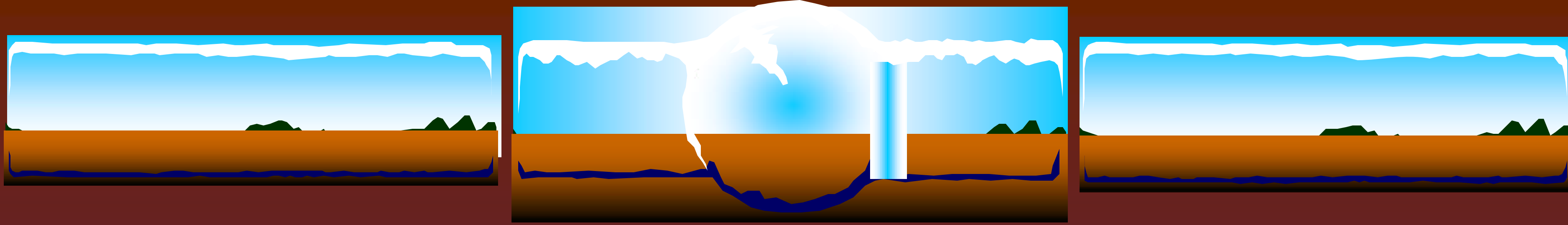


DOE's EGS Program Review

Stress- and Chemistry Mediated Permeability Enhancement/Degradation in Stimulated Critically-Stressed Fractures

Derek Elsworth (PI)

Abraham Grader, Phil Halleck and Chris Marone (Co-PIs)

Penn State University

and Peter Rose (EGI)

1.814.865.2225 (Vx)/ 1.814.865.3248(Fx)

elsworth@psu.edu

Project Objective

- Define interactions between stress and chemistry in controlling magnitude and the longevity of permeability-enhancement on hydraulically and chemically stimulated critically-stressed fractures
  - Agents generating porosity: shear dilation, sub-critical cracking, dissolution and corrosive fluids, thermal stresses and effects
  - Agents destroying permeability: stress-mediated dissolution and sub-critical crack growth
- Develop Constitutive models [s -t -T-C-Q]
- Upscale to determine influence on fluid and thermal production using THMC coupled models

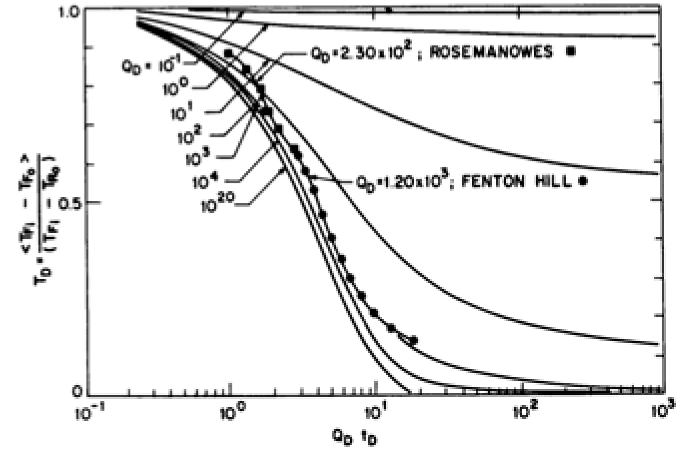
EGS Problem

- Why is project important to EGS program?
  - A long-lived, low-impedance, broadly-swept, high heat transfer system is essential in addressing the 5cents/kWh goal
  - Minimizing short-circuiting and maximizing reservoir management
  - Minimizing seismicity and maximizing controlled permeability enhancement is crucial
- What technical issue does the project address?
  - Reservoir generation and longevity
- Addresses Technical Challenges:
  - Reservoir design and development: Short-circuit mitigation and permeability control
  - Reservoir Operation and Management
- Addresses Barriers:
  - Inadequate stimulation technology and reservoir control
- How will project help to achieve overall program goals?
  - Add fundamental understanding of stimulation and permeability control
  - Develop tools for O&M and permeability and stress control

Background/Approach

- Define the controls on the development of reservoir permeability:
  - Stress (s -t) – critically stressed and shear
  - Chemistry (C) – incl. stimulants
  - Temperature (T)
  - Hydraulic regime (Q)
- Develop Constitutive models [s -t -T-C-Q]
- Upscale through coupled THMC codes
  - Parametric studies for various development strategies Q-C

Purpose

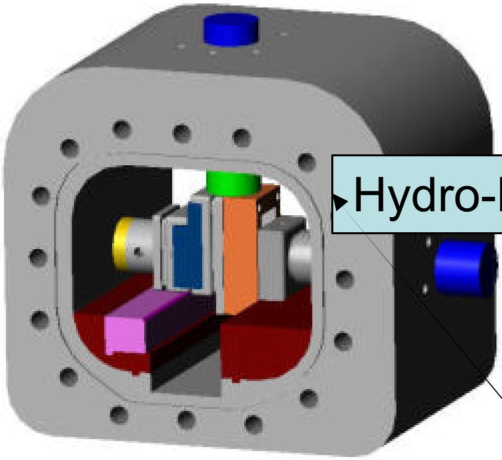


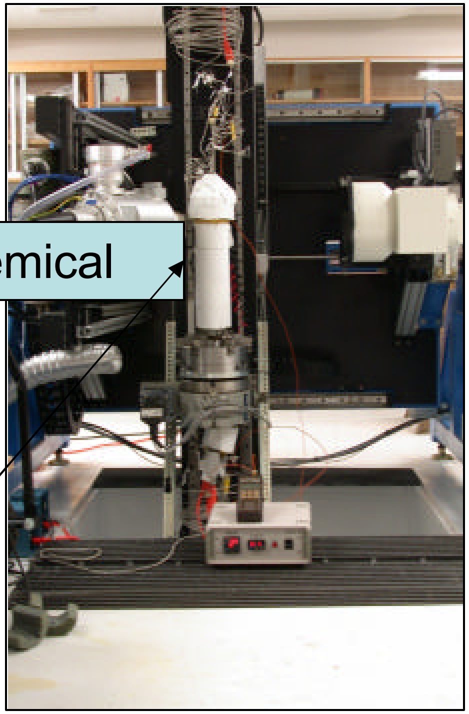
Elsworth, JGR, 1989

- Towards the engineering of "EGS":
  - Long-lived
  - Low-impedance
  - High heat flow
- Consistent understanding of the evolution of flow connections resulting from stimulation
  - Physical (effective stresses)
  - Chemical (dissolution/precipitation)
- Critical influences of:
  - Mechanical Influences [THM]
  - Chemical Influences [THC]

  THMC
- Importance where fractures are "critically stressed"
- Resolve anomalous observations

Approach



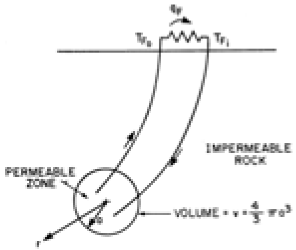


Hydro-Mechanical

Hydro-Chemical

Constitutive Models

Modeling/
Upscaling



Results/Accomplishments

- Experimental studies
  - CT-Reactor
  - SDS-Reactor
- Constitutive modeling
- Modeling

Experimental Studies – CT-Reactor

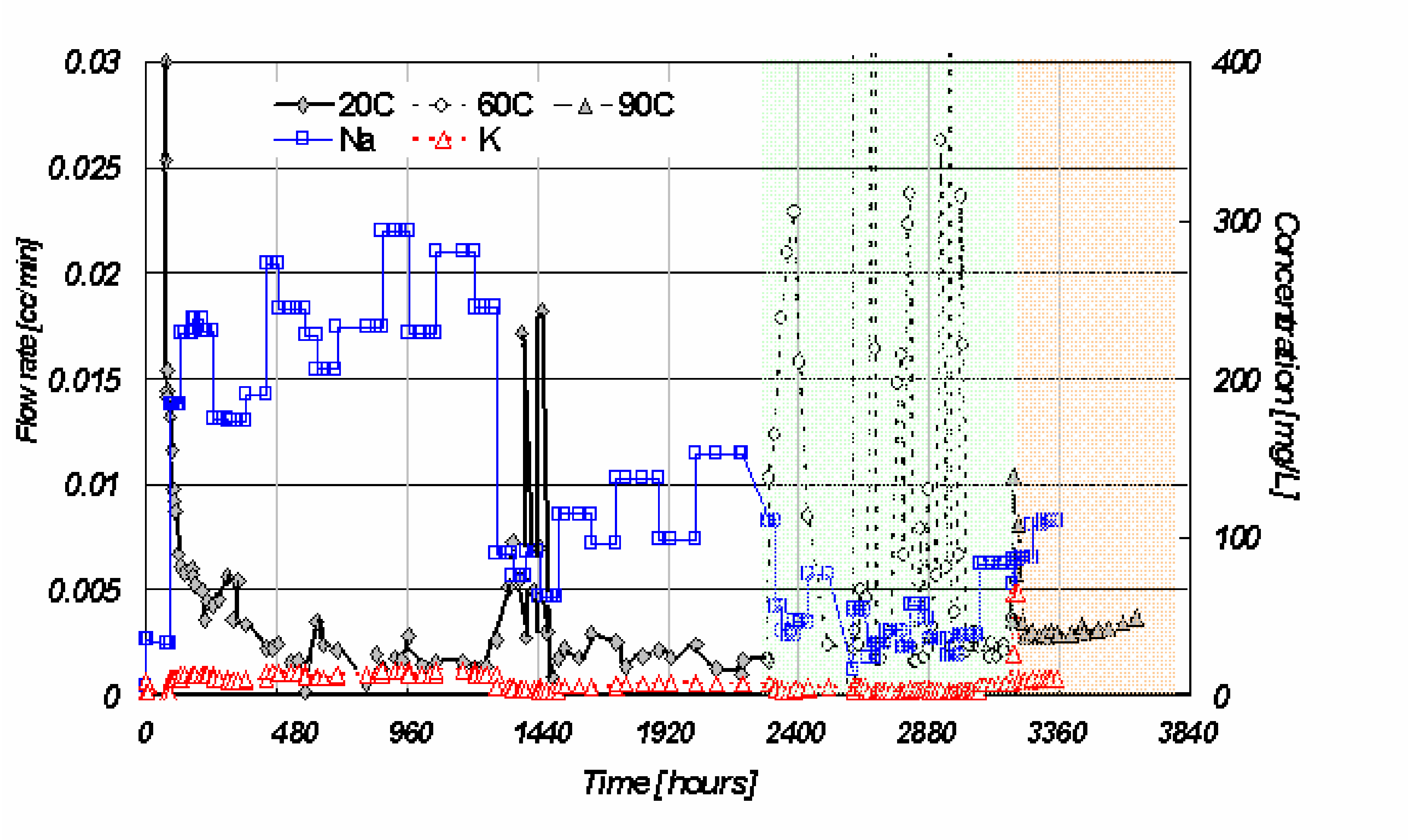
Tools:

- ✓ Q_{fluid}
- ✓ Q_{mass}
- ✓ x-ray CT

?k & ?b ?

