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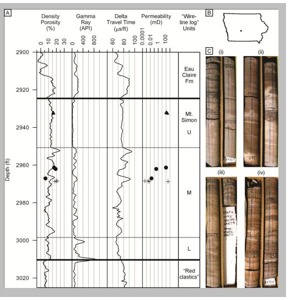

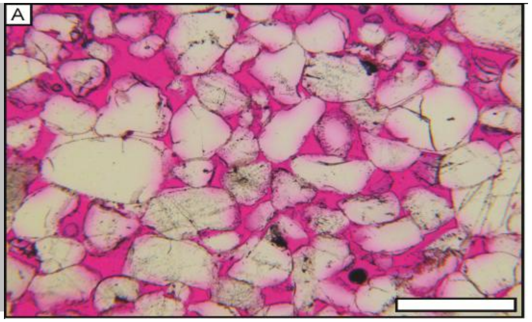

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Elasto-Plastic Constitutive Behavior in Three Lithofacies of the Cambrian Mt. Simon Sandstone, Illinois Basin, USA

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Sandia National Laboratories
Albuquerque, NM, USA

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Outline

- Practical Considerations and Geologic Background
- Axisymmetric Compression Geomechanical Testing
- Nonlinear Elasticity and Elastic-Plastic Coupling
- Constitutive Modeling with Kayenta
- Conclusions

Motivation and Regional Framework

Precambrian Structure Map of Iowa and Location of CAES Keith #1 Well

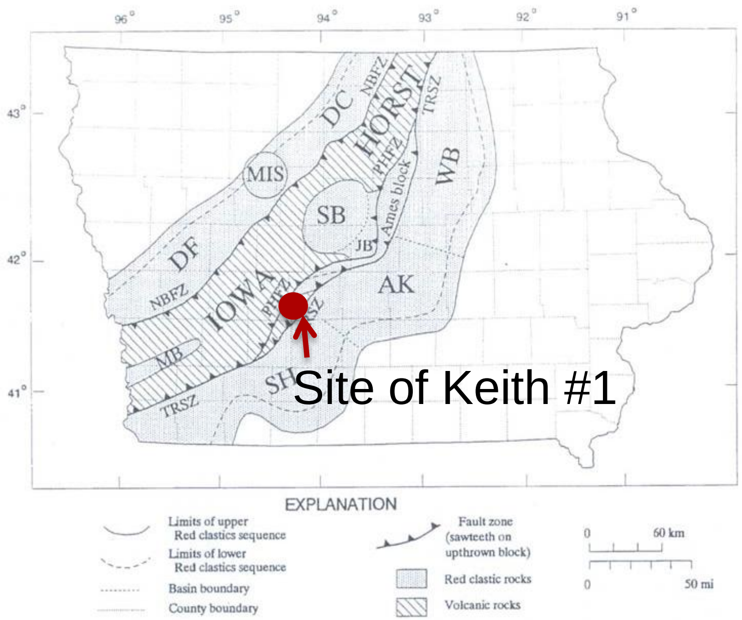
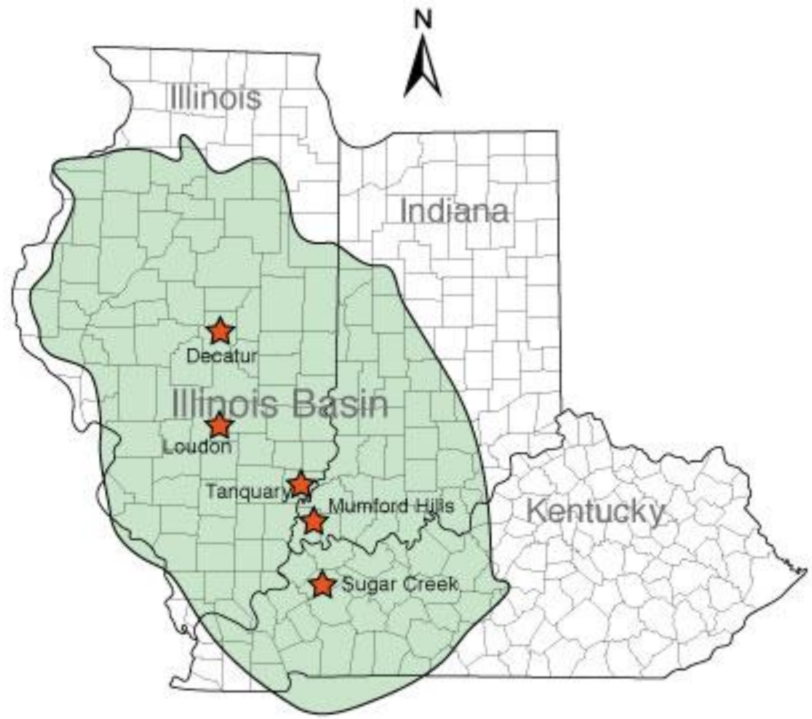


Figure 12. Structural components of the Midcontinent Rift System (MRS) in Iowa (modified from Anderson, 1992; and Anderson, 1995, fig. 1, p. 56, copyright ©1995 Kluwer Academic Publishers, used with kind permission from Kluwer Academic Publishers). NBFZ, Northern Boundary Fault Zone; TRSZ, Thurman-Redfield Structural Zone; PHFZ, Perry-Hampton Fault Zone; DF, Defiance Basin; DC, Duncan Basin; SH, Shenandoah Basin; AK, Ankeny Basin; WB, Wellsburg Basin; SB, Stratford Basin; JB, Jewell Basin; MB, Mineola Basin; MIS, Manson Impact Structure.

