Short-timescale Chemo-mechanical Effects and Their Effect on the Transport Properties of Fractured Rock

By

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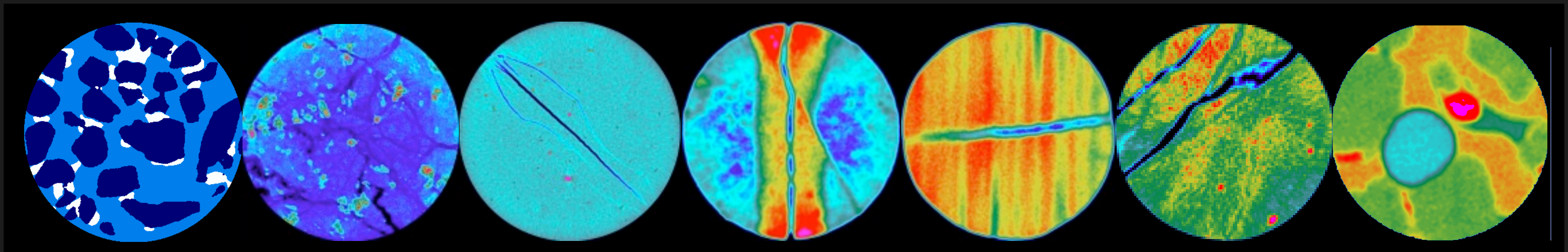
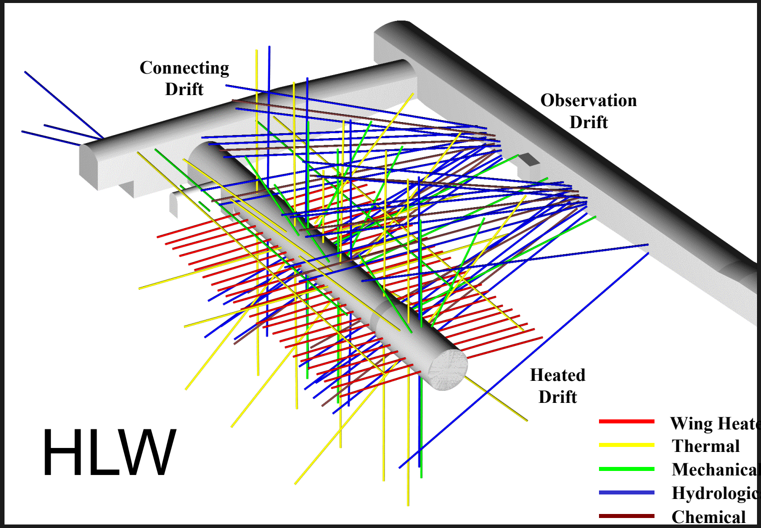


What is the importance?



What are the roles of:

Stress fields and paths [M]

Thermal fields and paths [T]

Chemical potential fields and paths [CB]

In the evolution of fluid transport [H] behavior?

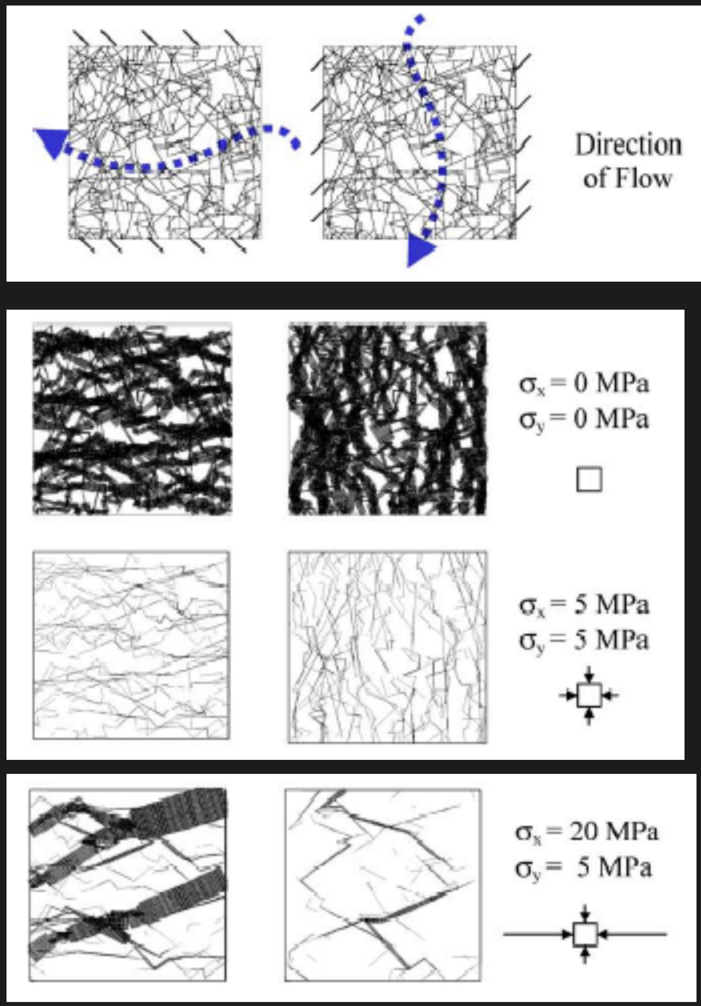
Specifically….. where fractures are present – what is the transmission sensitivity?… and …

Specifically….. whether fracture permeabilities increase or decrease with net dissolution/precipitation, pressure-solution, …..? ……And how quickly do they do this?

………… and what are the controls on these processes?

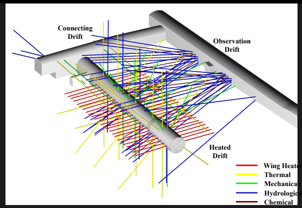
Typical Modes of Analysis for THMC Systems:

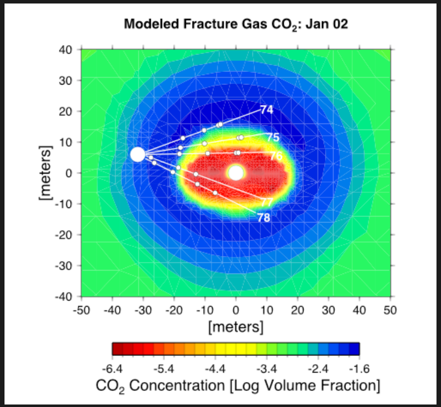
THM - GeoMechanics

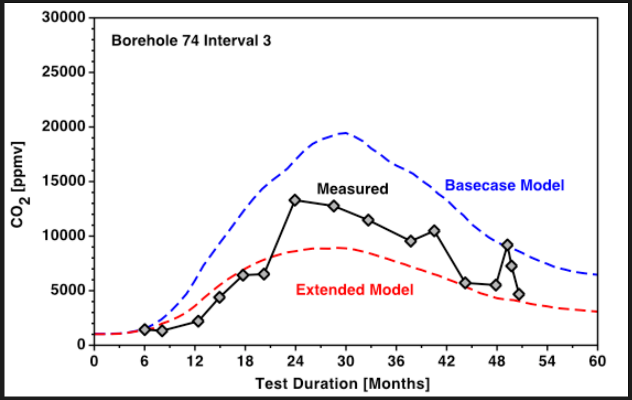


e.g. K.-B. Min (2004)

THC - GeoChemistry







[Courtesy: E. Sonnenthal]

What is the form of the THMC linkage C-to-M?.... And is it important?

Road Map

Overview

Observations of anomalous C-M coupling

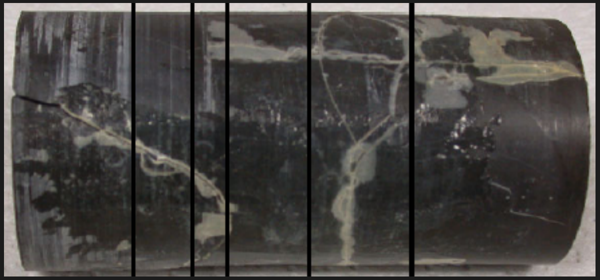
- Constrained experiments
- Observed response
- Constraints on behavior

Mechanistic models for response

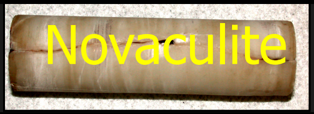
- Lumped Parameter Models
  - Granular systems
  - Fractures
- Scaling relations in space and time
- Distributed parameter models

