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Compaction Localization, Elastic-Plastic Coupling, and Constitutive Modeling of Castlegate Sandstone Deformation

DOE Basic Research Relevant to Geological CO_2 Sequestration

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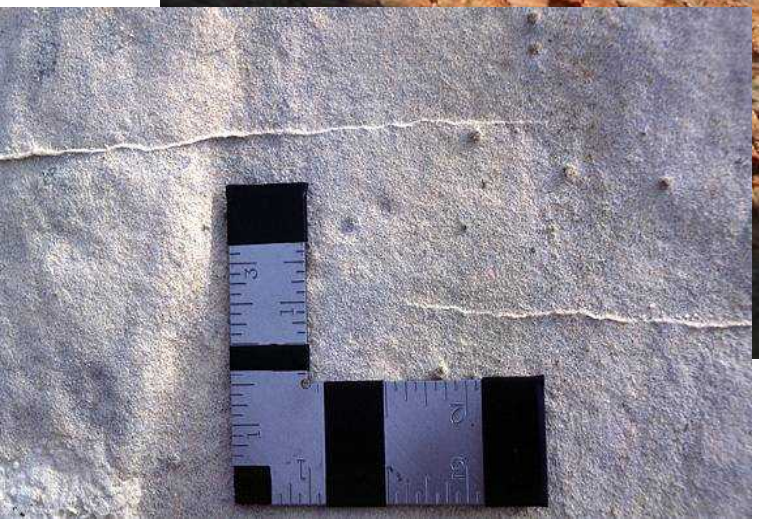
- *Overview*
- *Localization Theory*
- *Castlegate Ss Experimental Summary*
- *Determining Elastic and Plastic Strains*
- *Localization Predictions vs. Observations*
- *Modeling Castlegate Elasto-Plasticity*



Compaction Bands in Aztec Sandstone, from Sternlof et al., 2004

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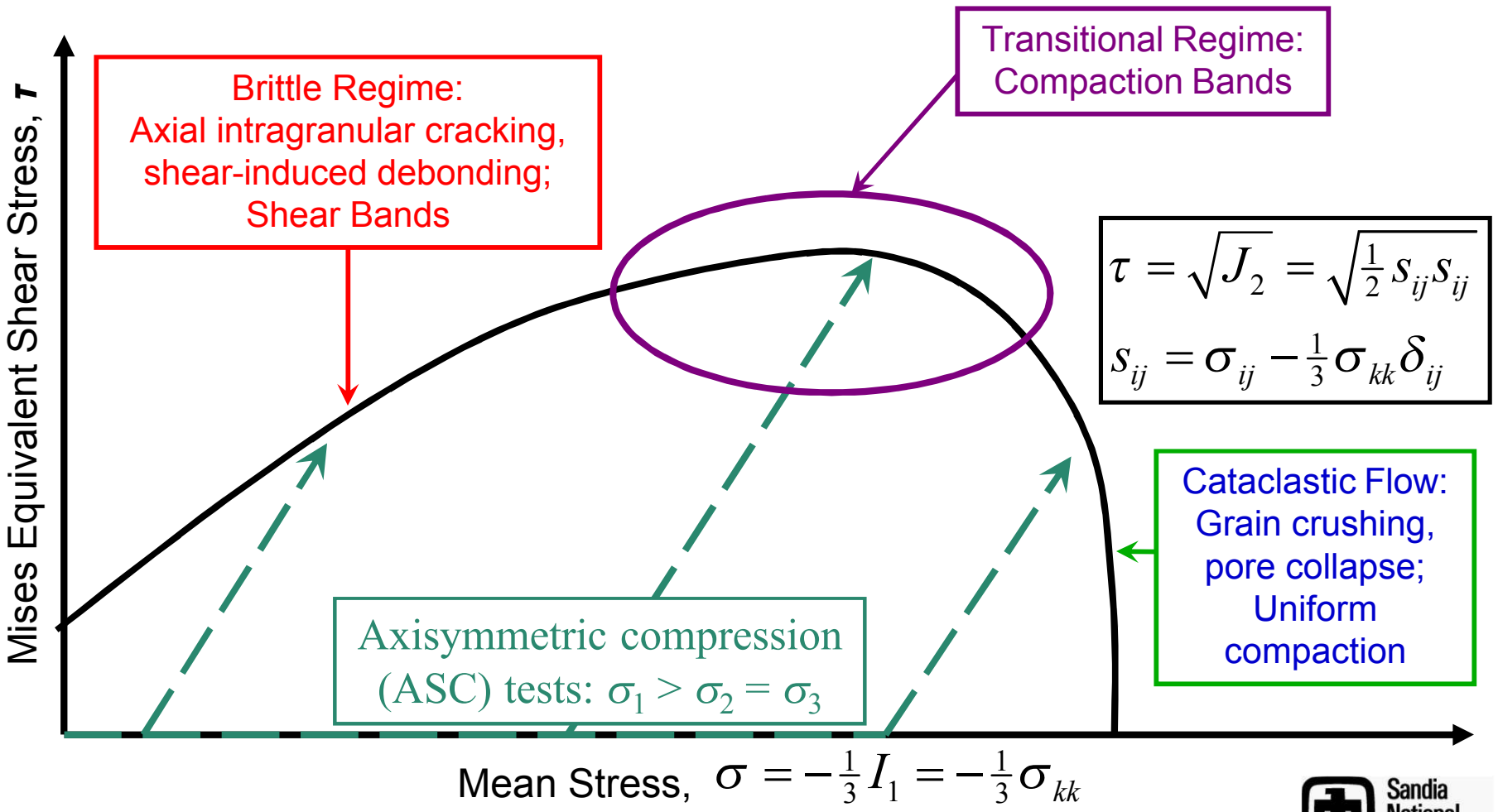
Microstructural Deformation & Failure Modes In Sandstones



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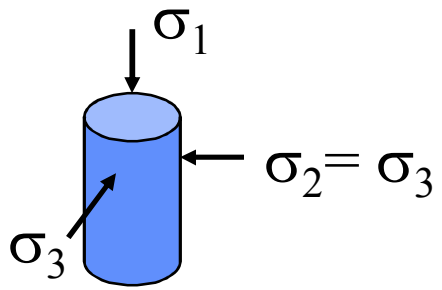
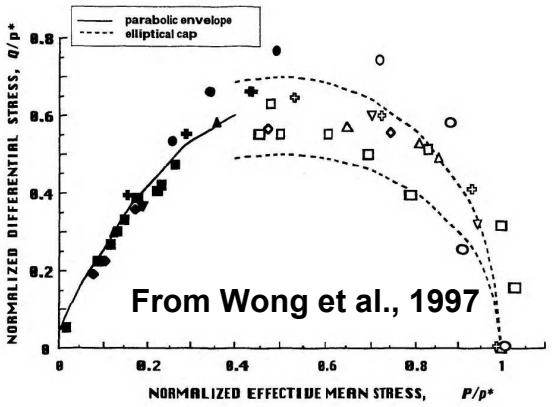
Overview of "Cap" Plasticity