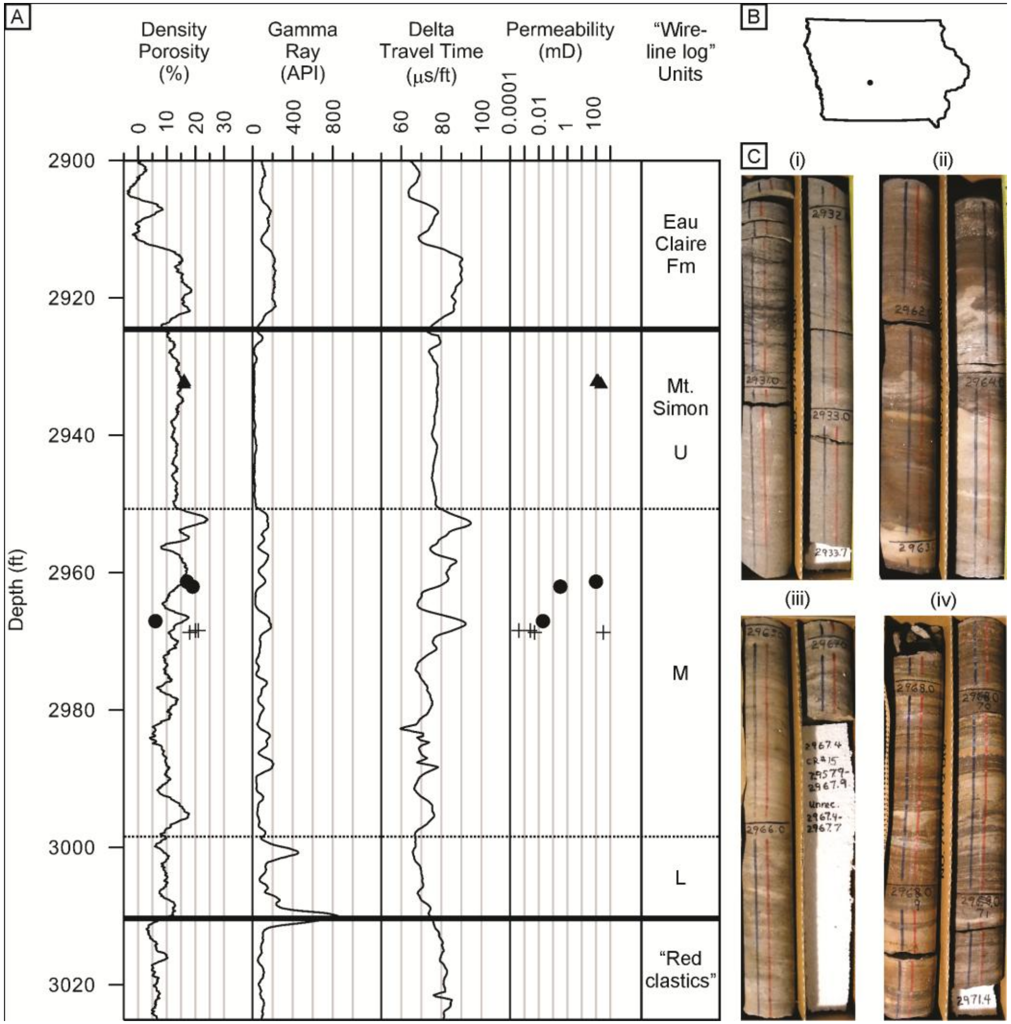
Mount Simon, Illinois Basin and CCS Injection Projects



http://sequestration.org/mgscprojects/index.html

Core, Well Logs and Sampling

- Three well-log units (U, M, L)
- Three sampled lithofacies (I, II, III)
- Similar porosities but markedly different permeabilities
- Distribution of facies similar to those on east flank of Illinois Basin (Saeed and Evans, 2012)
- Similar to lower portions of Illinois Basin lithofacies (Bowen et al. 2011) incl. main injection horizon but lacking upper “B-cap” muddy facies



