Determining Failure Behavior at Hydraulic Fracturing Conditions through Experimental Rock Deformation*

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Abstract

Production of shale reservoirs through hydraulic fracturing techniques has fundamentally changed the U.S. energy landscape. The induced fracture systems are the primary source of transmissivity from the reservoir to the wellbore, so it is vital to understand and predict the extent of the induced fracture network. Geologic observations of natural fluid-pressure assisted fracture networks and microseismicity associated with induced fracturing demonstrate that the resulting geometries are complex. Typical explanations invoke reactivation of preexisting fractures; while natural fractures are important, we suggest that complex fracturing at multiple scales is characteristic of failure at the mixed tensile and compressive stress states associated with hydraulic fracturing. Previous experimental work has demonstrated that the conventional Griffith and modified Griffith failure criterions are inaccurate in predicting the failure strength and fracture angle for mixed stresses; fracture in these conditions involves both opening and shear modes with characteristic fracture morphologies and damage accumulation important in understanding hydraulic fracture networks. We report an experimental rock deformation study to develop a failure criterion for fracture in mixed stress states appropriate to hydraulic fracturing. Triaxial extension experiments employing necked (dogbone) samples were performed on four different rock types representing different porosity, grain structure, and composition. The results demonstrate a characteristic failure envelope for the transition from opening-mode fracture at very low mean stresses, to Coulomb shear fracture at high mean, compressive stress states. Fracture mode and orientation vary systematically across the transition similarly for all the rock types. The results support the hypothesis of a universal failure criterion scalable by rock strength. The results show a constant shape to the failure envelope, such that the ratio of unconfined compressive strength to tensile strength decreases with increases in absolute strength. Additionally, fracture orientation (angle between the fracture and

maximum compressive stress) increases linearly with mean stress across the transitional regime. We suggest that the empirical failure envelope can be used to predict failure modes and fracture characteristics for a given reservoir by scaling the failure criterion to the tensile strength of the reservoir and considering in situ stress states.

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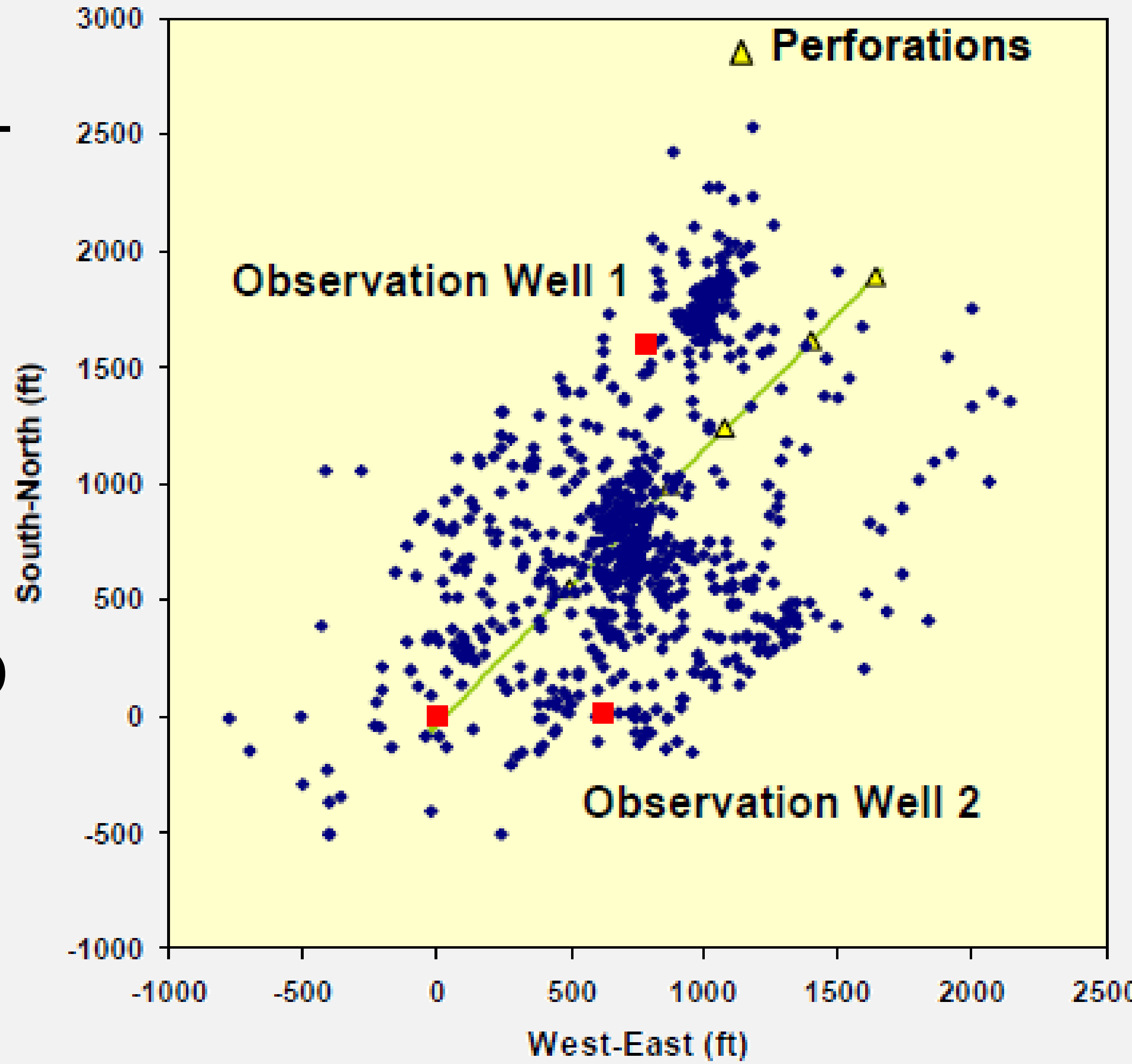
June 1, 2015

Understanding Hydrofracture Networks

- Expect bimodal propagation of opening-mode fracture in plane normal to S_{HMIN}
- Observations indicate fracturing is considerably more complex
- Activated volume is 3-D
- New and reactivated fractures in both opening and shear modes