DIORITE	
Diameter [mm]	64
Length [mm]	90
Matrix Porosity [%]	<0.01
Temperatures [°C]	20-60-90
Effective Stress [MPa]	13
Delta Pressure [MPa]	1.3

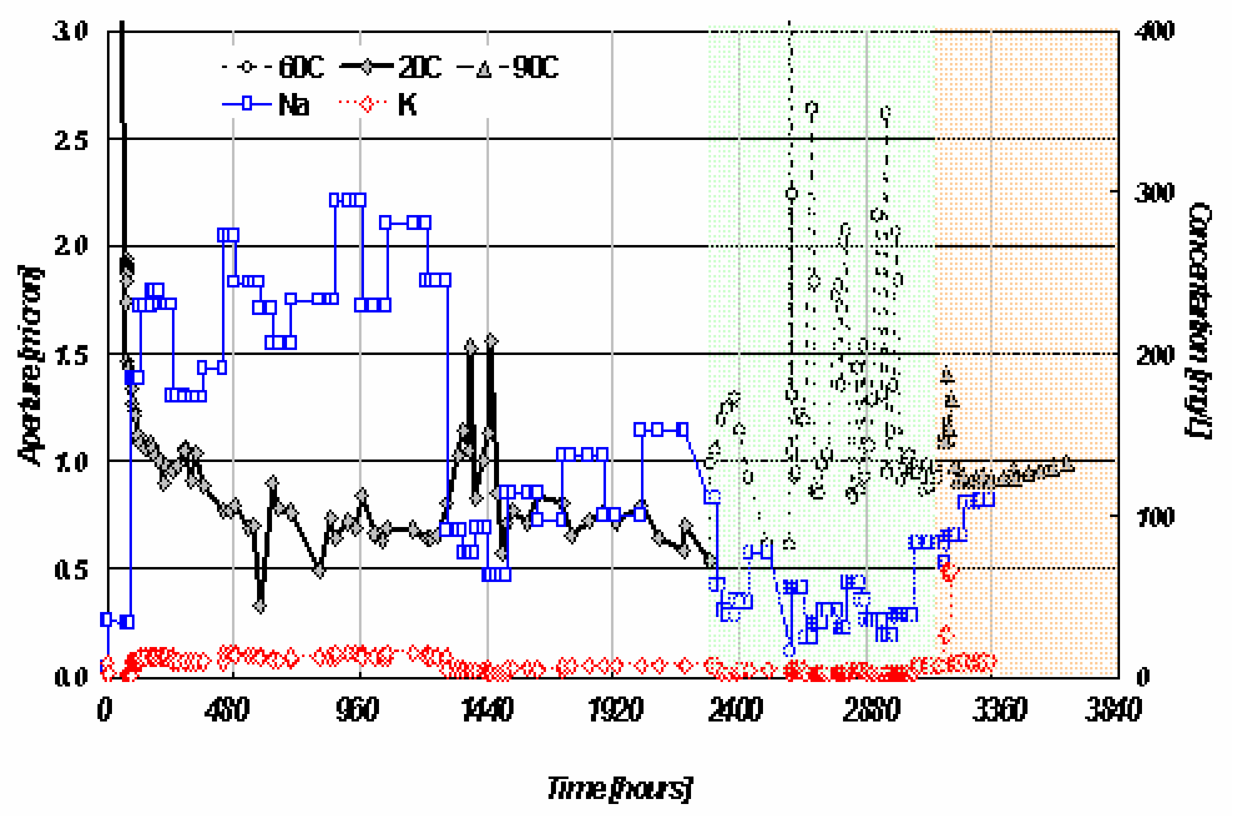
Change in Flow Rate and in Mass Concentration of Major Ions with Test Duration



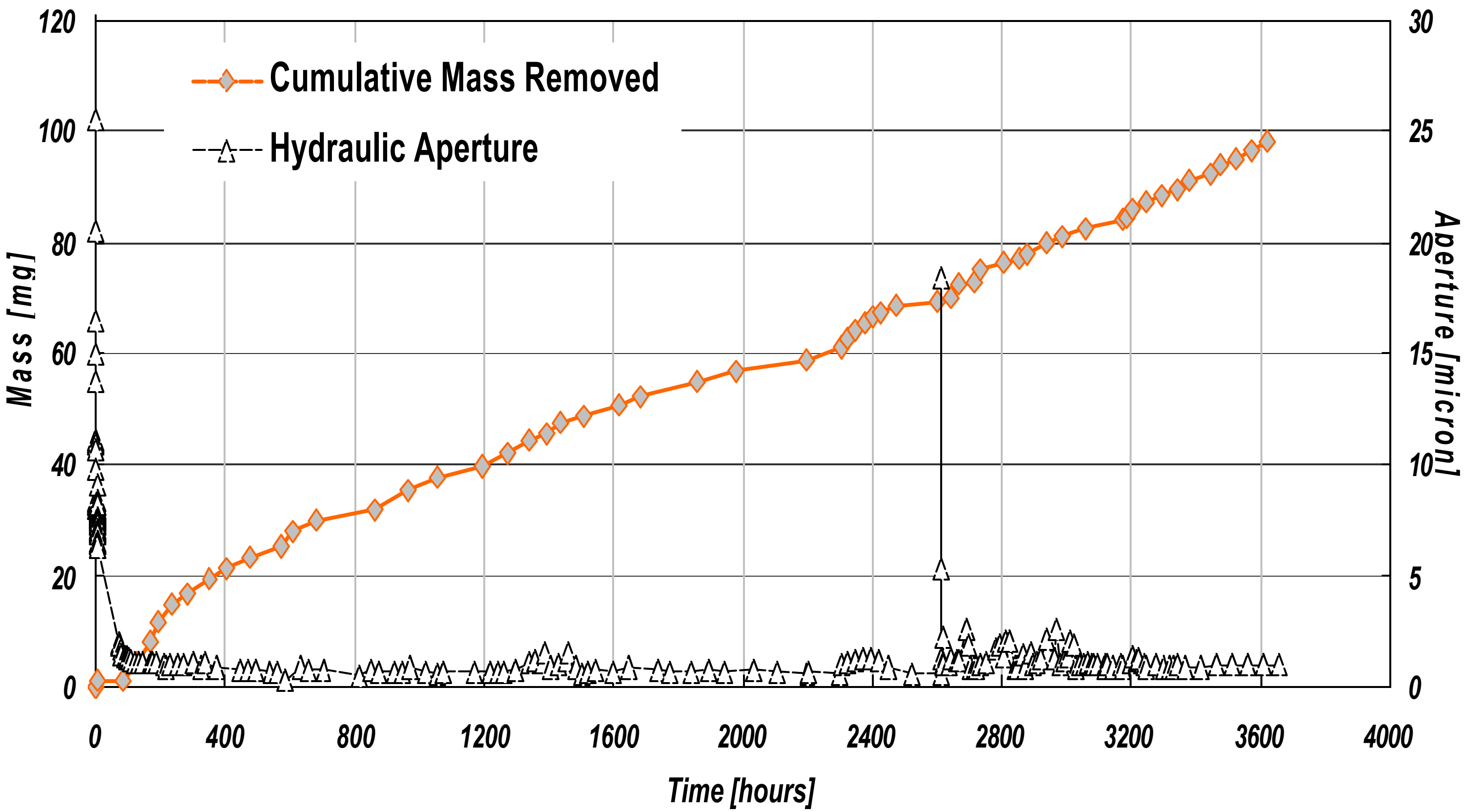
Change in Hydraulic Aperture and in Mass Concentration of Major Ions with Test Duration

$$Q = d \; \frac{b^3}{12} \; \frac{dp}{dl}$$

Q: Recorded Flow Rate
d: Sample Diameter
: Water Viscosity
dp: Differential Pressure
dl: Sample Length

