SAND2013-1202P

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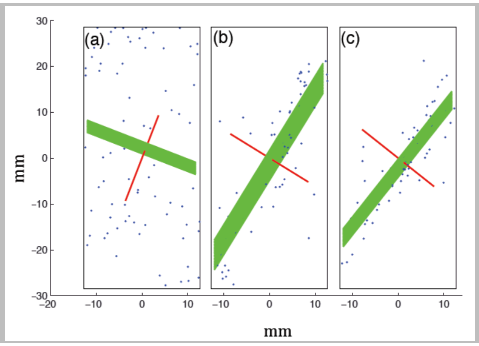
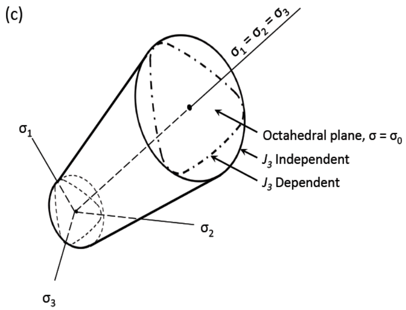
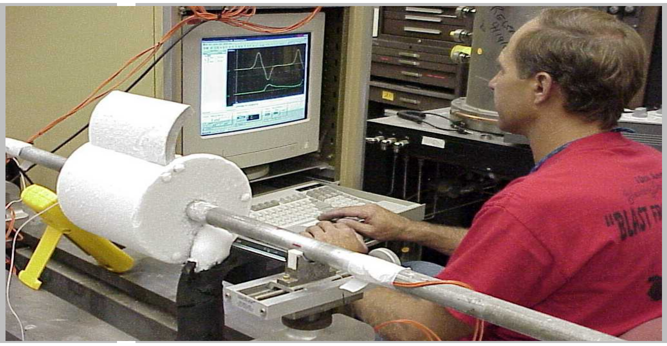






Geomechanics Research & Interests

Mathew Ingraham, 6914

U.S. DEPARTMENT OF ENERGY

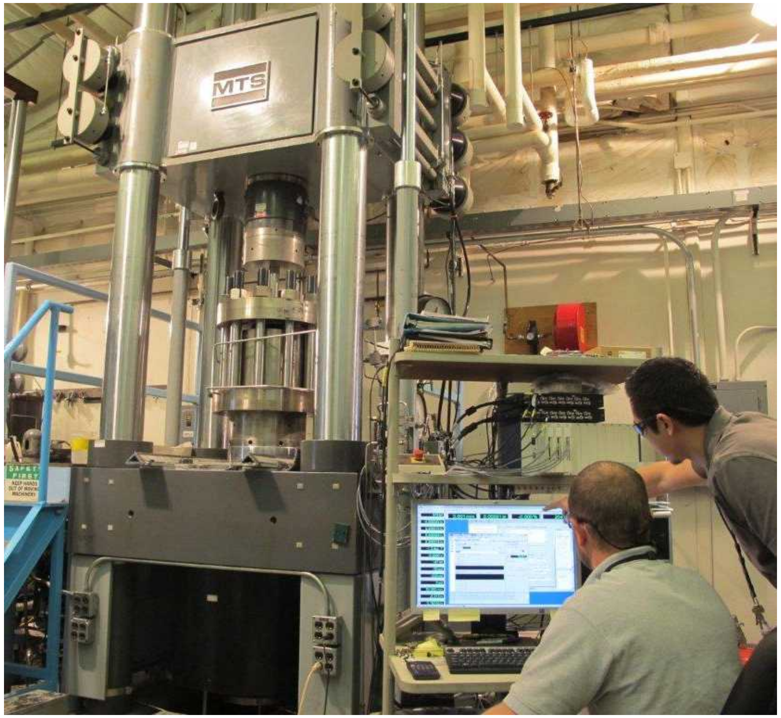
NNSA National Nuclear Security Administration

Outline

- Facilities
- Lab Activities
  - Materials Testing
  - Specimen Preperation
- Research Interests
  - True Triaxial Testing of Castlegate Sandstone
    - Response
    - Acoustic Emissions
    - Constitutive Parameters
  - Acoustic Tomography
  - Constitutive properties of shale
  - Creep Closure of Shale

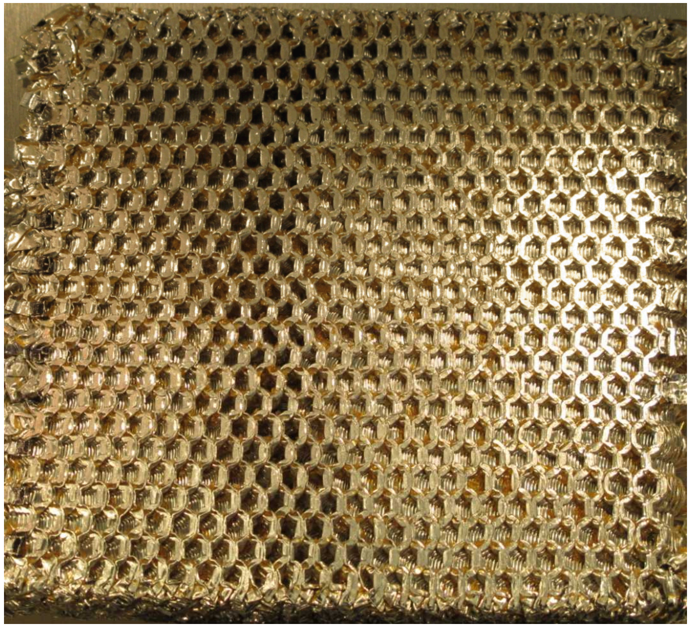
Facilities

- 4 Uniaxial frames with pressure vessels (<1,000,000 lbs, <145,000 psi)
- Axial-Torsional frame (220,000 lbs, 7400 ft-lbs)
- True Triaxial system (σ_2<14.5 ksi + σ_3)
- 10^{-10} /s < Strain rate < 10^{2} /s
  - Creep Frames
  - Split Hopkinson Bar
- -65^{o}C < Temperature < 300^{o}C



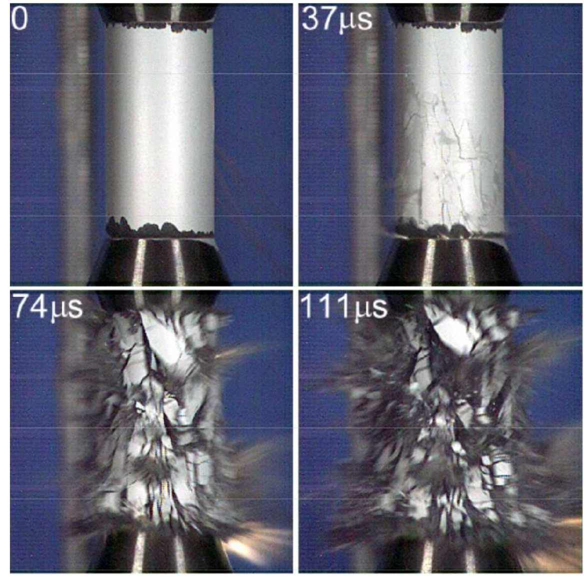
Materials Testing

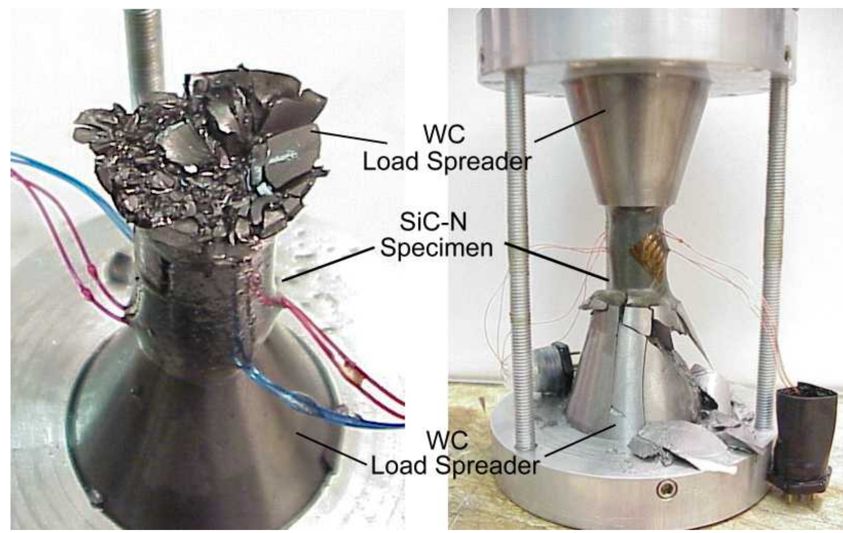
- 70% Geomaterials
  - Sandstone
  - Salt
  - Shale
  - Granite
  - Limestone
- 30% Engineering Materials
  - Bulk Metals
  - Honeycombs
  - Silicon Carbide
  - Ceramics
  - Carbon Composites



Materials Testing

- Uniaxial
- Axial – Torsion
- Hydrostatic
- Axisymmetric
- True Triaxial
- Active and Passive Acoustics
- Impact (Hopkinson Bar)
- Creep



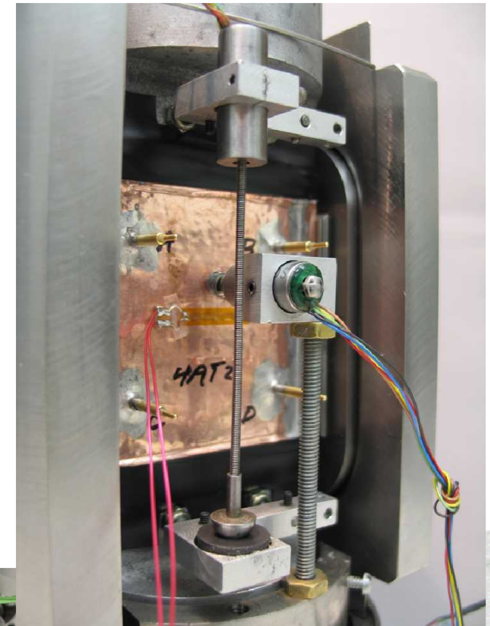


Materials Testing Ex.

