Click to see animation of fracture simulation.

Numerical Simulation of Reservoir Structures, Part I: Rheology of Reservoir Rocks*

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Search and Discovery Article #40483 (2010)
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*Adapted from oral presentation at AAPG Convention, Denver, Colorado, June 7-10, 2009. Please refer to closely related articles by Seth Busetti and co-workers: Numerical Simulation of Reservoir Structures, Part II: Propagation of a Pressurized Fracture in Rock Layers with Damage Rheology, Search and Discovery article #40484 (2010), and by Vincent Heesakkers, Seth Bushetti, and Ze'ev Reches, Numerical Simulation of Reservoir Structures, Part III: Folding of a Layered Rock Sequence in a Ramp System, Search and Discovery article #40485 (2010).

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Abstract

We simulated rock mechanics tests to model rock rheology for use in numerical simulations of the development of reservoir structures. Experiments show that during folding, fracturing, and faulting of the upper crust, rocks progress from quasi-linear elastic to non-linear elastic behavior. In order to solve complex mechanical processes under realistic in-situ conditions, we combine experimental and field observations with finite element simulations. In a series of three abstracts presented in this meeting we describe our efforts using the code Abaqus. Part I describes the elastic-plastic rheology of damaged rocks and implementation in numerical simulations of experiments with Berea Sandstone. In the companion articles we apply the rock rheology to hydraulic fracturing (Part II - Busetti et al.) and ramp-folding (Part III - Heesakkers et al.) problems.

Experiments show that rocks are weakened by stress-induced damage that coincides with the non-linear portion of the stress-strain curve. Typically, this curve displays four stages: 1) elastic (linear or non-linear); 2) strain hardening and the onset of microcracking; 3) crack coalescence; and finally 4) strain softening and fracture propagation. Besides plasticity, non-linear elastic and visco-elastic rheology have been used as proxies to accommodate large deformation during strain hardening.

We converted stress-strain and damage characteristics for several reservoir rocks into numerical material models. Failure conditions are described by a yield surface that is curved in tension (failure occurs at 90°). We used fracture maps and acoustic emissions data to set the finite element damage parameter, d, a stiffness multiplier defined as the ratio of damaged to intact rock. Our benchmark tests are for Berea Sandstone: four-point beam bending (Weinberger et al., 1994) and dog-bone shaped samples under triaxial extension (Ramsey and Chester, 2004; Bobich, 2005). The simulations agree with experiments for confining pressures, Pc, of 10 to 150 MPa and reflect the four stages of damage mentioned above. For Pc < 60 MPa, the onset of damage occurs at 0.05-0.1% extensional strain and increases exponentially until failure at 0.1-0.3%. Prior to first fracture, stiffness degrades 5-10%. Multiple fractures occur in regions of 15-20% stiffness reduction. In the dog-bone setup, damage widens as Pc increases. Results of simulations suggest that the rheology can be utilized in more complex problems.

Acknowledgements

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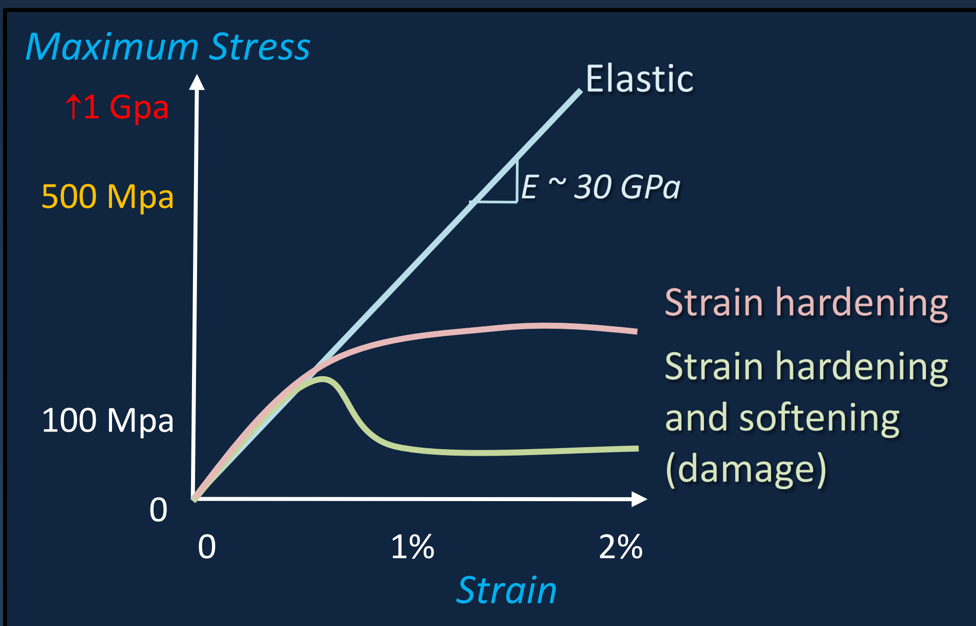
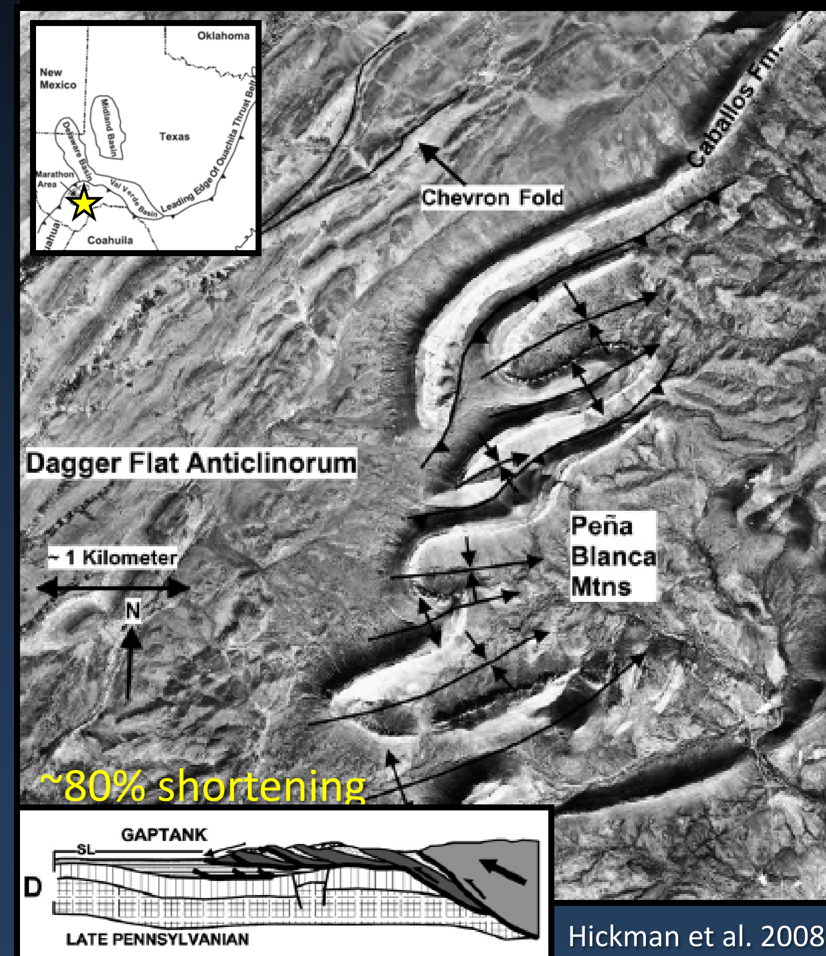
Development of Reservoir Structures

