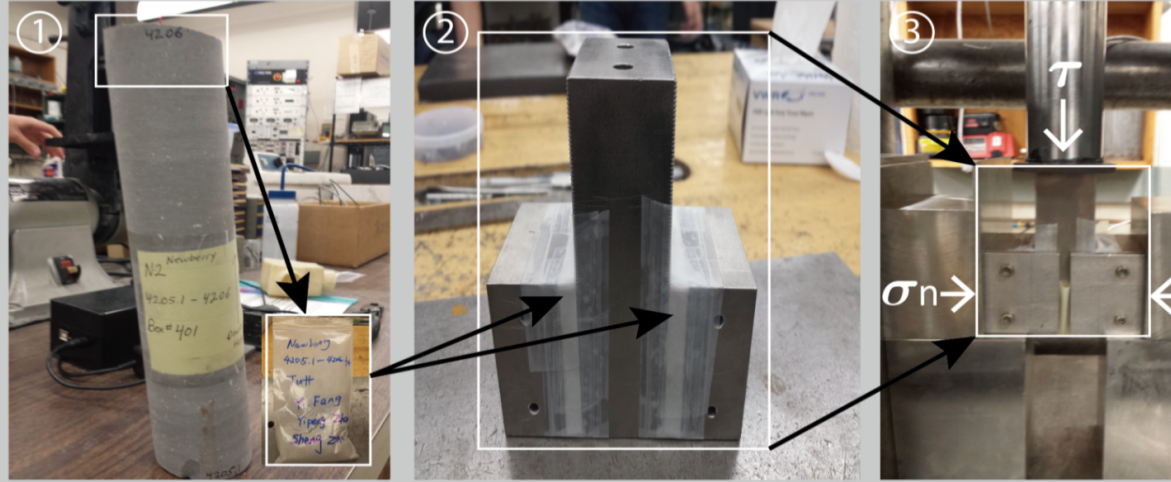
1. Shear Failure Analysis suggests that if seismicity occurs at great depth, it should occur continuously up the rock column, and not with a gap.