- Bolt Fatigue
  - Performed testing to analyze the effect of damage accumulation on resonant frequencies
  - Sandia performed mechanical testing

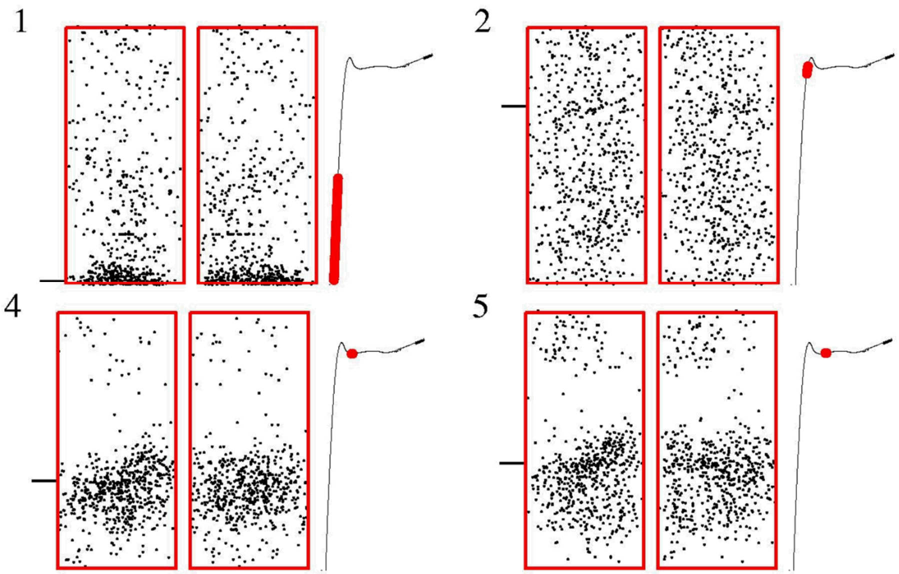
Specimen Preparation

- Precision Machining
- Coring and subcoring
- Instrumentation
  - Strain Gauges
  - LVDT’s
  - Acoustic Transducers
- Jacketing
  - Viton
  - Polyolefin
  - PVC
  - Copper
  - Lead
  - Urethane



Specimen Preparation/Analysis

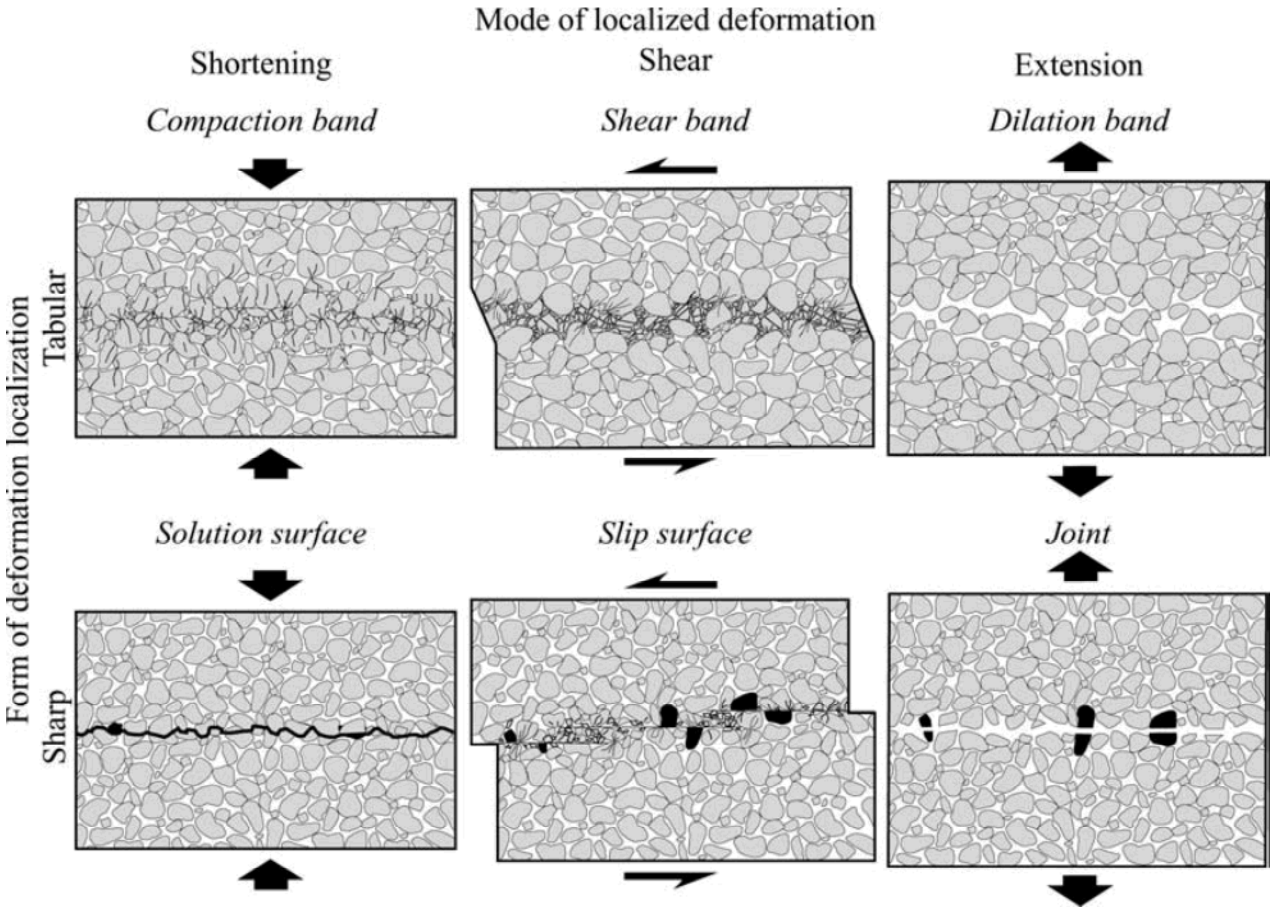
- More Preparation
  - Epoxy impregnation
  - Rhodamine doping
- Analysis
  - LSCM
  - Porosimetry
  - Wavespeed
  - Acousic event location
  - Thermal conductivity



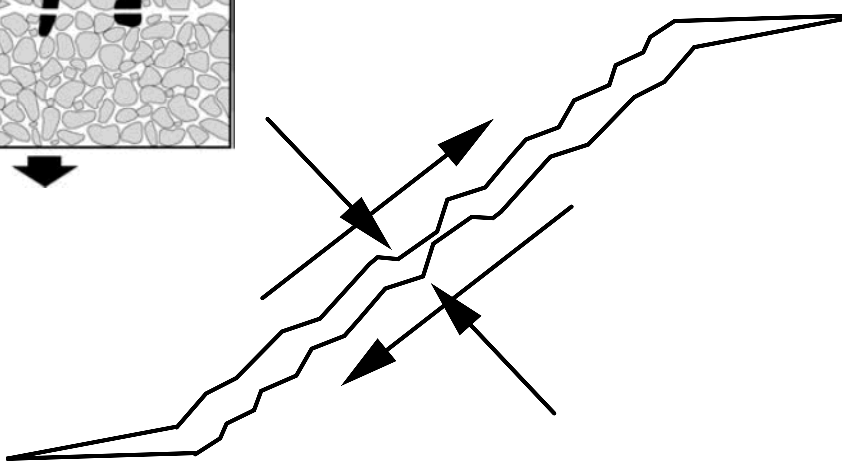
Castlegate Sandstone

- Composed primarily of quartz grains cemented with calcite
  - ~26% porosity
  - ~0.2 mm grain size
- Fluvial
- Cored from an outcrop in Utah by Terratek
- Transversely isotropic
  - 10-15% stronger normal to bedding

