Click to see animation of fracture simulation.

Numerical Simulation of Reservoir Structures, Part II: Propagation of a Pressurized Fracture in Rock Layers with Damage Rheology*

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Search and Discovery Article #40484 (2010)
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Abstract

We use finite element simulations to study the effect of local geologic conditions during hydraulic fracturing of rock layers with damage rheology. This work is part of our study on structural processes in reservoir rocks using numerical simulations with the code Abaqus. Part I (Busetti et al.) covers rock rheology and benchmark simulations, and Part III (Heesakkers et al.) studies the role of visco-plastic rheology on ramp induced thrust-folding.

Hydraulic fractures frequently propagate through multiple layers of naturally fractured rock, each with distinct stress state and material properties. Thus, we examine fracture propagation as a function of mechanical properties of the host and neighboring layers, layer dimensions, tectonic stress state, and internal pressure. We model a wellbore-scale section of layers with frictional contacts located away from near-borehole effects. Beds of high elastic modulus and yield strength reflect potential “fracture barriers”. Rheology is for elastic-plastic damaged rock based on experiments of Berea Sandstone, Indiana Limestone, and Barnett Shale (see Part I). We first investigated the up-section propagation of a vertical hydrofracture 0.25 m tall, embedded in a 0.3 m host layer, overlain by 1 to 8 horizontal layers from 0.125 to 1 m thick. We establish tectonic stresses for depths of ~2.5 km and then apply increasing pressure (0 - 100 MPa) to viscous fluid in the fracture to simulate a single injection stage.

The results suggest that the model parameters are interrelated. We found the following parameters reduce the tendency to propagate fractures: (1) thinner layers; (2) lower inter-layer friction; (3) higher vertical stress; (4) higher elastic modulus ratio between the host and overlying layers. Higher stress ratio ($S_v > S_h$) increased the tendency for longer fractures; lower stress ratio ($S_v \approx S_h$) increased the tendency for multiple sub-vertical fractures. The models indicate that interlayer slip is a strong mechanism to locally accommodate pressurization strain. We anticipate that slip along preexisting fractures and bedding planes could redirect flow along diffuse fracture patterns. The simulations indicate that to predict propagation of hydrofractures, one should consider fracture interaction with preexisting structures and their local stress. Future models will explore the effect of fracture inclination as well as growth in three dimensions.

Acknowledgement

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June 2009

Hydraulic Fracturing in Tight Reservoir Rocks

Actual geologic conditions are quite complex…

…actual hydraulic fractures are equally complex…

2 ft

Heterogeneous Reservoir Rock, Alternating Barnett Shale Lithologies

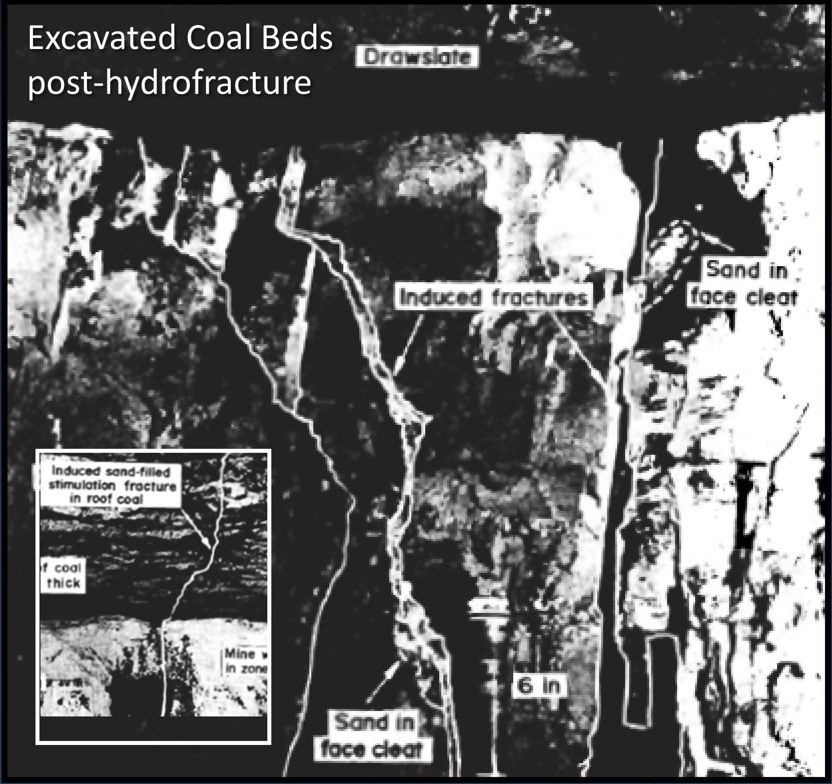
Barnett Shale, TX

*http://www.geo.utexas.edu/scientist/milliken/barnettshale.htm

Heavily Fractured, Water-Bearing Ellenberger Limestone

Courtesy of Devon Energy

Excavated Coal Beds post-hydrofracture



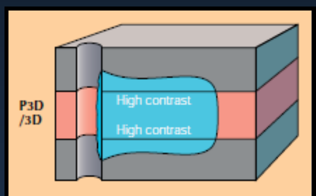
Bureau of Mines, 1977

Goal: Understanding the process under in-situ geologic conditions

Models for Hydrofracturing – Geologic Complexity

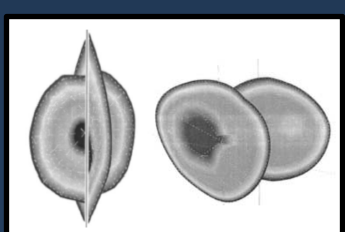
"Geometric Models"

Simple Rheology
Simple Propagation
No Interactions



Brady et al. 1992

Simple Rheology
Complex Propagation
No Interactions

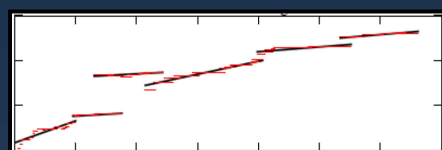


Yamamoto et al. 2004

Simple Rheology
Simple Propagation
Simple Interactions

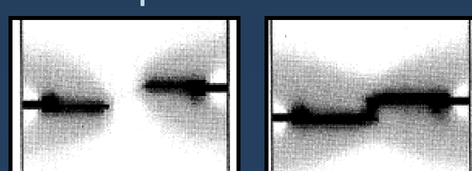
Murphy et al., 1988

Simple Rheology
Complex Propagation
Complex Interactions



Sim 2004

Complex Rheology
Simple Propagation
Complex Interactions



Weinberger et al. 2000

Rock Rheology

- Linear Elastic [1]
- Linear elastic, non-linear cohesive zone [2]
- Elastic-plastic, non-linear cohesive zone [3]
- Non-linear elastic, continuum damage [4]
- **Elastic-plastic, continuum damage [5]**
- Elastic-plastic, damage, fluid penetration[6]

[1] e.g., Hubbert and Willis, 1957; Haimson, 1967; KGD; PKN; Radial; Desrouches et al., 1994
[2] after Barenblatt, 1962
[3] e.g., Papanastasiou, 1997
[4] Weinberger et al., 2000
[5] this work
[6] future work