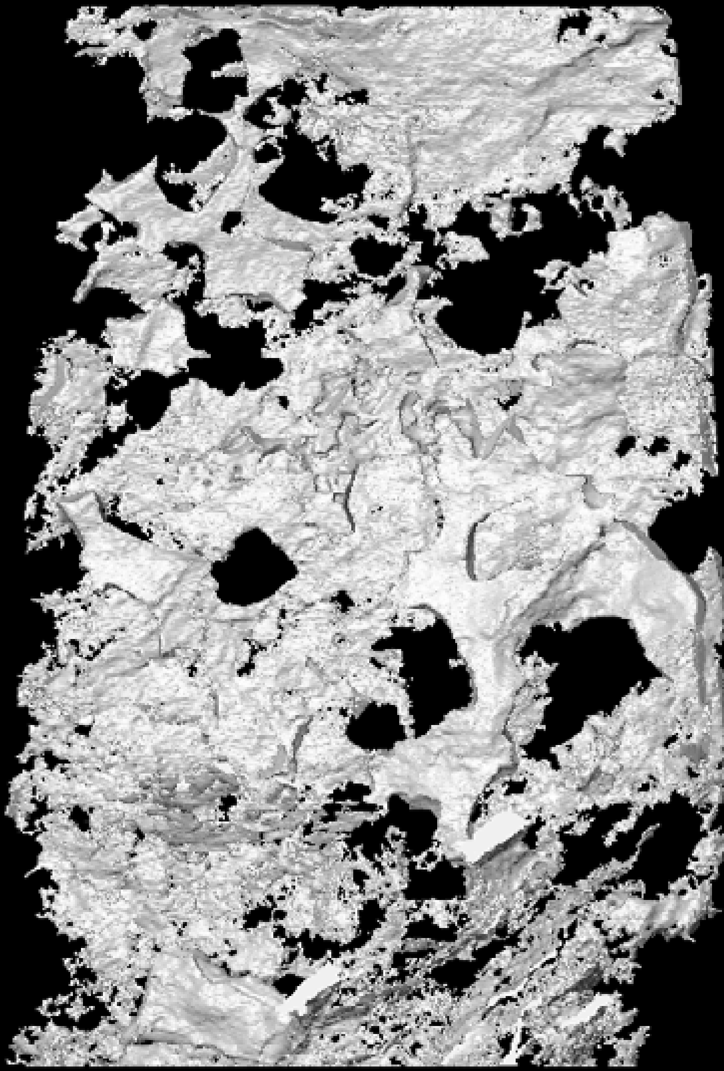


Change in Hydraulic Aperture and Dissolved Mass Removed with Test Duration

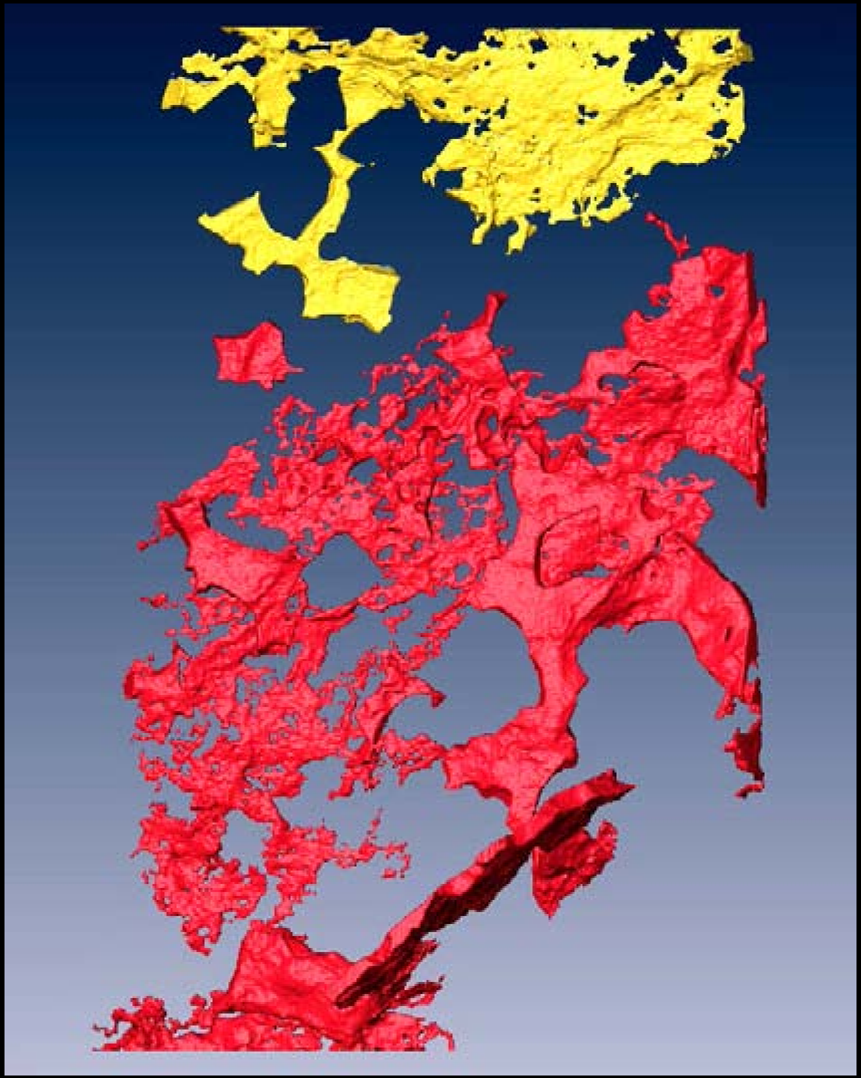


Three-dimensional view of the fracture voids within the fracture

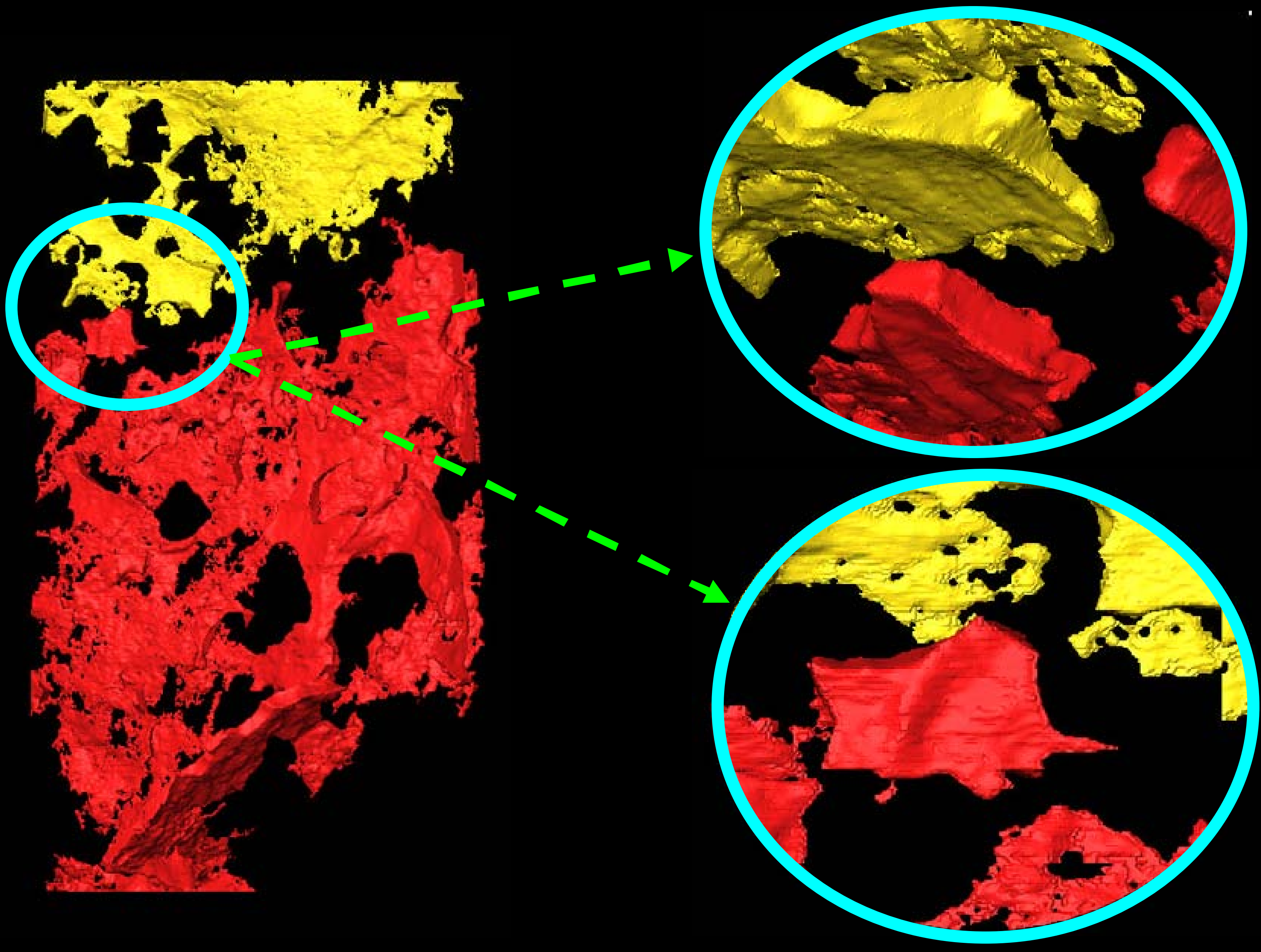
Initial



Final



Three-dimensional view of the fracture voids within the fracture



Change in Hydraulic Aperture Produced for Various Contact Area Ratios of the Contacting Fracture