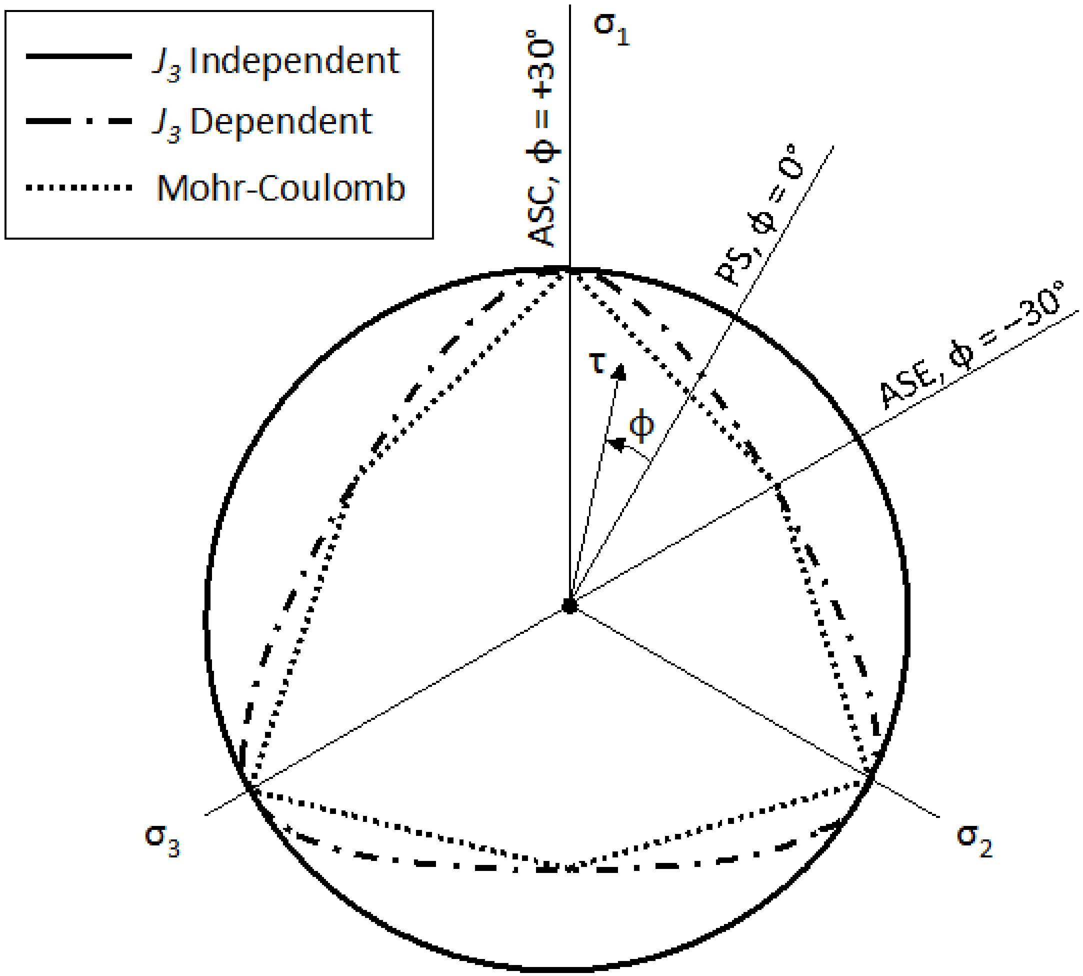
Sandstone Failure Structures



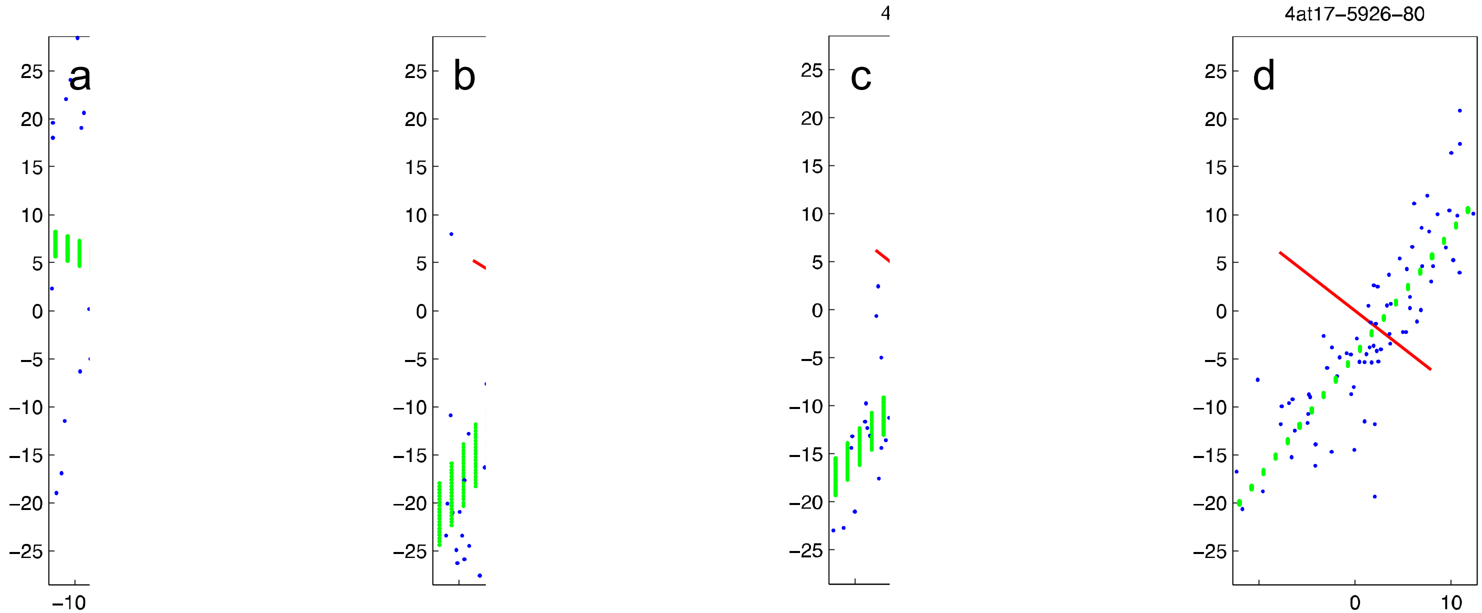
Aydin, Borja & Eichhubl, 2006

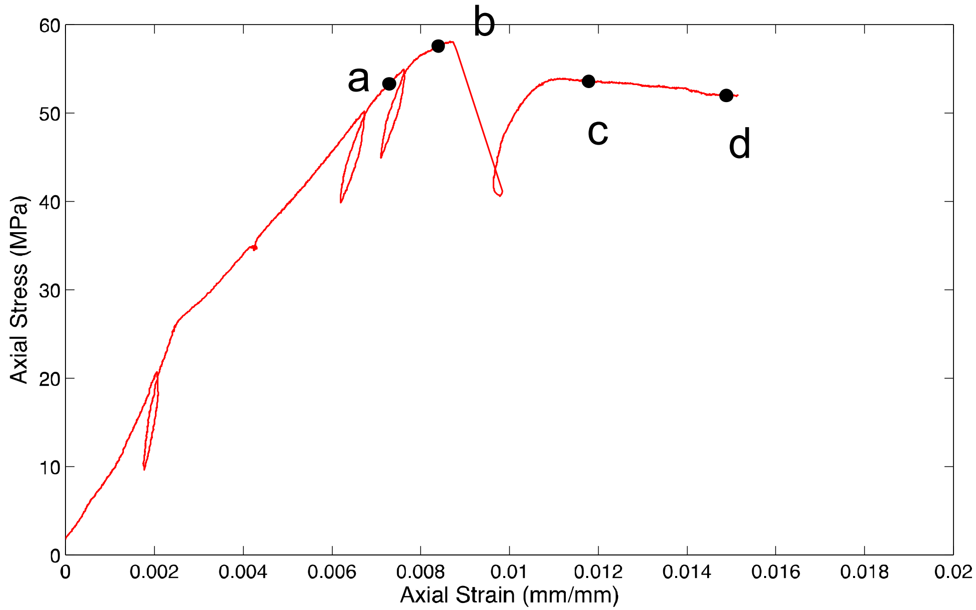


Yield Criteria



Shear Band

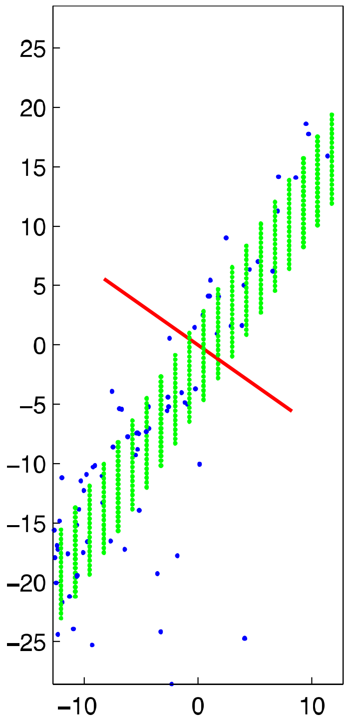


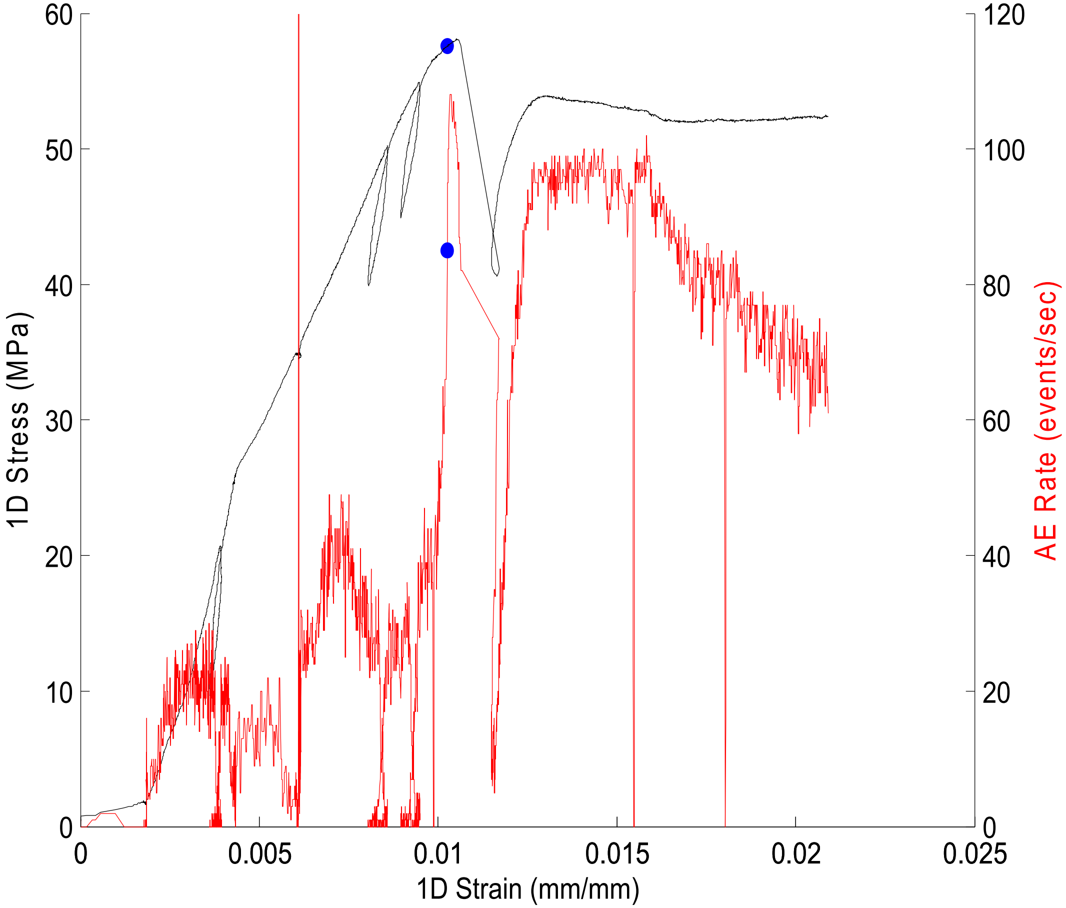


$$\phi = 0$$

$$\sigma = 30$$

Shear Band

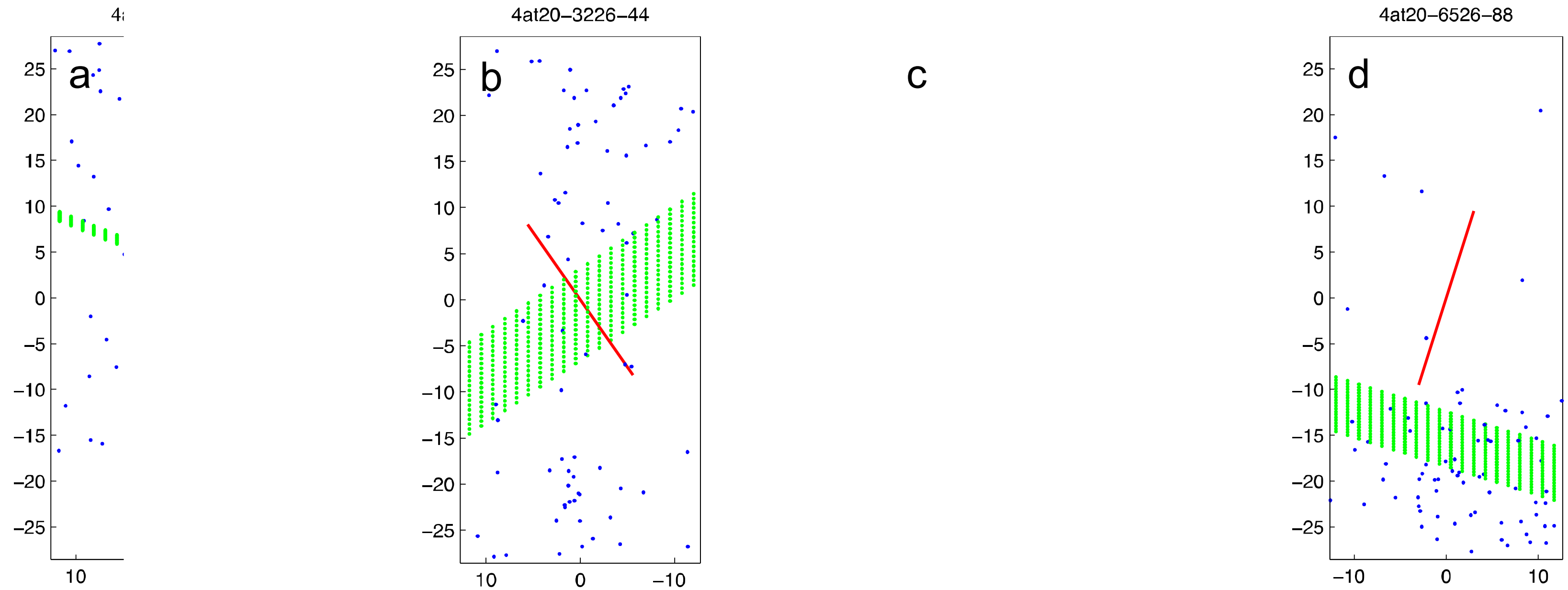


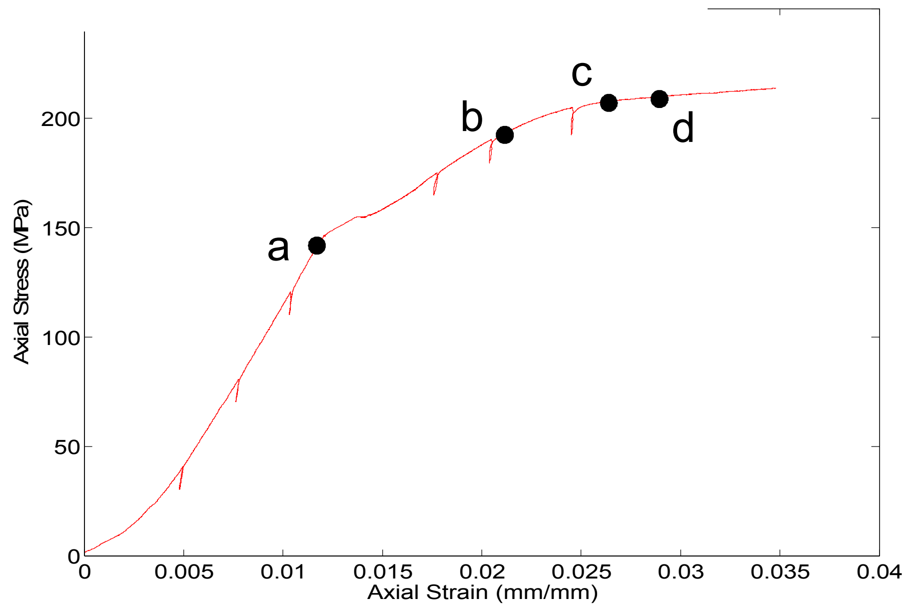


$$\phi = 0$$

$$\sigma = 30$$

Compaction Localization

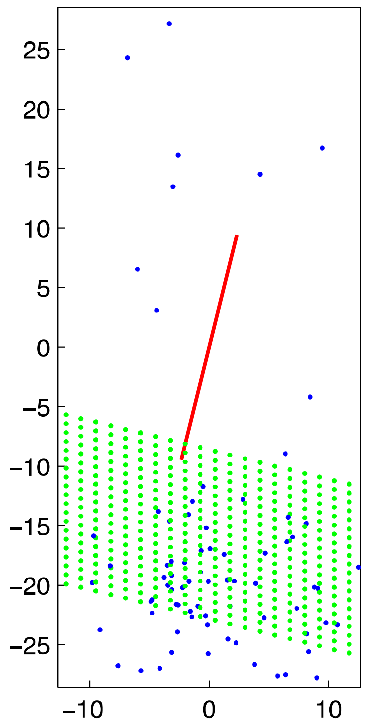




$$\phi = 0$$

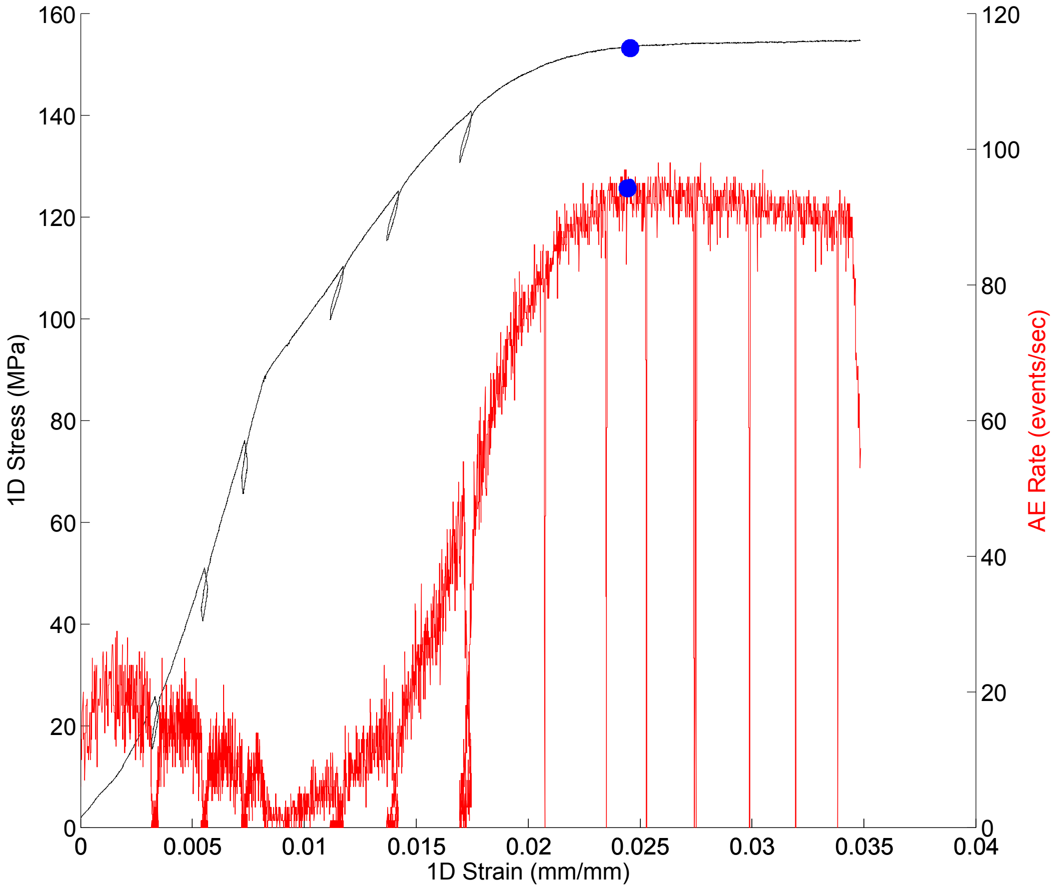
$$\sigma = 150$$

