# Reactive Flow and Permeability Dynamics I & II
Derek Elsworth, Penn State

**Basic Observations of Permeability Evolution – Lab-to-field**

**Impacts on Permeability**

- Mechanical effects (pore pressure and thermal effects)
  - Controls on effective stress
  - Stress-porosity linkages for fractures
    - Compaction
    - Dilation
    - Rate-state models
  - Porosity-permeability linkages to fracture dilation
  - Other mechanical effects (wear)
- Reactive chemical effects
  - Laboratory observations
  - Linkages among porosity/permeability/dissolution/precipitation
  - Mechanistic models for chemical-mechanical effects
  - In situ observations/characterizations of chemical-mechanical effects
  - Forward/reverse feedbacks on stress-permeability

**Reservoir-Scale Evolution of Permeability**

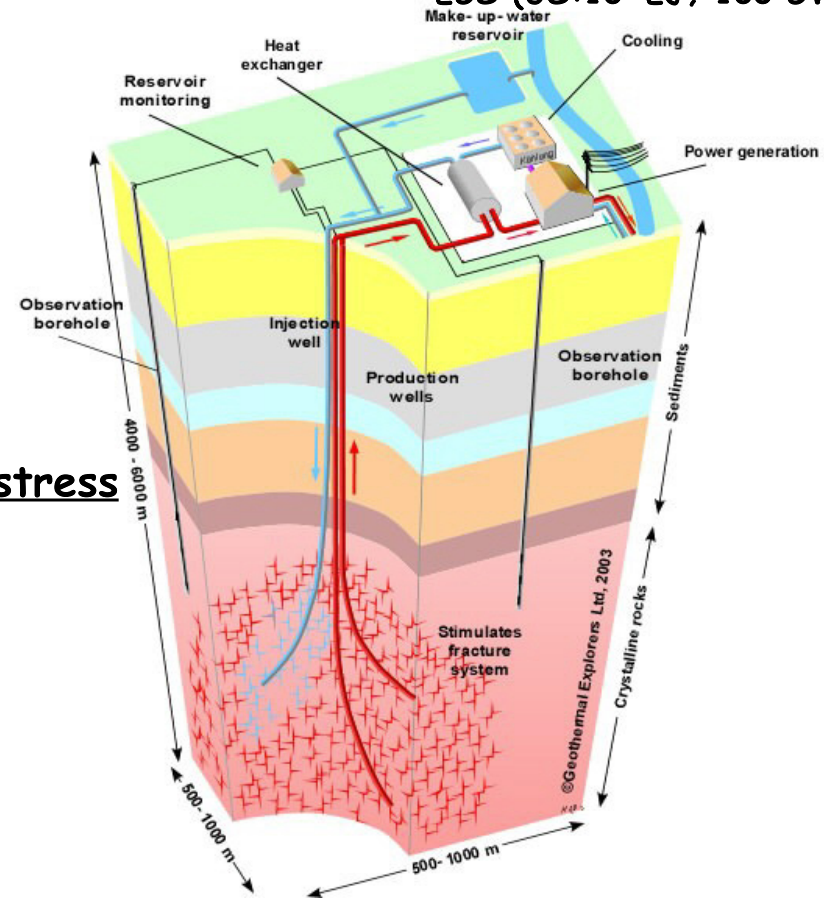
- Spatial distribution
- Timing
- Seismicity as an indicator

**Summary**

# Basic Observations of Permeability Evolution

## 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 <u>effective stress</u>
- <u>Effective stresses</u> influence
  - Permeability
  - Reactive surface area
  - Induced seismicity

## Understanding T H M C is key:
- Size of relative effects of THMC
- Timing of effects
- Migration within reservoir
- Using them to engineer the reservoir

Permeability
Reactive surface area
Induced seismicity

# Scaling Between Laboratory and Observation

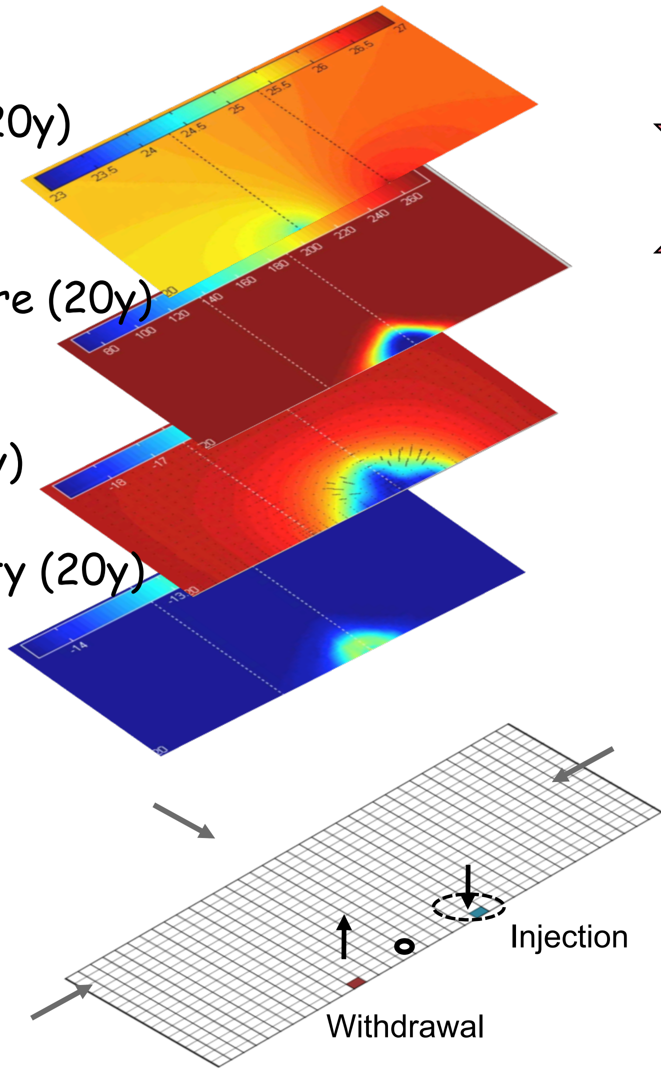
**Model (linkage)**

Pressure (20y)

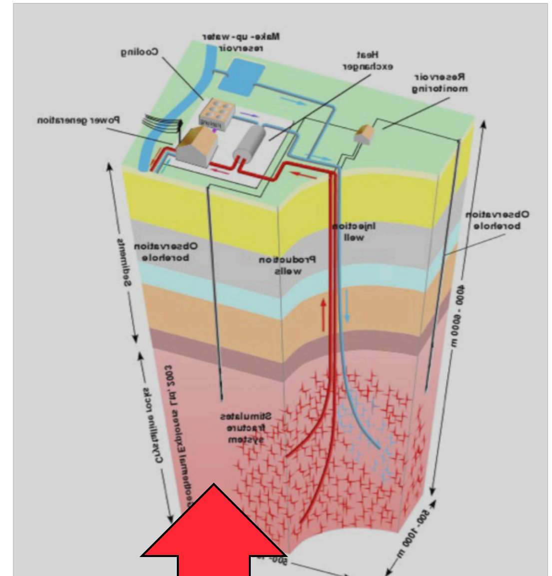
Temperature (20y)

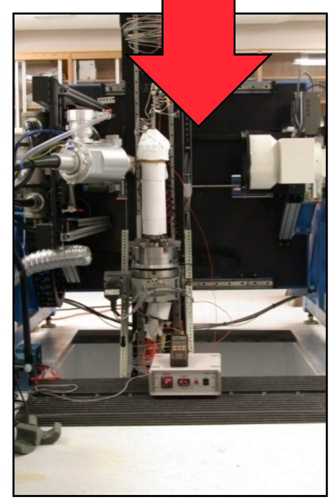
Deviatoric stress (20y)

Permeability (20y)




**Prototype (reality)**





**Experiment (constitutive behavior): K=f(THMC)**

# Controls on Reservoir Evolution

**Many processes of vital importance to EGS are defined by coupled THMC processes.**

Thermal sweep/fluid residence time

Short circuiting

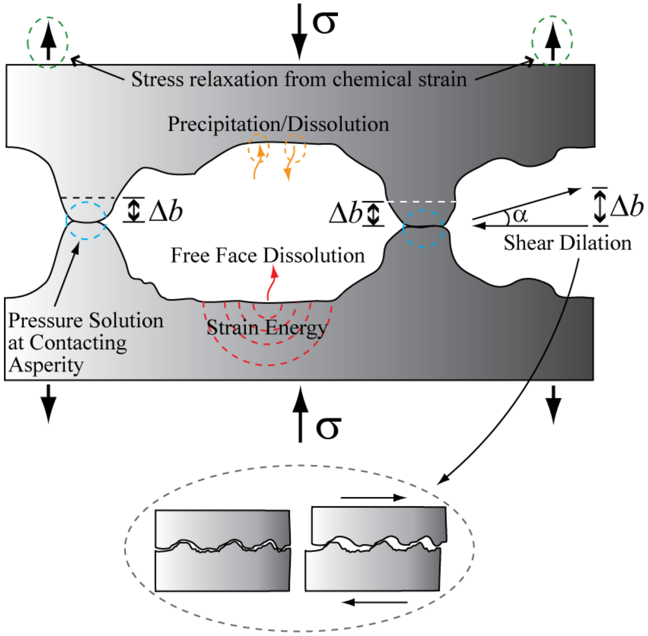
Induced seismicity

Prolonged sustainability of fluid transmission

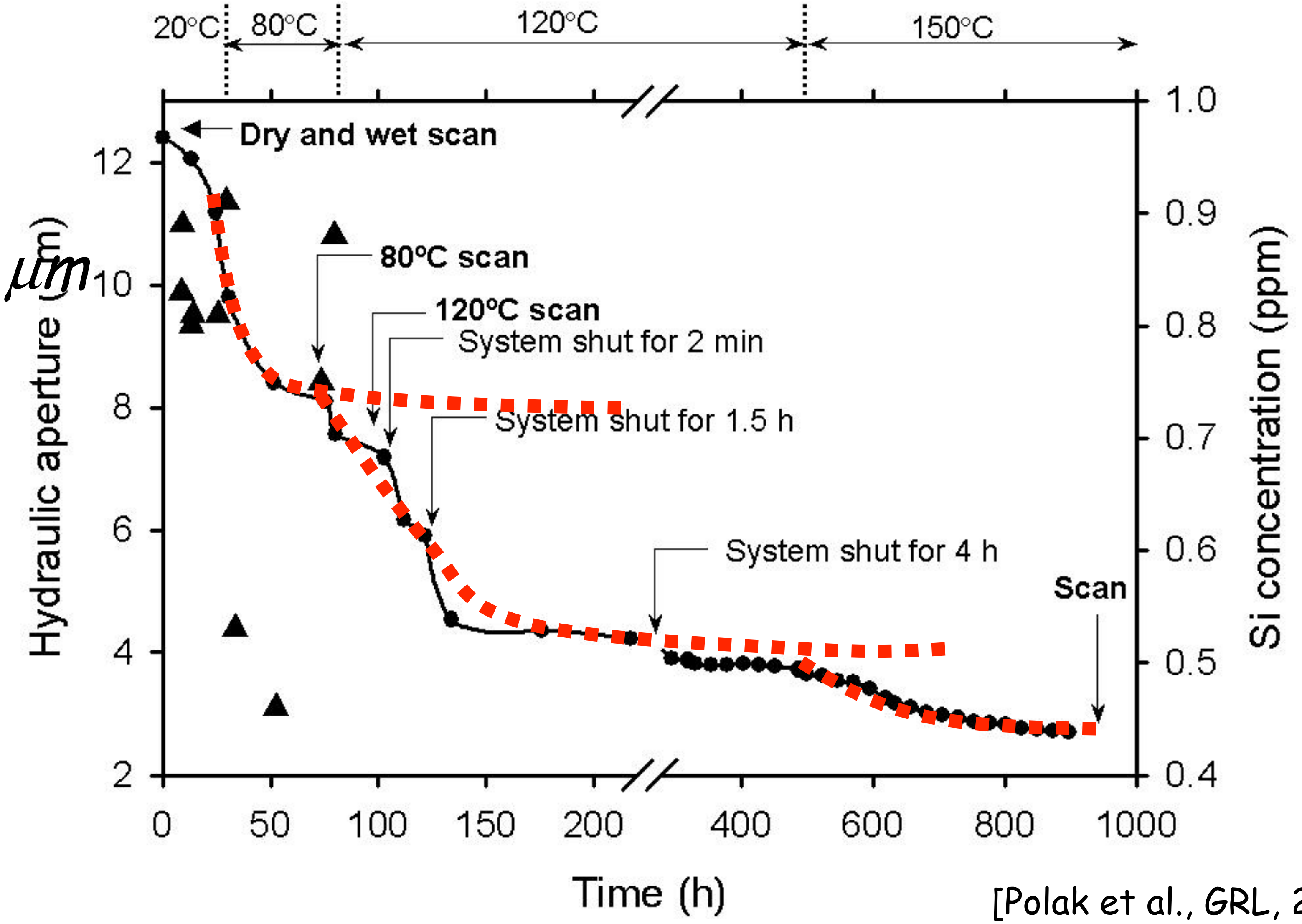
**Fractures dominate the fluid transfer system**

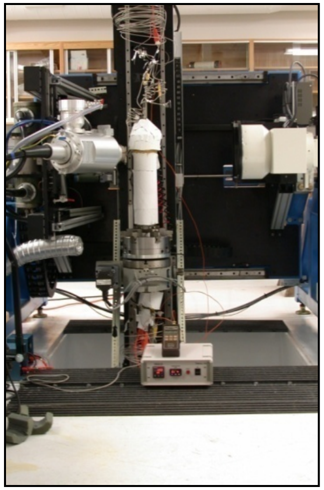
Transmission characterized by:

- History of mineral deposition
- Chemo-mechanical creep at contacting asperities
- Mechanical compaction
- Shear dilation and the reactivation of relic fractures



# Typical Response of Fractures (Dissolution)

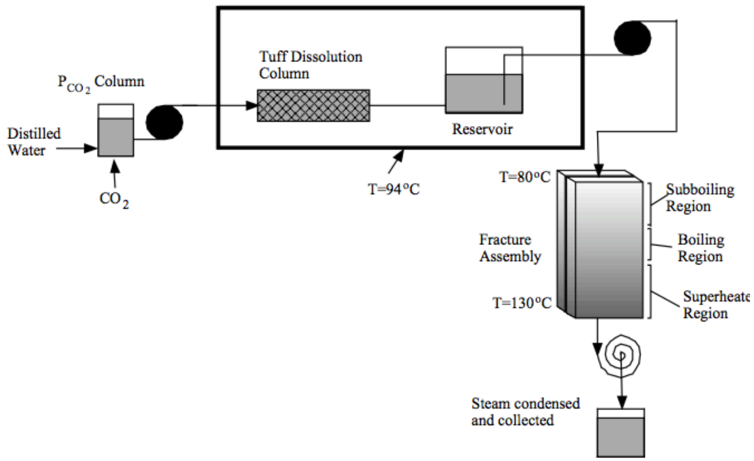


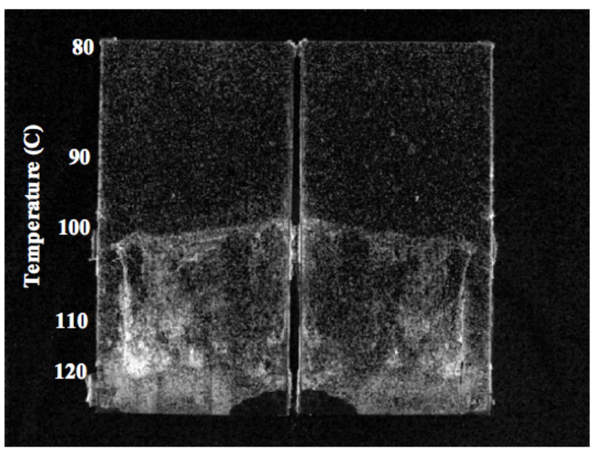
[Polak et al., GRL, 2003]

# Typical Response of Fractures (Precipitation)

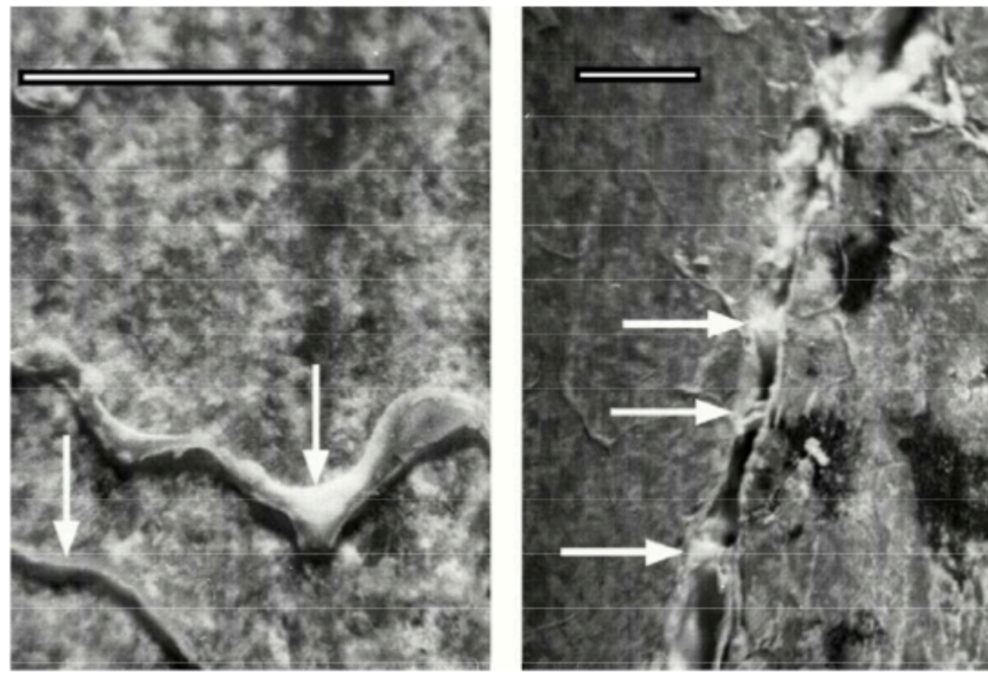
Experimental arrangement




Thermal gradient along fracture




Precipitation



[Dobson et al., 2001]

# Reactive Transport [1]

**Advection-Dispersion Equation**

$$\frac{\partial c_i}{\partial t} + \nabla \cdot (c_i \mathbf{u}) - \nabla \cdot (D_i \nabla c_i) = R_i + k_{i+}(c_i - c_i^{eq}) \tag{1}$$

**For the reaction:**

$$A + B \underset{k_2}{\overset{k_1}{\rightleftharpoons}} C \tag{2}$$

$$\begin{aligned} \text{Forward rate} &= k_1[A][B] \\ \text{Reverse rate} &= k_2[C] \end{aligned} \tag{3}$$

At equilibrium: Forward rate = Reverse rate

$$k_1[A][B] = k_2[C] \tag{4}$$

$$\therefore \quad [A][B] = \frac{k_2}{k_1}[C] \tag{5}$$

For closed system and one mole each of [A] and of [B], with $k_1 = 1$ and $k_2 = 10$, then:

$$\frac{[A][B]}{[C]} = \frac{(1 - X)^2}{X} = \frac{10}{1} \tag{6}$$

And $(1 - X) = [A] = [B] = 0.916$ and $X = [C] = 0.0839$.

# Reactive Transport [2]

**Implementation:**

$$\begin{aligned} R_A &= -k_1[A][B] &+& \; k_2[C] \\ R_B &= -k_1[A][B] &+& \; k_2[C] \\ R_C &= +k_1[A][B] &-& \; k_2[C] \end{aligned} \tag{7}$$

Generalized:

$$R_i = -k_i^{\,f} \prod_{j=1}^{N} [c_j^{\,f}]^{\alpha_j^{\,r}} + k_i^{\,r} \prod_{j=1}^{N} [c_j^{\,r}]^{\alpha_j^{\,r}} \tag{8}$$

Heats of reaction:

$$H_i = R_i \Delta H_i \tag{9}$$

And heat balance requires:

$$\rho c \frac{\partial T}{\partial t} + \nabla \cdot (T\,\mathbf{u}) - \nabla \cdot (\lambda \nabla T) = H_i \tag{10}$$

**Basic Observations of Permeability Evolution – Lab-to-field**

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**Reservoir-Scale Evolution of Permeability**

- Spatial distribution
- Timing
- Seismicity as an indicator

**Summary**

# Basic Observations of Permeability Evolution

## Observation

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

## Stress Changes

Inert changes (THM)
Reactive changes (MC)

## Understanding T H M C is key:

- **Size of relative effects of THMC**
- **Timing of effects**
- **Migration within reservoir**
- **Using them to engineer the reservoir**

## Resource

- **Hydrothermal (US:$10^4$ EJ)**
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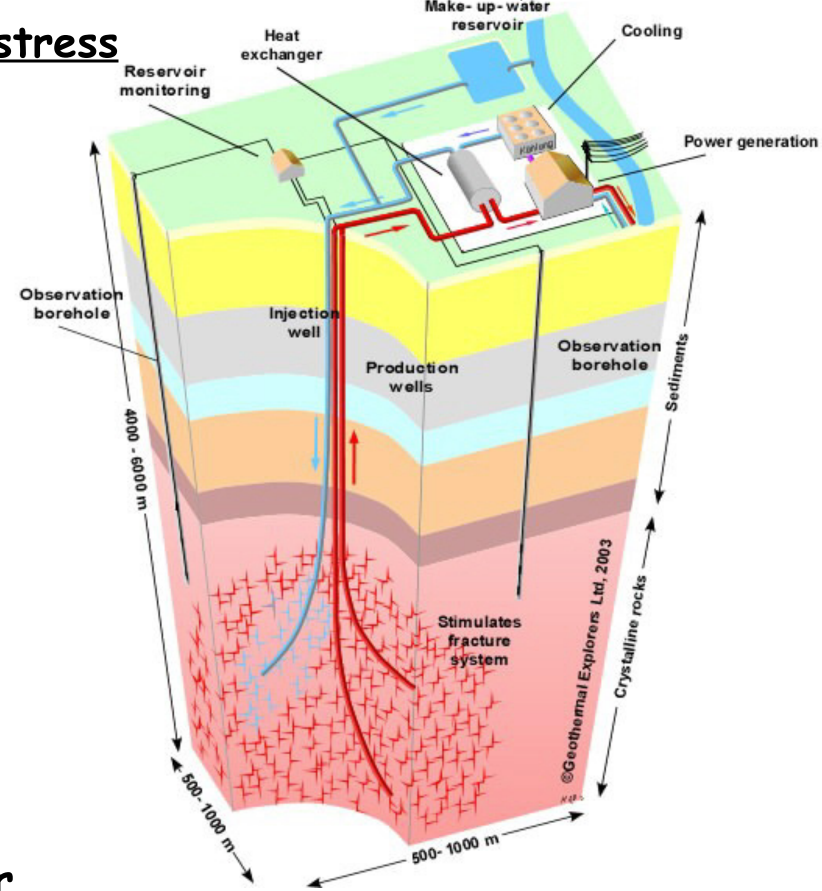
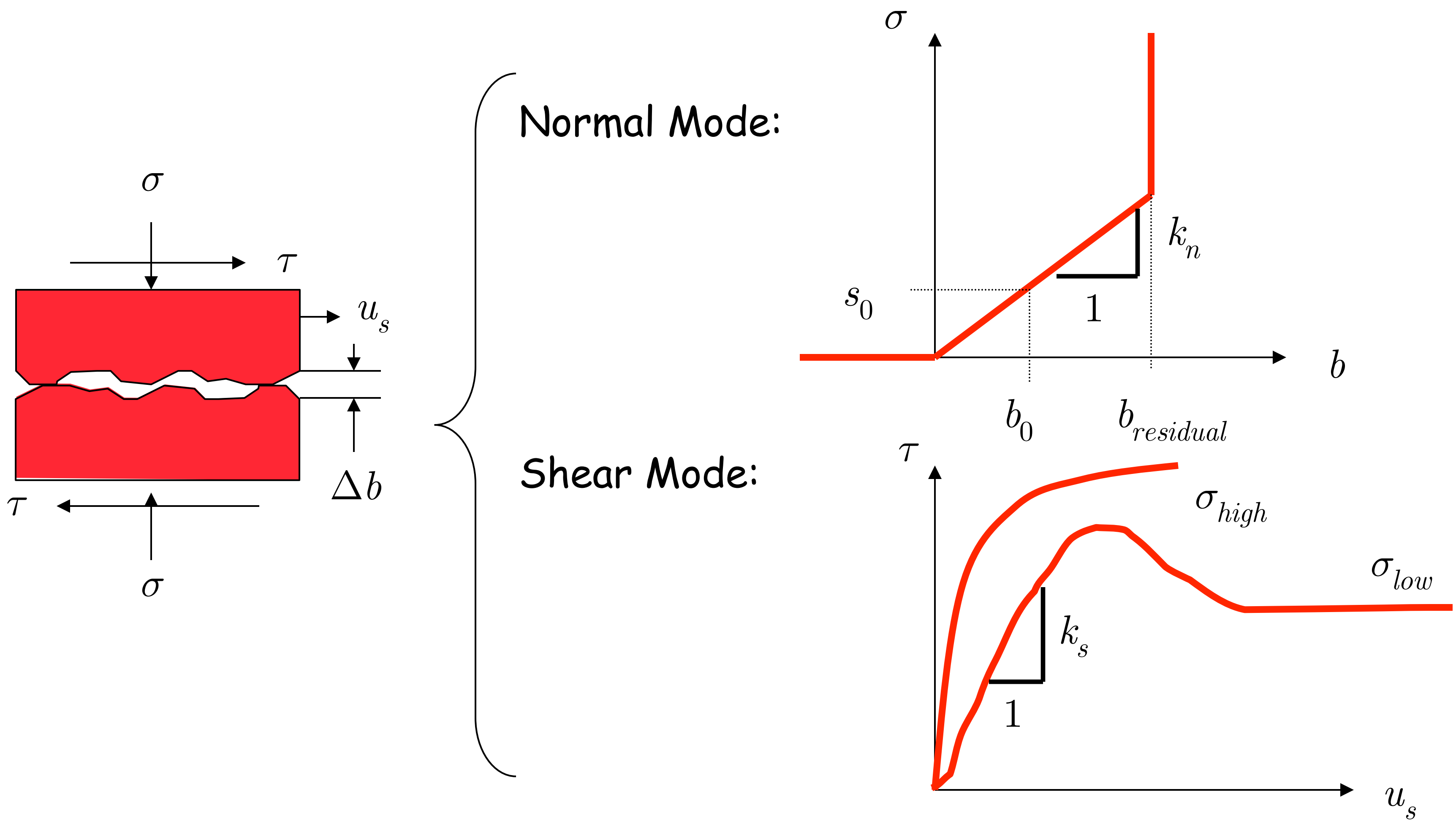


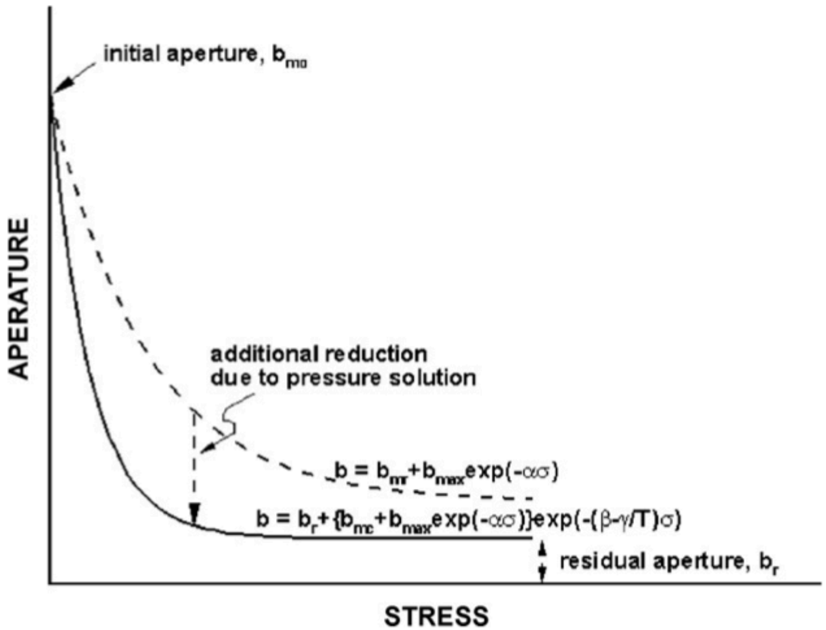

Permeability
Reactive surface area
Induced seismicity

# Permeability Changes in Fractures - Deformation



# Normal Compression of Fractures

Mechanical closure with stress

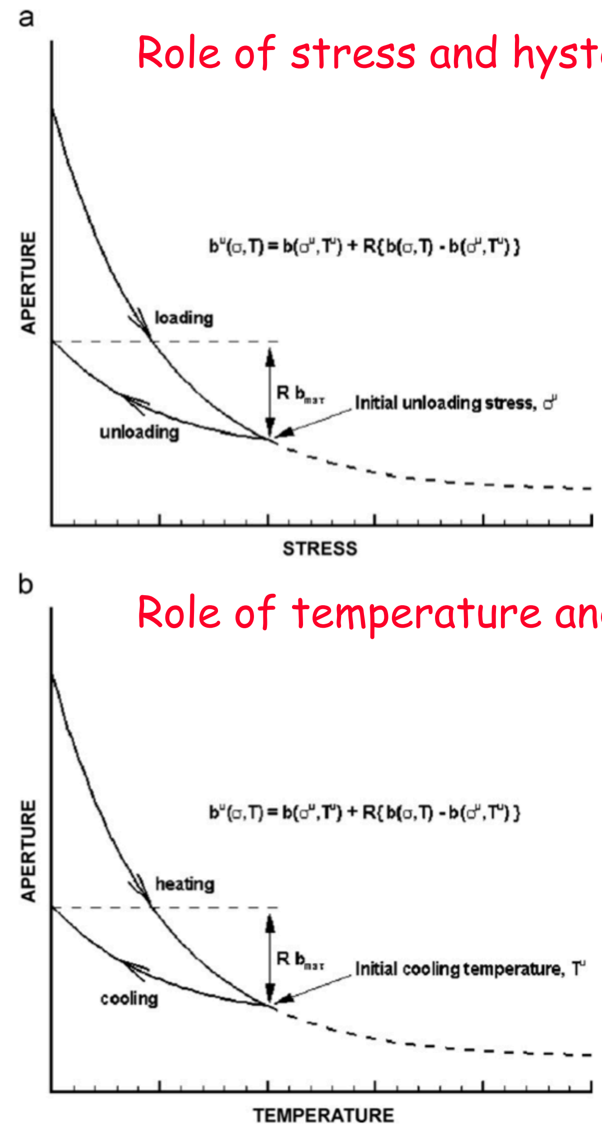



$$b_{normal} = b_r + b_{max}\exp(-\alpha\sigma')$$

$$\Delta b_{normal} = b_{max}\exp(-\alpha\Delta\sigma')$$

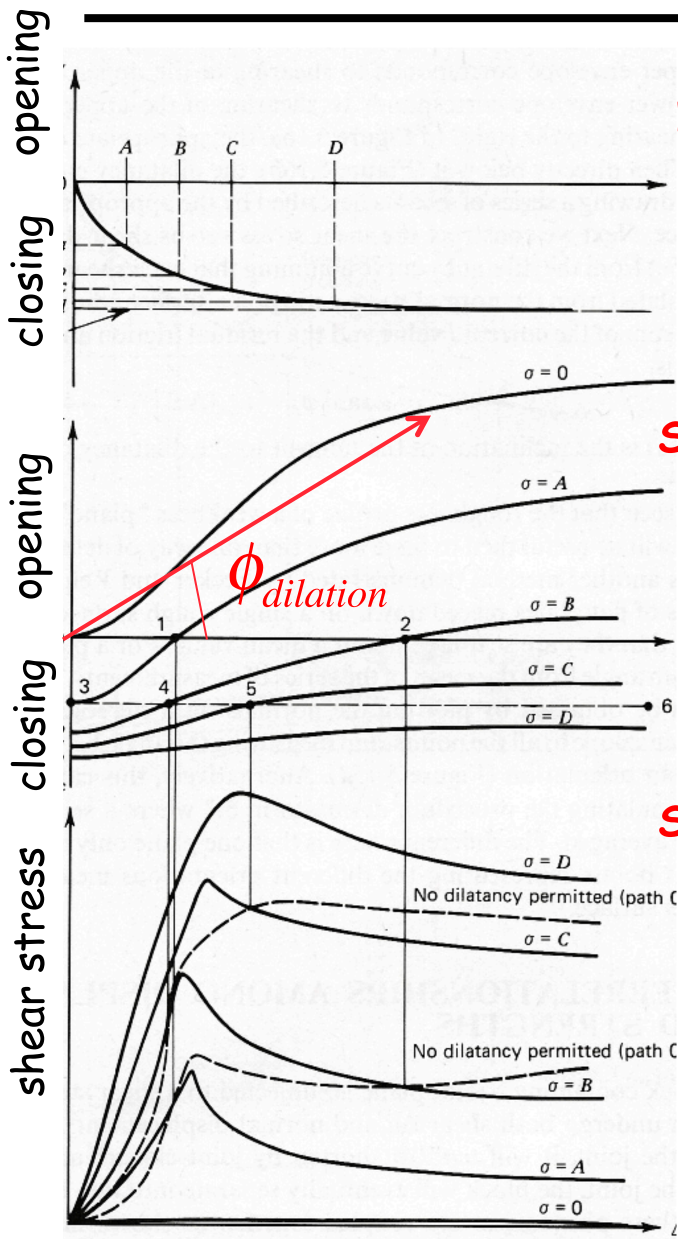
Role of stress and hysteresis

Role of temperature and hysteresis




[Min et al., IJRM, 2009]