Our Aim is to Model:

✓ Complex Rheology
✓ Complex Interaction
✓ Complex Propagation

Scope of the Study

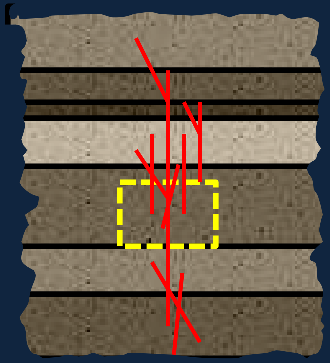
Tectonic Stress State

✓2D Plane Strain

Scale

Far Field (geologic conditions)

✓Single layer (1s meters)



Simulation Time

✓Short Duration

Layer Properties (*Rheology, Geometry)

✓Isotropic Host Layer

Fracture Interactions

✓Fracture Propagation

✓Fracture Pattern

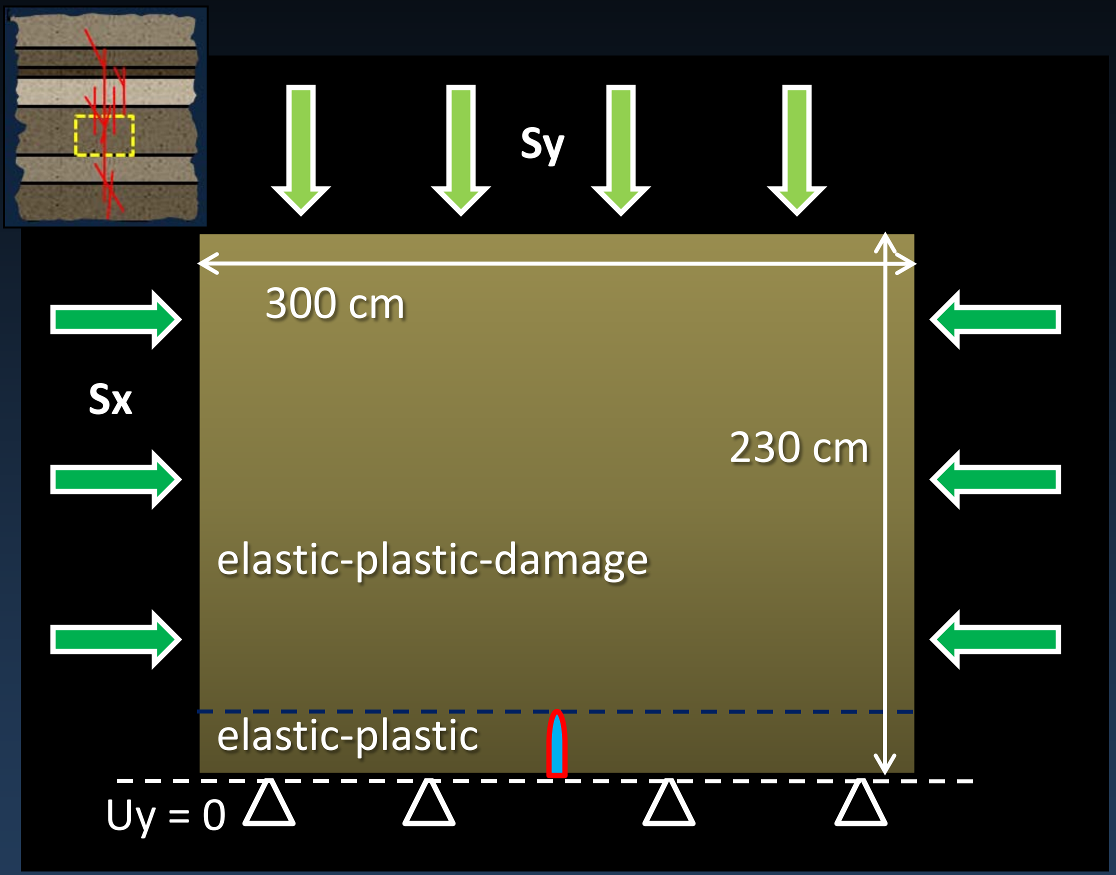
Fluid Properties

✓Internal Pressure

✓Pressure Distribution

**Part I*

FEM Model Configuration



Tectonic Loading:

Sy = 50 MPa

Sx = 10-45 Mpa

Pressure Loading:

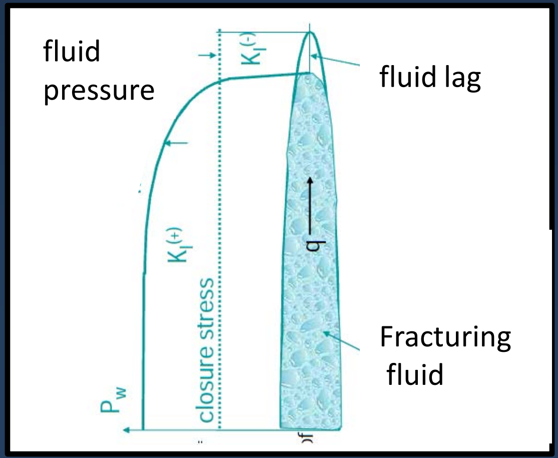
No fluid penetration

Pf(t) = linear increase

(a) constant pressure

(b) non-linear distributed pressure:

$$dp/dx = 12\mu q/w^3$$



Modified from Papanastasiou, 2002

Finite Element Analysis:

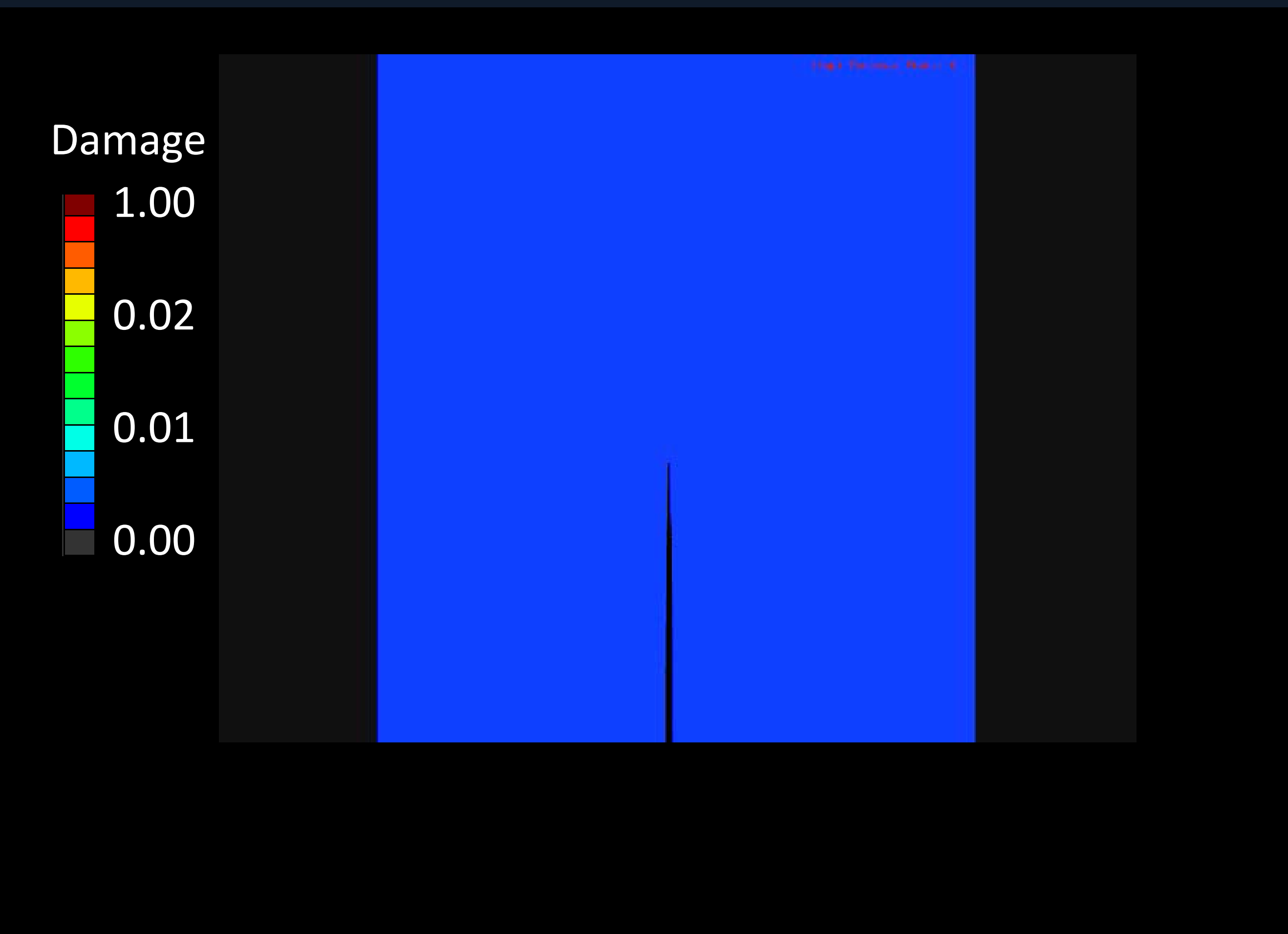
2D plane strain

explicit dynamic solver (Abaqus/Explicit)

2680 linear quad/tri elements

Hydraulic Fracture Propagation Simulation

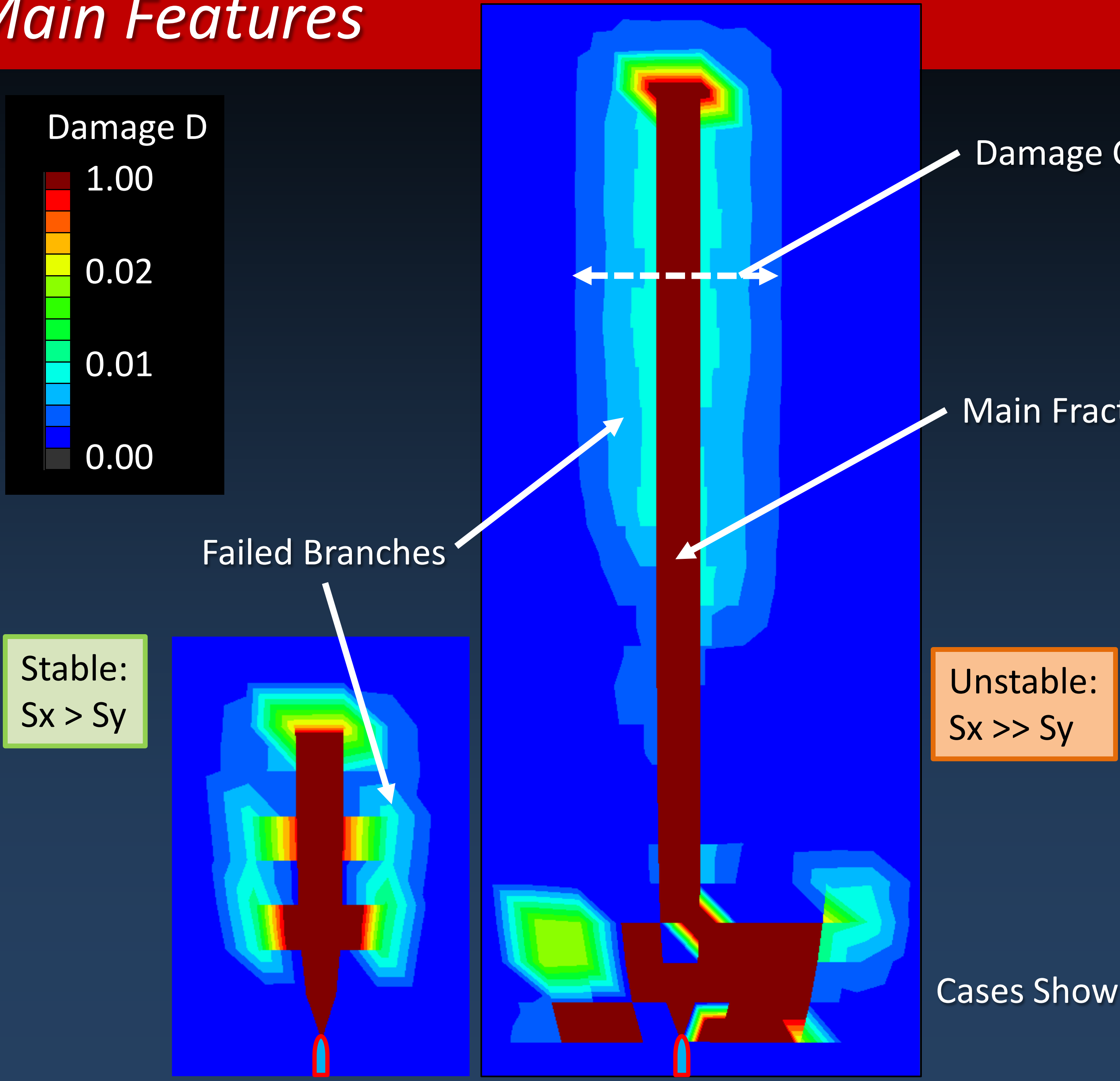
20x 50y dp/dx=0



Hydraulic Fracture Propagation Simulation

20x 50y dp/dx=0

Main Features



Cases Shown: Extension Only (P = 0)