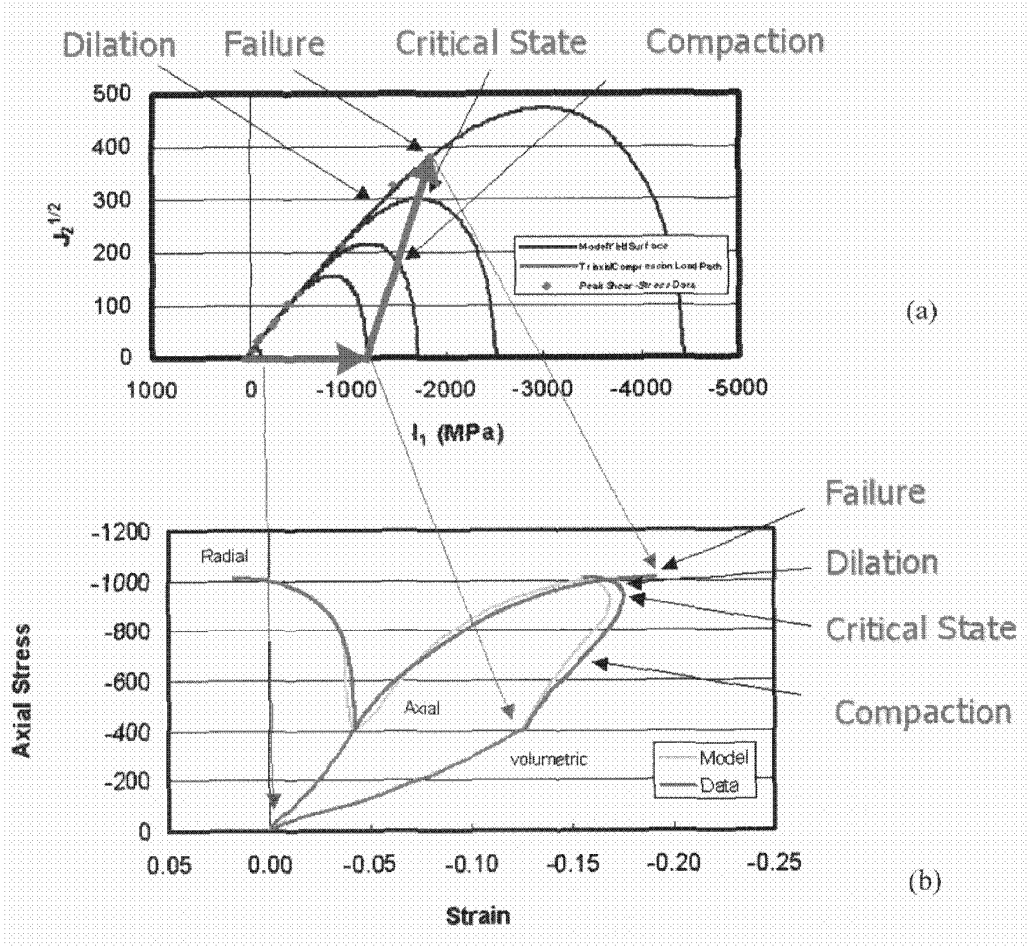
Axisymmetric Compression Tests

$$\sigma = I_1/3 = (\sigma_1 + 2\,\sigma_3)/3$$

$$\tau = J_2^{1/2} = (\sigma_1 - \sigma_3)/(3^{1/2})$$







From Fossum and Brannon, 2004

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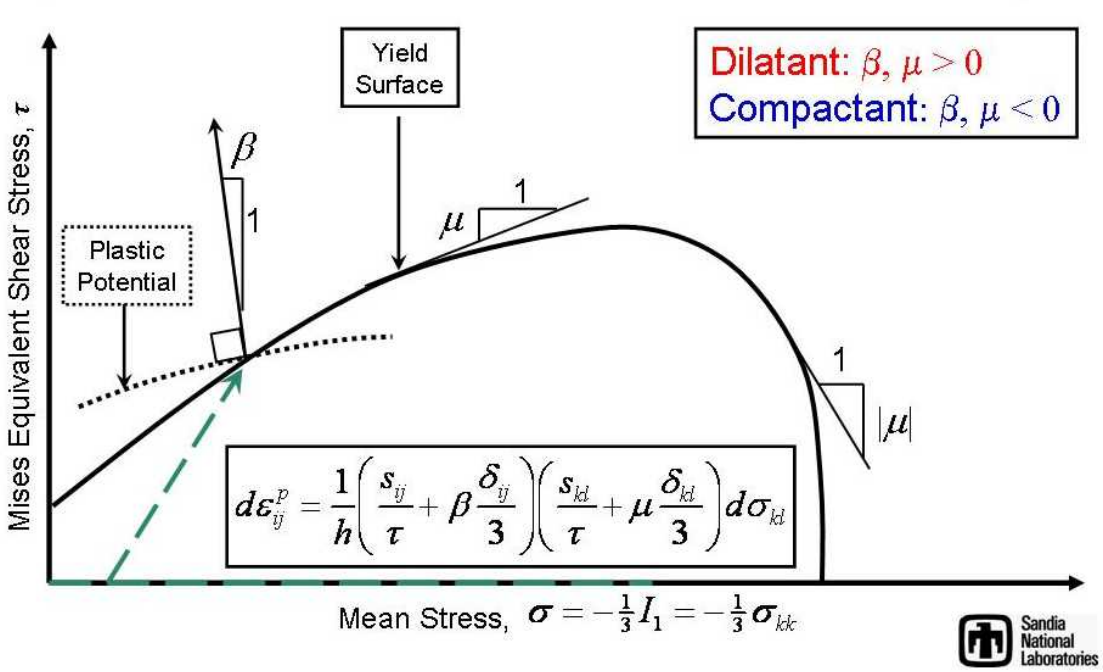
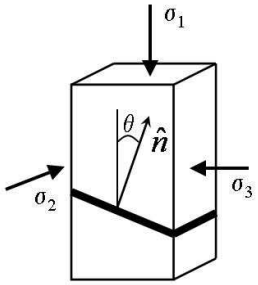
Localization Theory

- Derives from Rudnicki and Rice (1975) formulation
- Models formation of a planar band of localized strain
- Inception of band is bifurcation from homogeneous deform.
- Attributable to a constitutive instability
  - Single yield surface (depends on I_1 and J_2)
  - Non-associated flow





Predicts mode of occurrence and band angle, θ

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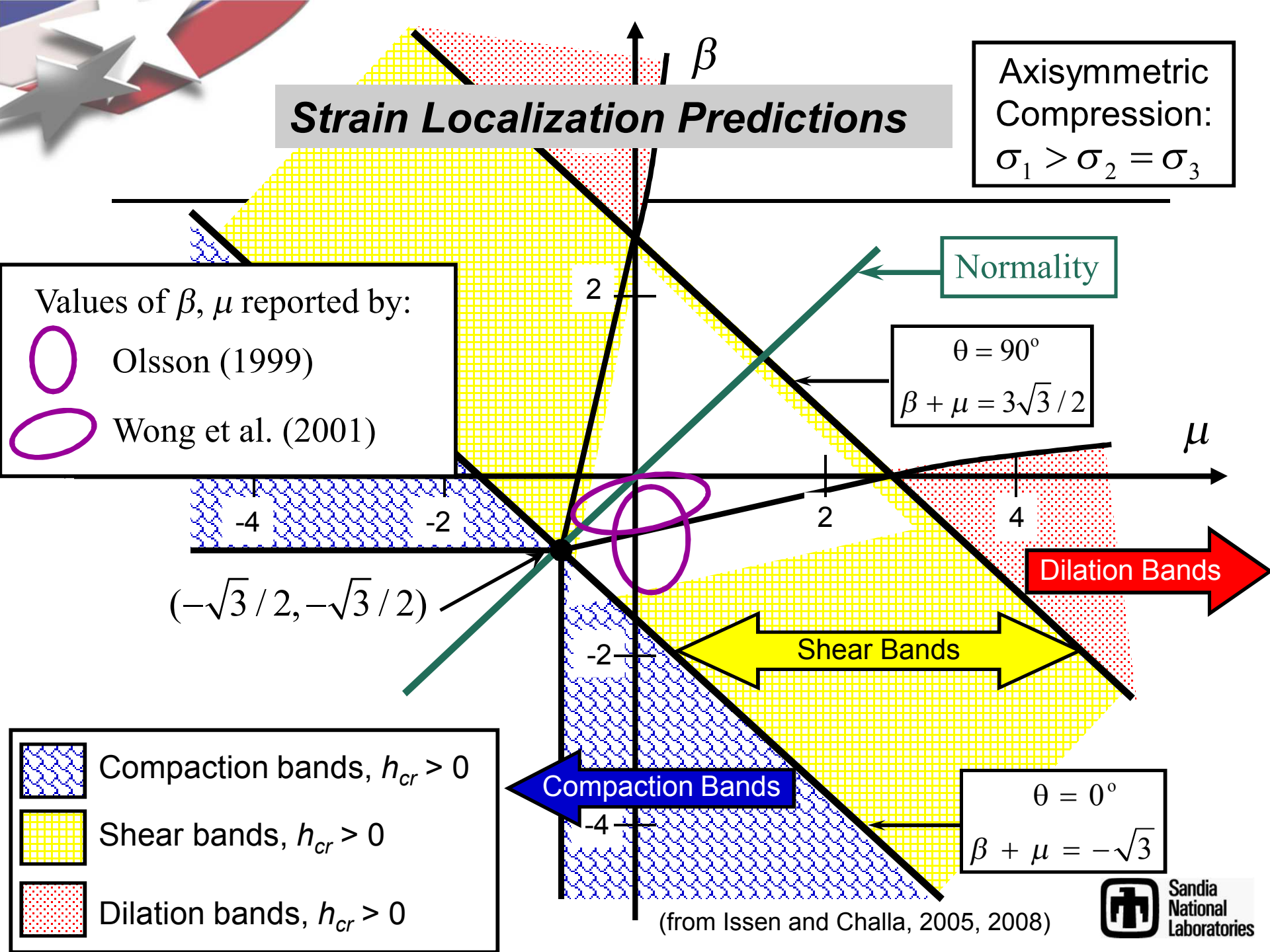
Strain Localization Predictions