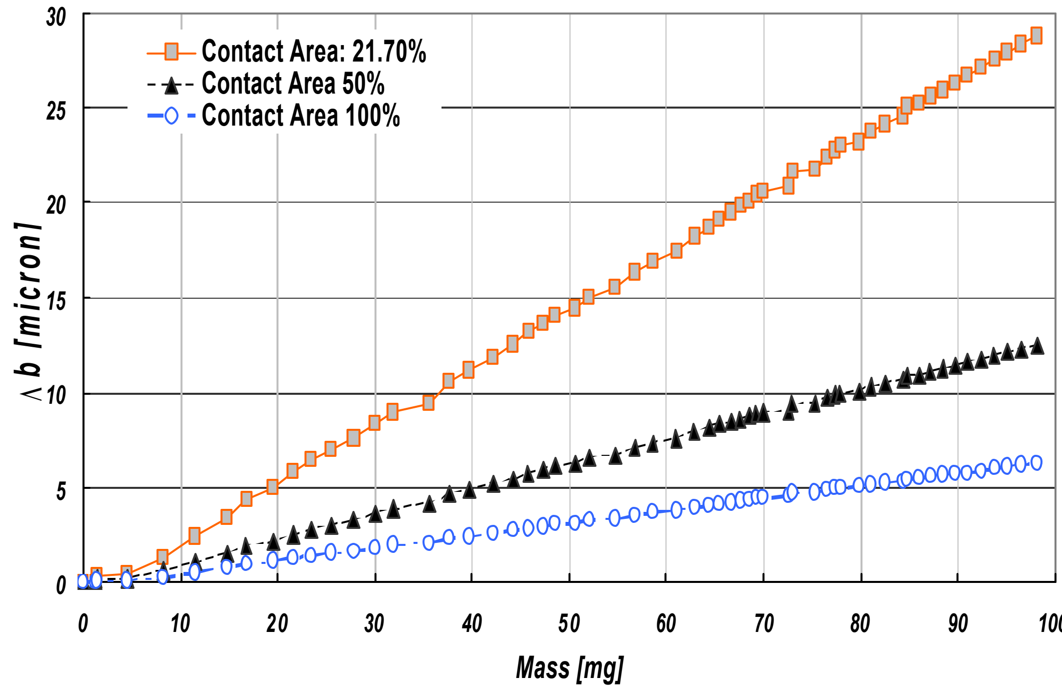
$$\Delta b = \frac{M \quad Ac}{\rho}$$

Δ***b***: Equivalent Change in Aperture

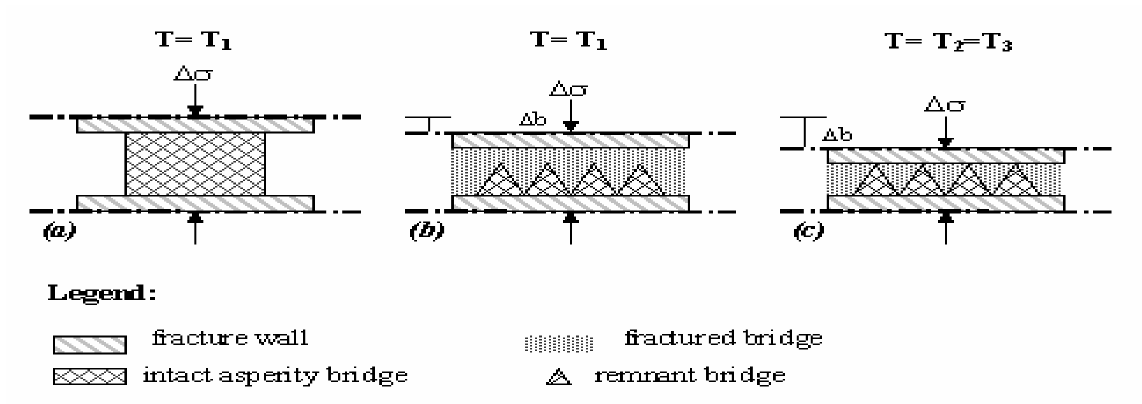
$M = \frac{\Delta M}{\Delta t}$: Mass Rate

Ac: Presume Surface Area of Removal

ρ: Density of Dissolved Material



Process Model of change in Aperture with Applied Stress

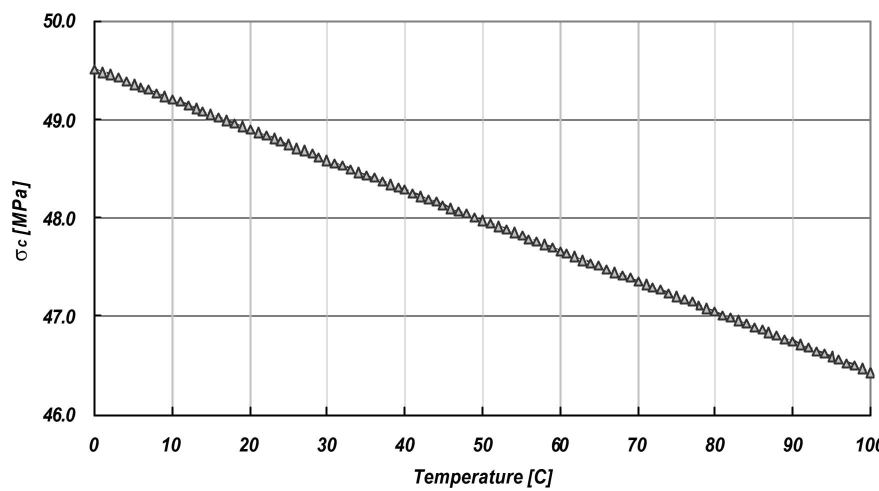


Change in Critical Stress with Temperature

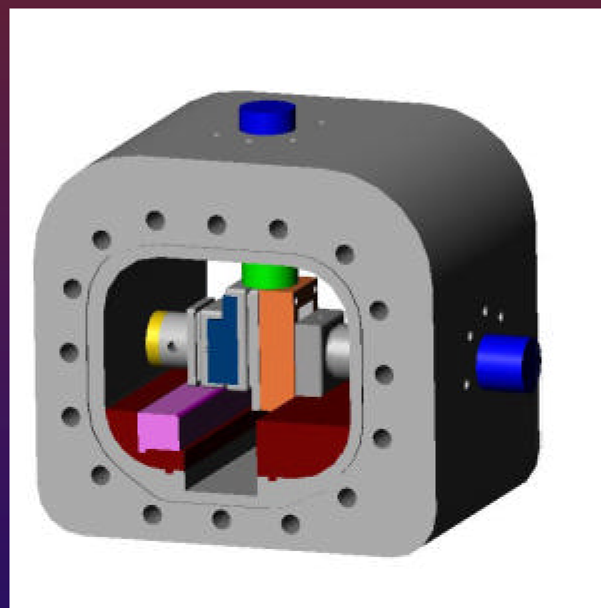
$$\sigma_c = \frac{E_m \left(1 - \frac{T}{T_m}\right)}{V_m}$$

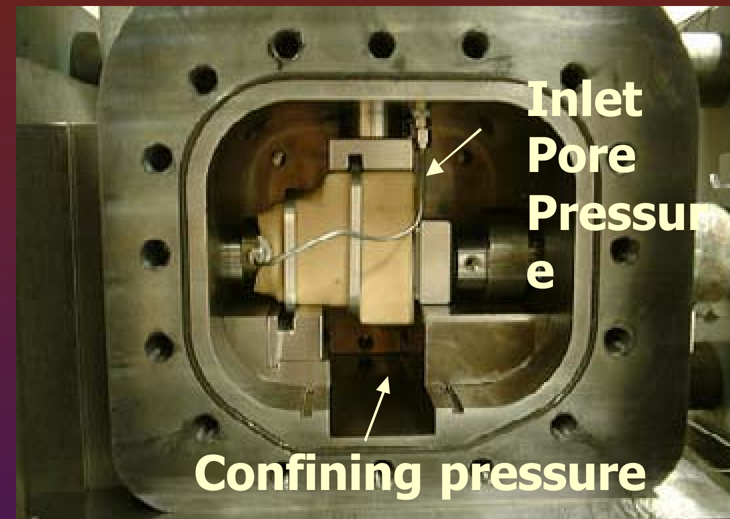
E

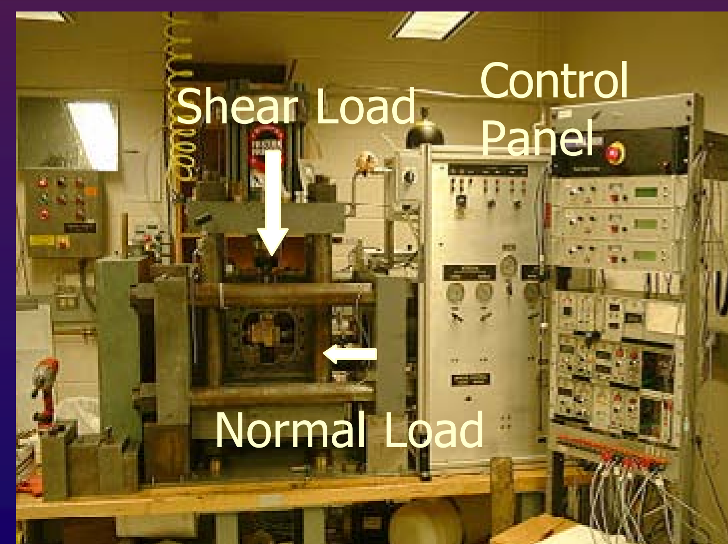
E_m: Heat of Fusion: **8.57** KJ/mol
T_m: Temperature of Fusion: **1883** K
V_m: Molar Volume: **3.75^{-05}** m^3/mol



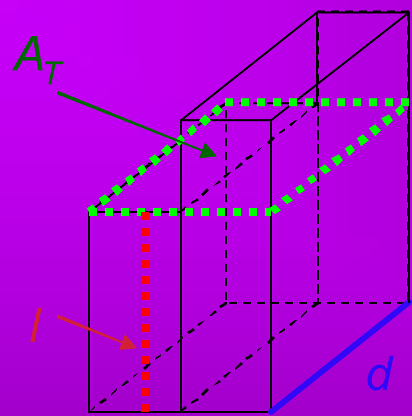
Experimental Studies – SDS-Reactor







Experimental Configurations



Tools:

- ✓ Q_{fluid}
- ✓ Q_{mass}
- ✓ ? u_n

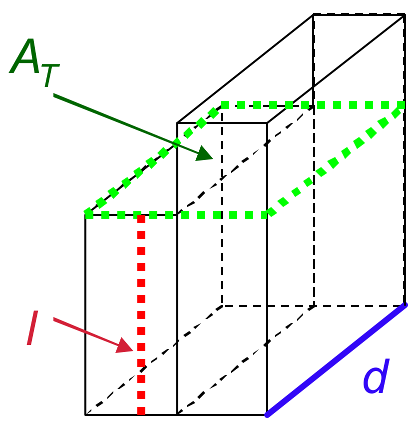
?k & ?b ?