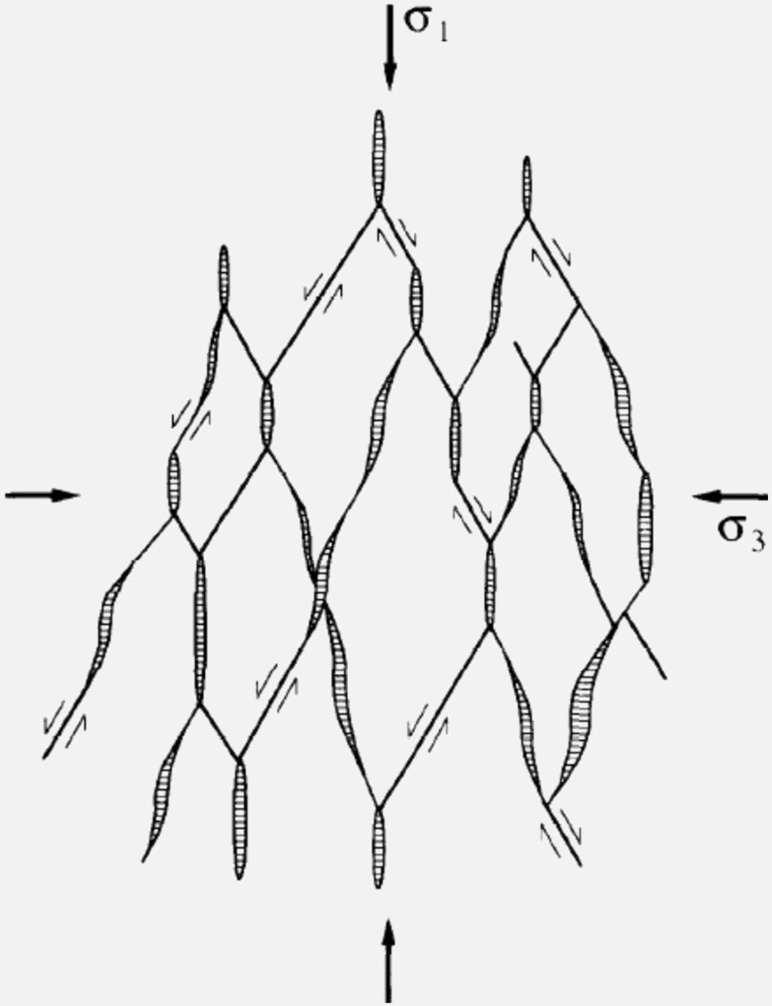
Cipolla et al, 2008

Understanding Hydrofracture Networks

- Explanation
  - Local heterogeneity in rock strength and in situ stress lead to multiple fracture mechanisms, fracture network complexity
- Hypothesis
  - Local stress states induced by hydrofracture produce fracture modes other than pure tensile fracture, even in homogeneous isotropic rock
  - The fracture modes activated while stimulating unconventional reservoirs may be predicted from in situ stress state and rock failure criteria
- Objectives
  - Conduct experiments and numerical modeling to provide critical information to understand fracture modes and predict behavior of reservoir rock

Mixed Mode Failure in Nature

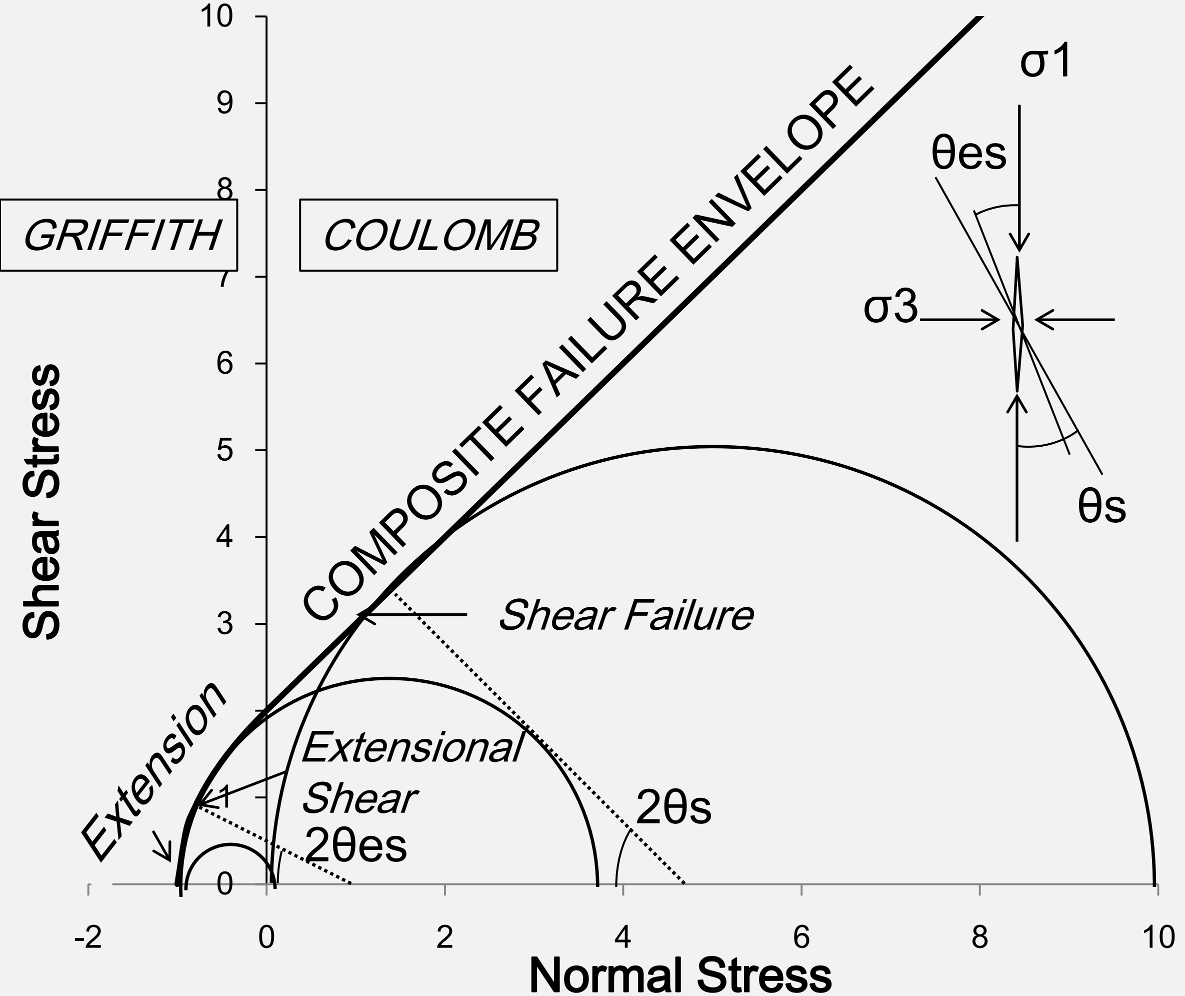
- Complicated fracture networks associated with mixed stress state
  - Elevated fluid pressures
  - Stress Contrasts
- Observed in volcanic, geothermal, metamorphic provinces
  - Earthquake swarms
  - Fault valve behavior
- Combination of mode I and II/III failure
  - Joints/veins and faults/shear fractures



