Fabric-based modeling of thermo-mechanical damage and healing around salt caverns

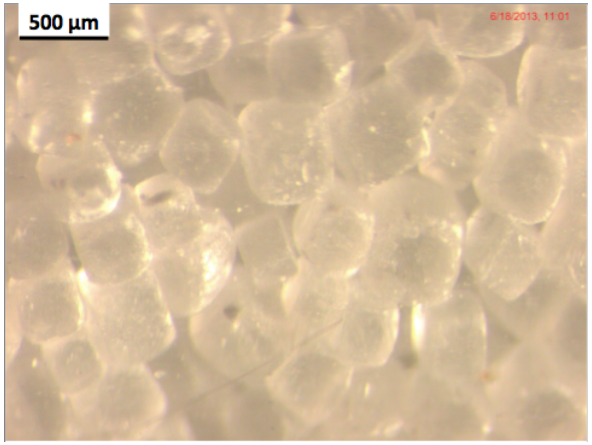
Cheng Zhu and Chloé Arson

Geosystem Group
School of Civil and Environmental Engineering
Georgia Institute of Technology

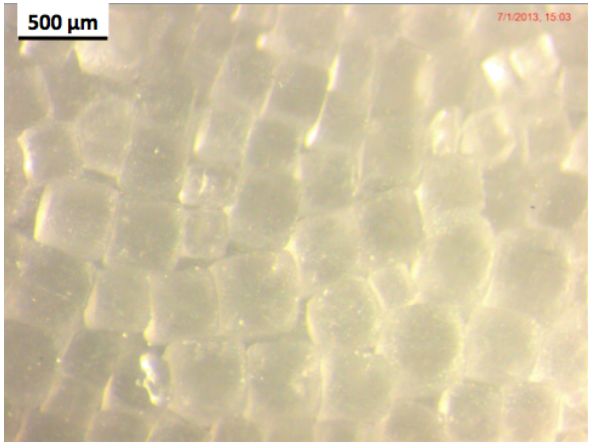
Mechanical Behavior of Salt VIII
at the South Dakota School of Mines & Technology
Rapid City, SD, USA, May 26-28, 2015

Part 2

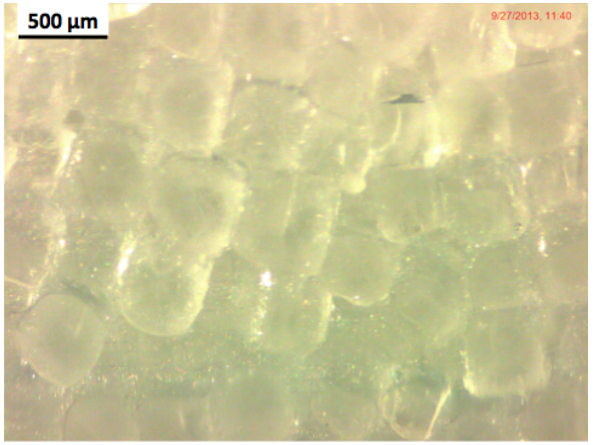
Microscopic Observation of Creep Processes in Table Salt



18 days

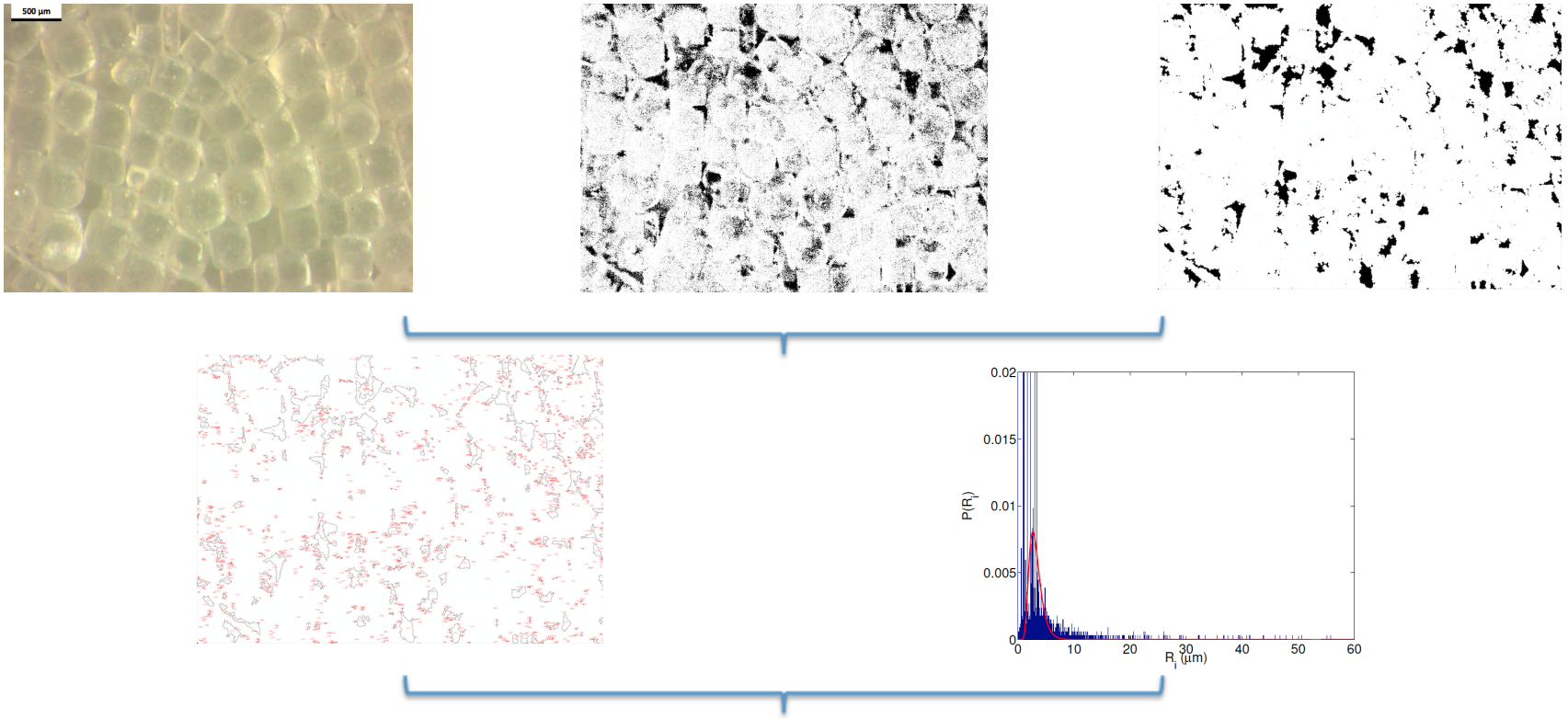


31 days



120 days

Statistical Image Analysis



Relationship between fabric descriptors and phenomenological variables?

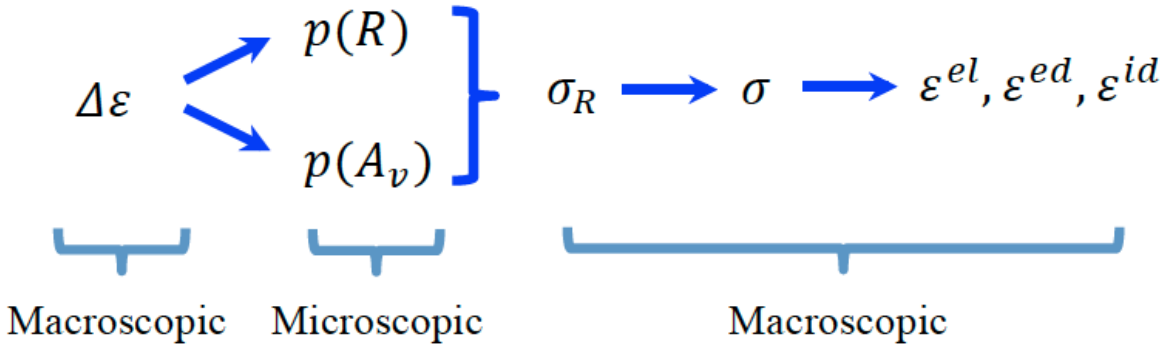
- **Distribution of sizes**: area of voids intercepted in the section (A_v)
- **Distribution of orientations**: radius of the void space projected in a plane of normal j (R_j, $j = 1, 2, 3$)