Conclusions

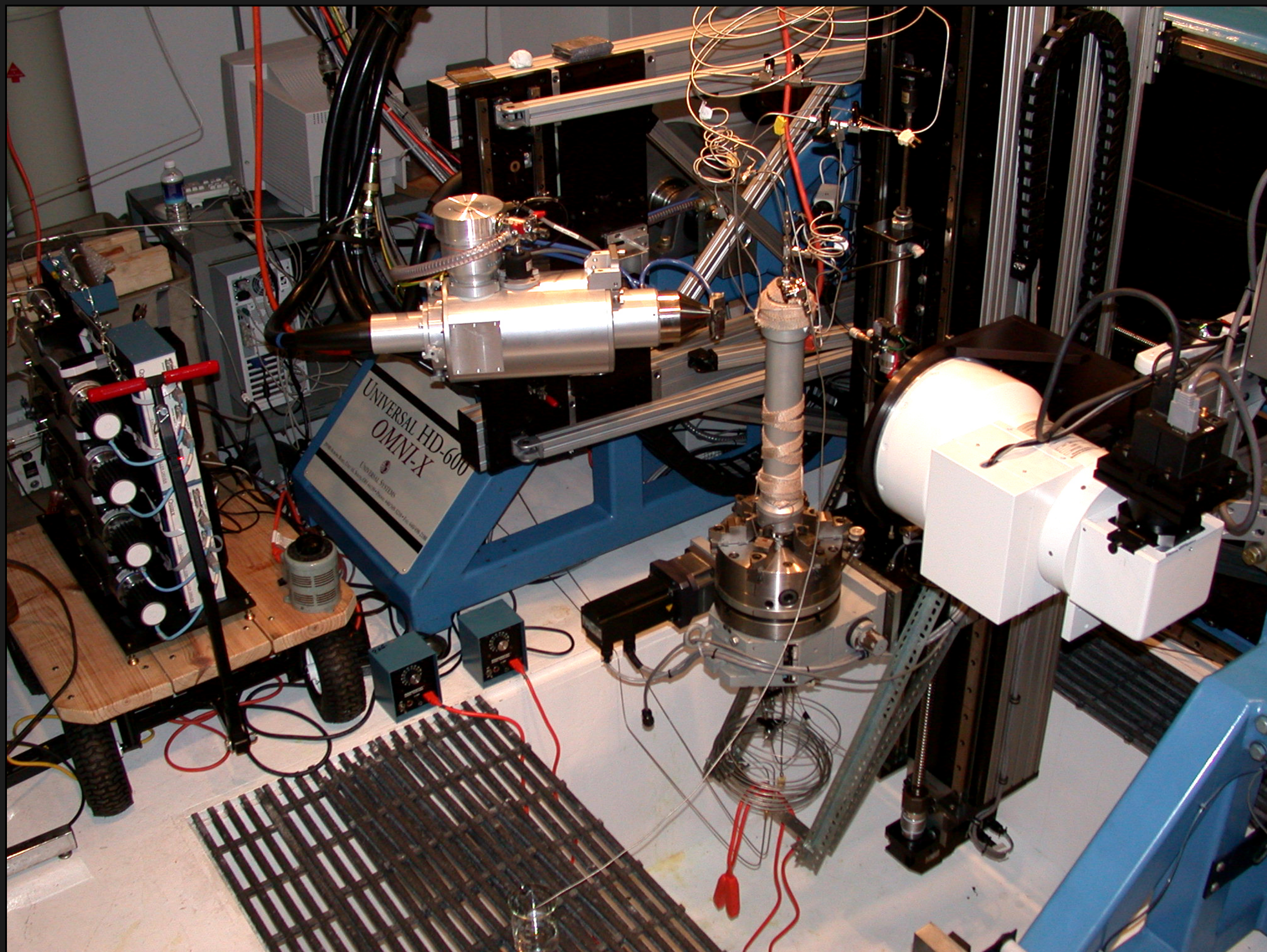
Experimental Configurations



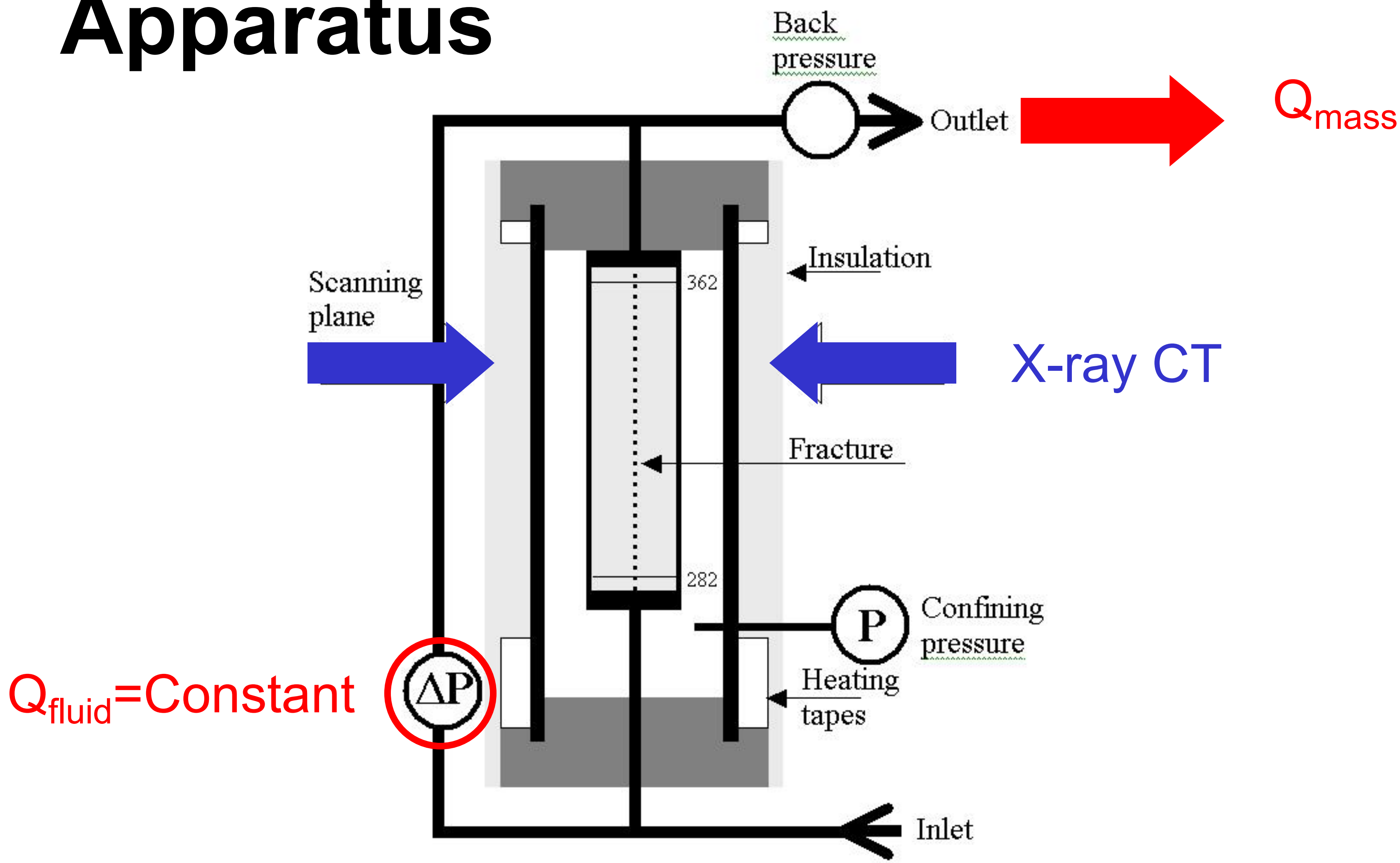
→ $\left\{ Q_{fluid},\ Q_{mass},\ \text{x-ray CT} \right\} \rightarrow \Delta k$

		 Novaculite	 Limestone
Matrix Porosity		<0.01%	<0.01%
Temperatures, ° C		20-150	20
Effective Stress, MPa		3.5	3.5
Permeants		DI	G/w & DI
Diss. Rate, k_+ [$Mol.m^{-2}.s^{-1}$]		$\sim 10^{-9}$	$\sim 10^{-6}$
Precip. Rate, k_- [$Mol.m^{-2}.s^{-1}$]		$\sim 10^{-7}$	

Experimental Arrangement

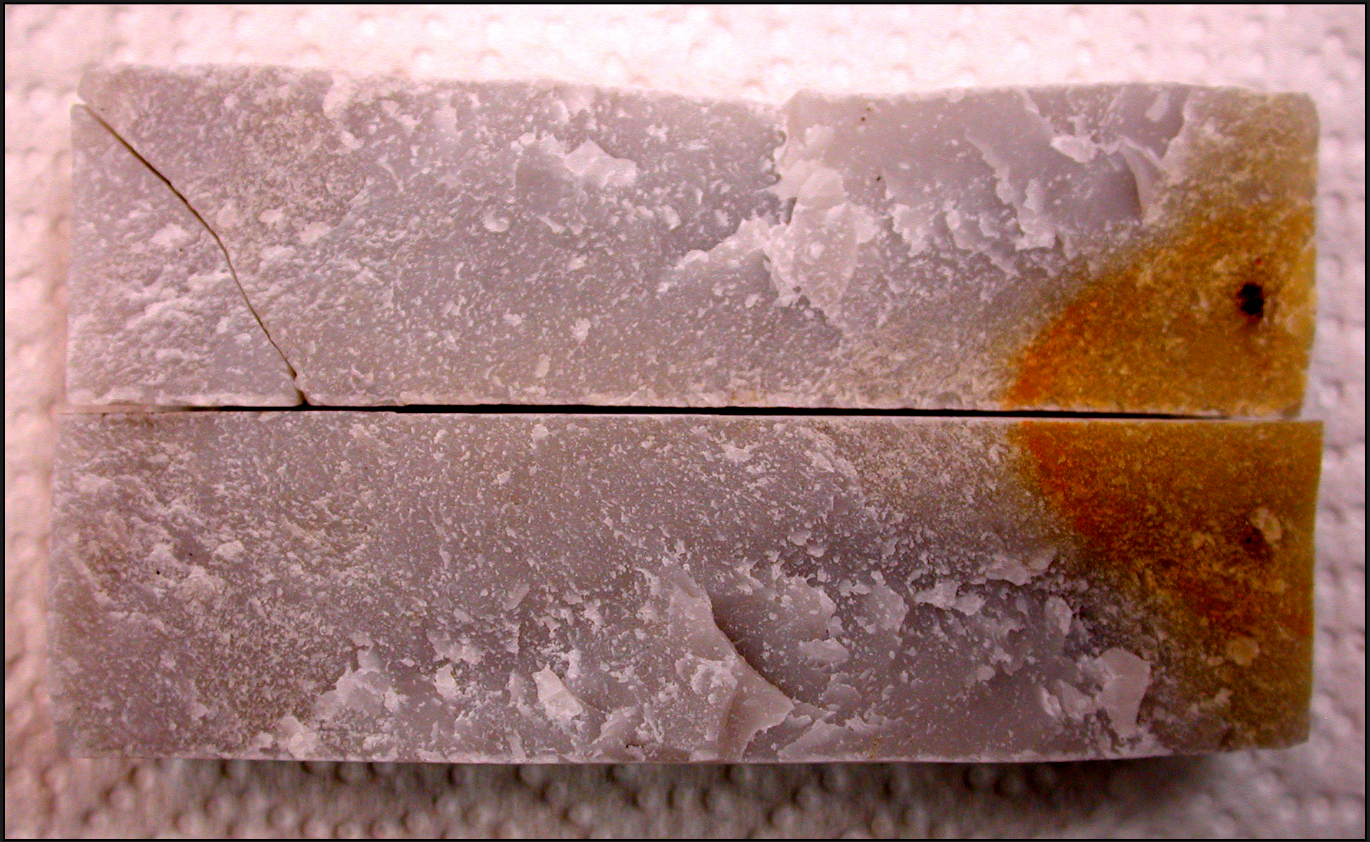

UNIVERSAL HD-600
OMNI-X

Apparatus

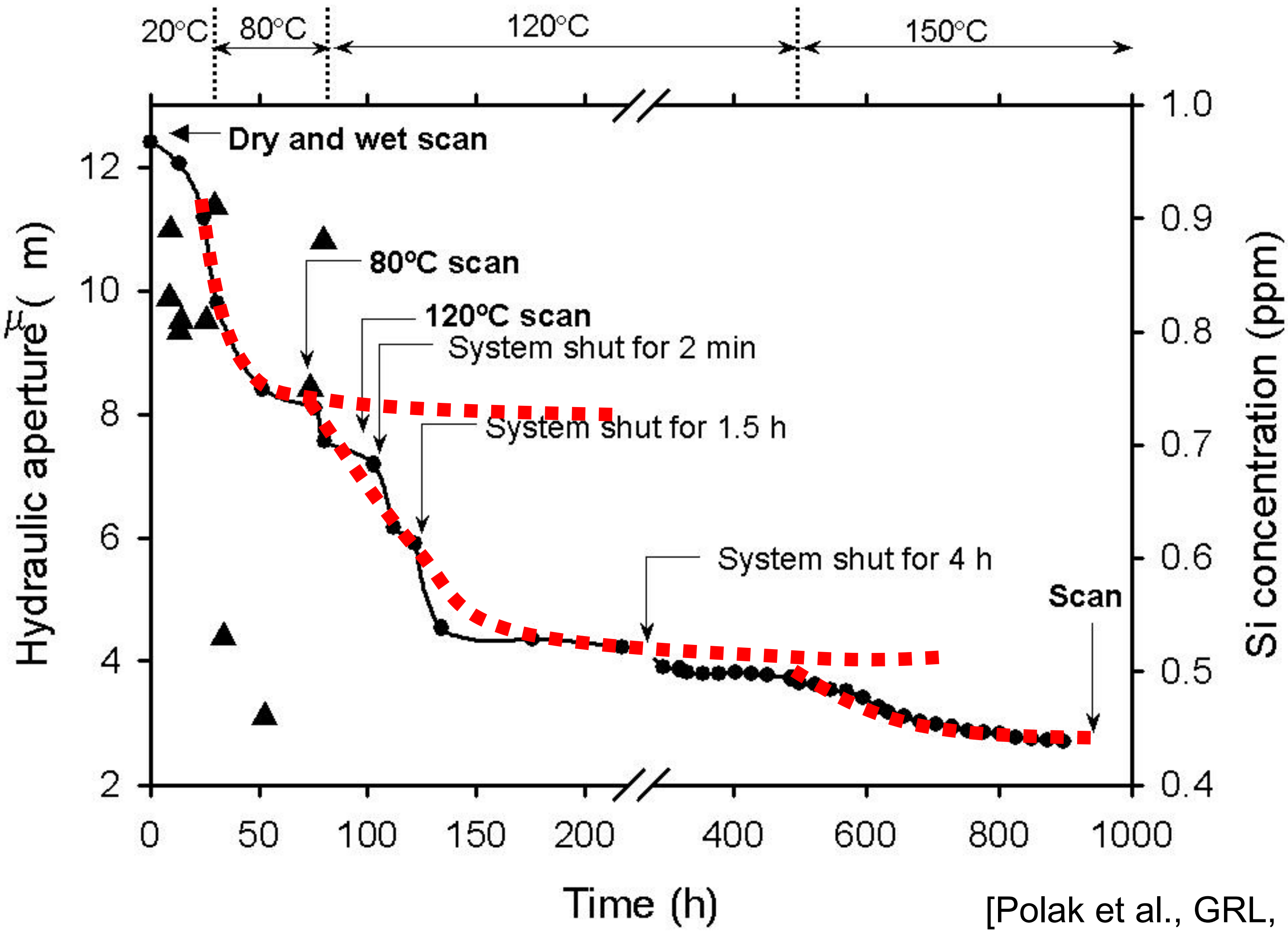


Back
pressure
Outlet
Q_{mass}
Insulation
Scanning
plane
362
X-ray CT
Fracture
282
P
Confining
pressure
Q_{fluid}=Constant
ΔP
Heating
tapes
Inlet

Arkansas Novaculite (99.5% Si; n<0.01%)