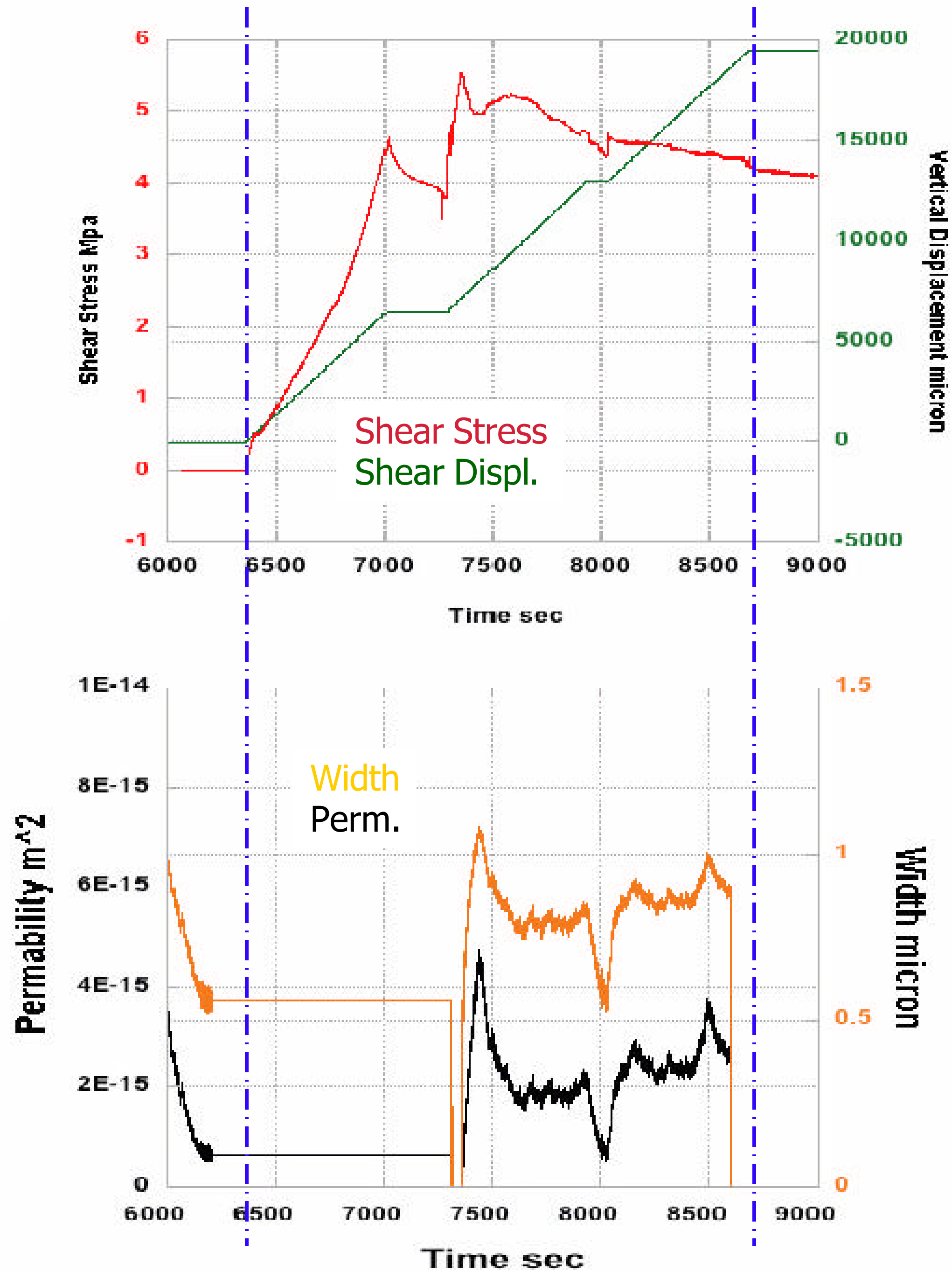
Novaculite	
Thickness [mm]	22.38
Width *d* [mm]	45
Length *l* [mm]	50
Matrix Porosity [%]	<0.01
Confining Pressure [MPa]	6
Differential Pressure [MPa]	0.1
Total Normal Stress [MPa]	10

Results

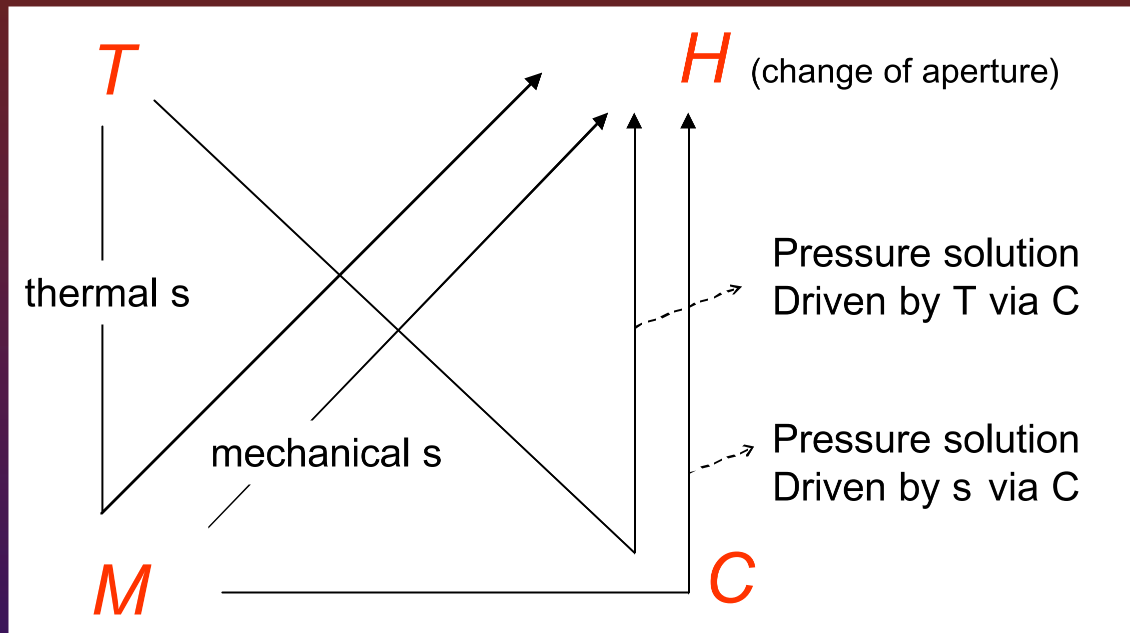
$$Q = d\ \frac{w^3}{12}\ \frac{dp}{dl}$$

$$k = Q\ \frac{l}{\rho\ \ g\ \ A_T}$$





Upscaling – THMC Constitutive Models for Transport



1) M mechanical deformation
2) T – M thermomechanical deformation

} Relatively well understood

3) M – C pressure solution-type change
4) T – C pressure solution-type change

} Improved understanding needed and this effect may be large

Final TMC induced aperture change

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

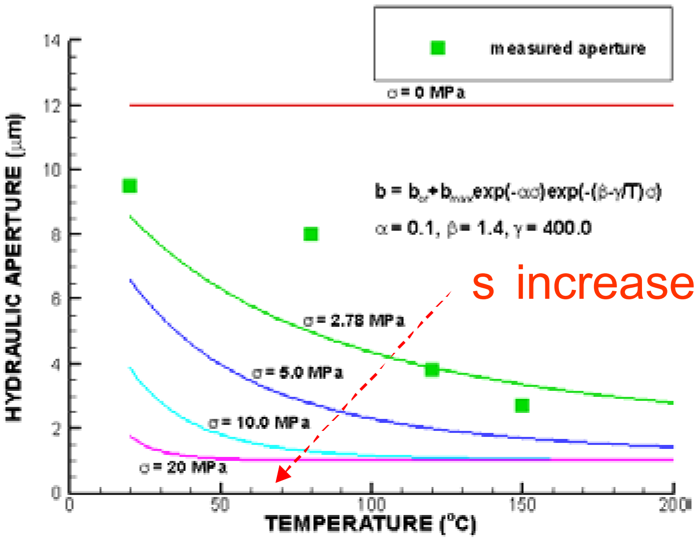
The shape simplified from critical stress

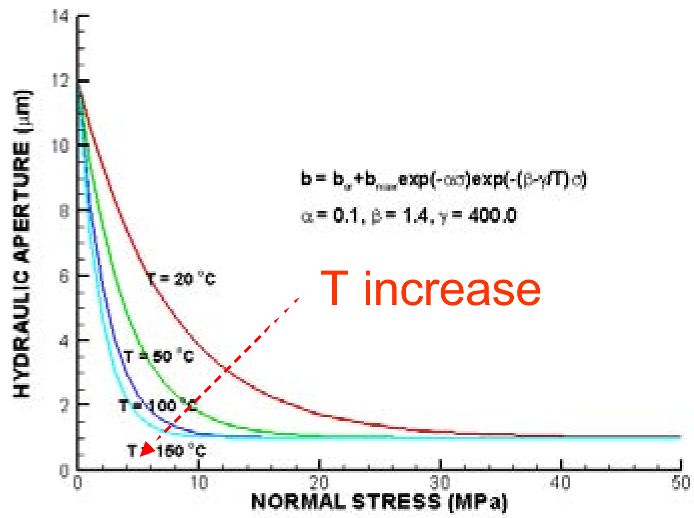
Stress has a dual role - mechanical deformation and acceleration of pressure solution

