Large-Volume Stimulation of Rock for Greatly Enhanced Fluids Recovery Using Targeted Seismic-Assisted Hydraulic Fracturing

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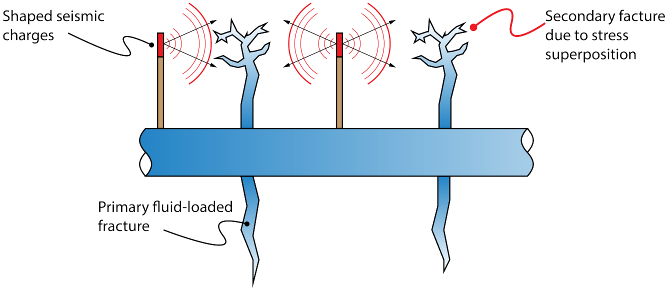
Goals and Objectives—I

Overall Project Goal

Develop and demonstrate a new technology for large-volume and targeted comminution of rock in low permeability formations to enhance recovery from unconventional oil and gas resources.
The technology is based on a strategically designed interaction of multiple induced seismic pulses that assist the hydraulic fracturing process to enhance shear and multi-planar crack formation.



Goals and Objectives—II

Objectives

To develop and demonstrate the proposed technology, this project will investigate two aspects of multi-source excitation:

- superposition of multiple sources of stress wave excitation with each other to generate dynamic stresses large enough to cause rock failure.
- interaction of dynamic stress wave loading with the main hydraulic-fluid pressurized crack to cause transitions from mode I (opening) to mode II (shear) and mode III (non-planar) failure.

Goals and Objectives—III

Research Focus: Year 01

The two project objectives will be met by addressing the following:

1. development of damage, permeability, and porosity models based on realistic conditions of failure under constraint and dynamic loading rate
2. development and validation of a continuum numerical simulation model for fully-coupled hydrodynamic response and failure

Research Focus: Years 02 and 03

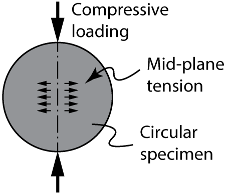
1. development of rock stimulation technology by multi-source excitation
2. demonstration of the multi-source technology using lab-scale field experiments.

Cardinal and Timely Importance

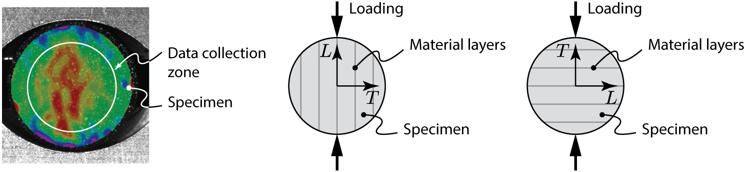
- Realities of UOG resource development using hydraulic fracturing:
  - Recovery efficiency on the order of 10%.
  - Three toggles: spacing, injectant rheology, and production choke management.
  - EOR shows promise, but is invariably limited to immediate vicinity of fractures.
- Constraints on UOG resource development in the US:
  - Space is becoming limited as infill drilling continues.
  - What was done in the past was done: cannot undo a fracturing job.
  - Focus on rate-of-return (leveraged industry) versus net value.
- To sustain this, we need to access greater volumes of these important resources in a **prudent** and **economic** manner!

Rate-dependent material and failure characterization

1. Several core samples acquired from various shale plays in Oklahoma and Texas.
2. Novel experiments conducted using the Brazilian disk configuration to quantify shale as a heterogeneous, orthotropic, bi-modulus material.