Structural Analysis:
- Structural *architecture*
- Kinematic *evolution*
- Distribution of **stress*
- Pattern of **strain*

*rock rheology = deformation behavior



Marathon-Ouachita Thrust Belt, West Texas



Hickman et al. 2008

Modeling Reservoir Structural Development

Objective:

Deformation Processes : geometry, stress, strain, strain-history

Upper Crust Conditions : brittle behavior, structural deformation

Finite Strain : large deformation including rock failure

Strategy:

Numerical Simulations

Use Finite Element Method for complex mechanics

1) *Methodology:*

Develop a material model for rock rheology

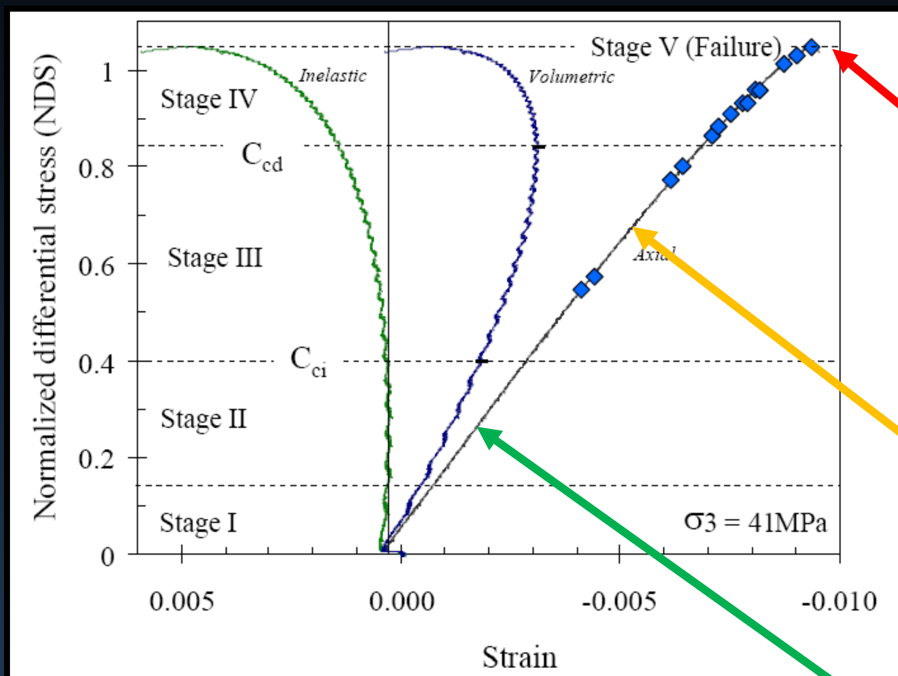
(1) rock behavior from rock mechanics experiments