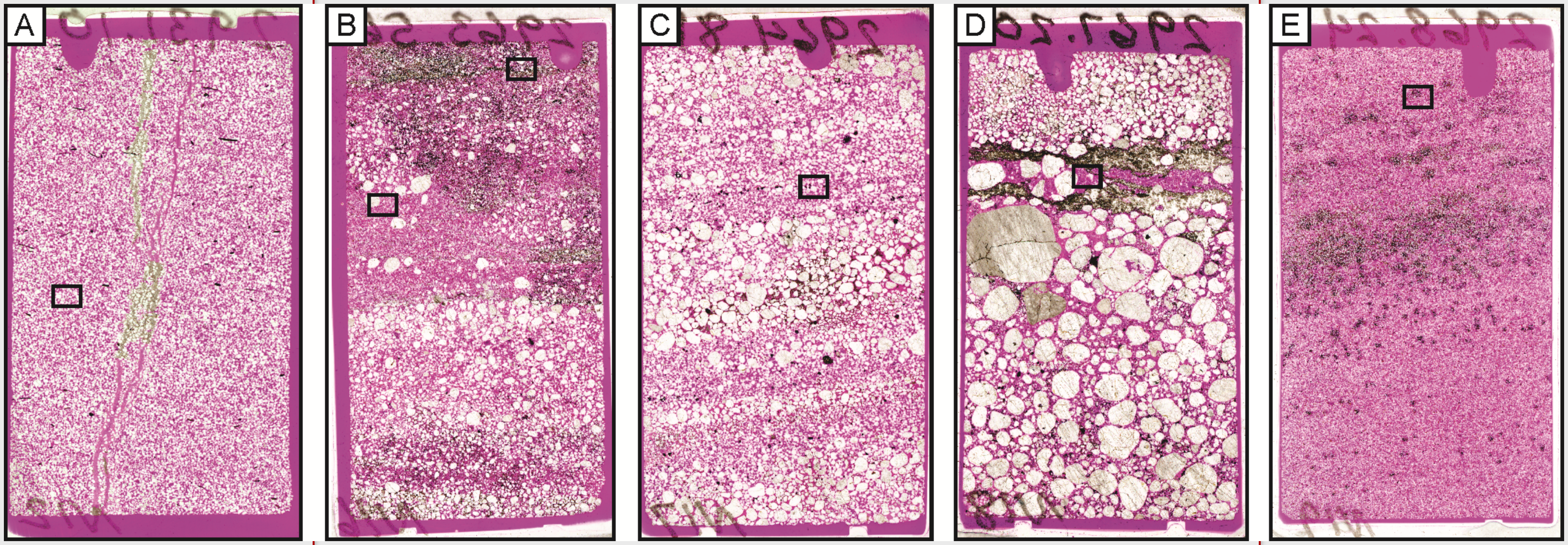
Lithofacies Interpretation

- I Lithofacies (main injection unit in IB): quartz-rich sand flat B1 facies of *Saeed and Evans* [2012] or the "sandy tidal" facies of *Fischietto* [2009]

- II Lithofacies: heterolithic T2 "mixed flat" facies and "sand flat to tidal channel" B2 facies of *Saeed and Evans* [2012] or the "mixed fluvial-eolian tidal" and "braided fluvial" facies of *Fischietto* [2009]

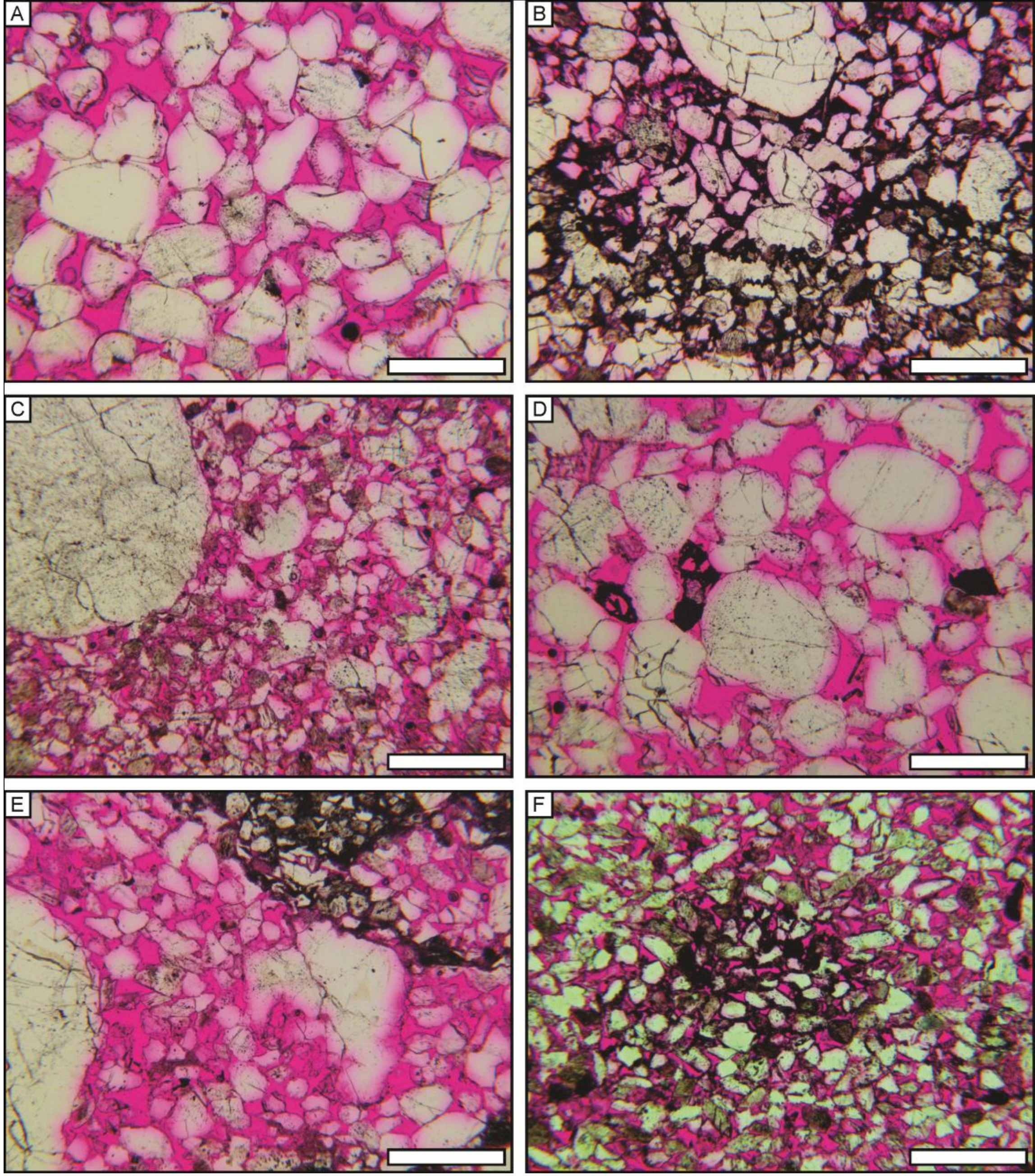
- III Lithofacies: mud flat T1 facies of *Saeed and Evans* [2012] or the muddy tidal facies of *Fischietto* [2009]