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

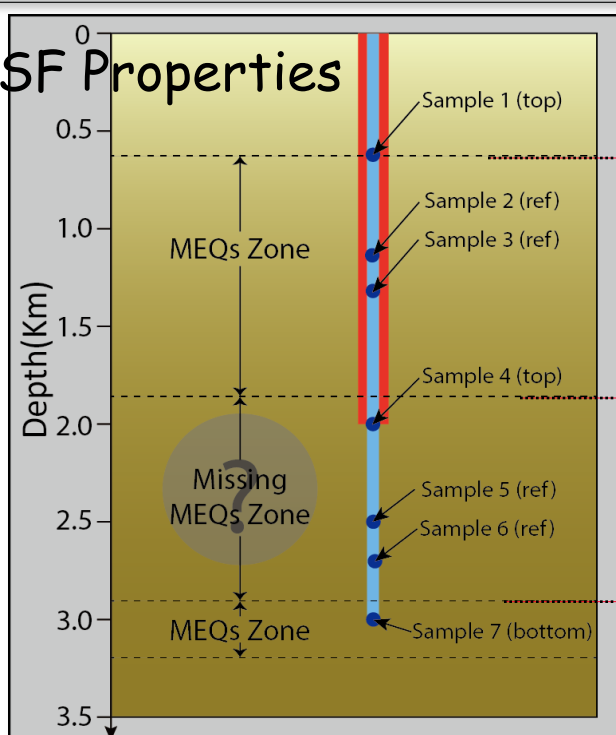
2. Friction Experiments



RSF Properties

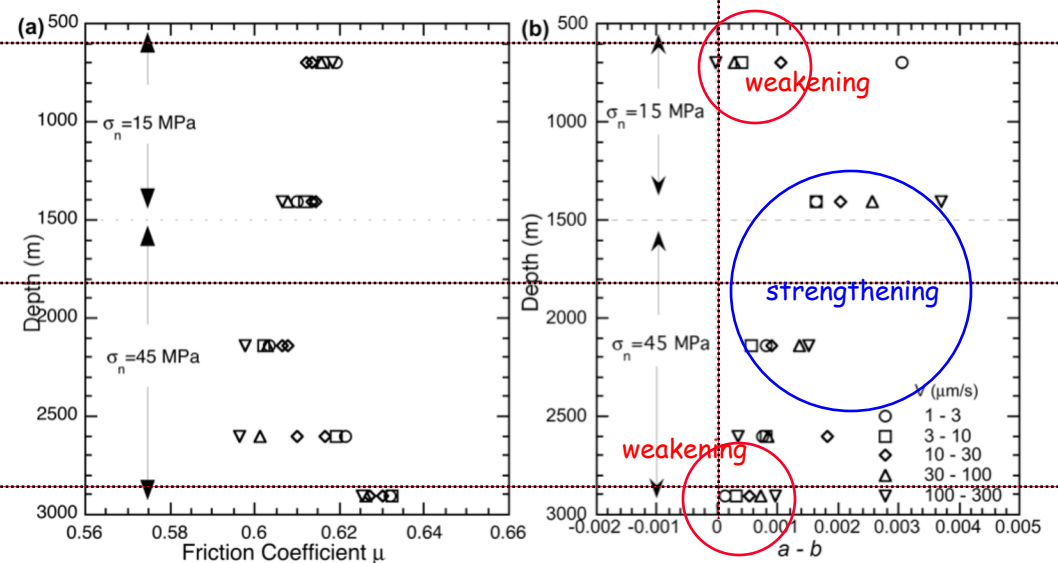