Compaction Localization

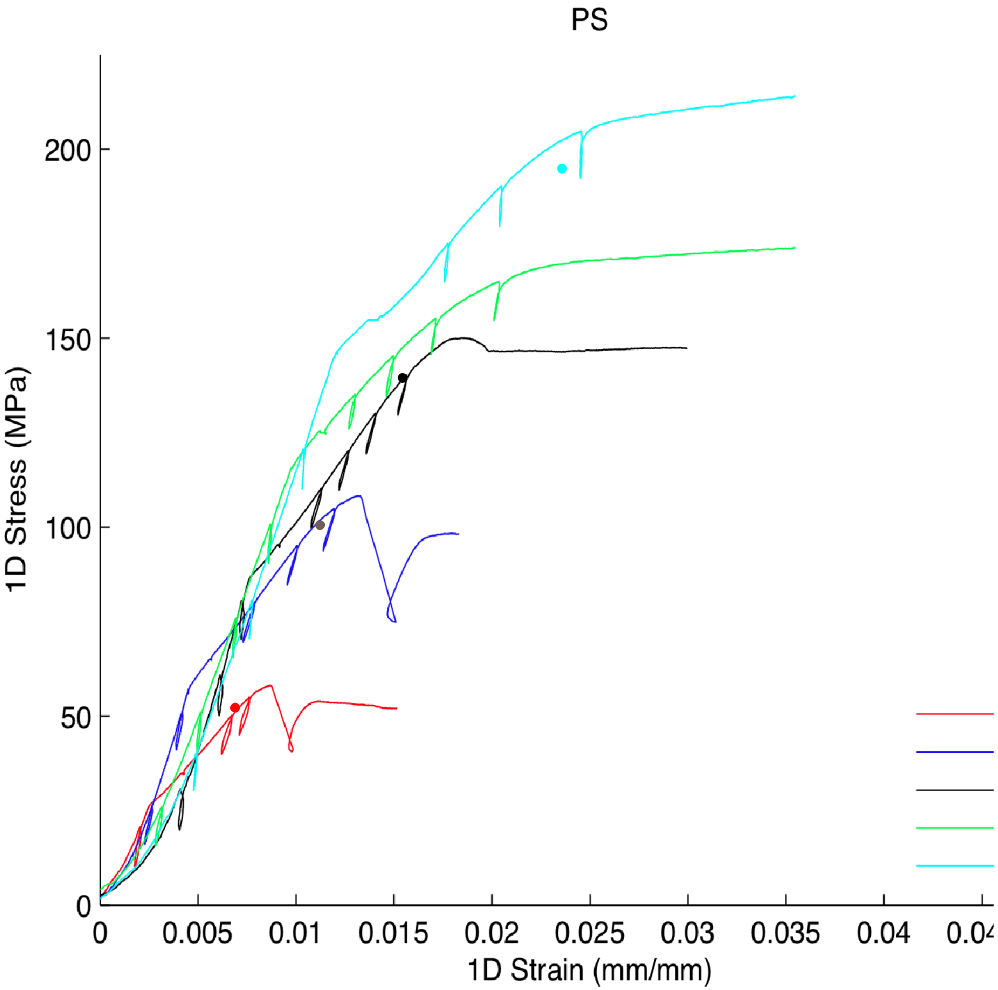


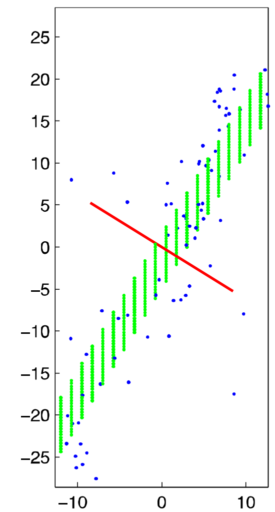
$$\phi = 0$$

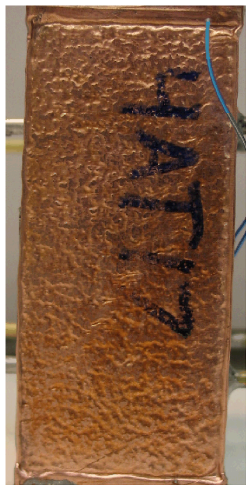
$$\sigma = 150$$

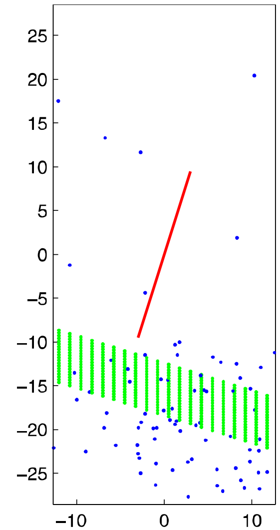


Effect of Mean stress

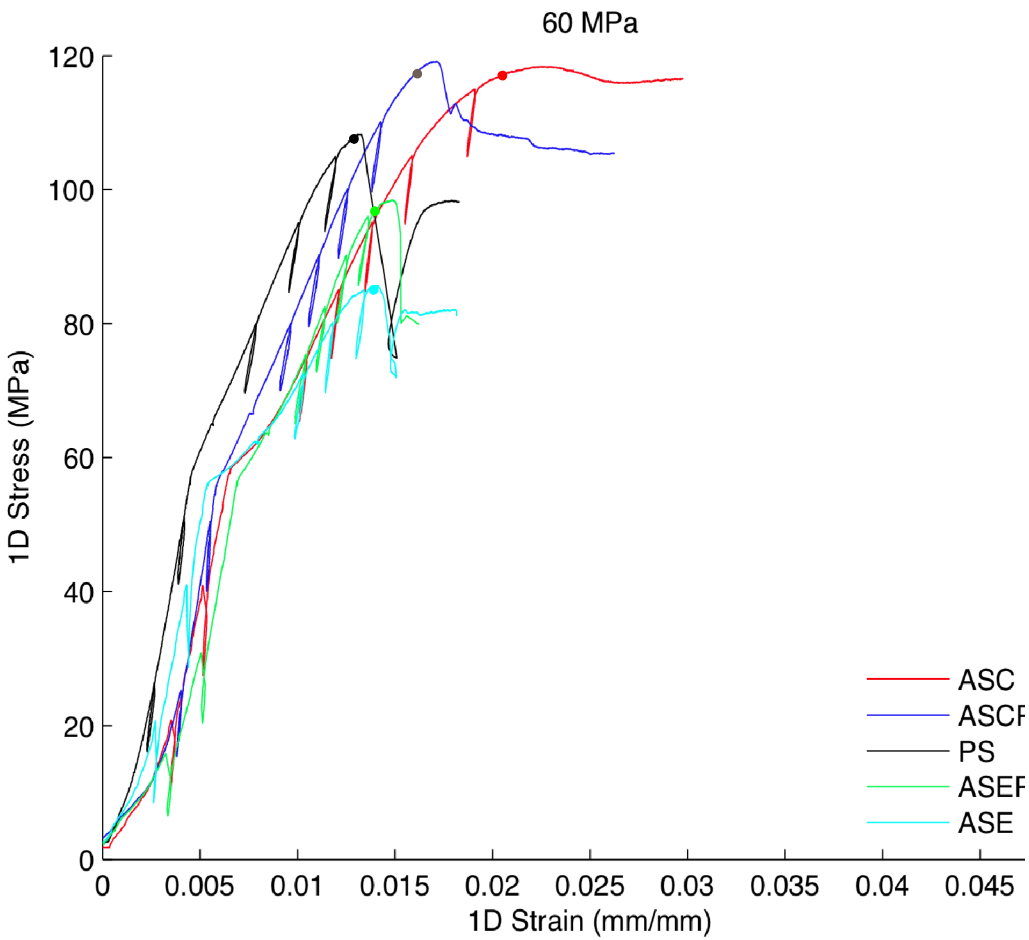


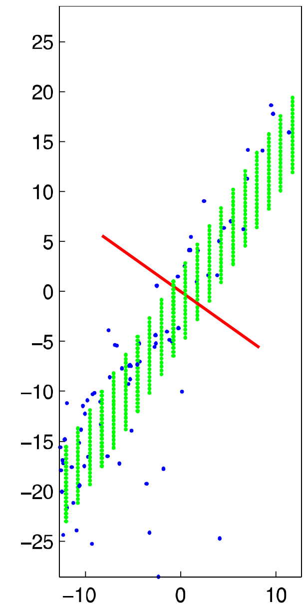


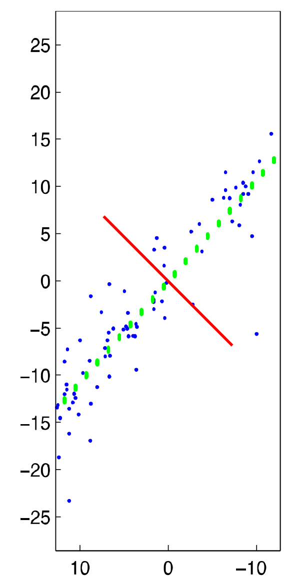




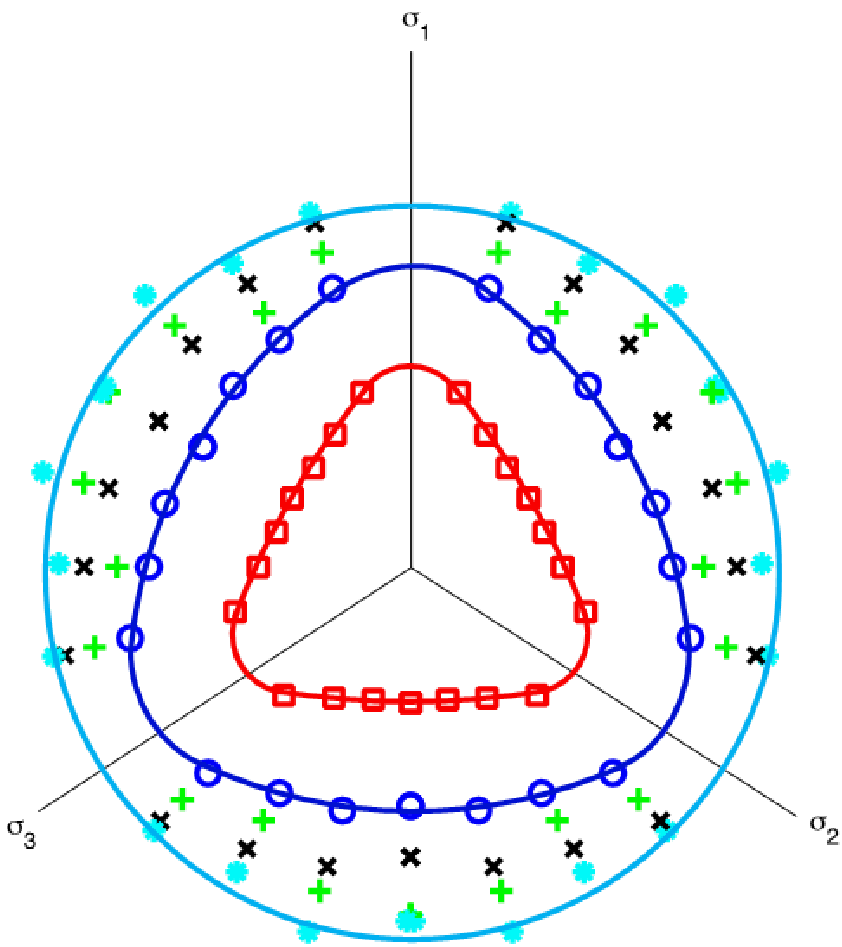
Effect of Stress State

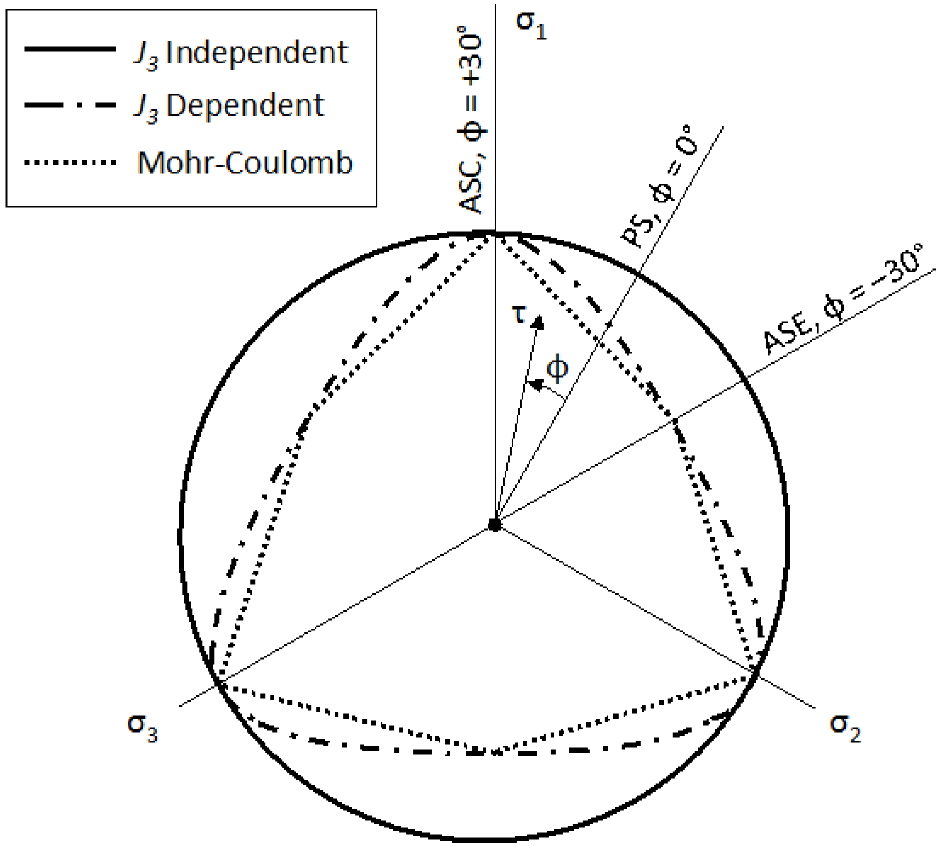






Yield Surfaces





Localization Predictions

- Predicted shear band angle

(Rudnicki & Olsson 1998, Rudnicki & Rice 1975)