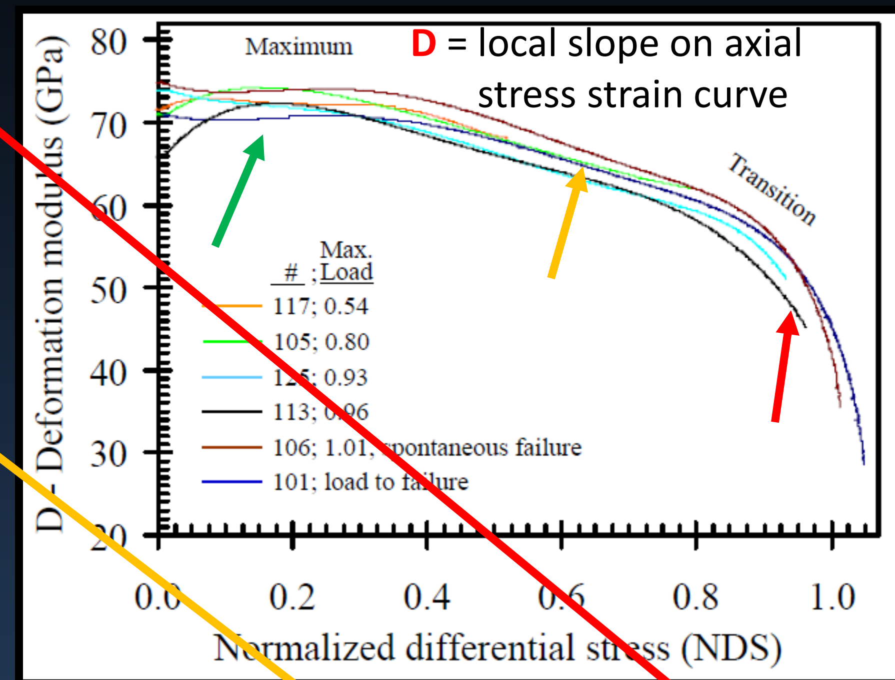
(2) FE benchmark simulations and analysis

2) *Application:*

Implementation in structural geology problems (Parts II and III)

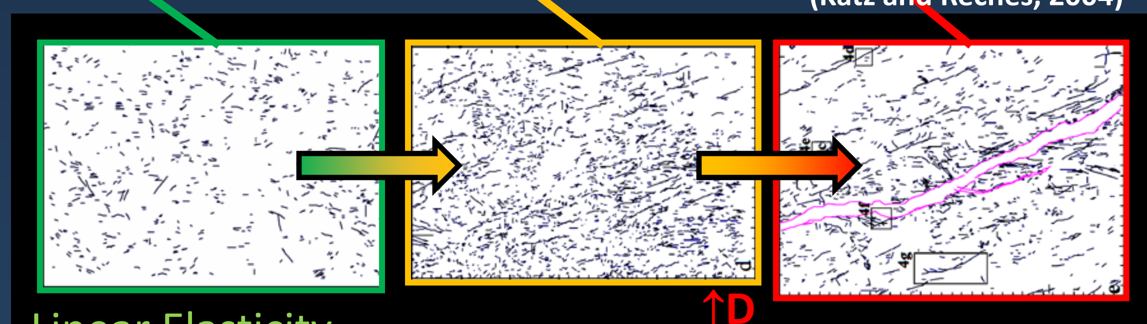
A Key Source of Non-linear Behavior – Brittle Damage





(Katz and Reches, 2004)

Maps of thin sections during progressive deformation identify the presence of microcracks surrounding fractures



Linear Elasticity

Strain Hardening

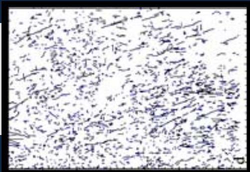
Failure and Propagation

Continuum Damage Mechanics Theory

Mathematical expressions for damage

Continuum damage models approximate the amount of stiffness and strength degradation due to microcracking

$\boldsymbol{d} = (A - A_{net})/A$



load bearing in τ, σ_c, σ_t ?

Experimental

$D = d(\sigma 1 - \sigma 3)/d\varepsilon$ — *Deformation modulus*

$D/D_{max} = E/E_{max}$ — *Stiffness degradation*

Theoretical

$\mathbf{D}^{el}/\mathbf{D}_0^{el} = (1 - \boldsymbol{d})$ — *Stiffness degradation*

$\sigma = \mathbf{D}^{el}\, \varepsilon^{net} = (1 - \boldsymbol{d})\mathbf{D}_0^{el}\, (\varepsilon - \varepsilon^{pl})$

Effective stress concept *(i.e., FE Abaqus)*

Damage Parameter, ***d***

1.00 -- *Macroscopic Failure* *(zero strength)*

0.75

-- *Yield Strength* *(coalesced microfractures)*

0.25

0.00 -- *No damage*

Several damage models have been developed :

Analytical - Budiansky and O'Connel, 1976
Numerical - Kachanov, 1990; 1993
DEM - Diederichs et al., 2004
FEM - Lyakhovsky, 1997
*FEM - Lee and Fenves, 1998; Abaqus**
FEM - Chen et al., 2006

Numerical Simulations

Goal: To model deformation processes using rock rheology

Requisites:
- ✓ *Develop rheology from common experimental data*
- ✓ *Application to small and large-scale deformation*
- ✓ *Use readily-available commercial software*