(from Issen and Challa, 2005, 2008)

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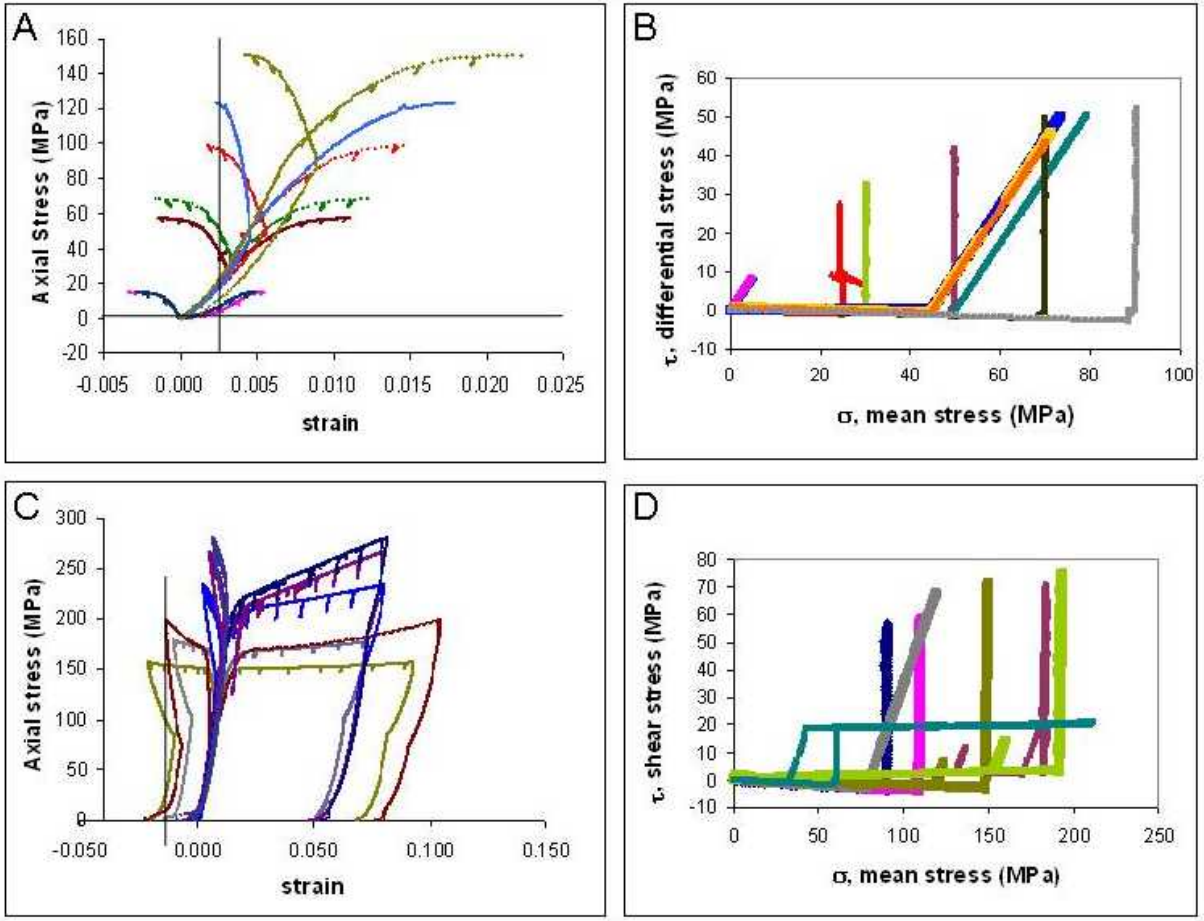
Castlegate Ss Experimental Summary

- Porosity ~ 28%
- Fine to medium grained (~0.2mm)
- 70-80% quartz
- Weakly lithified
- Studied previously

(Vinegar et al., 1991; Olsson and Holcomb, 2000; DiGiovanni et al., 2001; Holcomb and Olsson, 2003)



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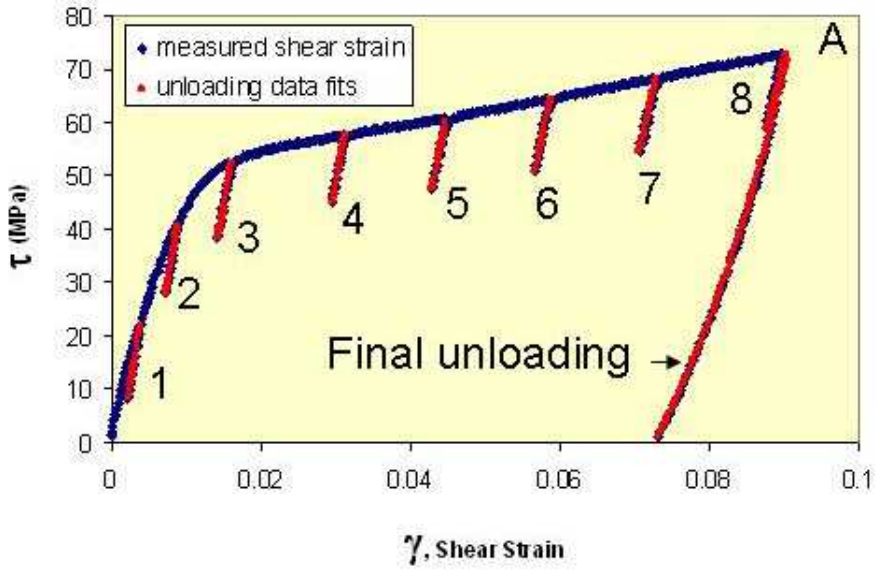
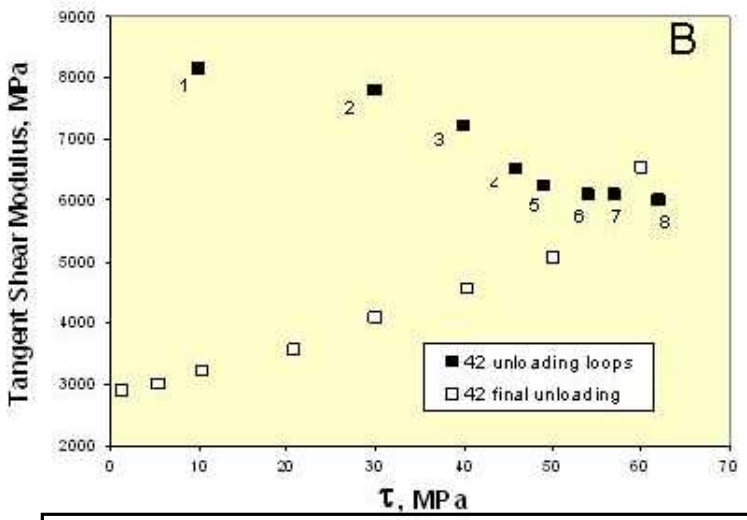
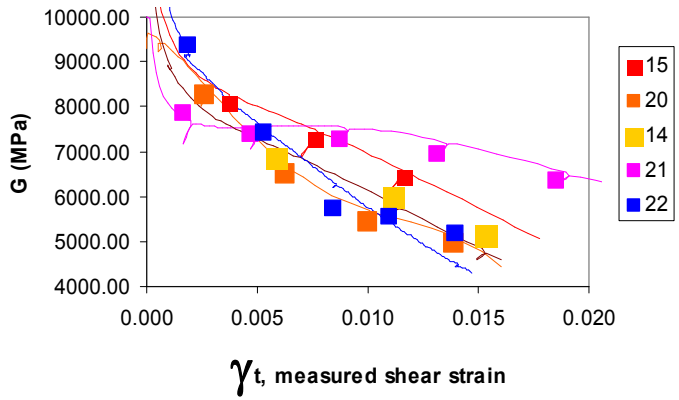
Elastic Moduli: Stress and Strain Dependence