RSF Properties



Friction

(a-b) at 15-45 MPa

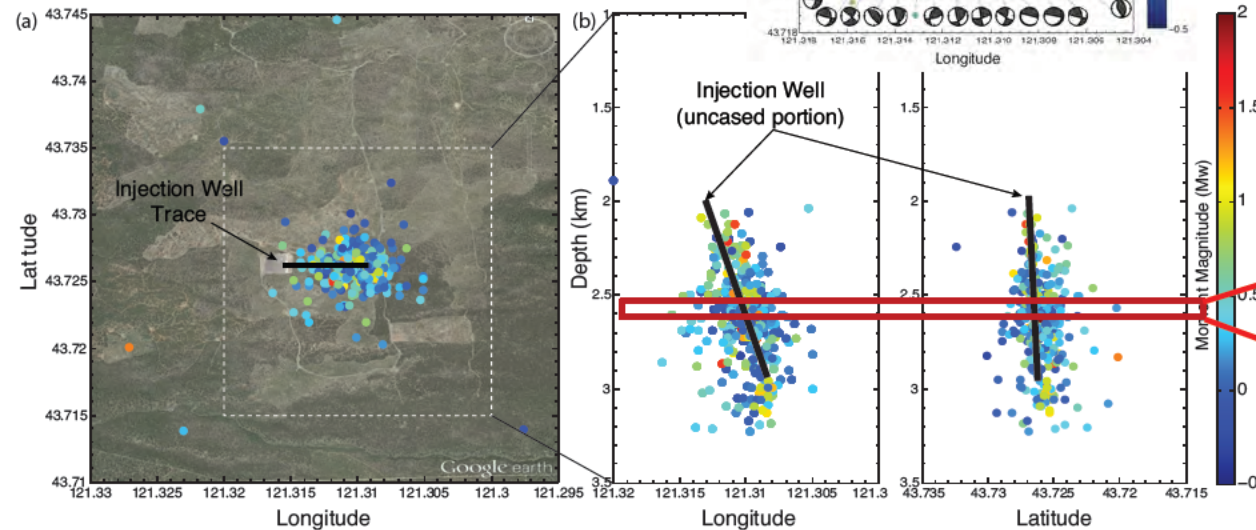
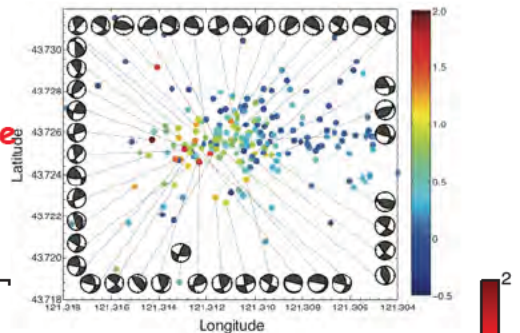
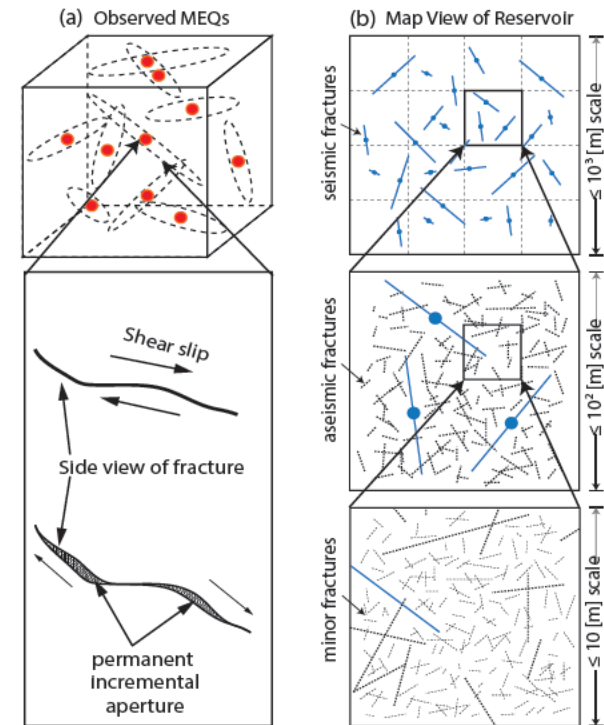