Hydraulic Fracture Simulations: Analysis / Discussion

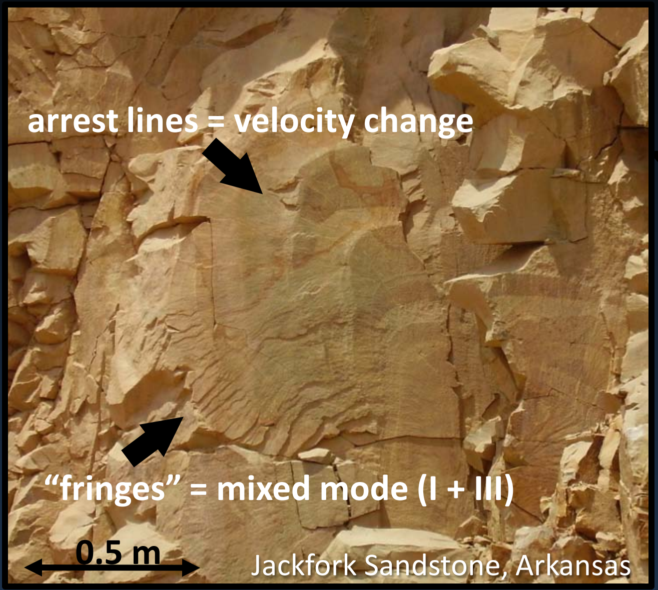
Discussion of Simulations – Highlights

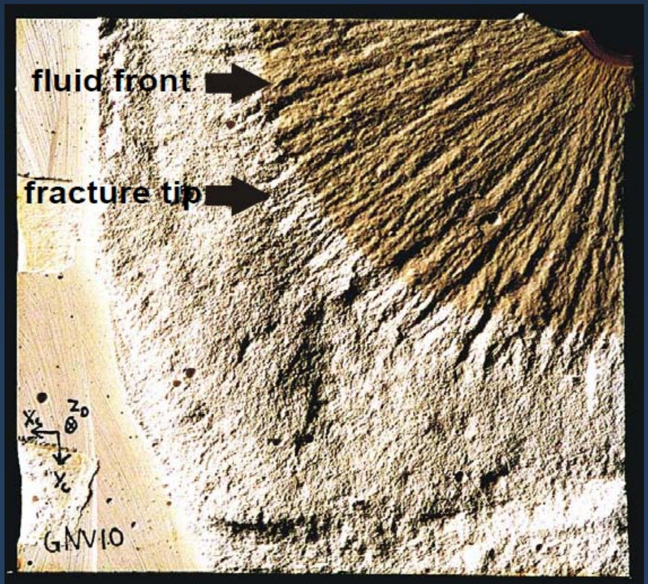
1. Fracture Morphology
    a. Fracture arrest and rupture
    b. Segmentation and branching
    c. Fracture velocity and stability (*not discussed here*)

2. Conditions Controlling Propagation
    a. Tectonic load / fluid pressure
    b. Fluid pressure distribution (*not discussed here*)

3. Example Reservoir Application

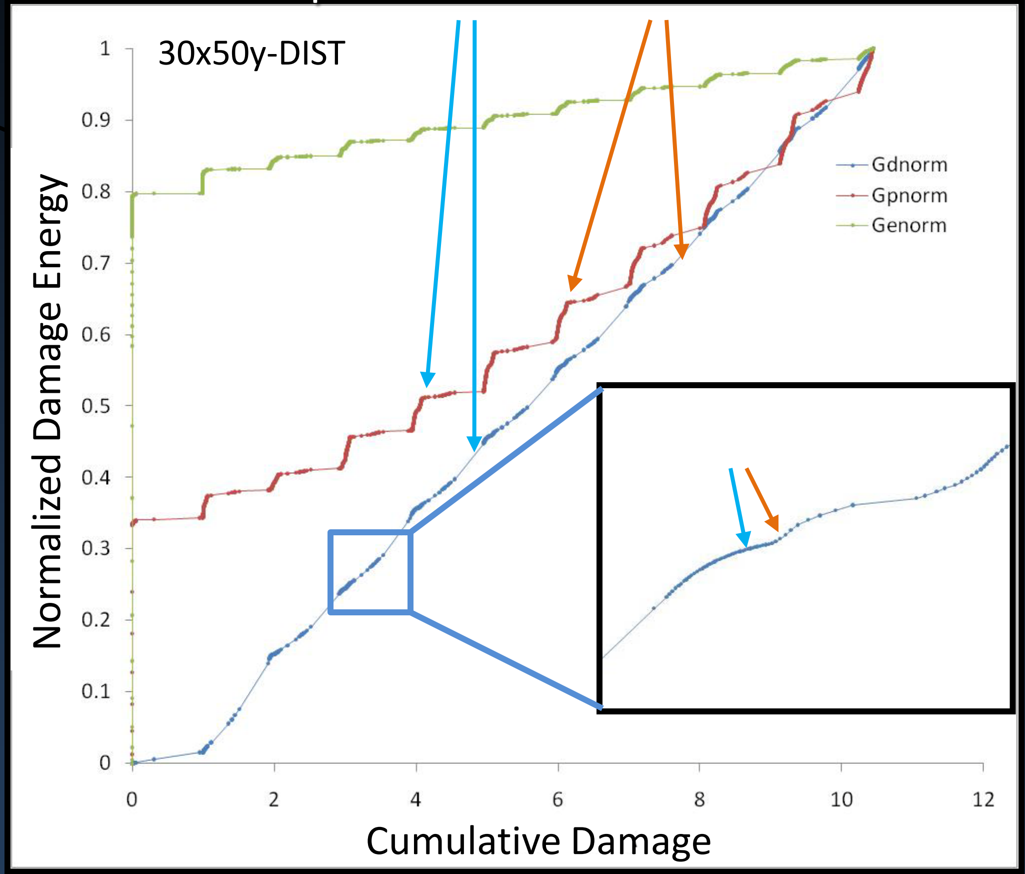
1a. Morphological Features: Fracture Arrest and Rupture





DelFrac Experimental Hydrofrac (Papanastasiou, 2002)

Multiple Growth and Arrest Periods



Cumulative (global) pattern shows build-up and release periods, ≈ stable or unstable fracture growth.