I Lithofacies	II Lithofacies	III Lithofacies



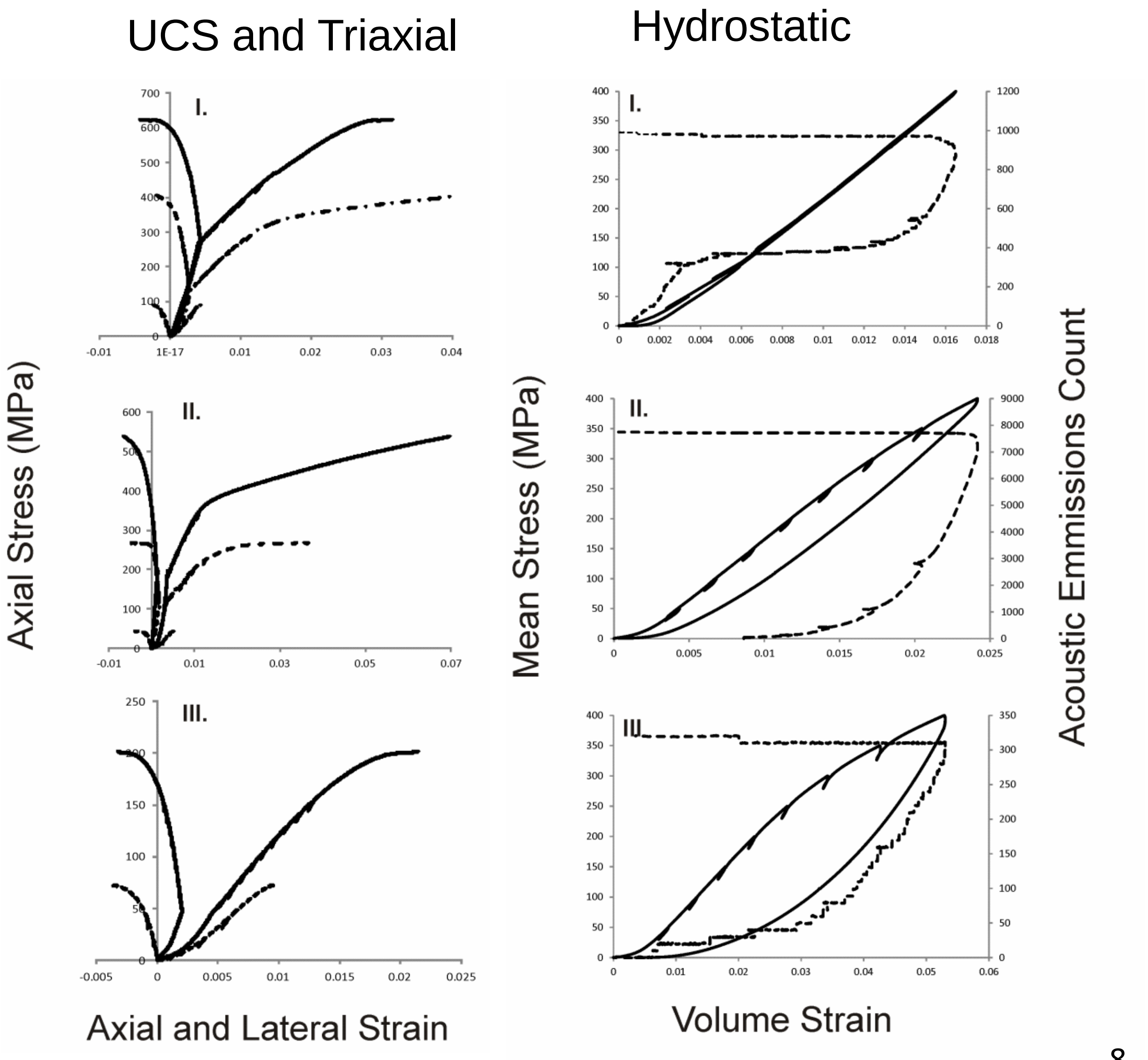
Microstructure and Cements of I, II, and III lithofacies

- I lithofacies (A) – fine grain size, well sorted, ubiquitous quartz cements
- II lithofacies (B,C,D,E) – poorly sorted, subarkosic, clay cement
- III lithofacies (F) – very fine to silty to mud grain size, abundant feldspar, clay and hematite cement



