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Development of Constitutive Parameters from True Triaxial Tests Performed on Castlegate Sandstone

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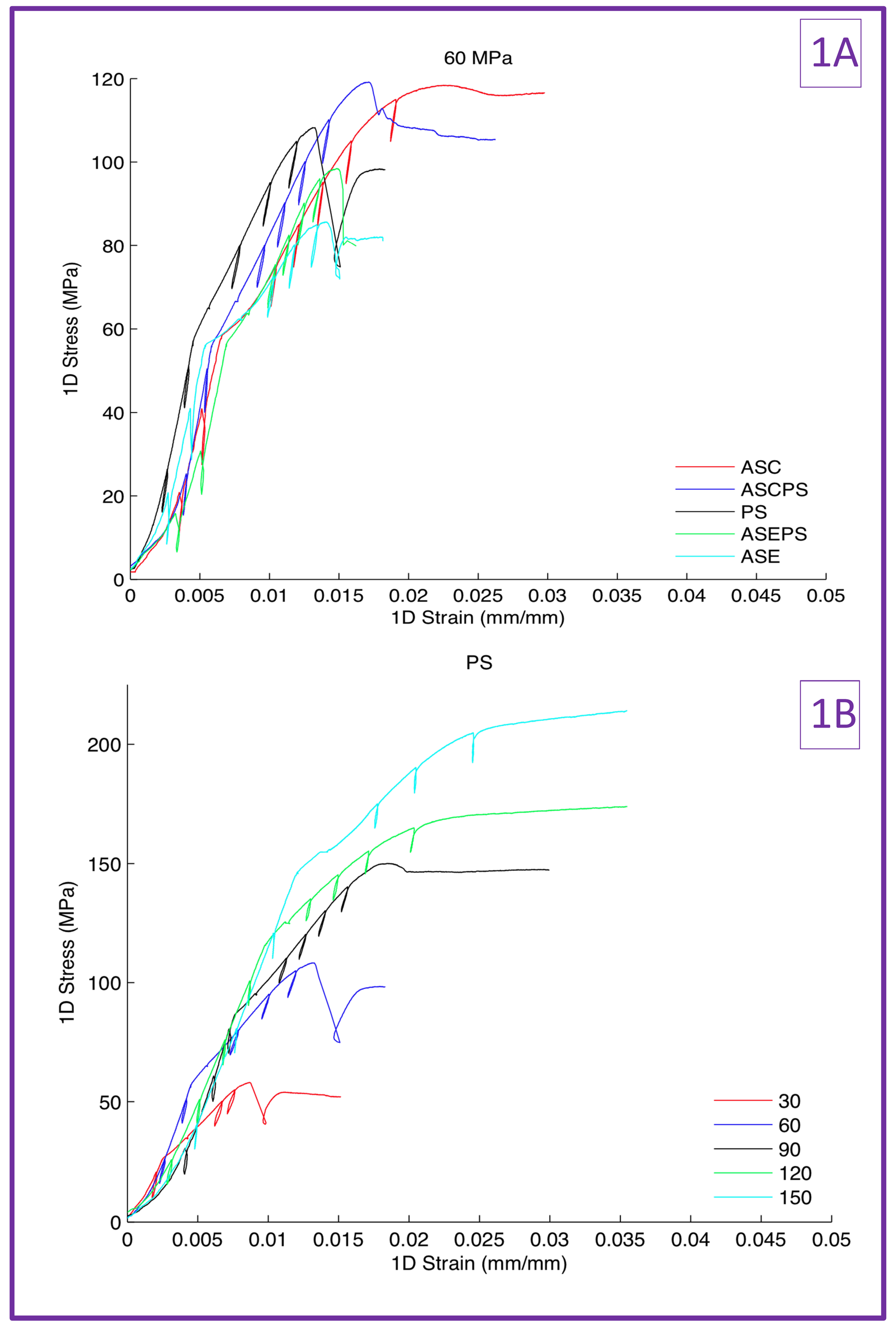