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

β – dilation coefficient
μ – local slope of yield surface
ν – Poisson's ratio

- Valid when:

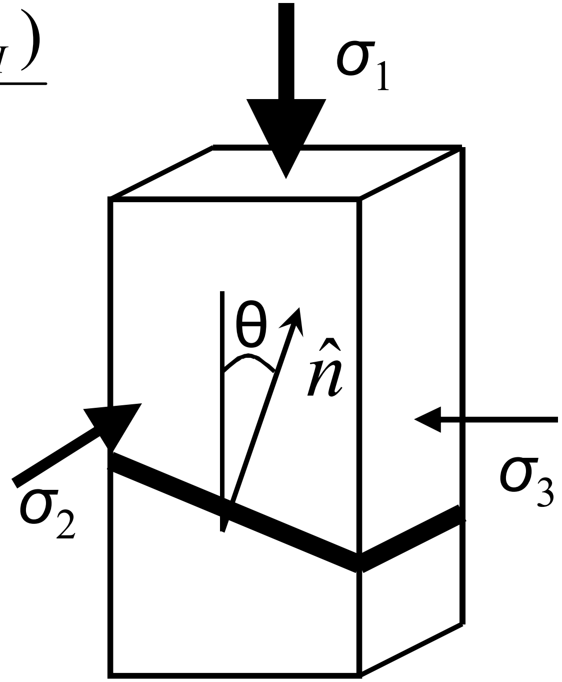
$$-\frac{3(N_I + \nu N_{II})}{1+\nu} \le \beta + \mu \le -\frac{3(N_{III} + \nu N_{II})}{1+\nu}$$

- Where:

$$N_I = {(\sigma - \sigma_3)}/{\tau}$$

$$N_{II} = {(\sigma - \sigma_2)}/{\tau}$$

$$N_{III} = {(\sigma - \sigma_1)}/{\tau}$$



Strain Partitioning

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

$$d\gamma_{A} = \frac{d\tau}{G}$$

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