Hill (1977) Mesh Model

Predicting Fracture from Failure Criteria

Common approach of employing a composite failure envelope – Coulomb and Griffith failure criterion



Predicts fracture modes and fracture orientation for:

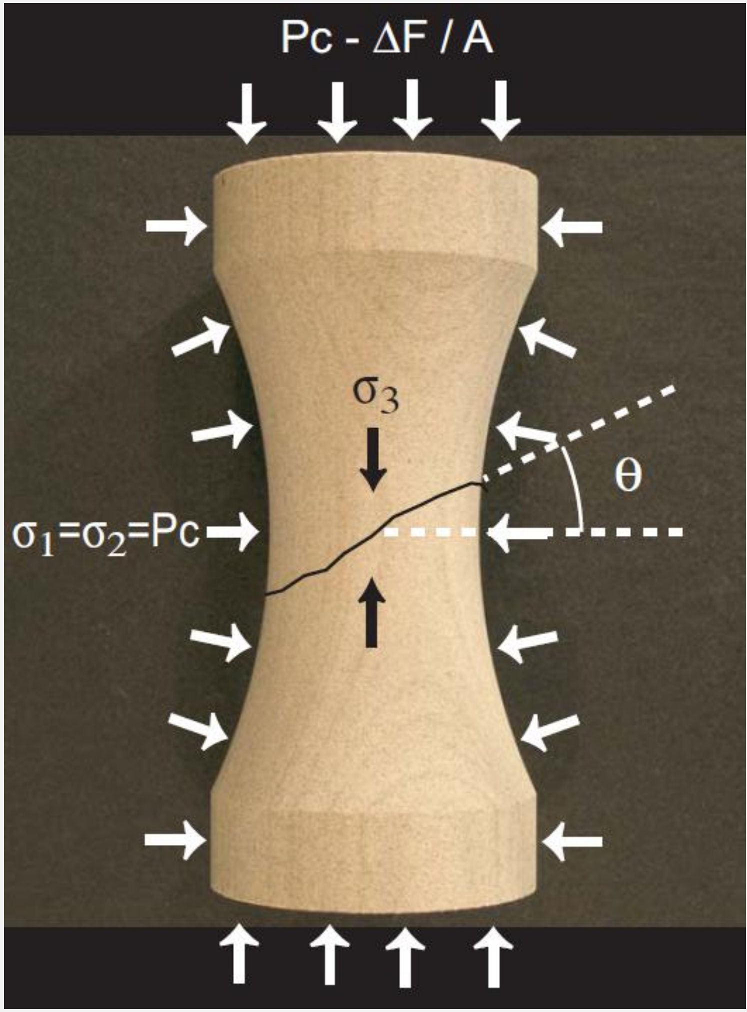
- Shear
- Extensional-shear
- Extensional

Conceptually valid but incorrect for tensile stress conditions

Sibson, 1996;
Fischer & Guest, 2011

Experimental Method

- Triaxial Extension Experiments
  - Confining Pressure = Sigma 1,2
  - Axial Stress = Sigma 3
  - Loaded hydrostatically, axial stress reduced, confining pressure constant
  - Confining pressure generates tension
- "Dogbone" geometry
  - Smooth radius of curvature
- Experiments performed at Sandia National Labs



After Bobich, 2005

Rock Types Tested

Past* and Current Work:

- Berea Sandstone
  - Reservoir sandstone analog
  - 16-19 % Porosity
  - Subarkosic
  - Fine grained
  - Bedding laminae of mafic minerals
- Carrara Marble
  - Tight, crystalline rock
  - 99% calcite
  - 250-350 micron grain

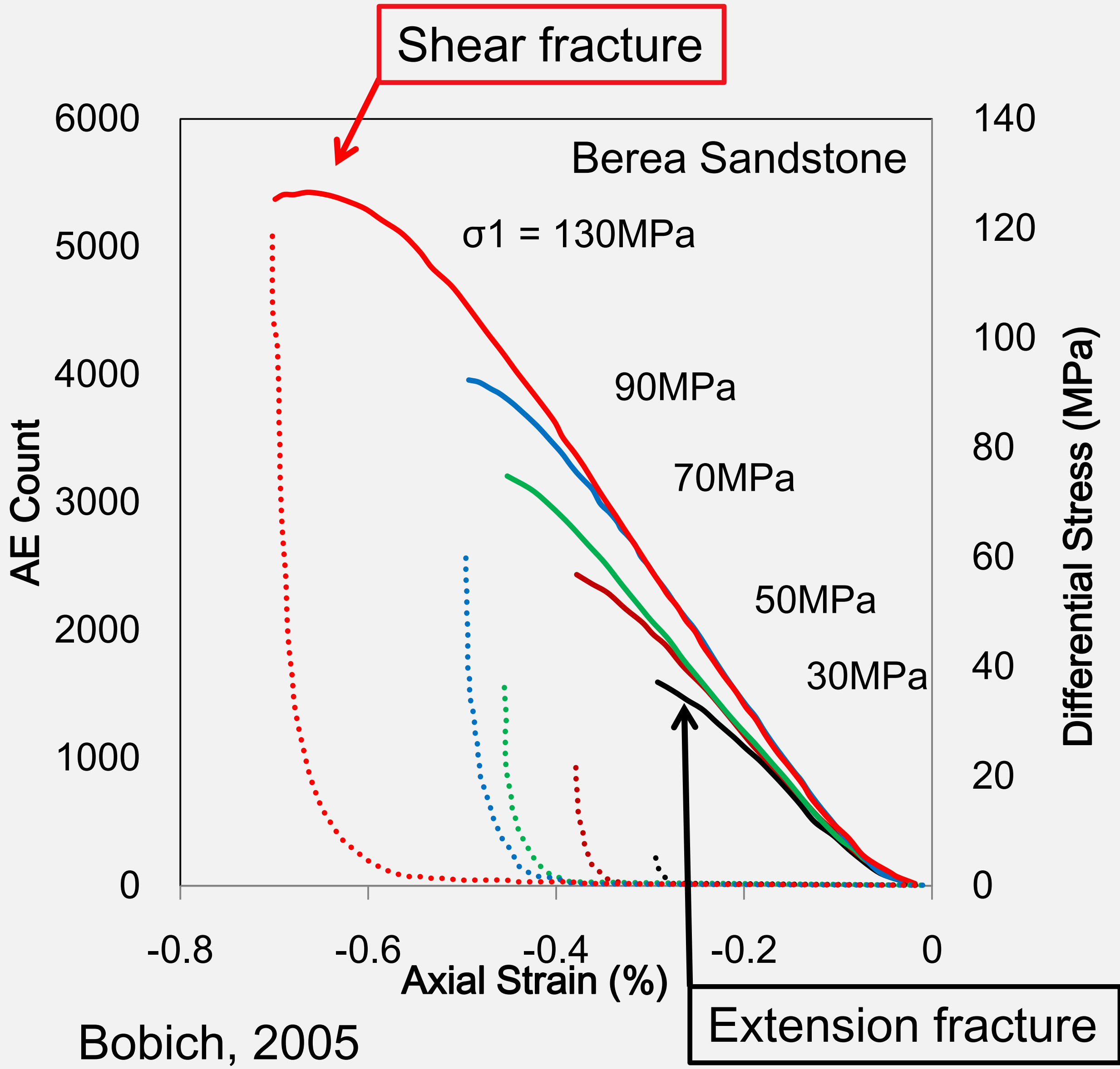
Current Work:

- Indiana Limestone
  - Carbonate reservoir analog
  - 15-20% porosity
  - Calcite-cemented grainstone
- Kansas Chalk
  - North Sea analog, unconventional analog
  - Upper Cretaceous Niobrara FM
  - 30% porosity
  - 99% calcite

*Ramsey (2003), Bobich (2005), Rodriguez (2005)

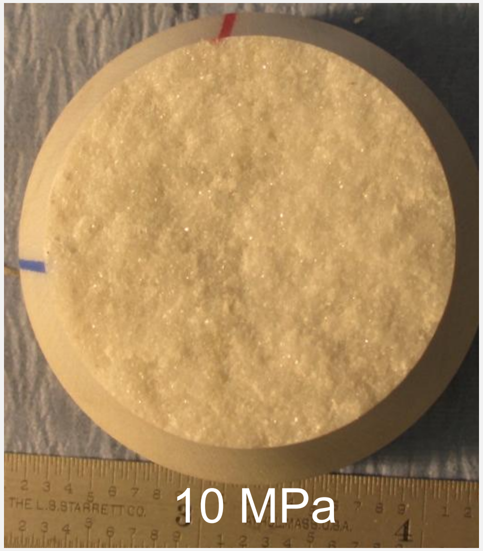
Failure Across Extension to Shear Transition

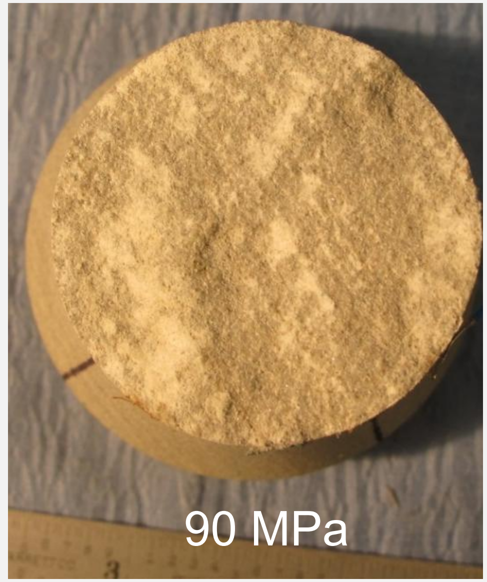
- Damage Accumulation
  - Increasing inelastic strain with σ1
  - Increasing acoustic emissions with σ1
  - Increase in off-fault cracks with σ1

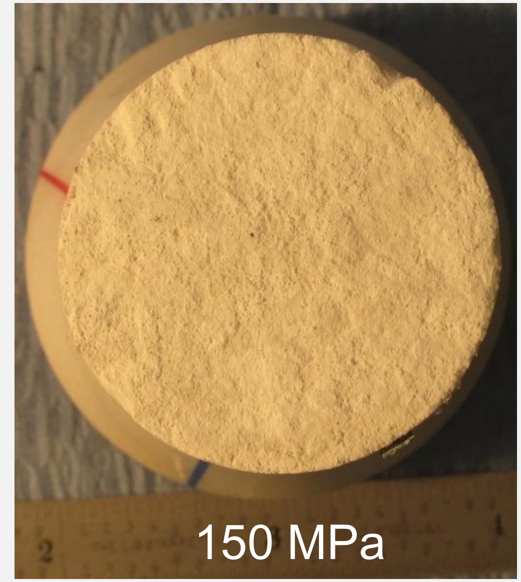


Bobich, 2005

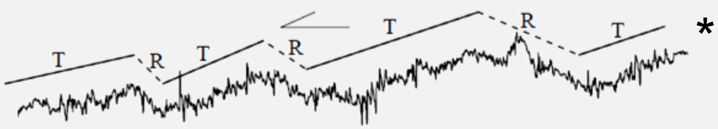
Fracture Morphology Across Mode Transition