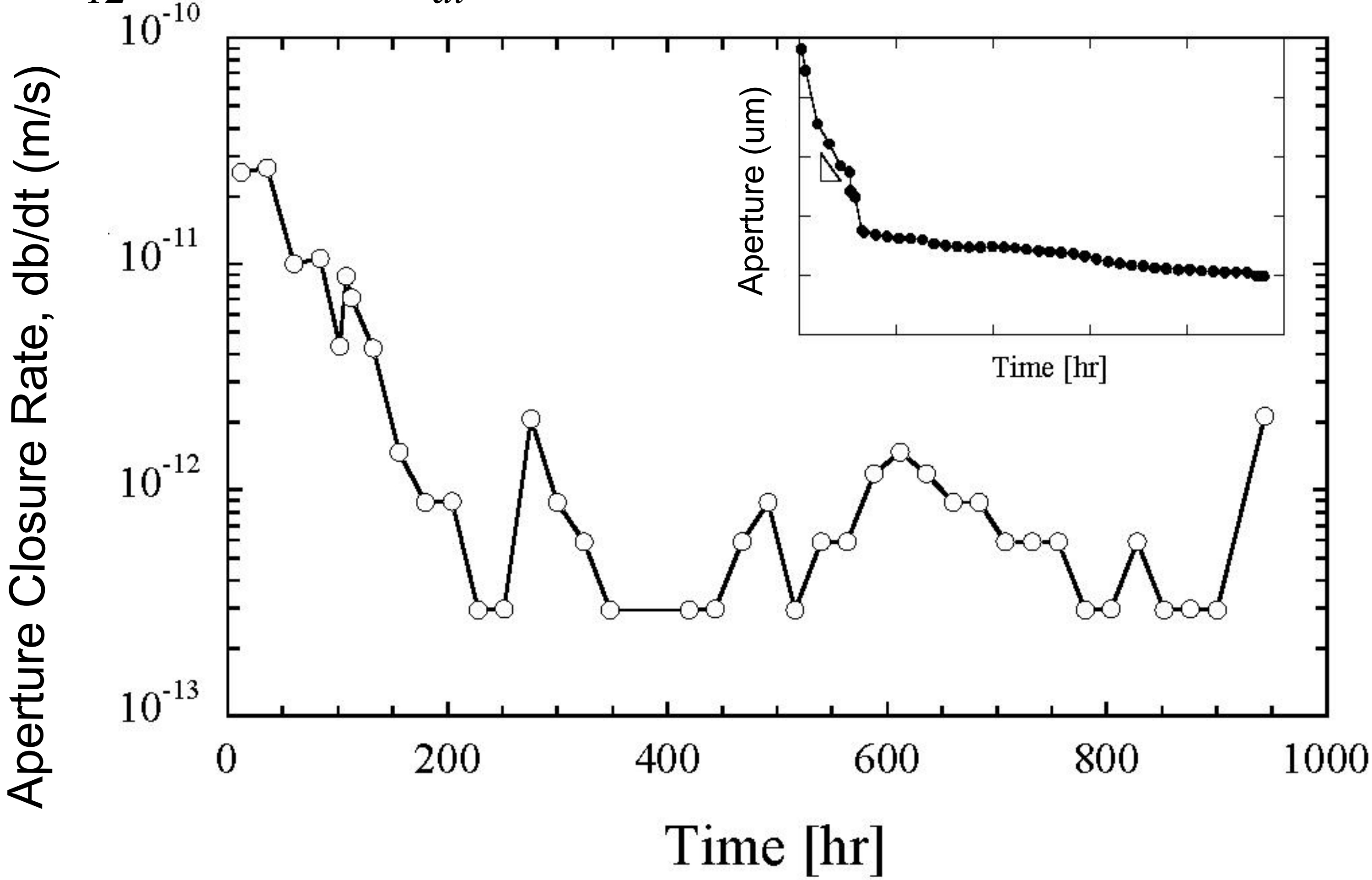
Typical Response



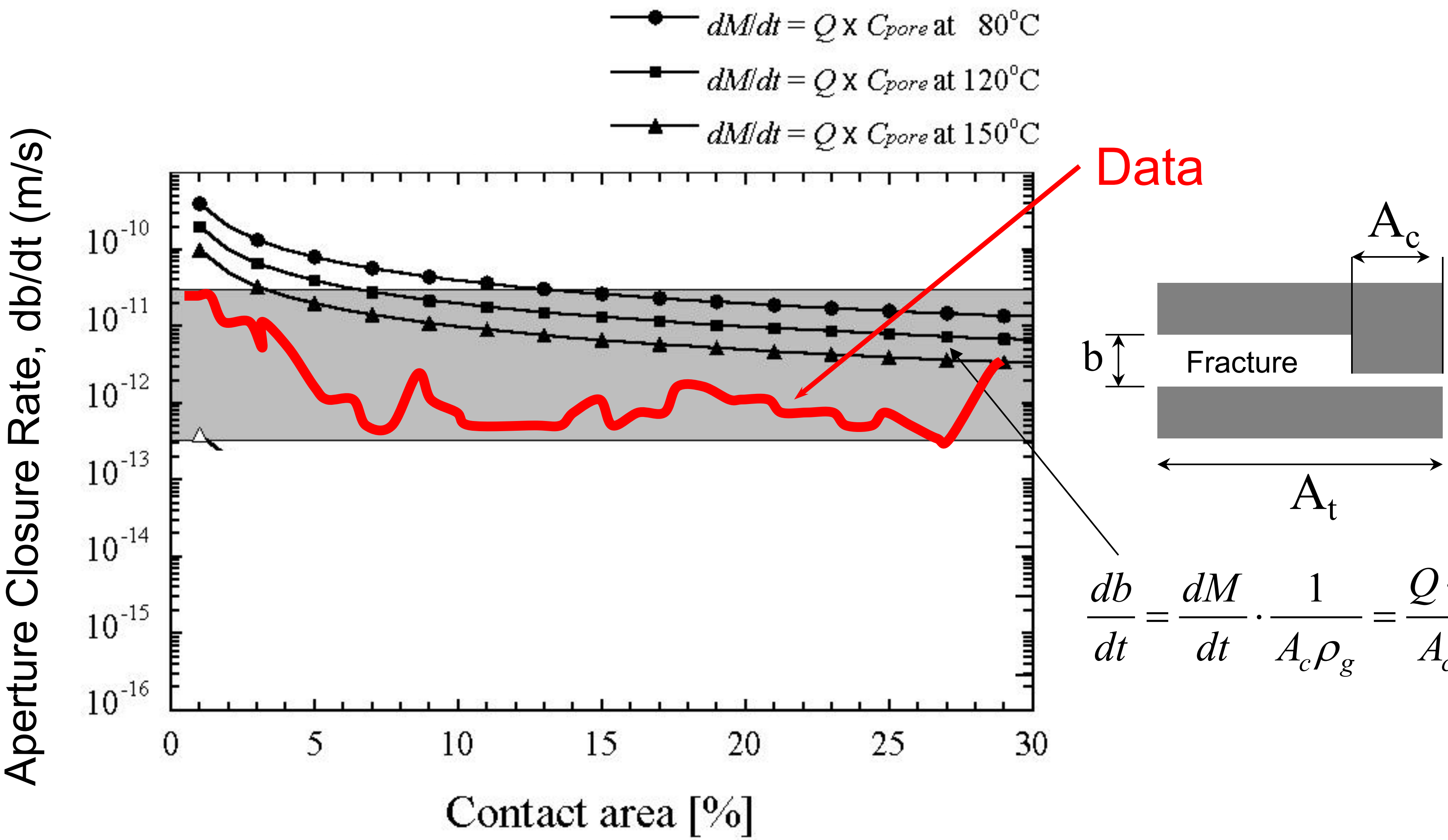
[Polak et al., GRL, 2003]