Micro-Macro Relationships

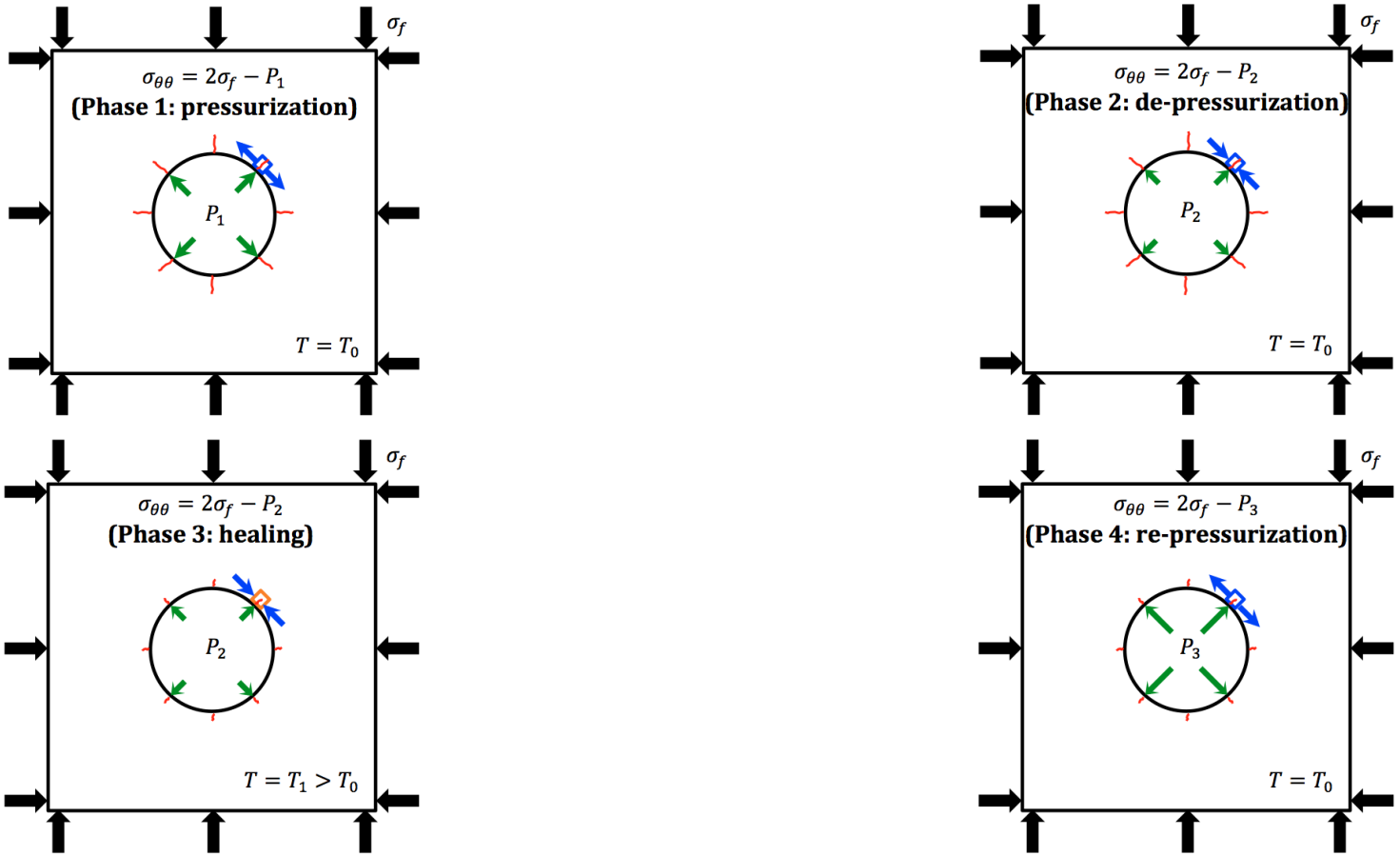
$$\Delta\varepsilon \rightarrow \Delta \boldsymbol{A} \rightarrow \overline{R}_1,\ \overline{R}_2,\ \overline{R}_3 \quad \underbrace{\rightarrow}_{\overline{R}_j = \int R_j p_j(R_j) dR_j} \quad p_j(R_j)$$

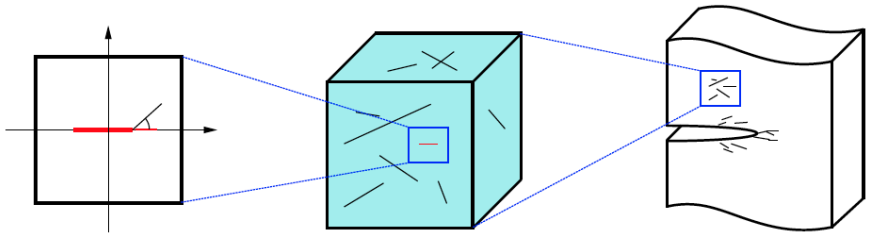
$$\Delta\varepsilon \rightarrow \Delta n_{3D} \rightarrow \Delta n_{2D} \quad \underbrace{\rightarrow}_{\overline{n}_{2D} = \int \frac{A_v}{A_{REV}} p_A(A_v) dA} \quad p_A(A_v) = a \times A_v^t$$

$$p_A(A_v),\ p_j(R_j) \rightarrow \sigma_R^{(i)} \rightarrow \boldsymbol{\sigma} \rightarrow \varepsilon^{el},\ \varepsilon^{ed},\ \varepsilon^{id}$$

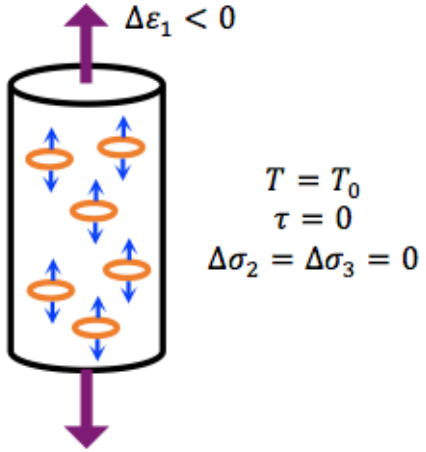


Simulation of Stress Paths Typical of Storage Conditions

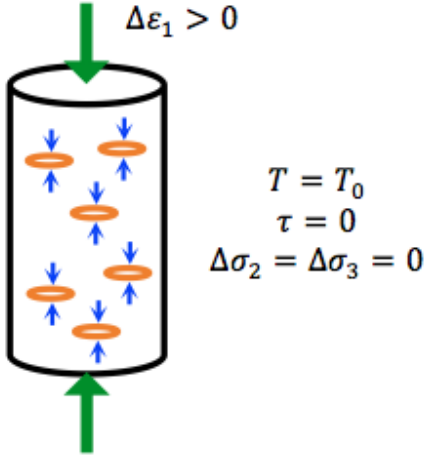




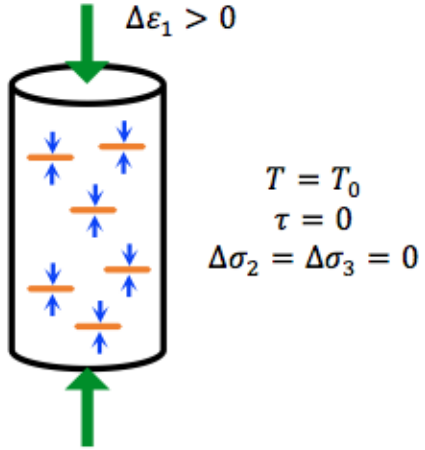
Simulation of Storage Stress Paths at the Material Point