- ***Shear modulus G is local slope of τ-γ curves for unloading loops and final unloading, at constant mean stress.***

- ***G decreases with γ_p at constant τ, and increases with τ at constant γ_p.***



Observed and modeled G degradation with total shear strain

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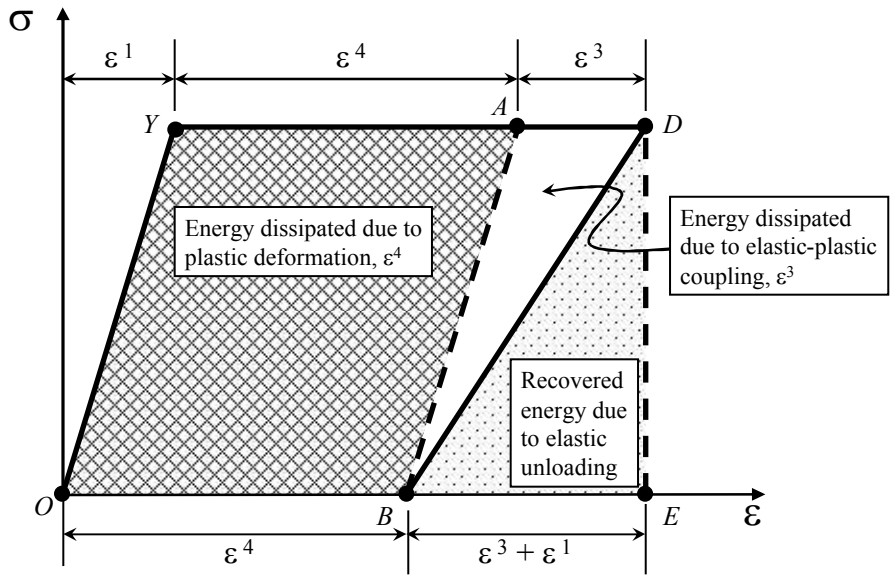
Incremental Strains and Elastic-Plastic Coupling



Schematic of uniaxial loading of an elastic-perfectly plastic material with elastic-plastic coupling (modulus decreases due to plastic strain). Elastic strain for the original modulus is ε^1, plastic strain is ε^4, and coupled strain is ε^3 (ε^2 is ignored here for simplicity).

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^1_{ij} + \dot{\varepsilon}^2_{ij} + \dot{\varepsilon}^3_{ij} + \dot{\varepsilon}^4_{ij}$$

$$\dot{\varepsilon}^1_{ij} = C_{ijkl}\dot{\sigma}_{kl}$$

$$\dot{\varepsilon}^2_{ij} = \frac{\partial C_{ijkl}}{\partial \sigma_{mn}}\sigma_{kl}\dot{\sigma}_{mn}$$

$$\dot{\varepsilon}^3_{ij} = \frac{\partial C_{ijkl}}{\partial \varepsilon^p_{mn}}\sigma_{kl}\dot{\varepsilon}^p_{mn}$$

$$\dot{\varepsilon}^4_{ij} = \dot{\varepsilon}^p_{ij} \text{ (plastic strain)}$$

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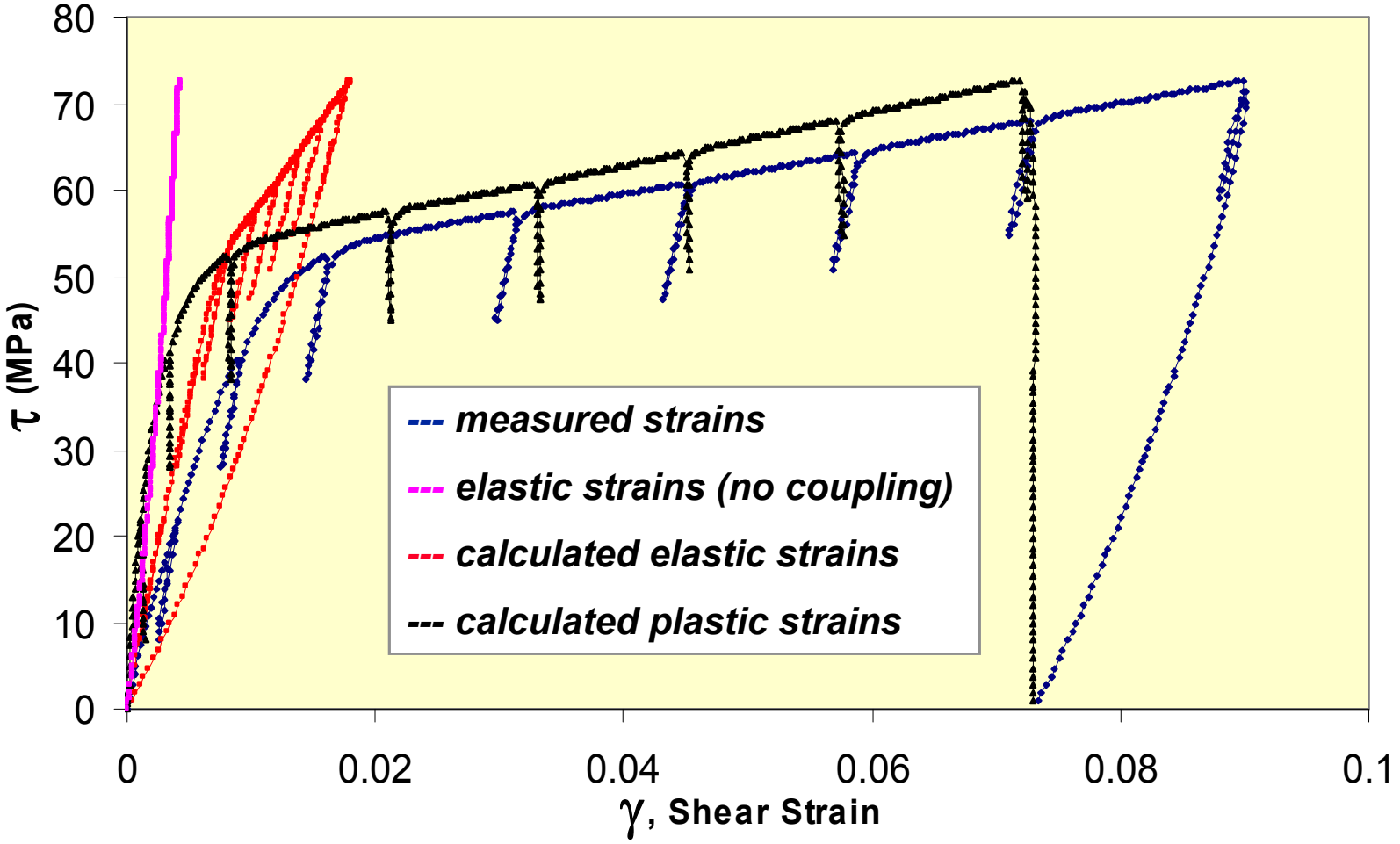
Partitioning Strain into Elastic and Plastic Portions