Hydraulic Measurements of db/dt

$$k = \frac{b^2}{12} \rightarrow b = \sqrt{12k} \rightarrow \frac{db}{dt}$$



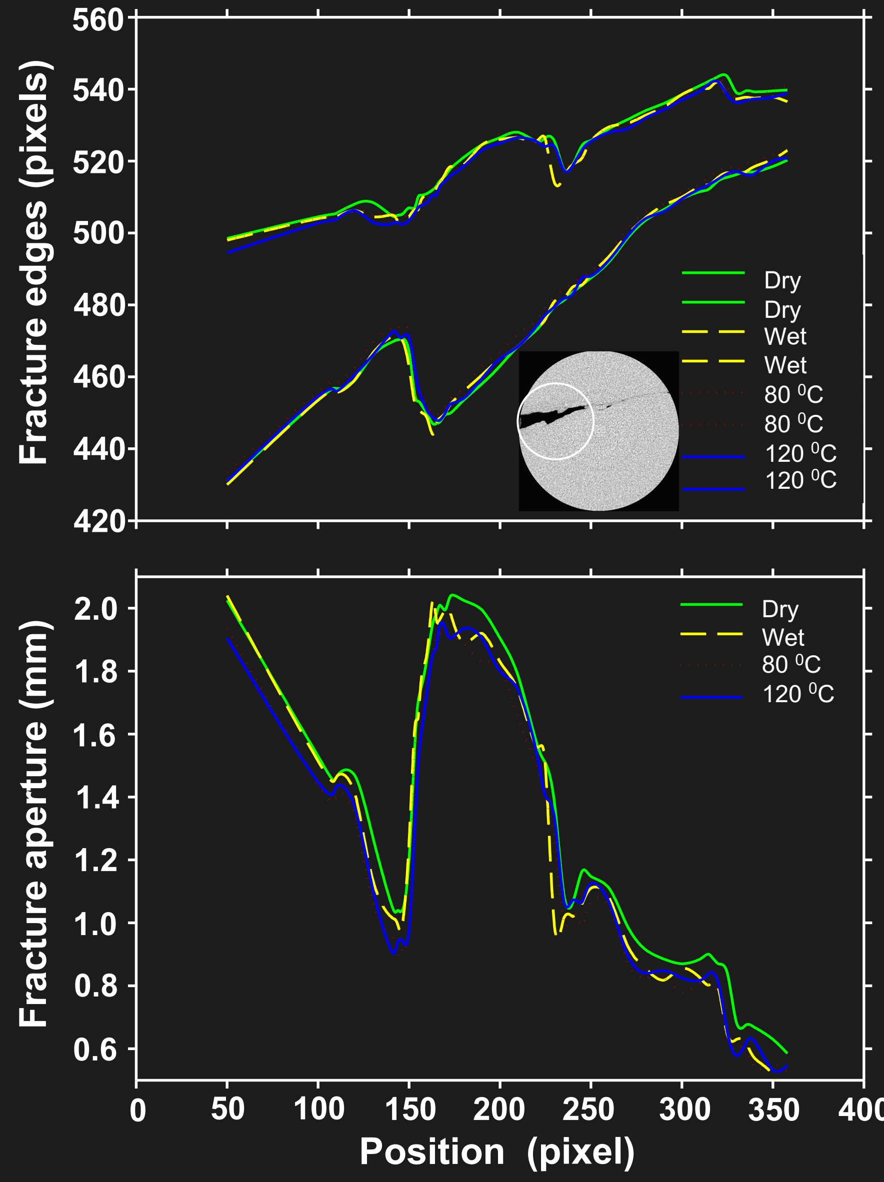
Mineral-Mass Measurements of db/dt

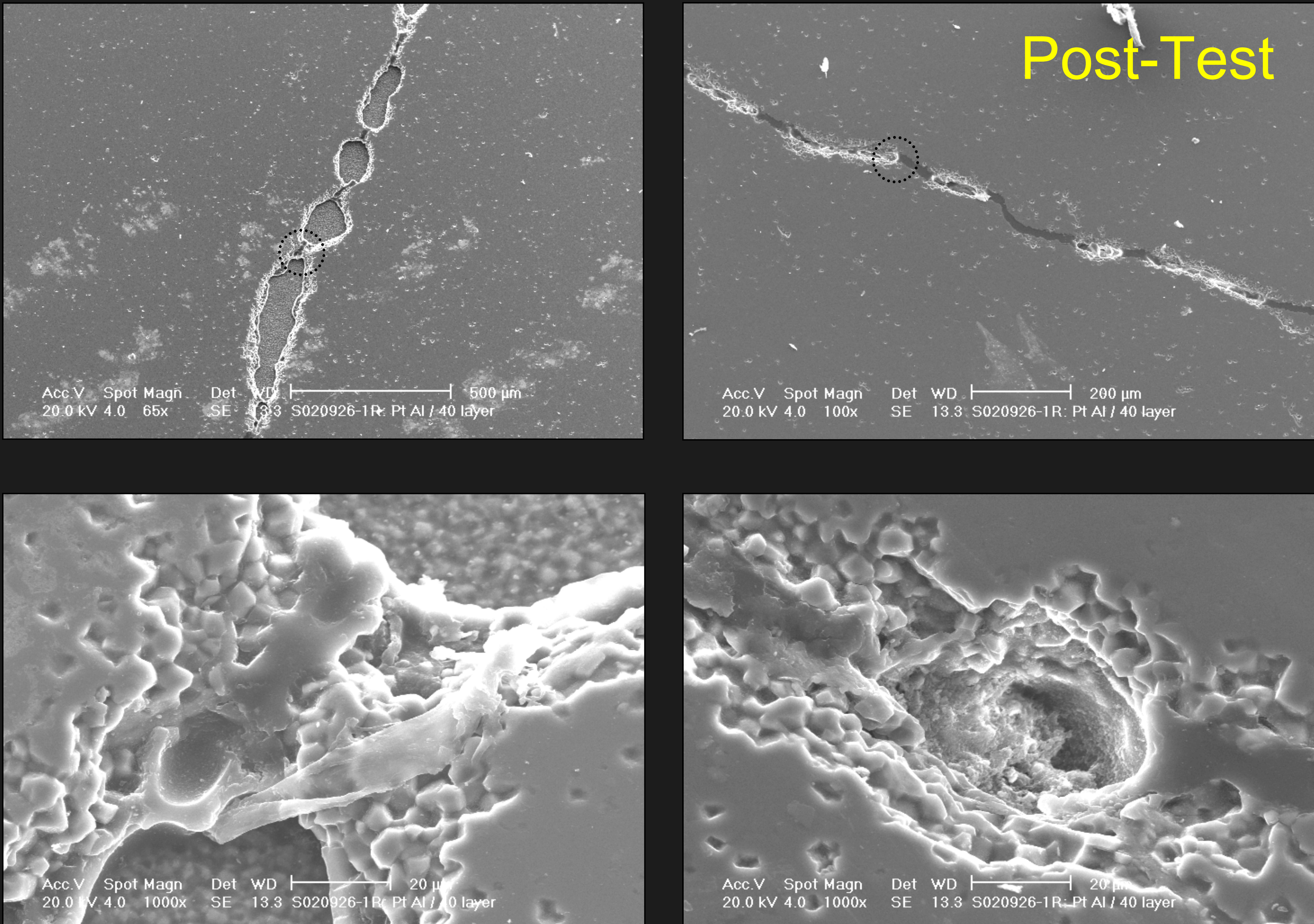


$$\frac{db}{dt} = \frac{dM}{dt} \cdot \frac{1}{A_c \rho_g} = \frac{Q \cdot C_p}{A_c \rho_g}$$

Imaging-Derived Aperture Changes

- Observed mean aperture change of 10 μm
- Resolution of 37 μm too low
- In areas of large absent chip, aperture changes are of the order 100 μm
- This amplification results from core rotation around a fulcrum




Post-Test
Acc.V Spot Magn Det WD 500 µm
20.0 kV 4.0 65x SE 13.3 S020926-1R: Pt Al / 40 layer
Acc.V Spot Magn Det WD 200 µm
20.0 kV 4.0 100x SE 13.3 S020926-1R: Pt Al / 40 layer
Acc.V Spot Magn Det WD
4.0 1000x SE 13.3
Acc.V Spot Magn Det WD
20.0 kV 4.0 1000x SE 13.3 S020926-1R Pt Al / 40 layer

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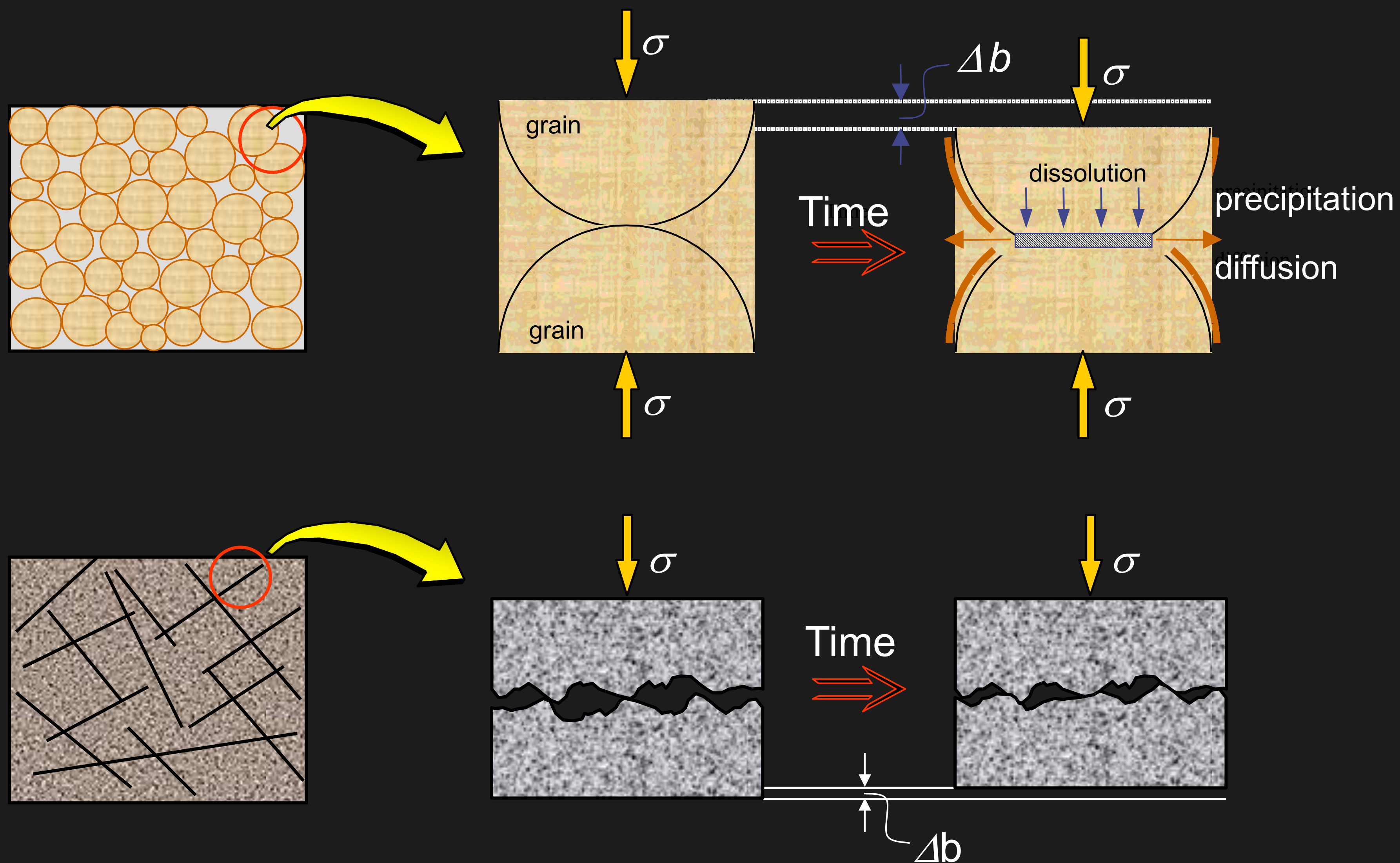
Dissolution Processes
Approaches to Determine Δk or Δb



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

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

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

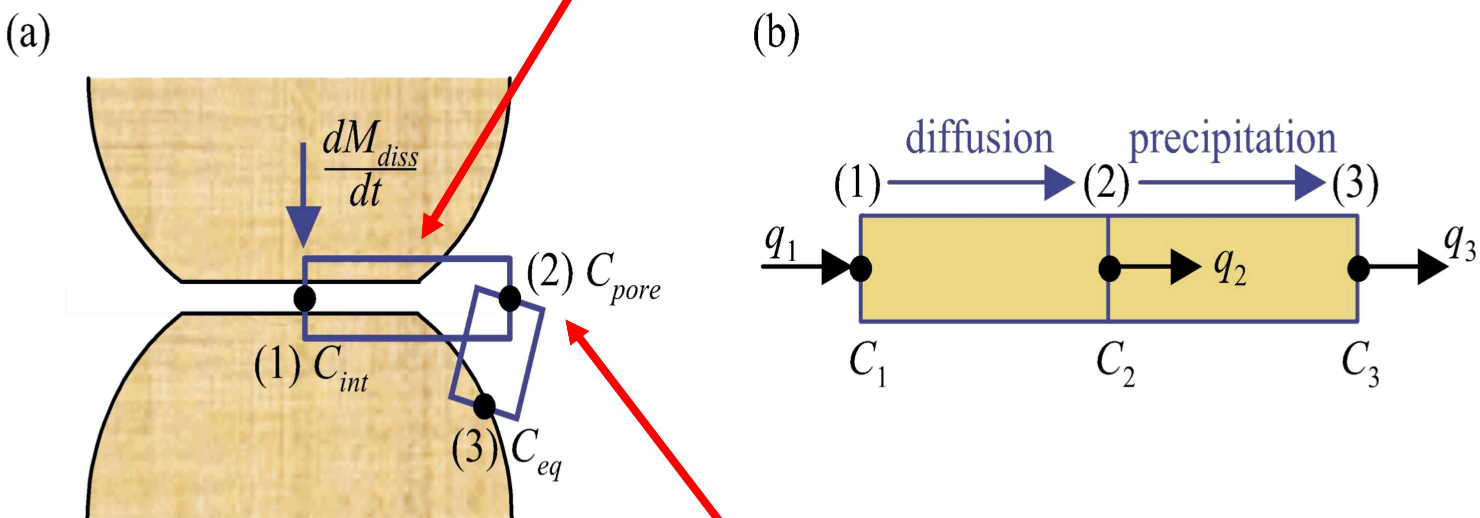
- Pore Precipitation

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

[Yasuhara et al., JGR, 2003]

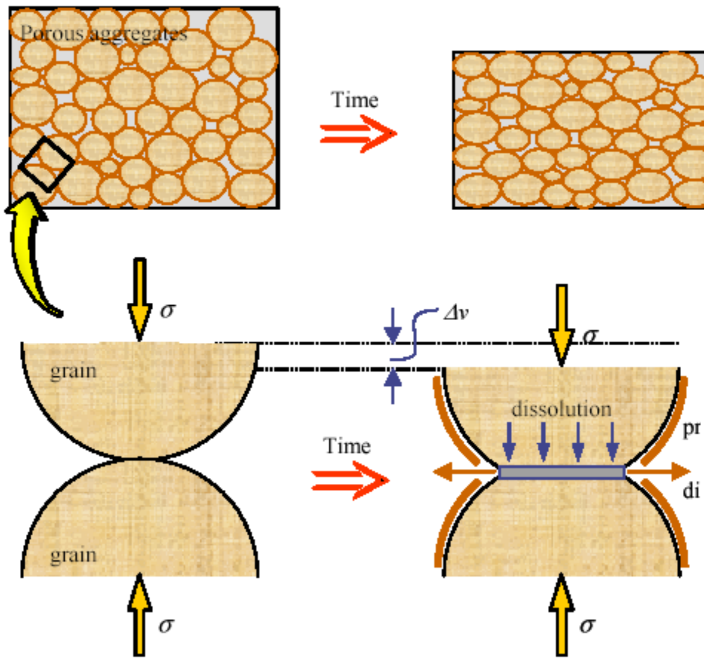
Mass Transfer Modes – Essential Components

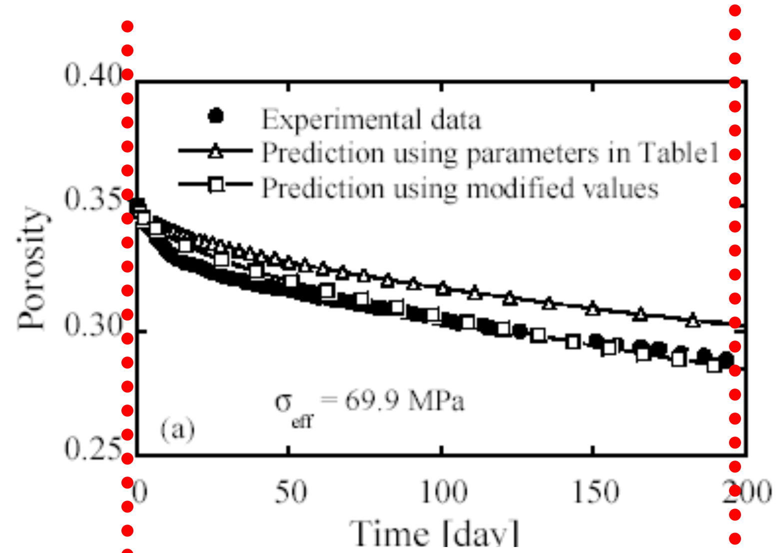
Contact geometry evolves with interpenetration