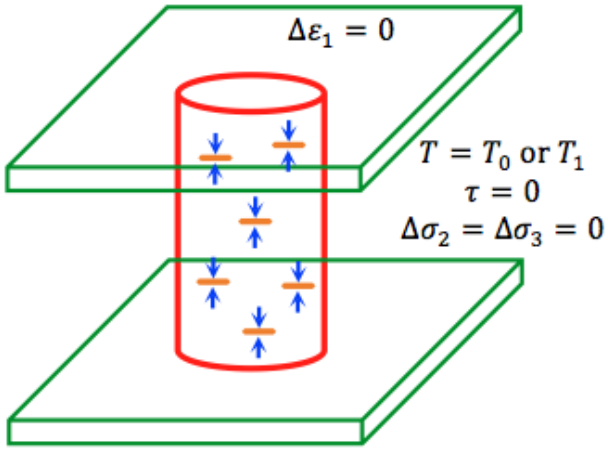
O — A — B: **uniaxial tension**



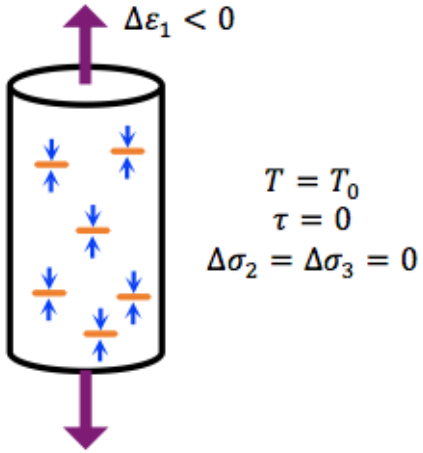
B — C — D: **unloading**



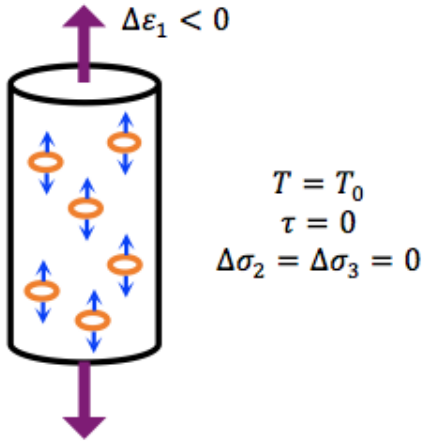
D — E: **further compression**



E — F: **confined healing**



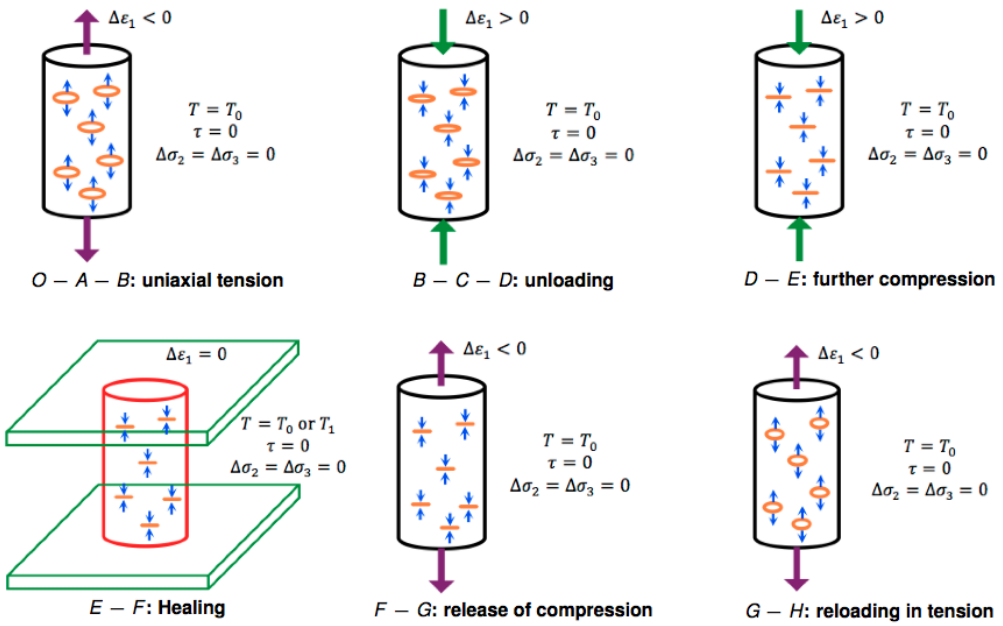
F — G: **release of compression**

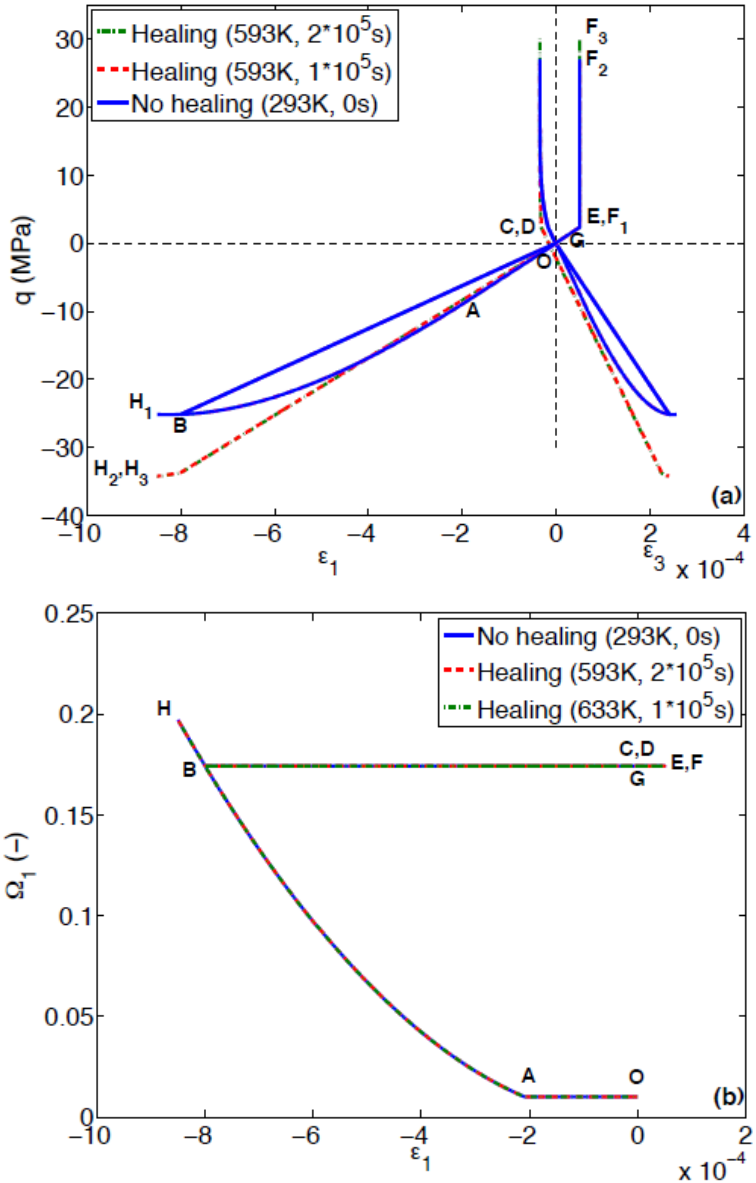


G — H: **reloading in tension**

Stress-Strain Relation and Damage Evolution

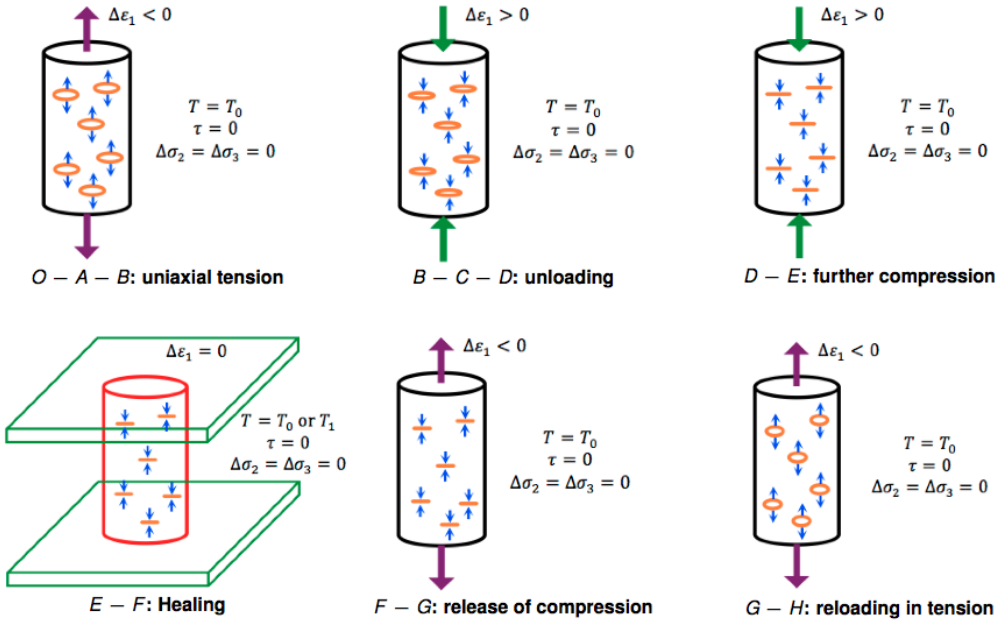
Scenario	T_1 (K)	t_{heal} (s)	D_C (m^2/s)
1	293	0	-
2	593	2×10^5	1.74×10^{-16}
3	633	1×10^5	3.52×10^{-16}

