# Sustainability of Hydraulic Fracture Conductivity in Ductile and Expanding Shales

ESD14084

Seiji Nakagawa, Jonny Rutqvist, Sharon Borglin,
Timothy Kneafsey, and Kunhwi Kim

Energy Geosciences Division, Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory

U.S. Department of Energy

National Energy Technology Laboratory

Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
Carbon Storage and Oil and Natural Gas Technologies Review Meeting

August 13-16, 2018

# Acknowledgment

This research is supported by

- Assistant Secretary for Fossil Energy, Office of Natural Gas and Petroleum Technology through the National Energy Technology Laboratory

Under the U.S. DOE, Contract No. DE-AC02-05CH11231

- Chevron Energy Technology Company

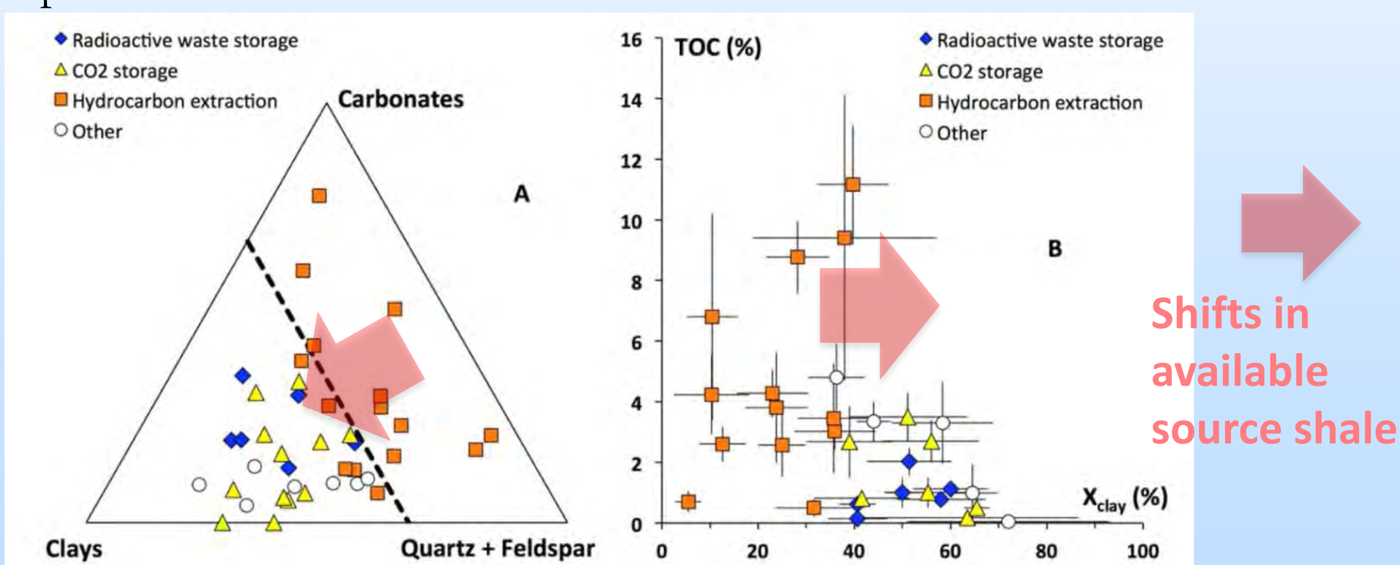
# Presentation Outline

- Technical Status
  - Motivation & Background
  - Goal and Objectives
  - Anticipated Products and Impacts
  - Project Tasks and Activities
  - **Results so far**
- Accomplishment to Date
- Lesson Learned
- Synergy Opportunities
- Project Summary

# Motivation and Background

- Research focus on hydraulic fracture closure and permeability loss due to shale and proppant deformation
- Pristine, high-TOC, low-clay-content oil and gas shale formations are being depleted

  →Expected increasing needs to produce from ductile shales in which hydraulic fractures are difficult to induce and sustain
- Need to understand the behavior of ductile/swelling shales for efficient and economical production




*Ductile shales with high clay content (>~40%) are currently difficult to exploit as a resource rock although hydrocarbons can still be found in them (Modified from Bourg, 2015).*