Axisymmetric Testing Results

- 1 hydrostat, 1 UCS, and 2 Triaxial Tests per facies
- 3.82 cm x 7.62 cm right cylinders with UV-cured polyurethane jackets
- Room T and nominally dry
- AE Counts on many of the tests
- Samples taken to failure at lower mean stresses
- One triaxial test for III lithofacies failed to record lateral strain data



Yield and Failure Envelopes

Failure envelope:

$$F_f(I_1) = a_1 - a_3 e^{-a_2 I_1} + a_4 I_1$$

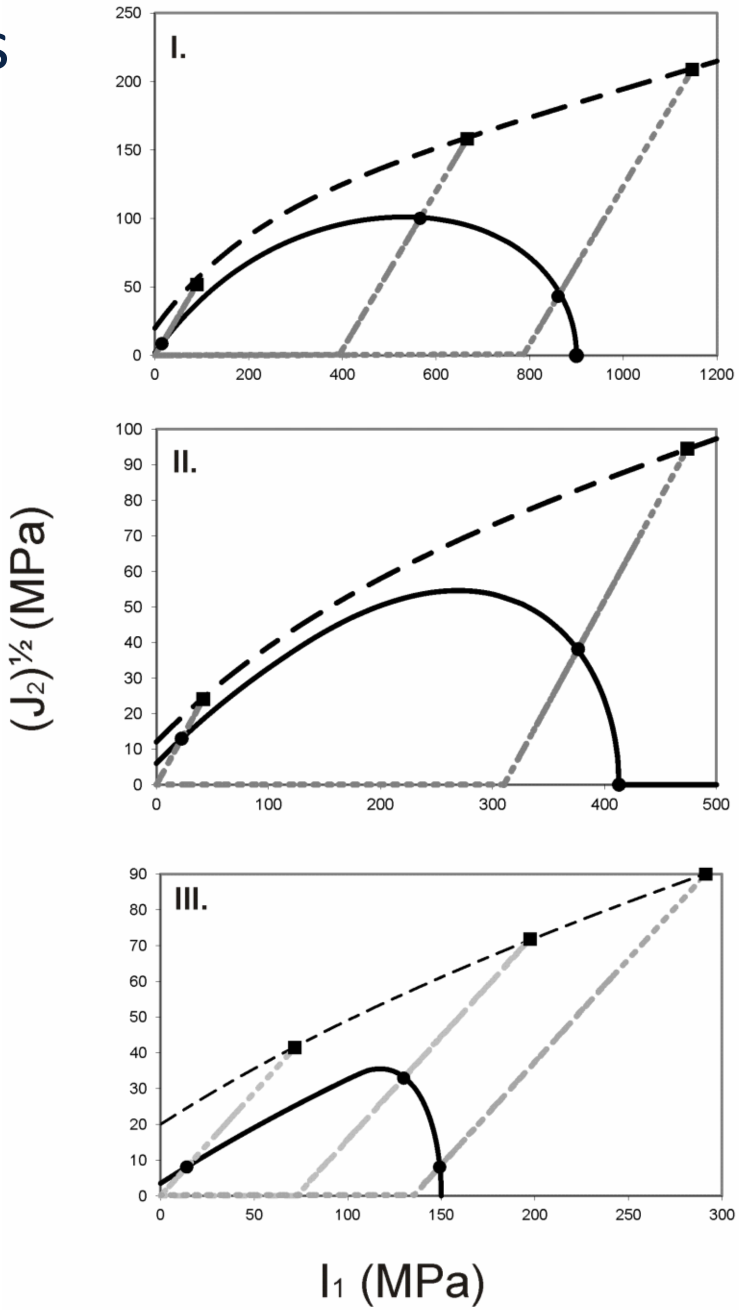
Yield Surface

$$\sqrt{J_2} = \frac{f_f(I_1) f_c(I_1)}{\Gamma(\theta)}$$

$$f_f(I_1) = F_f(I_1) - N$$

$$f_c^2(I_1, \kappa) = 1 - \frac{(I_1 - \kappa)(|I_1 - \kappa| + (I_1 - \kappa))}{2(X - \kappa)^2}$$

(After Brannon et al., 2009; Pelessone, 1989)