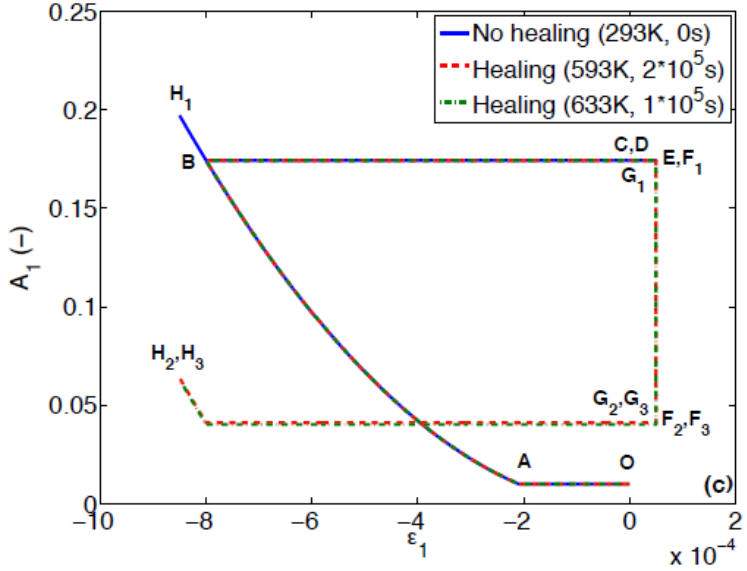


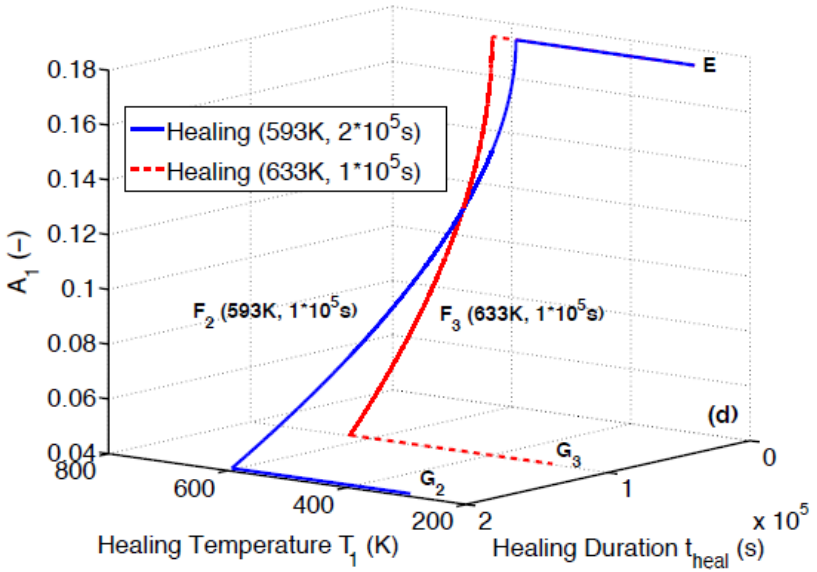


Net Damage Evolution

Scenario	T_1 (K)	t_{heal} (s)	D_C (m^2/s)
1	293	0	-
2	593	2×10^5	1.74×10^{-16}
3	633	1×10^5	3.52×10^{-16}

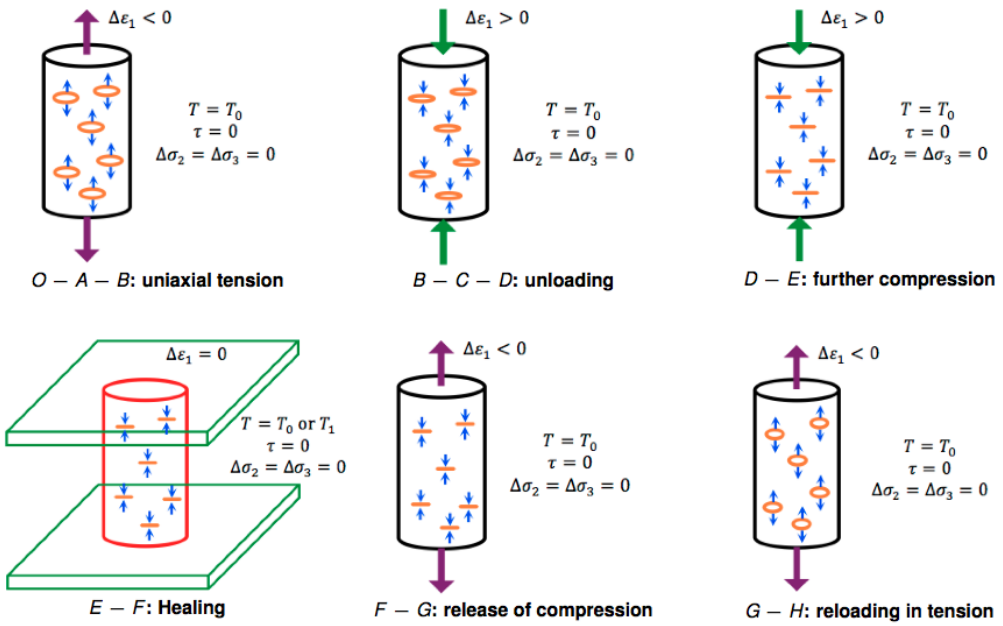


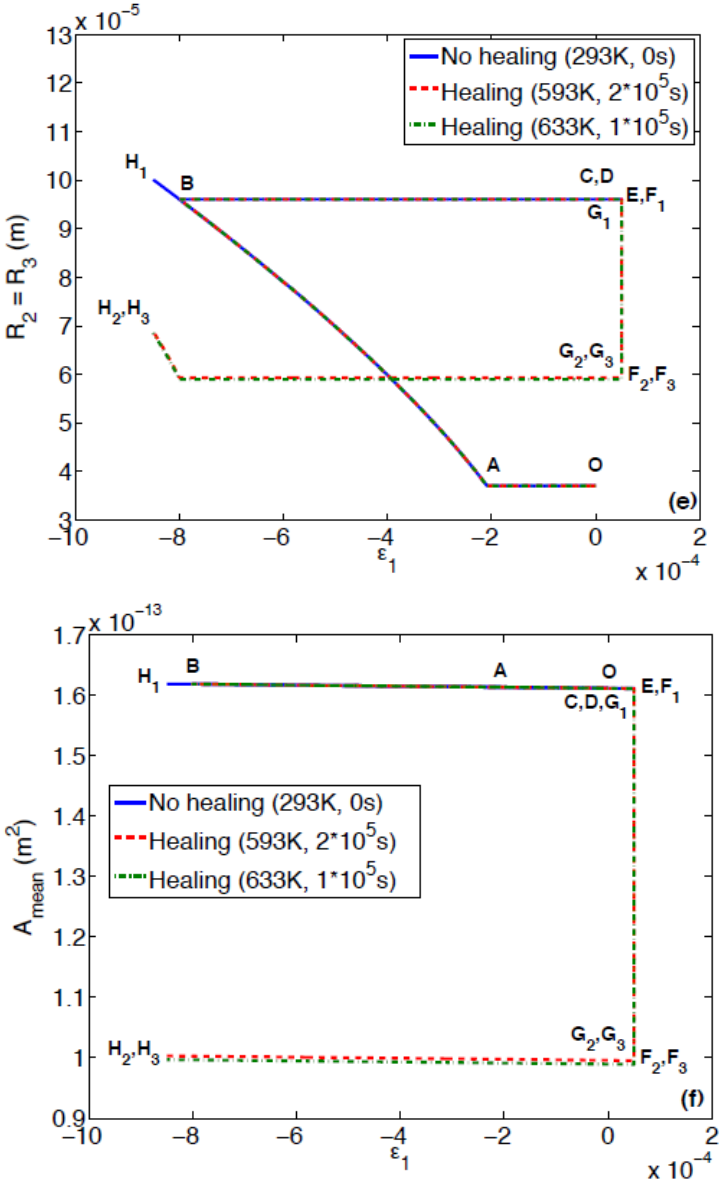




Microstructure Evolution

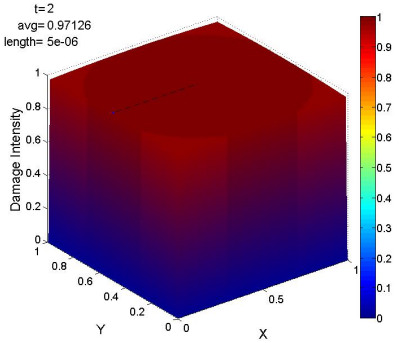
Scenario	T_1 (K)	t_{heal} (s)	D_C (m^2/s)
1	293	0	-
2	593	2×10^5	1.74×10^{-16}
3	633	1×10^5	3.52×10^{-16}