# Project Goals/Objectives

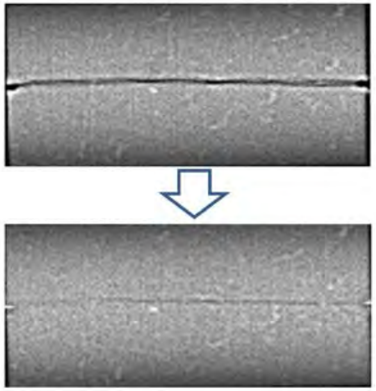
To investigate and understand

(1) How hydraulic fractures produced in ductile and swelling shale behave over time to reduce their aperture and permeability,

(2) How the proppant deposition characteristics (e.g., monolayer vs multilayer), grain size, and spatial distribution (isolated patches vs connected strings and networks) affect the sustainability of the fracture conductivity,

(3) How the near-fracture shale-matrix fluid transport is affected by the evolving conductivity of the fracture.

- **Long-duration core-scale laboratory visualization** experiments under (moderately) elevated temperature and stress
- **Various natural shale samples** with different ductility and mineral compositions (clay contents)
- **Numerical modeling** of the shale deformation and fluid transport (tool/methodology development) ; Check against the laboratory experiments



Compaction of a fracture in swelling clay rich Opallinus Clay due to viscoplasticity

# Anticipated Products and Impacts

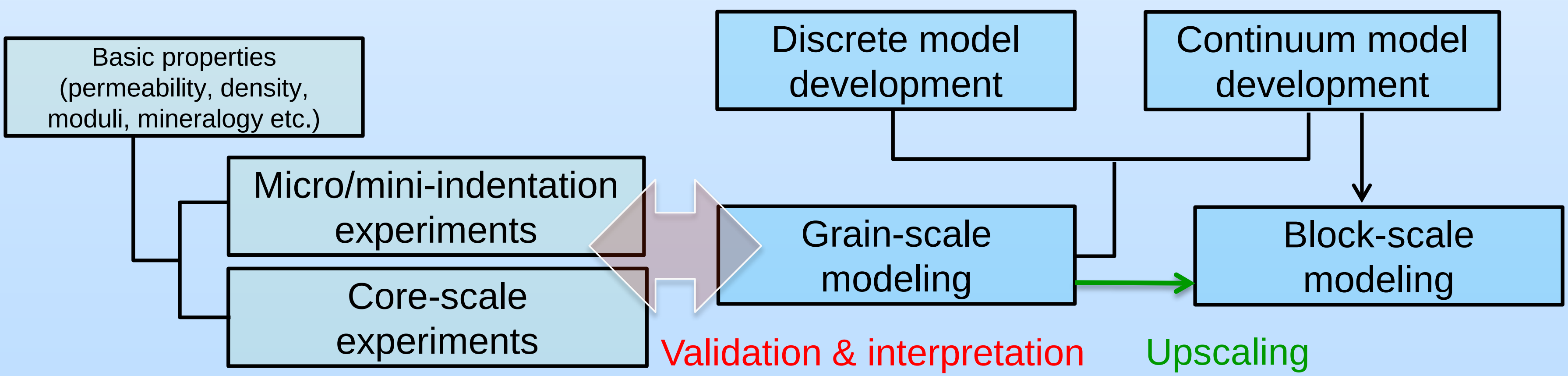
- **New experimental tool** (fracture/proppant compaction visualization system) **and methodology** for measuring and visualizing time-dependent compaction of a fracture in ductile shale
- **Numerical tools and the simulation methodology** based upon TOUGH-FLAC and TOUGH-RBSN codes for predicting long-term behavior of hydraulic fractures in ductile and swelling shales
- Laboratory and modeling **data correlating shale properties, time-dependent compaction, permeability changes, over an extended period of time**
- Particularly, data/knowledge/modeling tools which **upscale** the small-scale (i.e., side-wall cores, chips) measurements to core (cm's) to field (m's) scale behavior of fractures in shale

**Anticipated impacts (our ultimate goals)**

- Improved prediction of long-term fracture sustainability
- Smart selection of fracturing intervals (formations)
- Optimization of injected proppant volume, refracturing
- Improved use of available and economical data/samples from wells (e.g., drill chips, sidewall cores)