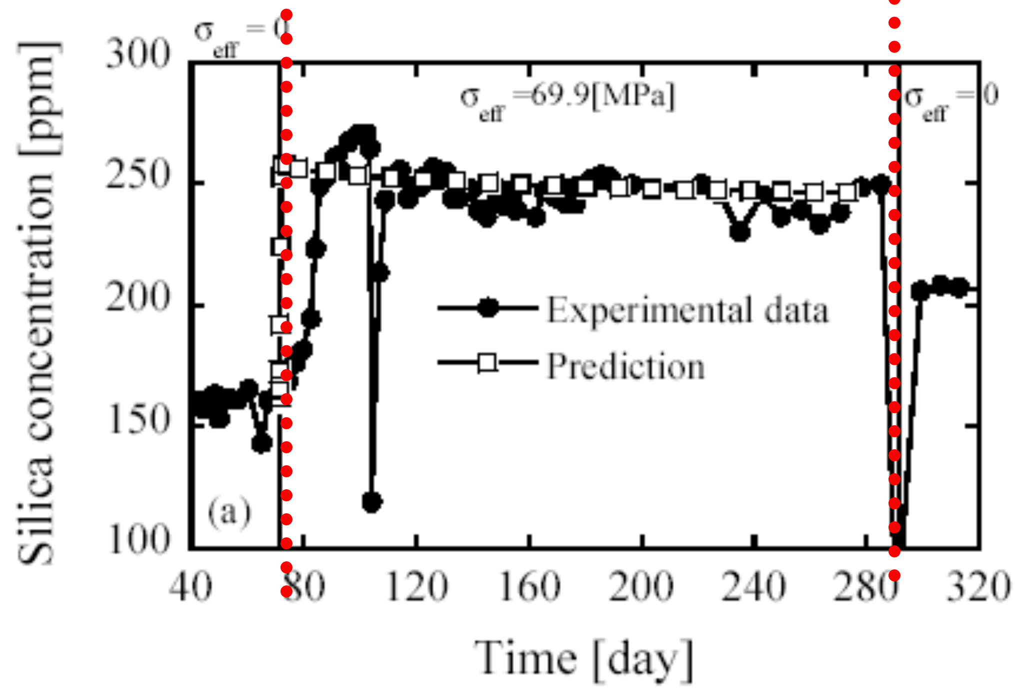


Pore concentration allows mass balance for arbitrarily open or closed systems

Matching Compaction Data

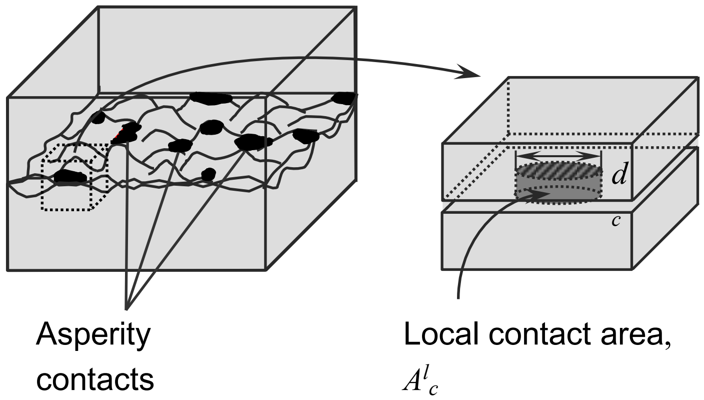




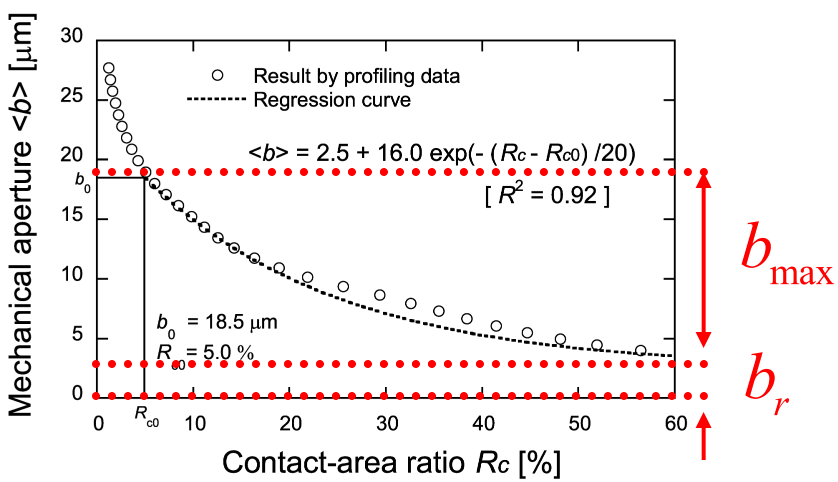


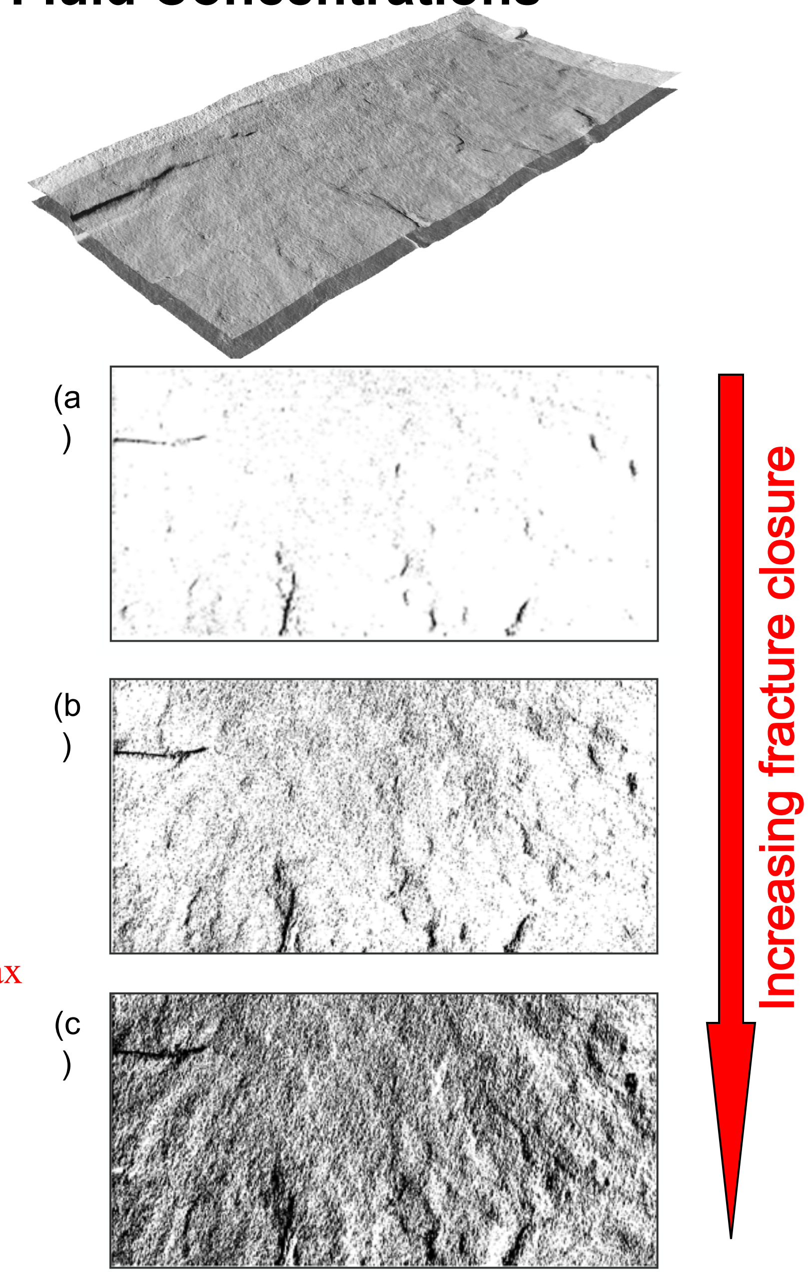
[Experimental data from Elias and Hajash, 1992]

Constraint on Fracture Apertures and Fluid Concentrations

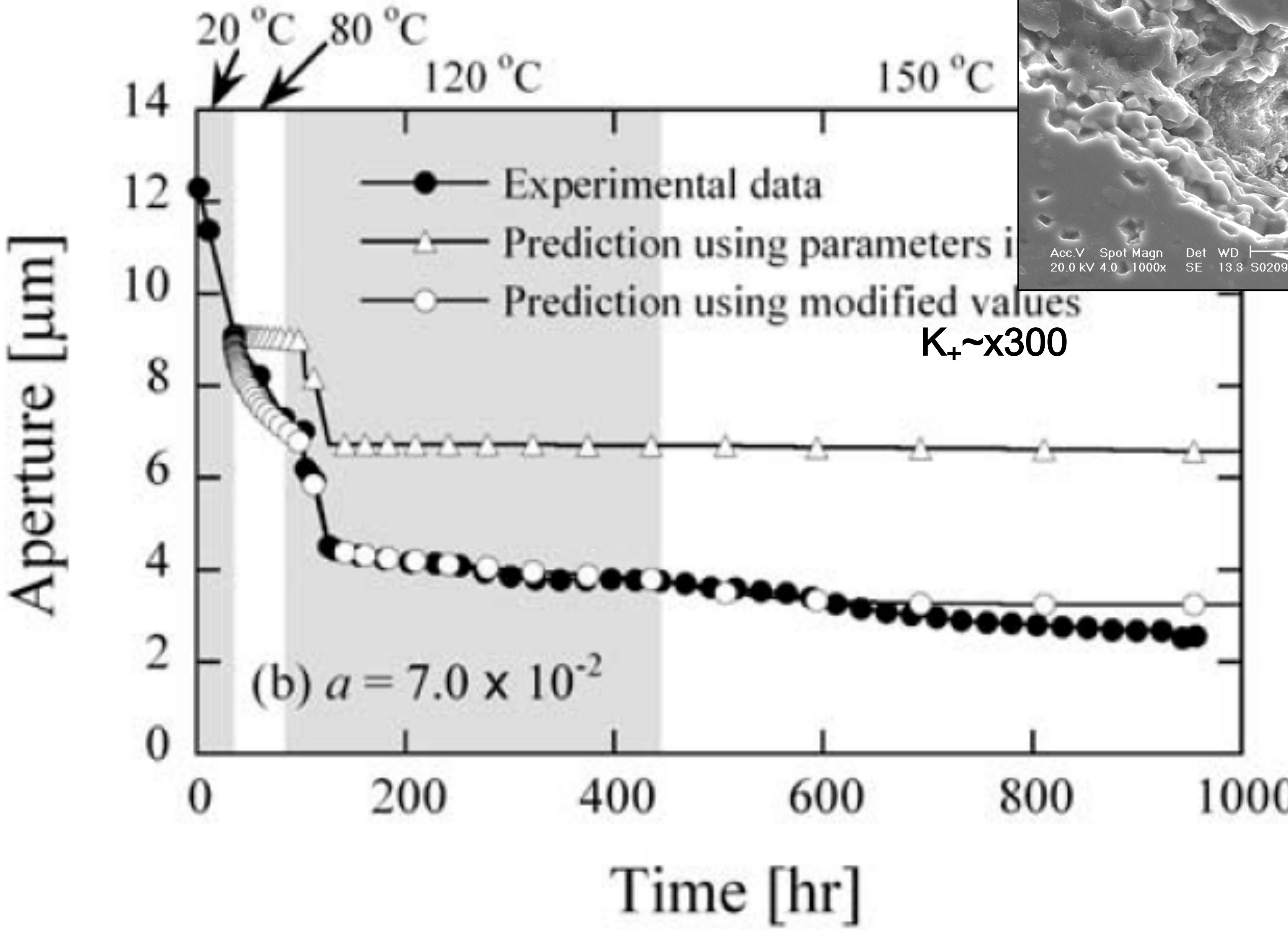


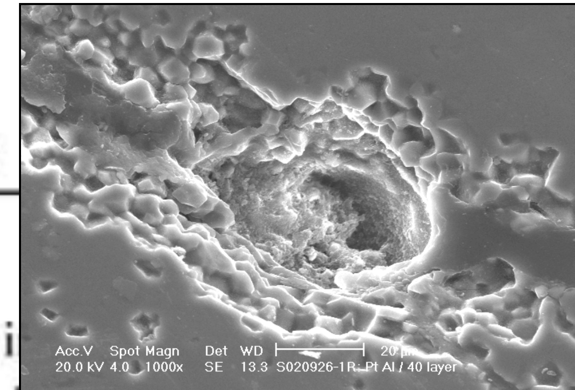
$$< b >= b_r + b_{\max} Exp[(R_c - R_{c0})/a]$$