Summary and Prospective Research

1. Summary
   - Continuum Damage Mechanics framework to model the anisotropy induced by crack opening and closure on stiffness and deformation of rock under mechanical and thermo-mechanical stresses
   - Phenomenological variables coupled to salt fabric descriptors to model crack opening, closure and rebonding: void area and crack length
2. Future Research
   - Calibration against experimental data at lab scale (loading/unloading cycles, in partnership with TAMU)
   - Model implementation in FEM codes
   - Extension to the case of anisotropic healing

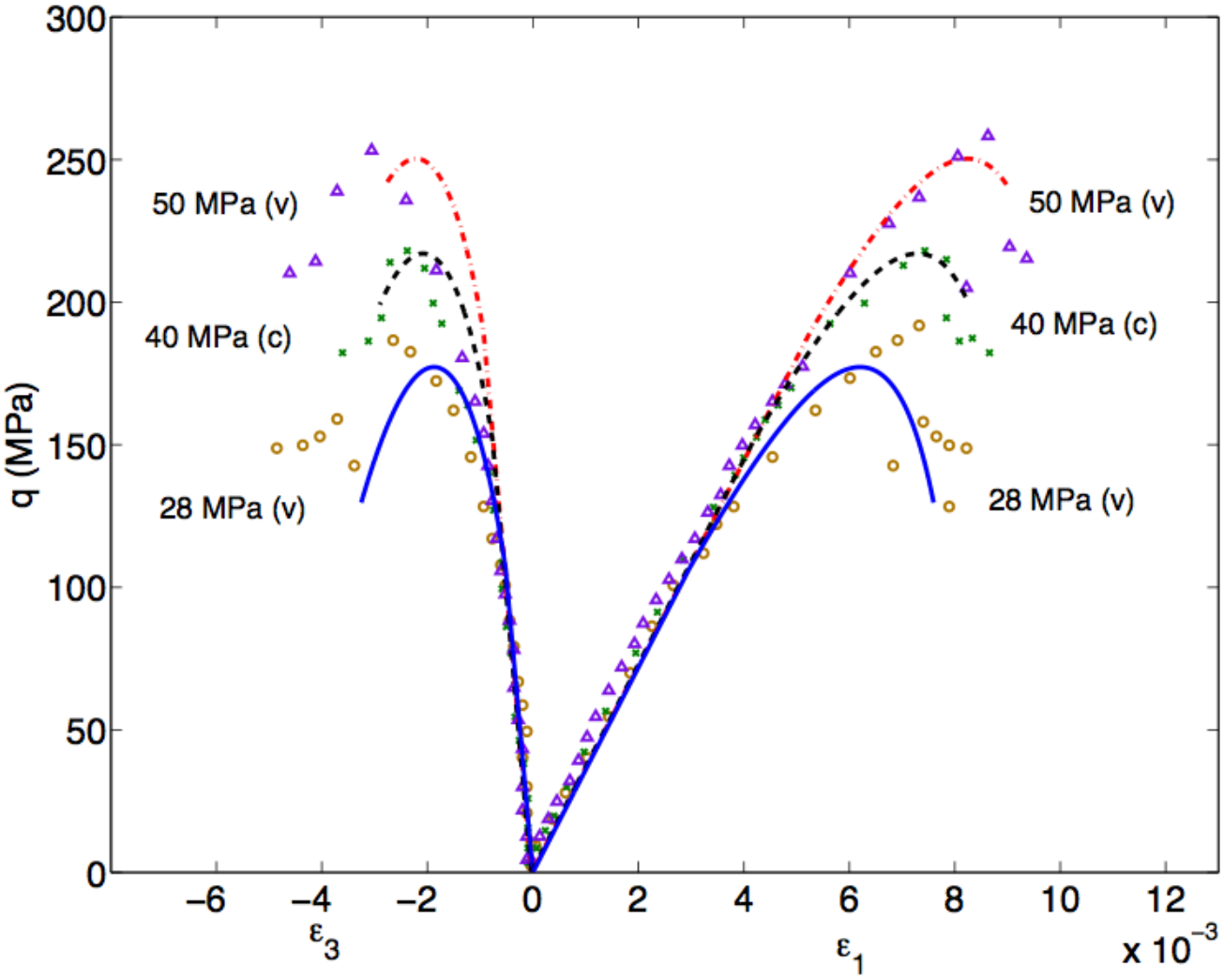


Thanks!

Contact:

chengzhu@gatech.edu
sites.google.com/site/chengzhurock

Model Calibration and Verification [Zhu & Arson, *Acta Geotechnica*, 2014]



Standard thermo-elastic parameters.
Calibration & Verification of the mechanical damage model
Experimental data from Dragon et al. [2002] (sandstone)

Thermo-mechanical Damage Model

- General expression of the free energy for a temperature change τ

$$\Psi(\varepsilon^E, \tau, D) = \frac{1}{2}\varepsilon^E : \mathbf{C}(\mathbf{D}) : \varepsilon^E + g\mathbf{D} : \varepsilon - \frac{1}{2\tau_0}\mathbf{c}(\mathbf{D})\tau^2 - \tau\mathbf{k}(\mathbf{D}) : \varepsilon^E$$

- Using thermodynamic conjugation relationships:

$$\boldsymbol{\sigma} = \mathbf{C}(\mathbf{D}) : \varepsilon^E + g\mathbf{D} - \tau\mathbf{k}(\mathbf{D})$$

- Increment of elastic deformation is decomposed into mechanical and thermal components:

$$d\varepsilon^E = d\varepsilon^{EM} + d\varepsilon^{ET}$$

Thermo-mechanical Damage Model (continued)

- The thermo-mechanical damage-driving force:

$$\mathbf{Y} = \mathbf{Y_1} + \mathbf{Y_2}$$

$$\mathbf{Y_1} = -\alpha(tr\varepsilon)\varepsilon - 2\beta(\varepsilon \cdot \varepsilon) - g\varepsilon, \quad \mathbf{Y_{1a}}^{+} = -g\varepsilon^{+}$$

$$\mathbf{Y_2} = \frac{1}{2\tau_0}\frac{\partial \mathbf{c}(\mathbf{D})}{\partial \mathbf{D}}\tau^2 + \tau\frac{\partial \mathbf{k}(\mathbf{D})}{\partial \mathbf{D}} : \varepsilon^E, \quad \mathbf{Y_2}^{d} = A \cdot \tau \cdot \alpha_T(\alpha + 2\beta)tr(\varepsilon^{E+})$$