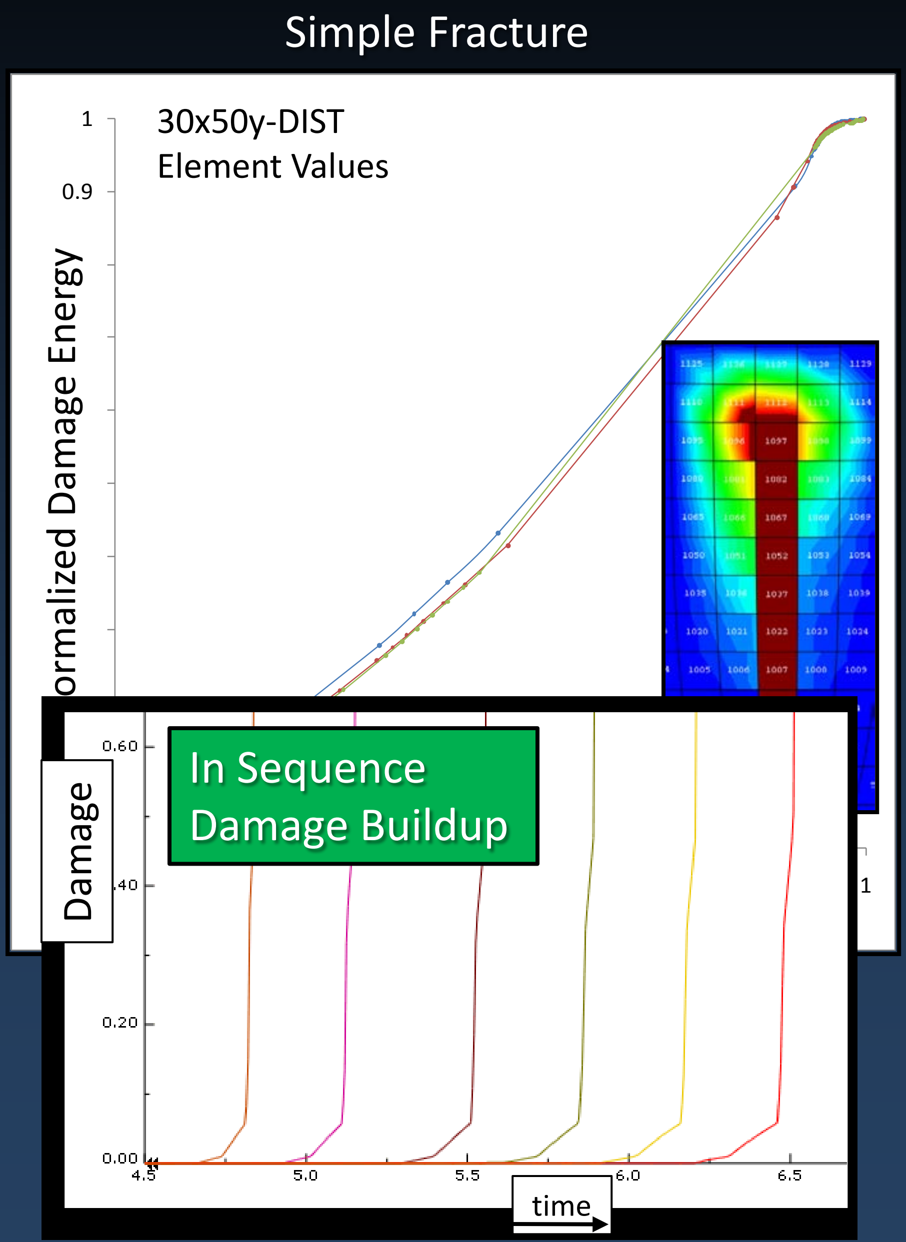
This is related to local dynamical behavior…

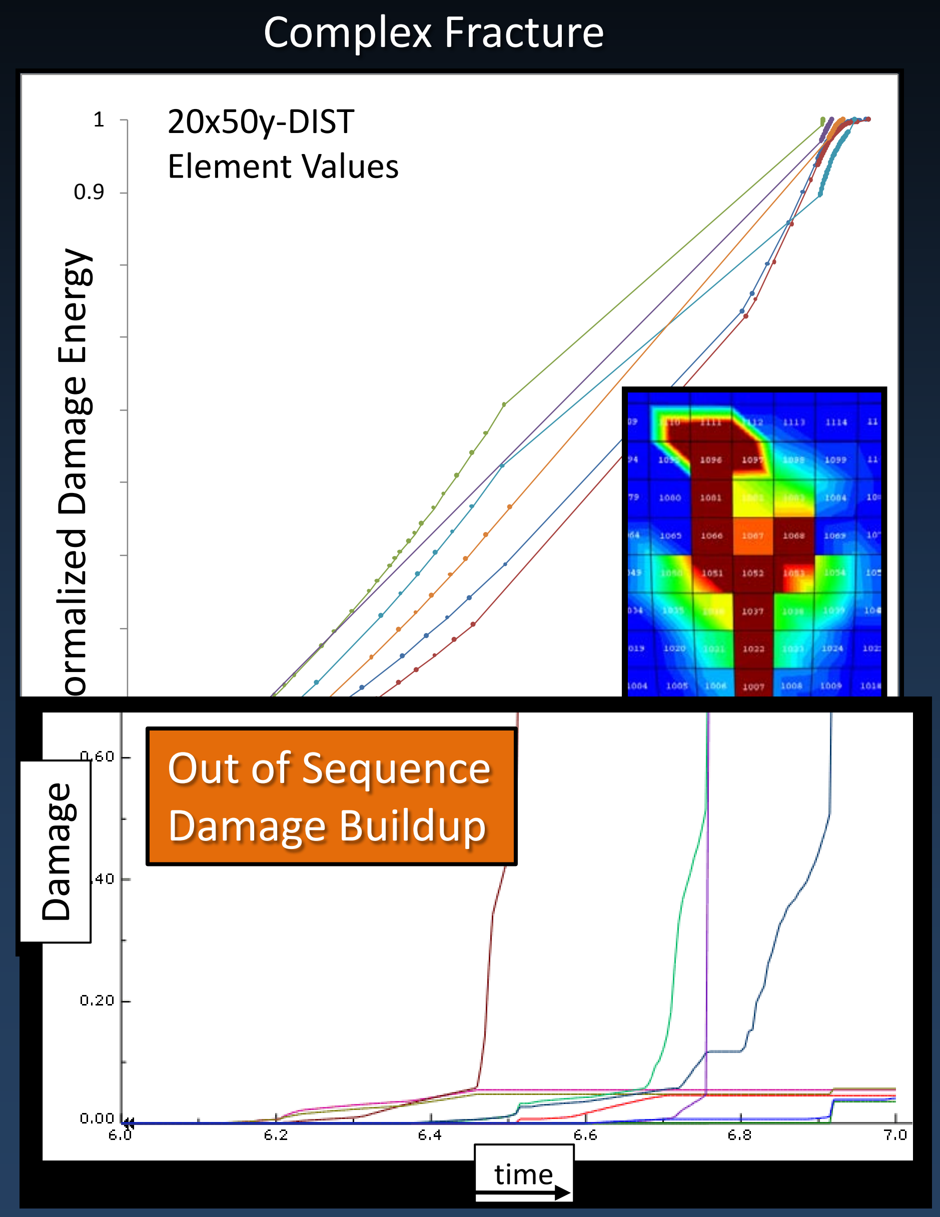
1b. Morphological Features: Branching and Segmentation