- Gradual, systematic transition
- Increasing shear component

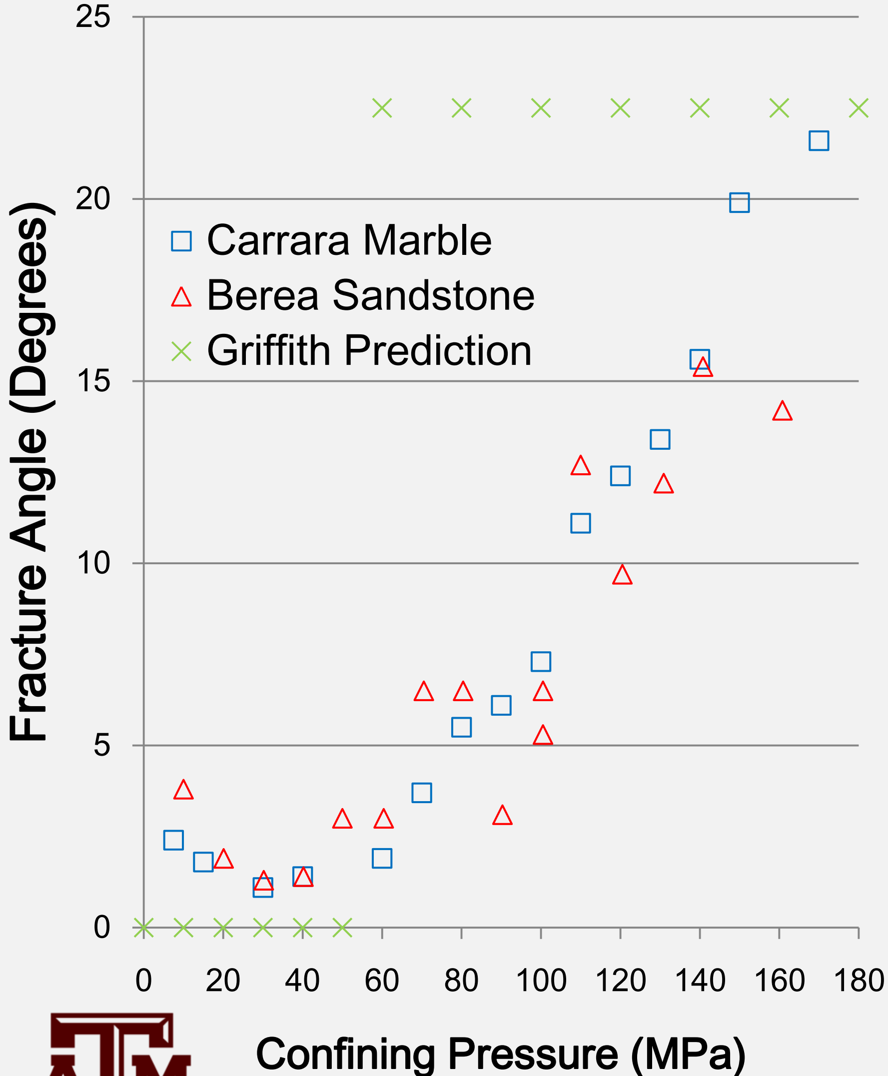


- Hybrid regime
  - Ramp – Flat – Ramp morphology
  - Hill type fracture mesh

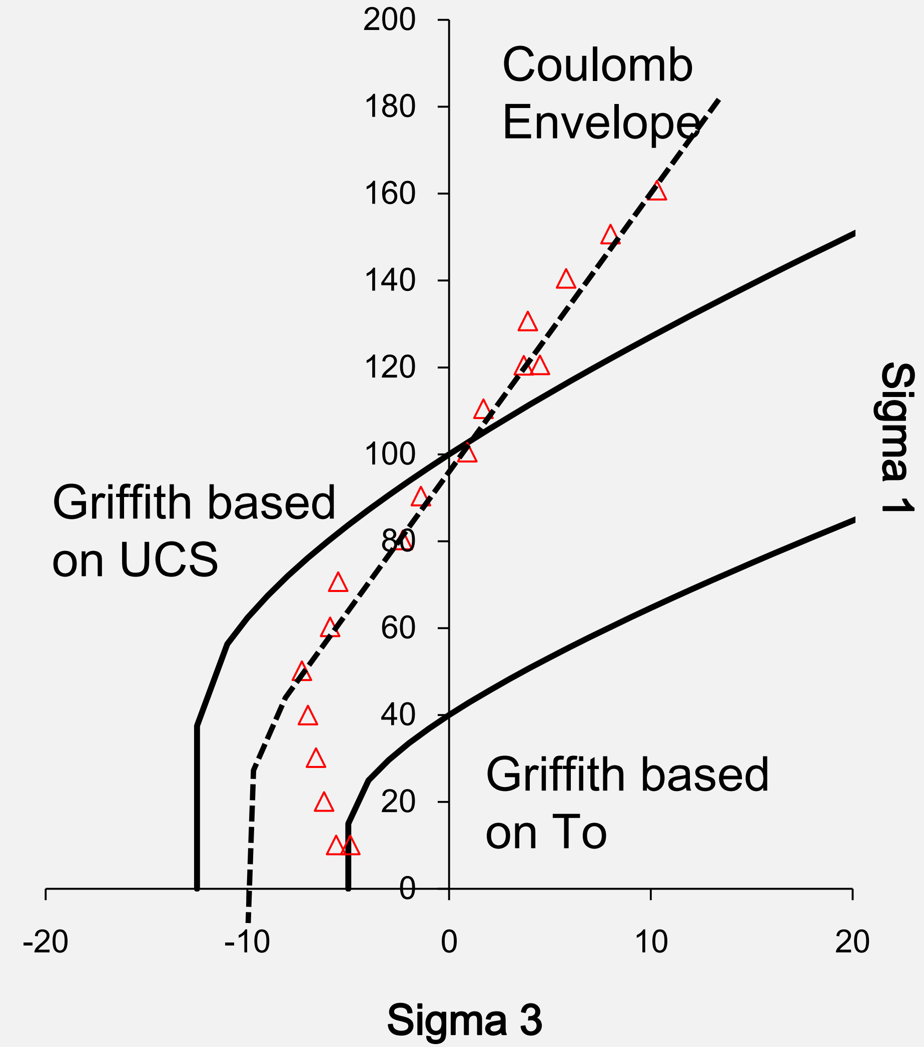
*Rodriguez (2005)