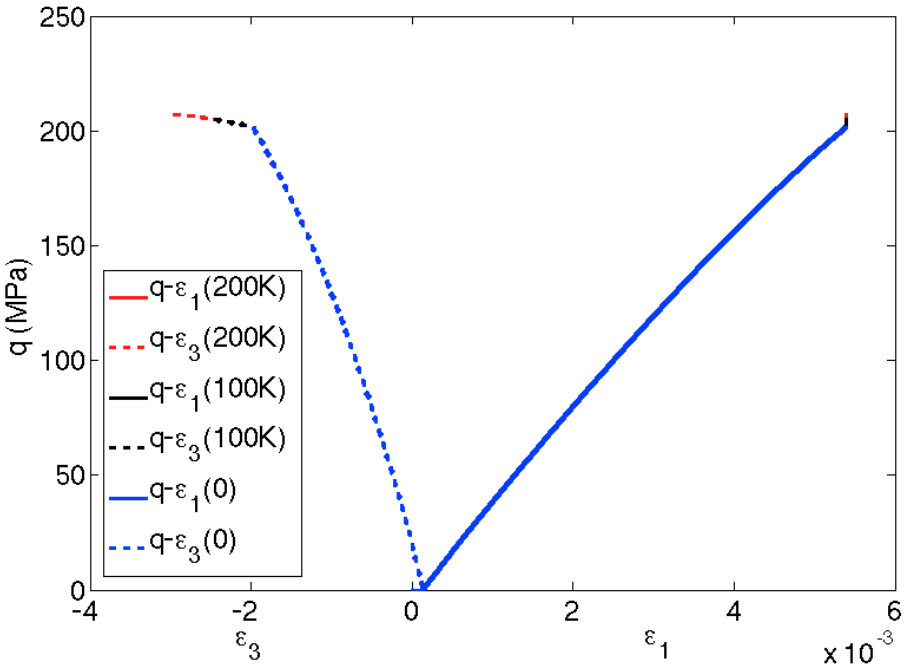
- Total damage-driving force components retained:

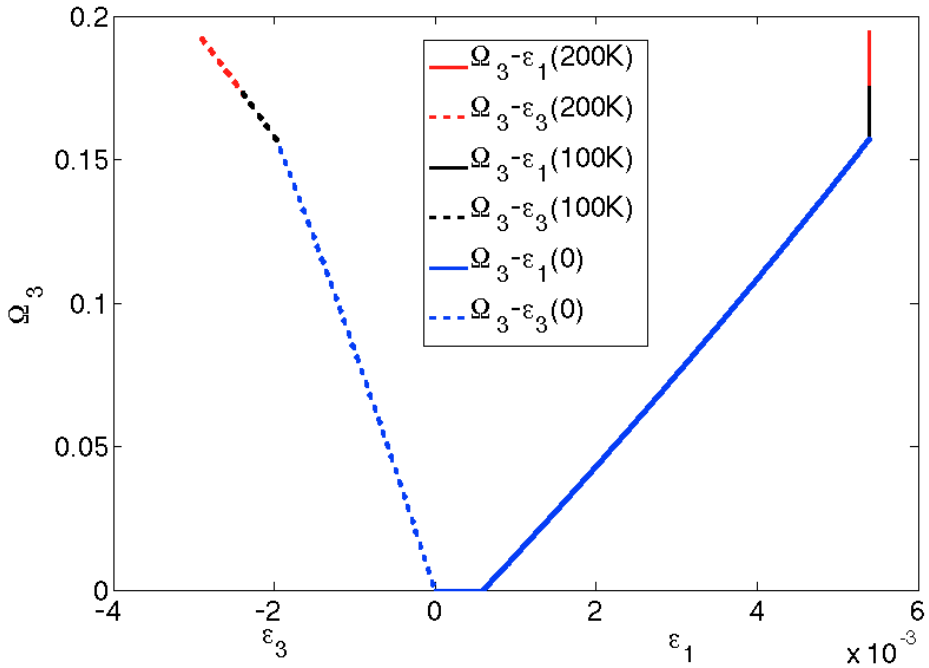
$$\mathbf{Y_d}^{+} = \mathbf{Y_{1a}}^{+} + \mathbf{Y_2}^{d} = -g\varepsilon^{+} + A \cdot \tau \cdot \alpha_T(\alpha + 2\beta)tr(\varepsilon^{E+})$$

- Damage criterion (Halm & Dragon, 1998):

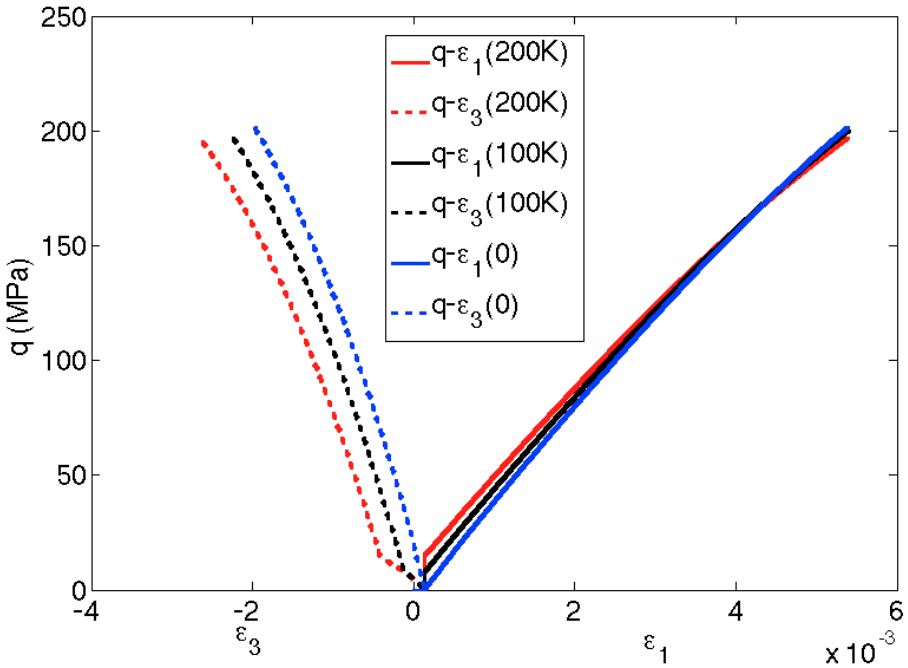
$$f_d(\mathbf{Y_d}^{+}, \mathbf{D}) = \sqrt{\frac{1}{2}\mathbf{Y_d}^{+} : \mathbf{Y_d}^{+}} - (C_0 + C_1\mathbf{D})$$

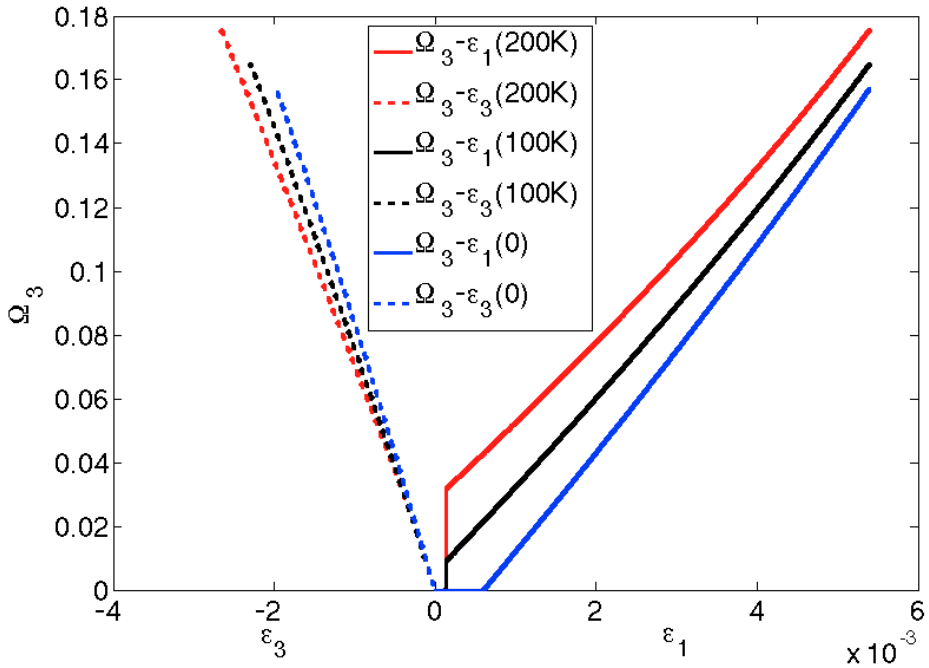
Parametric Study (0, 100K, 200K) - Stress vs. Strain