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

$$d\gamma_{D} = d\gamma^{p}$$

$$\beta = -\frac{d^{p}\varepsilon}{d^{p}\gamma} \qquad d^{p}\gamma = d\gamma_{C} + d\gamma_{D}$$

- Strain is separated into 4 forms: Elastic, elastic stress dependent, plastic strain dependent, plastic
- A,B,C are recovered upon unloading γ^{e}, however C and D are the inelastic increment of strain needed for localization theory
- A and B are found by calculating strain with the modulus without G_0 evolution

Separated Strains

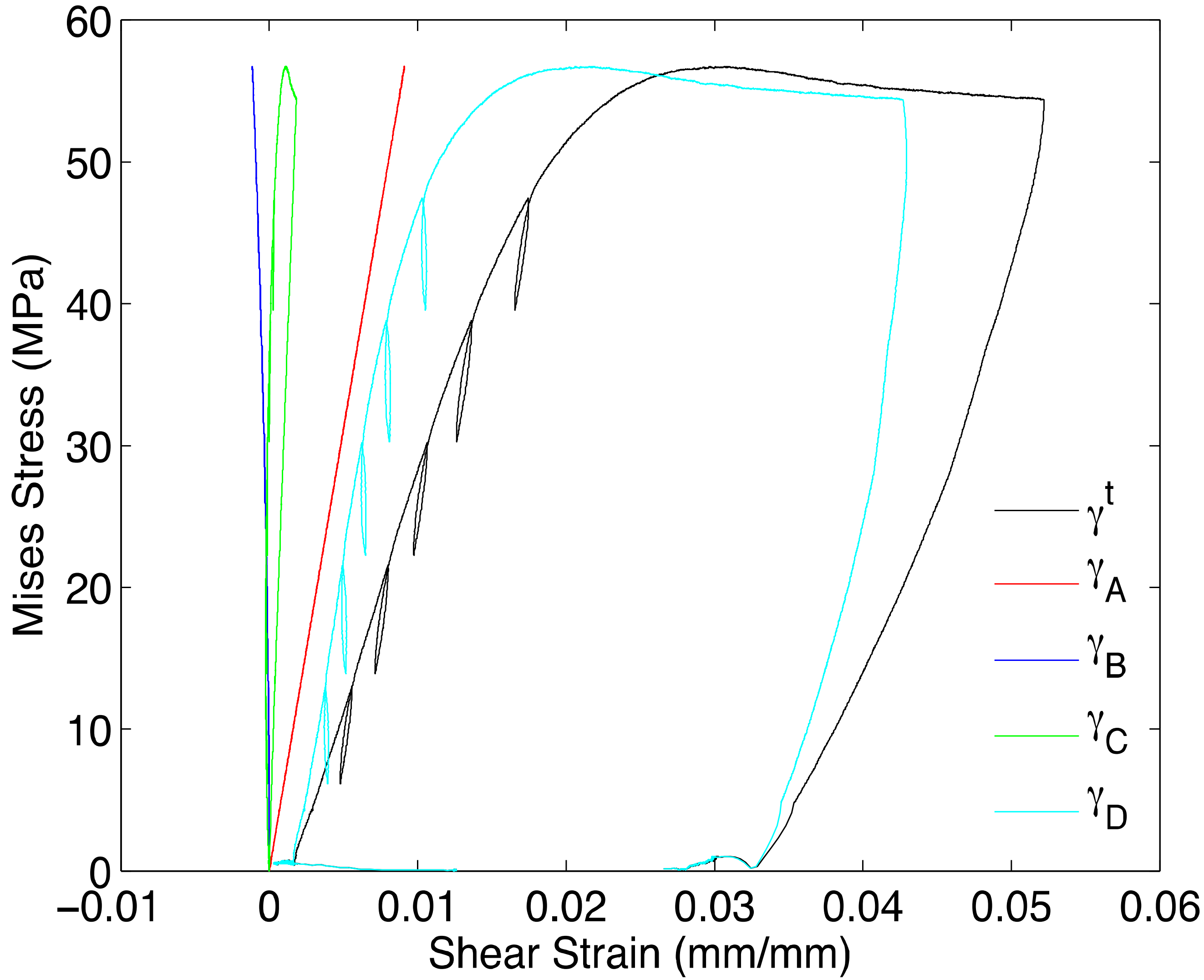
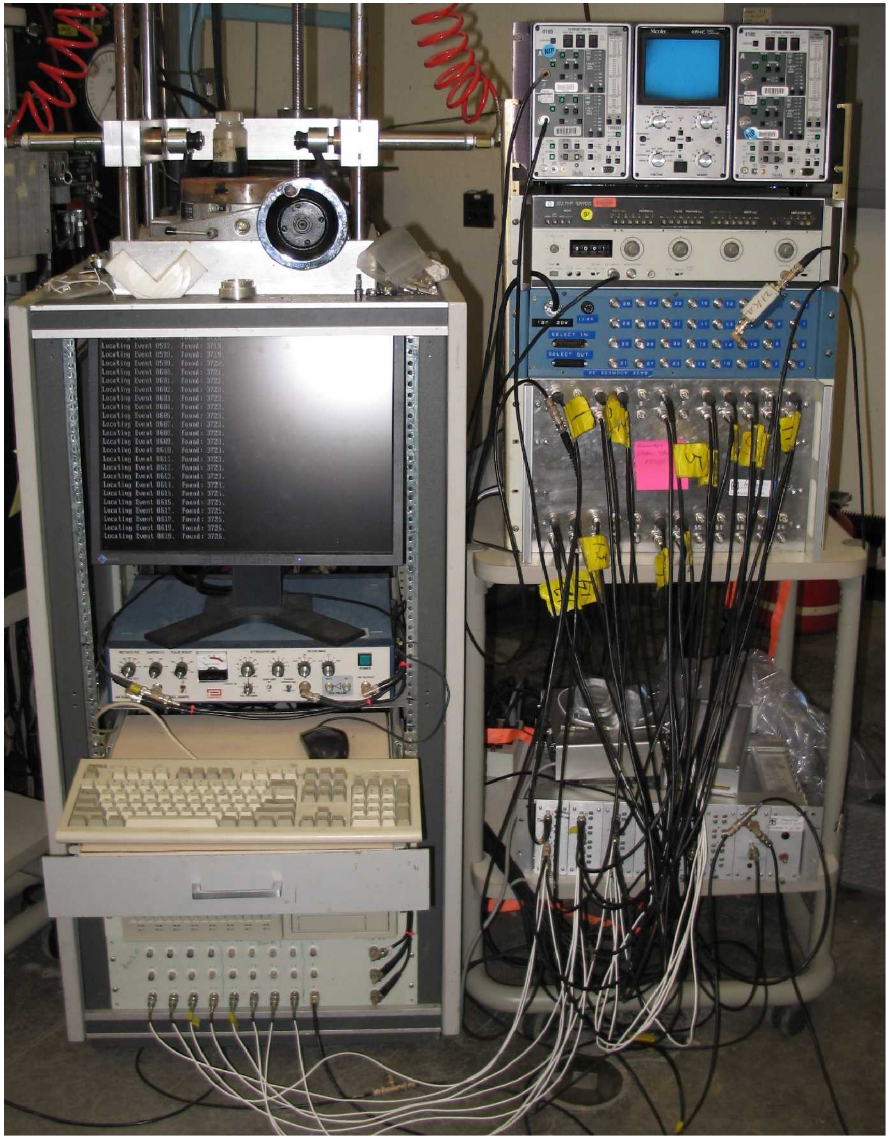