Evaluation of Composite Failure Criterion

Fracture Angle



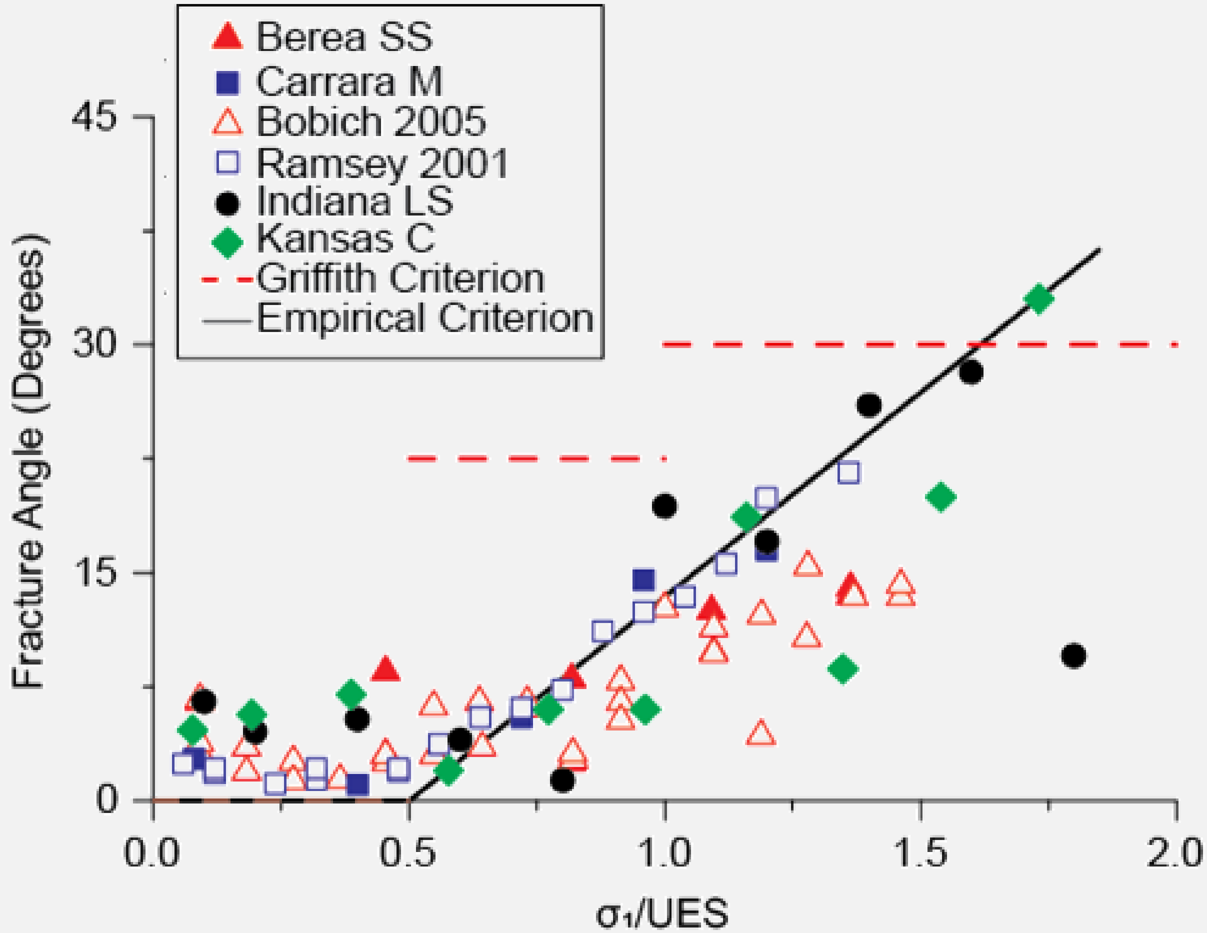
Fracture Strength



Ramsey (2003), Bobich (2005)

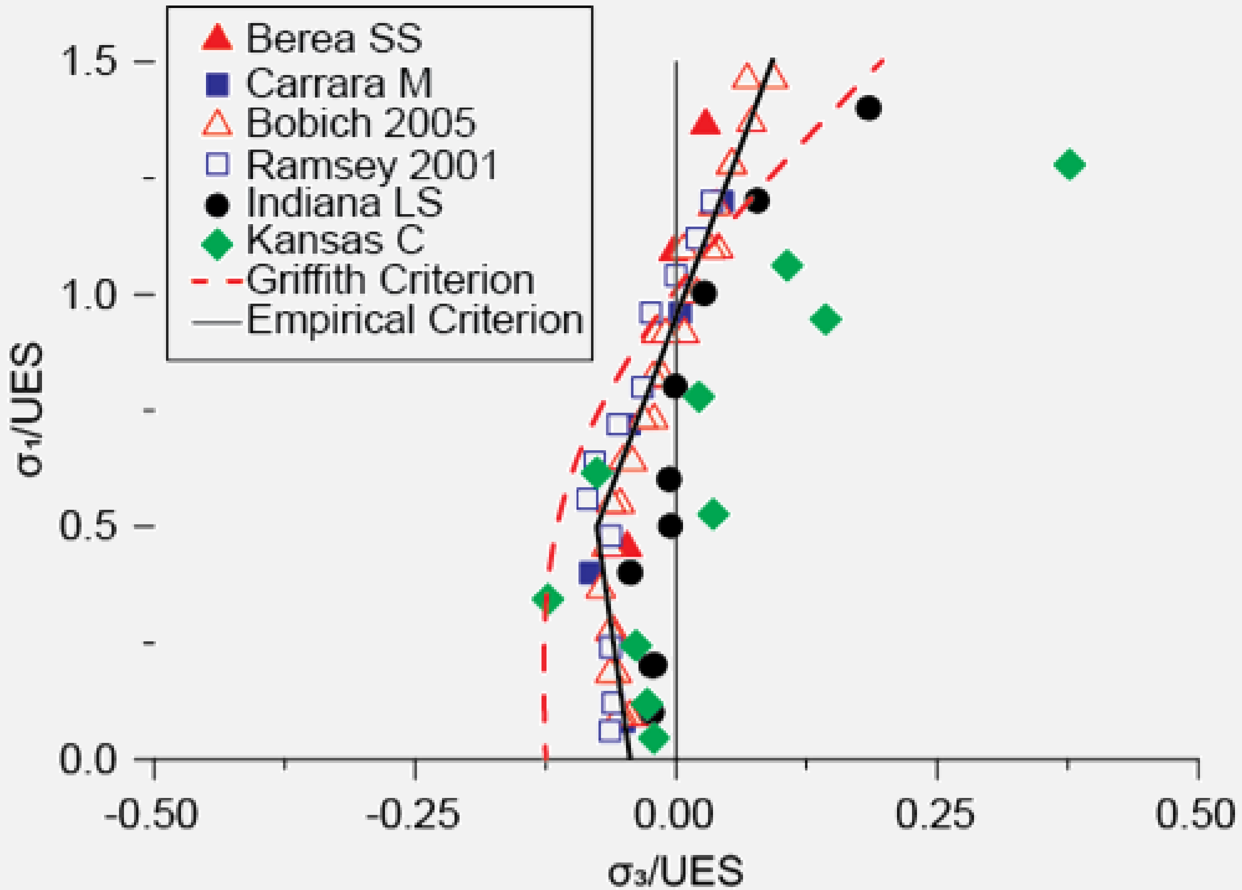
Universal Failure Behavior for All Rocks

- Confining pressure normalized to UCS in extension
- Higher relative pressures tested for Indiana
- Noisy, but consistent trend
- Griffith inaccurate



Universal Failure Behavior for All Rocks

- Increasing tensile strength with increasing sigma 1
- Linear transition to shear
- Failure envelope based on normalized comparison
- UCS:T_0 = 20:1
  - Griffith = 8:1