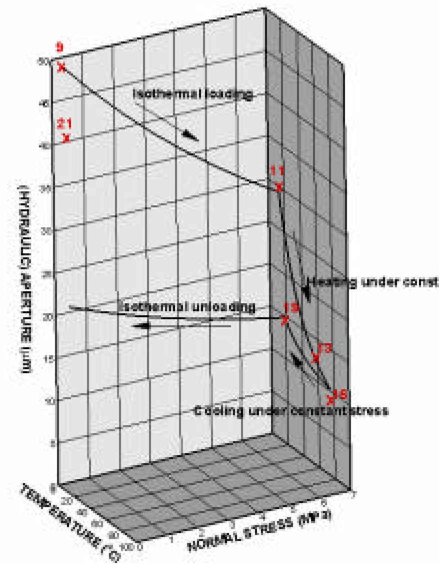
Final equivalent permeability was calculated on orthogonally fractured rock using cubic law

$$k = \frac{b^3}{12s}$$

T-M-C induced aperture change





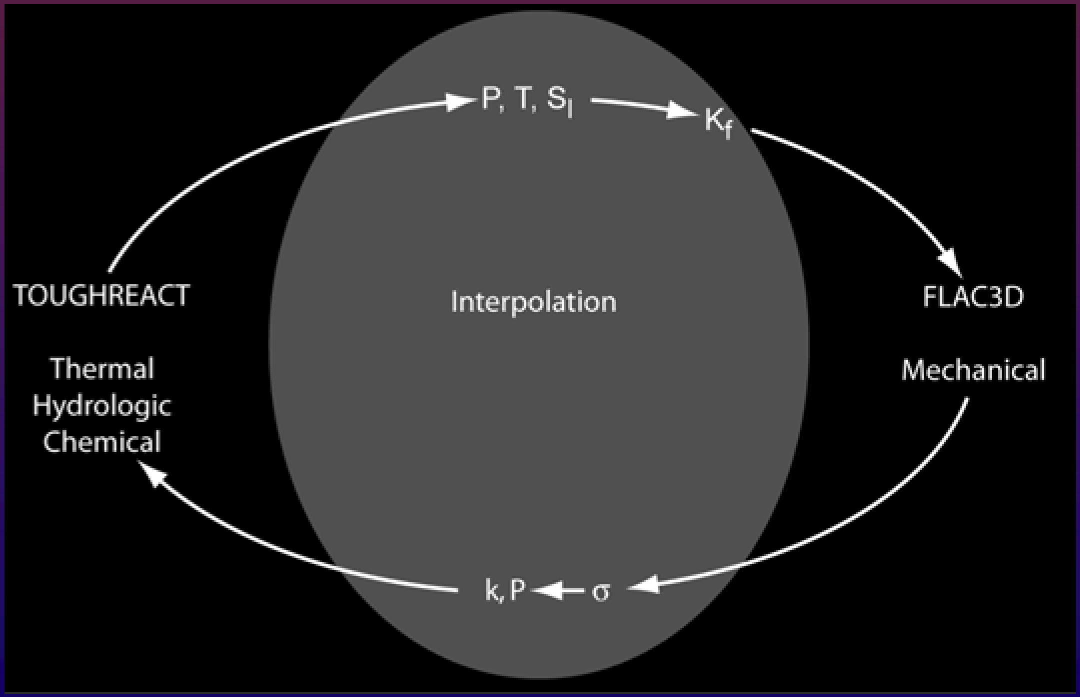


- Application to novaculite (laboratory) and granodiorite (field) matches relatively well
- Further study regarding the effect of unloading/cooling is under way
- Experiment with increasing stress under isothermal condition is planned

Upscaling – THMC Modeling

TOUGHREACT – Accommodation of temperature, multi-component phase equilibria, pressure diffusion, multi-phase hydrologic transport, and chemical dissolution/precipitation (Time dependent)

FLAC3D – Mechanical constitutive relations (Stress equilibrium)



- FLAC3D

$$_{ij,j} = -F_i$$

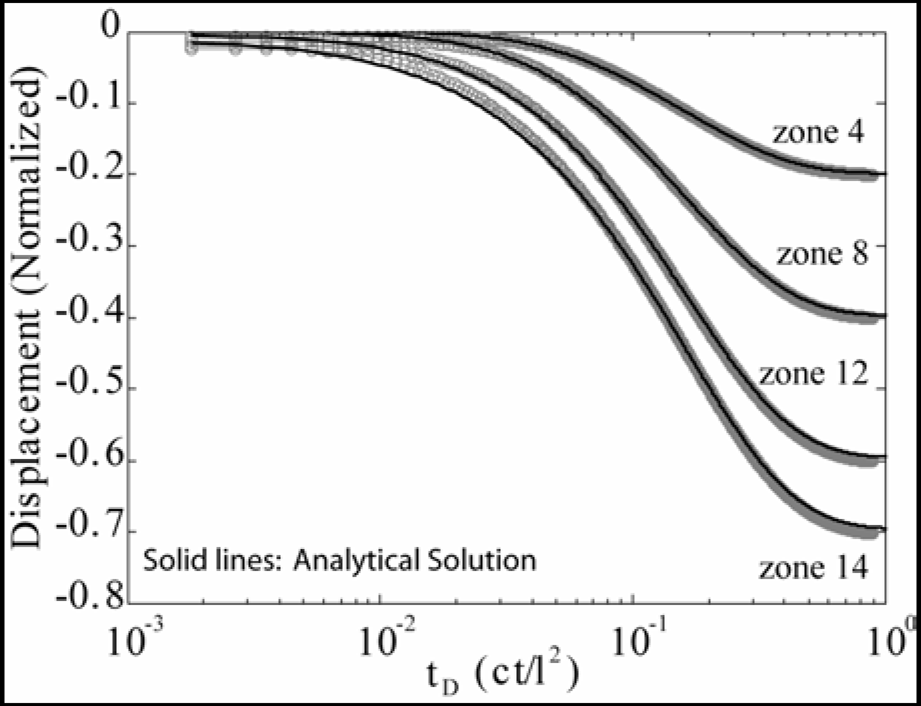
$$_{ij} = 2G \;_{ij} + \frac{2G}{1-2} \;_{kk} \;_{ij} - \;_{P}p \;_{ij} - \;_{T}T \;_{ij}$$

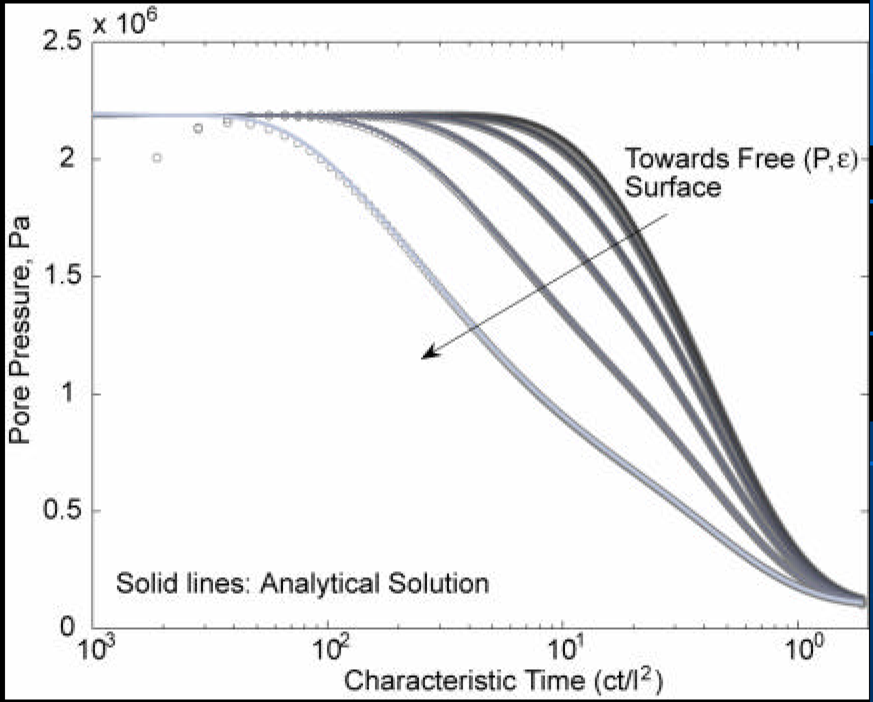
$$G\nabla^2 u_i + \frac{G}{1-2} u_{k,ki} = \;_{P}p_{,i} + \;_{T}T_{,i} - F_i$$

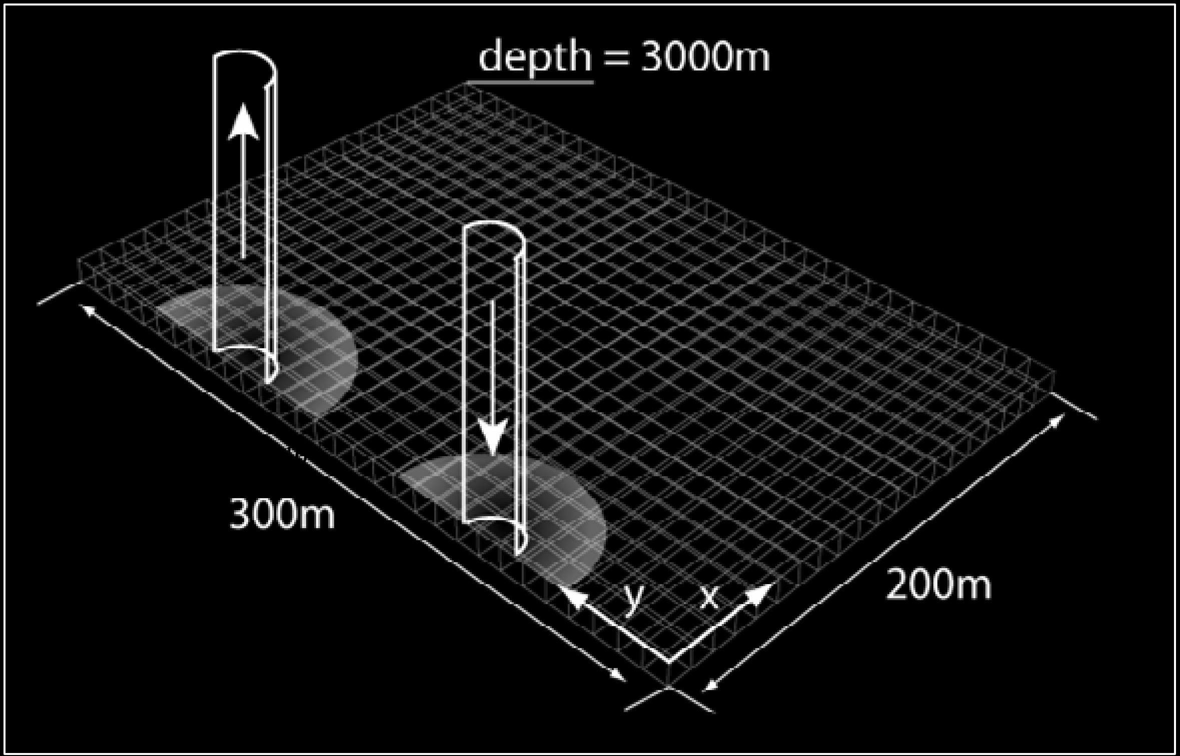
- TOUGHREACT

$$\frac{d}{dt}\int_{V_n} M^l \, dV = \int_{\Gamma_n} F^l \cdot n \, d\Gamma + \int_{V_n} q^l \, dV$$