Table of Band Angles

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

Acoustic Emission System

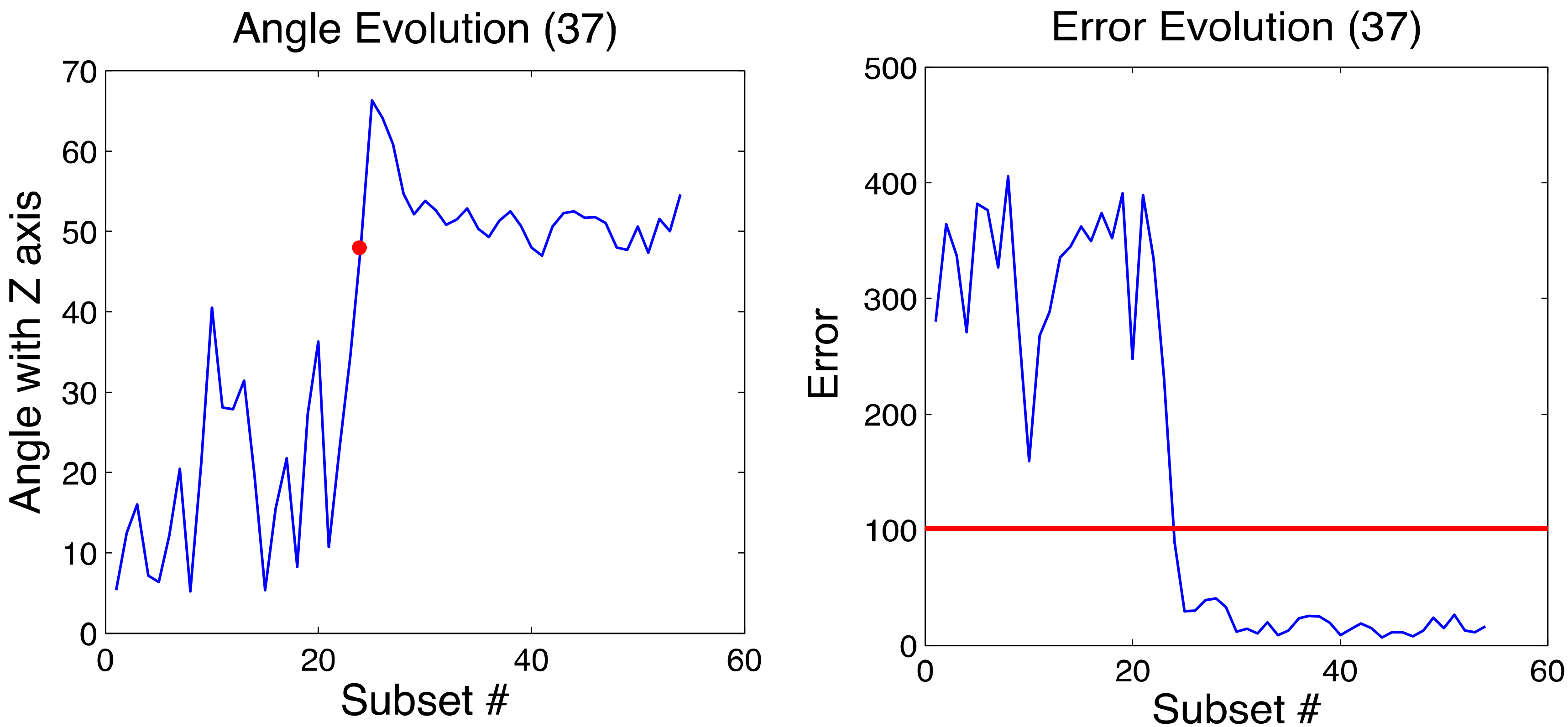
- Strategic Test waveform digitizers
- 60 db amplifiers
- Sandia built discriminator system
- Attached computer for data recording
  - Control and data recording implemented through MATLAB



AE Locating

- Events located through a simplex RMS error reduction routine by minimizing the error between the guessed location and the location calculated by the normalized event arrival times.
- Planes are fit using a simplex least squared error routine where the error is minimized between the estimated plane and the data points in the axial direction.
- Localization was determined by examining the normalized error returned from the LSE solver.
  - When the error dropped below 100 the specimen was determined to have localized
  - This drop correlates well with a tightening and a shift in the band normal angle.

Localization



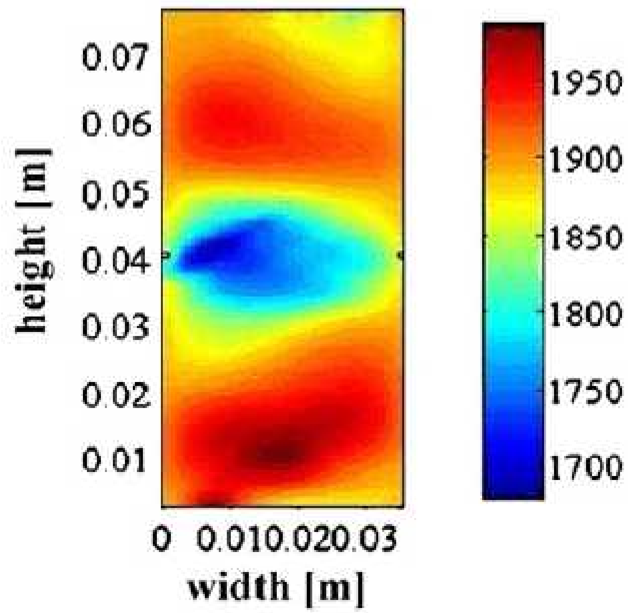
$$\phi = -14.5$$

Angle at localization 48°

$$\sigma = 60$$

NDE: Acoustic Tomography

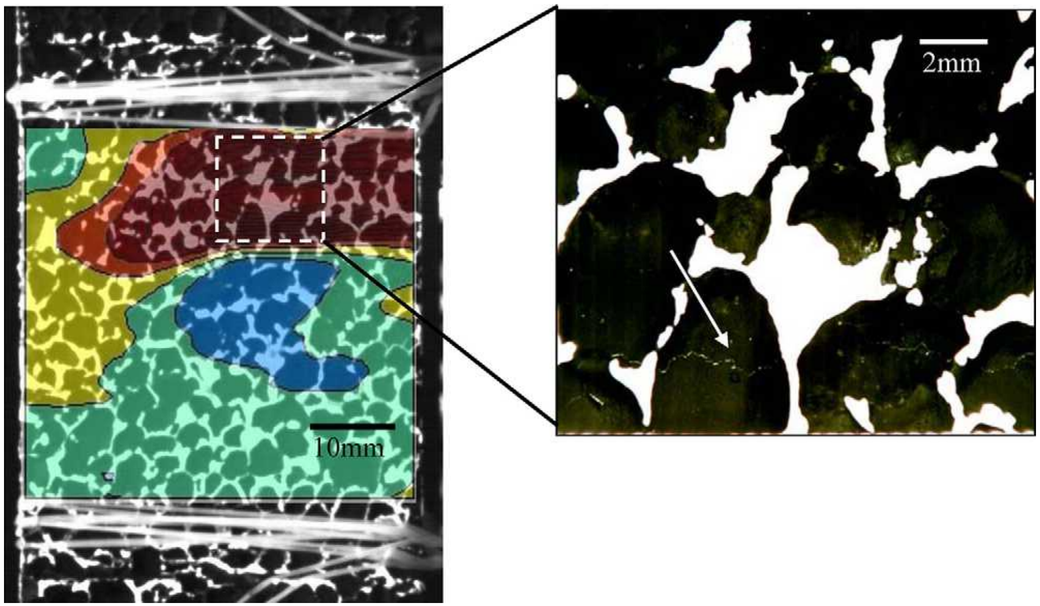
- Track dynamic modulus
- Low velocity regions indicate damage
- Resolution increases with increasing the number of crossing raypaths
- In the lab this is done with a number of source/reciever transducers
- In the earth this is achieved with a number of geophones