Jackfork Sandstone, Ouachitas, Arkansas

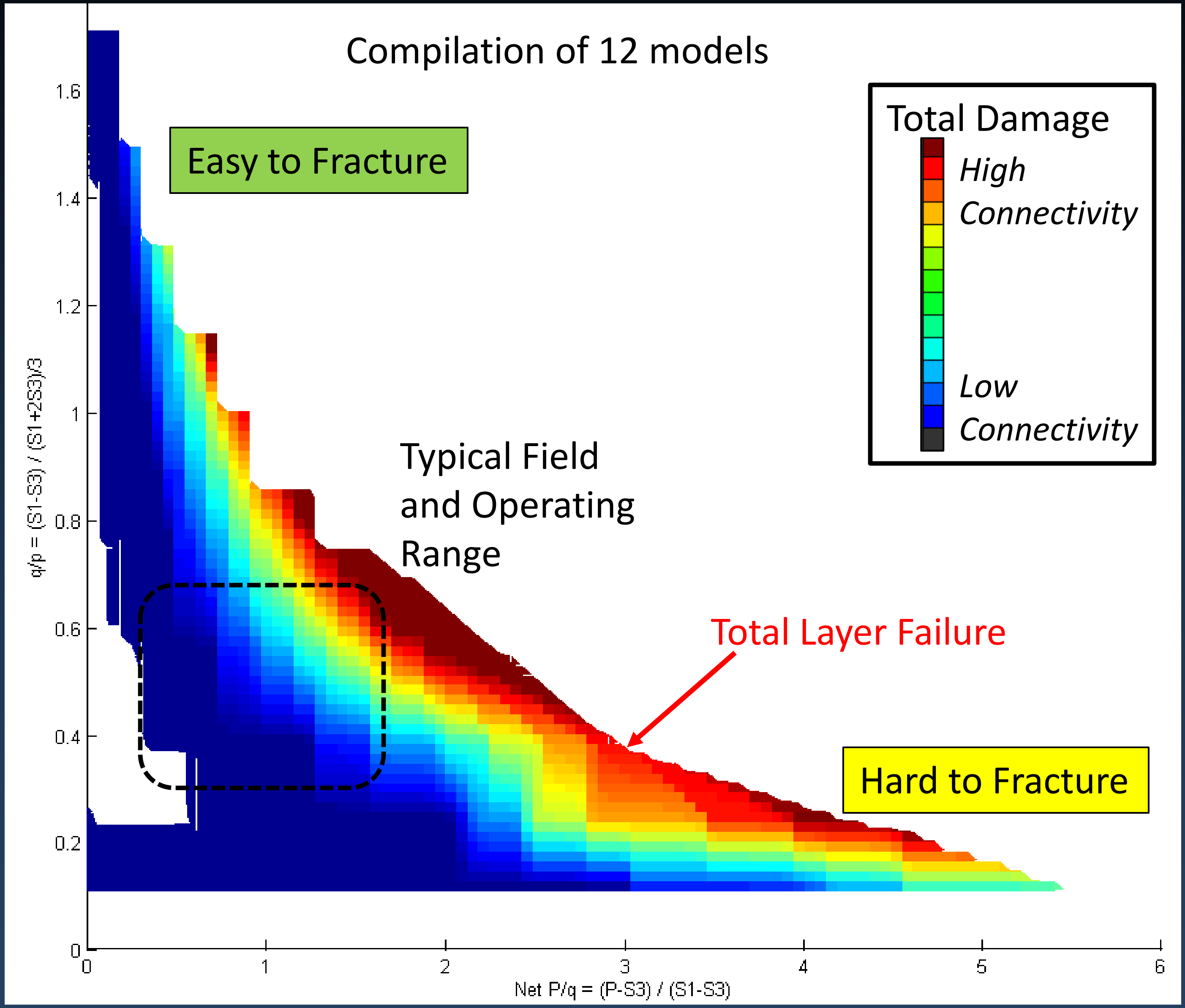
Carmel Fm. Limestone, Cedar Mountain, Utah

1b. Morphological Features: Segmentation and Branching





2a. Damage as a Function of Tectonic and Fracture Pressure



Tectonic Stress: Sy >> Sx

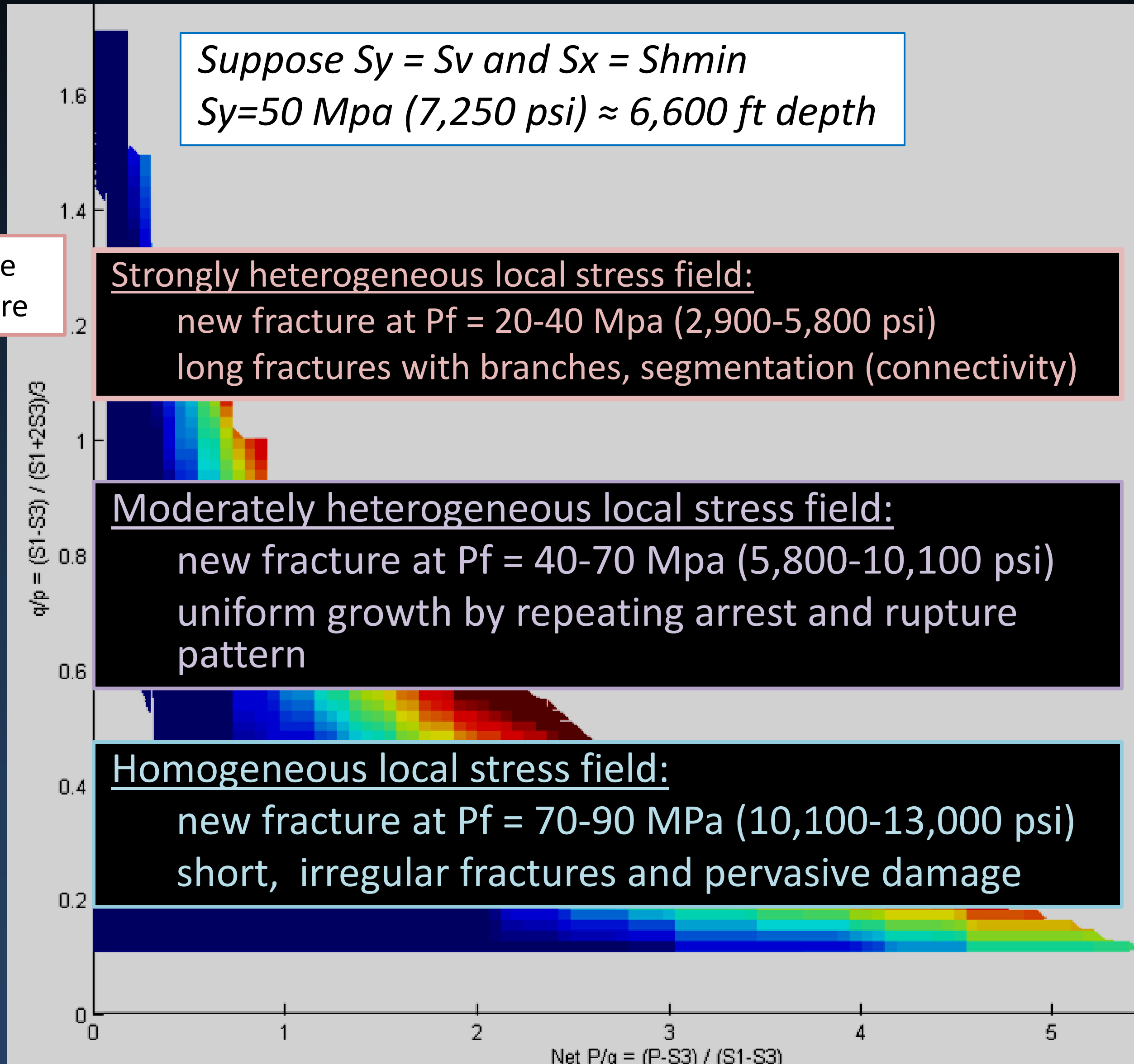
Increasing Fluid Pressure in the Fracture