Modeling Results - Novaculite





[Yasuhara et al., JGR, 2004]

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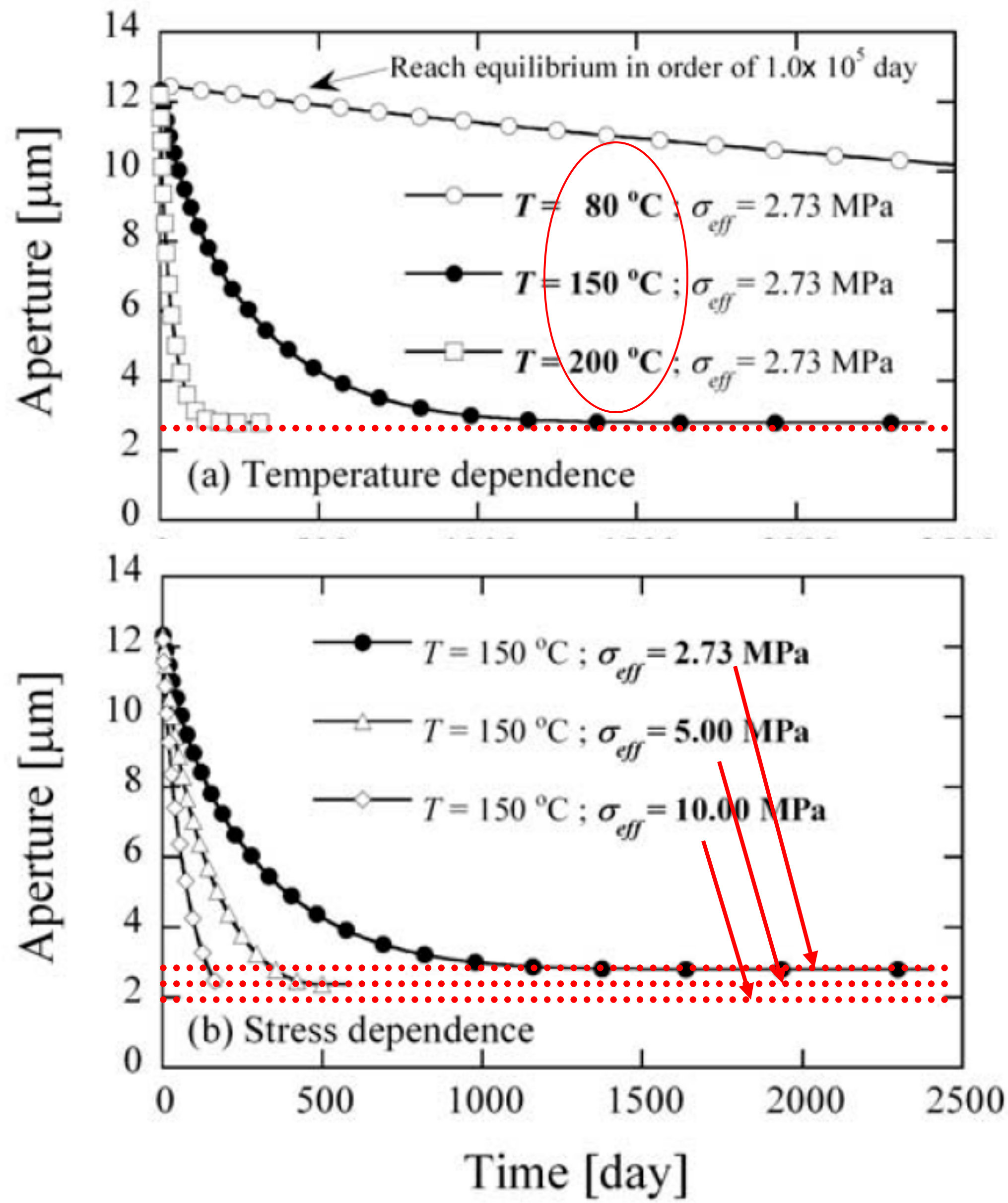
    - **Scaling relations in space and time**
    - Distributed parameter models
- Conclusions

Projected Response of Novaculite

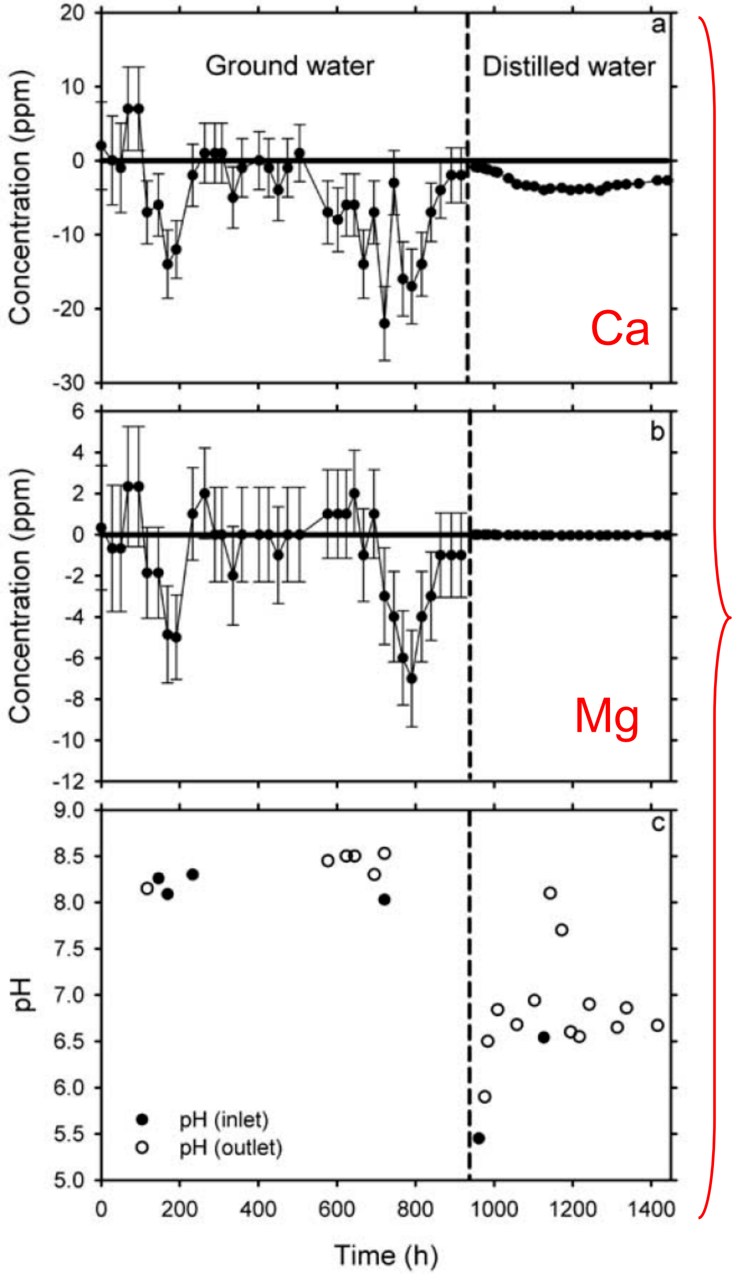
Define projected behavior for varied temperatures

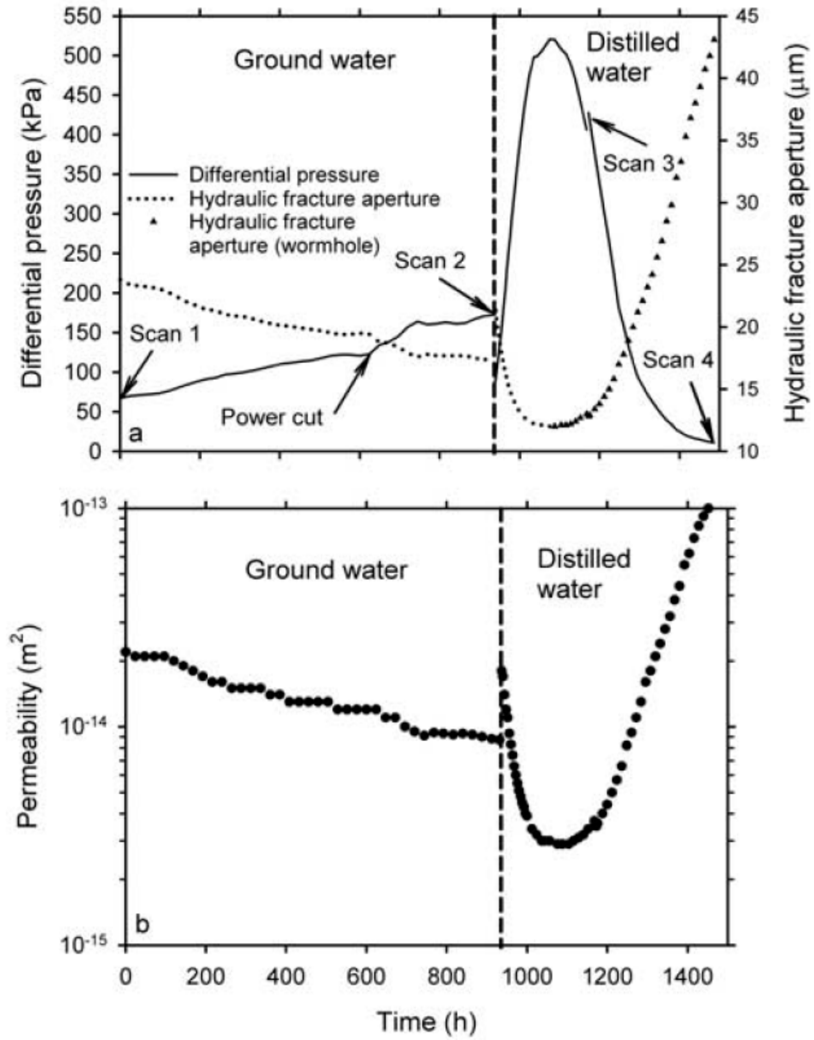
….and mean stress magnitudes



[Yasuhara et al., JGR, 2004]

Fractured Limestone – Features of Response

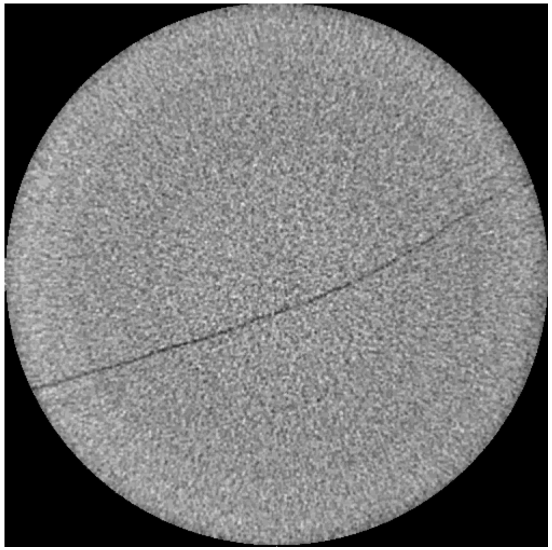




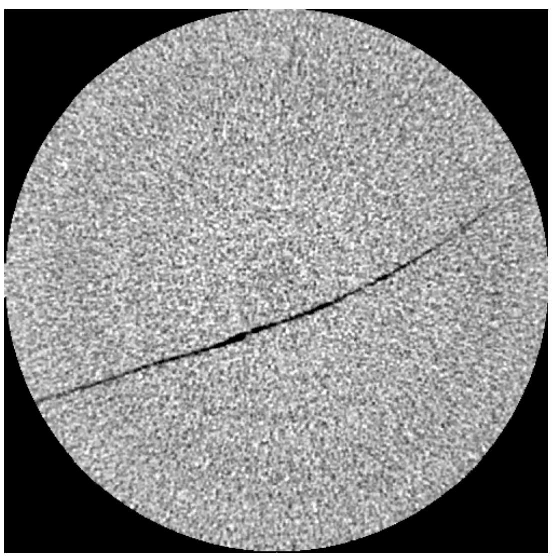
[Polak et al., WRR, 2004]