Nonlinear Elasticity and Elastic-Plastic Coupling

Secant and Tangent Moduli

Shear Modulus Stress Dependence

$$G = G_0(1 + G_1\tau + G_2\sigma)$$

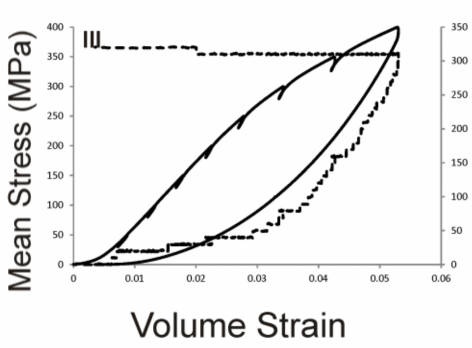
Bulk Modulus Stress Dependence

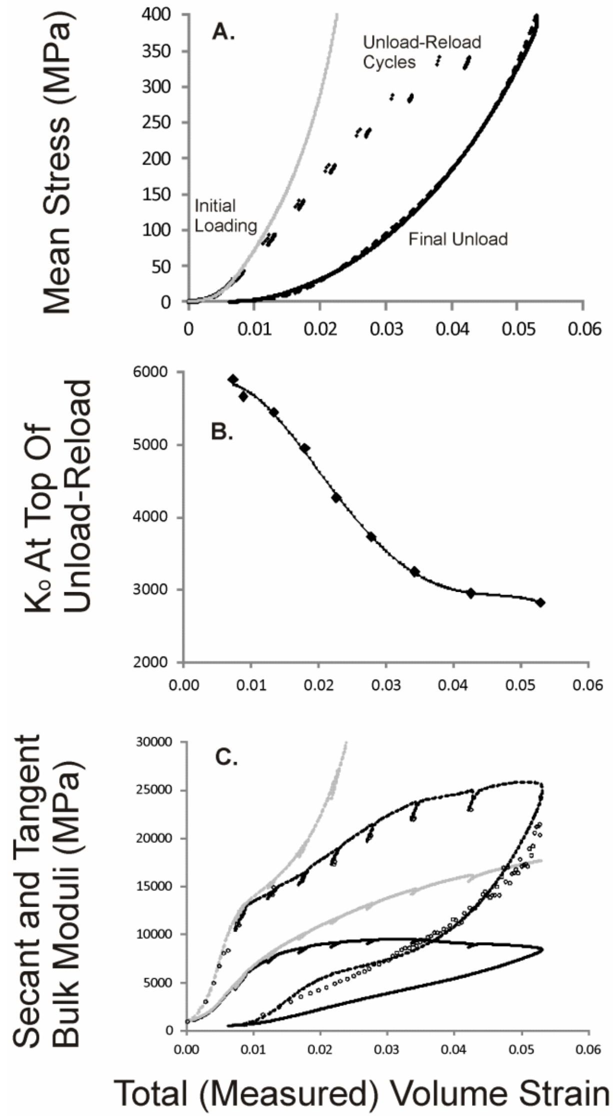
$$K = K_0\left(1 + K_1\sigma - K_2 e^{-K_3\sigma}\right)$$

Tangent Bulk Modulus

$$K_{\tan} = \left\{\frac{1}{K} - \frac{\sigma}{K^2}\left(K_0K_1 + K_0K_2K_3e^{-K_3\sigma}\right)\right\}^{-1}$$