3. Example Reservoir Application

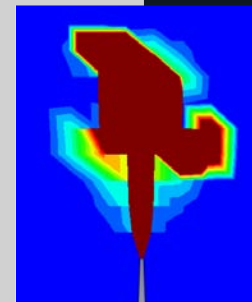
Y: Local Stress State
X: Injection Pressure

Tectonic Stress: Sy >> Sx

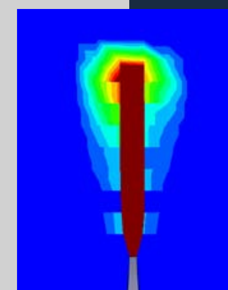
Suppose Sy = Sv and Sx = Shmin
Sy=50 Mpa (7,250 psi) ≈ 6,600 ft depth



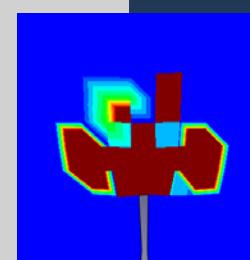
Strongly heterogeneous local stress field:
- new fracture at Pf = 20-40 Mpa (2,900-5,800 psi)
- long fractures with branches, segmentation (connectivity)



Moderately heterogeneous local stress field:
- new fracture at Pf = 40-70 Mpa (5,800-10,100 psi)
- uniform growth by repeating arrest and rupture pattern



Homogeneous local stress field:
- new fracture at Pf = 70-90 MPa (10,100-13,000 psi)
- short, irregular fractures and pervasive damage



Increasing Fluid Pressure in the Fracture

Summary

Approach / Rationale

Use explicit/dynamic FEM simulations and elastic-plastic-damage rheology

(covered in Part I)

Failure criteria for compression and tension

Dissipative processes: brittle microcracking damage, plasticity

Non-local complex rheology: damage and failure outside the crack-tip zone

Results

The elastic-plastic-damage rheology yields:

- Development of branches and segments that are associated with strain build-up periods, which tend to cause broader zones of damage

- High sensitivity to loading conditions:

Fracture Morphology

Fracture Evolution

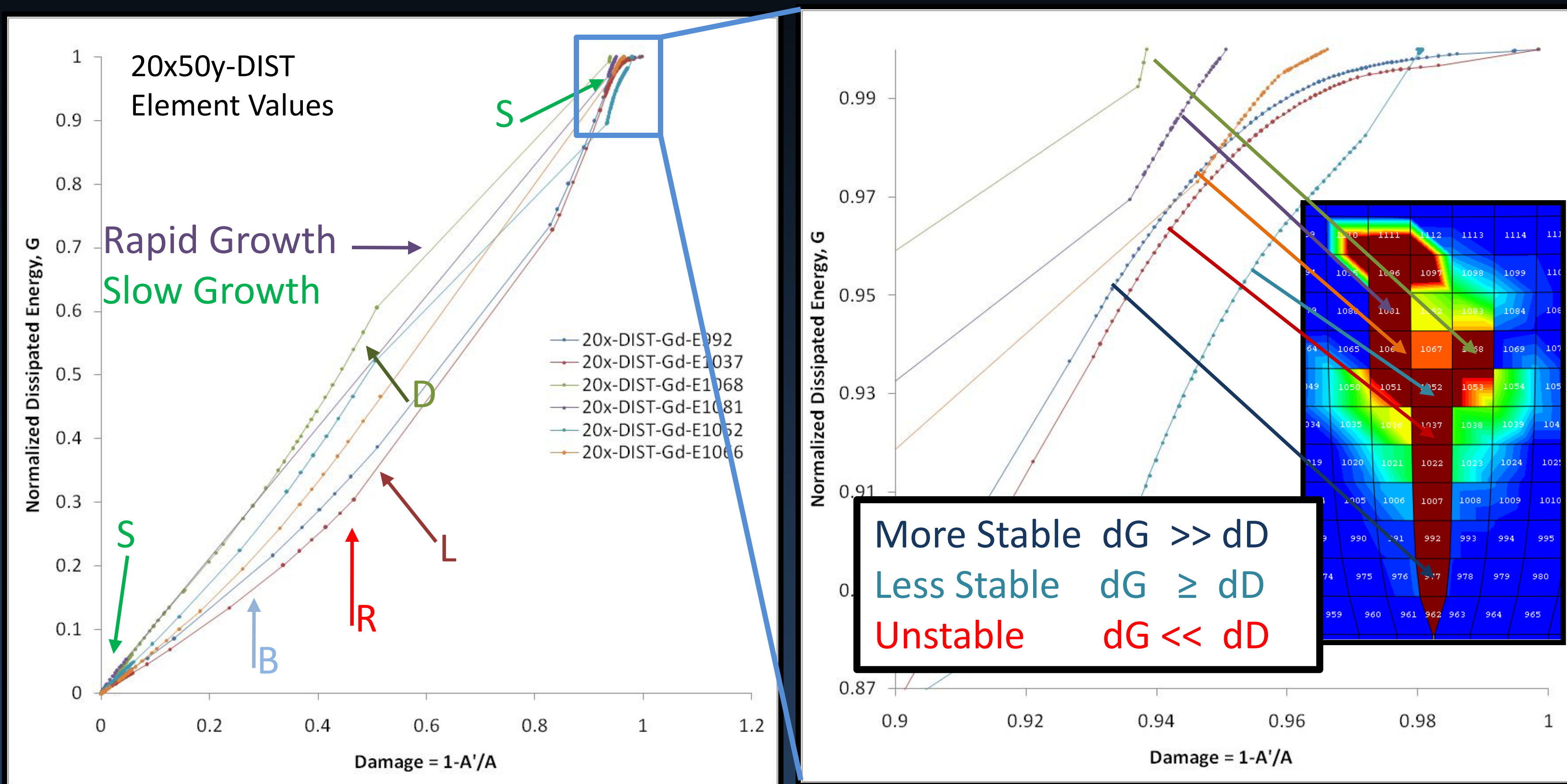
Distributed Damage = Connectivity

- Shows potential for reservoir analysis:

Continued analysis of Barnett Shale field data

Backup slides

2c. Dynamical Features: Fracture Velocity and Stability



Buildup – damage accumulation → *Localized* (dG/dD ↓) → in-plane (simple)
→ *Diffuse* (dG/dD ↑) → out-of-plane (complex)