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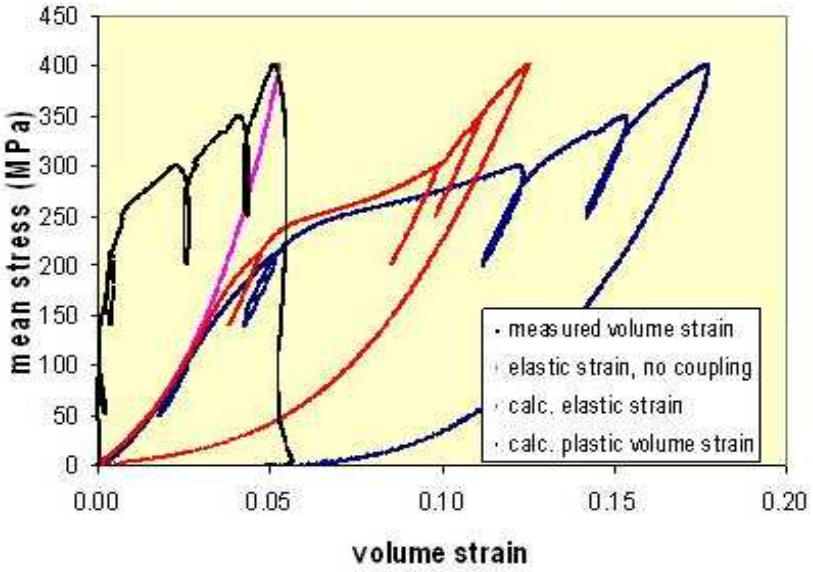
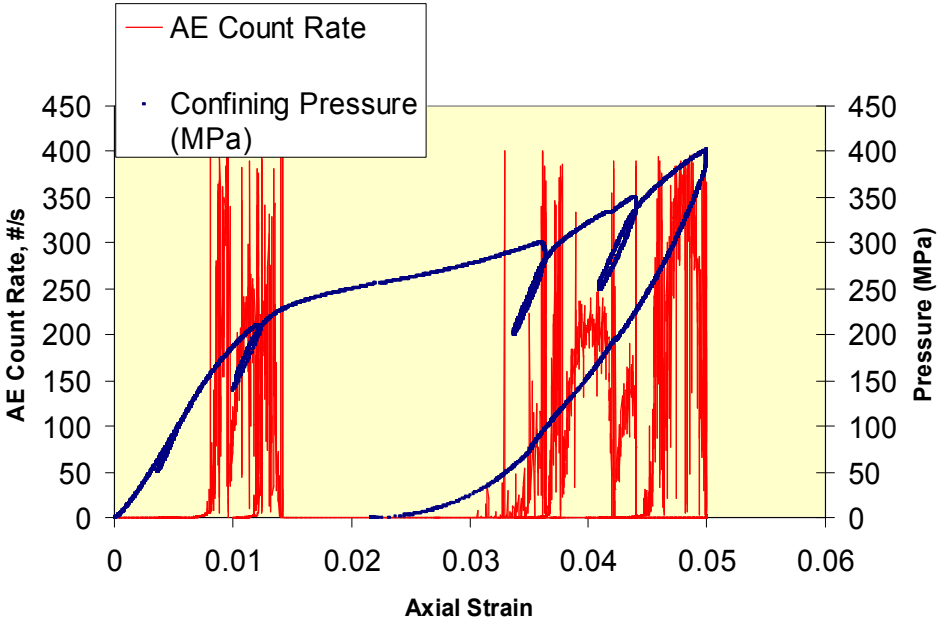
Strain Partitioning During Hydrostatic Compression



Nearly a third of total volume strain is attributable to elastic-plastic coupling in this experiment

This is due to influence of microcracks (formation of which is observable by acoustic emissions, AE) on elastic bulk modulus



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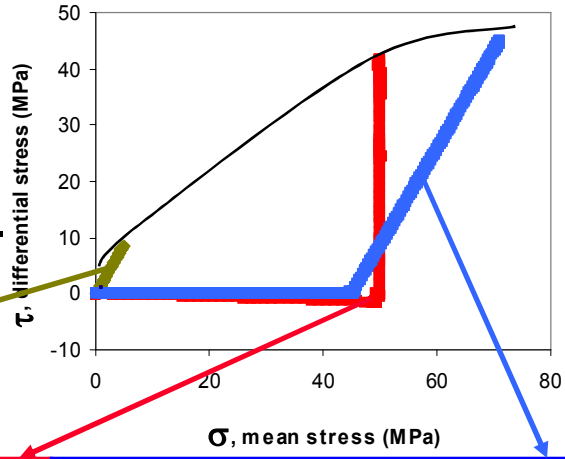
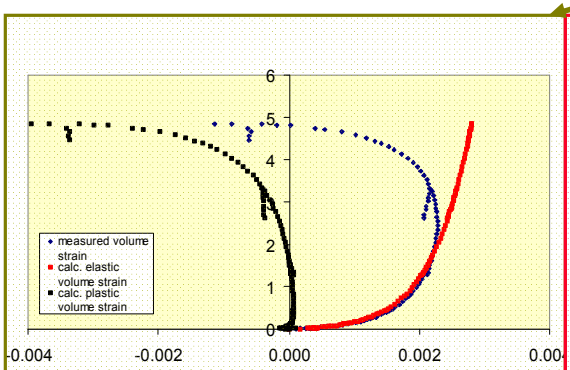
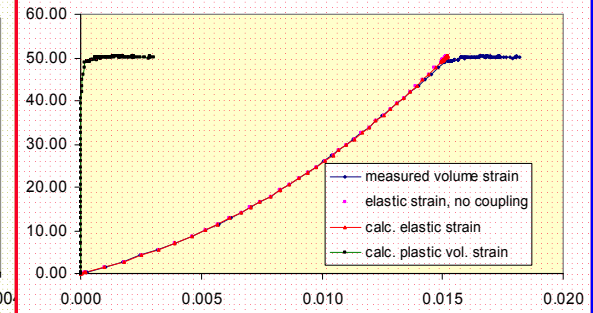
More Examples

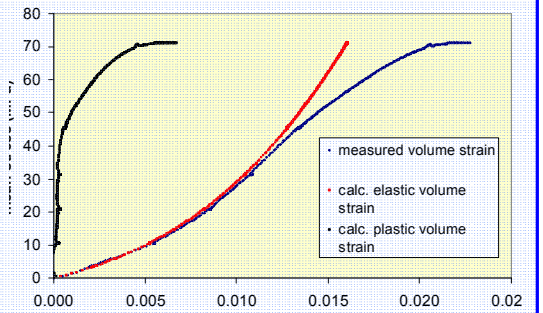


σ (MPa)