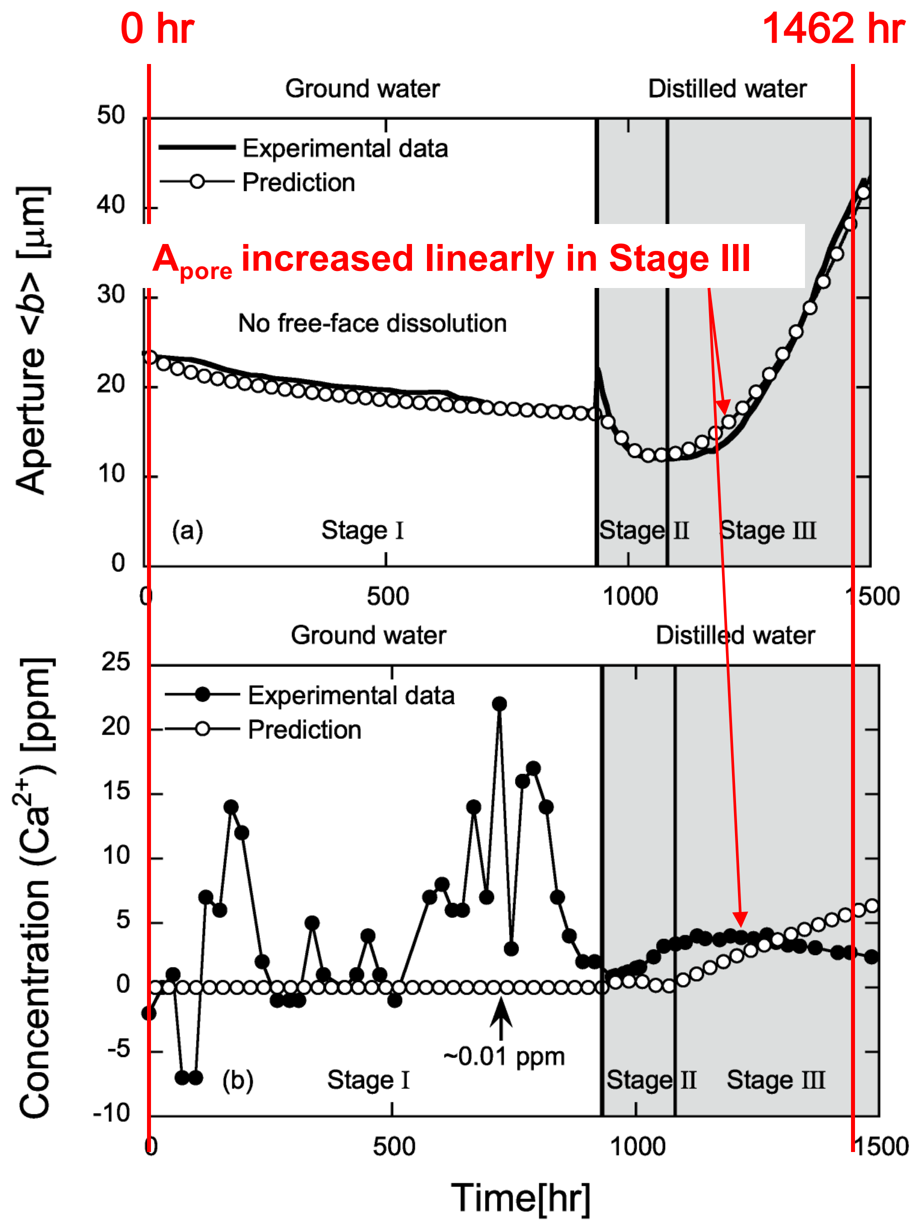
Fractured Limestone – Features of Response