Finite Element Method

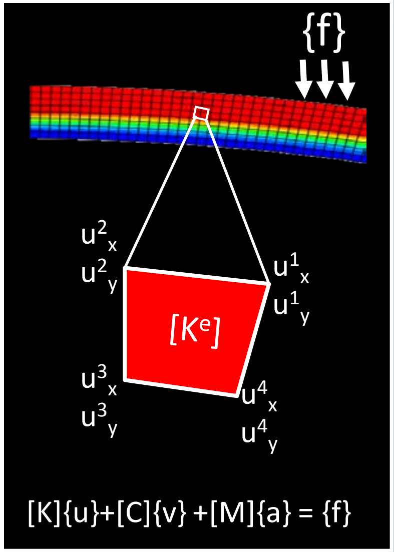
1:1 Scale Models

Fully 3D* and 2D plane strain models

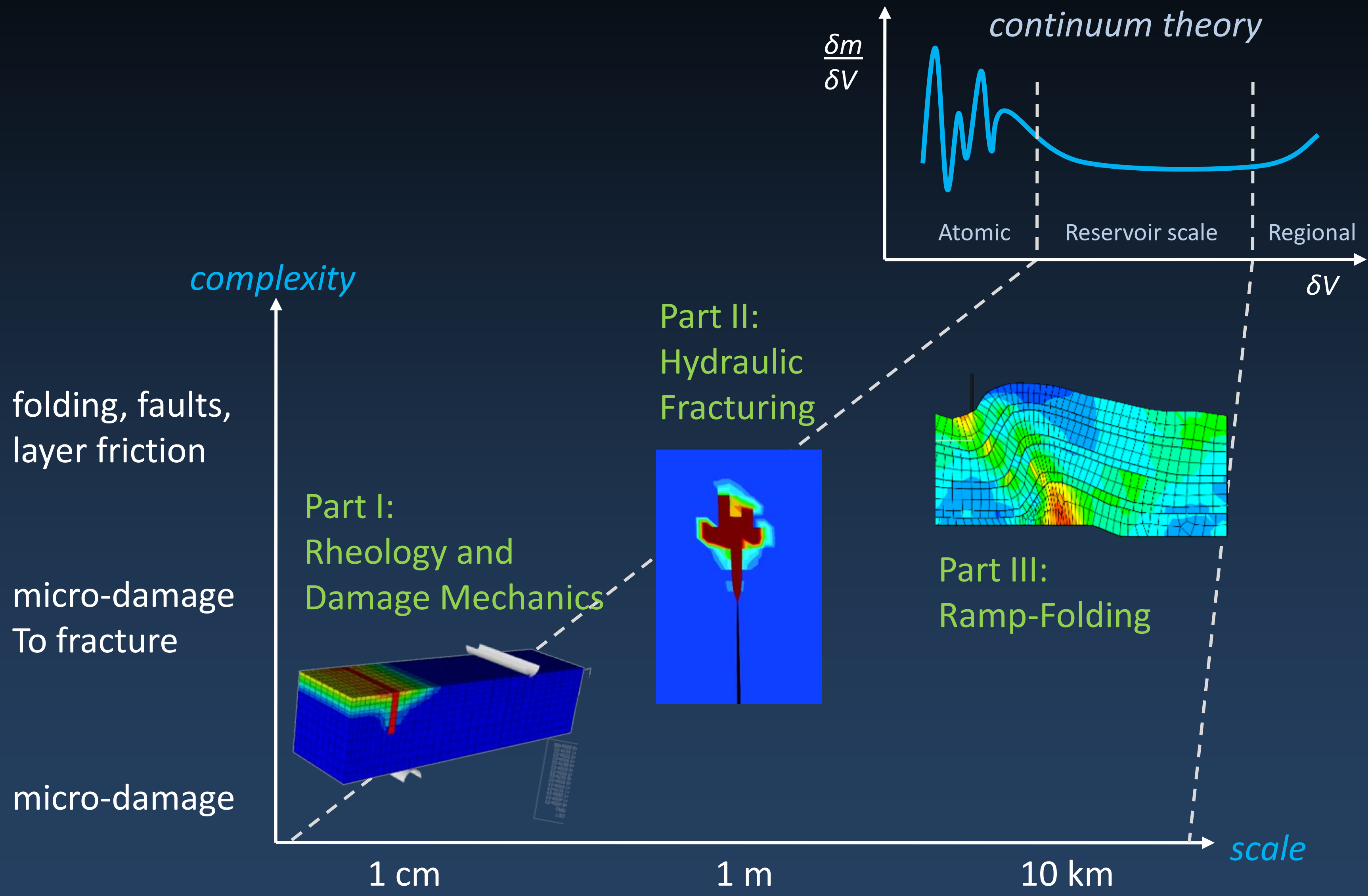
Confining Pressure

Dynamical Solutions:
- quasi-static tectonic loading
- transient deformation including continuum-failure

Explicit/Dynamic Solver: Abaqus/Explicit 6.7-5



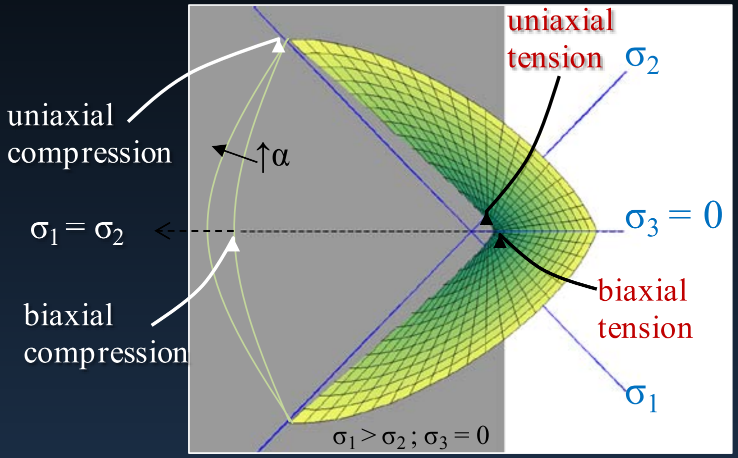
Simulating Deformation – Multi-scale Approach