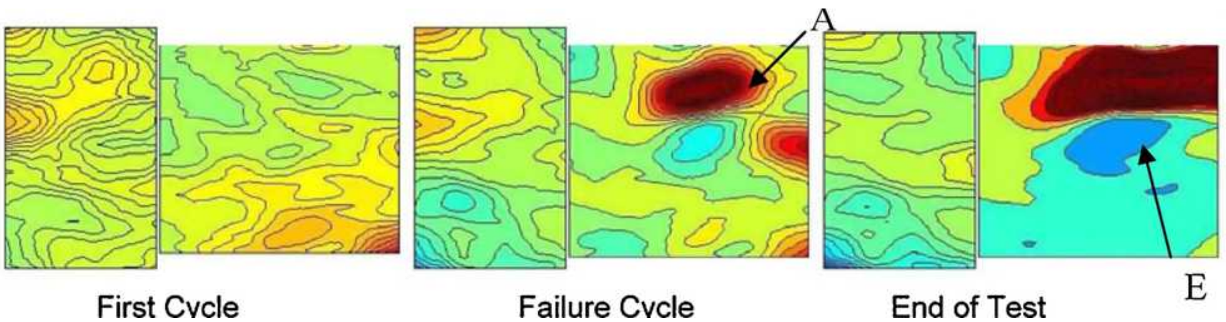
Charalampidou et al. 2012

NDE: DIC

- Utilizes pattern tracking to calculate surface strain
- Can be performed in 2D and 3D for surface strain
- Utilizing 3D voxel files (µCT scans) volumes can be correlated (calculate volume strains)



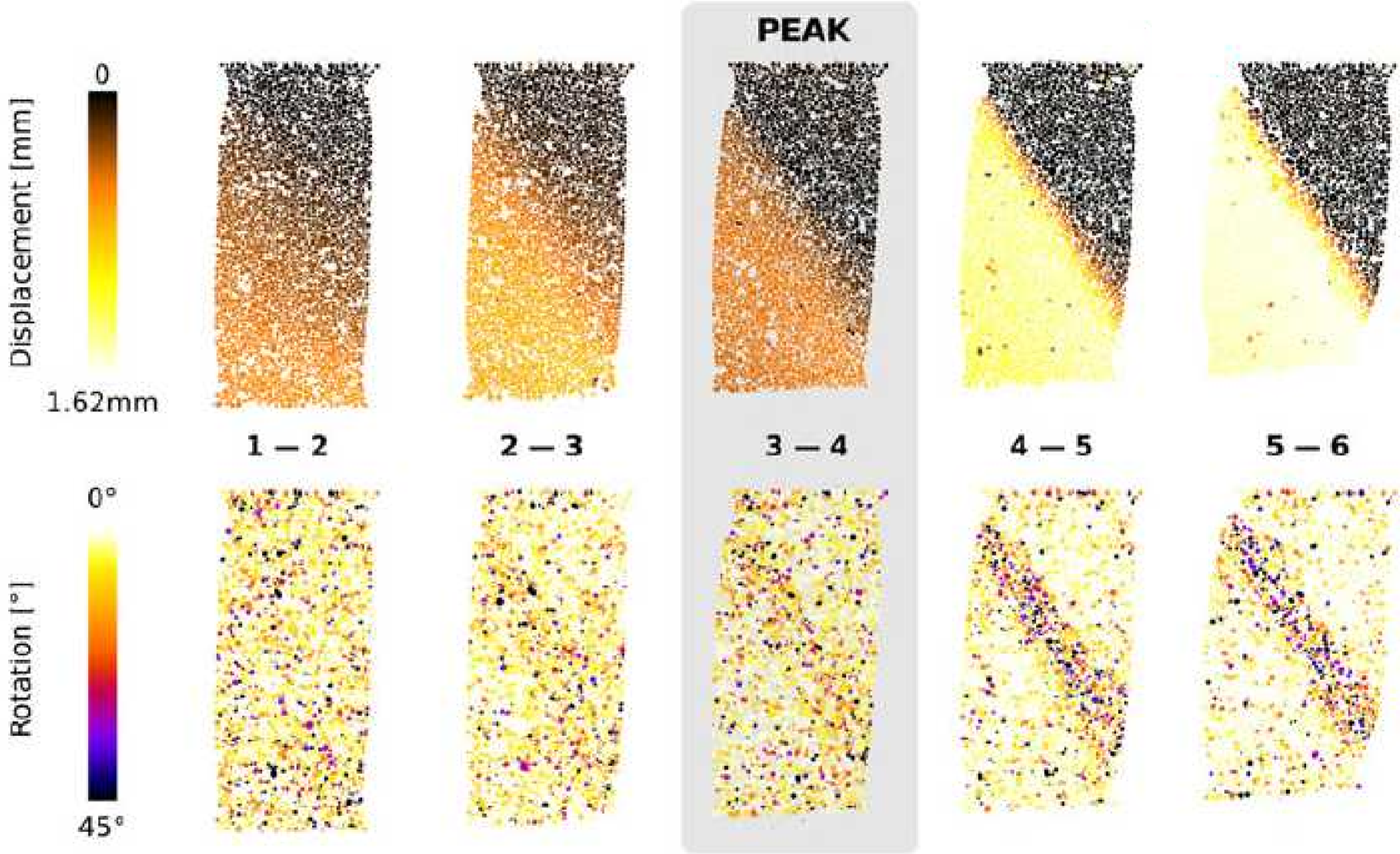
Images from Ingraham et al. 2008



NDE: µCT-analysis

- CT measures density changes in the material and through a back projection algorithm applied to many radiographs taken from different radial directions develops a 3D map of density variation.
- µCT data can be used to perform digital image correlation or digital volume correlation
  - Pre and post test scans must be available
  - Allowing for analysis of volume and shear strains in 3D
- If scans are of sufficient quality individual grains can be tracked

NDE: µCT-scanning



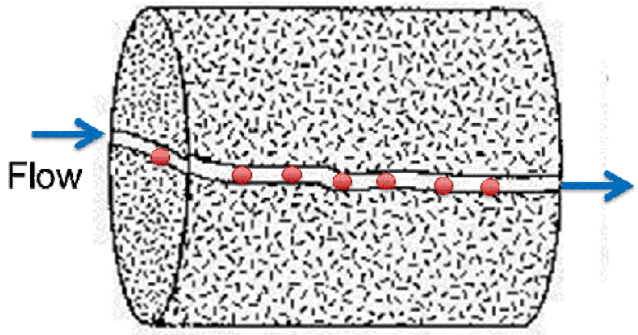
Ando et al. 2012

Constitutive properties of shale

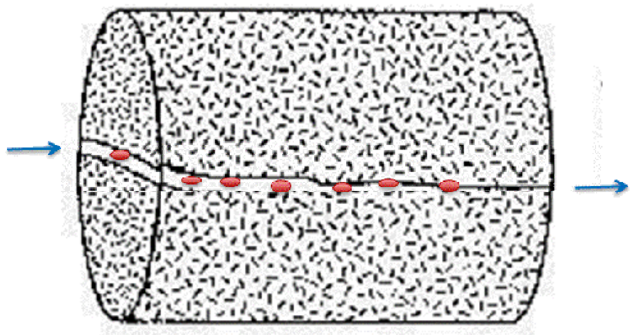
- Little is known about the constitutive properties of shales
  - Difficult to machine samples (friable)
  - Difficult to perform consistent tests (specimen variation)
  - High dependence on pore pressure
    - Relatively impermeable (partially saturated)
- Requires large sample sizes of multiple materials
  - Anisotropic
  - Heterogeneous

Proppants in fractured shale

- Common problem in shale gas extraction is production decline of wells
  - Restimulation (refracturing) of these wells often leads to increased production for a short period
  - One thought regarding the reason for this is creep closure of the fractured rock around proppants



Post stimulation



Reduced flow after creep closure

Proppants in fractured shale

- Without proppants wells do not produce nearly as well
  - Proppants are a catch 22
    - Proppants are necessary to keep the fracture open and gas flowing
    - Proppants introduce stress concentrations on the fracture surface accelerating creep in the region of the proppant.
  - Can we build a better proppant?
  - Proppant distributions within fractures?
- Creep properties of shale
  - Mechanism
    - Mechanical
    - Chemical
    - Thermal effect
  - Spalling
  - Rate

Other interests

- Coupled mechanical-chemical-thermal response
  - Effect of this on constitutive property evolution and diagenesis
- Improvement of existing models and codes used to perform subsurface modeling
- NDE techniques
- Complex testing systems
- Control systems and control theory

Questions?