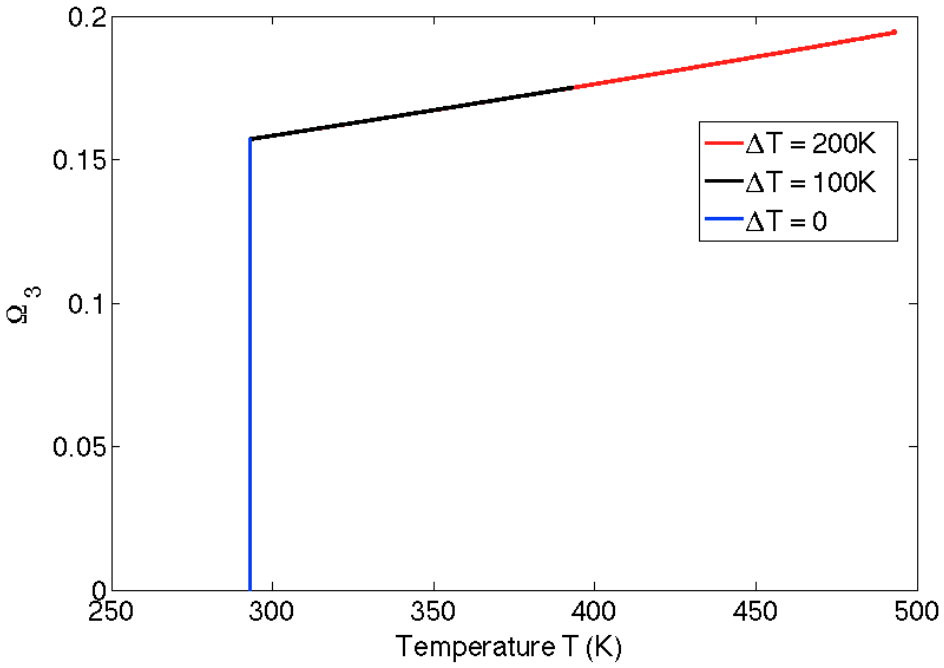


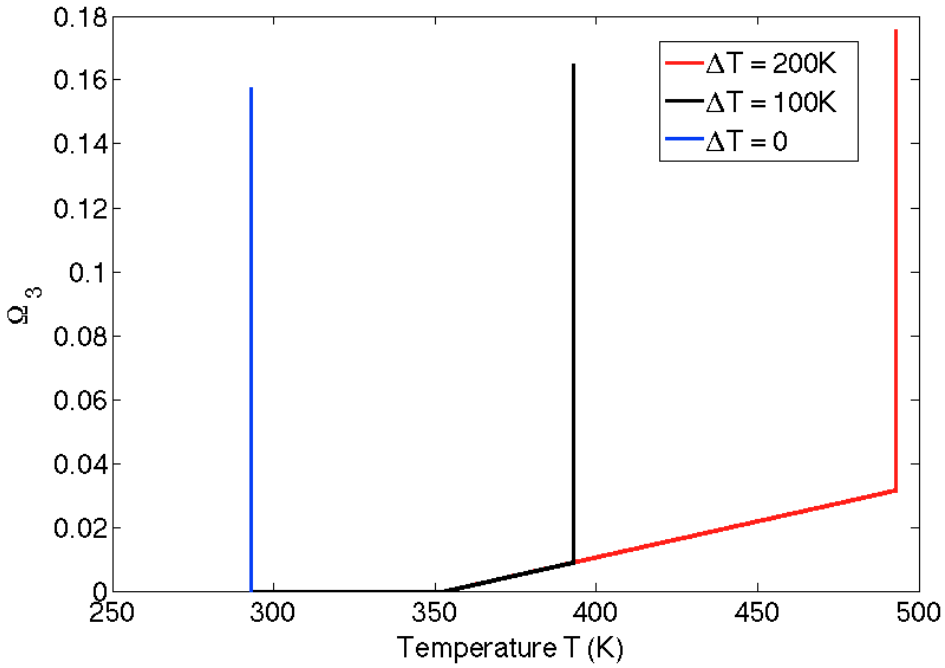
Parametric Study (0, 100K, 200K) - Damage vs. Strain



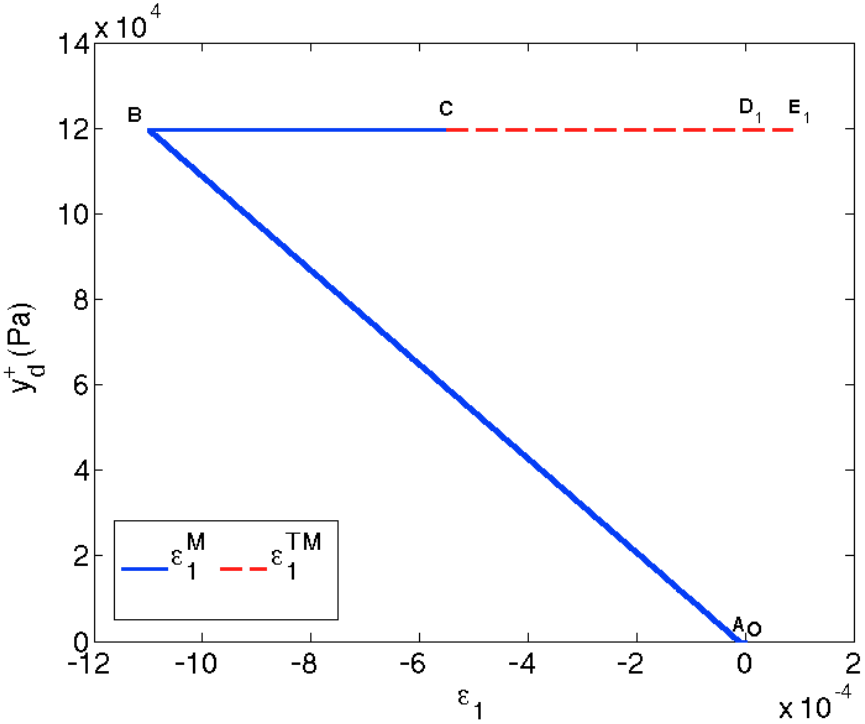


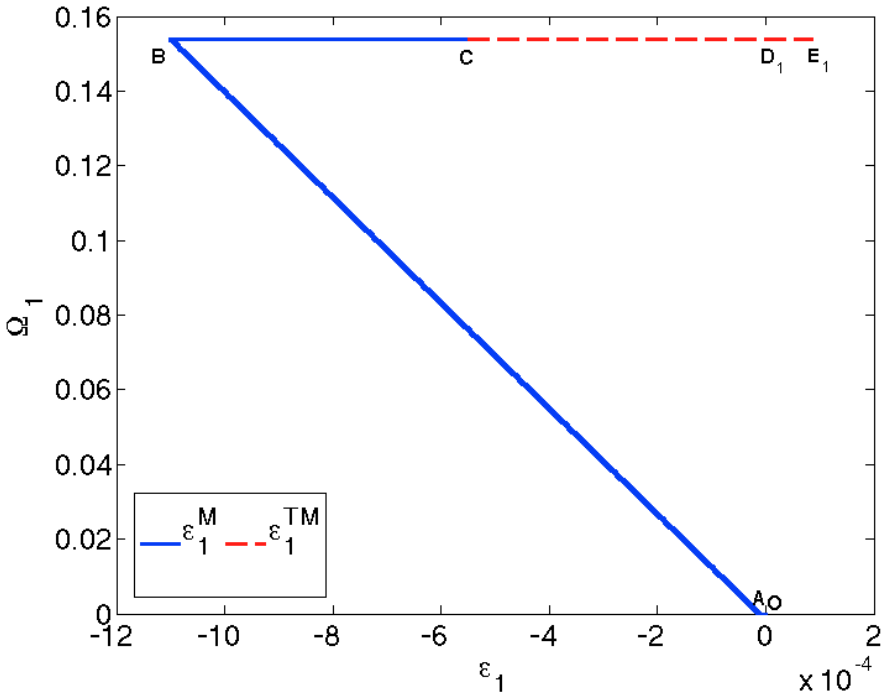
Parametric Study (0, 100K, 200K) - Damage vs. Temperature