Failure Criteria – Elastic-Plastic Yield

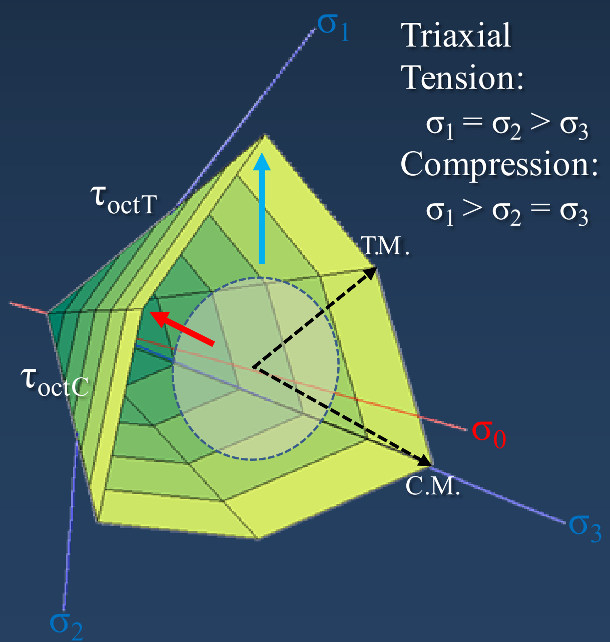
Advantages of the Model*

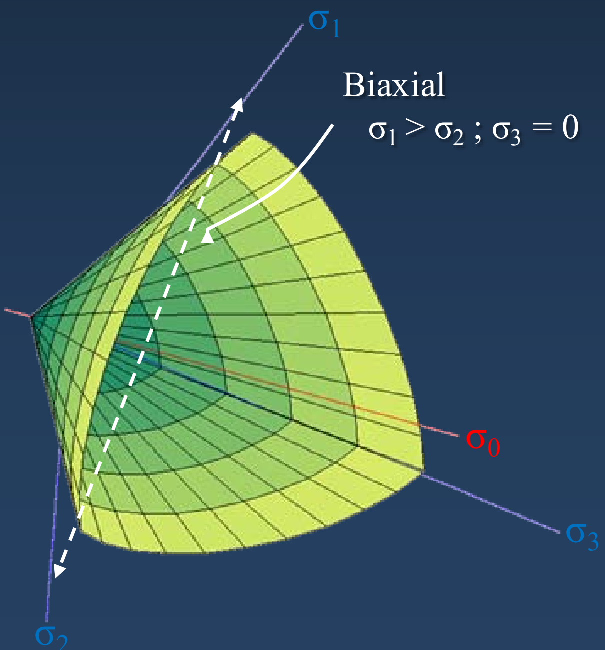
- ✓ Pressure dependent yield
- ✓ Modification of Mohr-Coulomb Plasticity
- ✓ Failure in tension and compression
- ✓ Variable σ_2 dependence (MC – DP)
- ✓ Elastic-plastic + damage (σ-ε^p)
- ✓ Parameters based on uniaxial tests



Disadvantages of the Model*

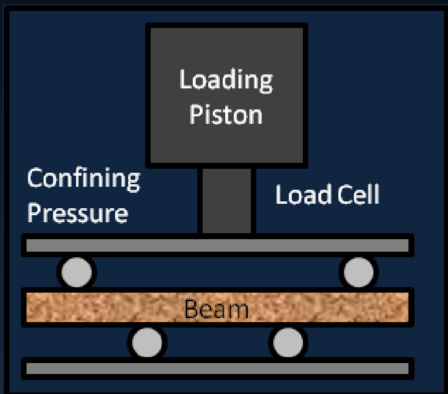
- Mechanics are intensive
- Requires input from a range of experiments
- Can be computationally expensive