Material Property Characterization Using DIC



$$\sigma_{xx} = \frac{2P}{\pi t}\left\{\frac{(D/2-y)x^2}{[x^2+(D/2-y)^2]^2}+\frac{(D/2+y)x^2}{[x^2+(D/2+y)^2]^2}-\frac{1}{D}\right\}$$

$$\sigma_{yy} = \frac{2P}{\pi t}\left\{\frac{(D/2-y)^3}{[x^2+(D/2-y)^2]^2}+\frac{(D/2+y)^3}{[x^2+(D/2+y)^2]^2}-\frac{1}{D}\right\}$$

$$\epsilon_{xx} = \frac{\sigma_{xx}}{E_x}-\nu_{yx}\frac{\sigma_{yy}}{E_y}$$

$$\epsilon_{yy} = \frac{\sigma_{yy}}{E_y}-\nu_{xy}\frac{\sigma_{xx}}{E_x}$$

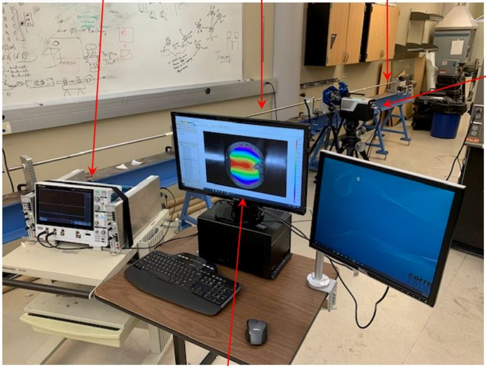
Analysis of Full-field Strain Data

- Use full field strain measurements from digital image correlation (DIC) to determine material properties
- Employ analytical stress-field equations for a disk under diametral compression
- Utilize least-squares analysis to determine unknowns in an overdeterministic fashion
- Properties of interest are tensile and compressive moduli along the two principal material directions, Poisson's ratios, and tensile strengths along the two principal material directions:
  - $E_L^{(t)}$ and $E_L^{(c)}$
  - $E_T^{(t)}$ and $E_T^{(c)}$
  - ν_{LT} (and ν_{TL})
  - $\sigma_L^{(t)}$ and $\sigma_T^{(t)}$

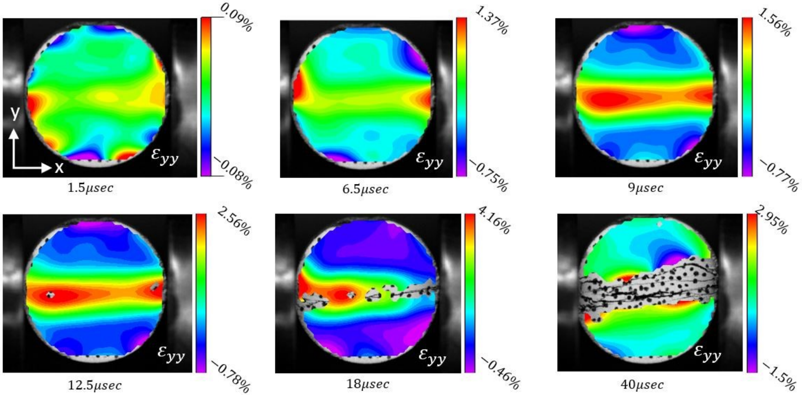
Results—Shales are Orthotropic and Bi-modulus

	Elastic Moduli (GPa)			Tensile Strengths (MPa)	
$E_L^{(t)}$	$E_L^{(c)}$	$E_T^{(t)}$	$E_T^{(c)}$	$\sigma_L^{(t)}$	$\sigma_T^{(t)}$
Mcdonald shale					
19.9±1.0	16.2±1.7	2.7±0.6	19.5±2.4	5.7±3.9	67.1±4.2
Rother shale					
45.5±3.5	38.8±1.8	9.8±2.0	10.1±1.9	16.7±4.1	3.8±0.5
Yost shale					
10.0±1.6	4.8±1.1	10.7±0.7	5.7±1.8	26.5±2.4	26.0±8.6