1-D Validation



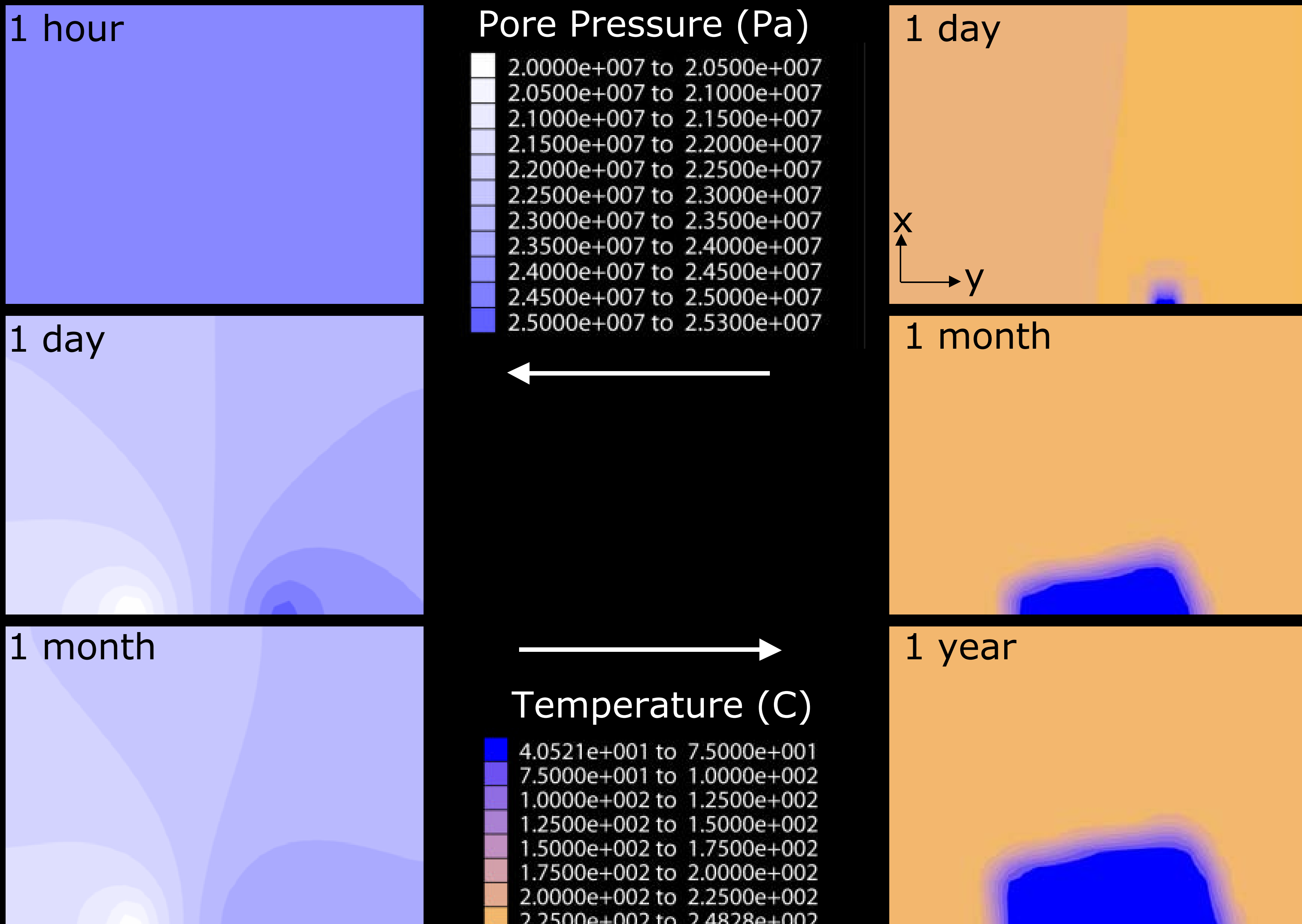




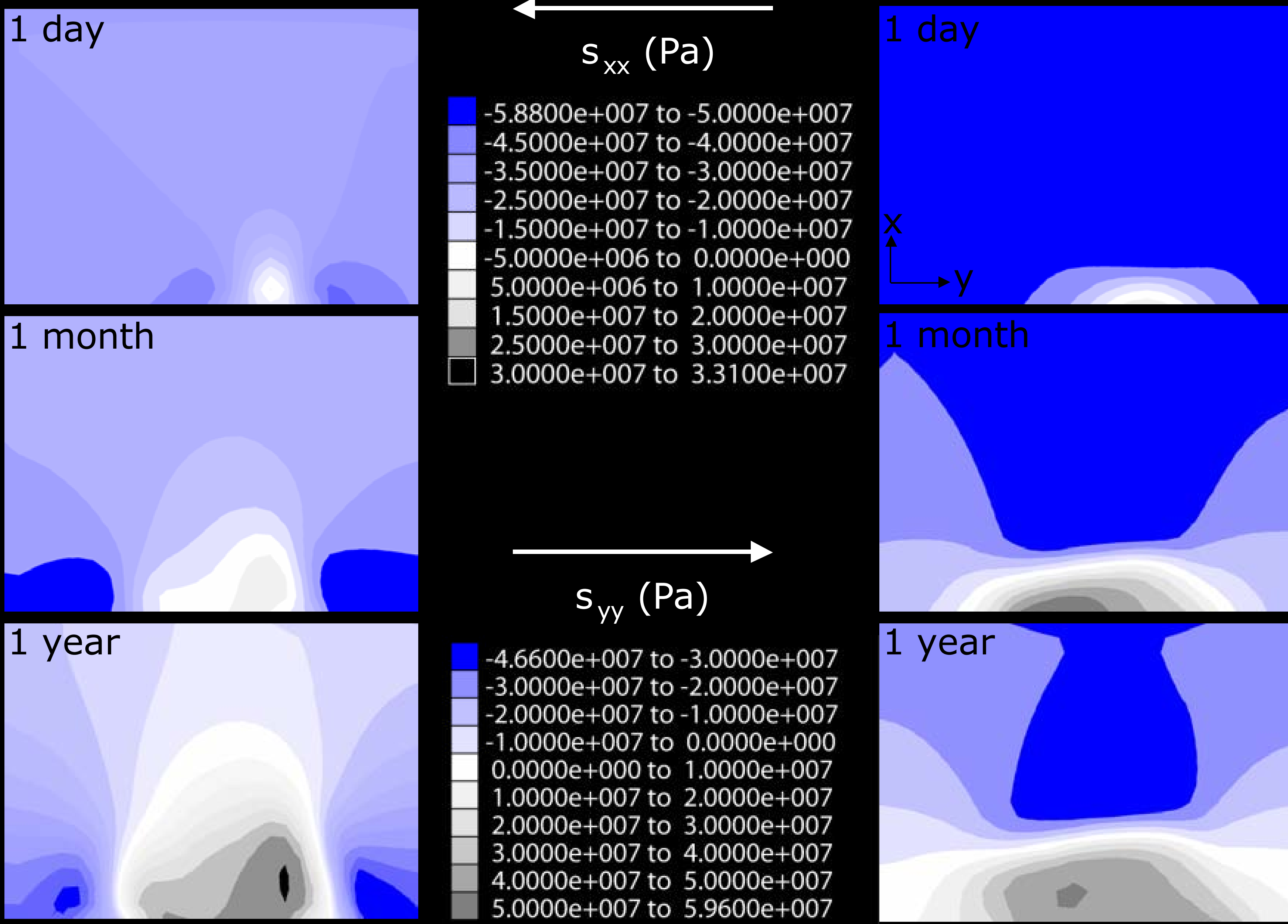
Parameter	Value
Deformation modulus (GPa)	58
Poisson ratio	0.22
Porosity	0.19
Initial permeability (m^2)	1.0×10^{-12}
Reservoir temp (C)	250
Water injection temp (C)	40