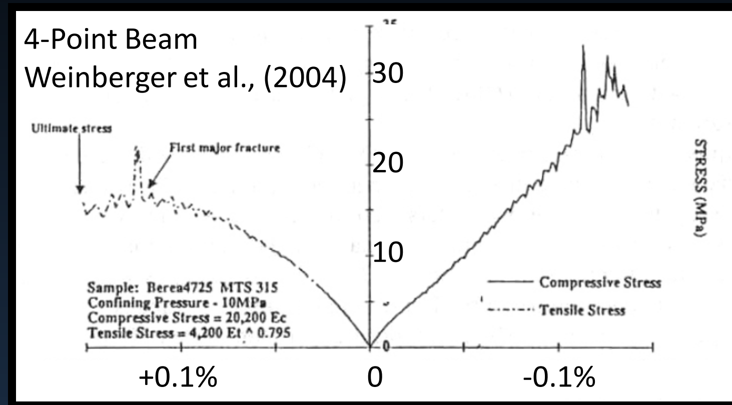




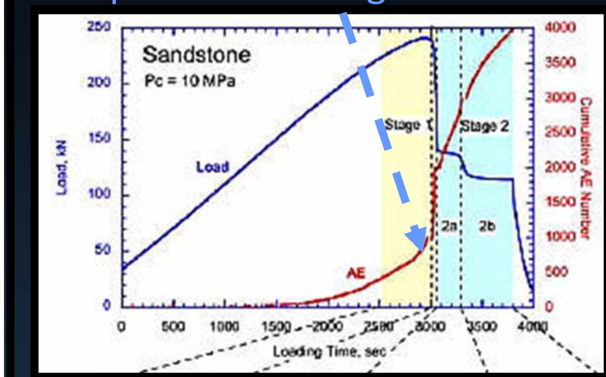
**Lubliner et al., 1989; Lee and Fenves, 1998; Abaqus "Concrete Damage Plasticity"*

Material Models – Berea Sandstone Experiments



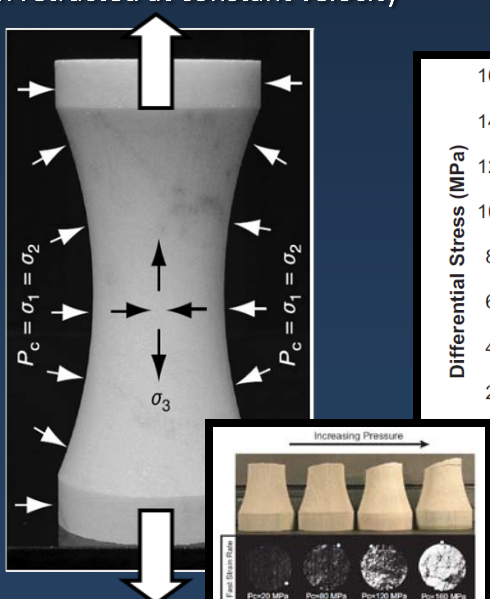


Compression Damage

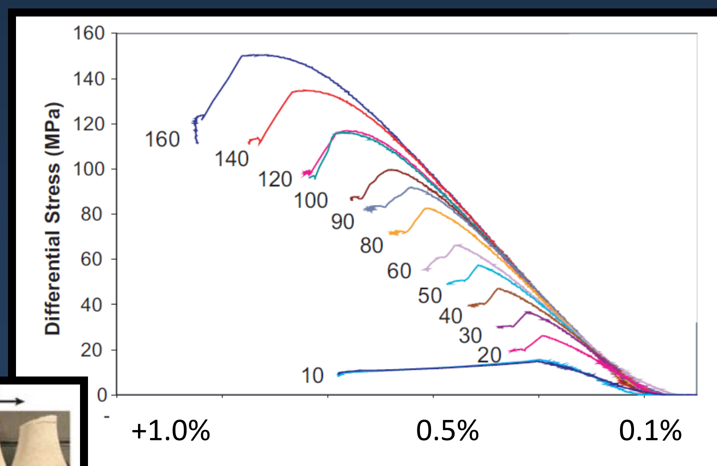


Stanchits and Dresen, 2003

Piston retracted at constant velocity

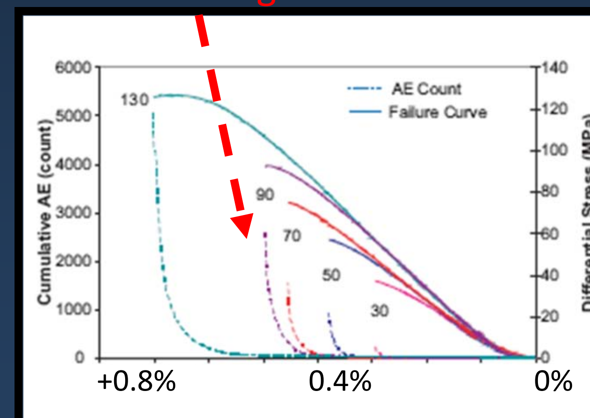


Thick-walled pressure vessel



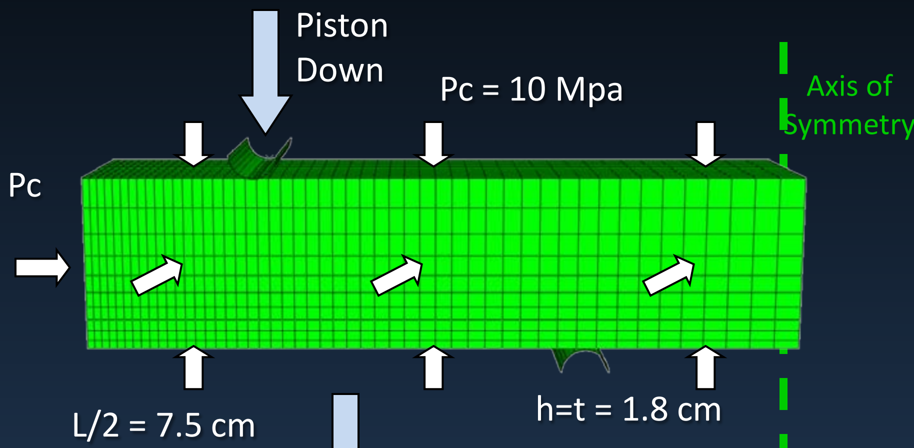
Dog-bone Extension
(Ramsey and Chester, 2004; Bobich, 2005)