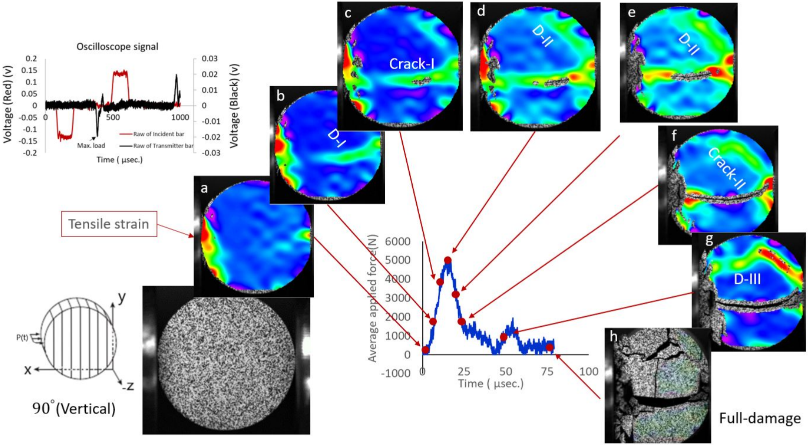
High Strain-rate Testing Setup



Dynamic Tensile Strength Testing



Static Versus Dynamic Failure



Materials Characterization Flow Chart

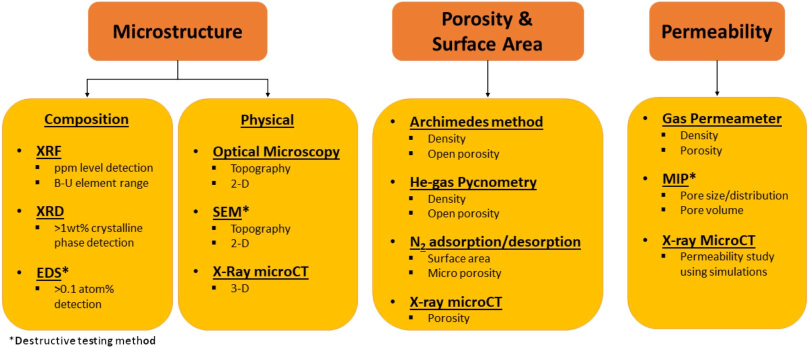


Figure: Characterization plan for the materials being used in the project

Microstructure Analysis of Shales

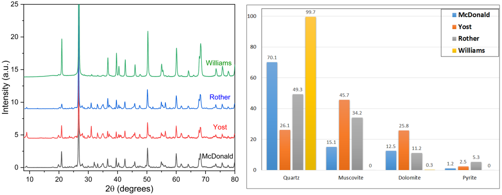


Figure: Quantitative composition analysis using XRD/XRF

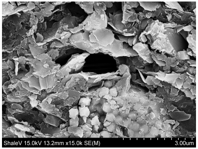


Figure: High-res SEM imaging shows natural macropores and minerals

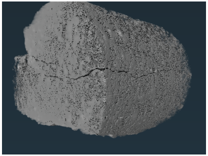


Figure: Non-destructive microCT analysis of shale shows internal cracks

- High amount of dolomite in Yost shales while moderate amounts in McDonald and Rother.
- Williams shale is nearly 100% quartz
- Natural macropores and minerals found using high resolution SEM
- Internal fractures identified using non-destructive micro-CT analysis

Microstructure Analysis of Shales by Mapping

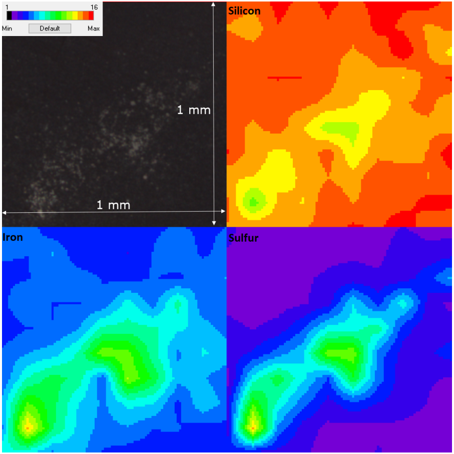


Figure: XRF mapping analysis on 1 mm^2 area shows the elemental distribution in shales

- XRF mapping analysis of Rother shale over 1mm x 1mm area shows Si, Fe and S elemental distributions.
- Concentrated regions with high amount Fe and S suggest the possibility of Pyrite.