# Shear Dilation of Fractures




Normal closure behavior

Shear dilatancy behavior

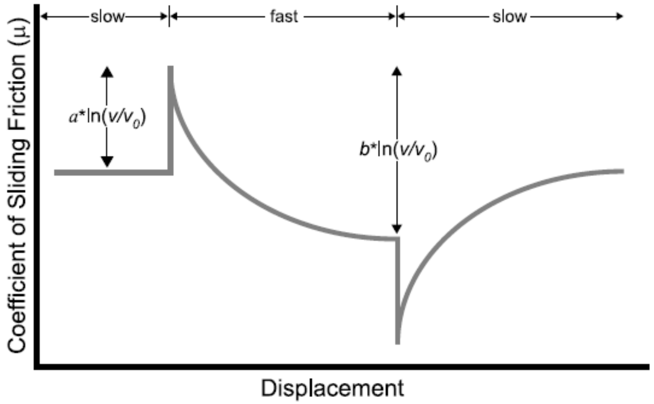
$$\Delta b_{shear} = \tau\left(\frac{s}{G} + \frac{1}{K_{shear}}\right)\tan(\phi_{dilation})$$

Stress-displacement behavior

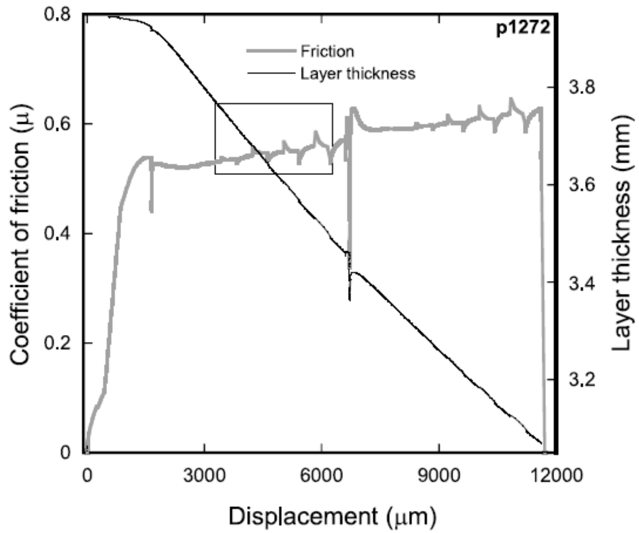
shear displacement

# Rate-State Friction [1]

## Velocity Steps




## Multiple Velocity Steps



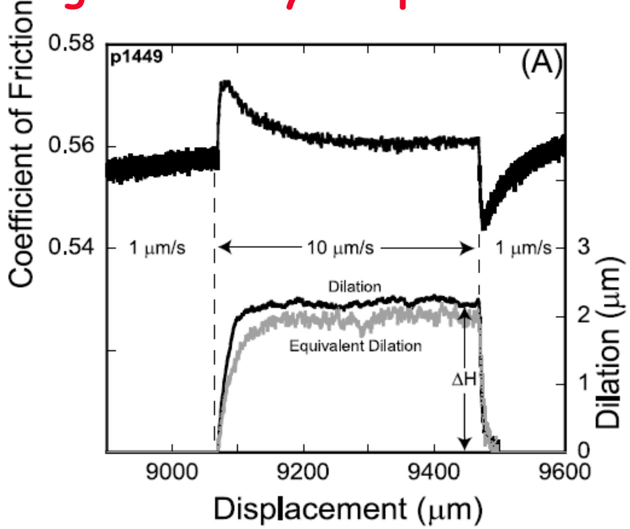

## R-S Friction

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

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

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

## Single Velocity Step




## Dilation

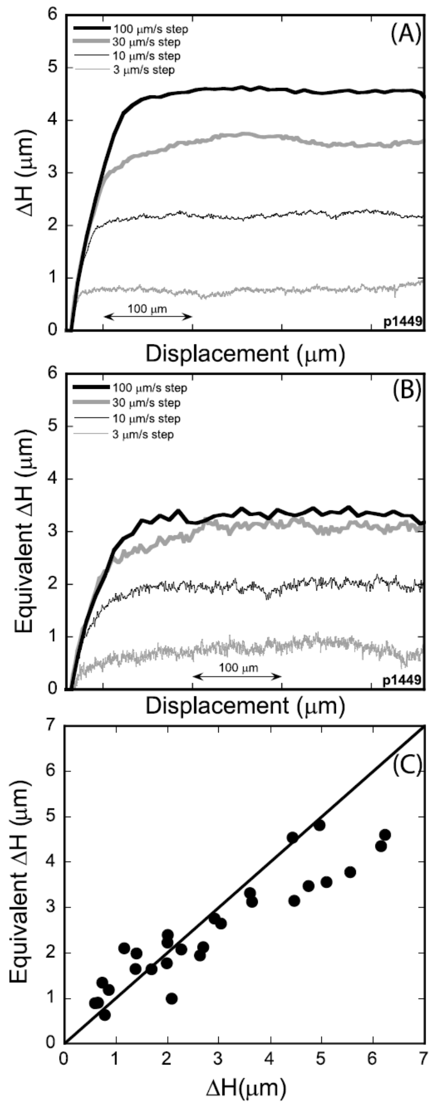
$$\frac{\Delta H}{H} \cong \Delta\phi = -\epsilon\ln\left(\frac{v}{v_0}\right) = -\epsilon\ln\left(\frac{v_0\theta}{D_c}\right)$$

## Permeability Evolution

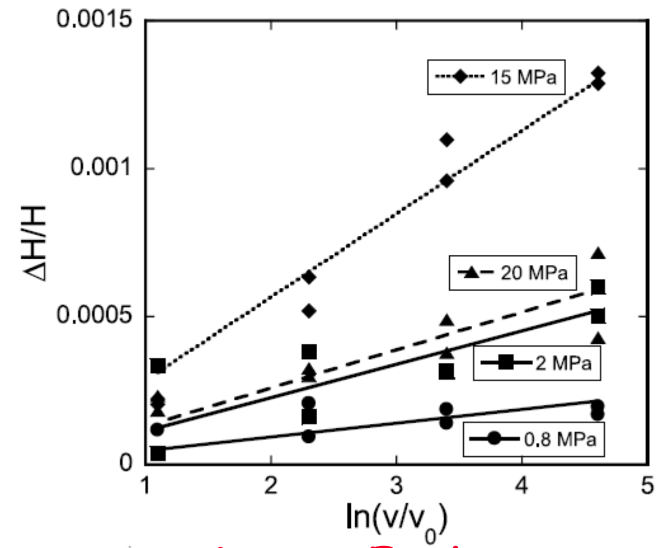
$$\frac{k}{k_0} = \left(1+\frac{\Delta b}{b_0}\right)^3 = \left(1+\frac{\Delta H}{H}\right)^3$$

# Rate-State Friction [2]

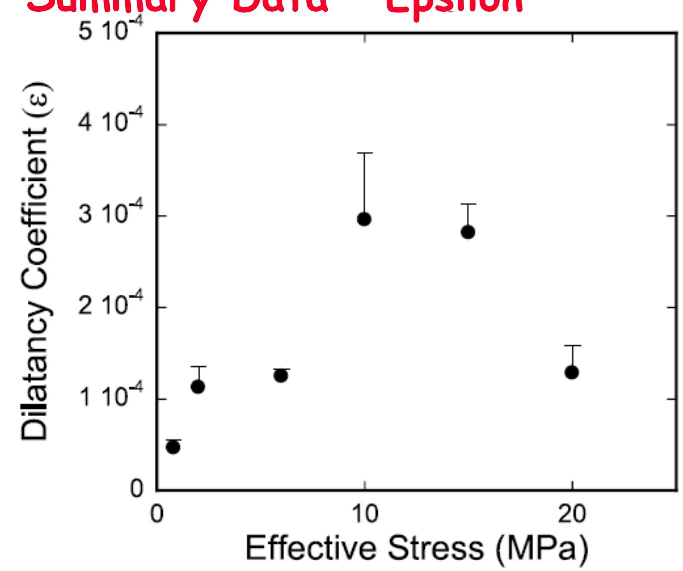
## Concurrent Displacement and Fluid Measurements



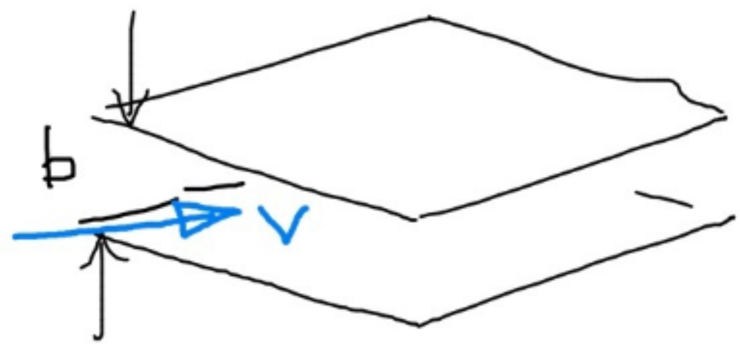

## Summary Data – Delta H

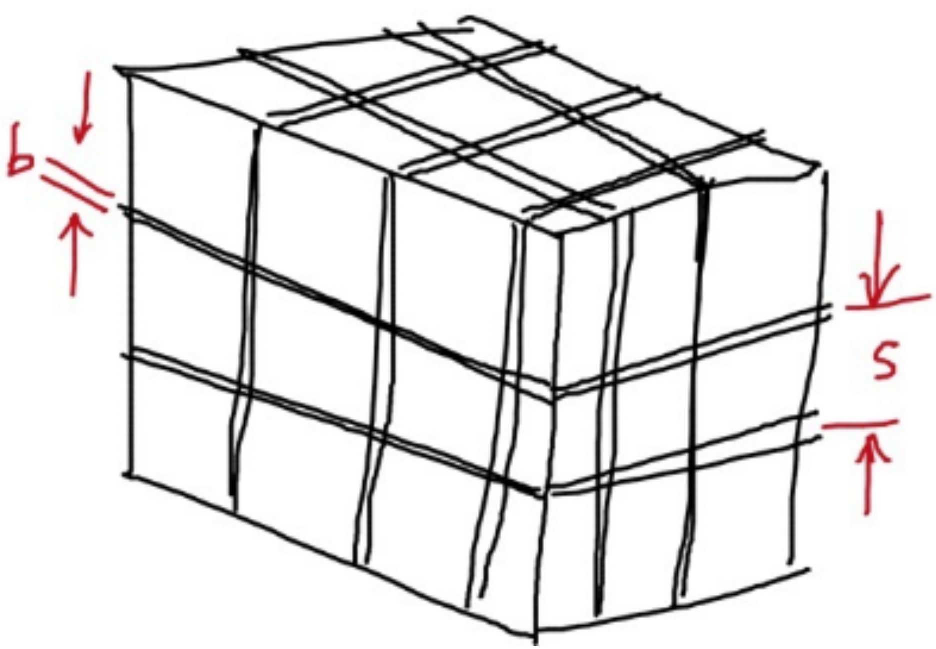



## Summary Data – Epsilon



# Porosity-Permeability Relationships




Single fracture versus bulk permeability

Single: $$\bar{v}_i = \frac{k_i}{\mu}\frac{\partial p}{\partial x} = \frac{b^2}{12}\frac{1}{\mu}\frac{\partial p}{\partial x}$$

Bulk: $$\bar{v}_b = \frac{b}{s}\bar{v}_i = \frac{b^3}{12s}\frac{1}{\mu}\frac{\partial p}{\partial x} = \frac{k_b}{\mu}\frac{\partial p}{\partial x}$$

Bulk permeability

$$k = \frac{b^3}{12s};\ \text{therefore}\ k_0 = \frac{b_0^3}{12s}$$

Initial fracture aperture ($b_0$)

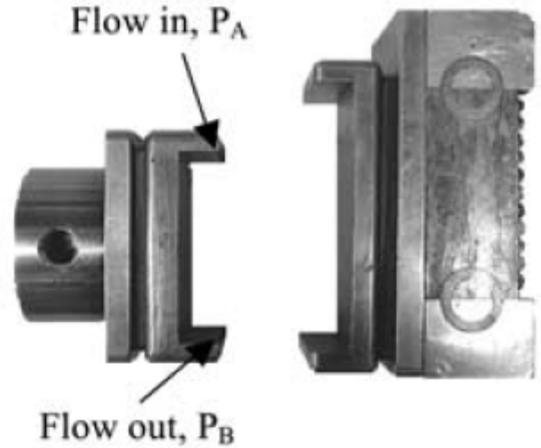
$$b_0 = \sqrt[3]{k_0 12s}$$

Change to new permeability (k)

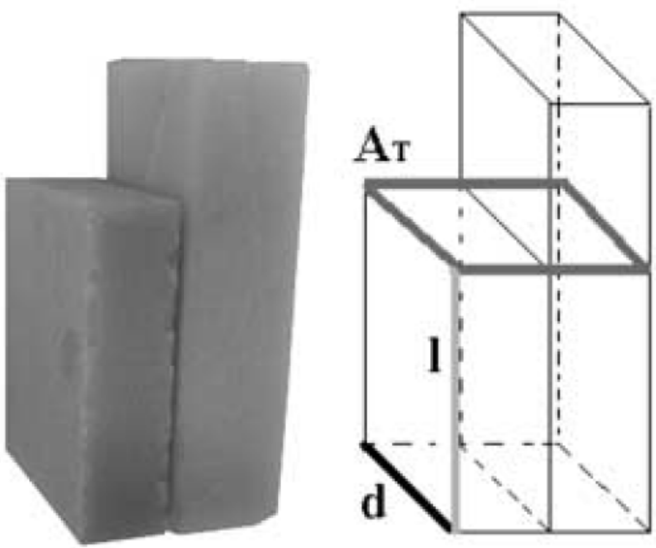
$$\frac{k}{k_0} = (1 + \frac{\Delta b}{b_0})^3$$

# Role of Wear Products

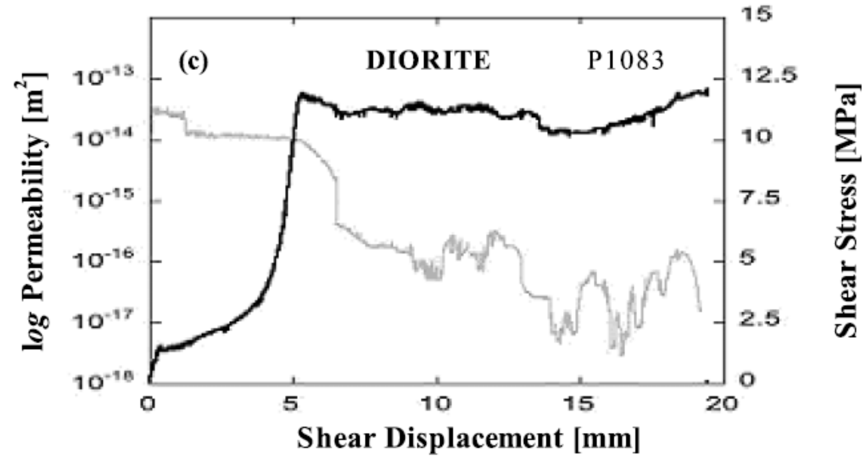
## Sample Holder



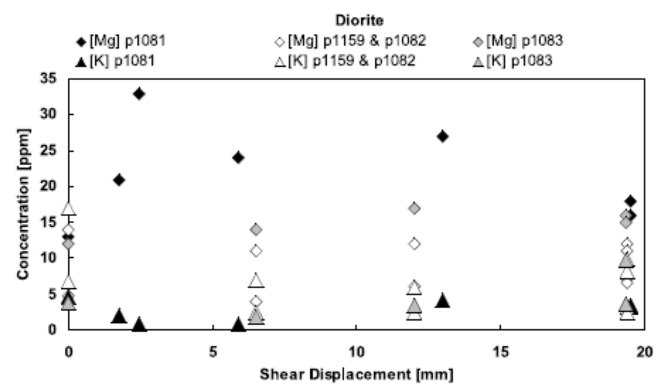

## Sample




## Shear-Permeability Evolution




## Dissolution Products



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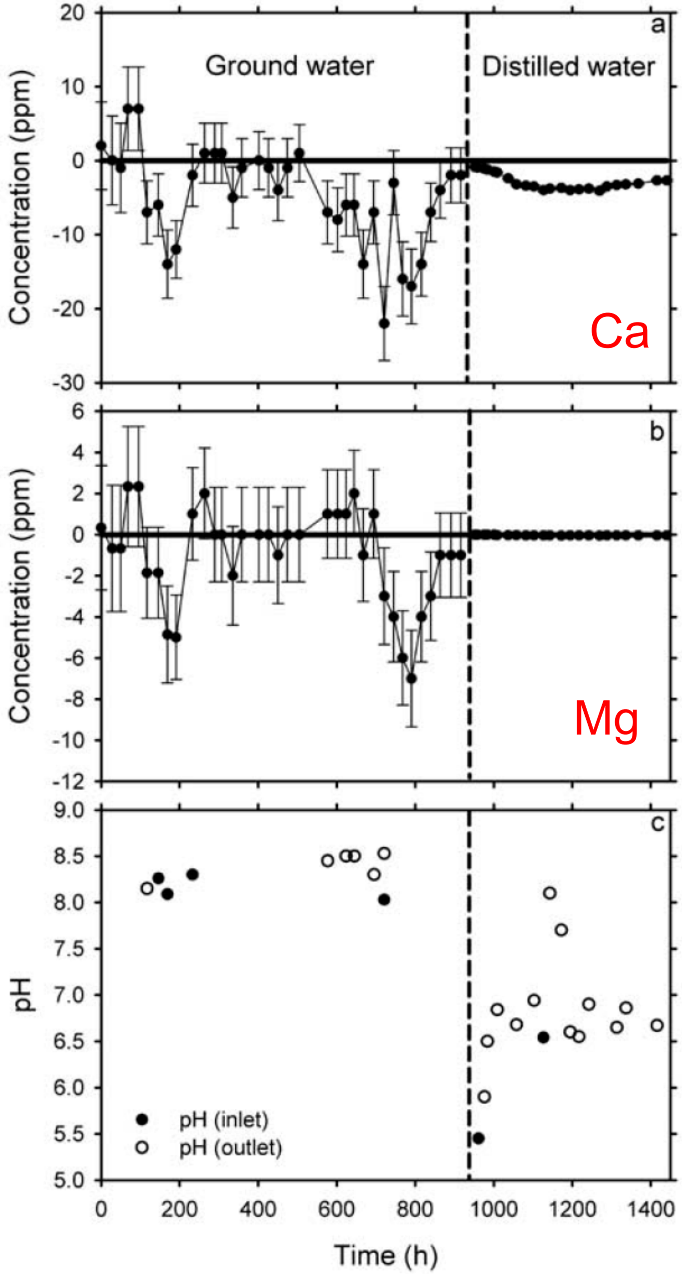
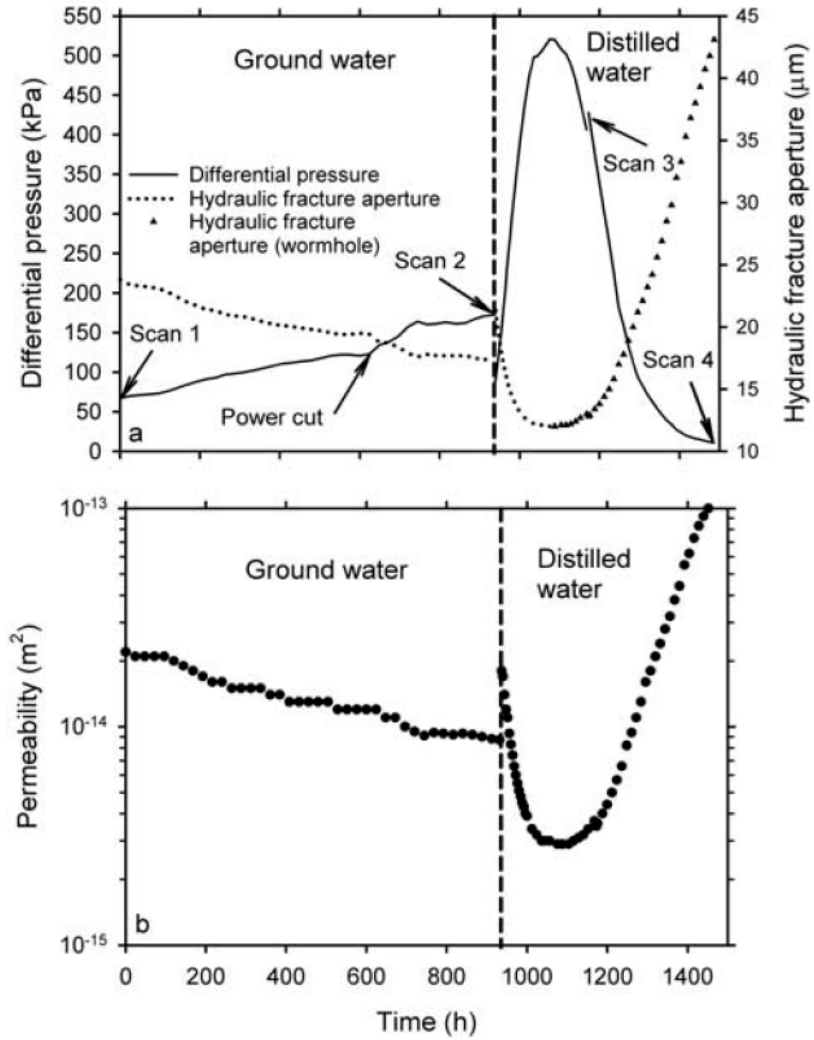
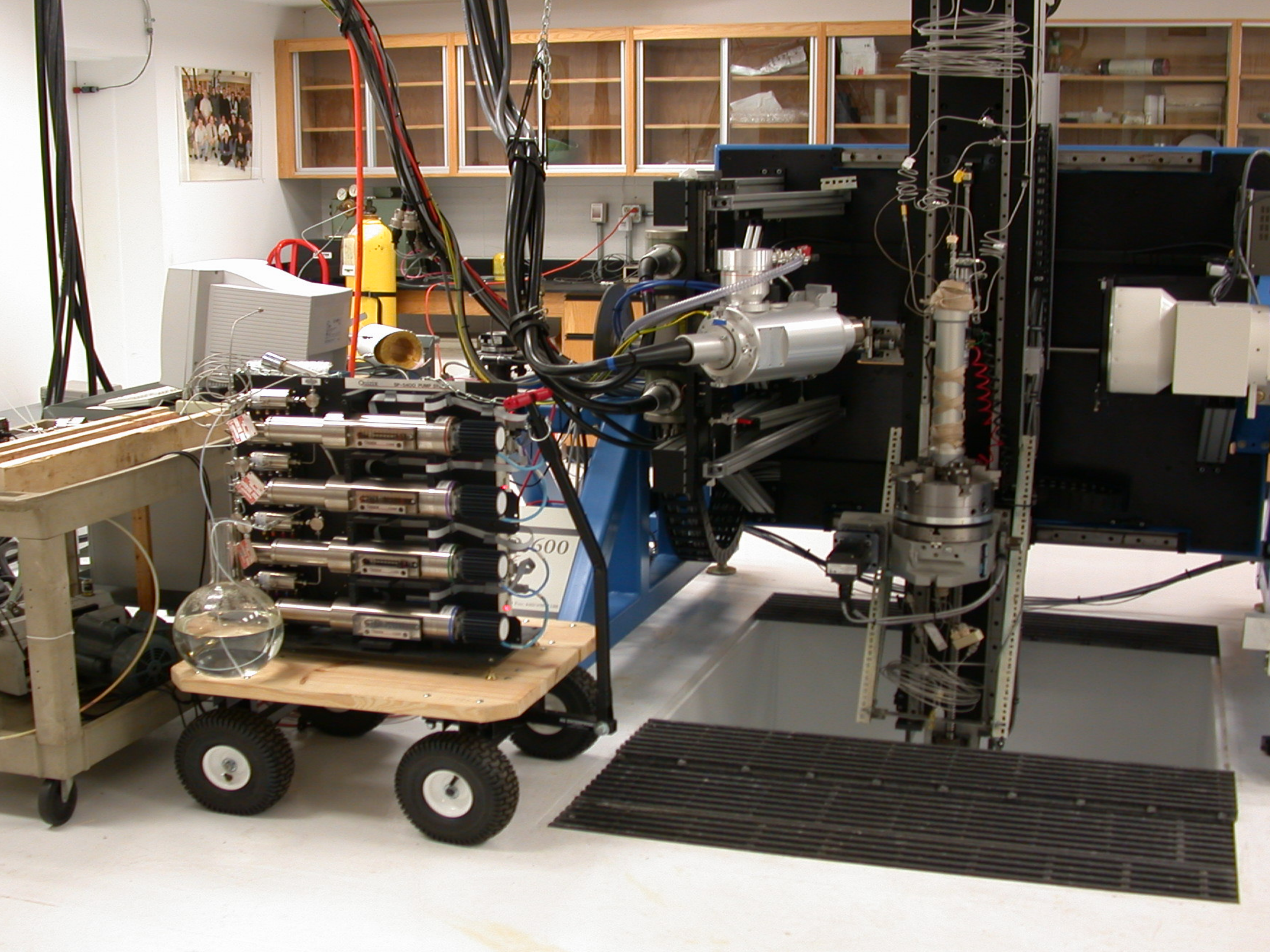
**Summary**

# Fractured Limestone – Features of Response



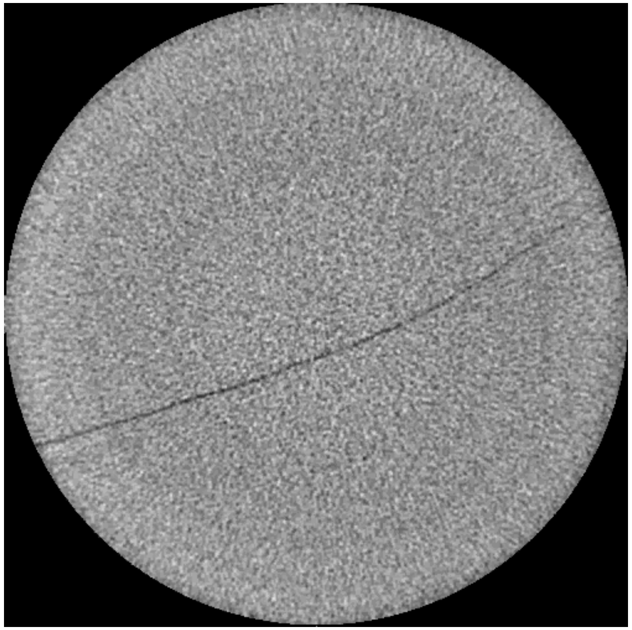




[Polak et al., WRR, 2004]

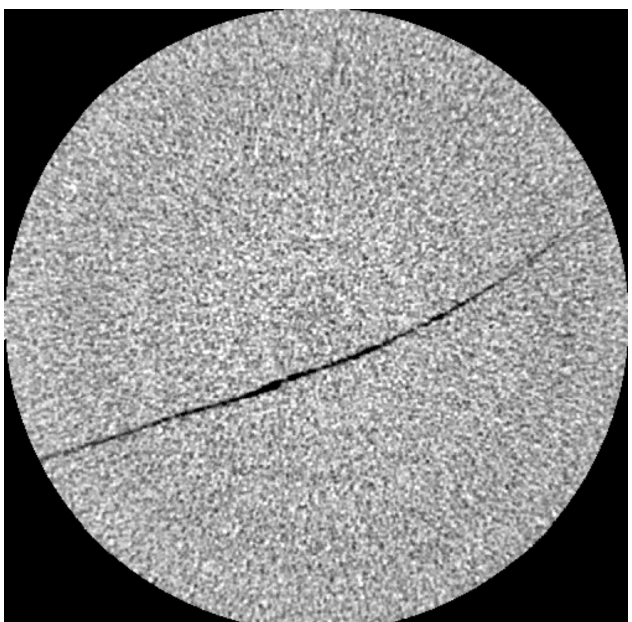


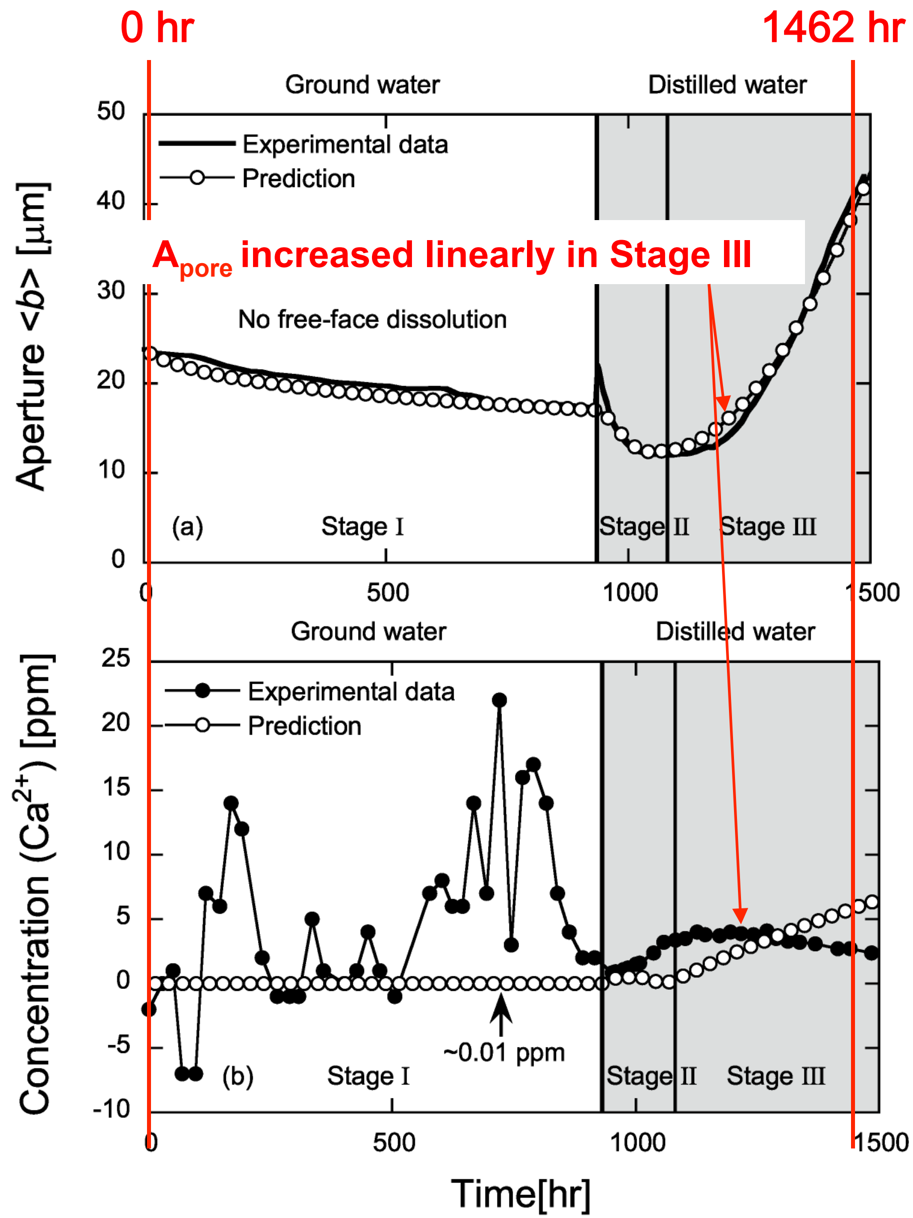
# Fractured Limestone – Features of Response

0 hr



1462 hr





# Reactive - Hydrodynamic Controls

## Peclet No. (Pe)

$$Pe = \frac{\text{Advective flux}}{\text{Dispersive flux}} = \frac{\langle q \rangle}{D_m} = \frac{v b_0}{D_m}$$

Pe < 1 Dispersion dominated –
Perturbations damped

Pe > 1 Advection dominated –
Perturbations enhanced

## Damkohler No. (Da)

$$Da = \frac{\text{Reactive flux}}{\text{Advective flux}} = \frac{2k_+ L}{\langle q \rangle} = \frac{2k_+ L}{v b_0}$$

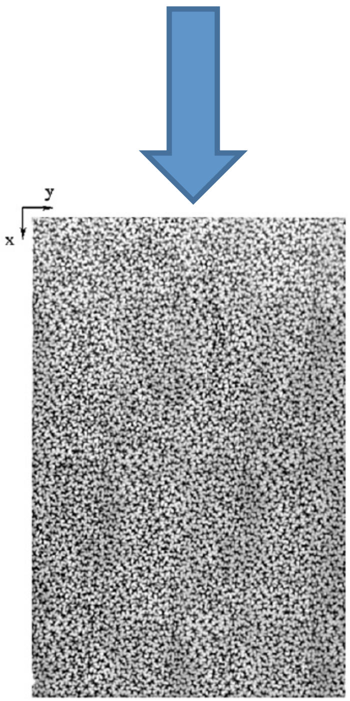
Da << 1 Reaction slow -
Undersaturated along fracture –
Perturbations damped

Da larger << 1 – Reaction faster
Saturated along fracture –
Perturbations enhanced