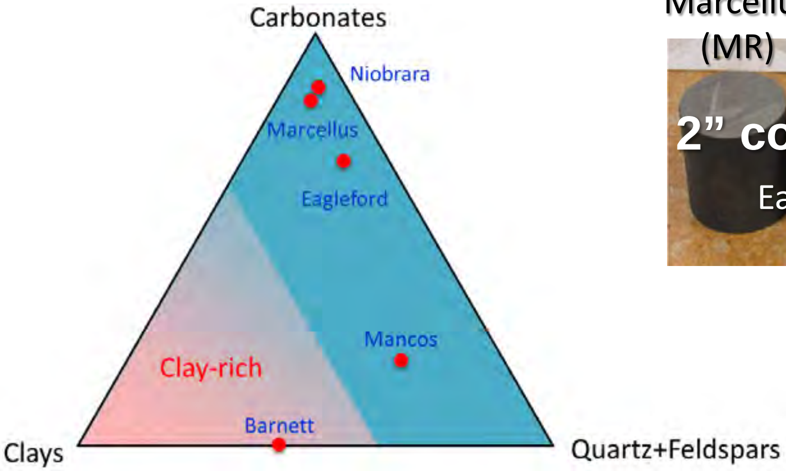
# Project Tasks and Activities

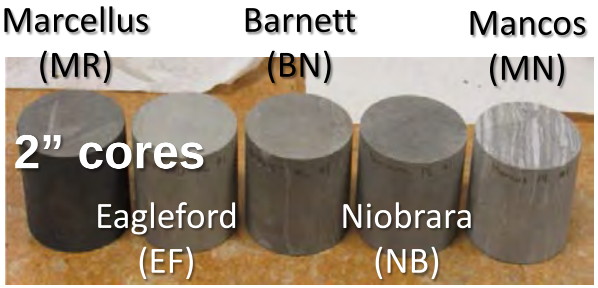
| | Laboratory Experiment Tasks | Numerical Modeling Tasks |
|---|---|---|
| Year 1 | • Develop and test experimental systems<br>• Shale characterization experiments | • Develop and test modeling methods<br>• Model lab micro Indentation tests |
| Year 2 | Core-scale Visualization Experiments (Optical/X-ray CT) | Modeling Fracture Closure Experiments (Grains- and/or Block-scale) |