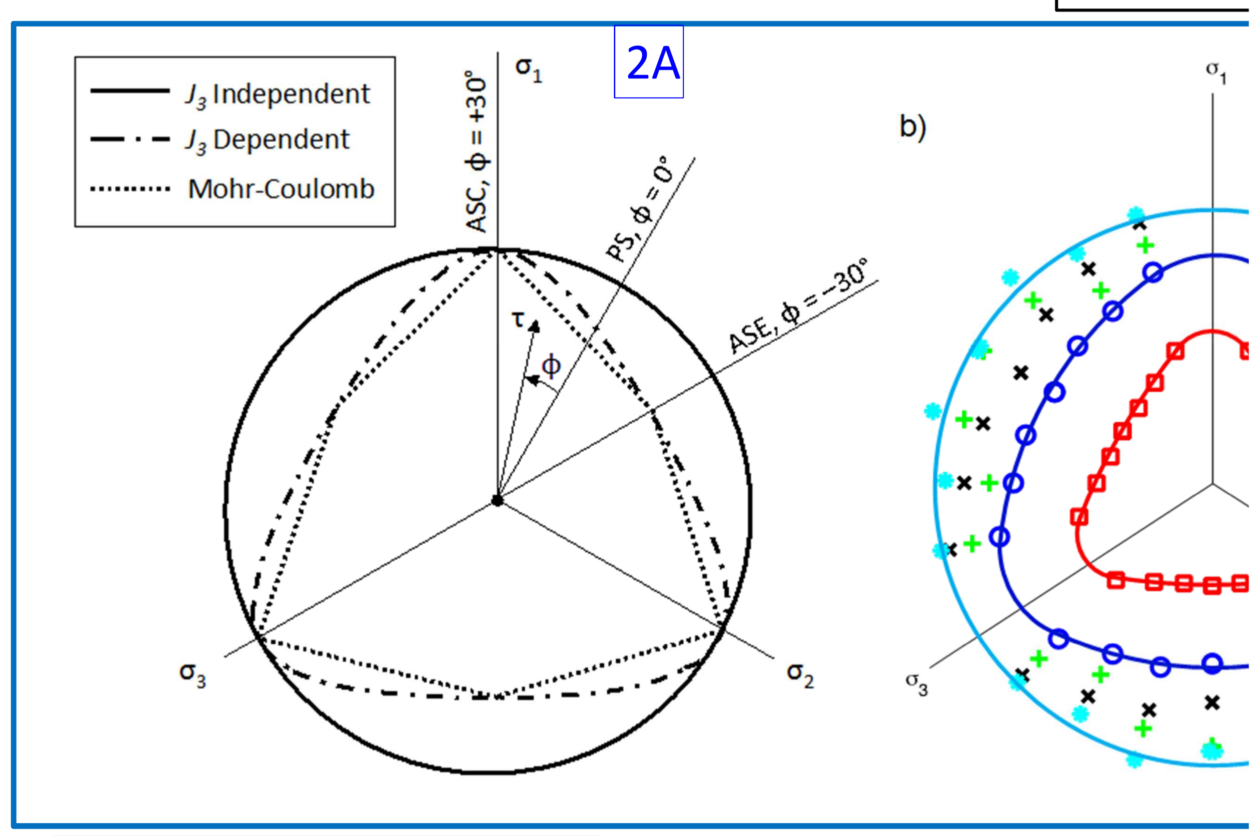
Experimental Methods:

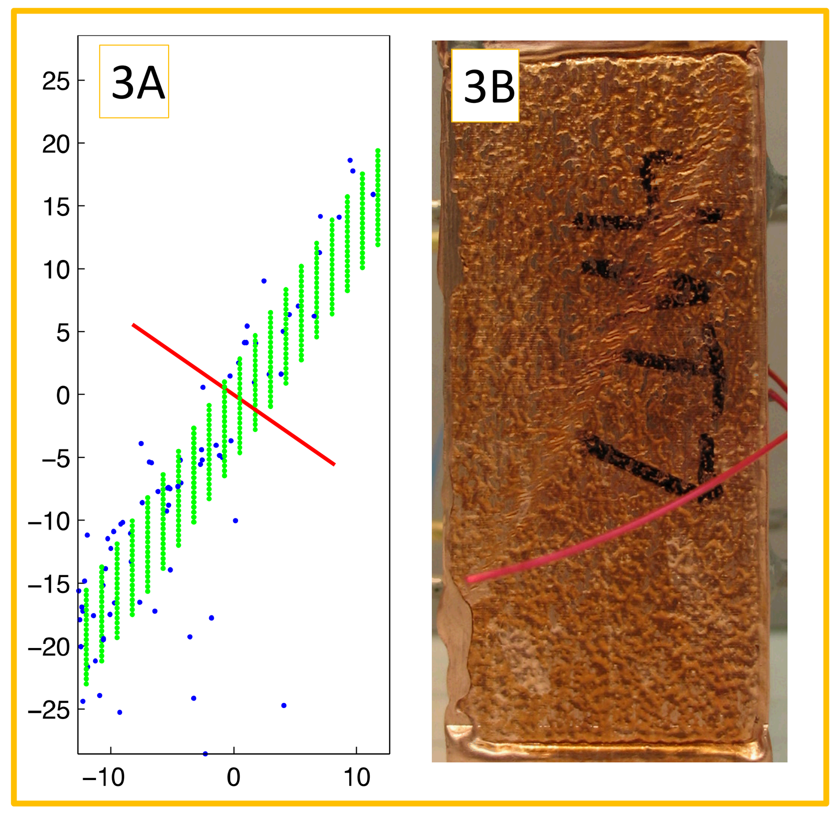
Conducted true triaxial tests to investigate influence of σ_2 on failure