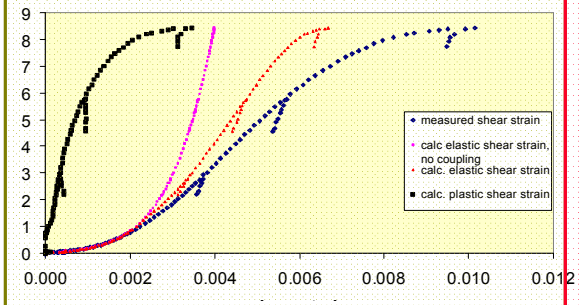
τ (MPa)

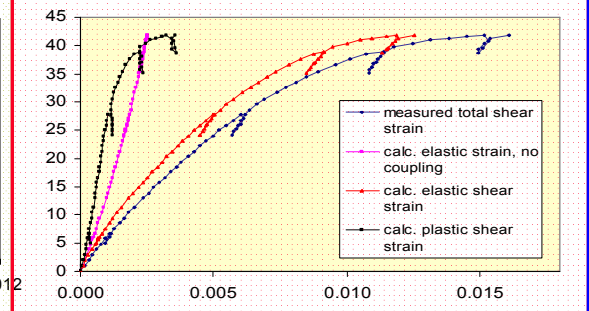


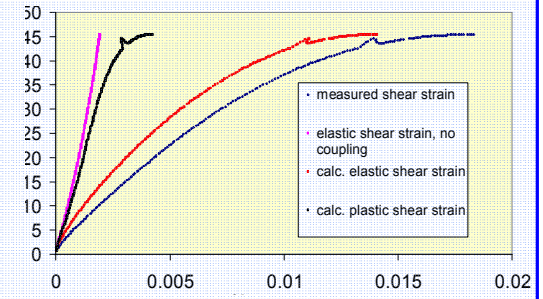




Volume Strain







Shear Strain

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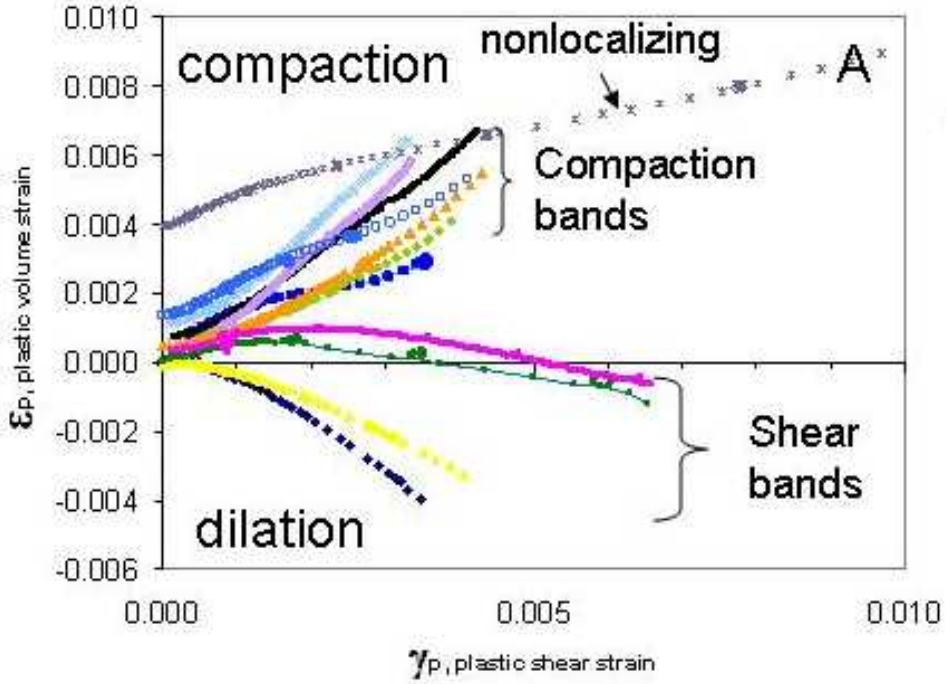
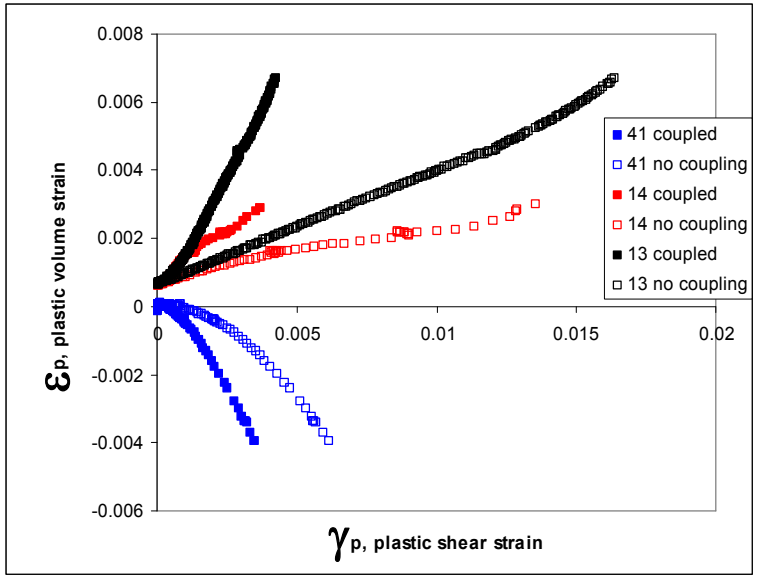
β calculation





β's are slopes of strain paths. Ignoring coupling over-estimates plastic shear strain and underestimates β

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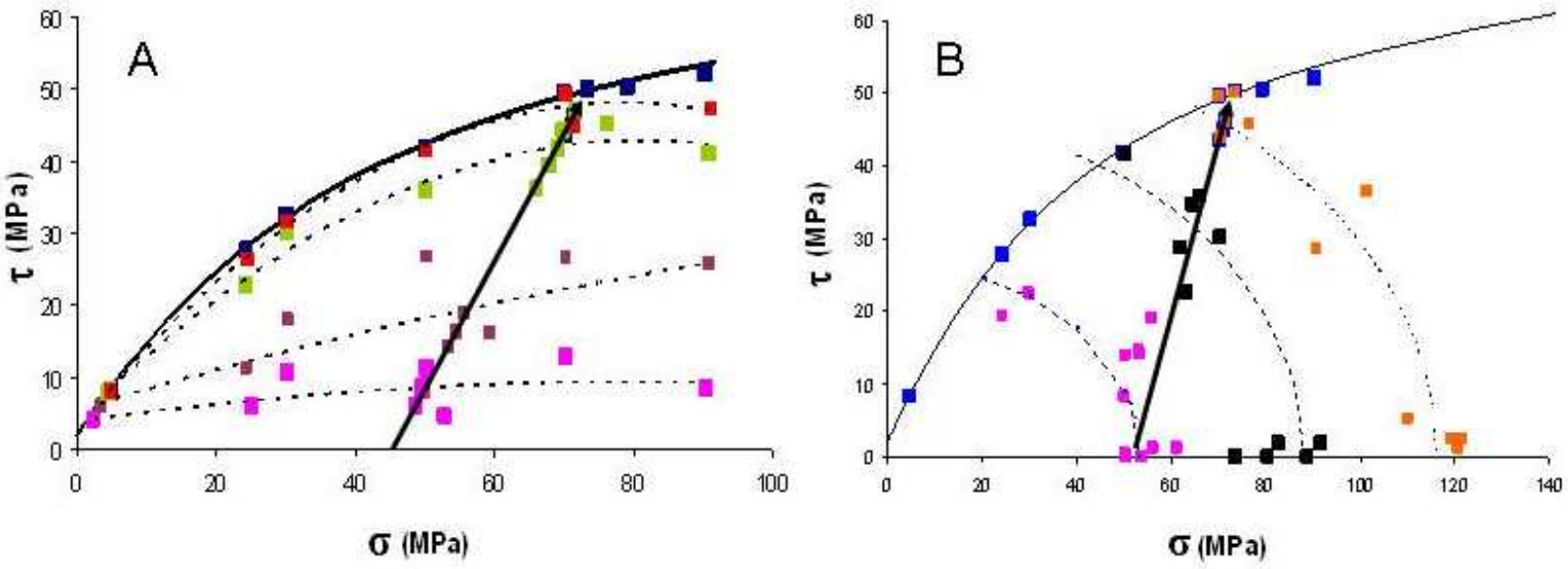
μ calculation