# Results So Far

## Baseline characterization of shale mechanical properties

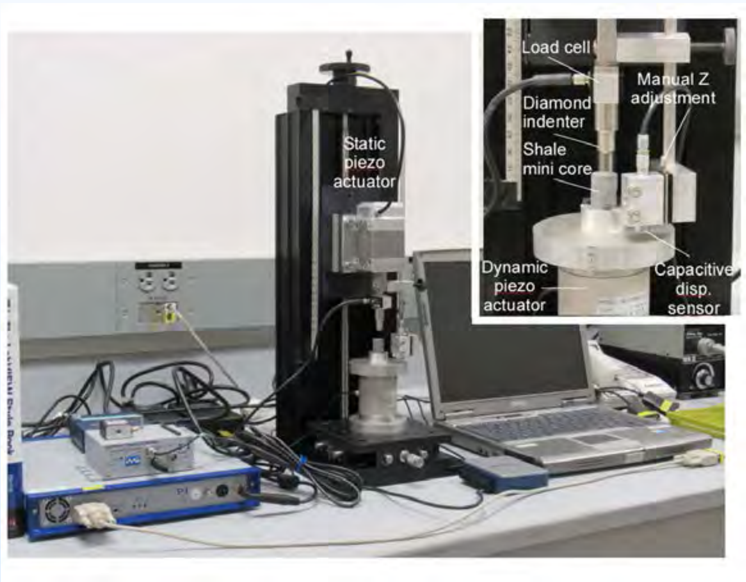


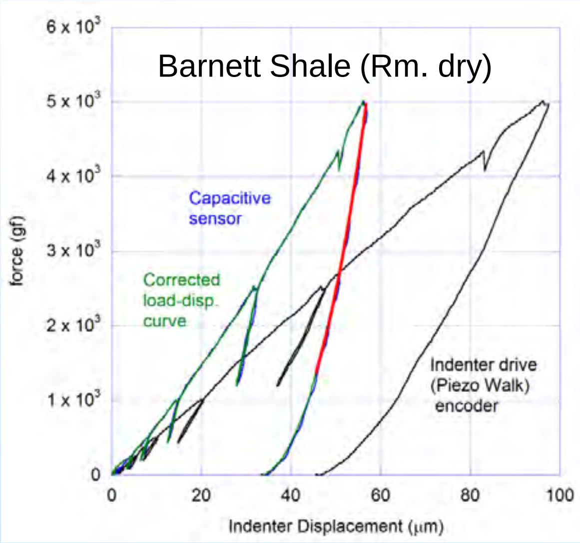



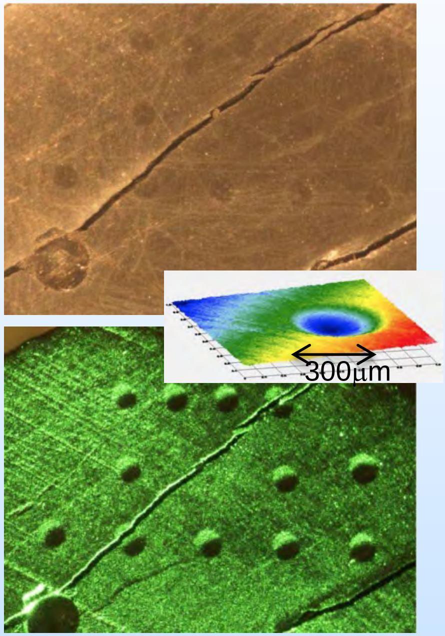

# Results So Far

## Proppant-scale shale (mm to ~1mm)property characterization and ductility measurements –Instrumented indentation test

### Home-made instrumented indentation system



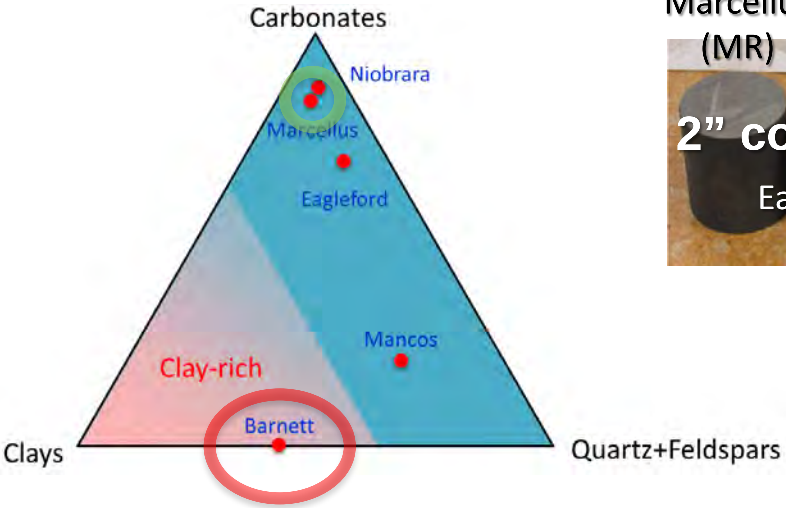

Various mechanical measurements can be done at small scales

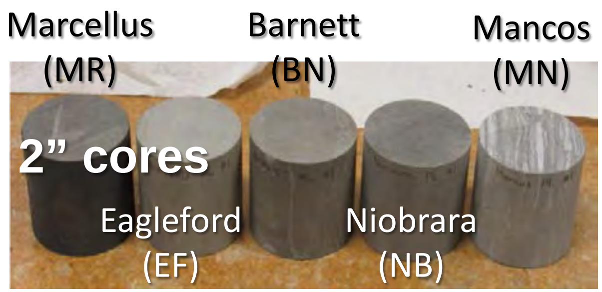
- Elastic modulus
- Hardness
- Ductility (defined via energy loss)
- Viscoelasticity (via creep test)

- Possibility to predict shale behavior from small side-wall cores and chips
- Provides “reconnaissance” before conducting long-term, core-scale tests

# Results So Far

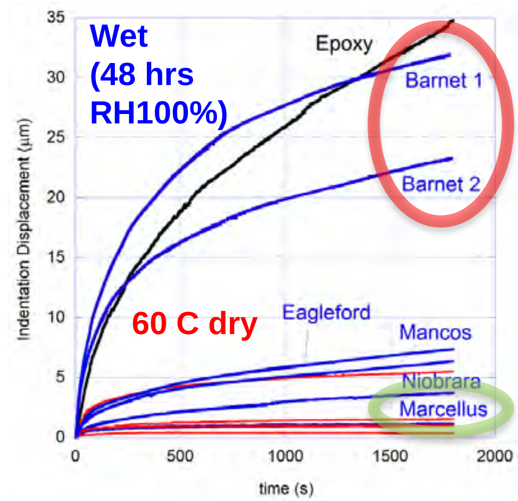
## Baseline characterization of shale mechanical properties