Porosity and Permeability of Shales

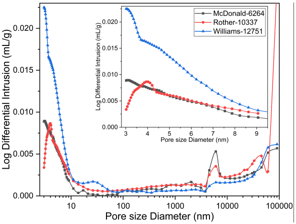


Figure: Macropore and mesopore analysis of shales with Mercury Intrusion Porosimetry (MIP

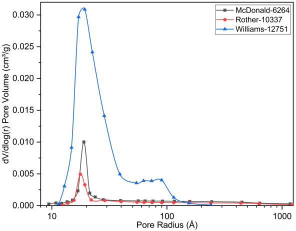
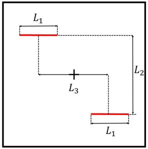


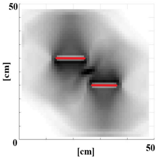
Figure: Macropore and mesopore analysis of shales using N_2 gas adsorption

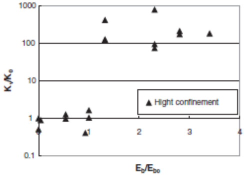
- Pore size distribution analysis of shales using MIP detected 7–10 μm macropores ¡ 10 nm mesopores.
- N_2 gas adsorption detected ¡ 10 nm mesopores all the shales
- Combined analysis shows that Williams shales have most of the porosity in the nanometer range while Rother and McDonalds have porosity generally in the macropore range.

Hypothesis and Preliminary Modeling Results

R.M. Younis and Y.J. Jing. "A Computational Investigation Of Seismic Wave Focusing As A Novel Means To Fracture Shale Reservoirs." *ECMOR XVI-16th European Conference on the Mathematics of Oil Recovery, EAGE* (2018).

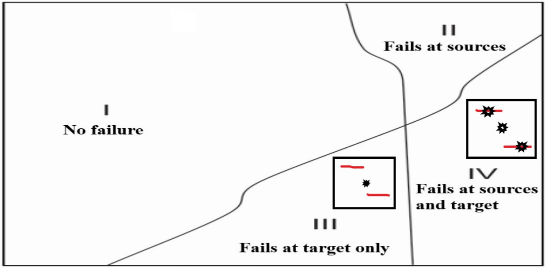






After W. Chen, et al.(2012) JPSE

$$\Pi_1 = \frac{L_2}{L_1}$$



$$\Pi_1 = L_1 \sqrt{\frac{G}{\rho_s}} \left(\frac{\mu}{\rho_f K} \right)$$

Coupled Model

Fully-coupled multiphase flow and transient poromechanics.
Resolve pressure P, saturation S_p, and rock displacement $\boldsymbol{u}$ fields.

$$\partial_t \left(\phi \rho_p S_p\right) + \nabla \cdot \left(\phi \rho_p S_p \boldsymbol{v}_r + \rho_p \boldsymbol{v}_p\right) + q_p = 0; p = \{w, o, g\} \quad (1)$$

$$\bar{\rho}\frac{\partial \boldsymbol{v}_r}{\partial t} + \bar{\rho}\boldsymbol{v}_r \nabla \cdot \boldsymbol{v}_r - \nabla \cdot \boldsymbol{\sigma} = 0. \quad (2)$$

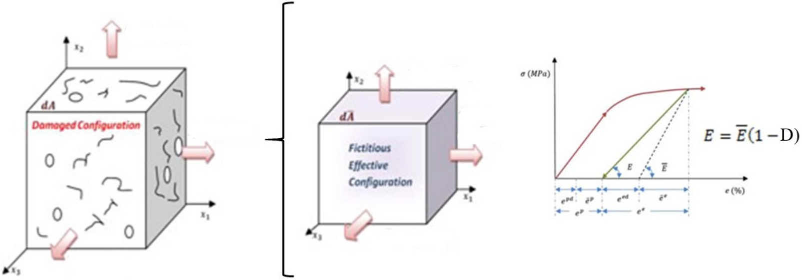
where,

$$\boldsymbol{v}_p = -\boldsymbol{K_D}\frac{Kr_p}{\mu_p}\nabla P, \quad \boldsymbol{v}_r = \frac{\partial \boldsymbol{u}}{\partial t}$$

$$\boldsymbol{\epsilon} = \frac{1}{2}\left(\nabla \boldsymbol{u} + \nabla^T \boldsymbol{u}\right)$$