- EGS Reservoir

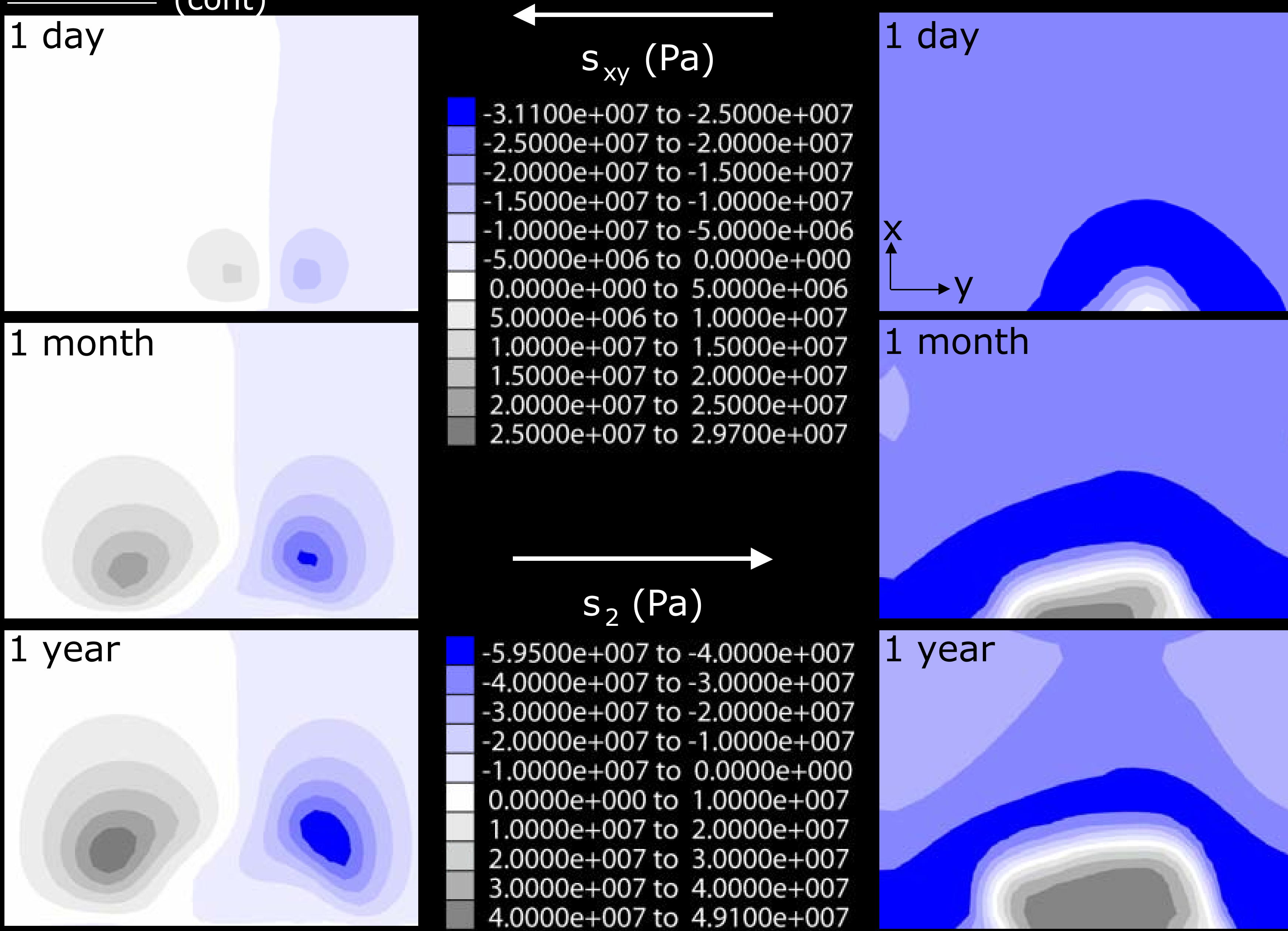
Conditions


1 hour
1 day
1 month
Pore Pressure (Pa)
2.0000e+007 to 2.0500e+007
2.0500e+007 to 2.1000e+007
2.1000e+007 to 2.1500e+007
2.1500e+007 to 2.2000e+007
2.2000e+007 to 2.2500e+007
2.2500e+007 to 2.3000e+007
2.3000e+007 to 2.3500e+007
2.3500e+007 to 2.4000e+007
2.4000e+007 to 2.4500e+007
2.4500e+007 to 2.5000e+007
2.5000e+007 to 2.5300e+007
Temperature (C)
4.0521e+001 to 7.5000e+001
7.5000e+001 to 1.0000e+002
1.0000e+002 to 1.2500e+002
1.2500e+002 to 1.5000e+002
1.5000e+002 to 1.7500e+002
1.7500e+002 to 2.0000e+002
2.0000e+002 to 2.2500e+002
2.2500e+002 to 2.4828e+002
1 day
x
y
1 month
1 year

Stress


1 day
1 month
1 year
s xx (Pa)
-5.8800e+007 to -5.0000e+007
-4.5000e+007 to -4.0000e+007
-3.5000e+007 to -3.0000e+007
-2.5000e+007 to -2.0000e+007
-1.5000e+007 to -1.0000e+007
-5.0000e+006 to 0.0000e+000
5.0000e+006 to 1.0000e+007
1.5000e+007 to 2.0000e+007
2.5000e+007 to 3.0000e+007
3.0000e+007 to 3.3100e+007
s yy (Pa)
-4.6600e+007 to -3.0000e+007
-3.0000e+007 to -2.0000e+007
-2.0000e+007 to -1.0000e+007
-1.0000e+007 to 0.0000e+000
0.0000e+000 to 1.0000e+007
1.0000e+007 to 2.0000e+007
2.0000e+007 to 3.0000e+007
3.0000e+007 to 4.0000e+007
4.0000e+007 to 5.0000e+007
5.0000e+007 to 5.9600e+007
1 day
x
y
1 month
1 year

Stress (cont)


1 day
1 month
1 year
s_{xy} (Pa)
-3.1100e+007 to -2.5000e+007
-2.5000e+007 to -2.0000e+007
-2.0000e+007 to -1.5000e+007
-1.5000e+007 to -1.0000e+007
-1.0000e+007 to -5.0000e+006
-5.0000e+006 to 0.0000e+000
0.0000e+000 to 5.0000e+006
5.0000e+006 to 1.0000e+007
1.0000e+007 to 1.5000e+007
1.5000e+007 to 2.0000e+007
2.0000e+007 to 2.5000e+007
2.5000e+007 to 2.9700e+007
s_2 (Pa)
-5.9500e+007 to -4.0000e+007
-4.0000e+007 to -3.0000e+007
-3.0000e+007 to -2.0000e+007
-2.0000e+007 to -1.0000e+007
-1.0000e+007 to 0.0000e+000
0.0000e+000 to 1.0000e+007
1.0000e+007 to 2.0000e+007
2.0000e+007 to 3.0000e+007
3.0000e+007 to 4.0000e+007
4.0000e+007 to 4.9100e+007
1 day
x
y
1 month
1 year

Results/Accomplishments

- **Awards**
  - Hide Yasuhara –Recipient of ARMA's 2006 NGW Cook Ph.D. Award

- **Invited Presentations**
  1. Elsworth, D., Yasuhara, H., Polak, A., and Liu, J. (2005) Short timescale chemo-mechanical effects and their influence on the transport properties of fractured rock. Keynote lecture. Proc. 11th International Conference on Computer Methods and Analysis in Geomechanics. Turin, June. Vol. 3 pp. 517-530.
  2. Elsworth, D. and Yasuhara, H. (2004) Short-timescale chemo-mechanical effects and their influence on the transport properties of fractured rocks. Keynote lecture. Euro-Conf on Rock Physics and Geomechanics. Potsdam. Germany. September.
  3. Elsworth, D. (2005) Stress- and chemistry-mediated changes in the mechanical and transport properties of porous and fractured rocks: observations and some unanswered questions. Third International Workshop on Water Dynamics, Sendai, Japan, November.
  4. Elsworth, D. (2005) Stress- and chemistry-mediated changes in the mechanical and transport properties of porous and fractured rocks: observations and some unanswered questions. Annual Meeting of the Geothermal Research Society of Japan, Obama, Nagaskai, Japan, November.
  5. Elsworth, D., Yasuhara, H., Liu, J., Polak, A., Grader, A., Halleck, P. 2005. Constrained observation of stress- and chemistry-mediated chages in the transport properties of fractured rock via physical and chemical signals supplemented by X-ray CT. EOS AGU Trans. (Dec AGU Mtg).

- **Publications**
  1. Taron, J., Min, K.-B., Yasuhara, H., Trakoolngam, K., and Elsworth, D. (2006) Numerical simulation of coupled thermo-hydro-chemo-mechanical processes through the linking of hydrothermal and solid mechanics codes. Proc. 41st US Symp. on Rock Mechs., GoldenRocks, Golden, Colorado, June, pp. ARMA/USRMS 06-1128.
  2. Faoro, I., Yasuhara, H., Grader, A., Halleck, P., Elsworth, D., and Marone, C. (2006) Long-term evolution of transport properties of a fracture from the Coso Geothermal Reservoir. Proc. 41st US Symp. on Rock Mechs., GoldenRocks, Golden, Colorado, June, pp. ARMA/USRMS 06-1089.
  3. Yasuhara, H., Polak, A., Mitani, Y., Grader, A., Halleck, P., and Elsworth, D. (2006) Evolution of fracture permeability through fluid-rock reaction under hydrothermal conditions. Earth and Planetary Science Letters. Vol. 244, pp. 186 – 200.
  4. Elsworth, D., and Yasuhara, H. (2006) Short timescale chemo-mechanical effects and their influence on the transport properties of fractured rock. Earth and Planetary Research Letters. Vol. 150, No. 10.
  5. Yasuhara, H., Polak, A., Mitani, Y., Grader, A., Halleck, P., and Elsworth, D. (2005) Evolution of fracture permeability through reactive flow at elevated temperature. Trans. Geotherm. Res. Council. Vol. 29, pp. 437 – 441.
  6. Yasuhara, H., and Elsworth, D. (2005) A numerical model simulating reactive transport and evolution of fracture permeability. In press. Int. J. Num. and Anal. Meth. in Geomechs. 40 pp.
  7. Elsworth, D., Yasuhara, H., Polak, A., and Liu, J. (2005) Short timescale chemo-mechanical effects and their influence on the transport properties of fractured rock. Keynote paper. Proc. 11th International Conference on Computer Methods and Analysis in Geomechanics. Turin, June. Vol. 3 pp. 517-530.

Conclusion

- Anticipate completion in Sept 2008 with 1-year NFX from Oct 2007
- Anticipated Benefits/Products
  - Understanding of spatial permeability evolution in EGS reservoirs:
    - Fundamental understanding of processes ? Development of constitutive models ? Upscaling via modeling
    - Routine stimulation and chemical stimulants
    - Sweep-efficiency, evolution, and propensity for short-circuiting
    - Reservoir longevity and O&M
  - Providing information where meager data exist – shear-perm inclusive of enigmatic time-dependent effects
  - Understanding of local-scale evolution of micro-seismicity
  - Development of modeling tool for coupled THMC effects