Facies III Hydrostat





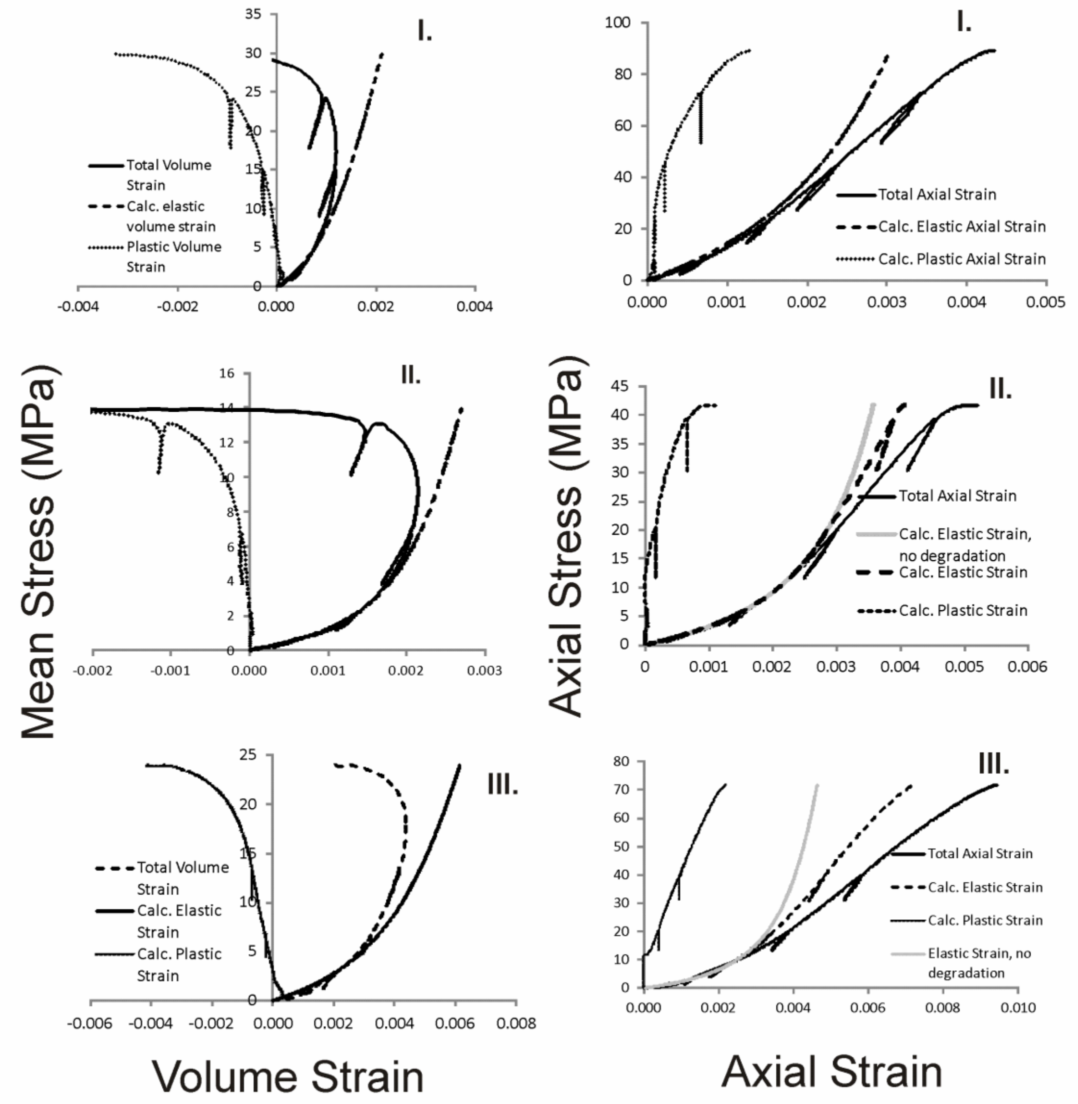
Evolution with Plastic Strain

$$K = K_0^{'}\left(1 - K_4 e^{-K_5/\varepsilon_p}\right)(1 + K_1\sigma - K_2 e^{-K_3\sigma})$$

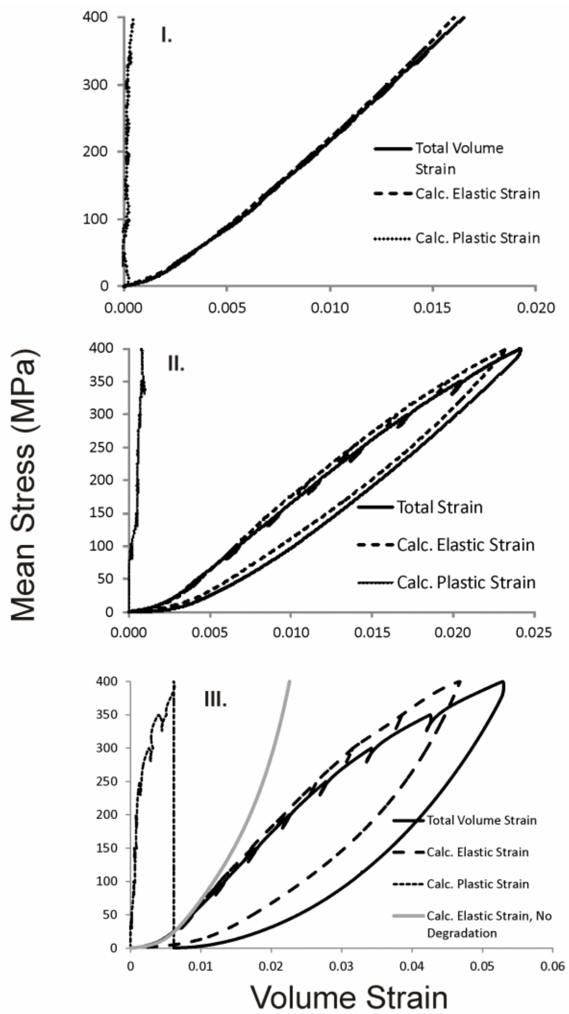
$$G = G_0^{'}(1 - G_3 e^{-G_4/\gamma_p})(1 + G_1\tau + G_2\sigma)$$

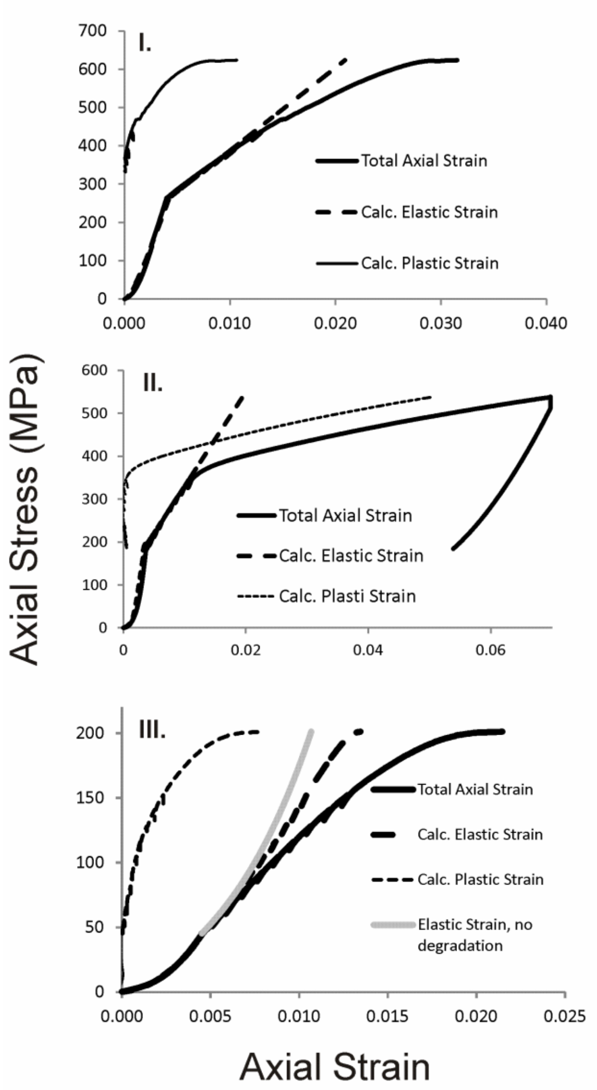
Strain Partitioning, UCS Tests

- Determine Stress- and Plastic Strain Dependence of Elastic Moduli
- Calculate Elastic Strains
- Determine Plastic Strains By Difference
- Elastic-Plastic Coupling (compare dark dashed lines with grey lines) accounts for bulk of total volume strain post-yielding