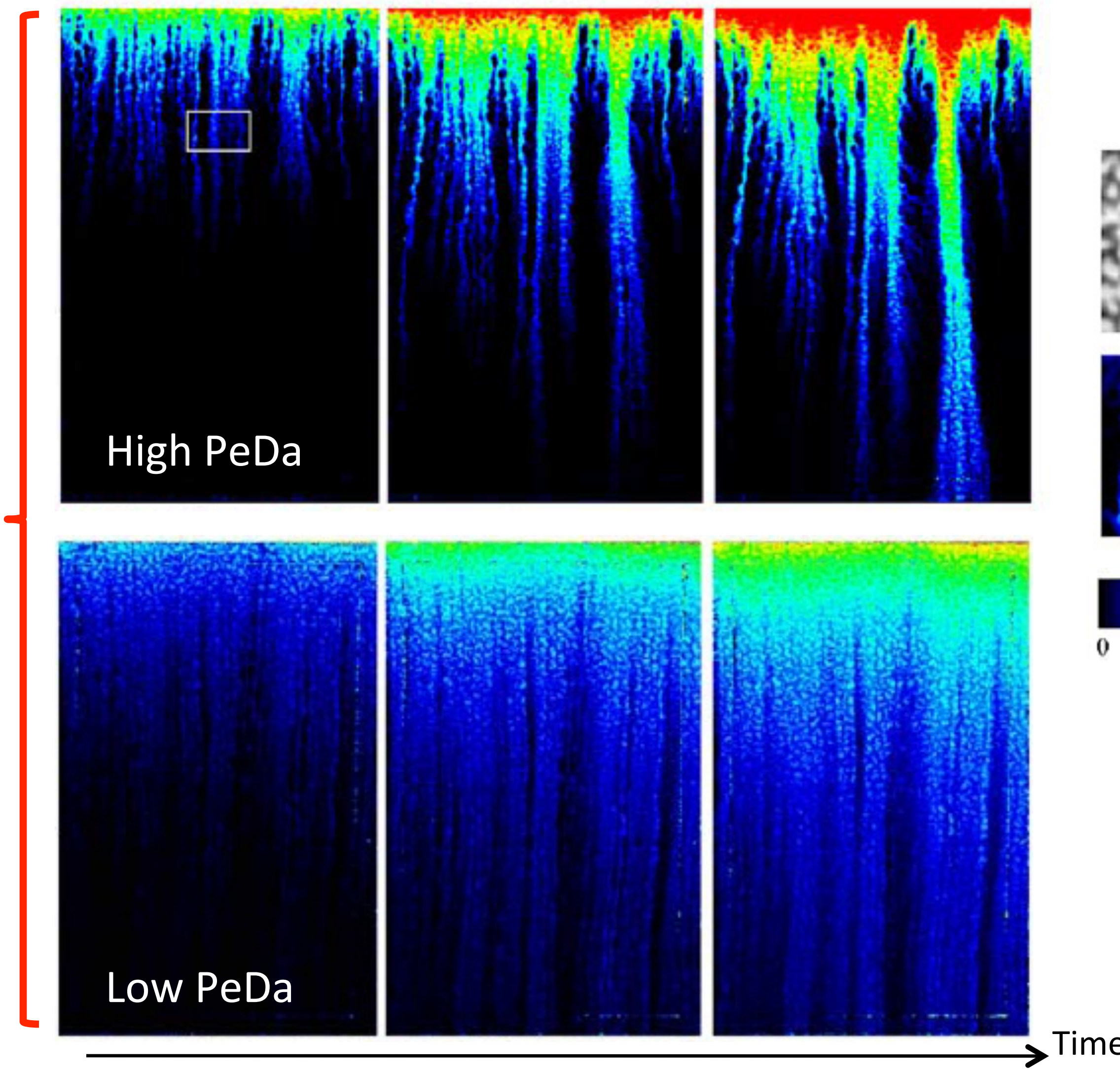
## PeDa No. (Removes <q>)

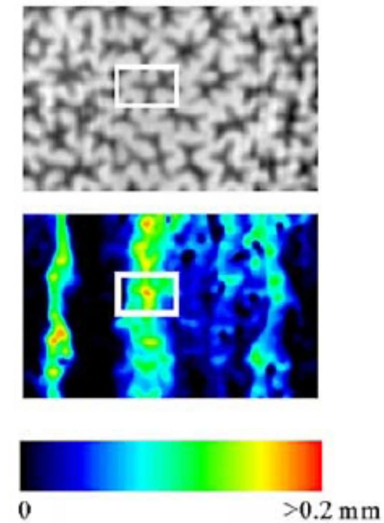
$$Pe.Da = \frac{\text{Reactive flux}}{\text{Dispersive flux}} = \frac{2k_+ L}{D_m}$$

# Reactive Hydrodynamics: Role of Damkohler Number (PeDa)




15 cm x 10cm
Voxel = 1 mm
Aperture:
Black (0)-
White(0.25mm)




[Detwiler and Rajaram, WRR, 2007]

# Reactive - Mechanical Controls

## Stress-Assisted Dissolution (PS)

$$\frac{dM_{diss}^{PS}}{dt} = \frac{3\pi V_m^2 (\sigma_a - \sigma_c) k_+ \rho_g d_c^2}{4RT}$$

## Free-Face Effects (FF)

Dissolution (diss)

$$\frac{dM_{diss}^{FF}}{dt} = k_+ A_{pore} \rho_g V_m \left(1 - \frac{C_{pore}}{C_{eq}}\right)^n$$

Precipitation (prec)

$$\frac{dM_{prec}}{dt} = k_- A_{pore} \rho_g V_m \left(\frac{C_{pore}}{C_{eq}} - 1\right)^n$$

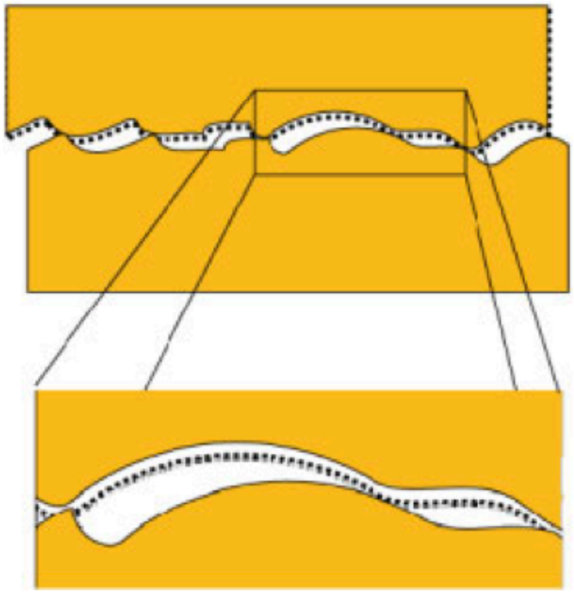
## Mass-Flux Ratio

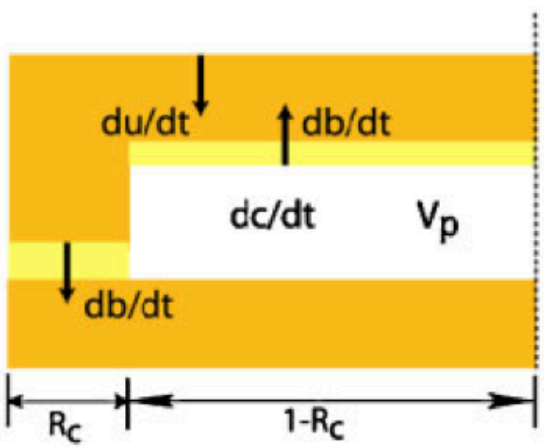
$$\chi = \frac{\text{Stress-Driven Flux}}{\text{Dissolution-Driven Flux}}$$

$$\chi = \left(\frac{\dot{M}^{PS}}{\dot{M}^{FF}}\right)_{diss} = \frac{3\pi}{4} \frac{d_c^2}{A_{pore}} \frac{V_m}{RT} \frac{(\sigma_a - \sigma_c)}{(1 - C_{pore}/C_{eq})^n}$$

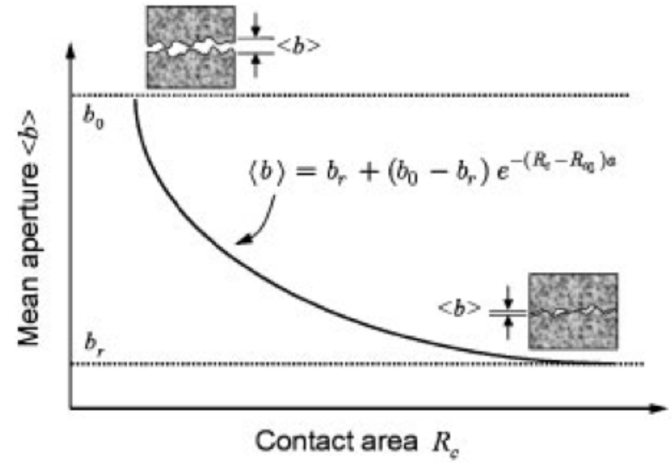
# Modes of Permeability Evolution

Fracture dilation and closure






Fracture closure




Change in aperture (positive in dilation):

$$\Delta b = \frac{\partial b}{\partial t}\Delta t$$

Link aperture change to fracture volume (porosity) change:

$$\frac{\partial b}{\partial t} = -\frac{\partial \cancel{V}_{ps}}{\partial t}\frac{1}{R_c A_f} + \frac{\partial \cancel{V}_{ff}}{\partial t}\frac{1}{(1-R_c)A_f}$$

Link fracture volume (porosity) change to fluid concentration change:

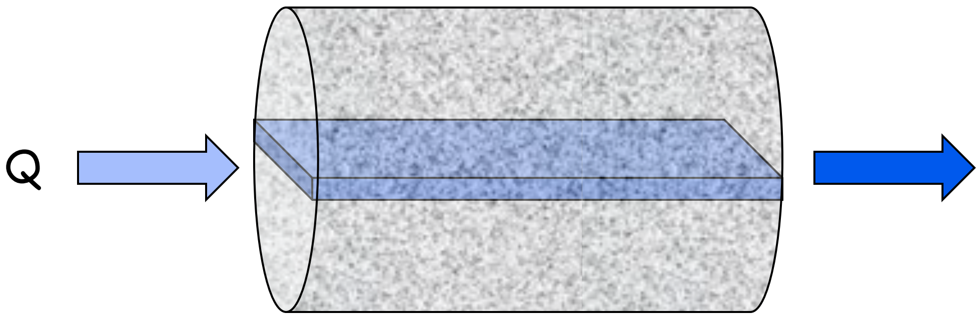
$$\frac{\partial \cancel{V}_i}{\partial t} = \begin{cases} -\dfrac{\partial c_{ps}}{\partial t}\dfrac{\cancel{V}_p}{\rho} \\ +\dfrac{\partial c_{ff}}{\partial t}\dfrac{\cancel{V}_p}{\rho} \end{cases}$$

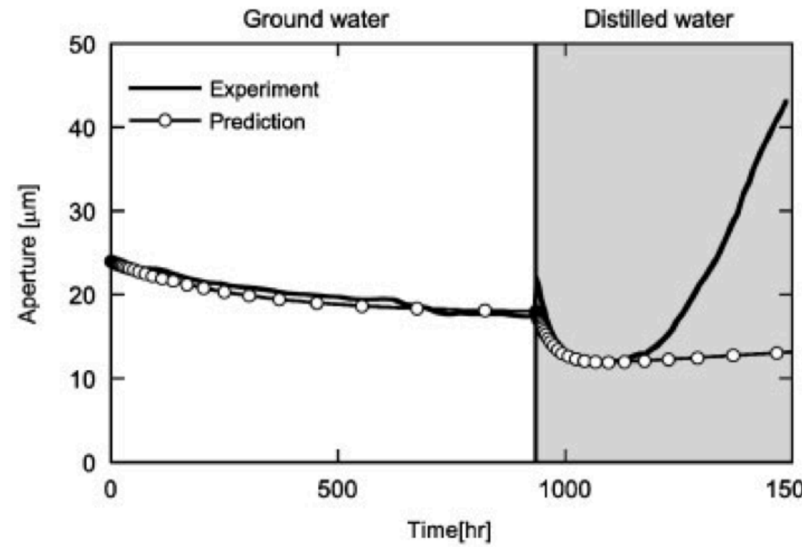
[Elsworth and Yasuhara, IJNAMG, 2009]

# Modes of Lumped Parameter Permeability Evolution

Isothermal response

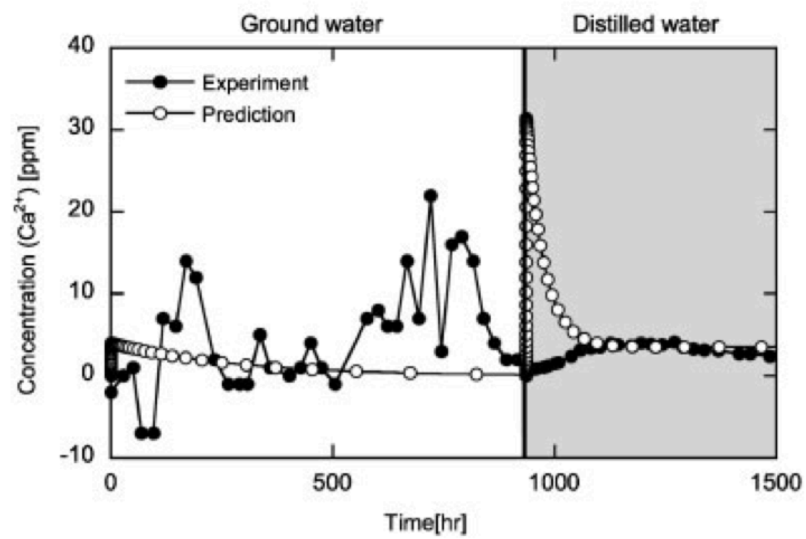
Flow geometry




Lumped mass balance equation

$$\frac{\partial c}{\partial t} \underbrace{- A e^{-Ft}}_{-\partial c_{ps}/\partial t} + \underbrace{B(c - c_{eq})}_{-\partial c_{ff}/\partial t} + \underbrace{Q\,(c - c_{in})}_{-\partial c_{Q}/\partial t} = 0$$

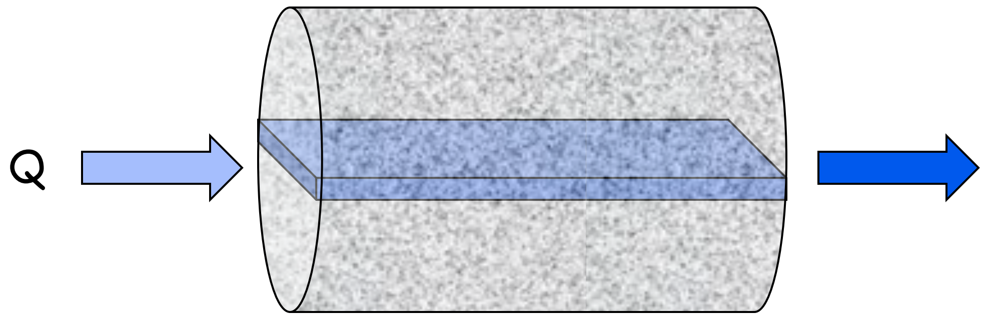


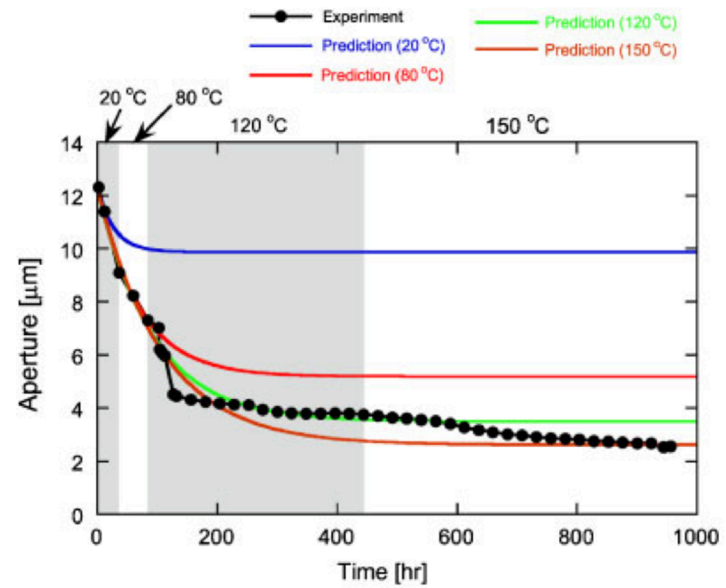

[Elsworth and Yasuhara, IJNAMG, 2009]

# Modes of Lumped Parameter Permeability Evolution

Non-isothermal response

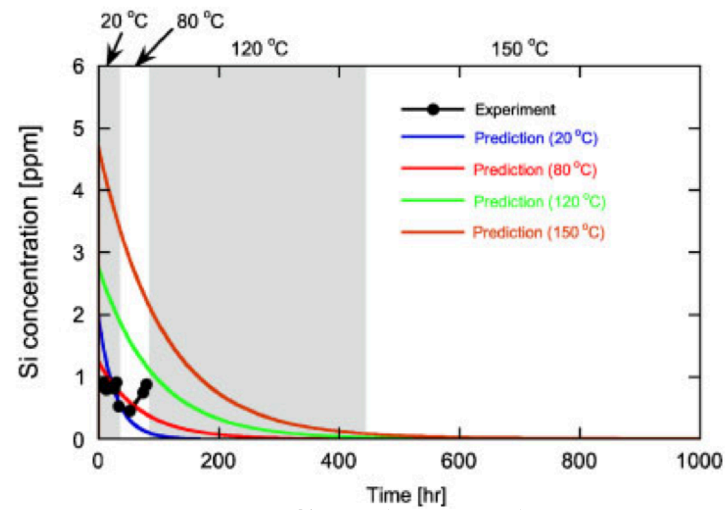
Flow geometry




Lumped mass balance equation

$$\frac{\partial c}{\partial t} \underbrace{- Ae^{-Ft}}_{-\partial c_{ps}/\partial t} + \underbrace{B(c-c_{eq})}_{-\partial c_{ff}/\partial t} + \underbrace{Q\,(c-c_{in})}_{-\partial c_{Q}/\partial t} = 0$$




[Elsworth and Yasuhara, IJNAMG, 2009]

# Component Model

Interface Dissolution

$$\frac{dM_{diss}}{dt} \approx \dot{\varepsilon}_{diss} \frac{d}{\omega} \rho_g \left( \frac{\pi}{4} d_c^2 \omega \right)$$

$$= \frac{3\pi V_m^2 \sigma_{eff} k_+ \rho_g d_c^2}{4RT}$$

$$\frac{dM_{diss}}{dt} = \frac{3\pi V_m^2 (\sigma_a - \sigma_c) k_+ \rho_g d_c^2}{4RT}$$

$$\sigma_c = \frac{E_m \left( 1 - T/T_m \right)}{4V_m}$$

Interface Diffusion

$$J = -D_b \frac{dC}{dx} \qquad J_m = -2\pi r \varpi D_b \left( \frac{dC}{dr} \right)_{r=d_c}$$

$$J_m = \frac{dM_{diff}}{dt} = \frac{2\pi \omega D_b}{\ln\left( d_c/2a \right)} \left( C_{\text{int}} - C_{pore} \right)$$

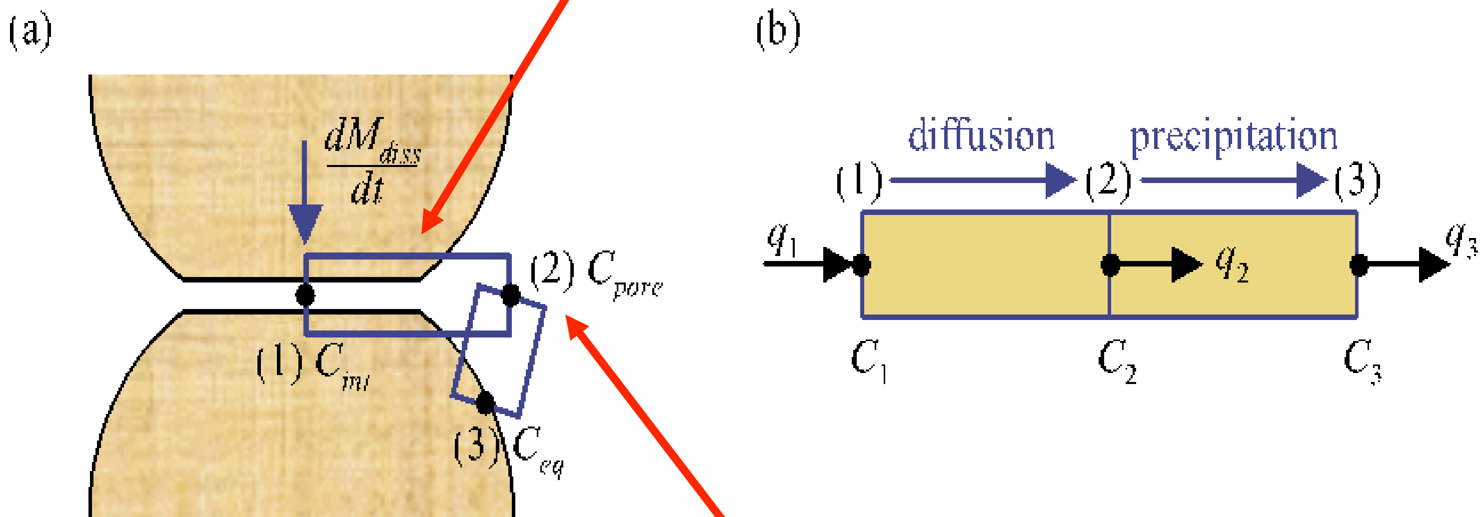
Pore Precipitation

$$\frac{dM_{prec}}{dt} = V_{pore} \frac{A}{M} k_- \left( C_{pore} - C_{eq} \right)$$

[Yasuhara et al., JGR, 2003]

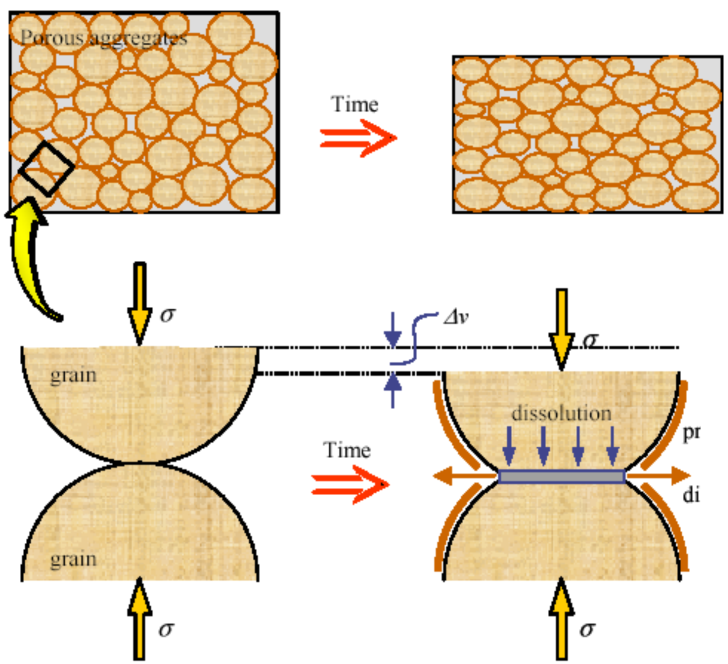
# Mass Transfer Modes – Essential Components

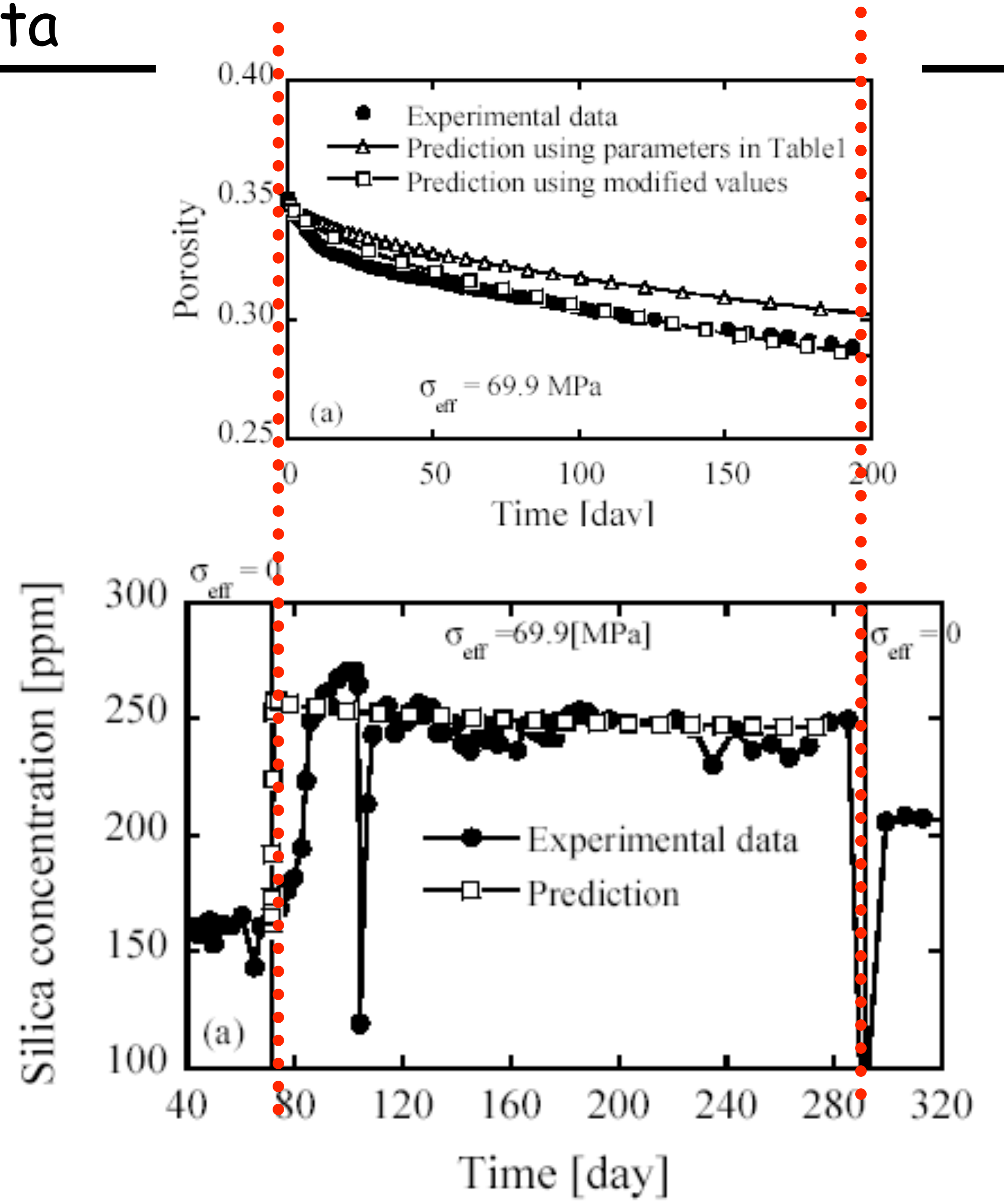
Contact geometry evolves with interpenetration




Pore concentration allows mass balance for arbitrarily open or closed systems

# Matching Compaction Data



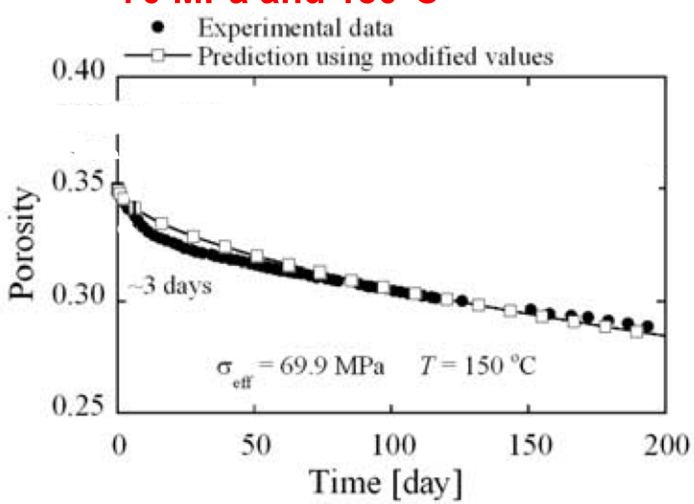




[Experimental data from Elias and Hajash, 1992]

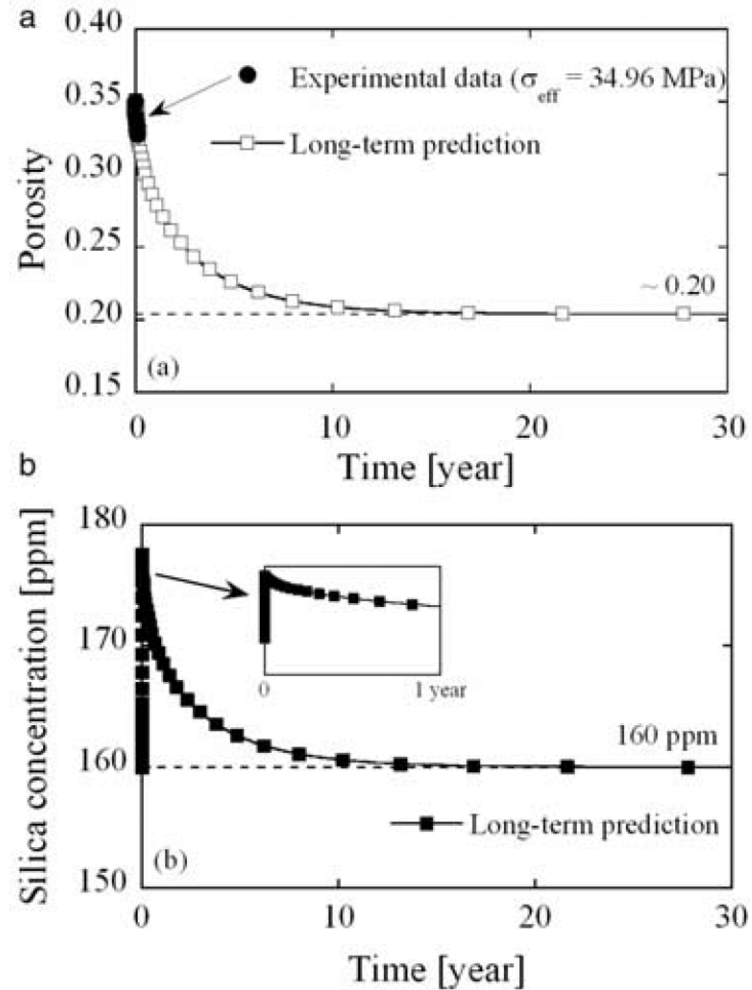
# System Evolution at 35-70 MPa and 150°C

**Observation** **Extension**

70 MPa and 150°C




35 MPa and 150°C

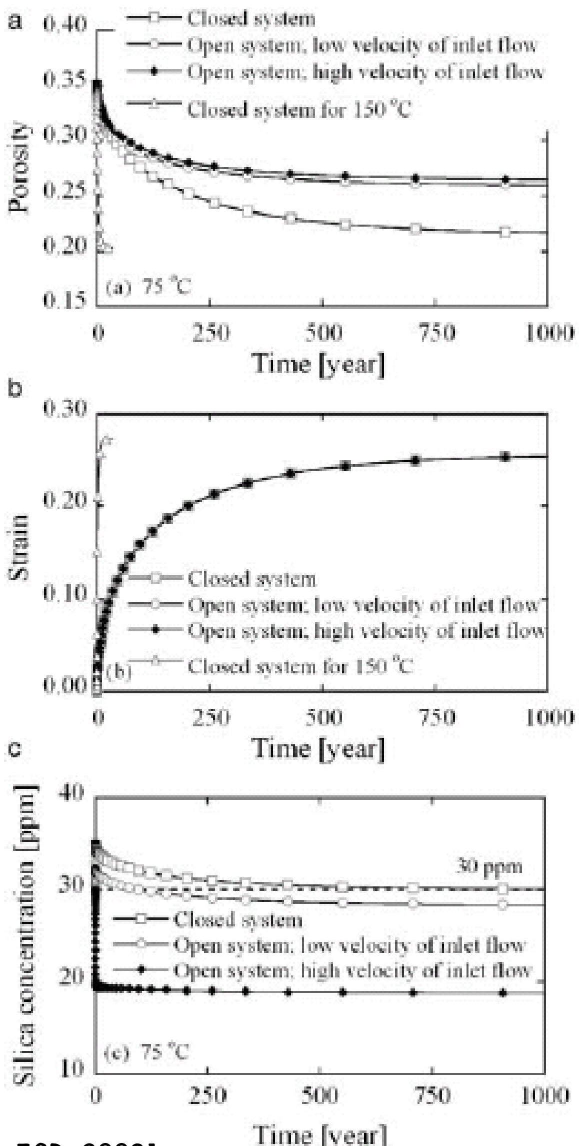



[Experimental data from Elias and Hajash, 1992]

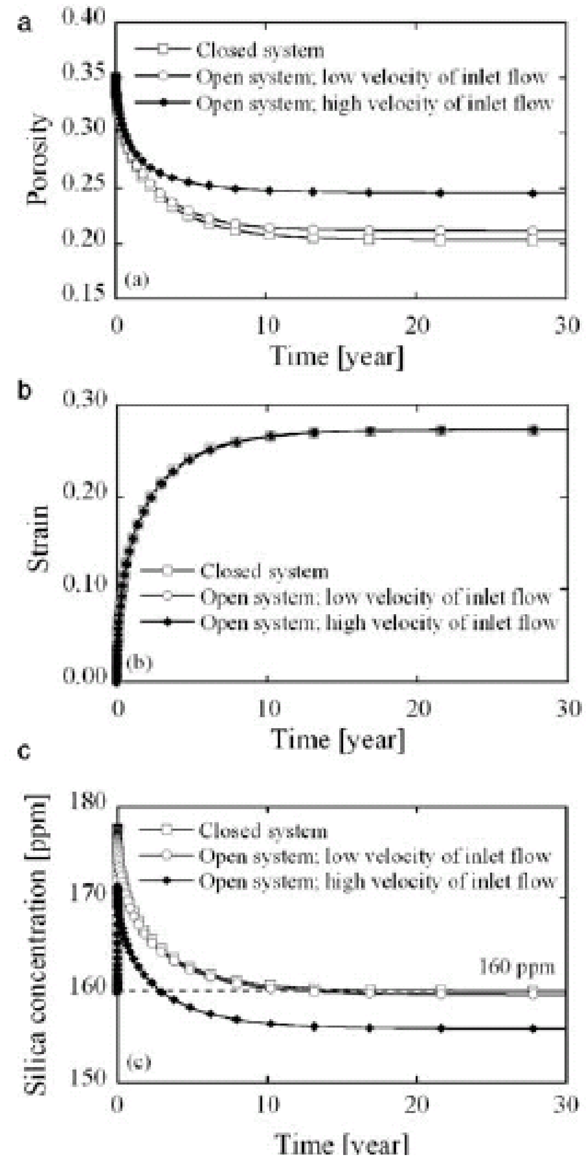
[Yasuhara et al., JGR, 2003]