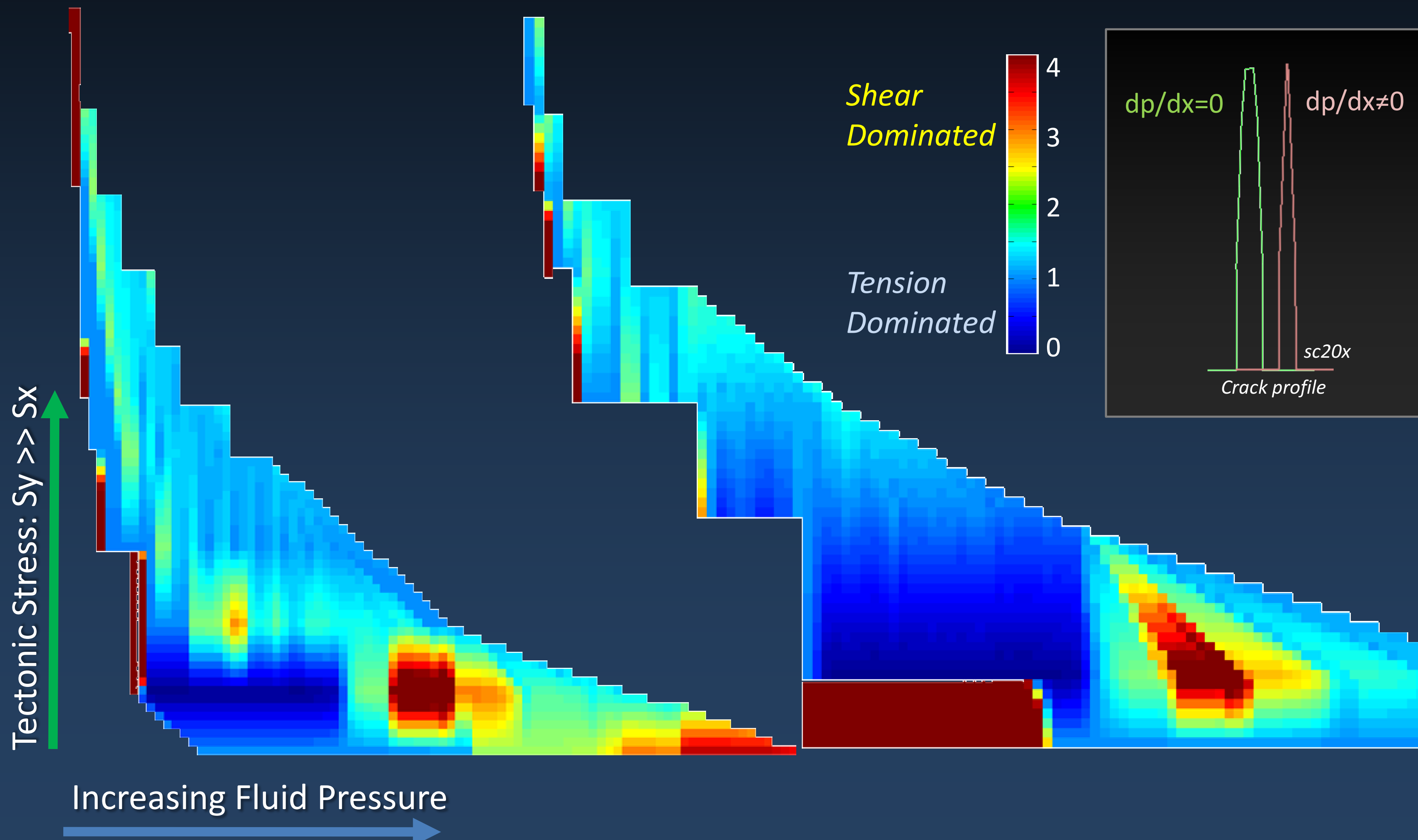
Rupture – ultimate yield and softening

Arrest – post-failure damage zone transference → *Localized* → self-similar, planar
→ *Diffuse* → unique, segments/branches

2b. Controls: Fluid Pressure Distribution

Uniform Pressure Distribution
Ratio Dc/Dt

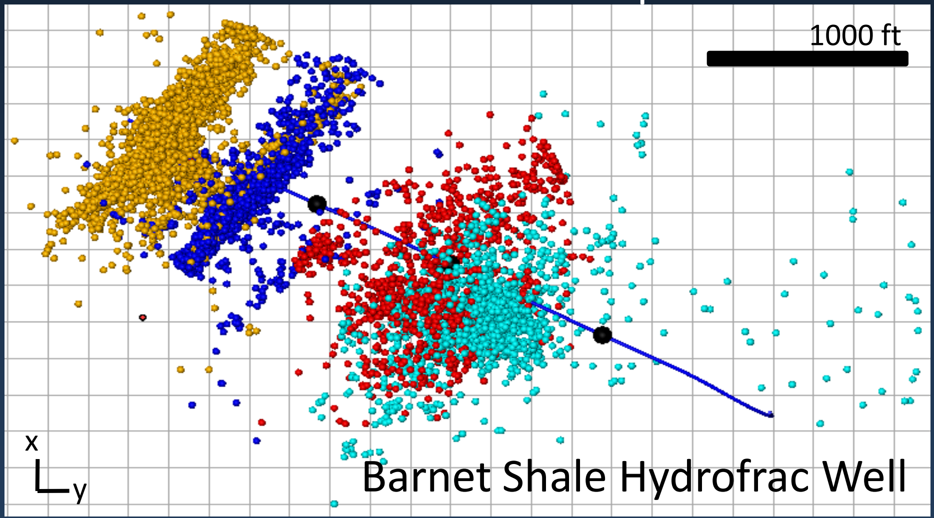
Non-linear Pressure Distribution
Ratio Dc/Dt



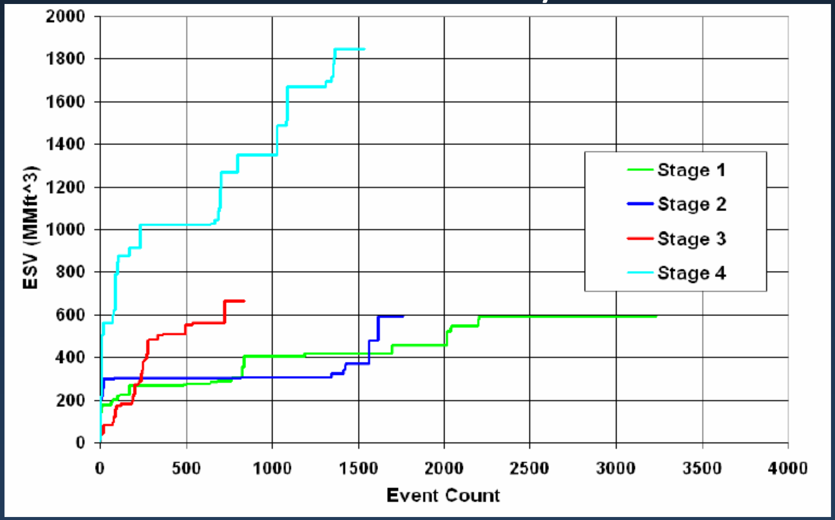
Hydraulic Fracturing in Tight Reservoir Rocks

Purpose	Observation Technique
Create new fracture volume	Microseismic, Fluid Volume Analysis
Increase fracture connectivity	Chemical Tracers, Well Connectivity
Stimulate fluid flow	Production Data

Microseismic Events Map



Fluid Volume Analysis



Modified from Daniels et al. 2007