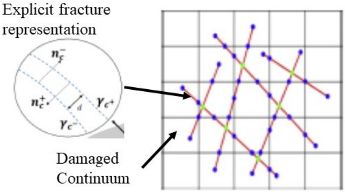
$$\boldsymbol{\sigma}_{ij} = \left(K_M - \frac{2G}{3}\right) tr\left(\boldsymbol{\epsilon}\right)\delta_{ij} + 2G\boldsymbol{\epsilon}_{ij} - \alpha P \delta_{ij}$$

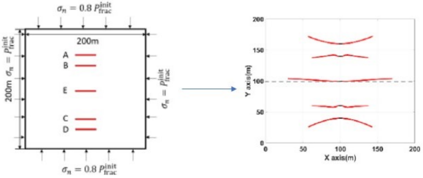
Continuum Damage Modeling



- Incorporate the damage models developed by experiment
- These produce a damage coefficient D field as a function of stress-strain history
- Hydrodynamic parameters (permeability and porosity) are functions of damage D
- Mechanical properties (K_m, G, and Biot coefficient α) are also functions of damage

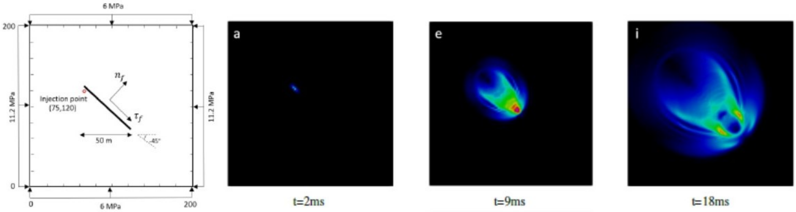
Discrete Fracture and Propagation





- Hydraulic fractures and their propagation captured explicitly
- Developed novel algorithm and implementation allowing complex fracture interaction
- Examples shows fracturing perforations A and B, followed by C and D, a production period, finally followed by fracturing of perforation E.

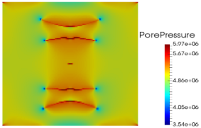
G. Ren and R.M. Younis. "An integrated numerical model for coupled poro-hydro-mechanics and fracture propagation using embedded meshes." To appear: Computer Methods in Applied mechanics and Engineering.



- Model captures stick-slip conditions and seismic nucleation
- Verified with available data on injection-induced seismicity
- Wave propagation and attenuation also verified

Z. Han and R.M. Younis. "Coupled Forward Simulation of Seismicity: a Stick-Slip Model for Fractures and Transient Geomechanics." In review: Computational Geosciences.

Build first-in-kind model that couples:



Multiphase Flow

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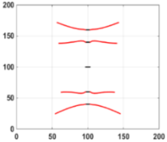

Hydraulic Fracture

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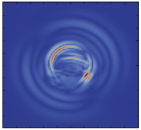

Poroelastic Seismic

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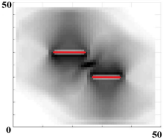
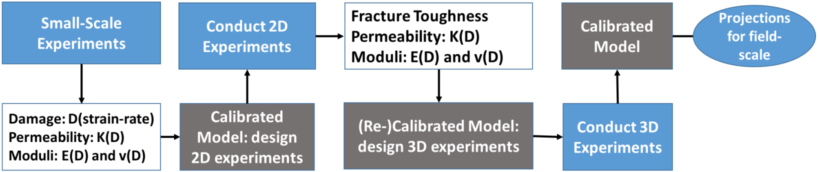


Dynamic Continuum Failure

Use model to match experiments and design the next round:



Thank you.