Linking MEQs to Permeability Evolution

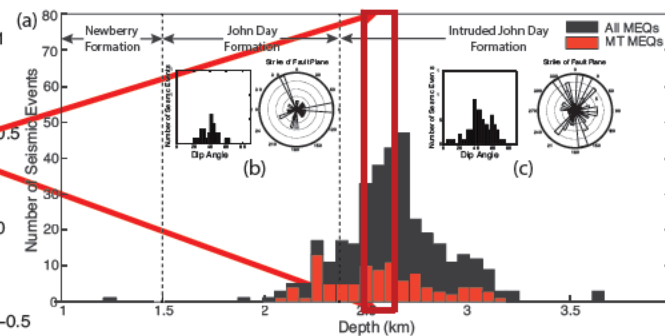
1. Seismicity induced by hydroshearing is controlled by the Mohr-Coulomb shear criterion.
2. The frictional coefficient evolves during seismic slip.
3. Two types of fractures:
 - Velocity-weakening/seismic fractures and,
 - Velocity-strengthening/aseismic fractures (fracture size smaller than the critical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

Workflow:

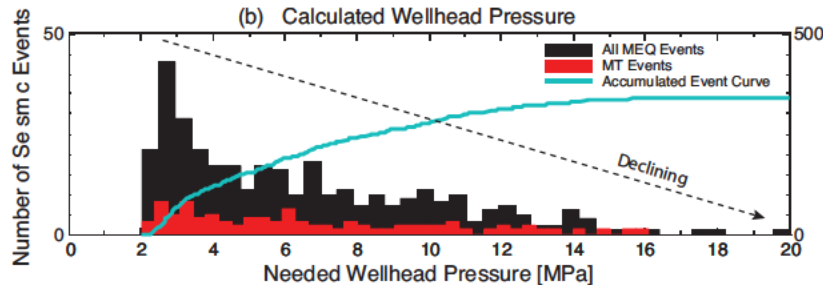
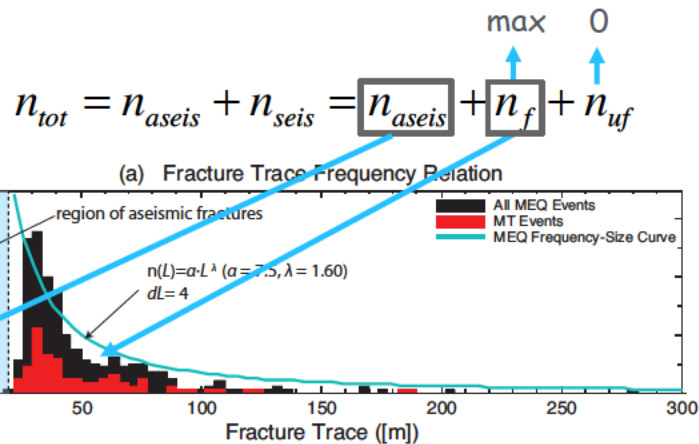
1. MT -> Orientation, mode of disp.
2. Magnitude, stress drop -> fracture size
3. Size -> roughness and dilation
4. Dilation/mode -> permeability evolution