# Timescales of Evolution of Granular Systems at 35 MPa and 75-150°C

75°C

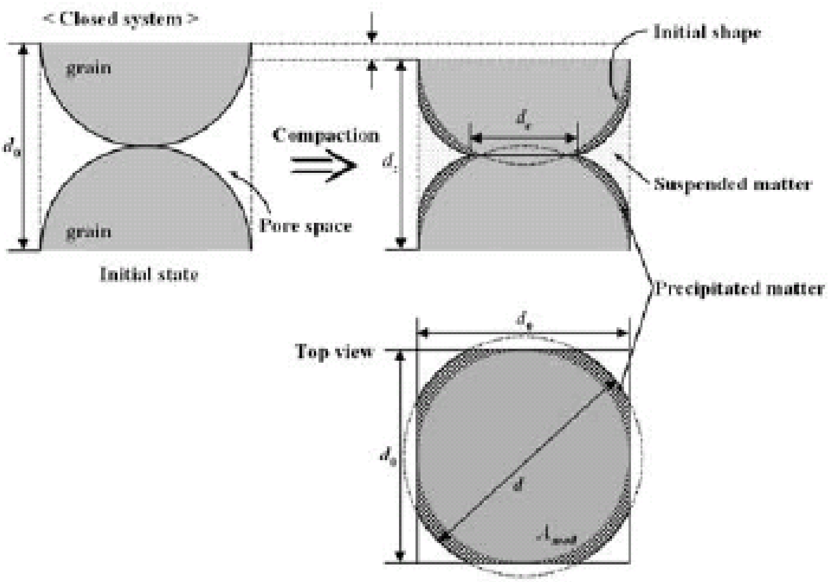



150°C

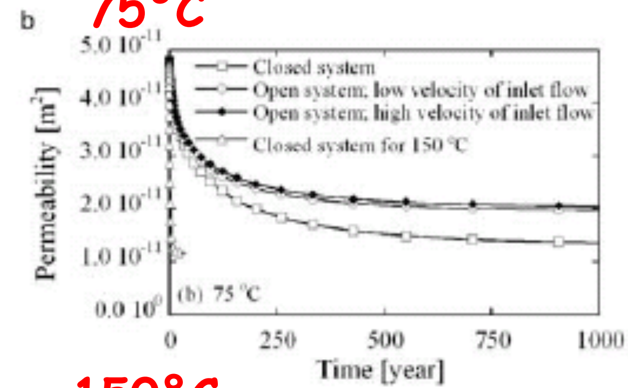



[Yasuhara et al., JGR, 2003]

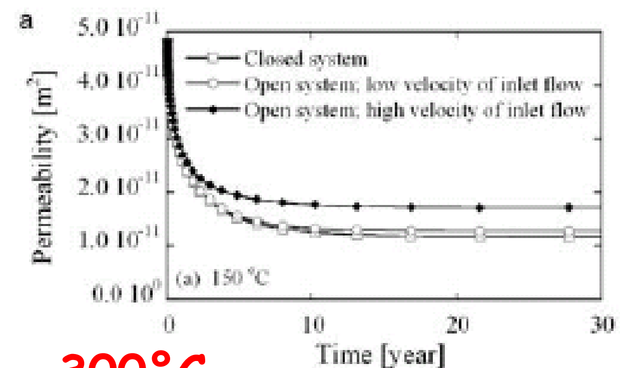
# Permeability Evolution in Granular Systems at 35 MPa and 75-300°C



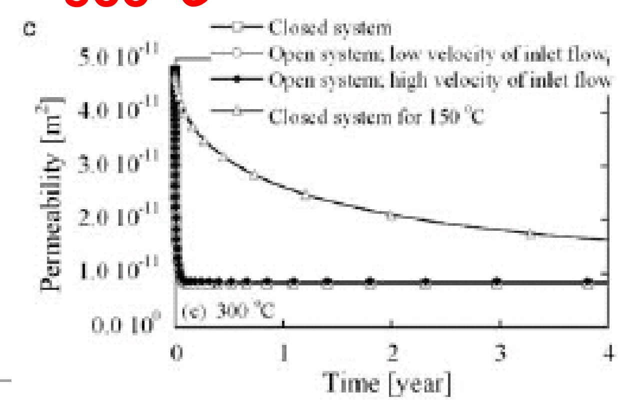

75°C




150°C




300°C



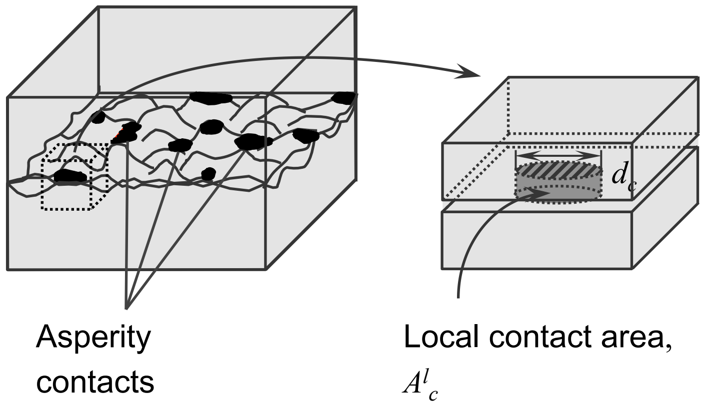

Capillary Model: $k = \dfrac{n\delta^2}{96}$

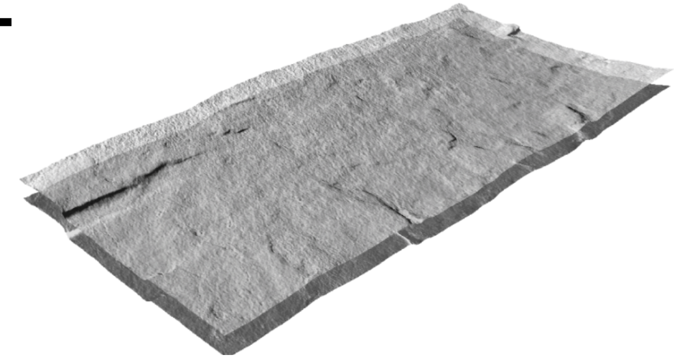
Pore Evolution: $V_p = (\pi/4)\delta^2 d_0$

Linked Permeability: $k \sim \dfrac{nV_p}{24\pi d_0}$

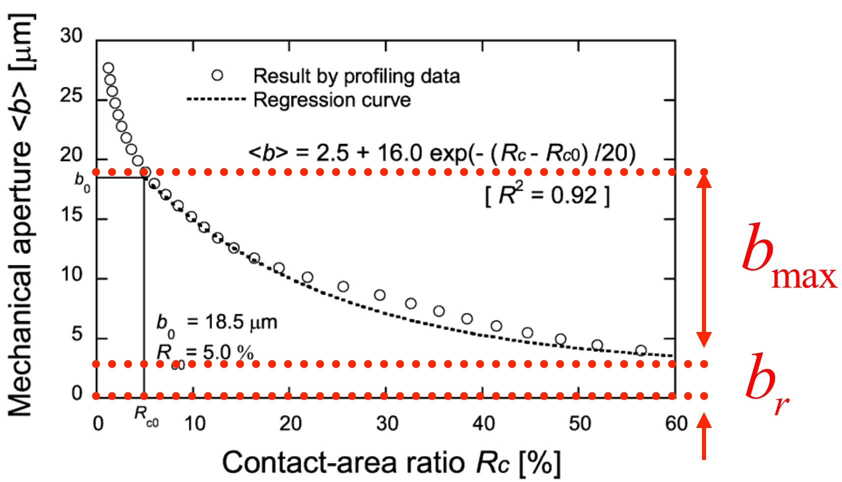
[Yasuhara et al., JGR, 2003]

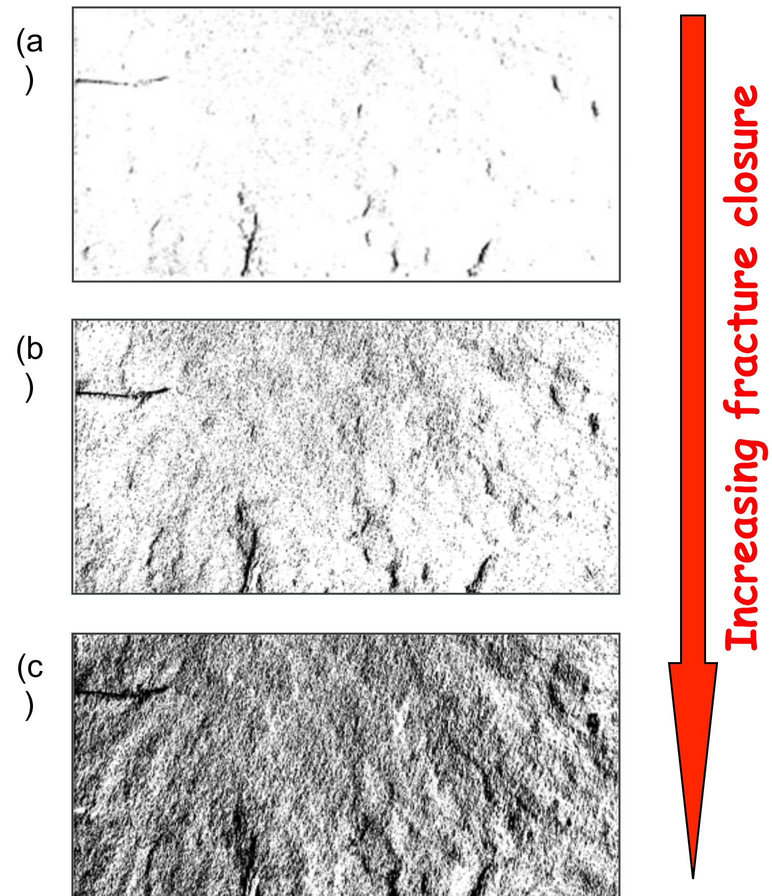
# Constraint on Fracture Apertures and Fluid Concentrations



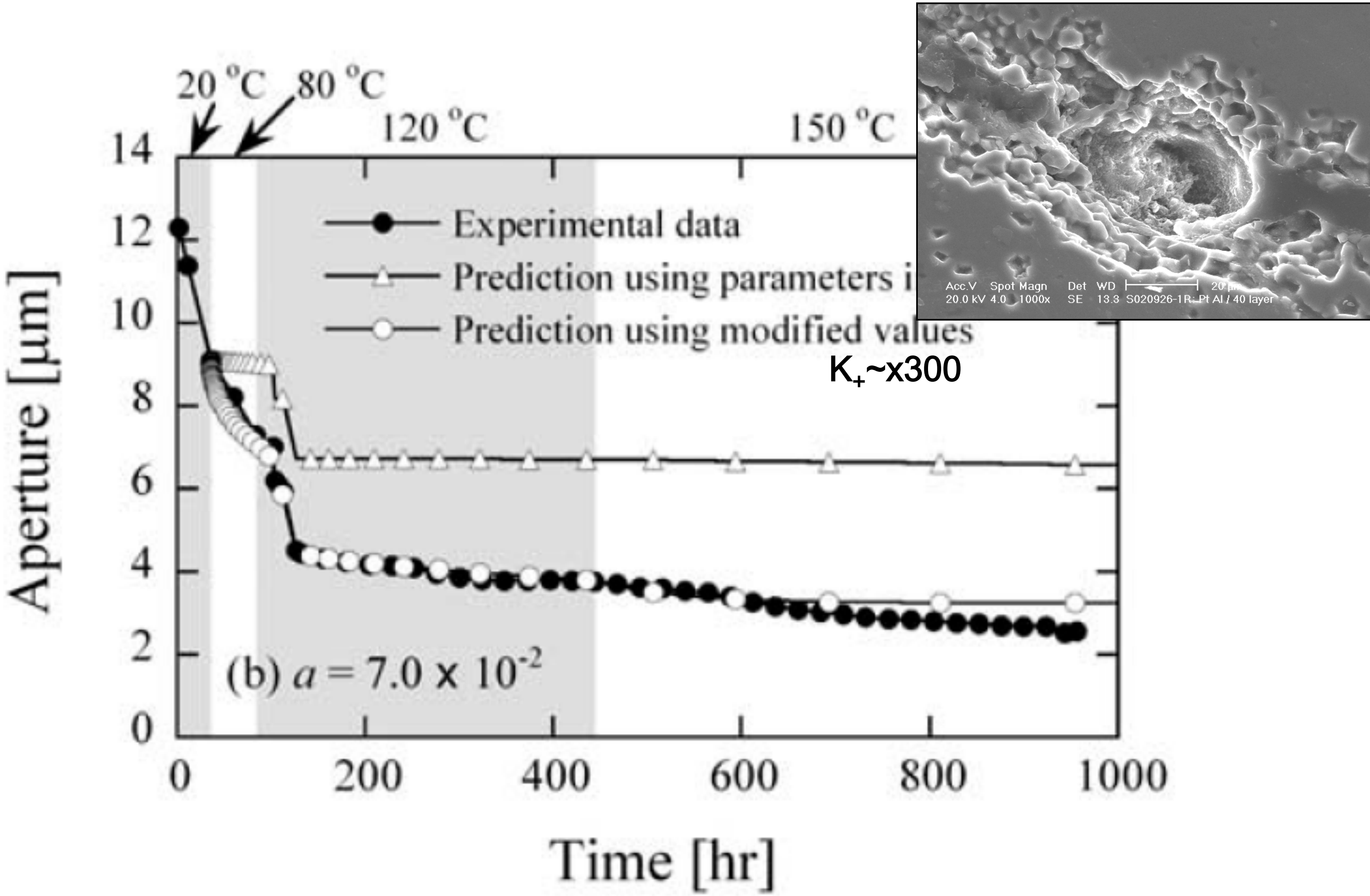



$$<b> = b_r + b_{\max} Exp[(R_c - R_{c0})/a]$$



# Modeling Results - Novaculite

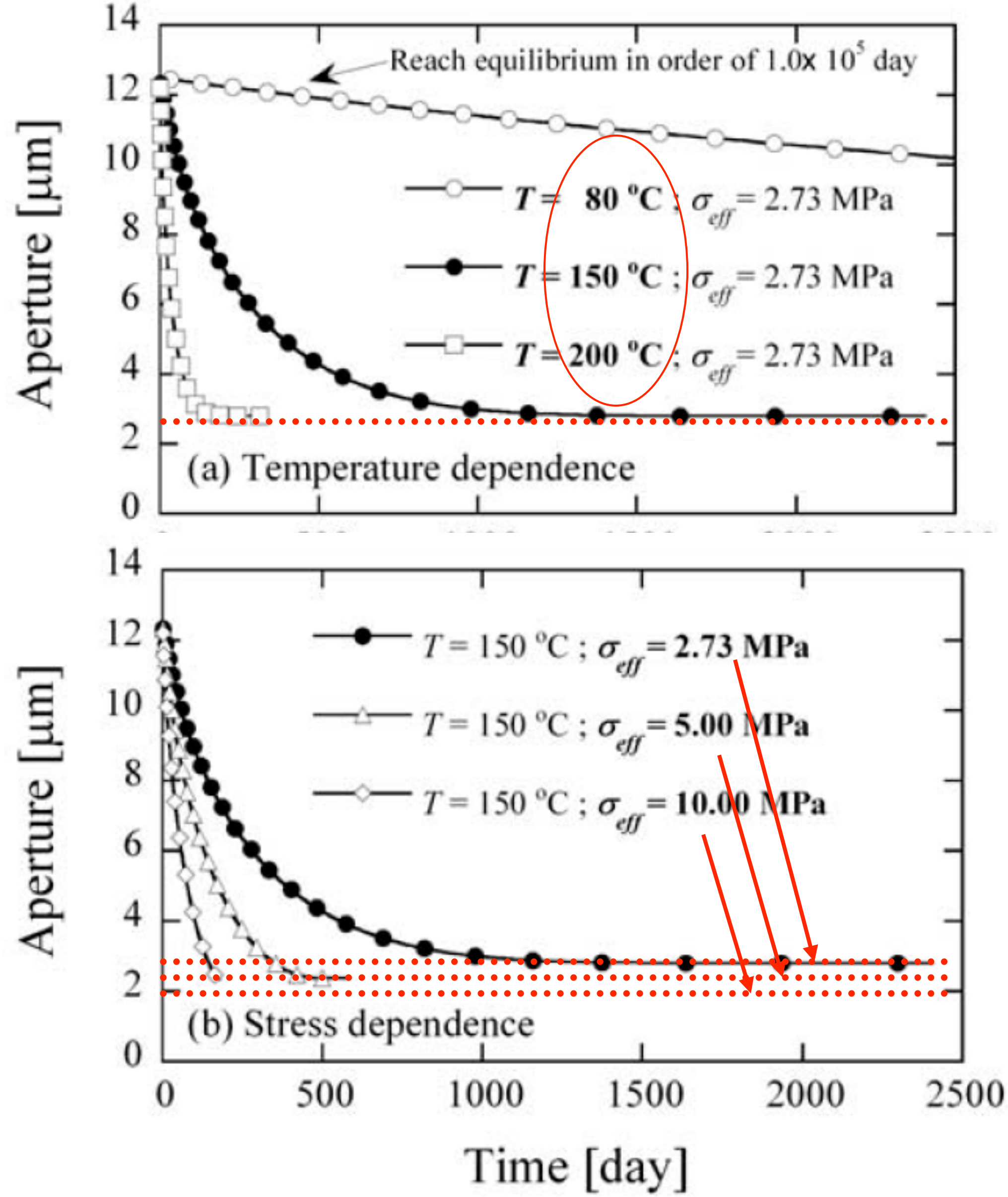



[Yasuhara et al., JGR, 2004]

# Projected Response of Fracture

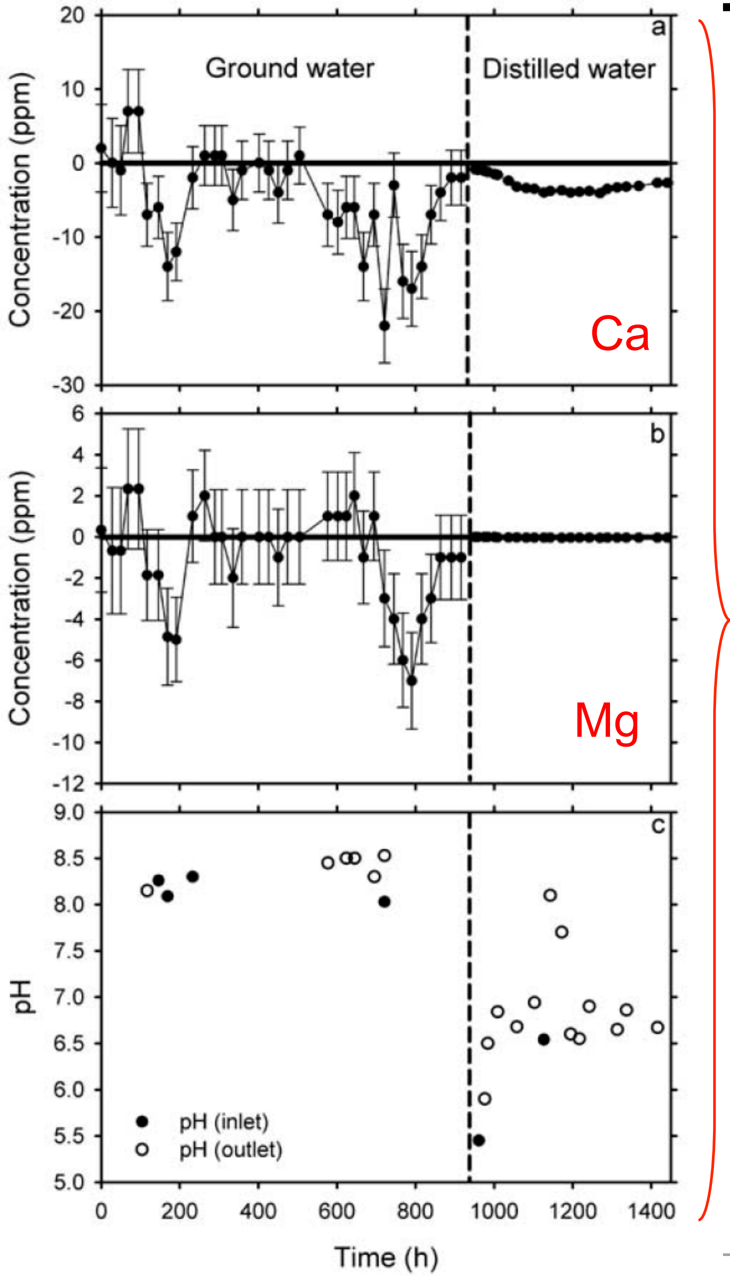
Define projected behavior for varied **temperatures**

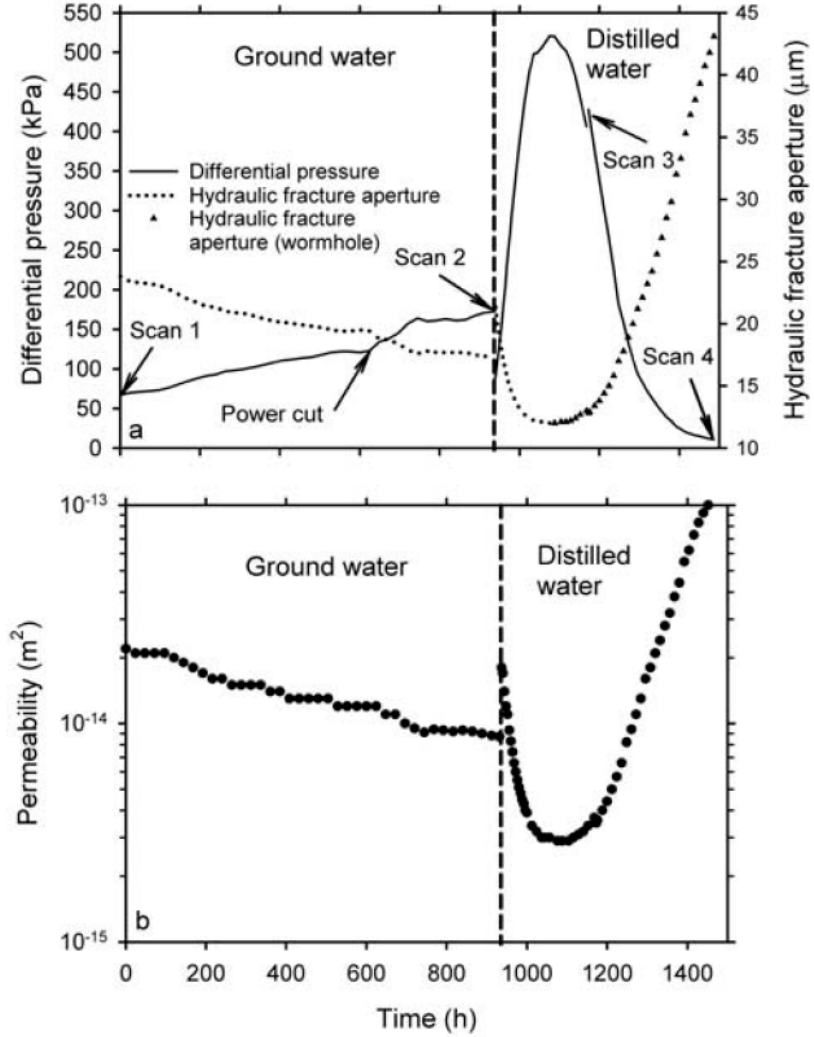
....and **mean stress** magnitudes




[Yasuhara et al., JGR, 2004]

# Fractured Limestone – Features of Response

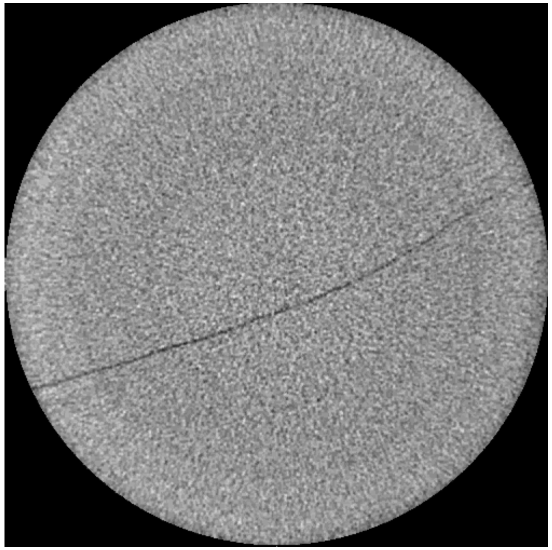


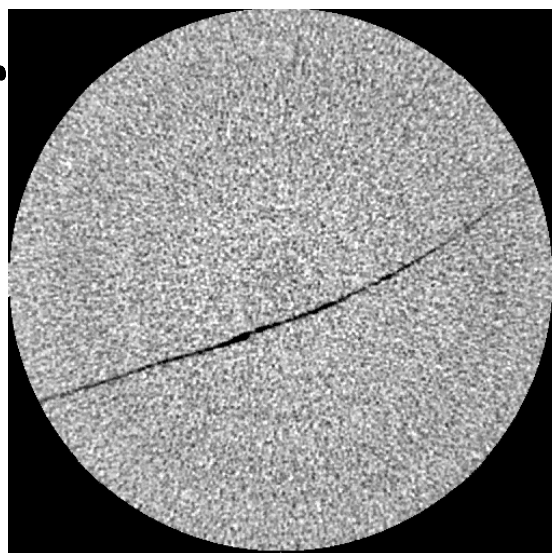

[Polak et al., WRR, 2004]

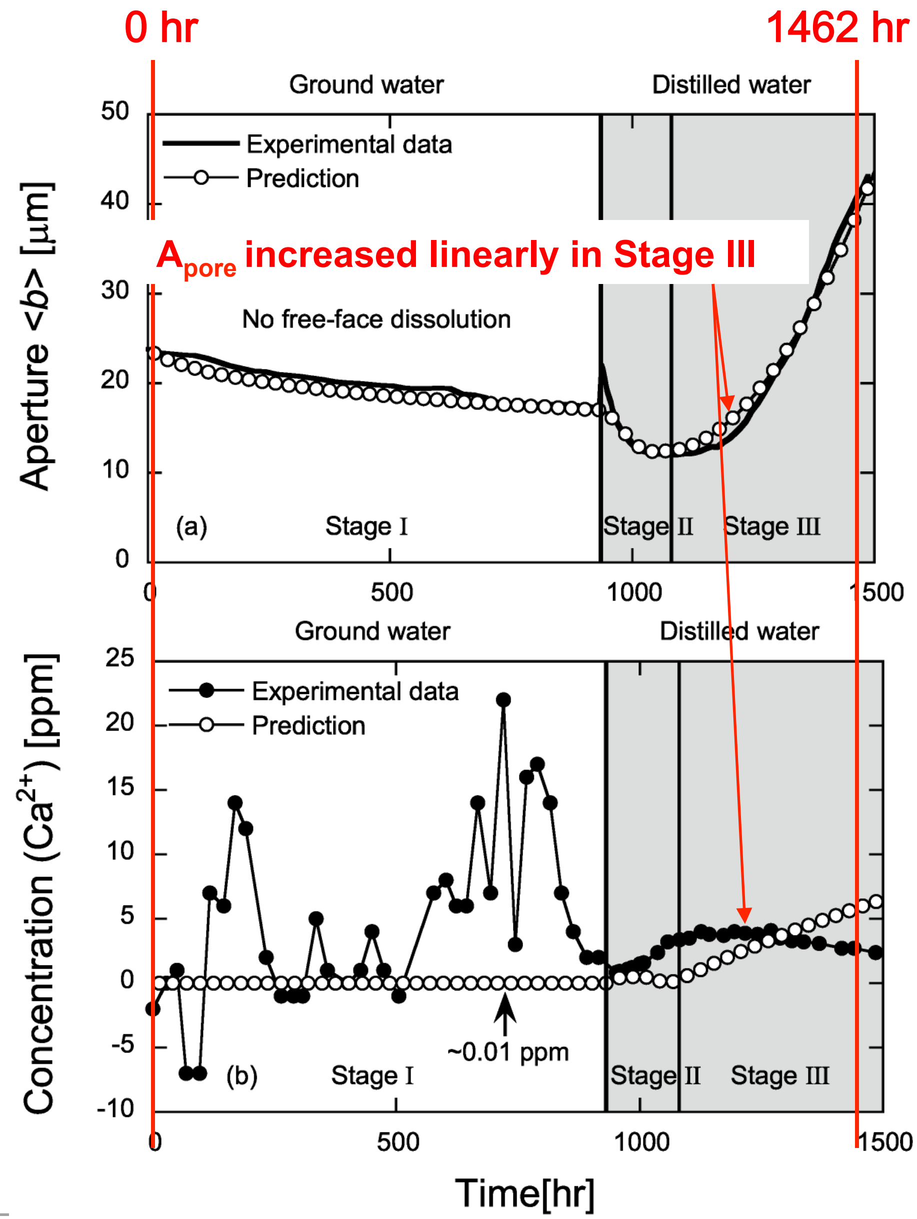
# Fractured Limestone – Features of Response