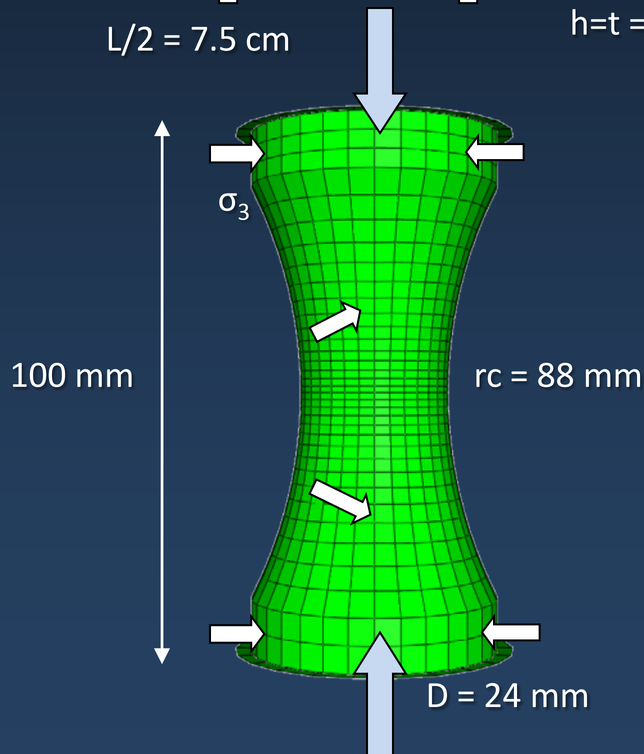
Tension Damage

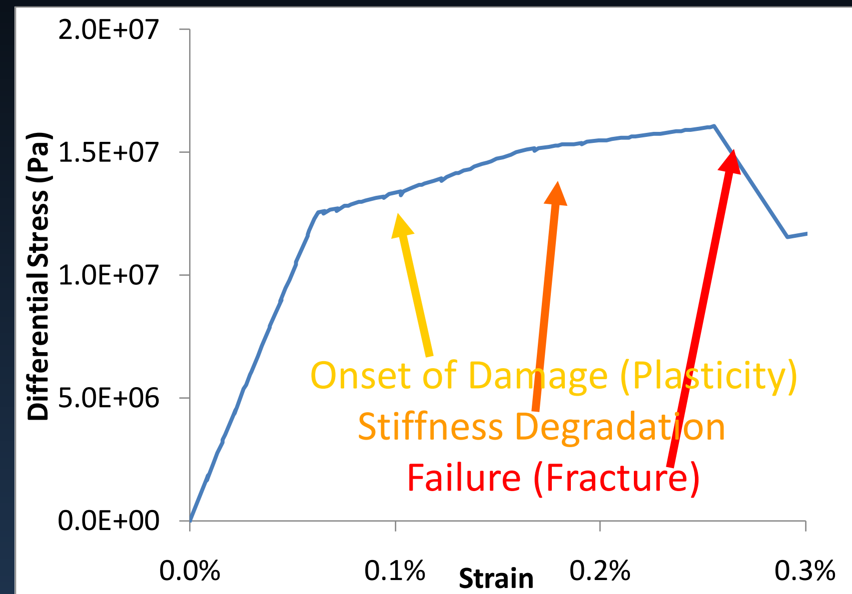


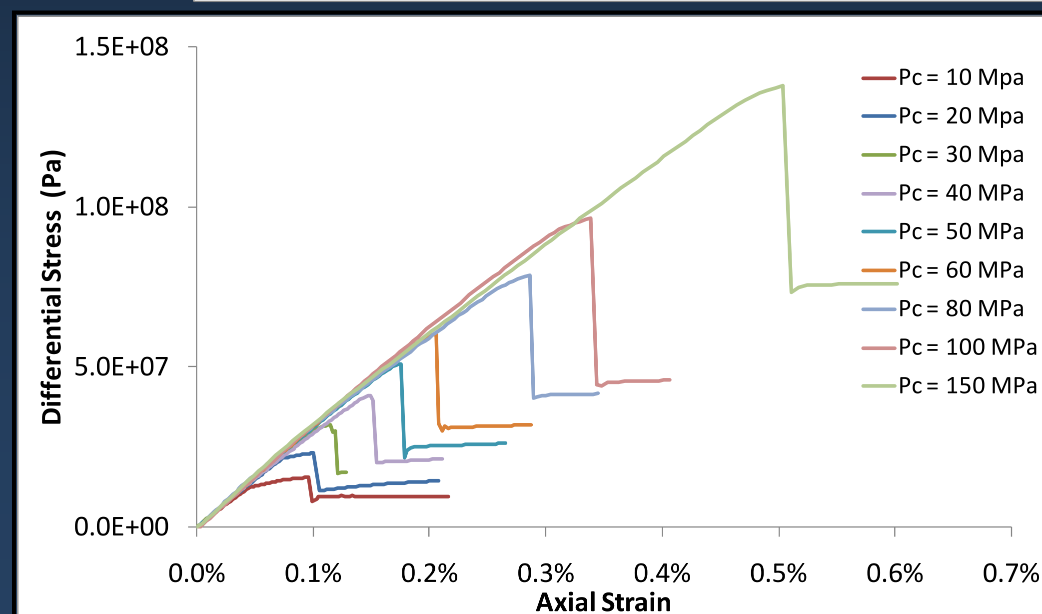
Bobich, 2003

Finite Element Models – Calibrating the BSS Rheology



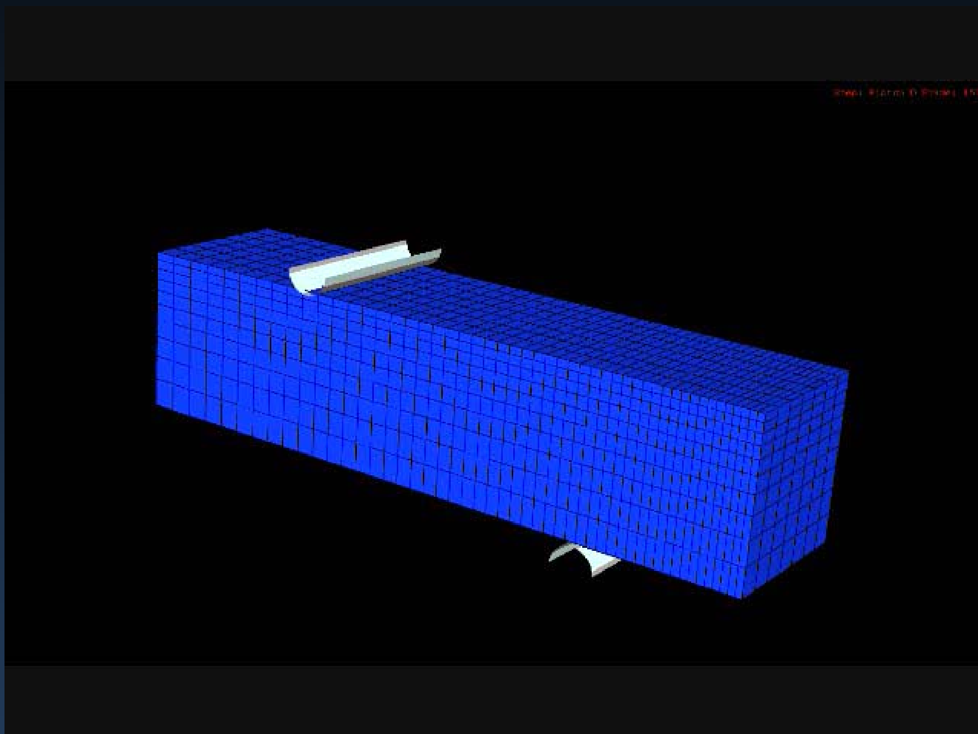


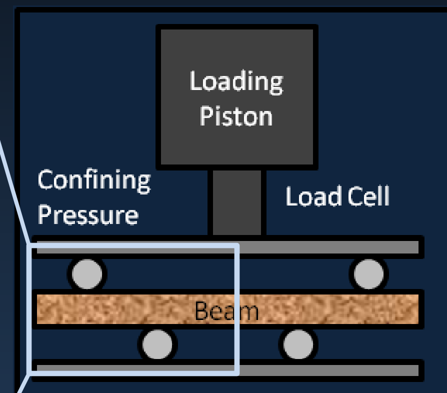


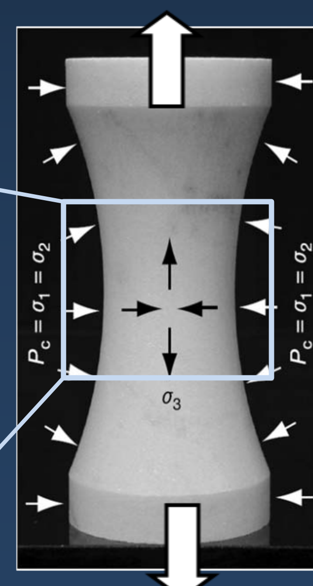


Simulated Deformation – Berea Sandstone Rheology

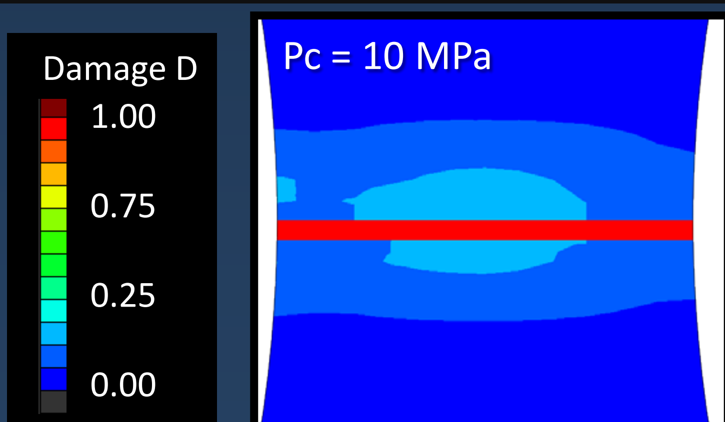
Simulations show that **macroscopic fractures** form in wide zones with **pervasive damage**







Pc = 10 MPa



Summary

1. We developed a numerical rock rheology to use in finite element simulations in order to study the development of reservoir structures

2. The rheology is based on multiple experiments for Berea sandstone and is implemented in the finite element code Abaqus

3. We calibrated the stress, strain, and damage behavior for a range of confining pressures

4. The numerical rheology is now ready to be implemented in geological problems