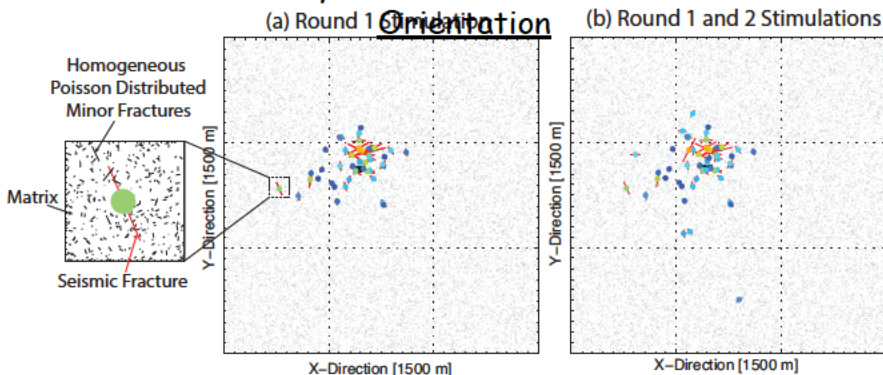
Seismic Events vs. Depth



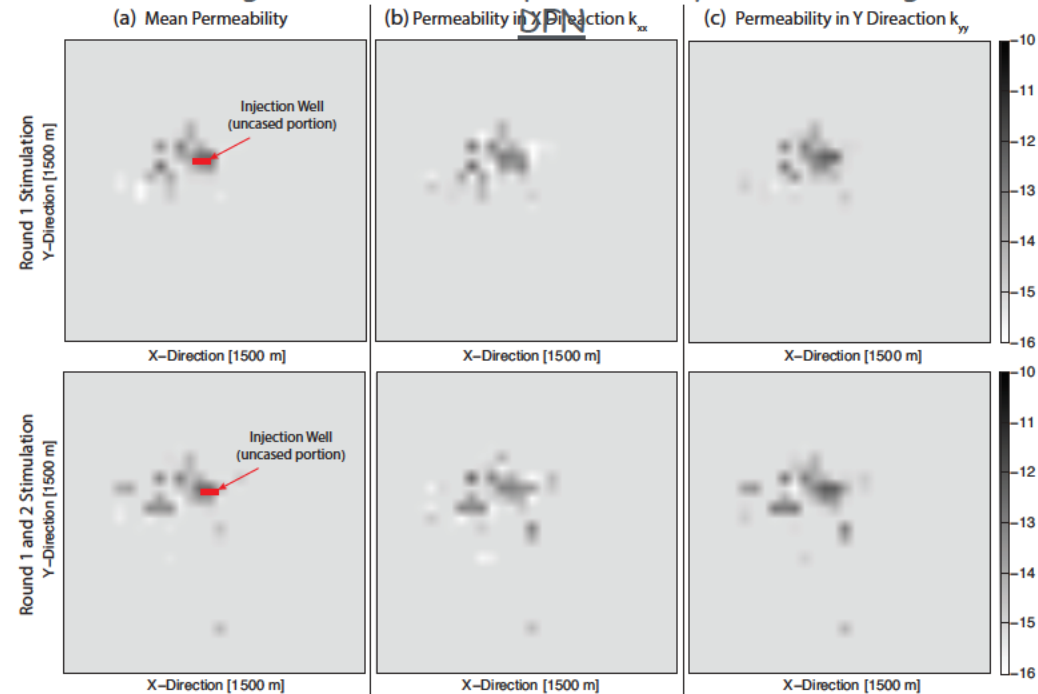
Seismicity-Permeability Validation



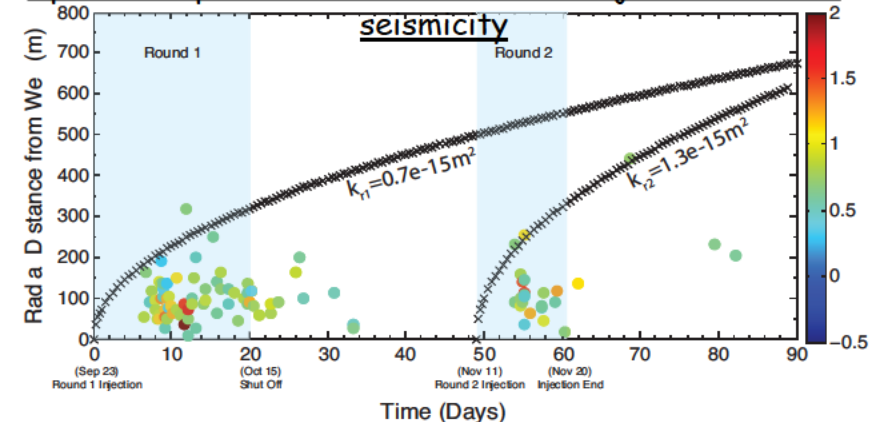
Statistically Inverted Fracture Trace and Orientation



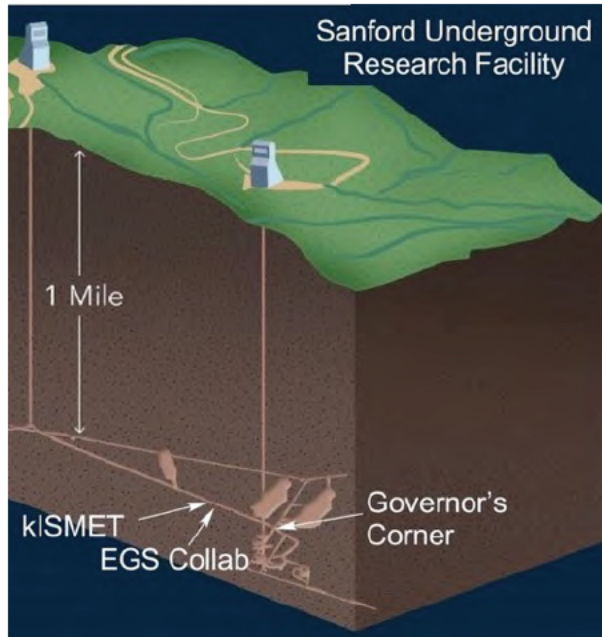
Cellular grid of stimulated permeability created using the