μ is slope of yield surface, here taken to be contour or constant plastic shear strain (A) or contour of constant plastic volume strain (B)

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Localization Parameters and Band Angles for Castlegate

Elastic-Plastic Coupling

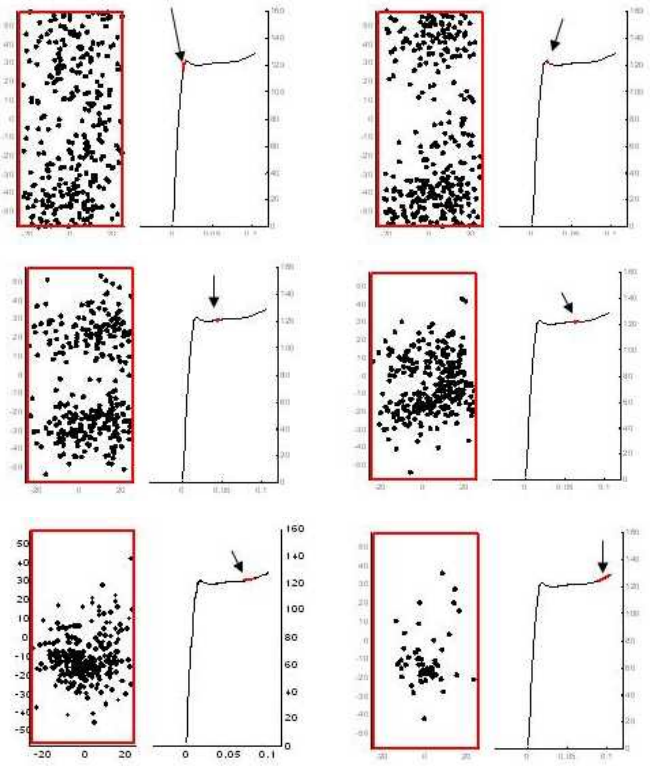
exper.	β	μ	ν	G	h_{cr}	θ
41*	1.10	0.91	0.24	4815	-4823	69.0
14*	-0.74	0.42	0.18	4597	389	34.4
13b#	-2.17	-0.36	0.29	4424	2360	0.0

No coupling

41*	1.15	1.02	0.12	8058	-7626	66.6
14*	-0.26	0.42	0.14	8918	-1397	40.1
13b*	-0.73	0.21	0.15	9263	353	31.3
13b#	-0.73	-0.36	0.15	9263	-396	22.2

*μ and h_{cr} calculated assuming shear yield surface
#μ and h_{cr} calculated assuming cap yield surface

θ is in degrees, G and h_{cr} in MPa



In situ band orientation determination by AE locations (exper. 13)

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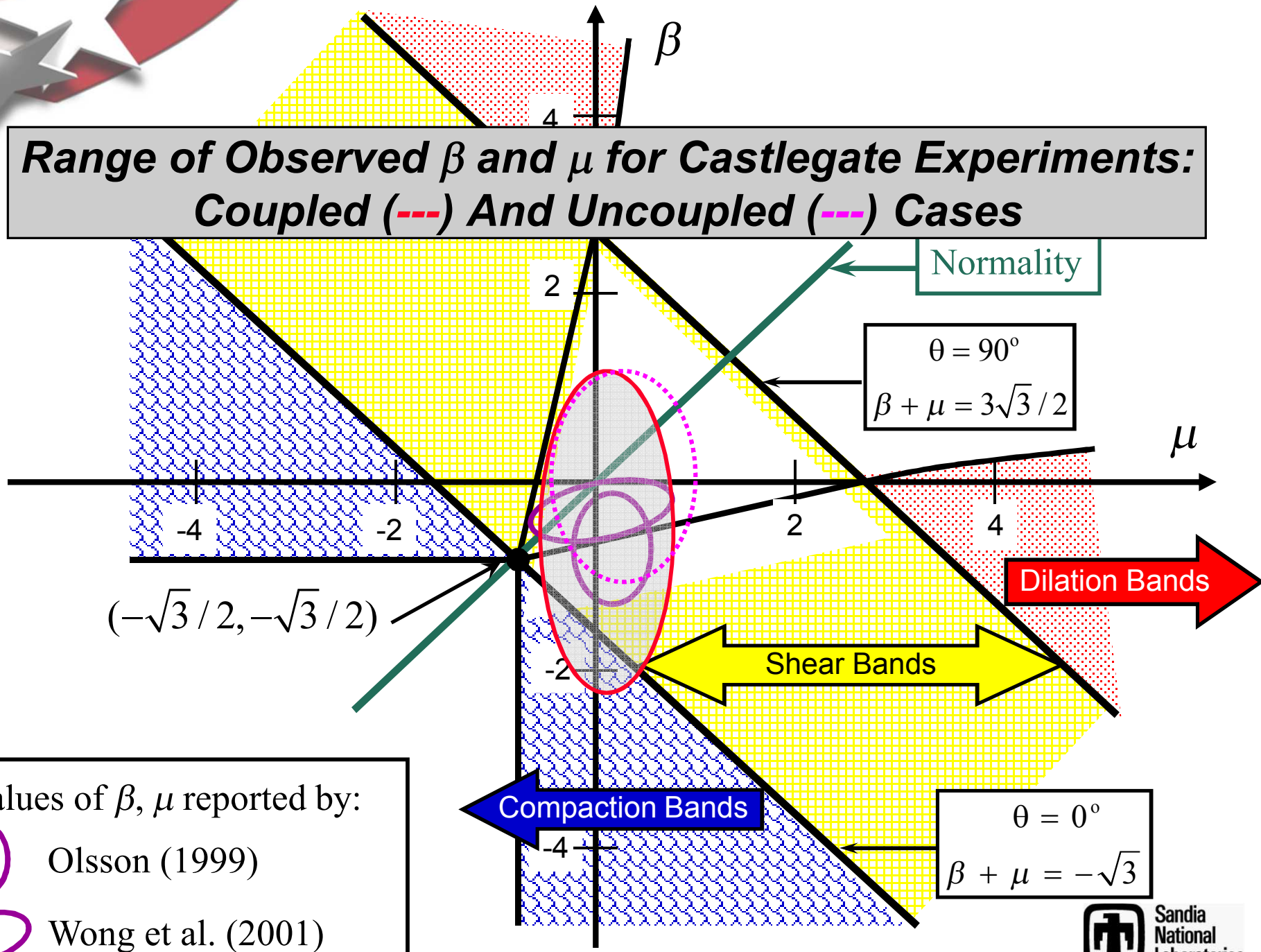
Range of Observed β and μ for Castlegate Experiments: Coupled (---) And Uncoupled (---) Cases



Values of β, μ reported by:

Olsson (1999)

Wong et al. (2001)