- Used smaller true triaxial apparatus at Sandia (Wawersik et al. 1997)
- Performed tests at constant mean stress, σ, and constant Lode angle, ϕ.
  - Mean stresses: 30, 60, 90, 120, and 150 MPa
    - Assessed J_3 dependence of failure
    - Enabled extraction of bulk and shear moduli from unload loops
  - Lode angles: 30° (ASC), 14.5°, 0°(PS), -14.5°, -30°(ASE)
    - Ranged from axisymmetric compression (ASC) to axisymmetric extension (ASE); determines the stress path in the Pi plane
    - Constant Lode angle, ϕ, is equivalent to constant N_{II}
- Evaluated strain localization predictions (Rudnicki & Rice 1975)
- Recorded acoustic emissions (AE); located AE within specimen
  - Plane fit through AE to locate band spatially and temporally (Fig. 3)
  - Onset of localization corresponds to drop in fitting error
  - AE band angle, θ, agrees with angle measured on jacket (Table 1)

Bulk Specimen Response:

- Typical mechanical responses (σ_1 vs. ε_1) are shown in Fig. 1 :
  - 60 MPa constant mean stress tests at five Lode angles (Fig. 1A)
  - 0° (PS) Lode angle tests at five mean stresses (Fig. 1B)
- Mean stress dependence (Fig. 1B):
  - Low mean stress: stress peak and drop; shear band forms
  - High mean stress: stress plateau; compaction band or no band
- Lode angle dependence (Fig 1A): moving from ASC to ASE:
  - Sharper stress peak
  - Lower stress required to initiate failure
- Failure depends on σ_2 (see Fig. 2; octahedral plane)
  - Low mean stress: failure surface is a rounded triangle
  - High mean stress: failure surface is circle
  - Failure depends on third invariant of deviatoric stress, $J_3 = \sigma'_1\sigma'_2\sigma'_3$





Localization Conditions:

Predicted band angle, θ, Rudnicki & Rice (1975) (see Eqn. 4) depends on:

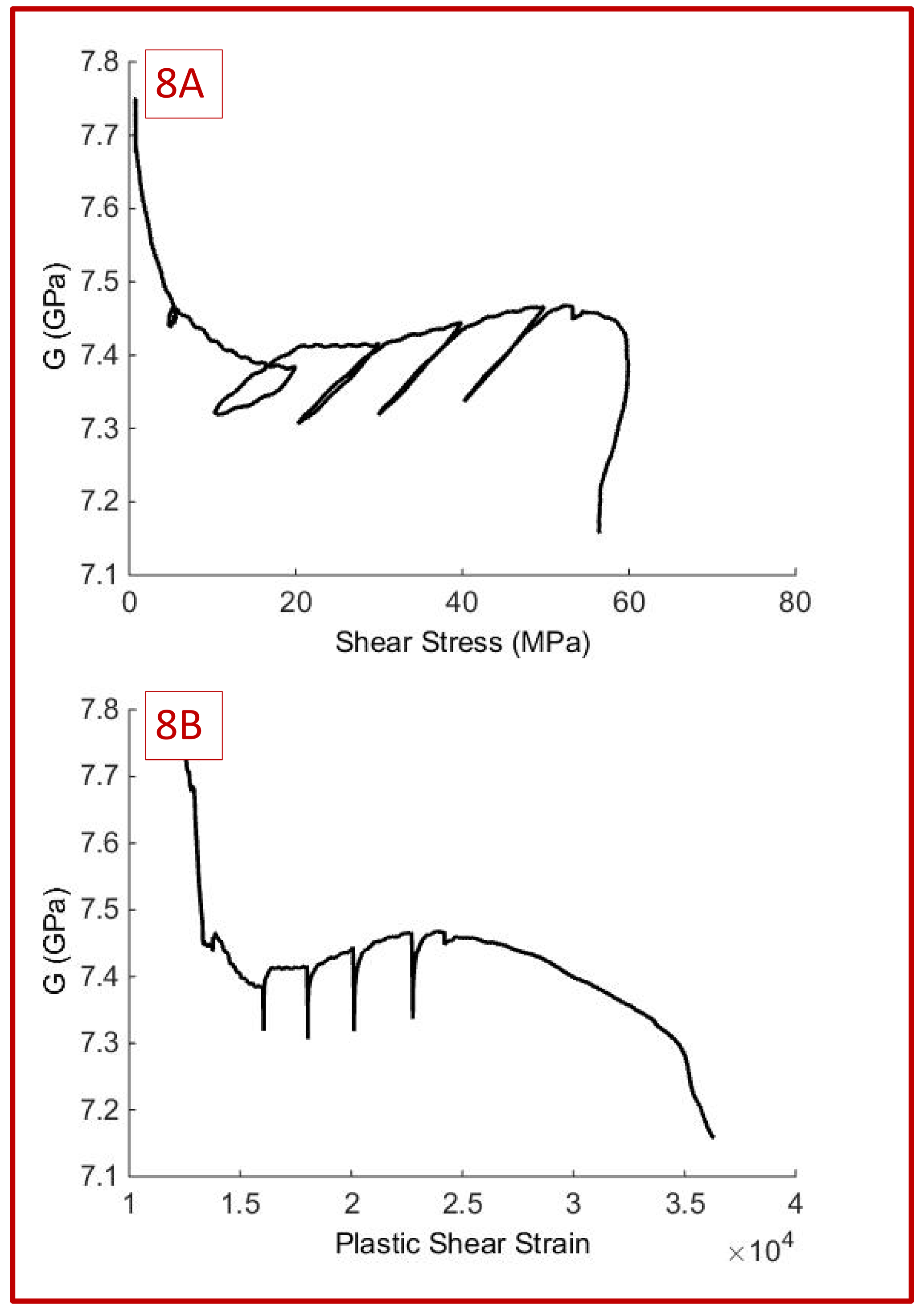
- Lode angle, through parameter N_{II}
- Friction factor, μ, which is yield surface slope
- Dilation coefficient, $\beta = -d^p\varepsilon / d^p\gamma$
- Poisson's ratio, ν, for elastic unloading

Strain Separation:

- Elastic bulk and shear moduli, K and G, are
  - Stress dependent (Fig 8A)
  - Plastic strain dependent (Fig. 8B)
- Total strain and strain increment (Eqn. 5)
- Strain separates into four parts (Eqn. 6):
  - A: elastic strain at constant modulus
  - B: strain due to stress dependent moduli
  - C: strain due to plastic strain dependent moduli
  - D: plastic strain
- Plot four strain components (Fig. 7)

Localization Predictions:

- Calculate increment of inelastic strain : C + D
- Plot yield surface; determine friction factor, μ
- Determine β from plot of $d^p\varepsilon$ vs. $d^p\gamma$
- Calculate predicted band angle, θ (Table 1)



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$$\theta = \frac{\pi}{4} + \frac{1}{2}\arcsin\left[\frac{\frac{2}{3}(1+\nu)(\beta+\mu) - N_{II}(1-2\nu)}{\sqrt{4-3N_{II}^2}}\right]$$

$$N_I = \frac{(\sigma-\sigma_3)}{\tau},\ N_{II} = \frac{(\sigma-\sigma_2)}{\tau},\ N_{III} = \frac{(\sigma-\sigma_1)}{\tau}$$

μ – Friction Factor, β – Dilation Coefficient, ν – Poisson's Ratio

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$$\gamma^t = \gamma^e + \gamma^p \qquad \gamma^e = \frac{\tau}{G(\tau,\gamma^p)}$$

$$d\gamma^t = d\left(\frac{\tau}{G(\tau,\gamma^p)}\right) + d\gamma^p$$

$$d\gamma^t = \frac{d\tau}{G} - \frac{\tau}{G^2}\left(\frac{\partial G}{\partial \tau}d\tau + \frac{\partial G}{\partial \gamma^p}d\gamma^p\right) + d\gamma^p$$