Spatio-temporal distribution of fluid-injected-induced seismicity



US DoE EGS Collab(oration) Project

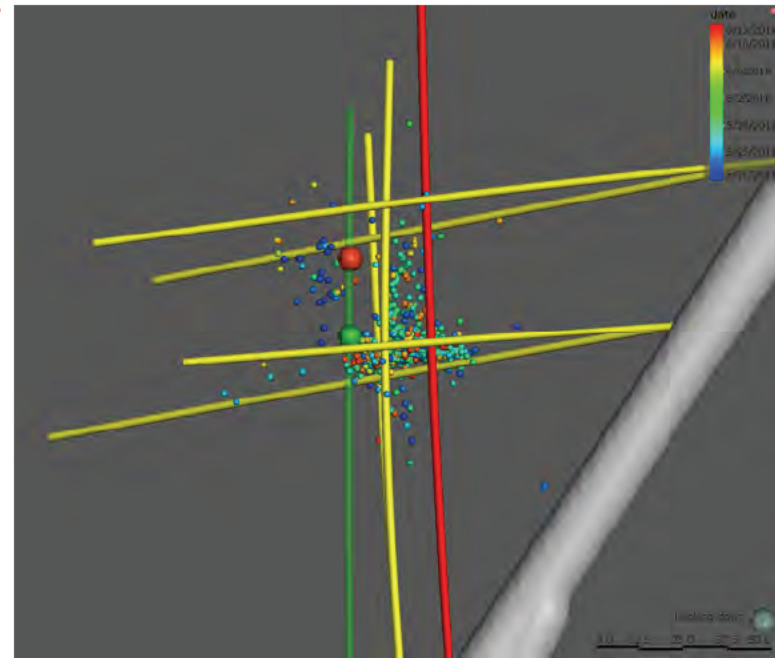
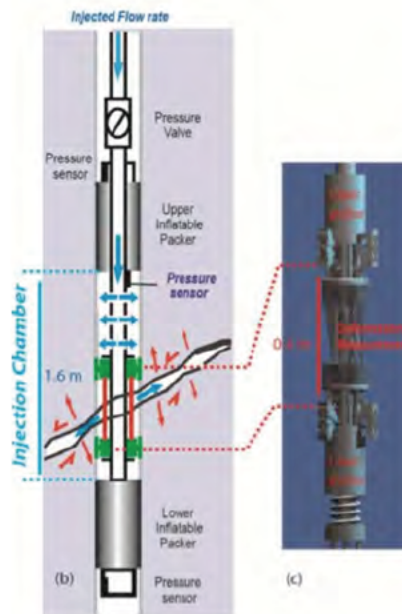
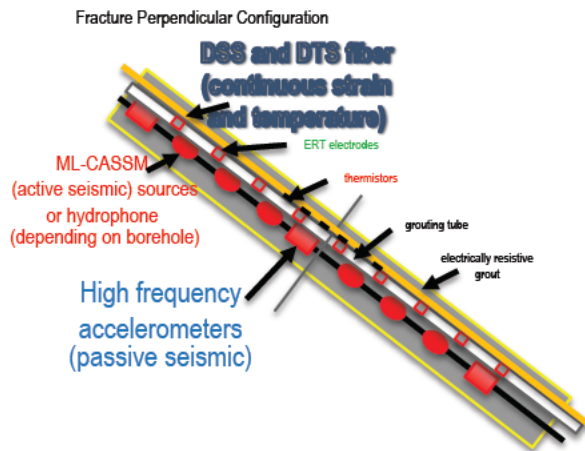