0 hr

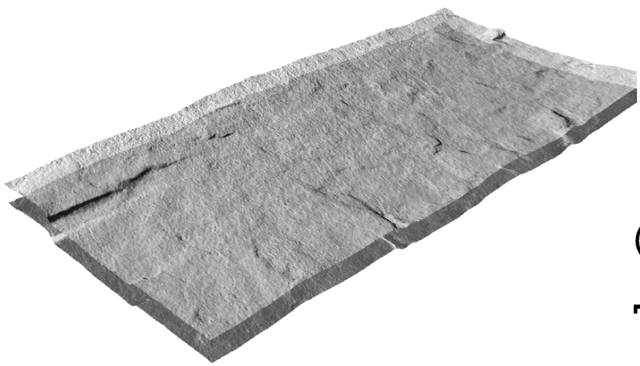


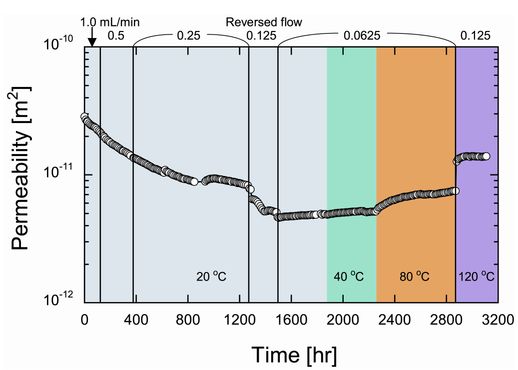
1462 hr

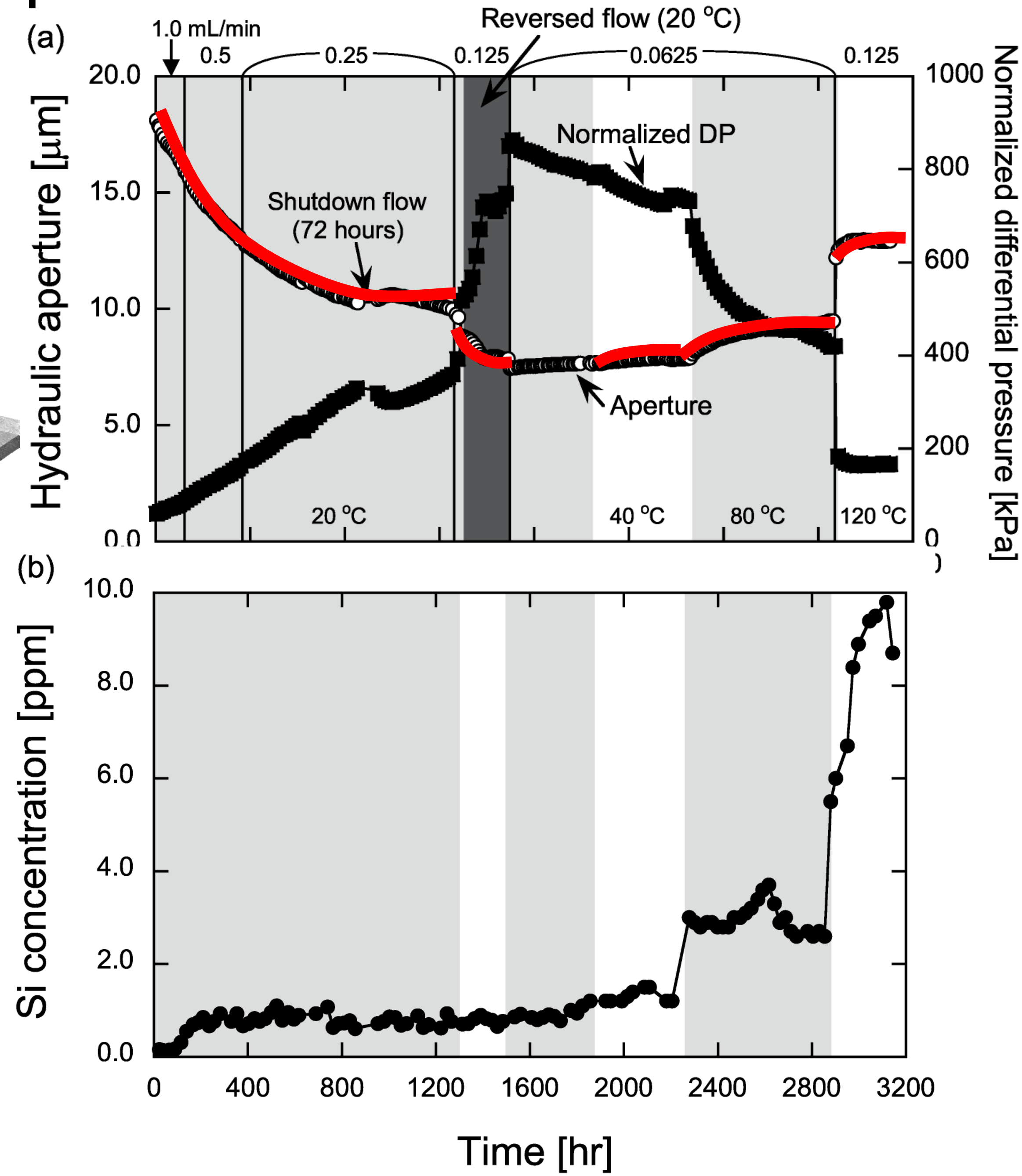




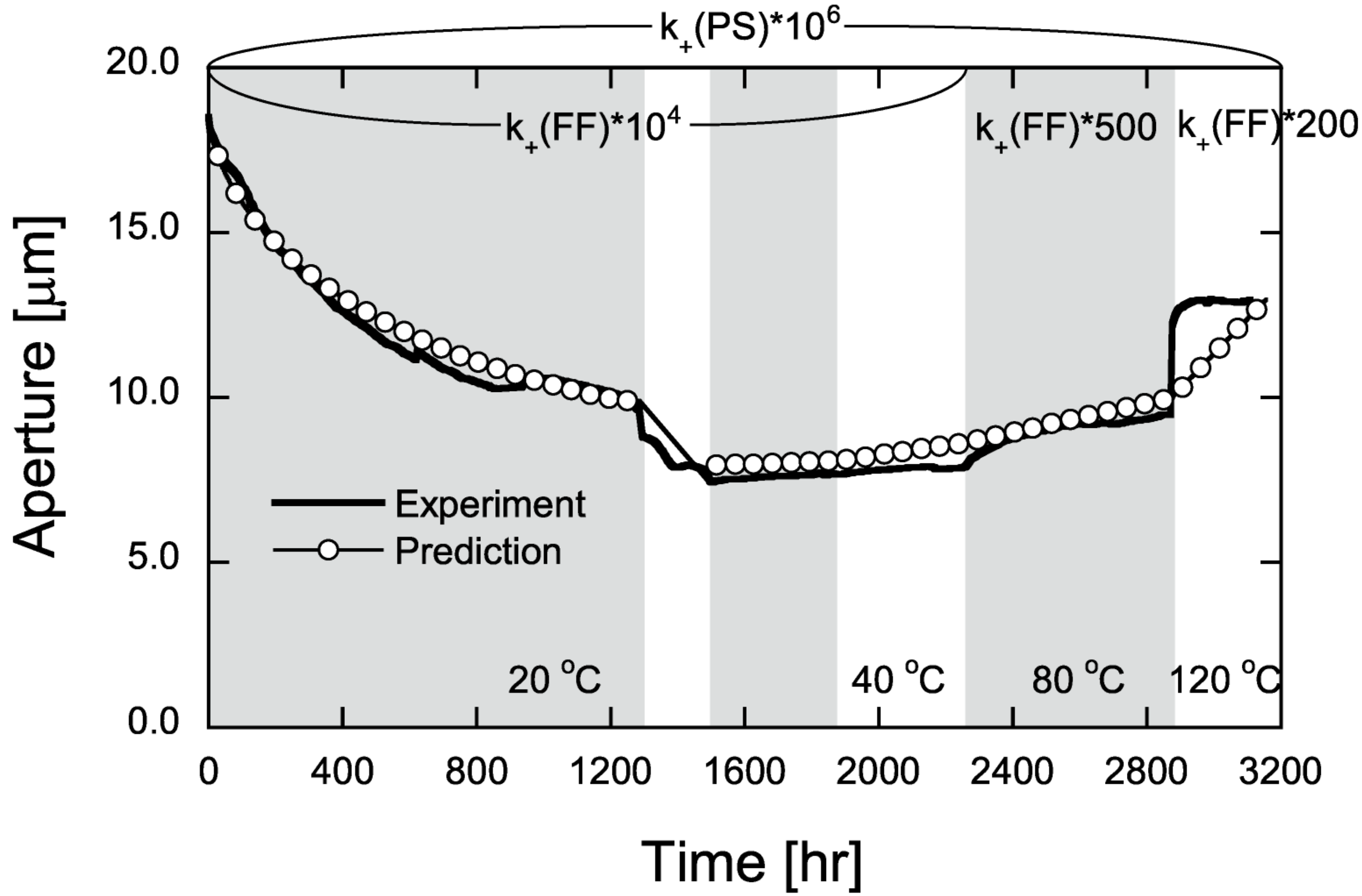
Novaculite – 20 week response







…..and Lumped Parameter Prognostic Model for Novaculite …

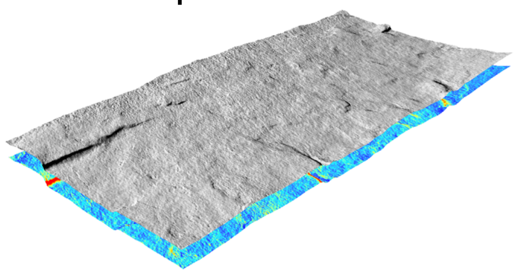


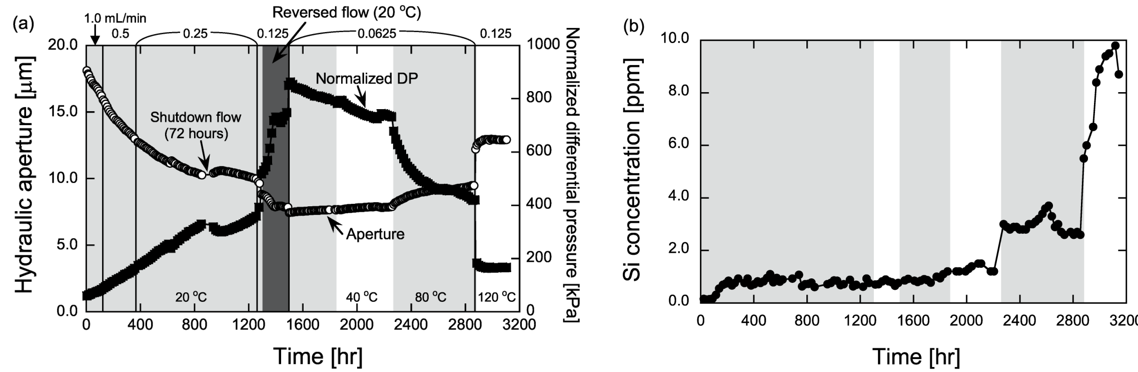
…..and CT Observations……

Road Map

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 $\nabla\left(\frac{b^3}{12\mu}\nabla p\right)=0$

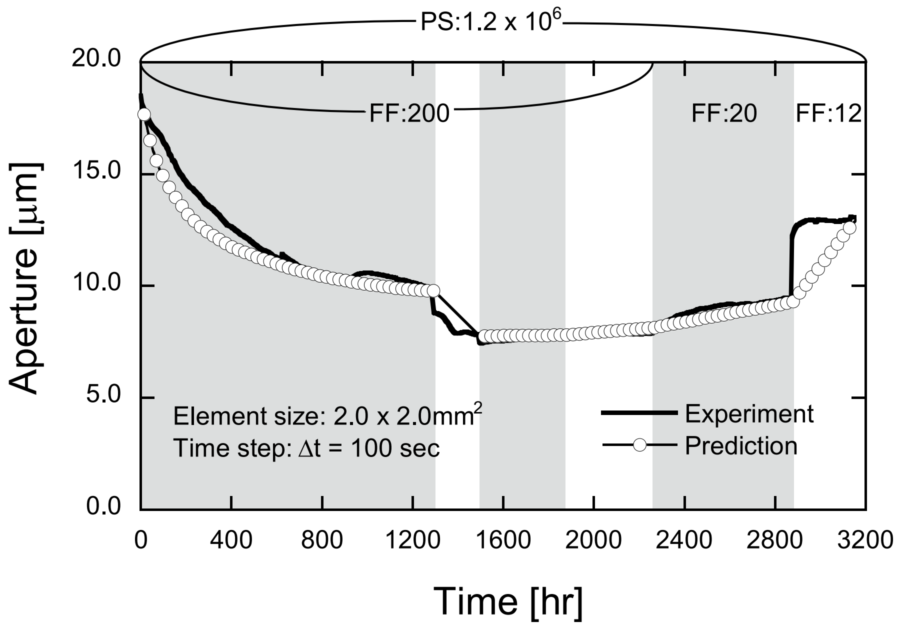
3. Dissolution at contact area and free-face (reaction)
→ Obtain concentration distribution + Modify aperture distribution due to dissolution

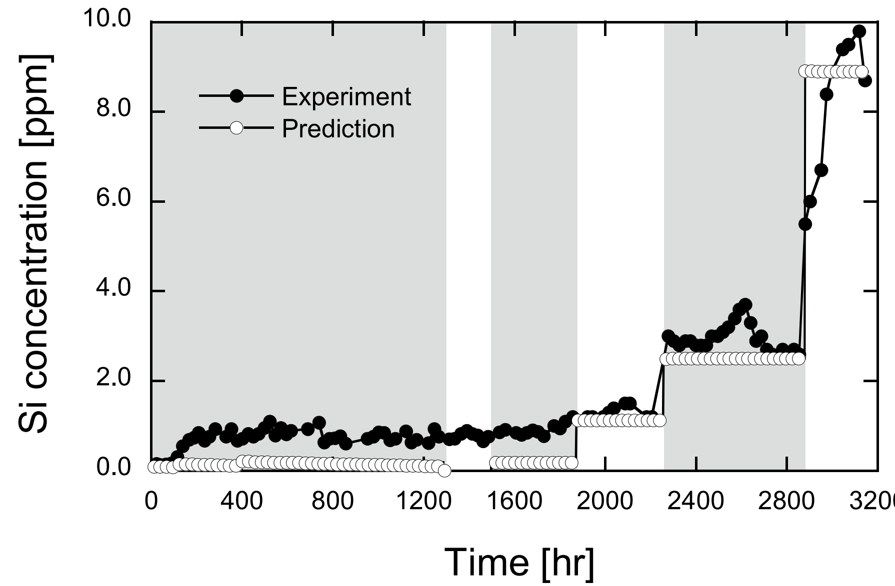
$$\frac{dM^{PS}}{dt}=\frac{3\pi V_m^2\rho_g k_+\left(\sigma_a-\sigma_c\right)A_e}{4RT}; \qquad \frac{dM^{FF}}{dt}=2A_e k_+\frac{C_{eq}-C_i}{C_{eq}}$$

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

Iteration

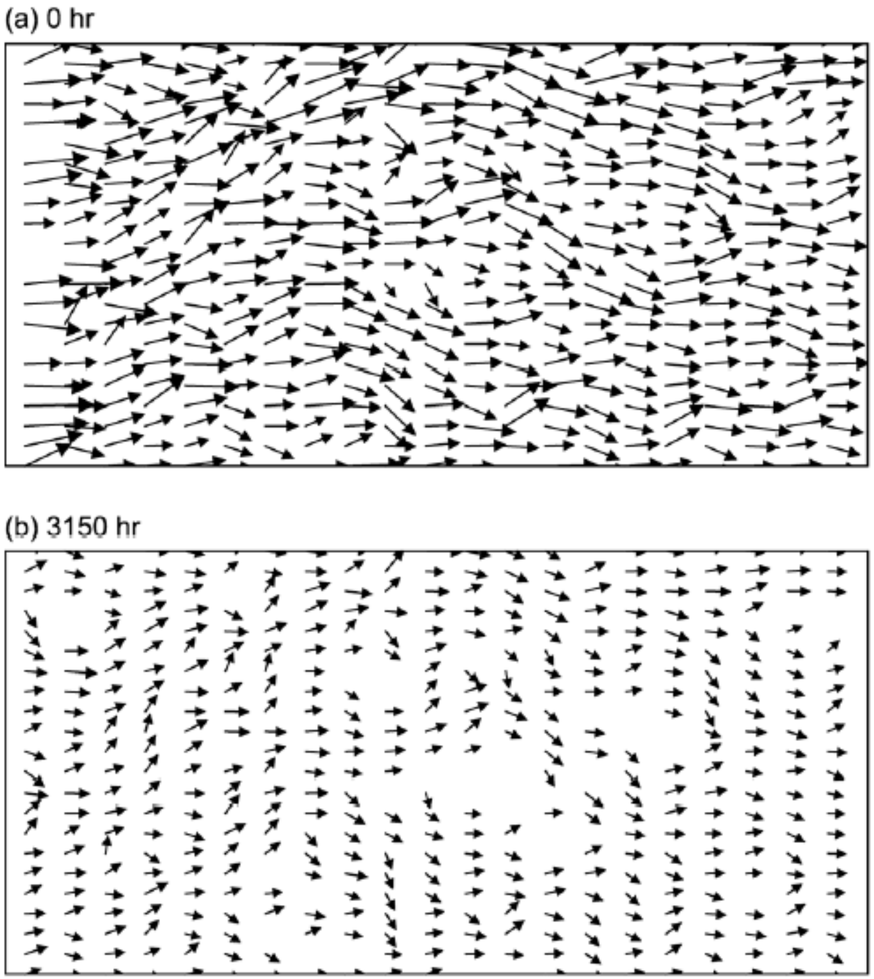
Distributed Parameter Model – Results for Novaculite …



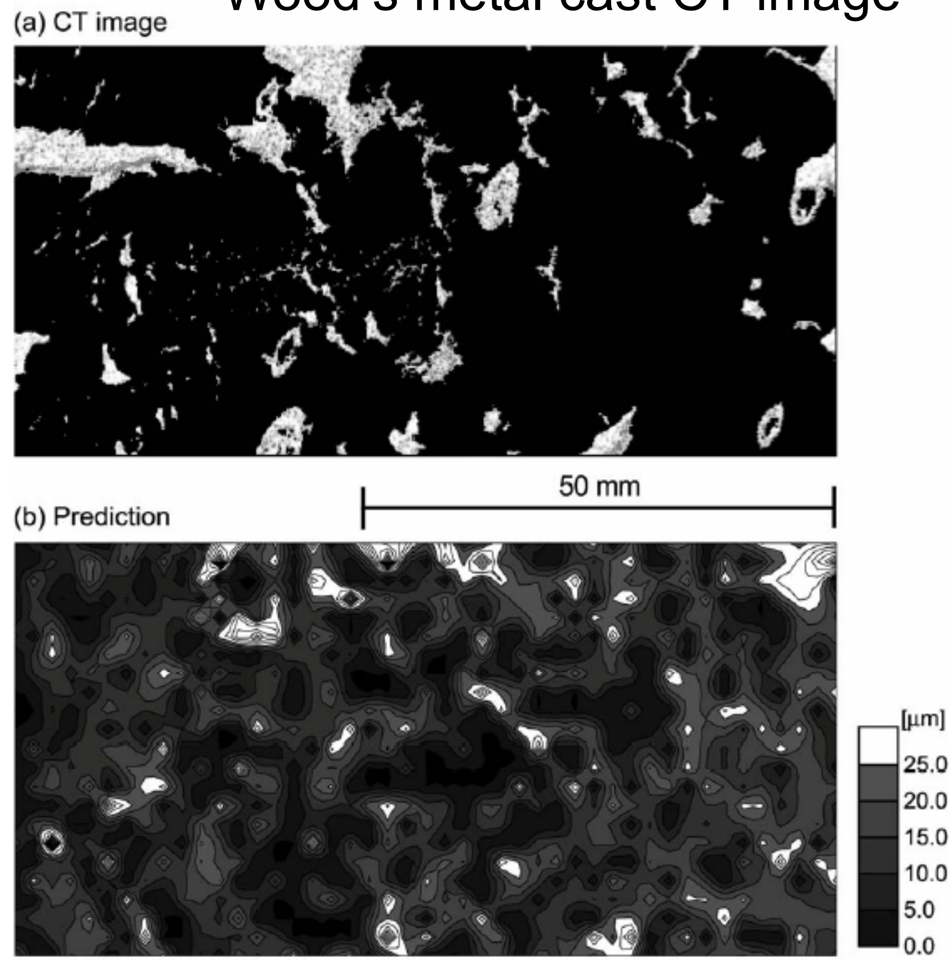


• Numerical model is capable of better replicating experiment – multiplier on k_+ is greatly reduced over lumped parameter case.

Reynolds' Flow Vectors and Measured/Predicted Aperture Distribution in Sample



Wood's metal cast CT image



Observations

1. Transport properties change in sometimes surprising modes as controlled by:
    - Stress
    - Thermal
    - Chemical-potential
    - Advective flux

    } Fields and paths

2. Coupled Mechanical and Chemical feedbacks can be both significant and relatively rapid – especially for systems far-from-equilibrium

3. Locations of mass redistribution exert a fundamental control on the form and strength of permeability change

4. These fields and paths exert strong control on bulk transport [and mechanical] properties – related mechanical properties are manifest as a creep-like response (visco-elastic/plastic)

5. Understanding these complex interactions seem a prerequisite to predicting behavior at prototype scales