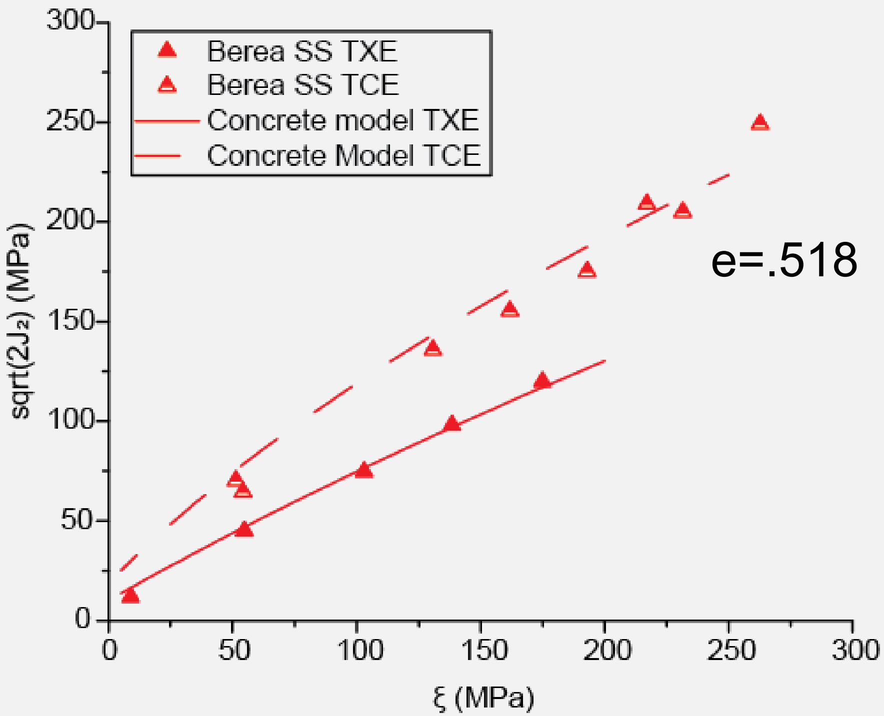
Application in Numerical Modeling

Menetrey & William, 1995

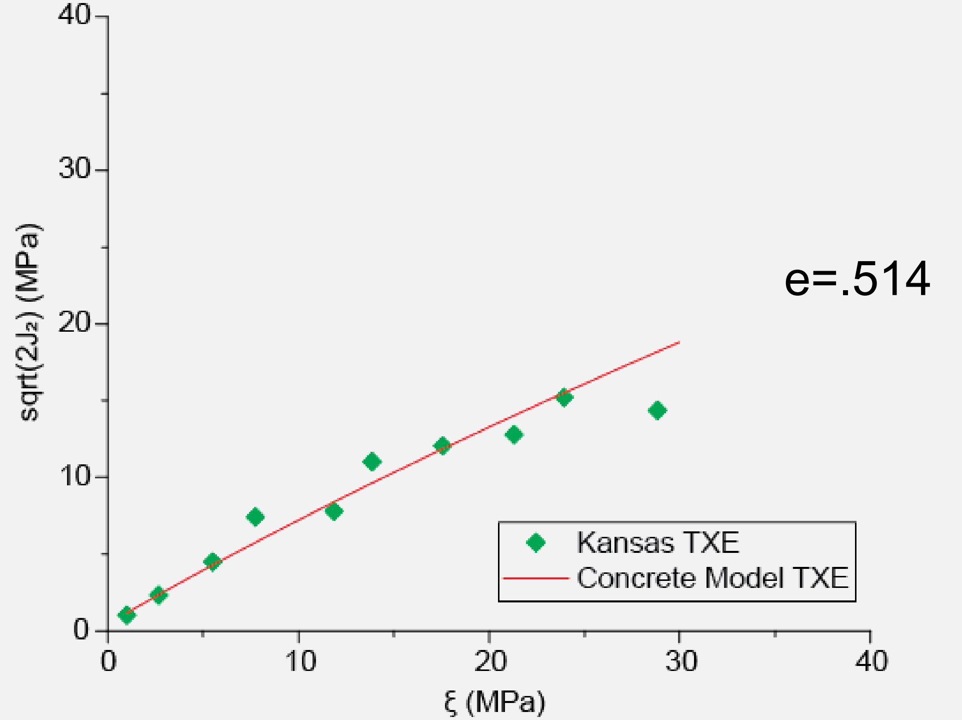
- Designed for biaxial concrete tests
  - Behavior in triaxial extension and compression
- Extension of Hoek Brown
  - Stress based approach
  - Incorporates intermediate principal stress effects
- Shape of deviatoric section changes from triangular to circular with increasing pressure
- Scaled by UCS, To, and eccentricity, e
- Easily extends to standard failure criterions