0 hr

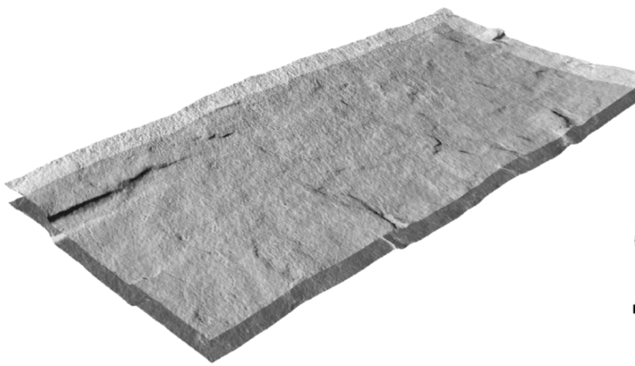


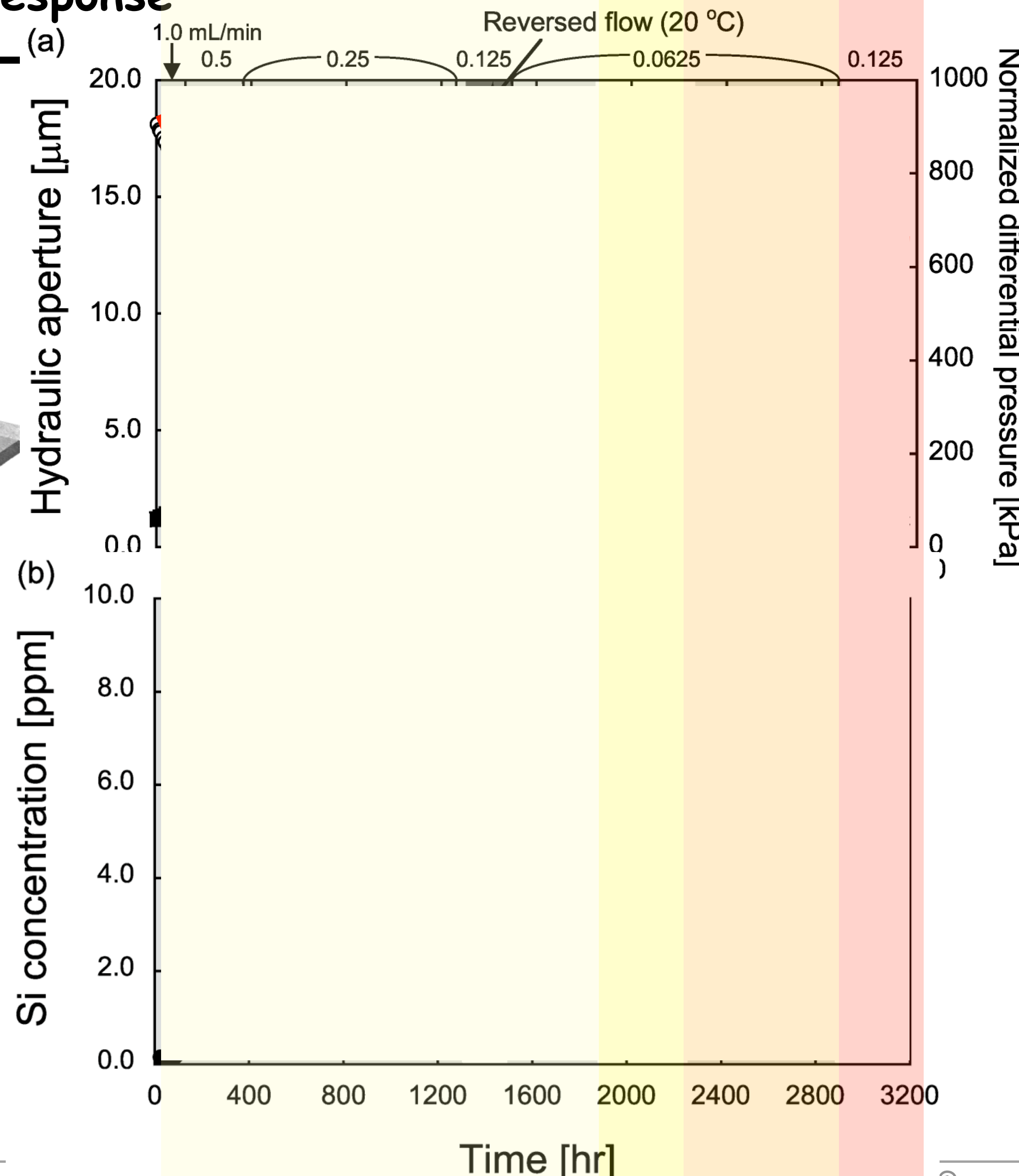
1462 hr



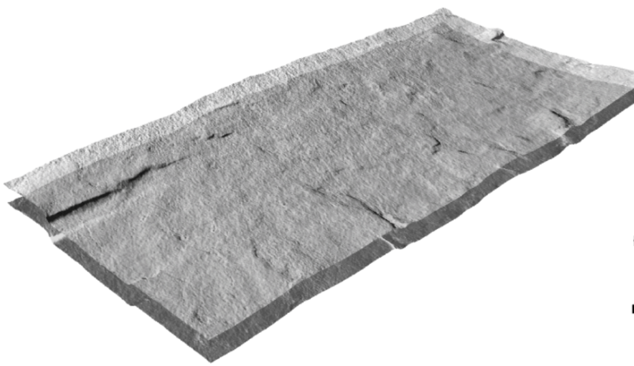


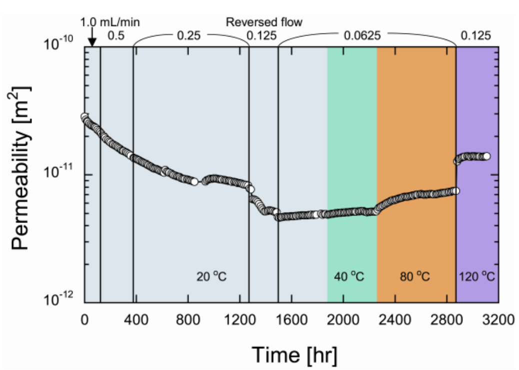
# Novaculite – 20 week response

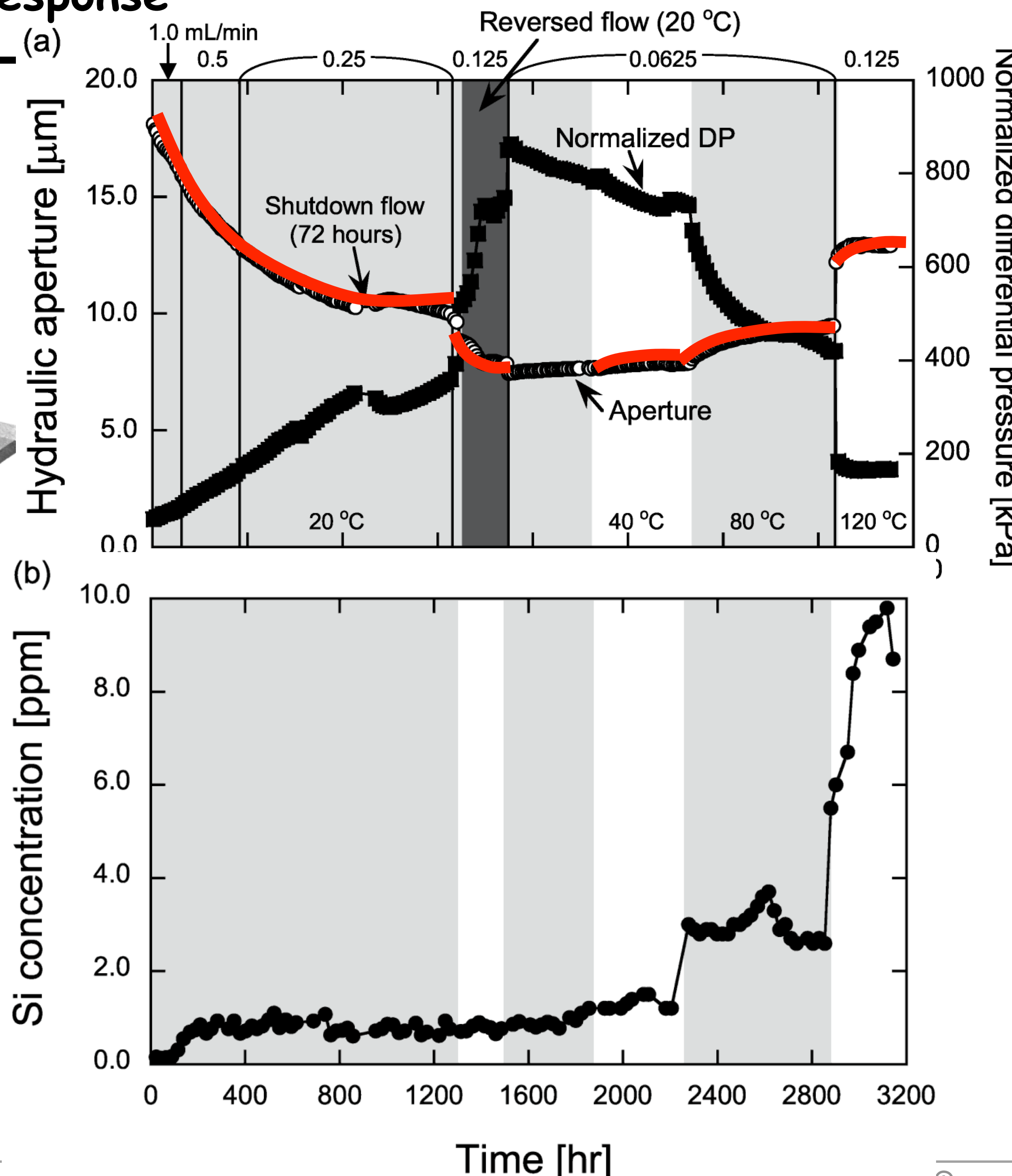




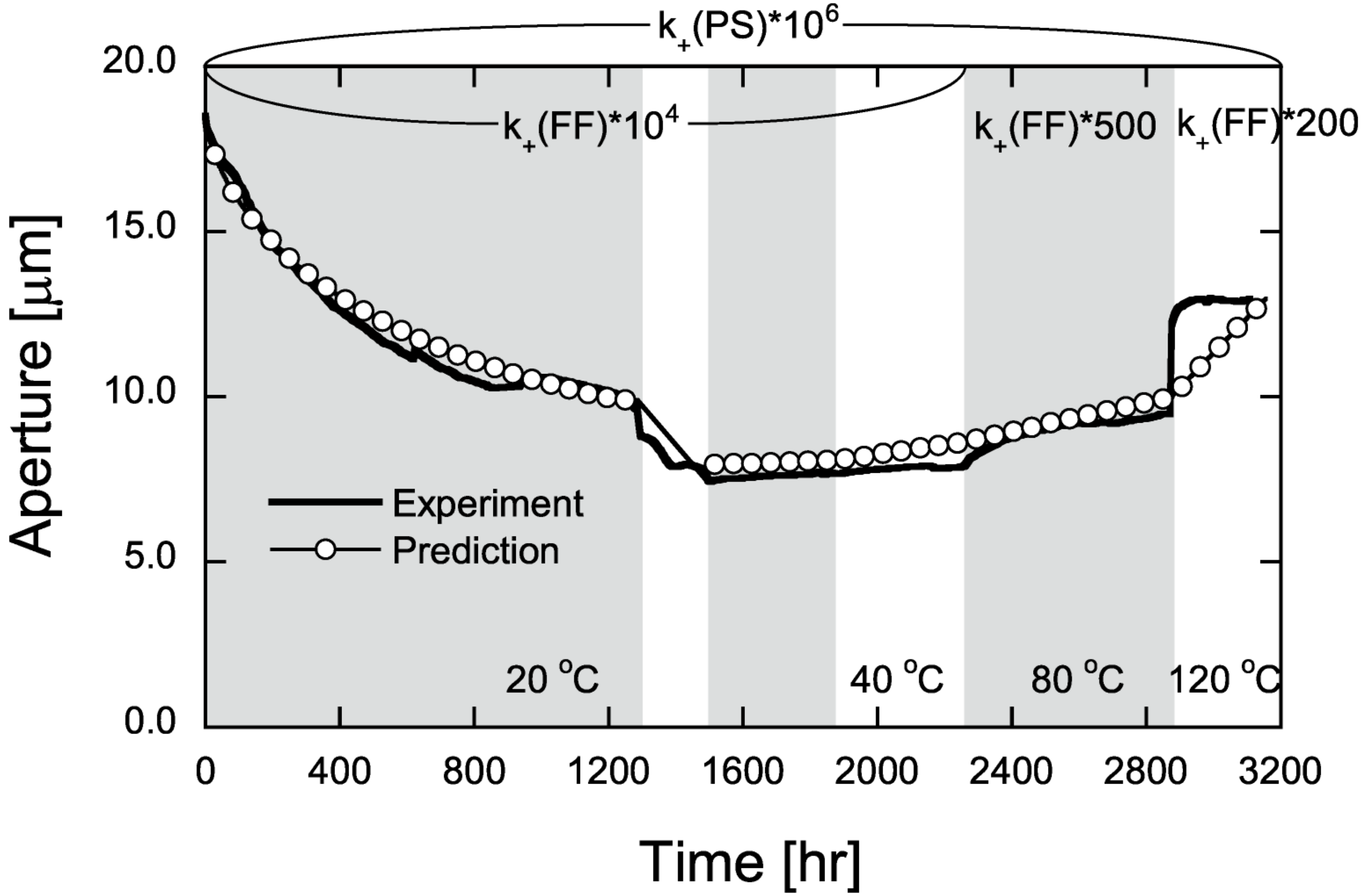
# Novaculite – 20 week response





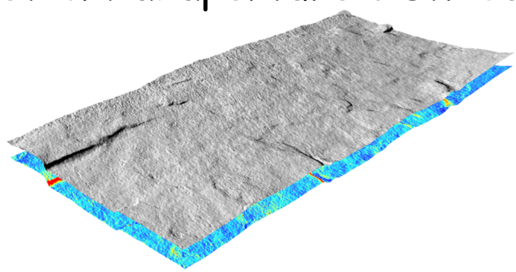



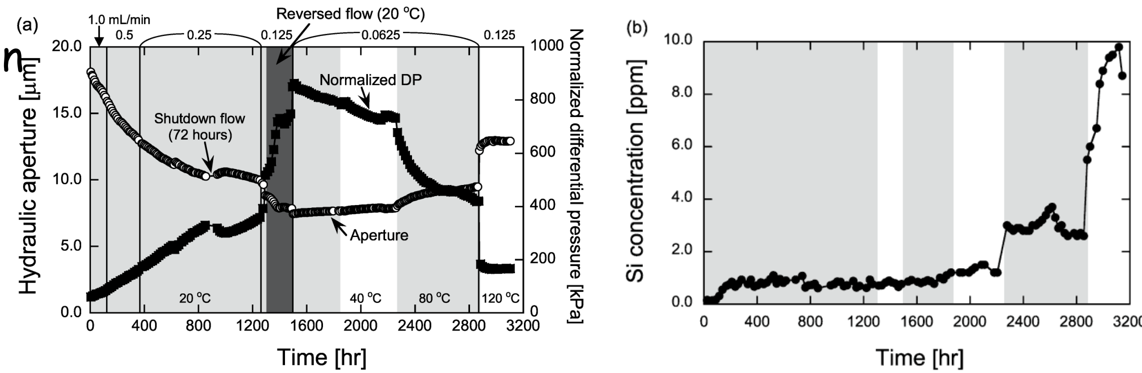
## …..and Lumped Parameter Prognostic Model for Novaculite …



# Distributed Parameter Models – Applied to Novaculite …

1. Set initial aperture distribution






2. Apply I.C. and B.C.
→ Obtain velocity distr. in a fracture by solving Reynolds' equation $\nabla\left(\frac{b^3}{12\mu}\nabla p\right)=0$

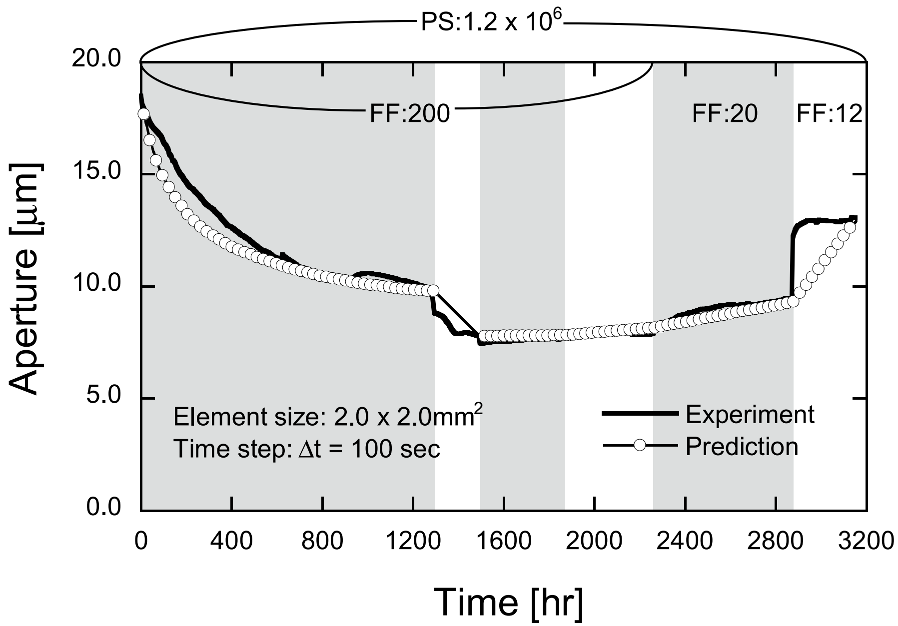
Iteration

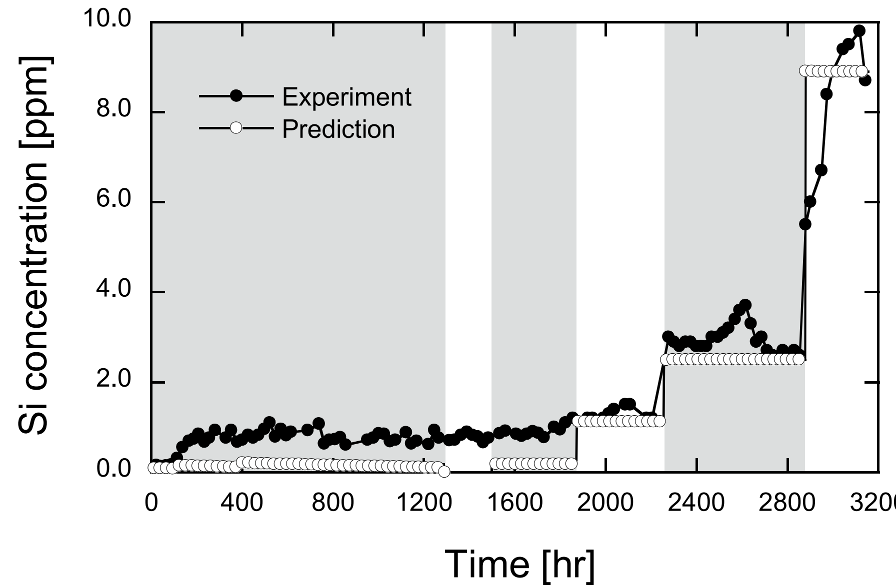
3. Dissolution at contact area and free-face (reaction)
→ Obtain concentration distribution + Modify aperture distribution due to dissolution

$$\frac{dM^{PS}}{dt}=\frac{3\pi V_m^2\rho_g k_+(\sigma_a-\sigma_c)A_e}{4RT}; \qquad \frac{dM^{FF}}{dt}=2A_e k_+\frac{C_{eq}-C_i}{C_{eq}}$$

4. Lagrangian-Eulerian method (Advection-diffusion)
→ Obtain concentration distribution within and out of domain

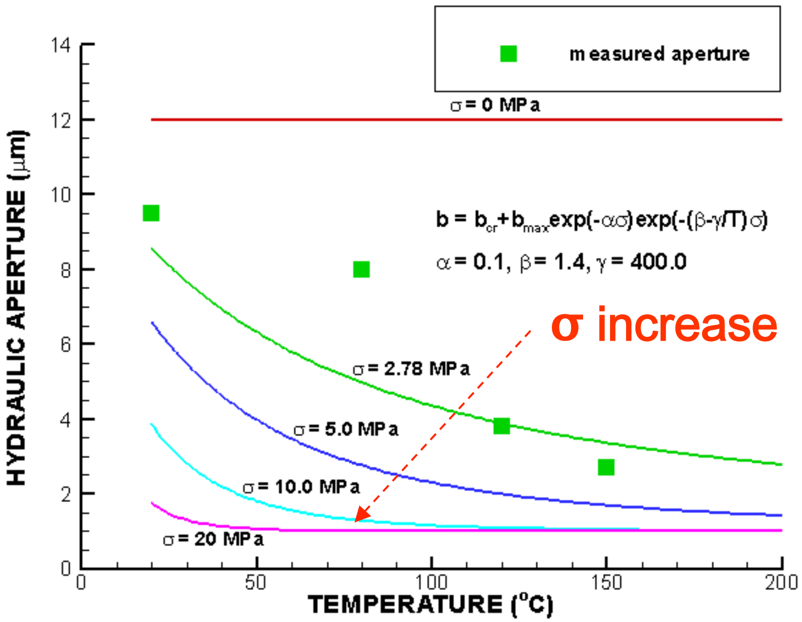
# Distributed Parameter Model – Results for Novaculite …

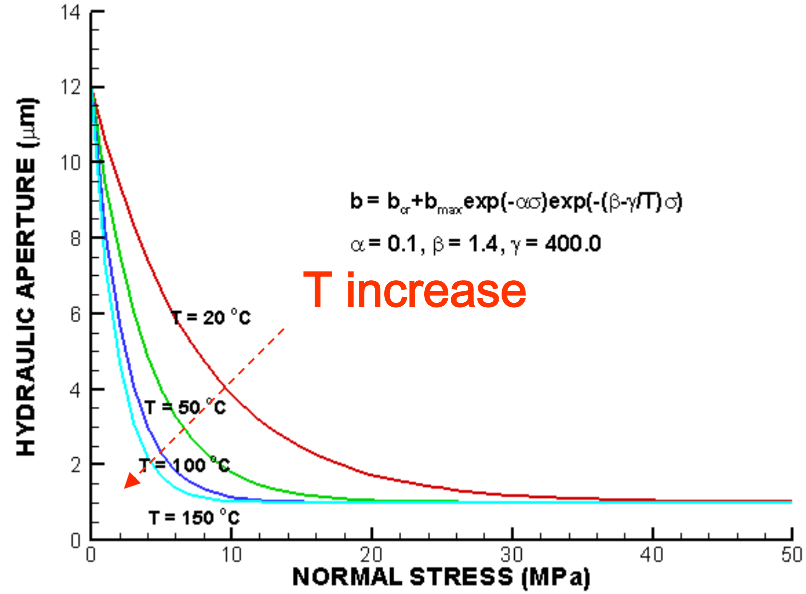



- Numerical model is capable of better replicating experiment – multiplier on $k_+$ is greatly reduced over lumped parameter case.

# TMC-Induced Aperture Change – Stress Control



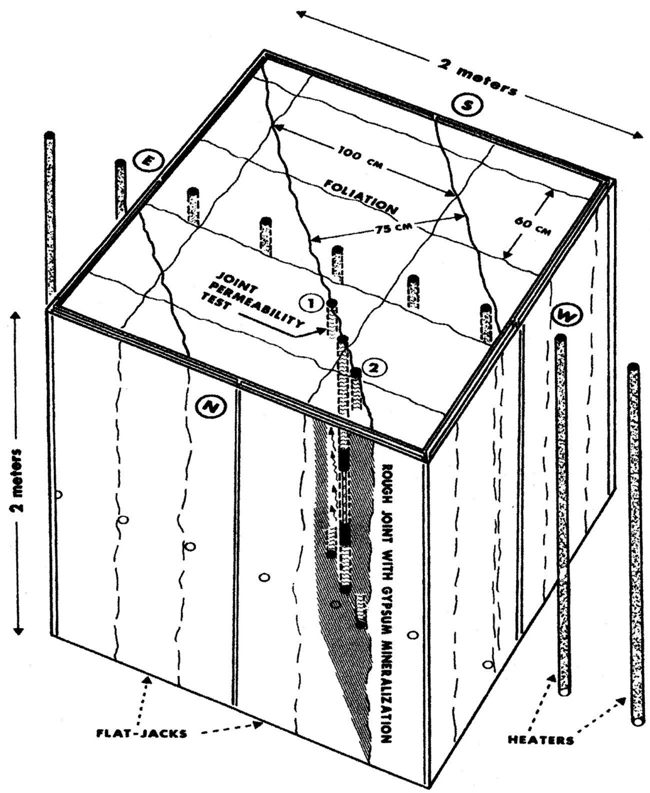

$$b = b_{cr} + \underbrace{\left\{ b_{mc} + b_{\max} \exp(-\alpha\sigma') \right\}}_{\text{M \& TM induced change}} \underbrace{\exp\left\{ -\left( \beta - \frac{\gamma}{T} \right) \sigma' \right\}}_{\text{MC \& TC induced change}}$$

Application to novaculite (laboratory) data under stress control

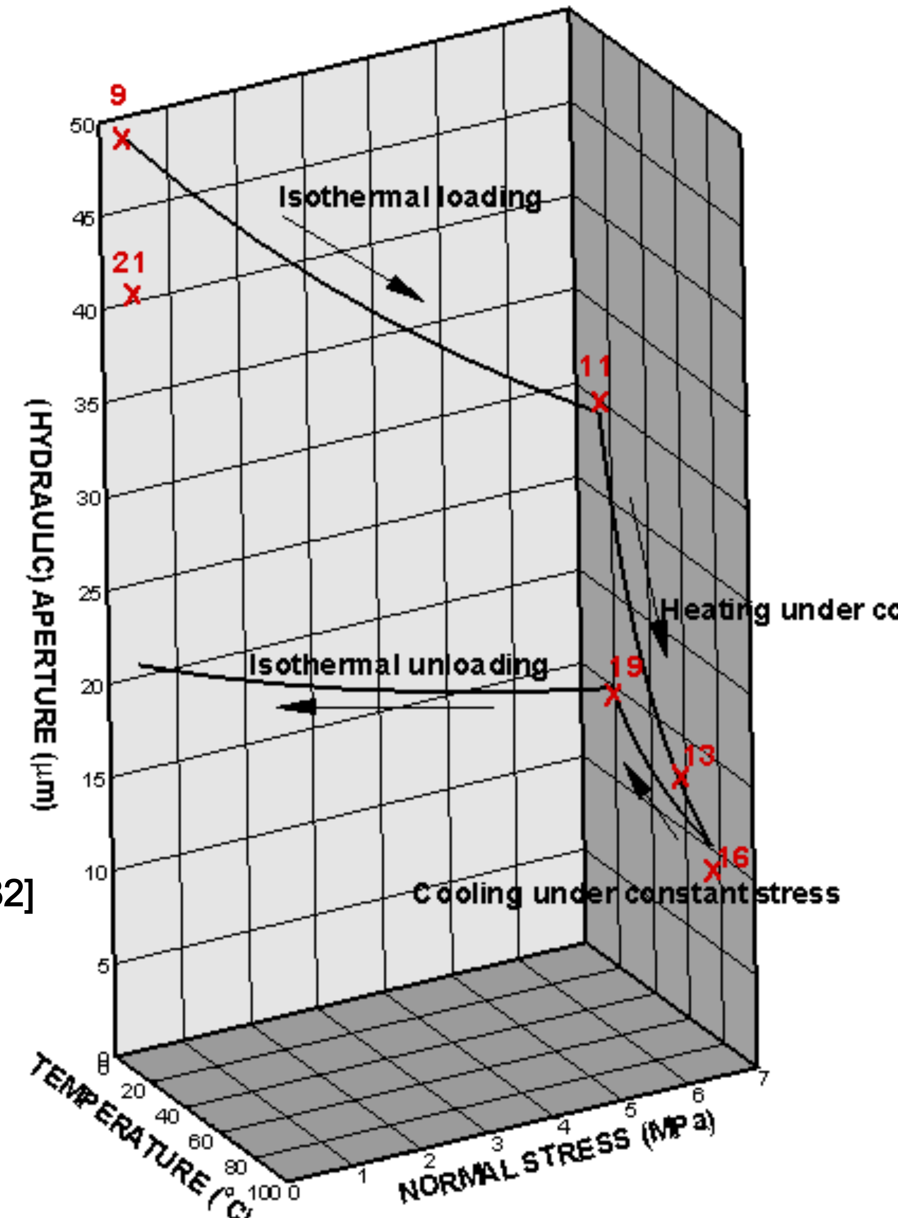
Sparse data but available data conform to the expected response based on micro-mechanical arguments

Experimental data needed at a variety of scales

# TMC-Induced Aperture Change – Stress Control




[Handin et al., 1982]

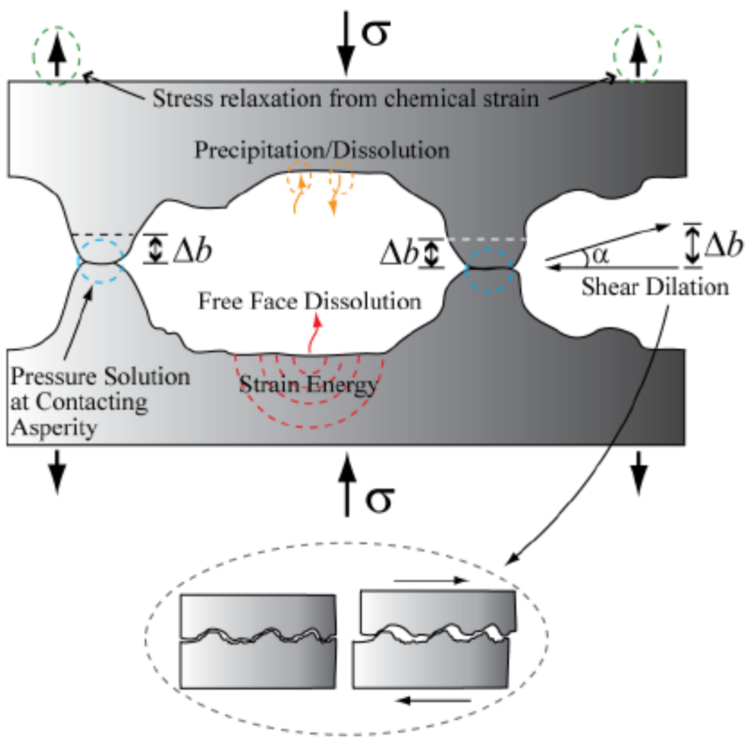


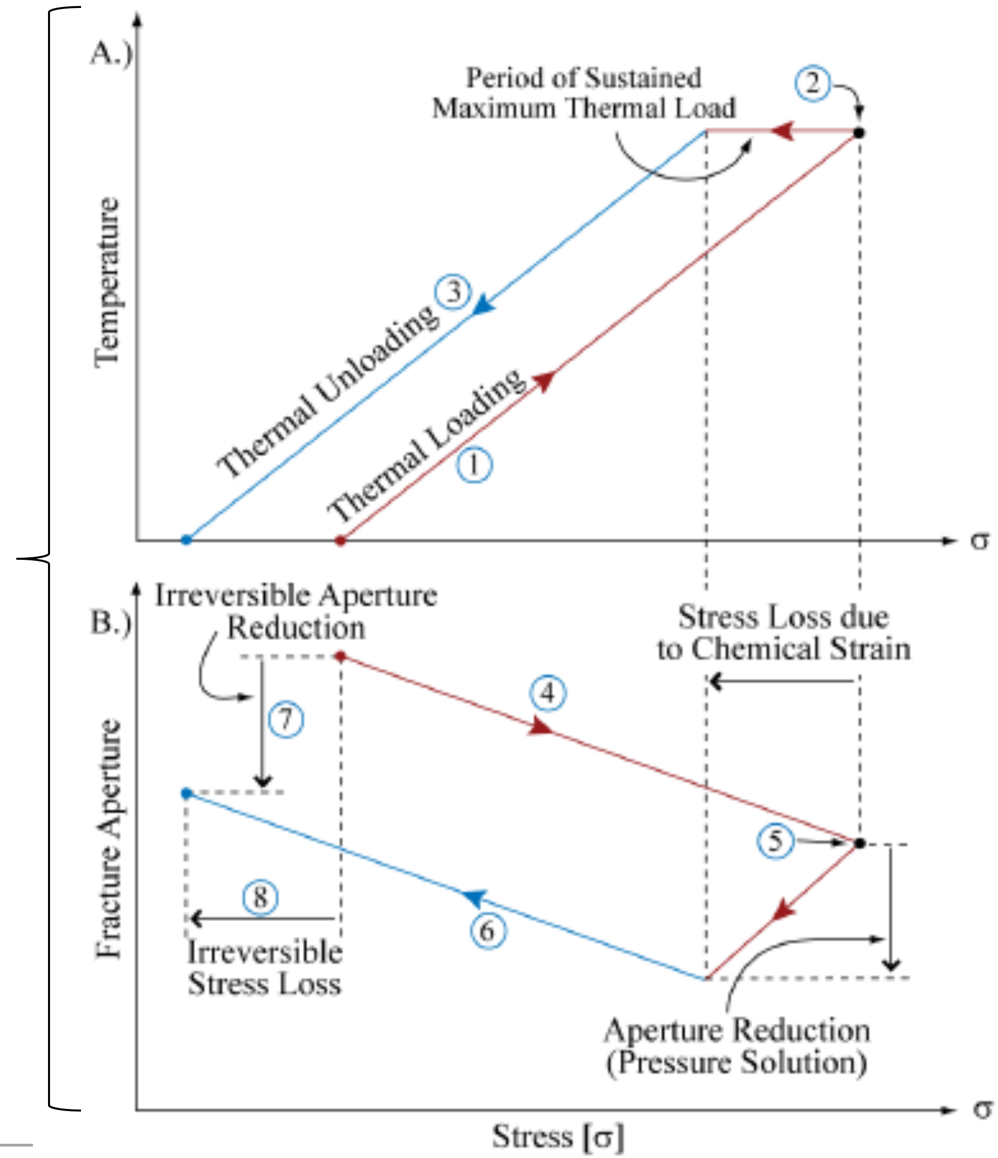

Application to granodiorite data (field) under stress control

Replicates most features on curve

Experimental data needed at a variety of scales

# The Role of Irreversible "Chemical" Strains on Mechanical and Transport Properties



# Reactive Flow and Permeability Dynamics
# Derek Elsworth, Penn State

**Basic Observations of Permeability Evolution – Lab-to-field**

**Impacts on Permeability**

- Mechanical effects (pore pressure and thermal effects)
  - Controls on effective stress
  - Stress-porosity linkages for fractures
    - Compaction
    - Dilation
    - Rate-state models
  - Porosity-permeability linkages to fracture dilation
  - Other mechanical effects (wear)
- Reactive chemical effects
  - Laboratory observations
  - Linkages among porosity/permeability/dissolution/precipitation
  - Mechanistic models for chemical-mechanical effects
  - In situ observations/characterizations of chemical-mechanical effects
  - Forward/reverse feedbacks on stress-permeability

**Reservoir-Scale Evolution of Permeability**

- Spatial distribution
- Timing
- Seismicity as an indicator

**Summary**

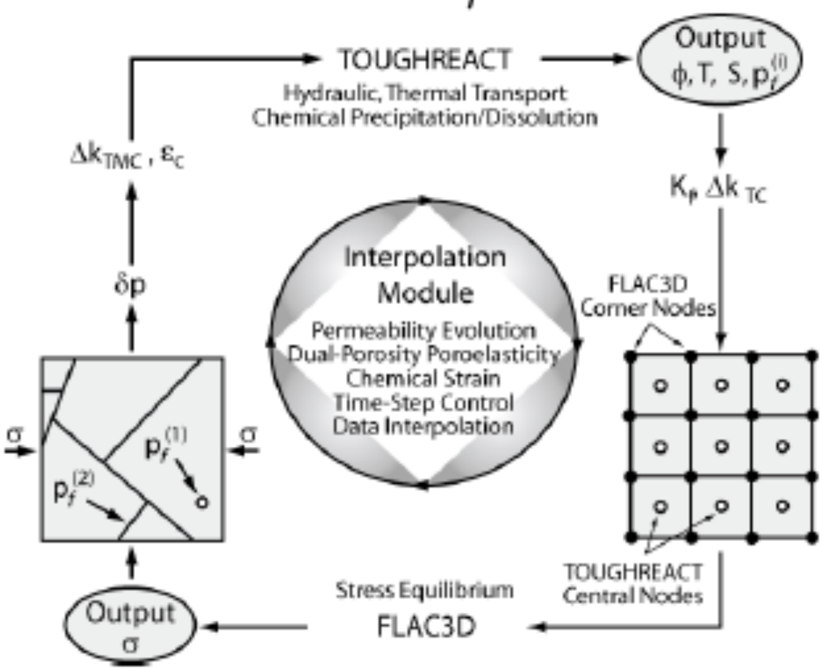
# Coupled THMC Modeling

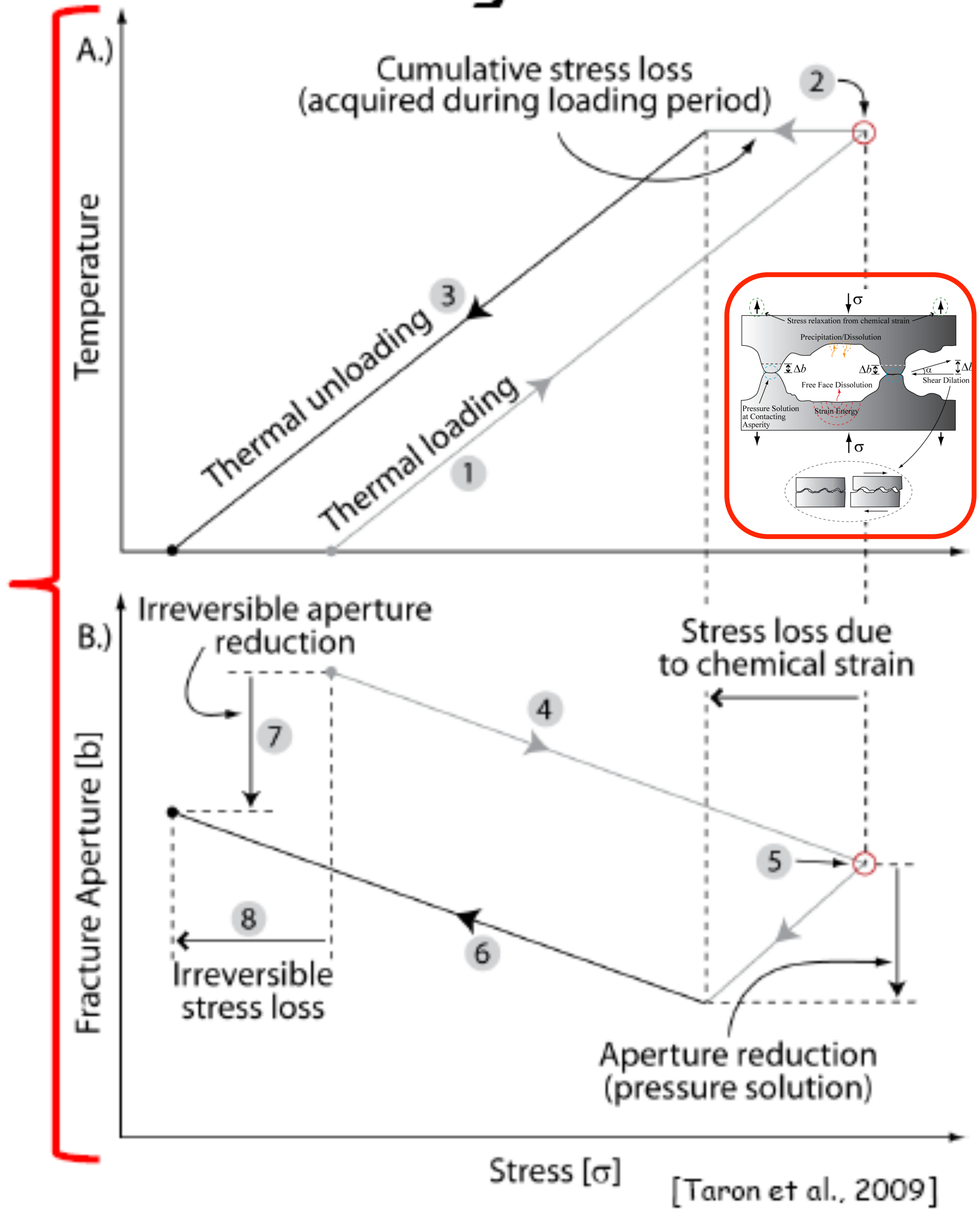
- **TOUGHREACT (THC)** – Accommodates non-isothermal, multi-component phase equilibria, pressure diffusion, multi-phase hydrologic transport, and chemical precipitation/dissolution (transient mass/energy balance)