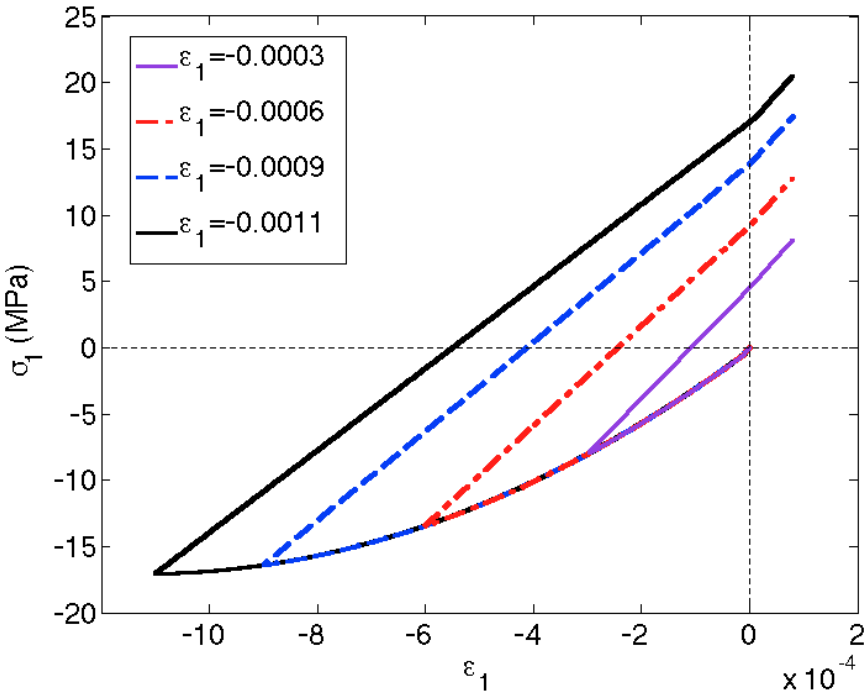


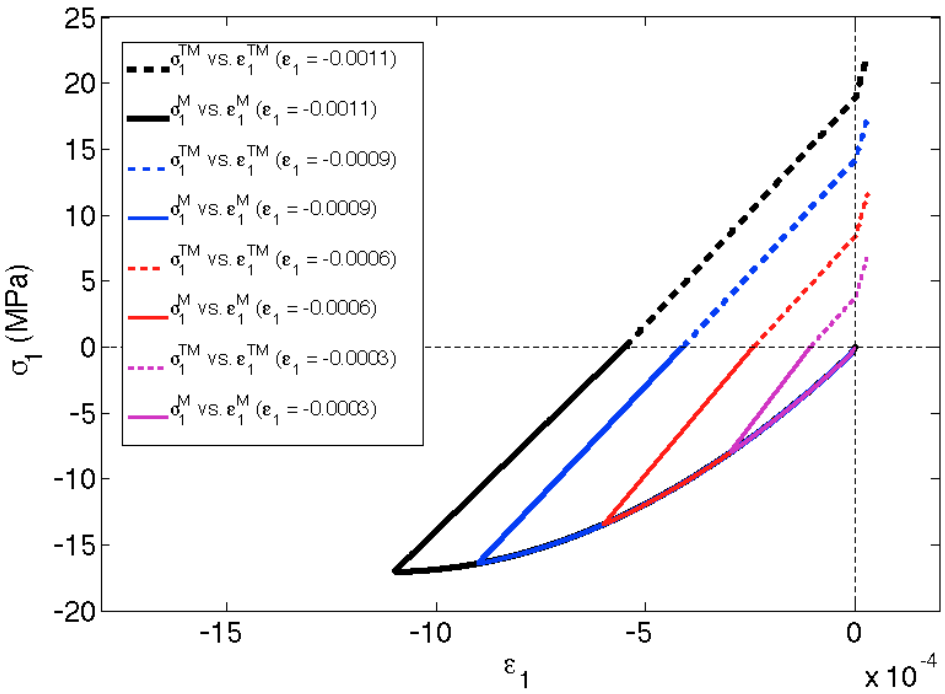
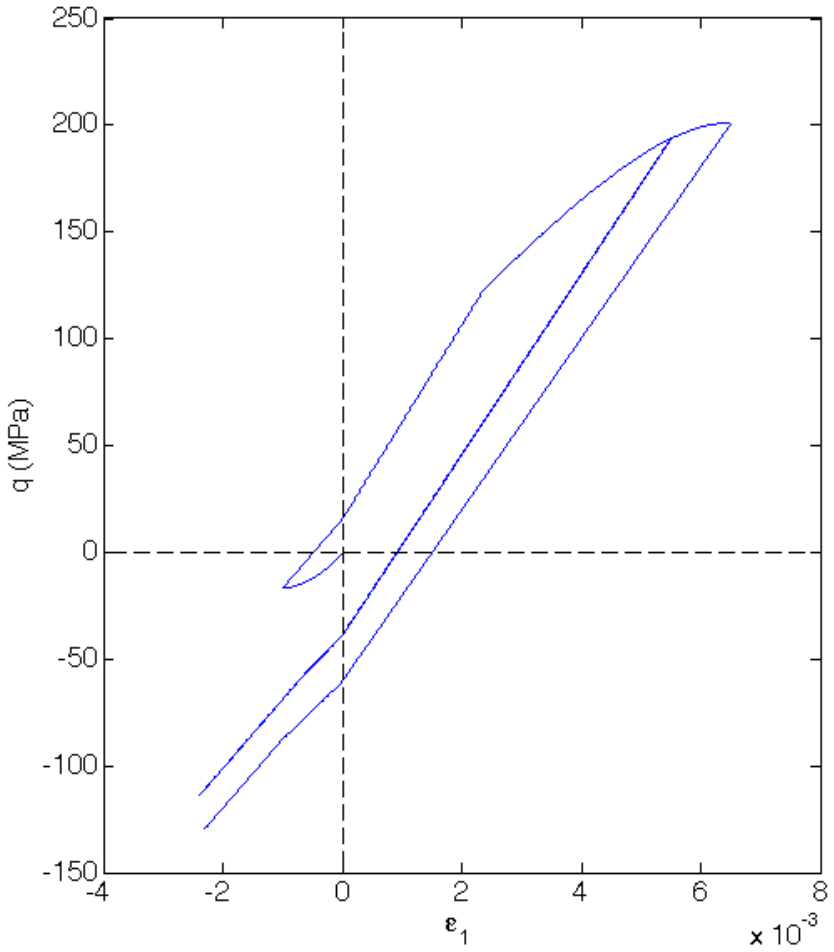
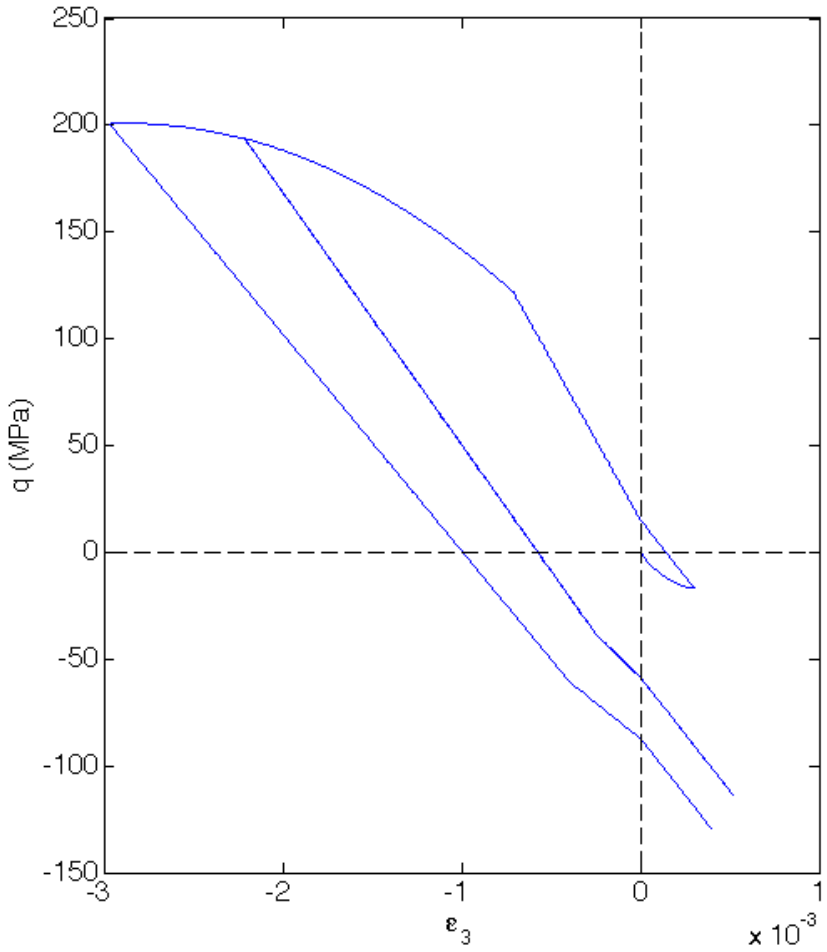
Damage Evolution for TM Crack Closure





Parametric Study on the Initial State of Damage





Response of Rocks under Loading Cycles