Menetrey & William, 1995

Berea Sandstone



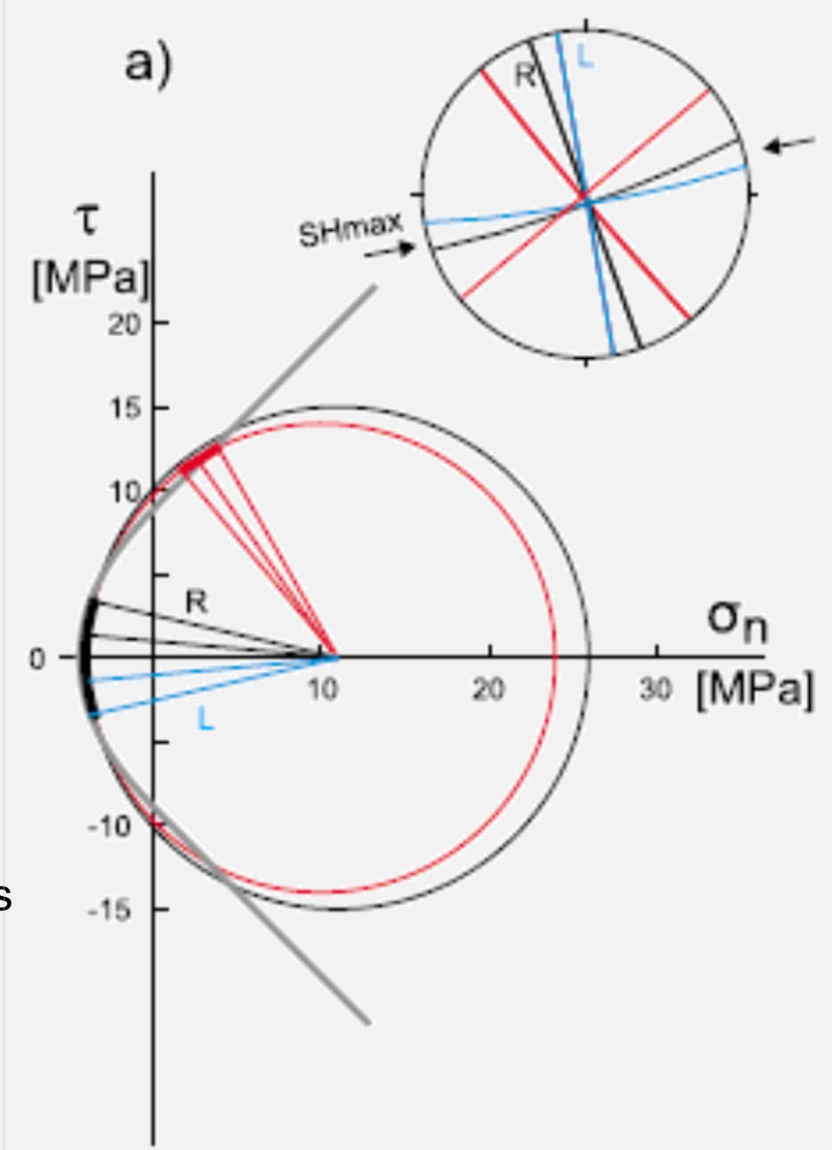
Kansas Chalk



- Excellent match for different stress states, different rock types
- Breaks down at higher confining pressures, shear enhanced compaction

Cotton Valley Revisited

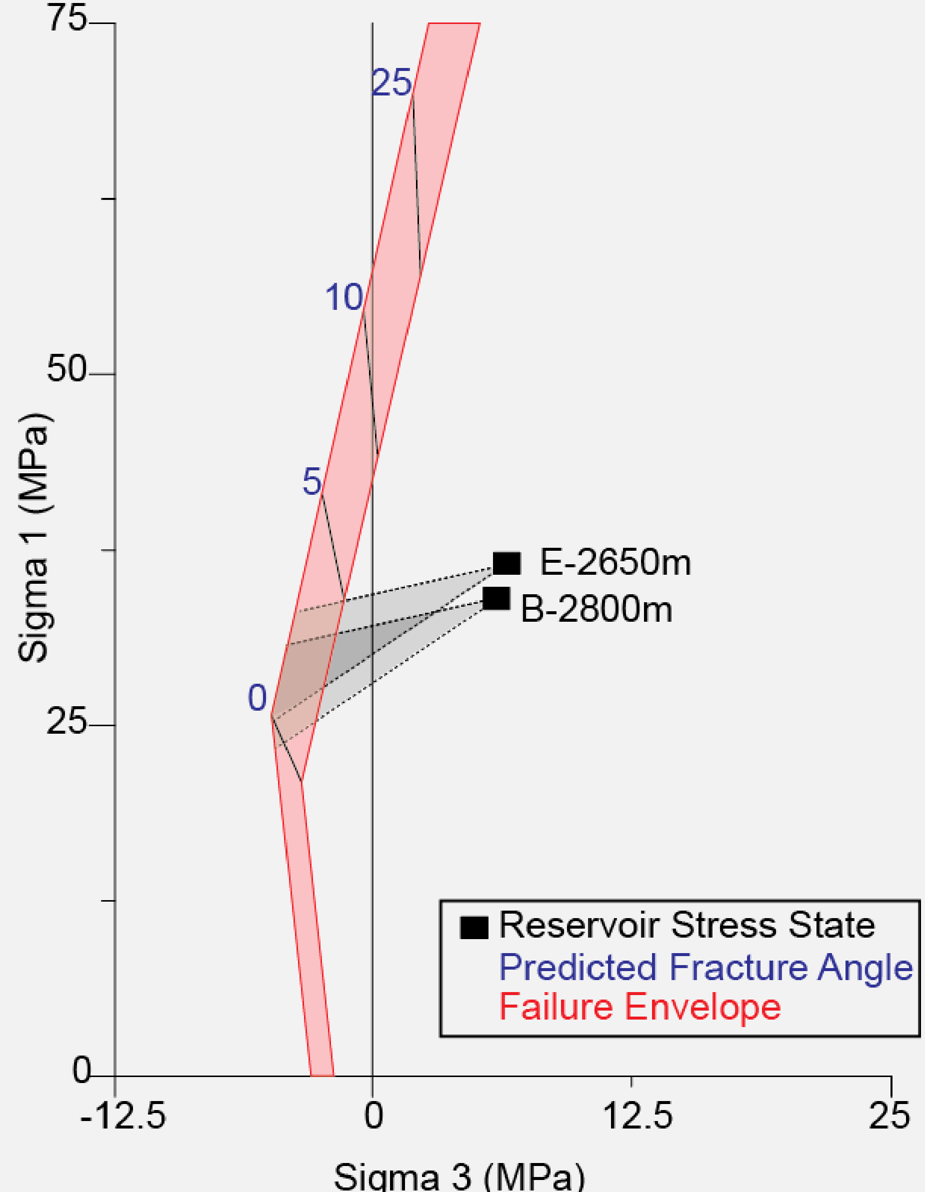
- 1997 Hydraulic Stimulation of Carthage Cotton Valley gas field, E TX
  - Low perm gas sands
  - Depths 2607-2838m (8550-9311ft)
  - DC, non DC microseimic sources, Hill type mesh
- *Shear and tensile earthquakes caused by fluid injection,* Fischer and Guest, 2011
  - Use reservoir stress state, rock properties
  - Tensile faulting, shear reactivation of preexisting feature
    - Faults striking 10° off Shmax classified as tensile
  - Disagrees with microseismic interpretation



Fischer and Guest, 2011

Cotton Valley Revisited

- Scaled failure envelope to range of failure conditions
  - 40-60 MPa UCS
- Effective reservoir stresses
- Stress perturbation around crack tip
  - Based off fracture mechanics
- Predict hybrid failure
  - Fractures 0-5°
  - Similar to 50-90 MPa Berea and Carrara Experiments
- Able to match seismic observations
  - Observed angles slightly higher
  - Stepped morphology



Conclusions

- Mixed mode failure likely occurring in many reservoir stimulations.
- Experiments demonstrate excellent basis for improving and scaling empirical failure criteria.
- Biaxial concrete model successfully describes failure condition for different stress states.
- Able to predict mixed-mode fracturing inferred for Carthage Cotton Valley tests.