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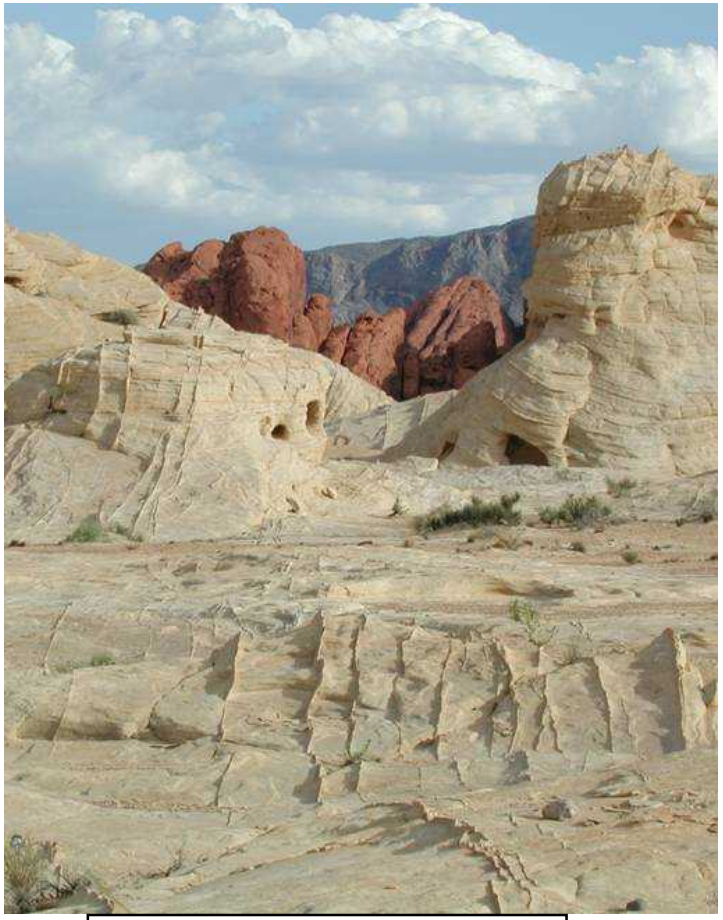
Conclusions



Sternlof et al., 2004

- **Observed degradation of elastic moduli with plastic deformation**
- **Elastic-plastic coupling influences localization predictions**
- **First time localization theory has successfully predicted occurrence of compaction localization in experiments, using experimentally determined constitutive parameters.**

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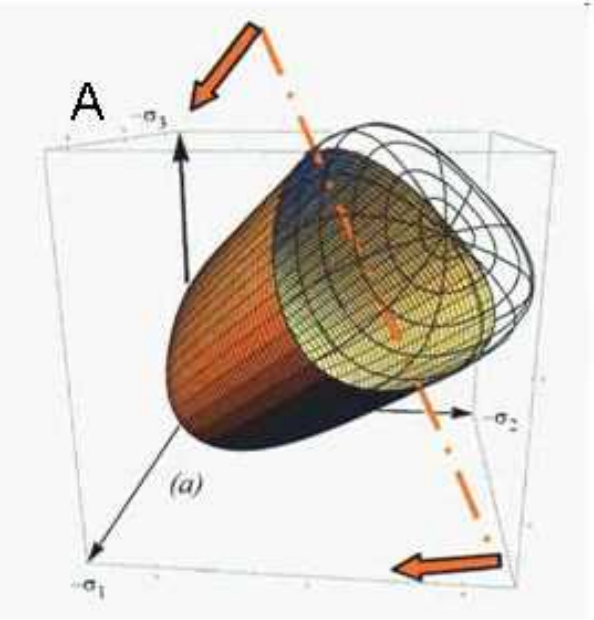
Sandia Geomodel

- **Elastic parameters (tangent moduli)**
- **Hydrostatic Pore Collapse**
- **Limiting Shear Surface (incl. kinematic hardening)**
- **Cap Curvature**
- **Non-associative plastic flow**



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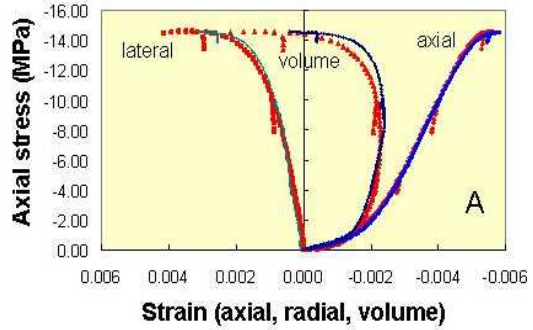
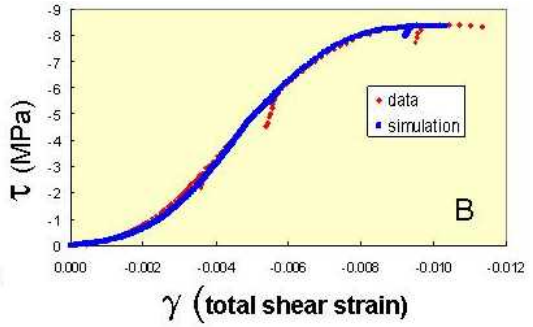
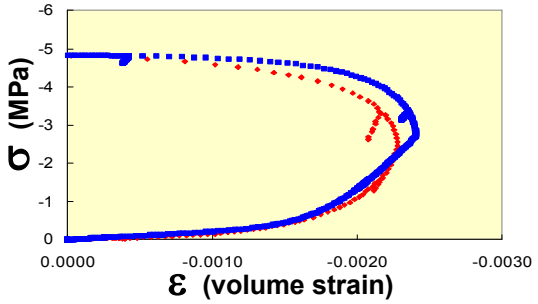
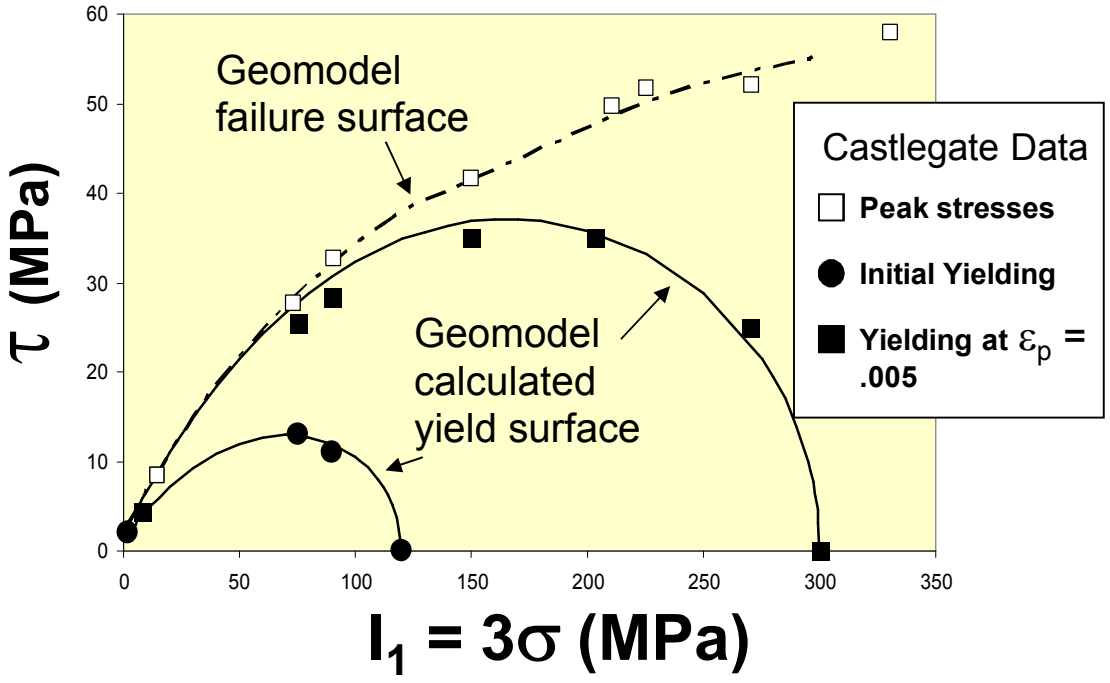
Geomodel Simulations of Castlegate Experiments







Yield and Failure Surfaces



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