At Sanford Underground Research Facility (SURF-DUSEL) - 1500m

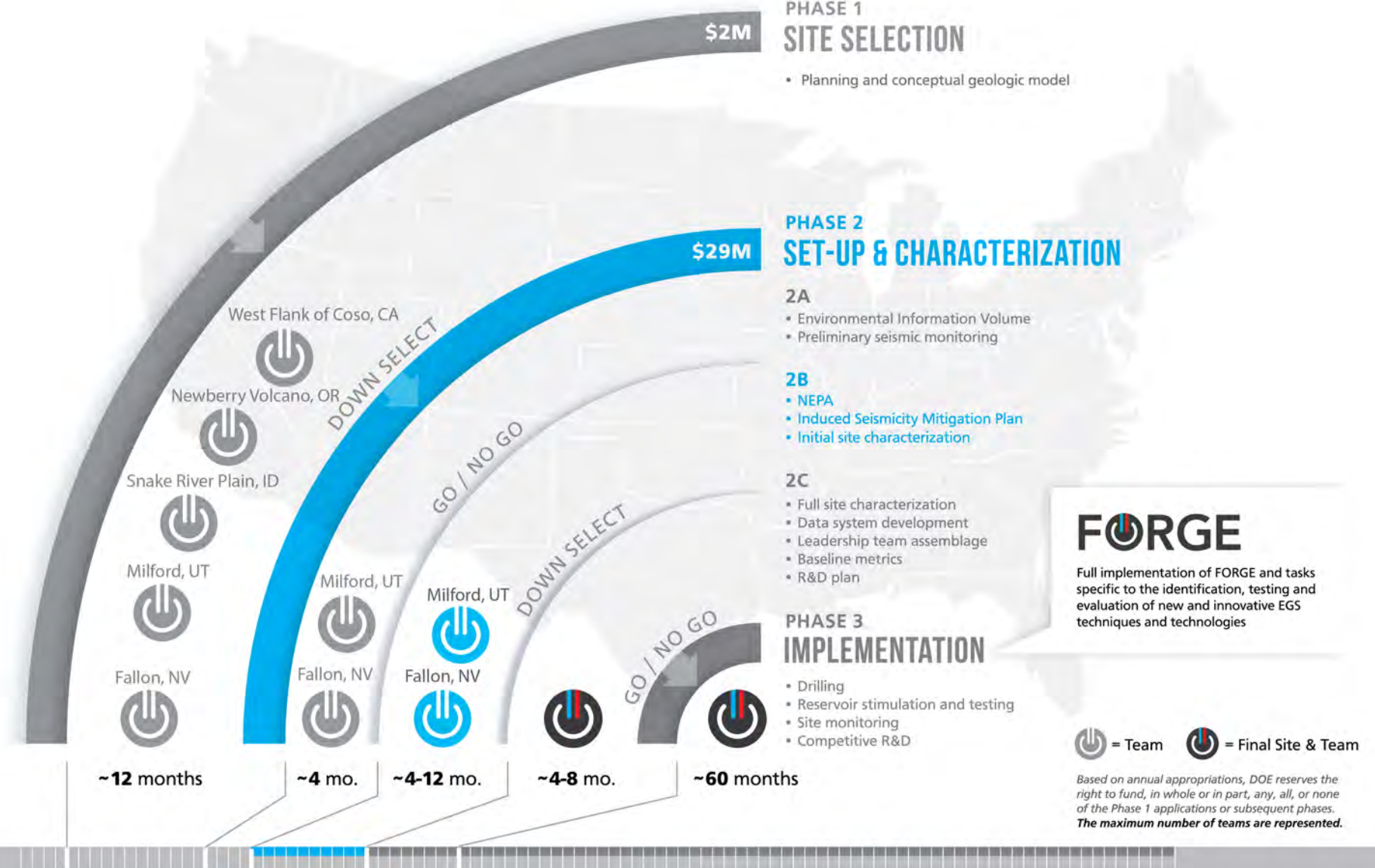
Experiment 1, intended to investigate hydraulic fracturing*, in situ

Experiment 2 designed to investigate shear stimulation*.

Experiment 3 will investigate changes in fracturing strategies - TBD.



Frontier Observatory for Research in Geothermal Energy (US DoE FORGE)



Conclusions

Heat/Energy Recovery is Key Parameter Defining Viability

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

Sensitivity spectrum of response: Hydrothermal $\rightarrow$ SGR $\rightarrow$ 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