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

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

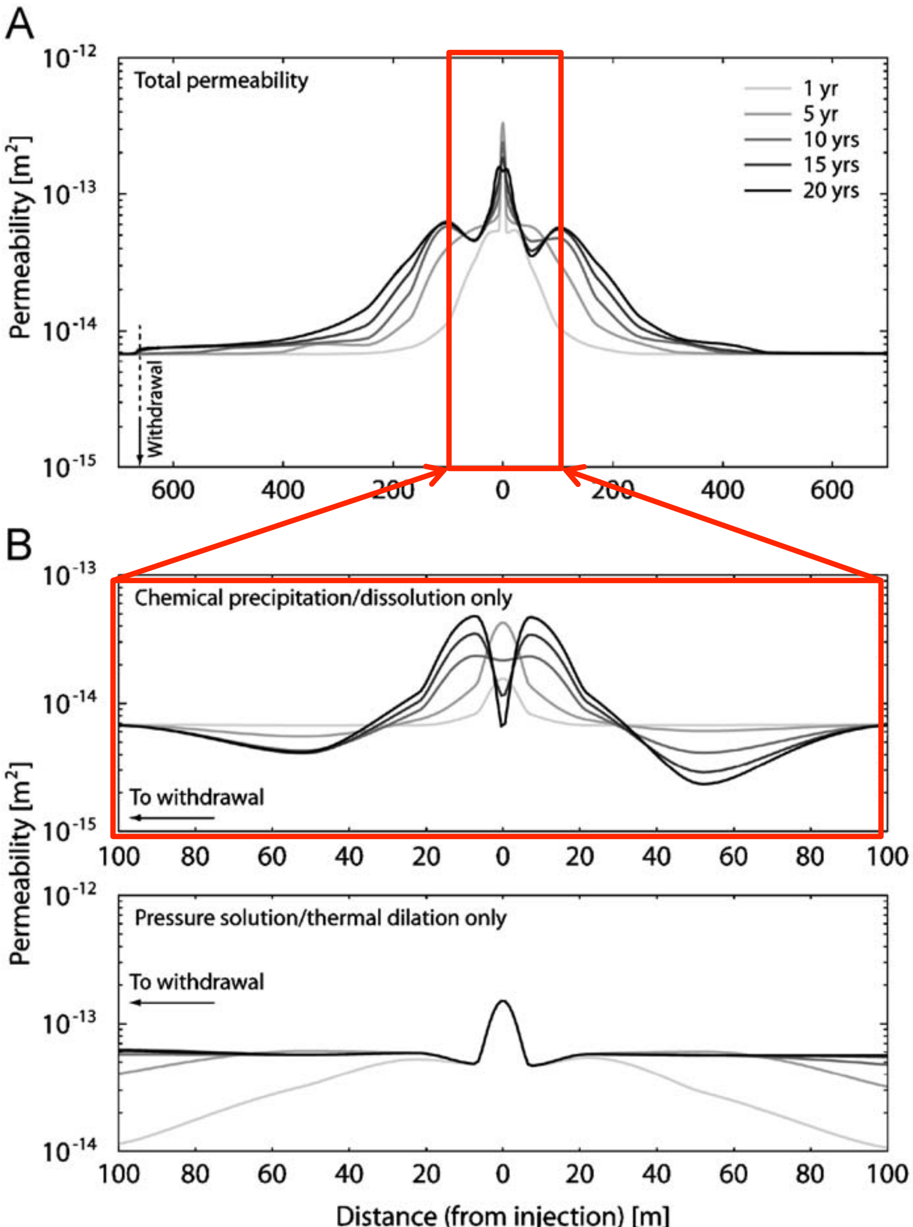
$$\nabla \cdot \boldsymbol{\sigma}^T = -\rho \mathbf{b}$$

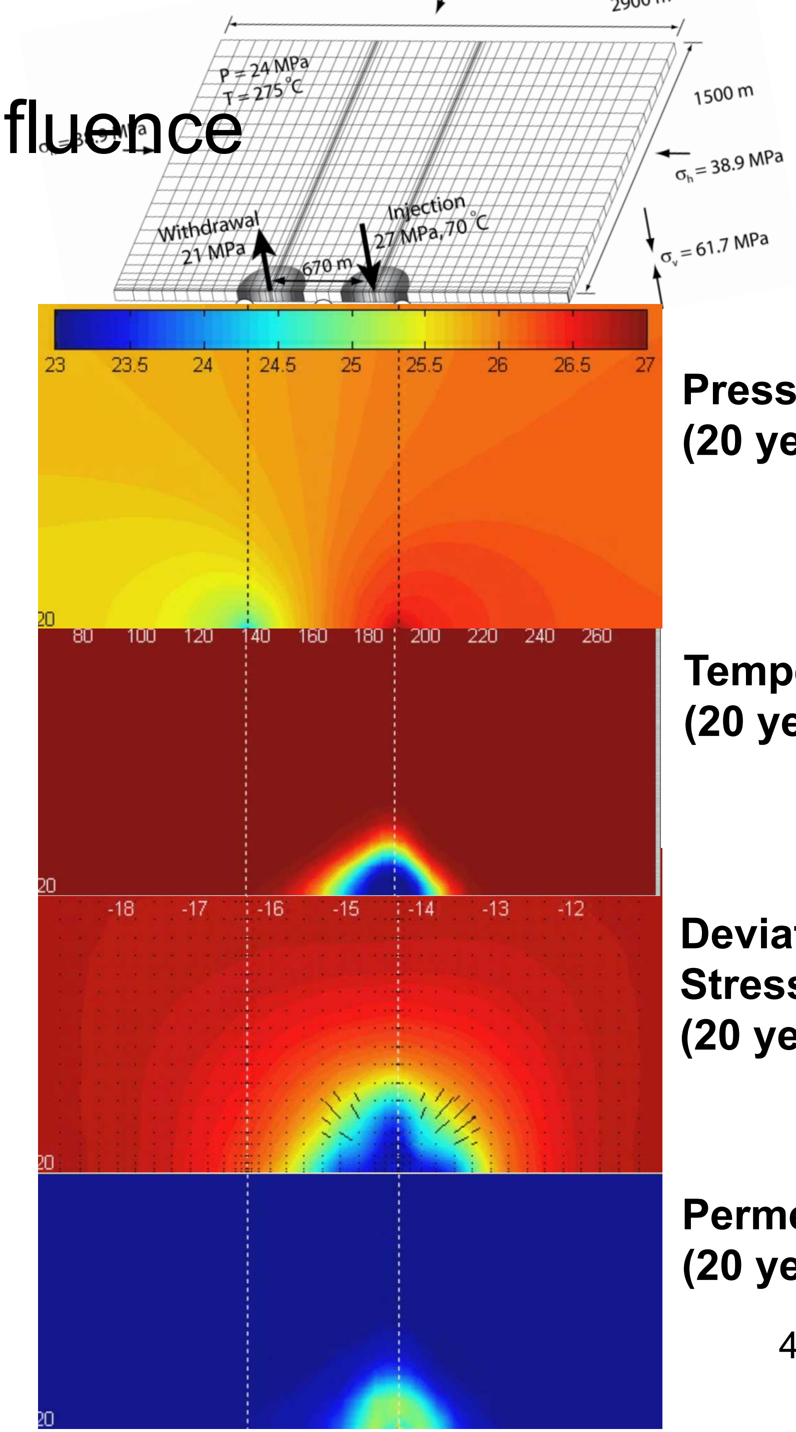


# Coupled THMC Modeling

## Chemical –vs- Mechanical Influence




**Pressure (20 years)**

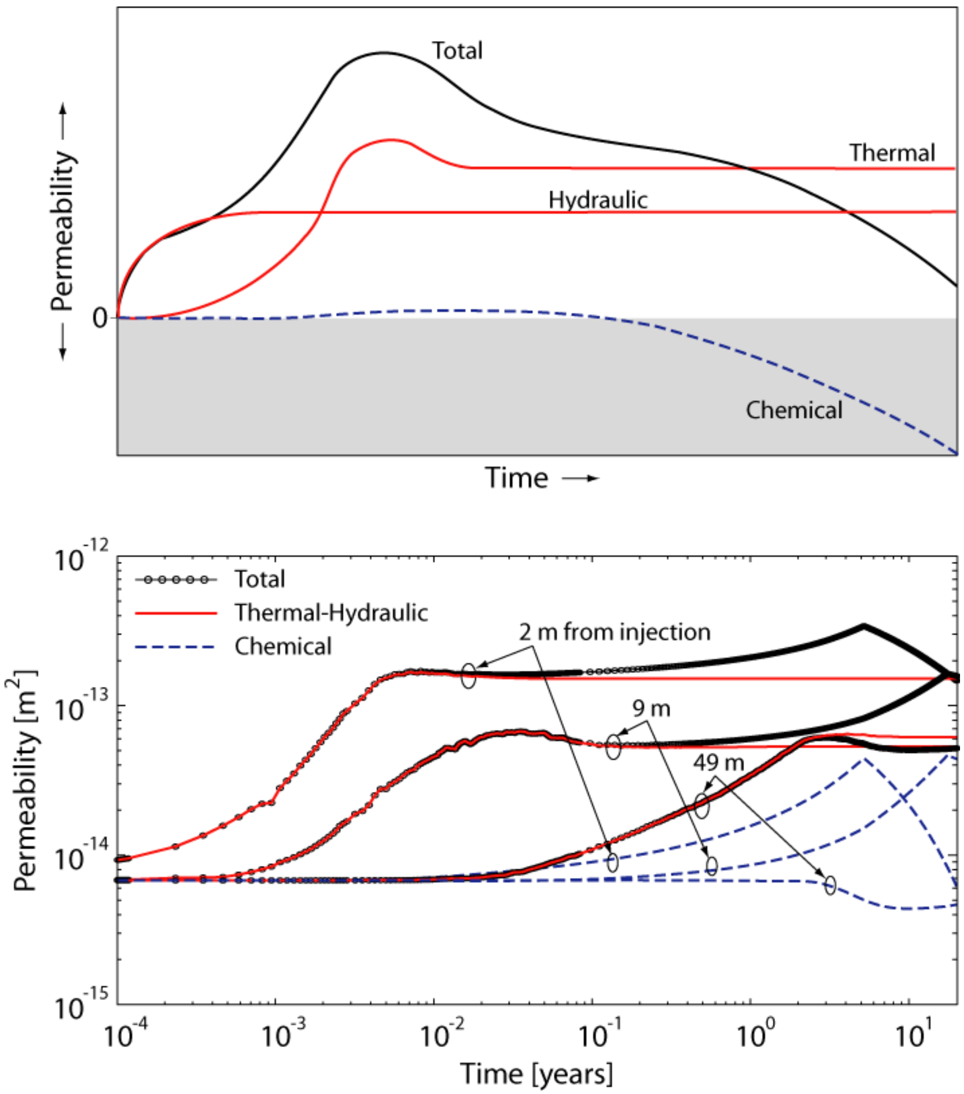
**Temperature (20 years)**

**Deviatoric Stress (20 years)**

**Permeability (20 years)**

[Taron et al., 2009]

# Timescales and Characteristic Times




Thermo-hydraulic processes combined in this model.

Onset of chemical permeability change a longer time-scale process.

Sharp onset of chemical change due to complete dissolution of all calcite in veins.

# Triggered Seismicity – Key Questions

THMC Model:

**Principal trigger - change in (effective) stress regime:**

Fluid pressure

Thermal stress

Chemical creep

**How do these processes contribute to:**

Rates and event size (frequency-magnitude)

Spatial distribution

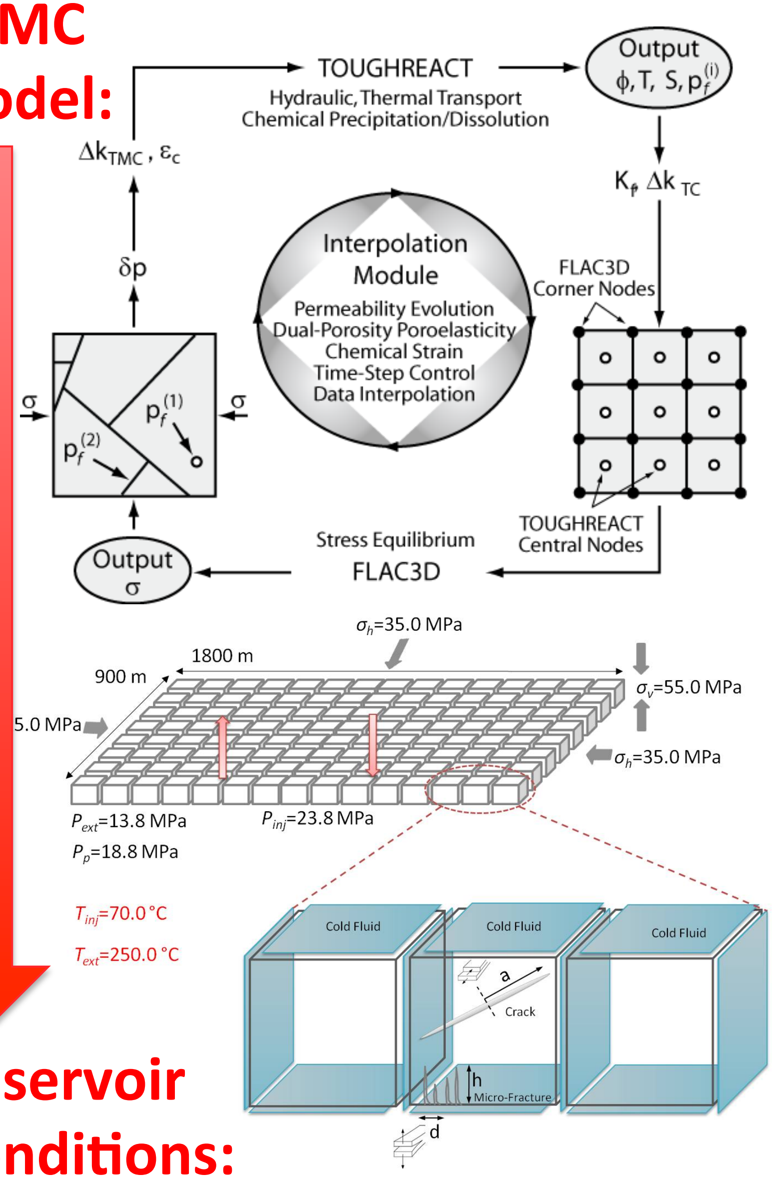
Time history (migration)

**How can this information be used to:**

Evaluate seismicity

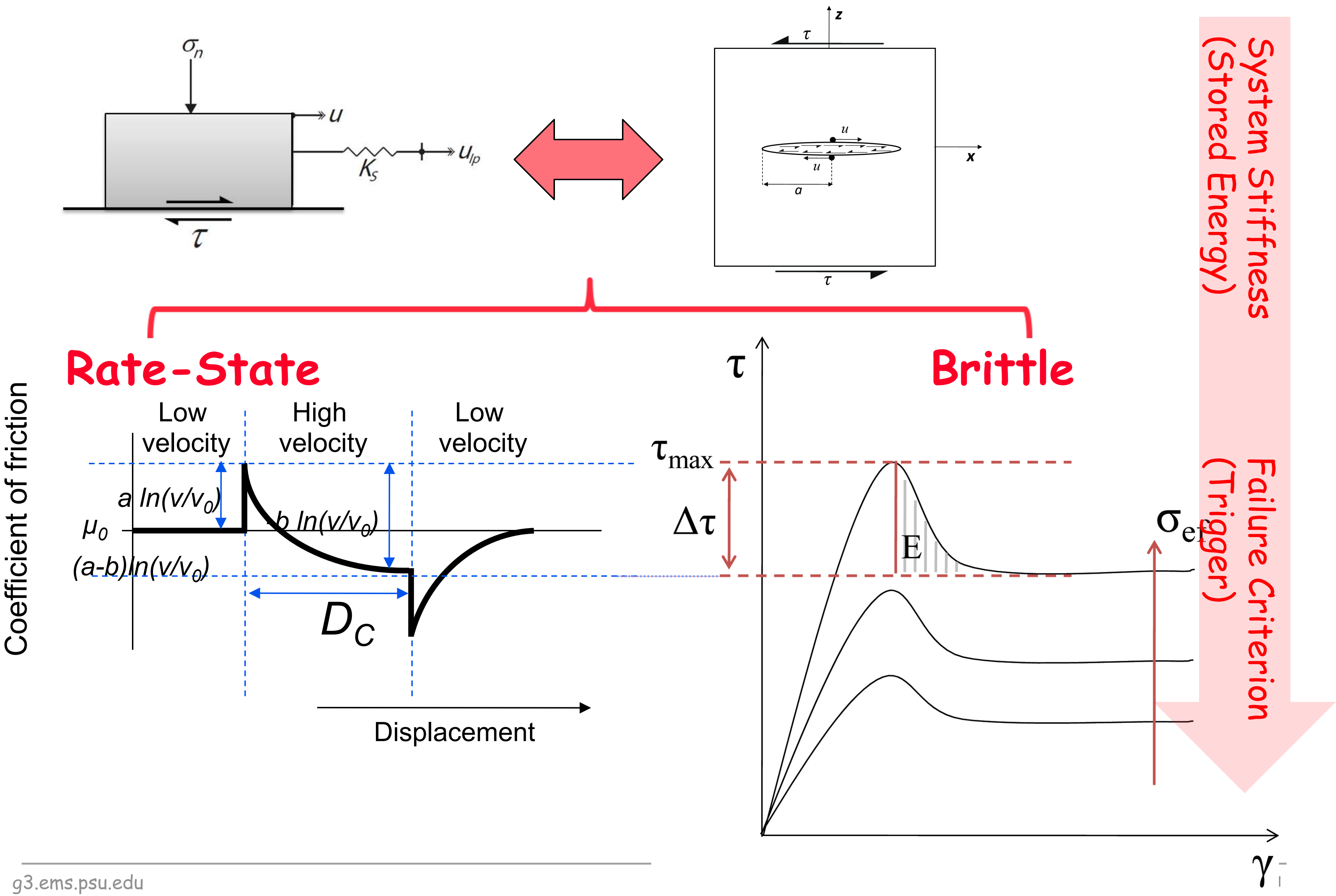
Manage/manipulate seismicity

Link seismicity to permeability evolution



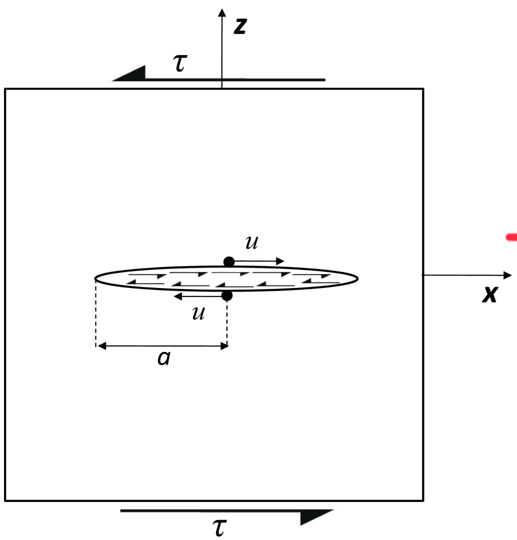

Reservoir Conditions:

# Approaches – Rate-State versus Brittle Behavior



# Component Behavior - Reservoir stiffness

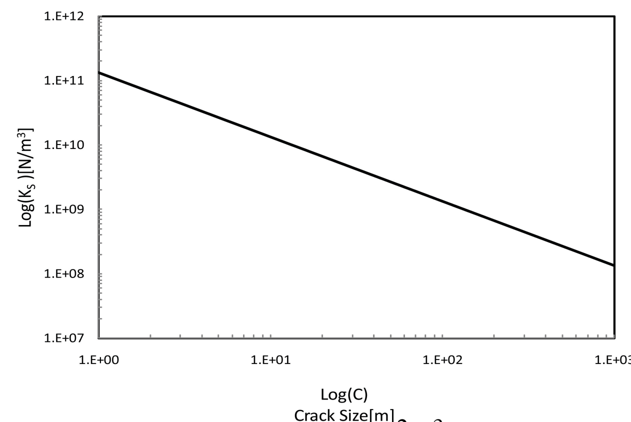
Penny-shaped Crack




**Stiffness:**

$$K_s = \frac{\tau}{u_m} = \frac{3G\pi(3\lambda+4G)}{8(\lambda+2G)}\frac{1}{a} = \frac{3G\pi(2-\nu)}{8(1-\nu)}\frac{1}{a}$$

$$K_s = \frac{4}{3}\frac{G}{a}$$



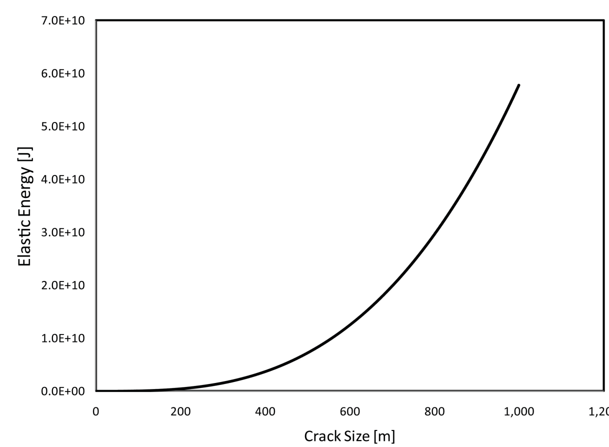

**Energy:**

$$E = \frac{1}{2}\int_{2A} \tau u \, dA = \frac{8(\lambda+2G)}{3G(3\lambda+4G)} = \frac{2\tau^2 a^3}{3G}$$

$$\mathrm{E}_p = \frac{2\tau^2 a^3}{3G}$$

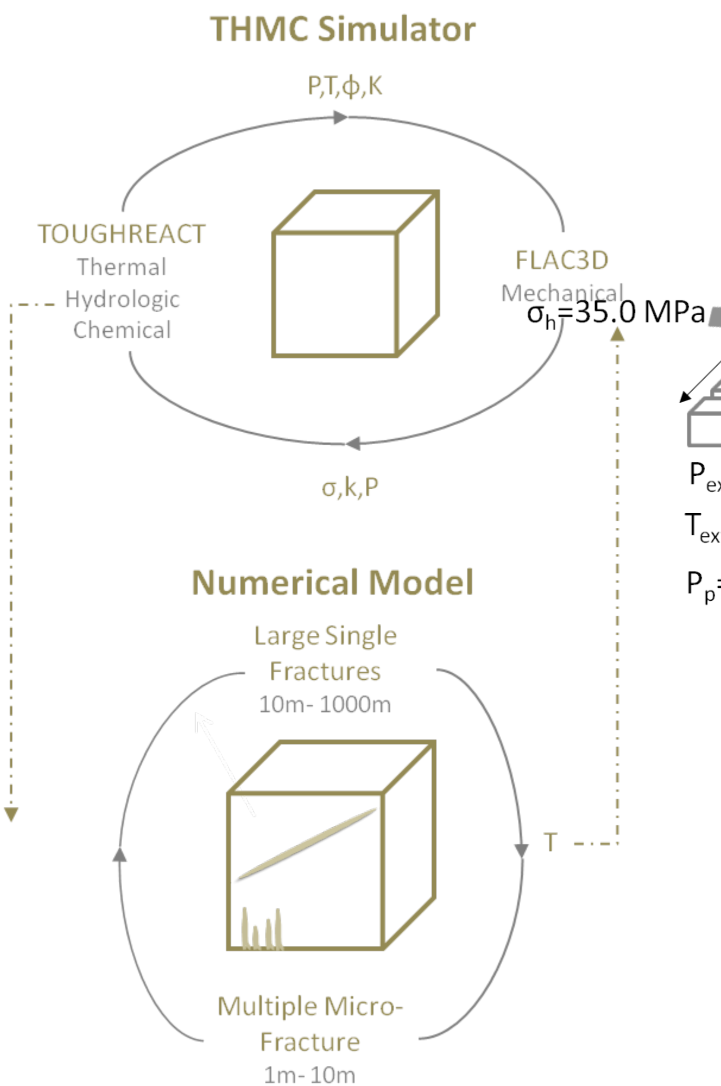
**Magnitude:**

$$\log E_p = 1.5 M_s + 9.1$$

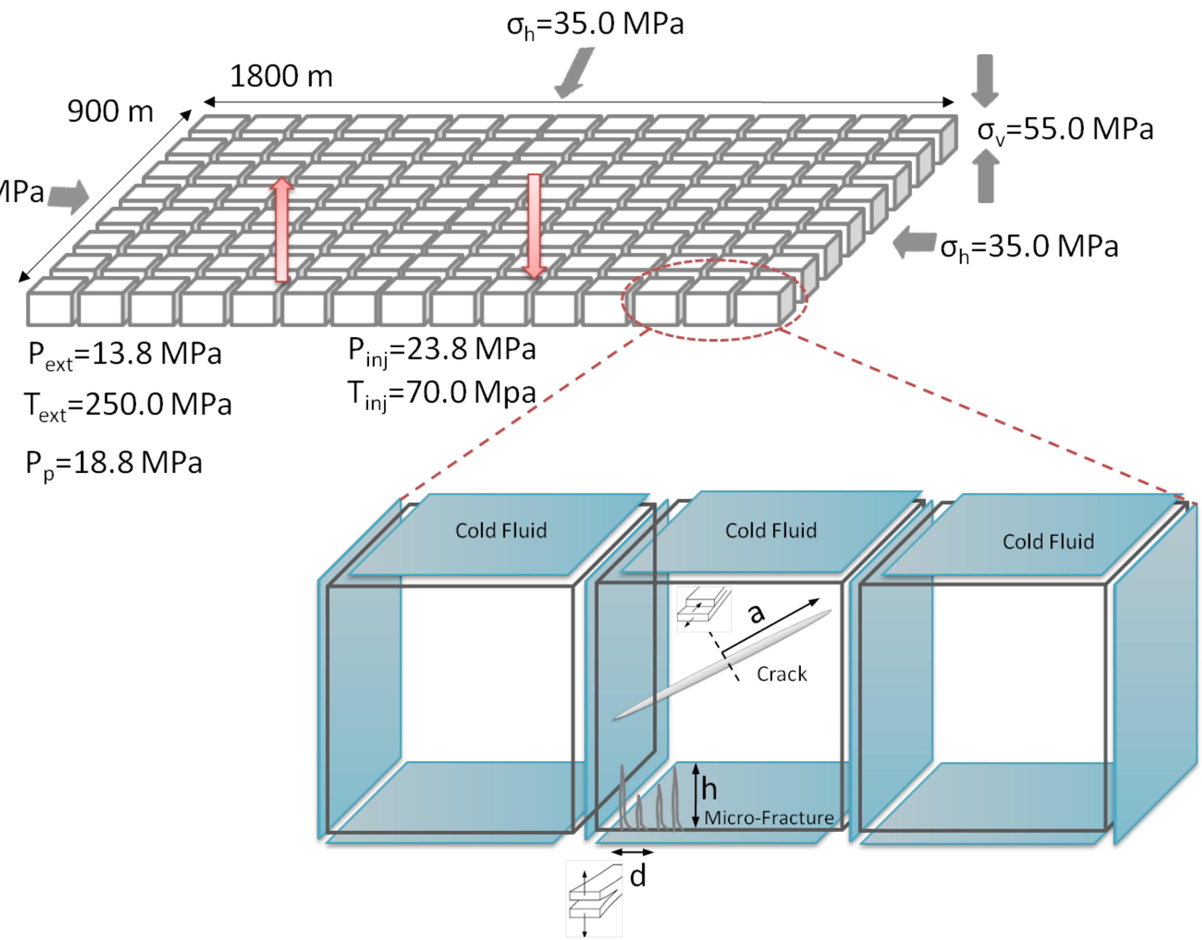


# Continuum THMC Model

## Model:

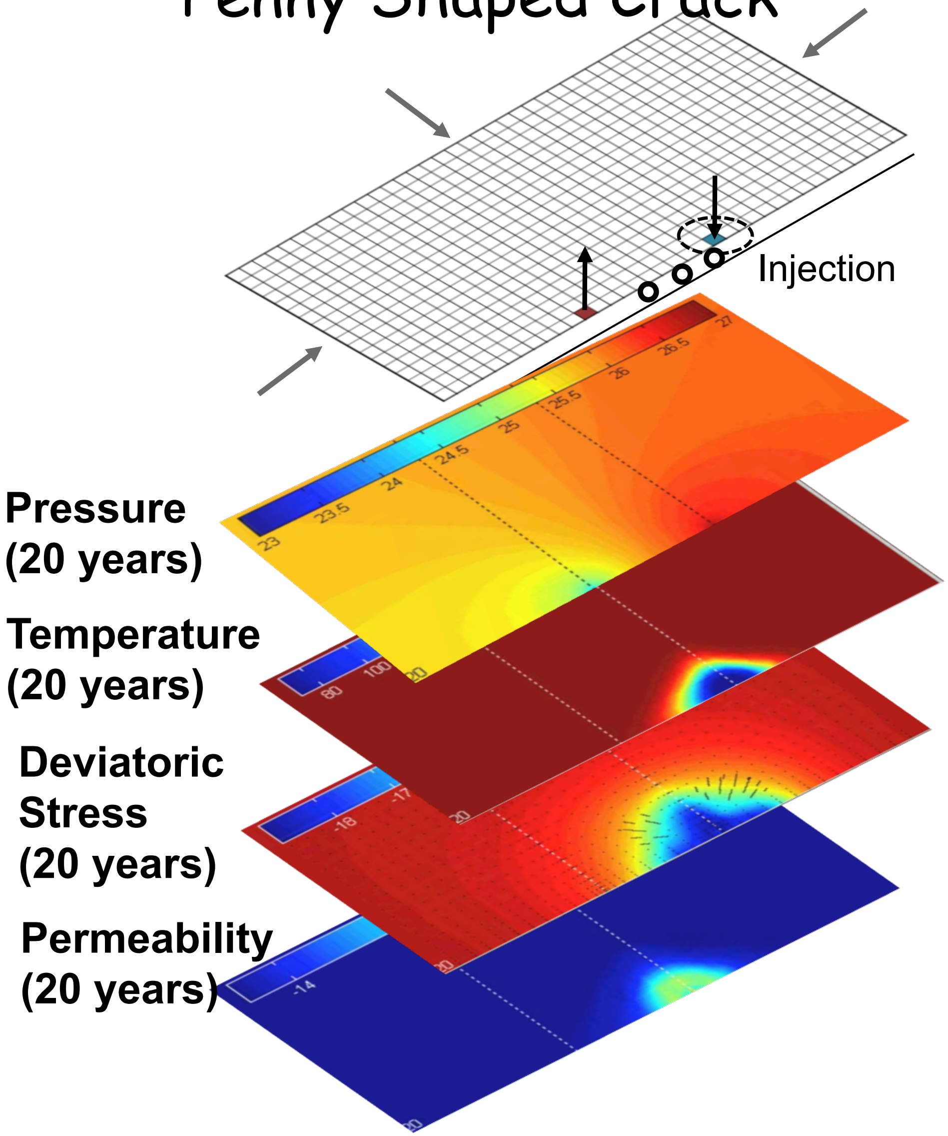


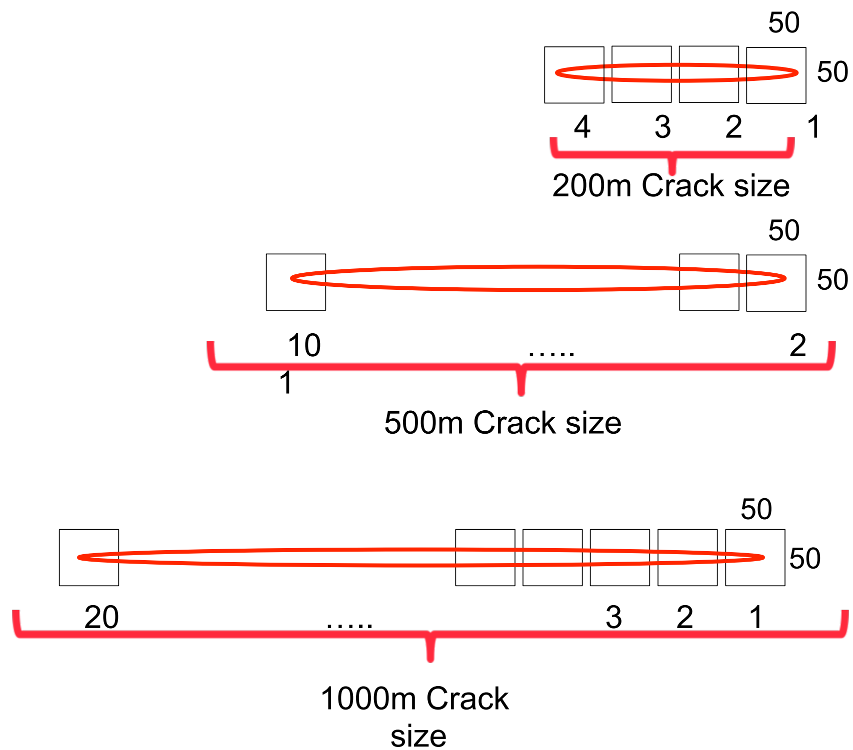

## Reservoir Conditions:



# Large Fracture Geometry

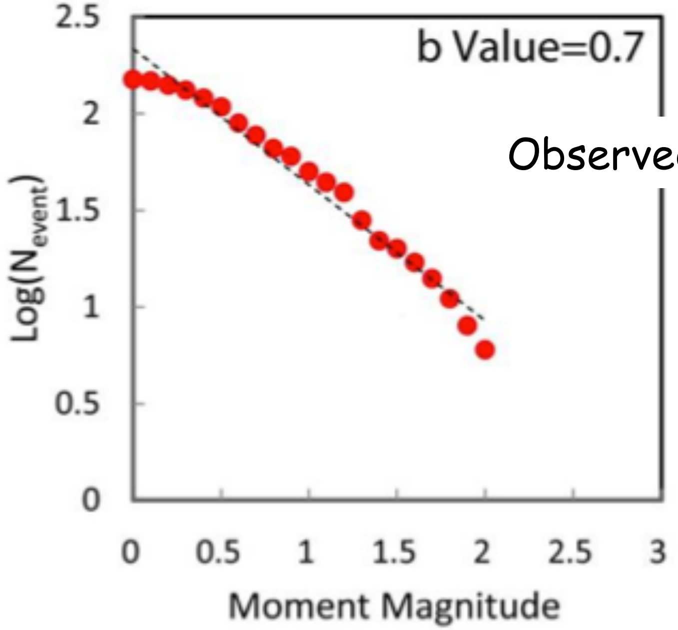
## Penny Shaped Crack



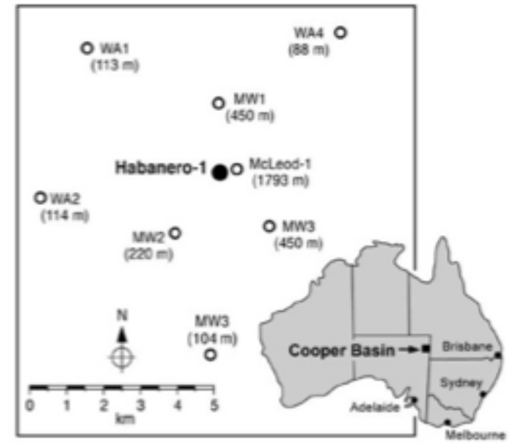



# Short-term Validation

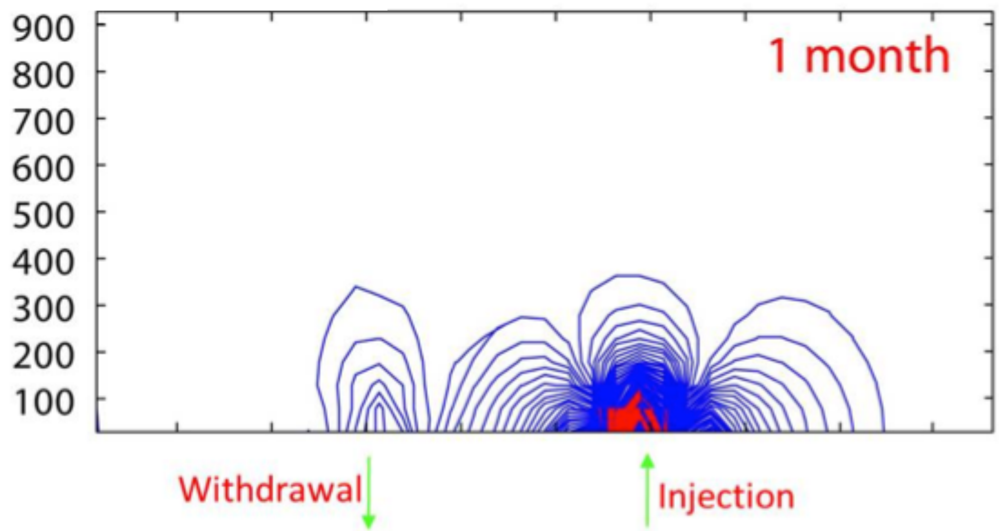
Model Results:



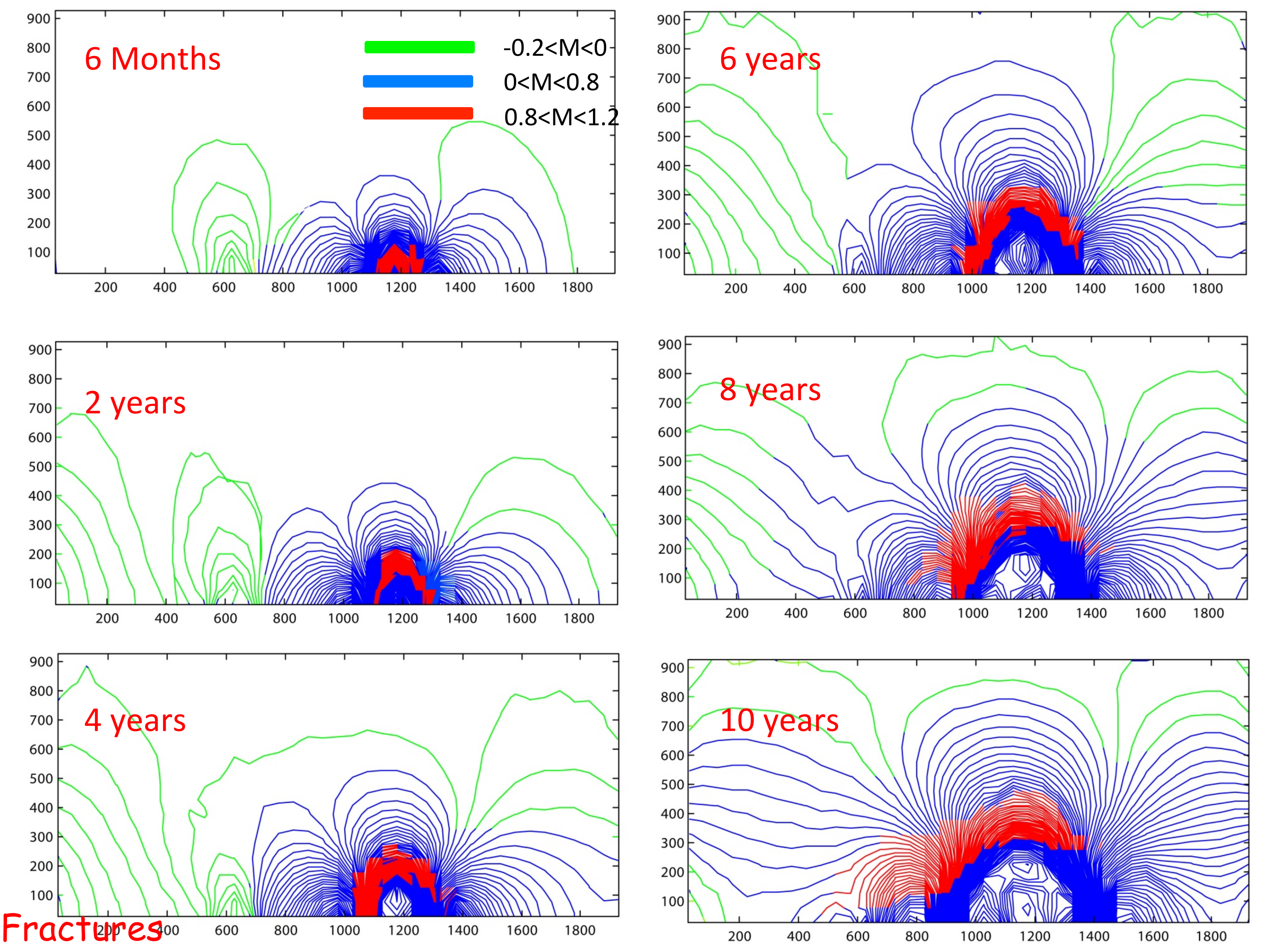

Observed b-value: ~0.7-0.8




Map of Cooper Basin Geothermal Field, Australia

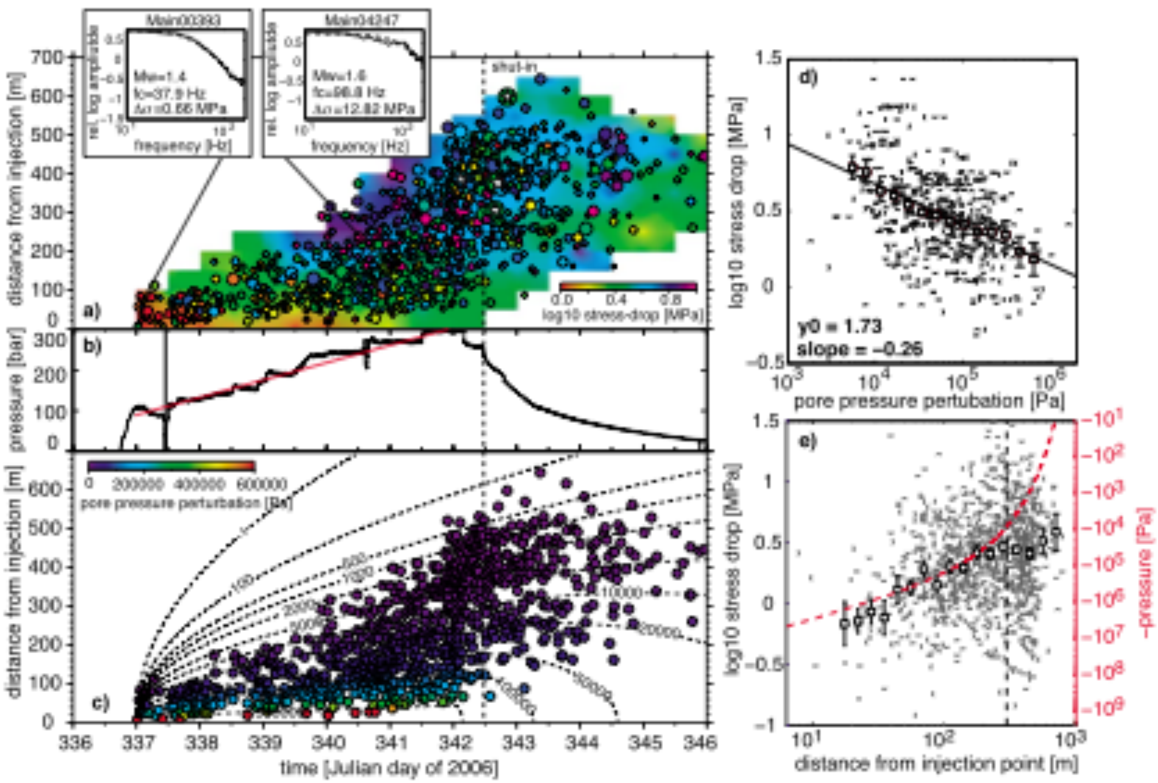


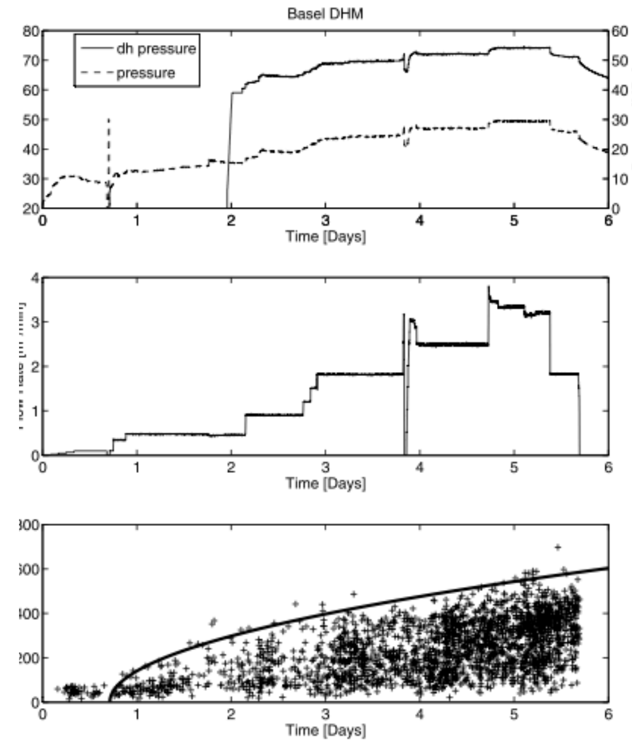
# Migration of Triggered Seismicity




200 m Fractures

# Observations of Induced Seismicity (Basel)




[Goertz-Allmann et al, 2011]

[Shapiro and Dinske, 2009]

# r-t Plot - Fluid and Thermal Fronts and Induced Seismicity

| | | |
|---|---|---|
| **Parameters utilized in simulation** | | |
| $k_0$ | Permeability[m$^2$] | $10^{-17}$ |
| $P_p$ | Pore Pressure[Mpa] | 14.8 |
| $P_{inj}$ | Fluid Pressure[Mpa] | 17.8 |
| $T_{res}$ | Reservoir Temperature[°c] | 250 |
| $T_{inj}$ | Fluid Temperature[°c] | 70 |
| $S$ | Fracture Spacing[m] | 10 to 500 |

Q: Flow rate

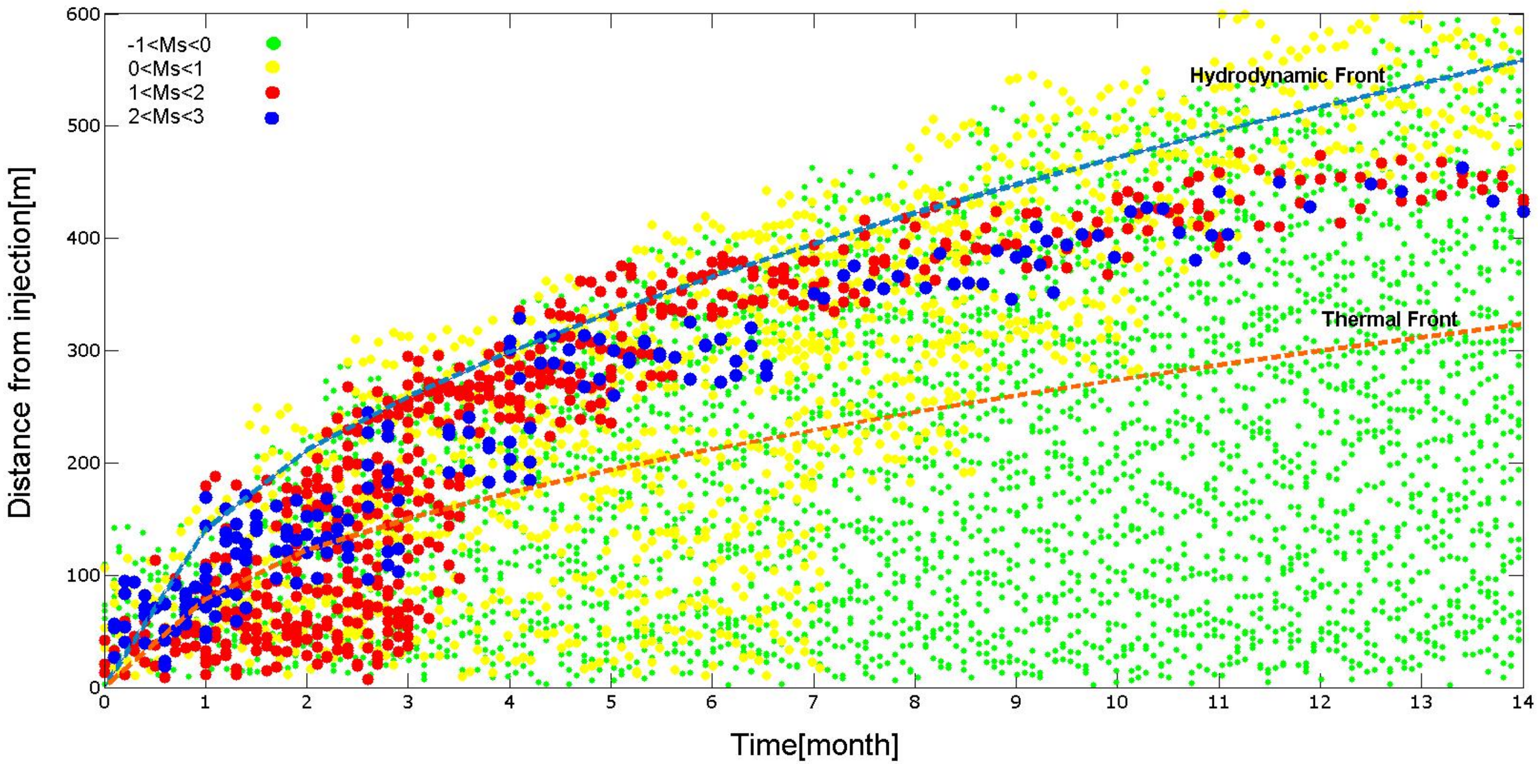
t : Time

h: Thickness

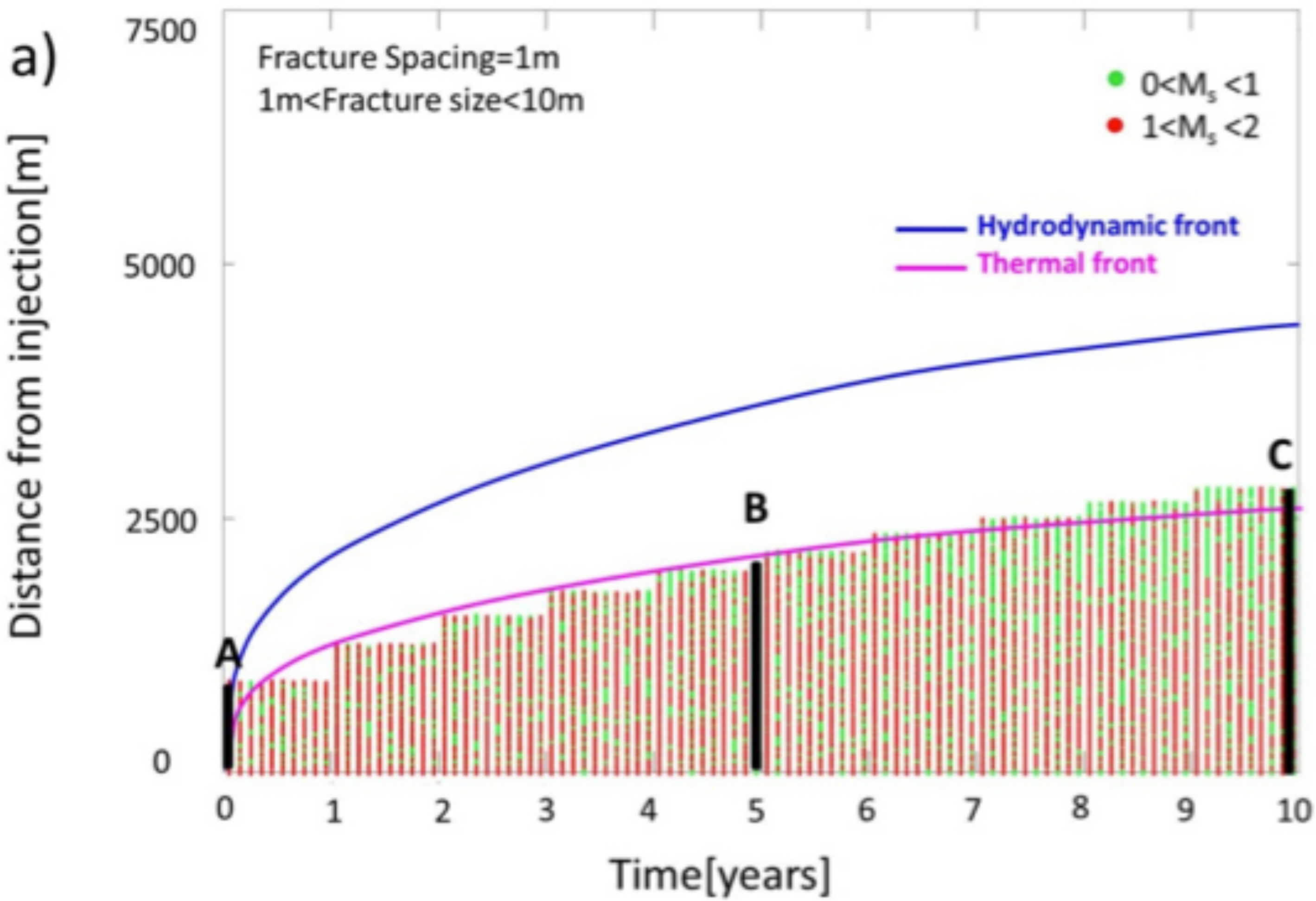
φ: Porosity

b: Aperture

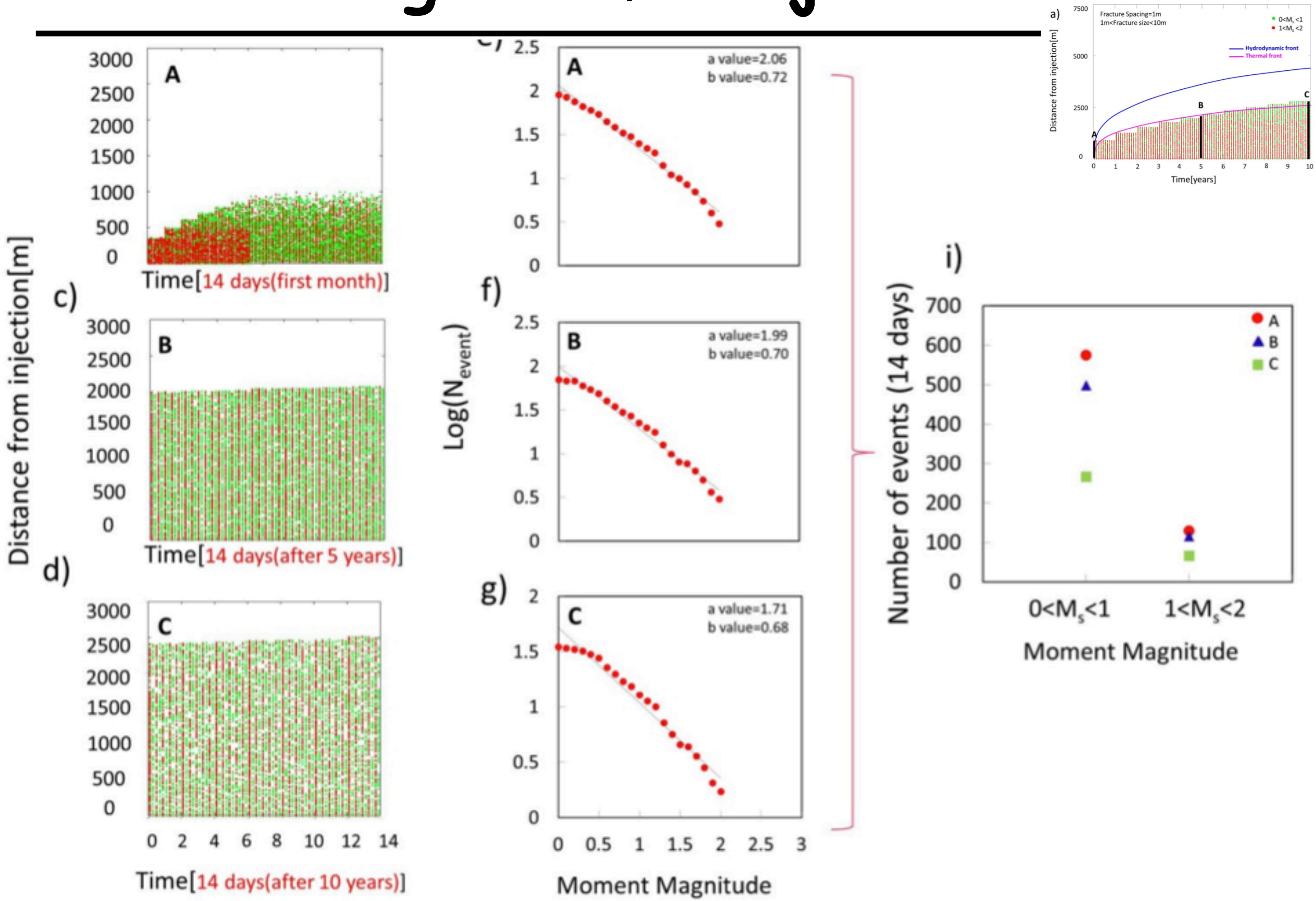
$$r = \sqrt{\frac{2Qt}{\pi h \phi}}, \qquad k_0 = \frac{b^3}{12S}$$



# Long-Term Projection

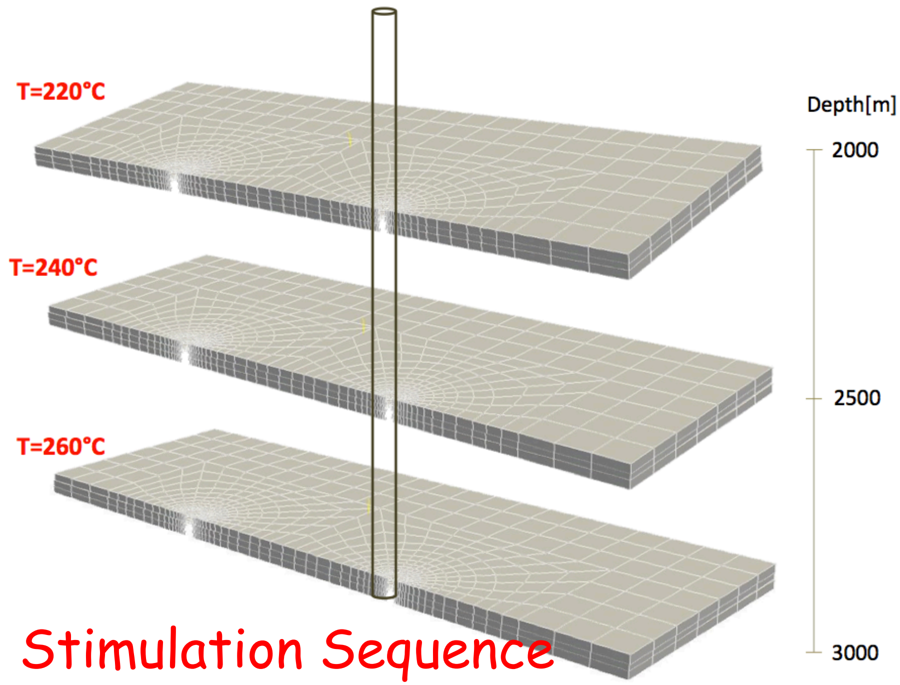


# Long-Term Projection

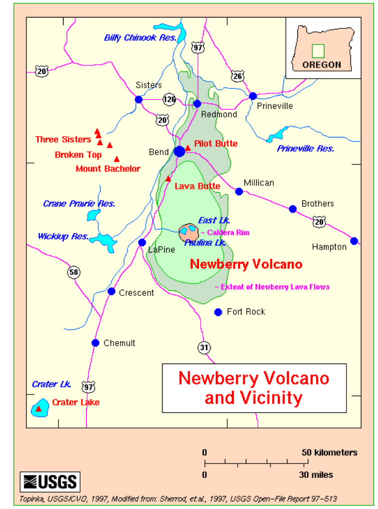


# Newberry Stimulation

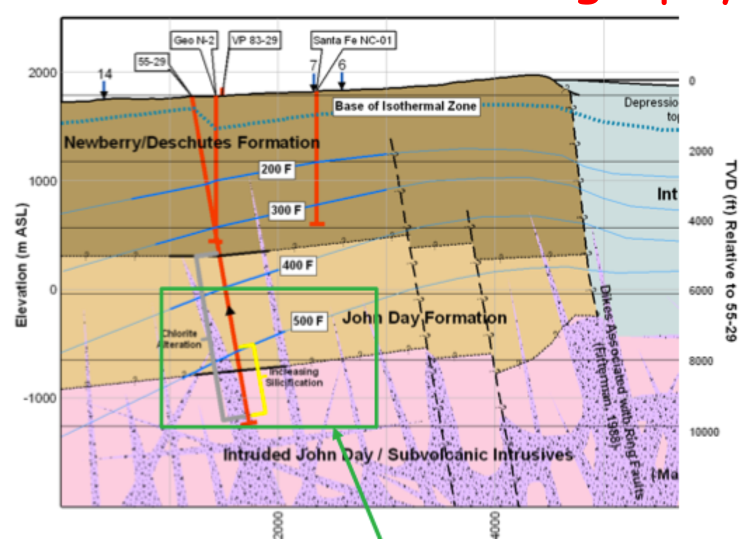
## Stacked Reservoir Model



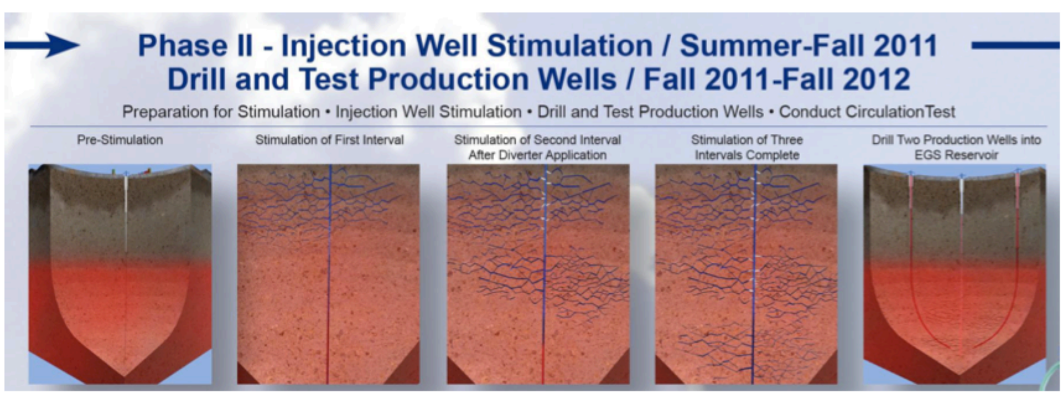

## Location




## Volcanic stratigraphy

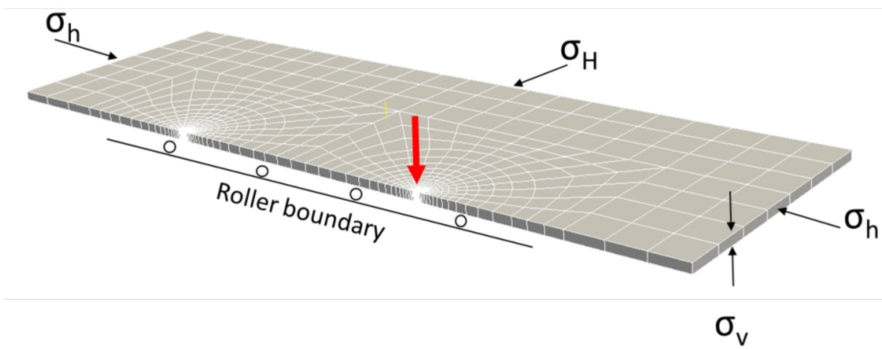


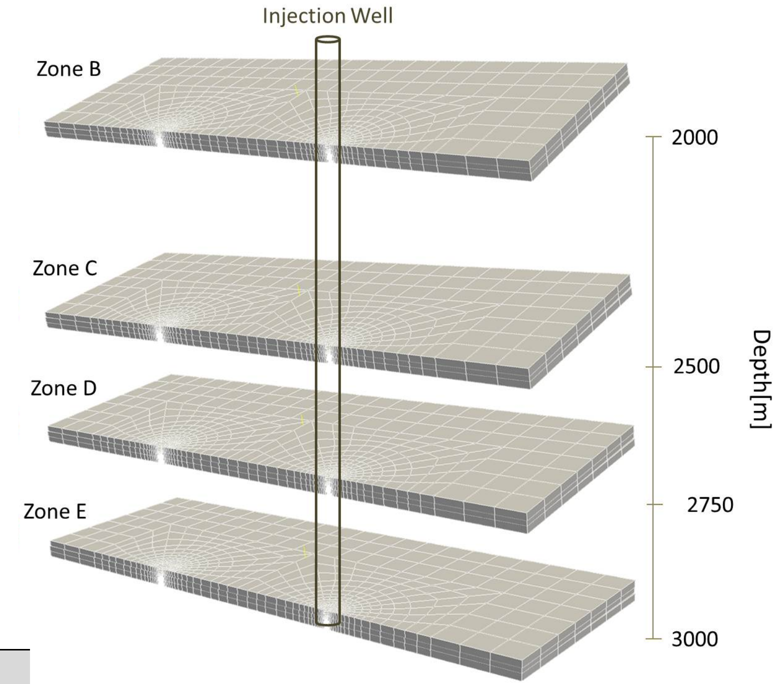

## Stimulation Sequence



# Zone Characterstics

## Stimulation zones




| Parameters | Unit | Depth[m] | | | |
|---|---|---|---|---|---|
| | | 2000 | 2500 | 2750 | 3000 |
| | | Zone B | Zone C | Zone D | Zone E |
| $S_{hmin}$ | MPa | 36 | 45 | 50 | 54 |
| $SH_{max}$ | MPa | 48 | 58 | 64 | 70 |
| $S_v$ | MPa | 48 | 60 | 66 | 72 |
| $P_{injection}$ | MPa | 29 | 33 | 35 | 37 |
| $P_{reservoir}$ | MPa | 24 | 28 | 30 | 32 |
| $P_{production}$ | MPa | 19 | 23 | 25 | 27 |
| Peak Strength | MPa | 25 | 30 | 35 | 38 |
| $T_{rock}$ | °c | 230 | 280 | 290 | 310 |
| $T_{injection}$ | °c | 20 | 20 | 20 | 20 |