Strain Partitioning; Hydro and Triaxial





Elastic-Plastic Constitutive Modeling

Kayenta Includes:

•Non-Associative Plasticity

•Stress Invariant Dep. Failure

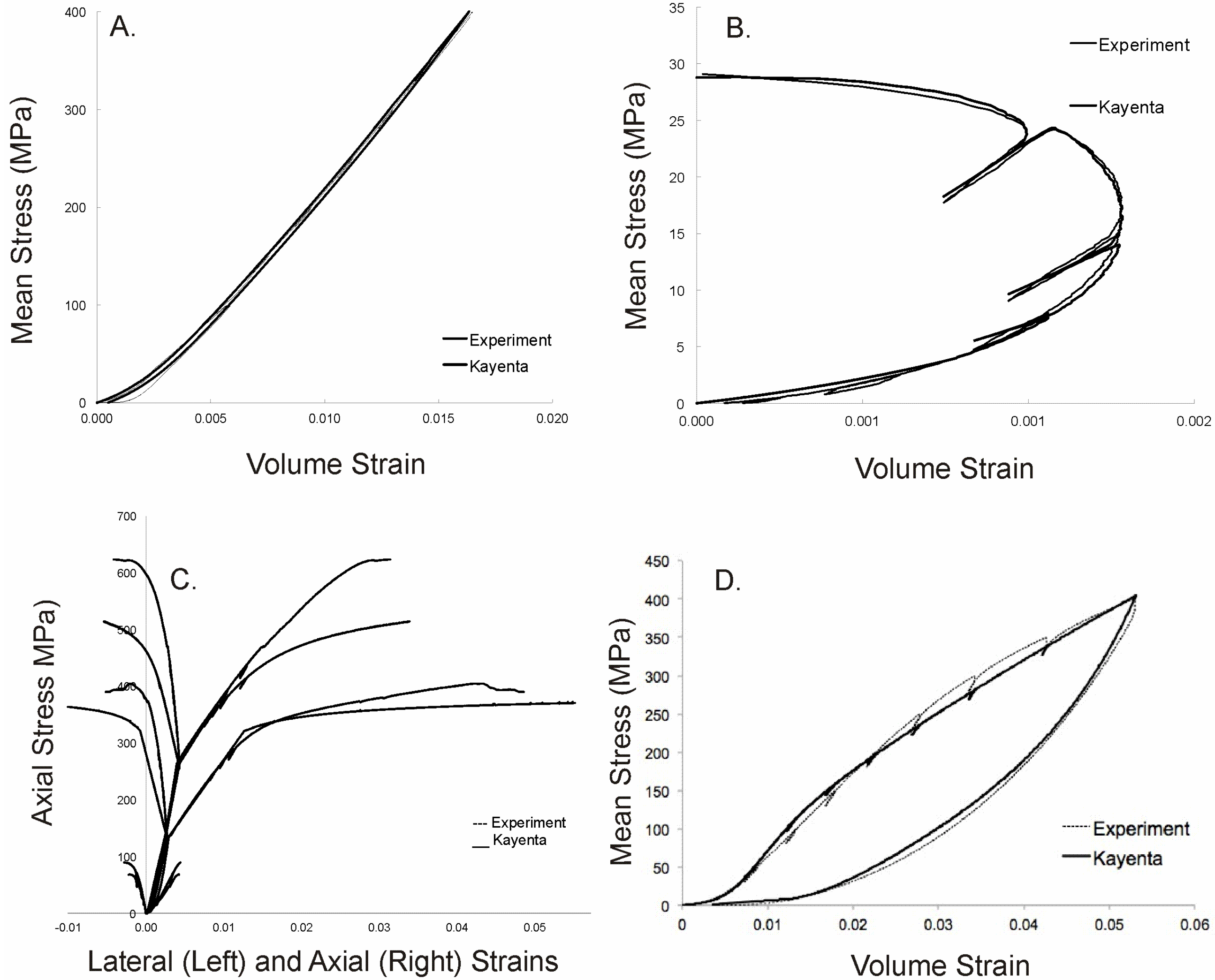
•Elliptical Cap Surface

•Kinematic Hardening

•Isotropic Hardening

•Nonlinear Elasticity

•Elastic-Plastic Coupling



Developed by Brannon et al. 2009

Conclusions

- Facies I (equivant to main injection horizon in Illinois Basin) is largely elastic to 300 MPa
- Weaker facies II and III exhibit elastic-plastic coupling
- Big difference in in yielding and failure envelopes although porosities are similar. Strongest control is cement type.
- Kayenta constitutive model captures essential features of Mount Simon lithofacies elastic-plastic geomechanical behavior observed in experiments. It can be included in most FEM models.