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$$d\gamma_A = \frac{d\tau}{G}$$

$$d\gamma_B = -\frac{\tau}{G^2}\left(\frac{\partial G}{\partial \tau}d\tau\right)$$

$$d\gamma_C = -\frac{\tau}{G^2}\left(\frac{\partial G}{\partial \gamma^p}d\gamma^p\right)$$

$$d\gamma_D = d\gamma^p$$

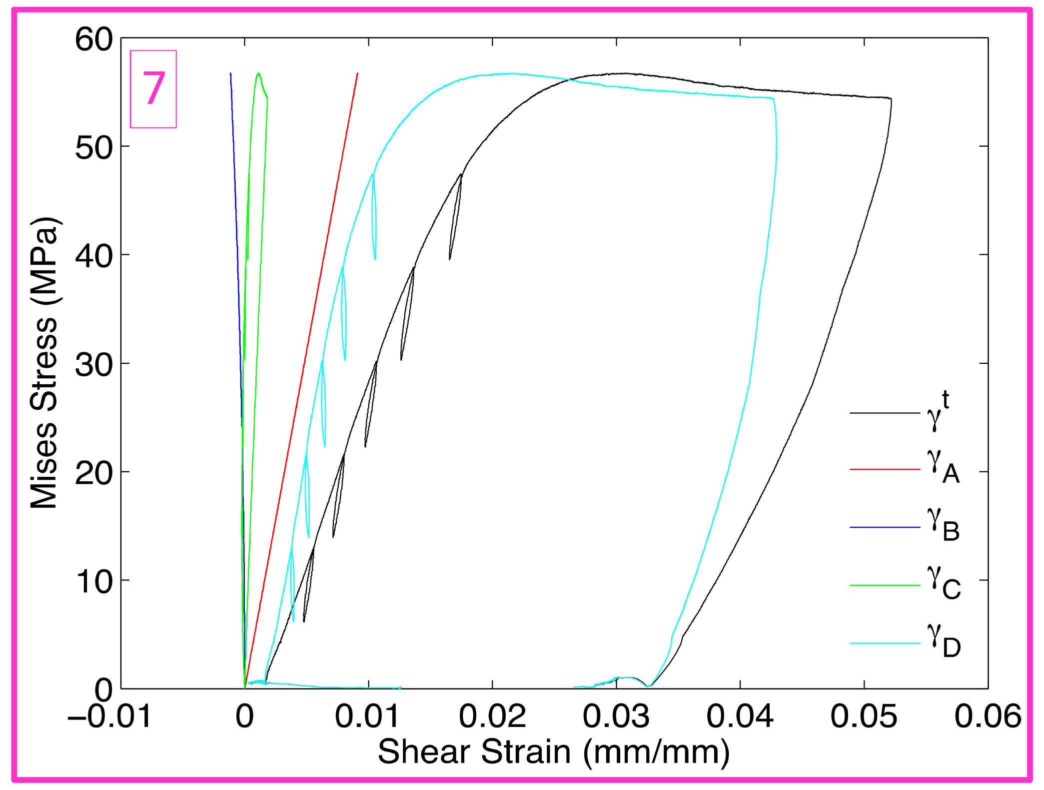

Table 1

Stress State	Mean Stress (MPa)	β	μ	Predicted θ	AE θ	Measured θ	Response Type
ASC	30	0.76	0.56	59	Conj. Bands	55-60	Shear
ASC	60	0.23	0.31	48	23	30-35	Shear
ASC	90	0.01	0.09	42	10-23	NA	CL
ASC	120	-0.29	0:-0.3	37:33	5-15	NA	CL
ASC	150	-0.66	-1.1:-3	3:0	NL	NA	NL
PS	30	0.09	0.94	57	58	61-80	Shear
PS	60	0.55	0.80	62	63	64	Shear
PS	90	0.08	0.67	54	54	58	Shear
PS	120	-0.23	0:-0.7	42:33	NL	NA	NL
PS	150	-0.75	-1.5:-4.4	15:0	16-25	NA	CL
ASE	30	0.76	0.85	80	51	65	Shear
ASE	60	0.65	0.49	68	NA*	70	Shear
ASE	90	0.04	0.13	54	41	46	Shear
ASE	120	-0.17	0:-1.9	50:23	Conj. Bands	45	Shear
ASE	150	-0.21	-1.8:-6	25:0	10-25	NA	CL

Conclusions:

- Mechanical response and failure (band orientation and failure surface) depend on σ_2
- Elastic moduli evolve with stress and plastic strain
- Strain separation was used to determine onset of yield and yield surfaces
- Reasonable agreement between localization predictions using strain separation and experimental results for Castlegate sandstone

Ingraham, MD, Issen, KA, Holcomb, DJ, "Response of Castlegate sandstone to true triaxial states of stress" J. Geophys. Res. Solid Earth, **118** (2013) p. 536, doi:10.1002/jgrb.50084.

Ingraham, MD, Issen, KA, Holcomb, DJ "Use of acoustic emissions to investigate localization in high-porosity sandstone subjected to true triaxial stresses" Acta Geotechnica, **8** (2013) p.645, doi: 10.1007/s11440-013-0275-y.

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