$S_{hmin}=0.75\ S_v$

$\Delta p=5$ MPa

# Zone Characteristics

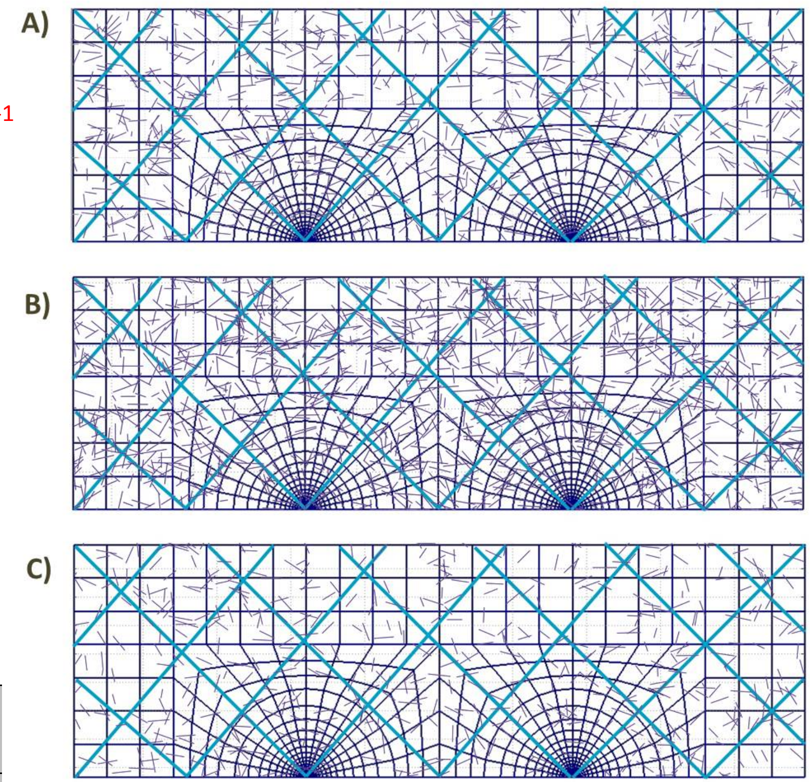
## Fracture Network Characterization

Large fractures: density of 0.003 $m^{-1}$ - spacing 300 m

Fracture density is 0.5 $m^{-1}$

0.9 $m^{-1}$

0.26 $m^{-1}$



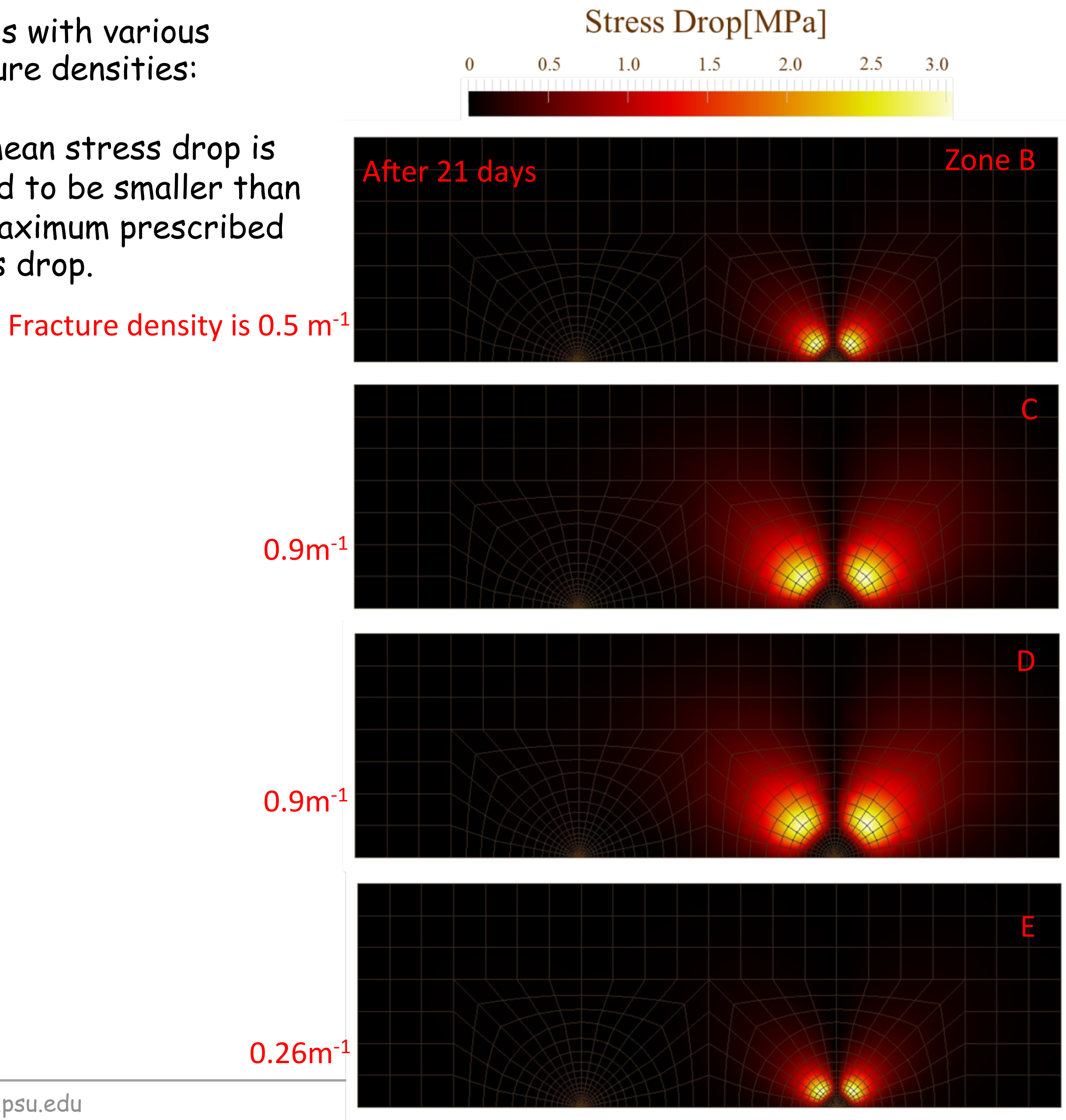

| Fracture Characterization | Unit | Depth[m] | | | |
|---|---|---|---|---|---|
| | | 2000 | 2500 | 2750 | 3000 |
| | | Zone B | Zone C | Zone D | Zone E |
| Density | $m^{-1}$ | 15/30m | 27/30m | 27/30m | 8/30m |
| Number of seeded fractures | - | 1000 | 1800 | 1800 | 600 |
| Fracture size | m | 10-1200 | 10-1200 | 10-1200 | 10-1200 |
| Fracture spacing | m | 1-300 | 1-300 | 1-300 | 1-300 |
| Standard deviation( $\bar{\sigma}$ ) | - | 19 | 19 | 19 | 19 |
| Mean( $\bar{\mu}$ ) | - | 360 | 360 | 360 | 360 |

200<Large Fracture<1200m
10<Small Fracture<200m

# Cumulative Stress Drop

Models with various fracture densities:

The mean stress drop is limited to be smaller than the maximum prescribed stress drop.




Development of stress drop begins earlier, reaches further from injection in a given time (~21 days) and is completed fastest for zones C and D.

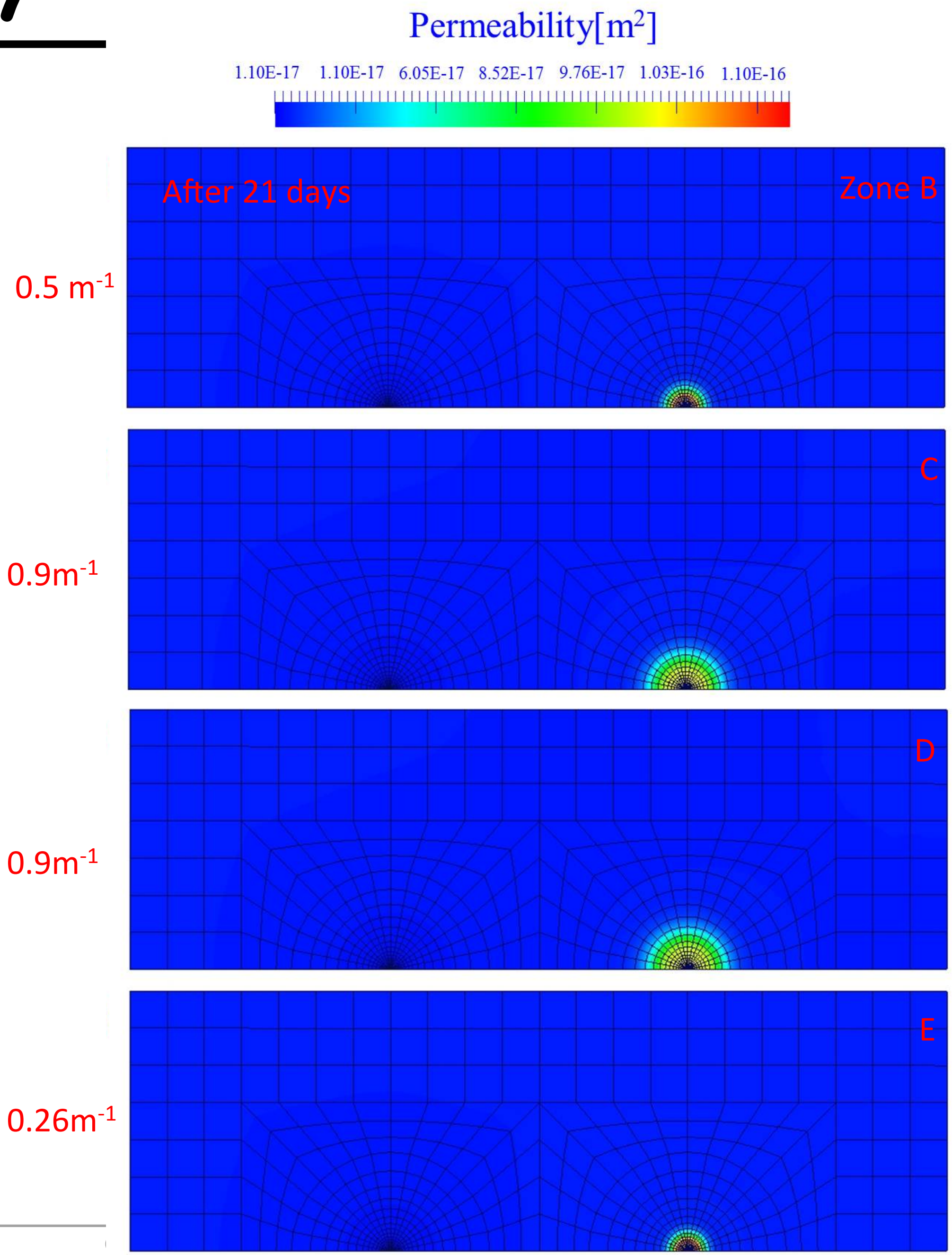

derek.elsworth@psu.edu

# Permeability

Comparison of average radial permeability changes for different fracture structures:

The mechanical shearing effect (dilation angle is 10°) occurs due to the change in effective stress driven by fluid and thermal effects and their influence on reservoir shear failure.

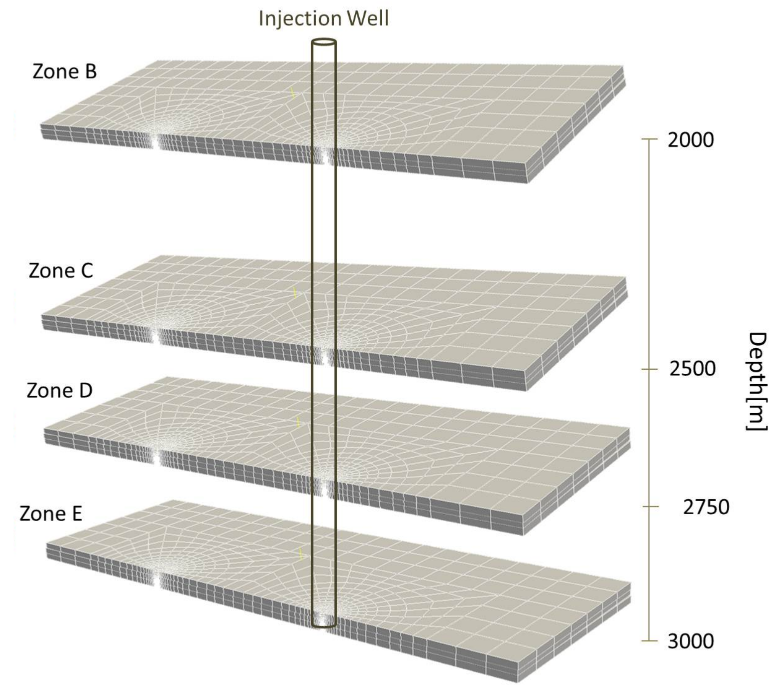
Permeability improvement in all zones is radially symmetric.



# Parametric Analysis

$$\log M_0 = 1.5M_s + 9.1$$

- Shear stress drop
- Fracture size, spacing




**Two different models applied:**

Moment magnitude evolution

1) Fracture density is the same at shallow to deep zones (0.9 $m^{-1}$ )

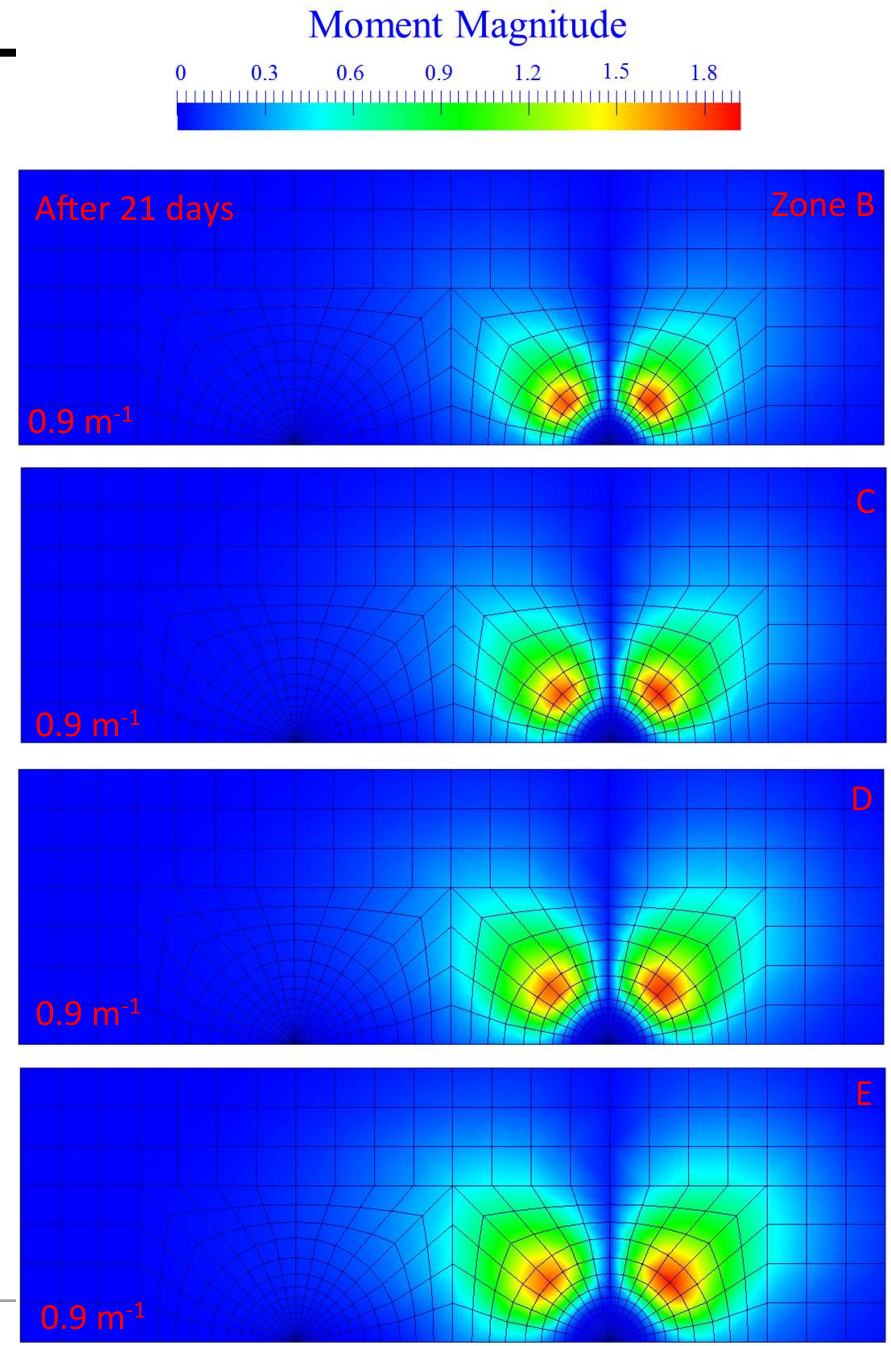
2) Fracture density is not the same at shallow to deep zones (0.5 $m^{-1}$, 0.9 $m^{-1}$, 0.26 $m^{-1}$ )

# Moment Magnitudes – Same Fracture Density

For the same fracture density:

With increasing stresses (reaching the deeper reservoir):

Migration rate of seismic event with time and location changes little - these events may form at the same rate for shallow to deep zones when the same fracture network is present.

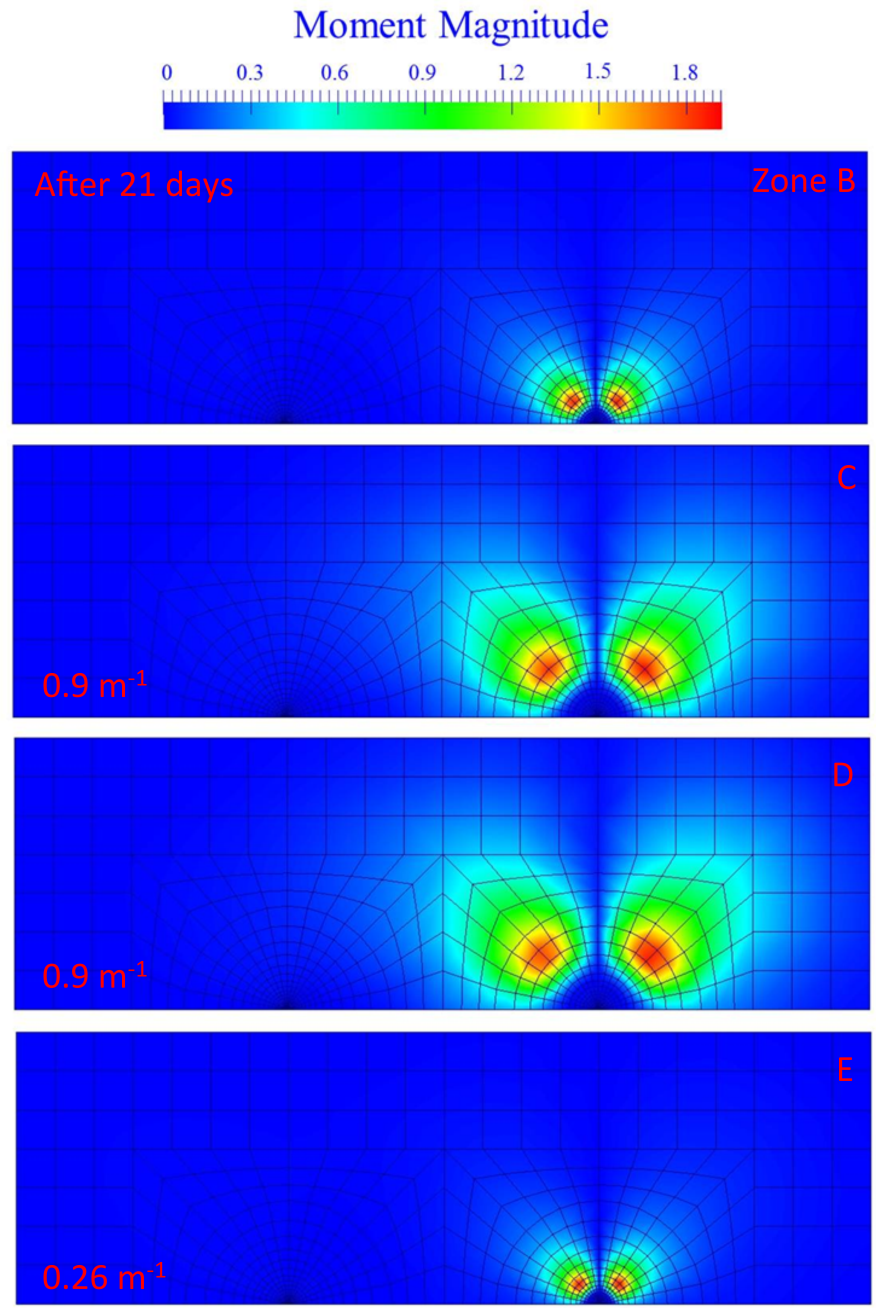


# Moment Magnitudes – Variable Fracture Density

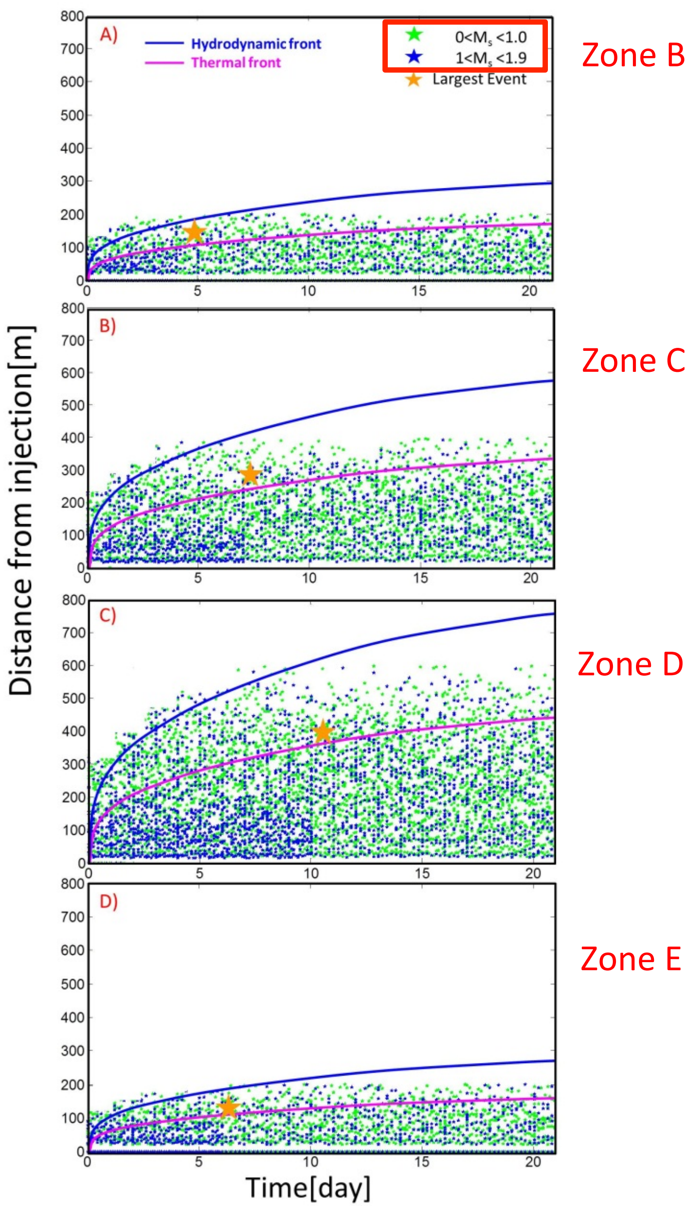
When we apply a differing fracture density:

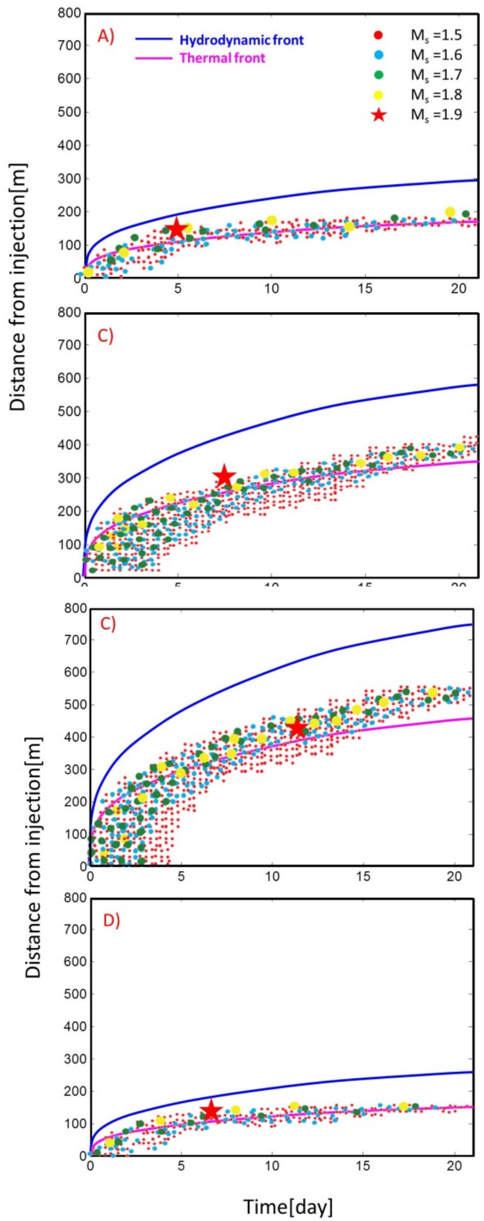
The rate of seismic event migration within the reservoir is controlled principally by the density and spacing of the fractures.

Highest fracture density generates both the most and the largest seismic events.



# Event Distribution over 21 Days

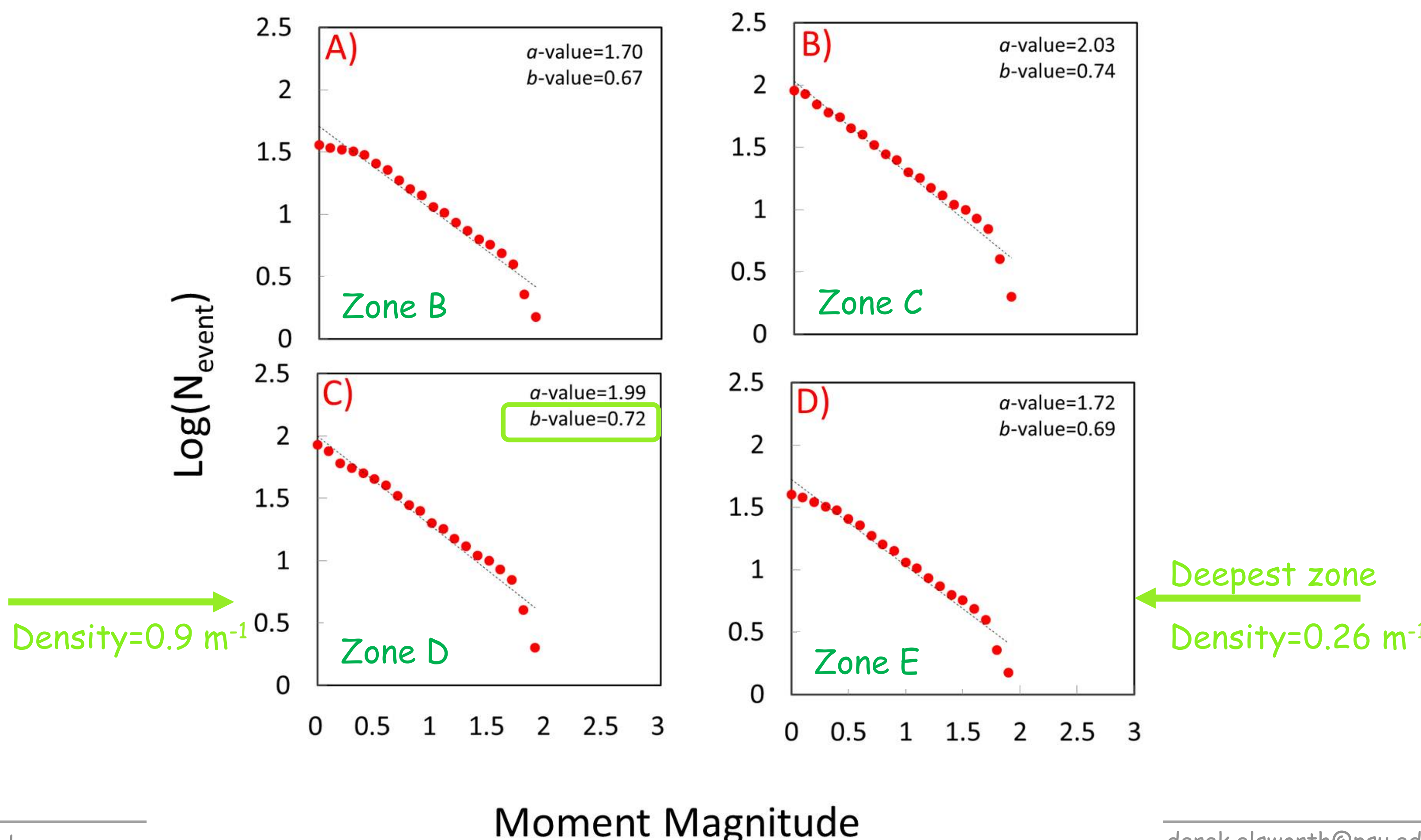


# b-value evolution over 21 Days

*b*-value magnitude [21 days Stimulation]

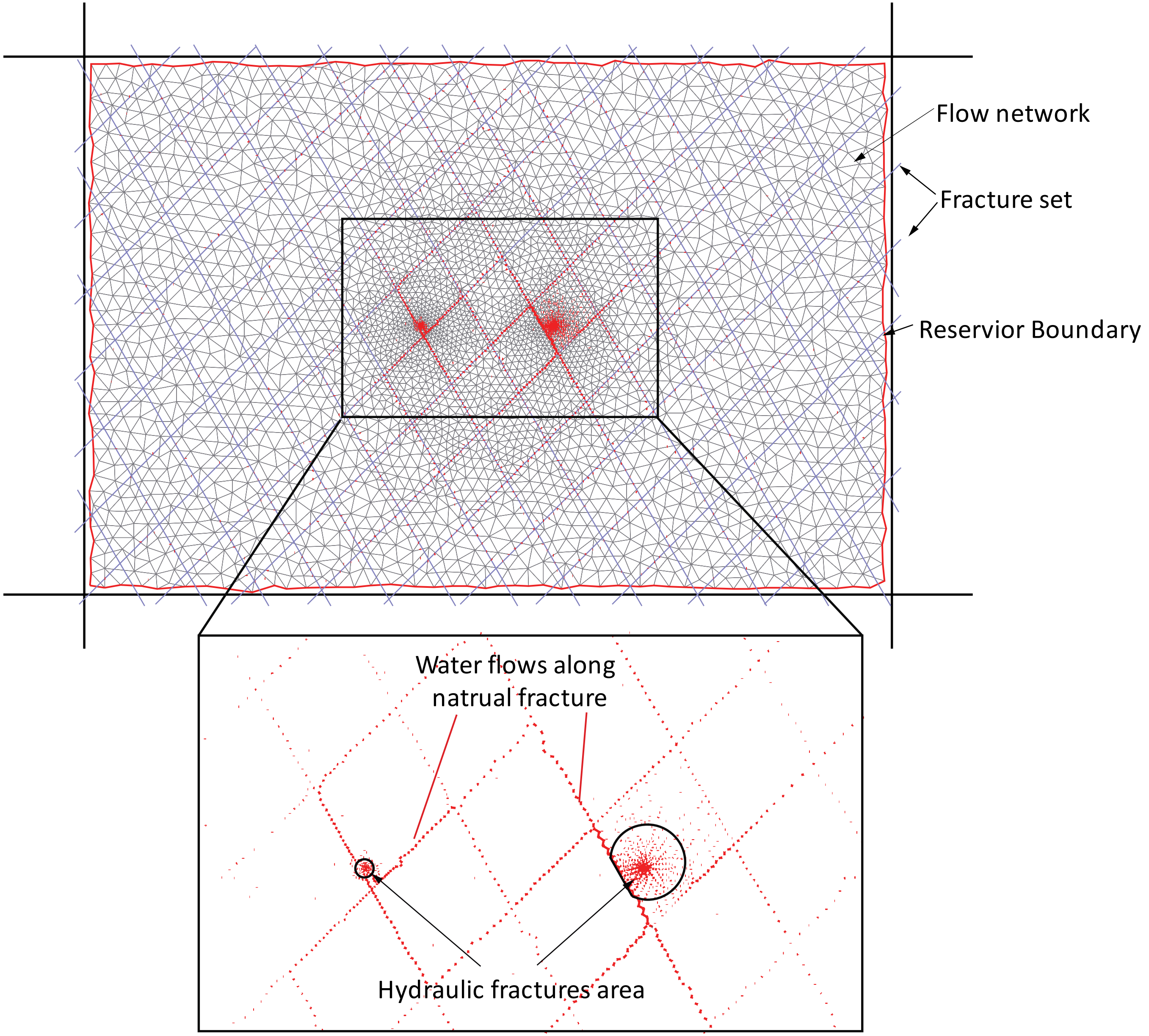
We characterize the induced seismicity by the *b*-value for three different fracture geometries (high to low density):






derek.elsworth@psu.edu

# Discontinuum Approaches



# Conclusions

**Complex THM and THC Interactions Influence Reservoir Evolution**

- Permeability evolution is strongly influenced by these processes
- In some instances the full THMC quadruplet is important
- Effects are exacerbated by heterogeneity and anisotropy

**Spatial and Temporal Evolution**

- Physical controls (perm, thermal diffusion, kinetics) control progress
- Effects occur in order of fluid pressure (M), thermal dilation (TM), chemical alteration (C)
- Spatial halos also propagate in this same order of pressure, temperature, chemistry

**Induced Seismicity**

- Mechanisms that control stress effects also influence seismicity
- Event magnitudes controlled by stress-drop and fracture size
- Distribution controlled by fracture location and sizes (if no new fractures created)
- Timing controlled by:
  - Relative magnitude of stress change effects (pressure, temp, chem)
  - Rates of propagation and self-propagation of those stress-change fronts
- Isolating principal mechanisms is one key to mitigating effect