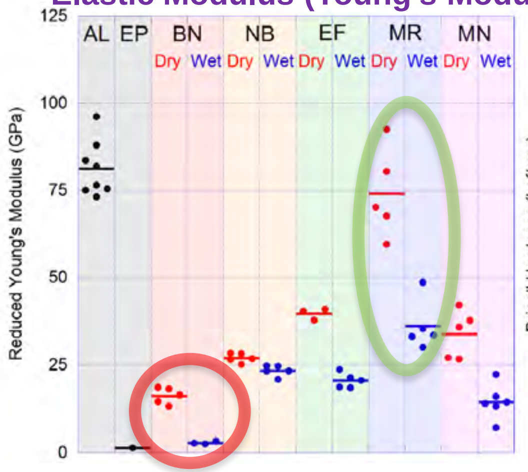





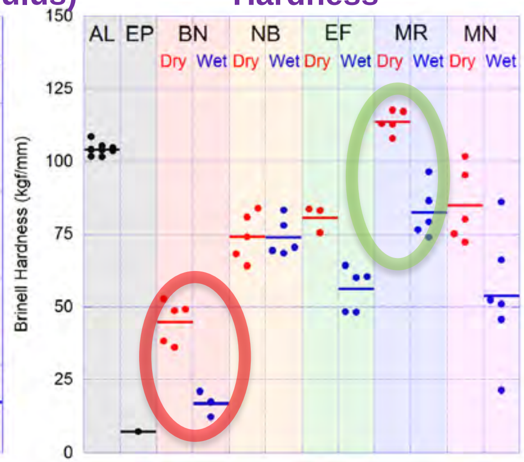
### Indentation creep



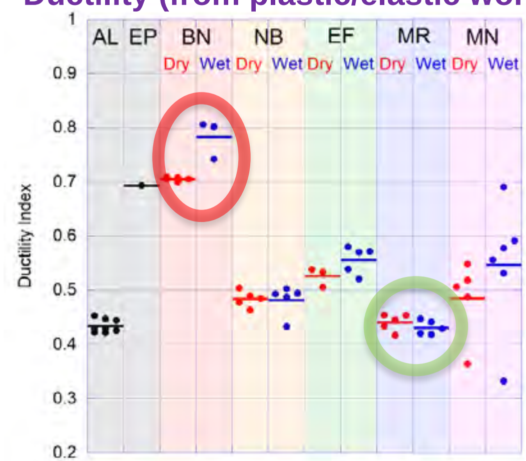

### Elastic Modulus (Young's Modulus)




### Hardness



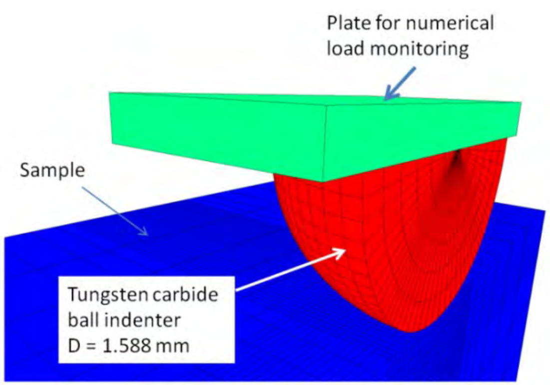

### Ductility (from plastic/elastic work ratios)



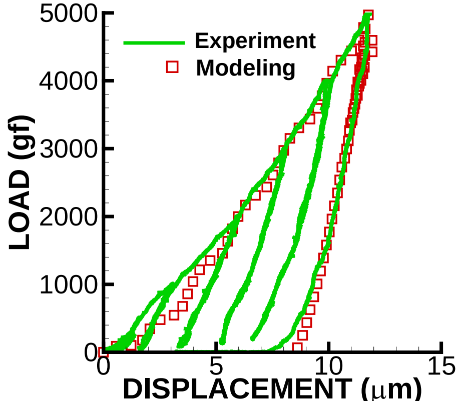
# Results So Far

## TOUGH-FLAC modeling of indentation experiments

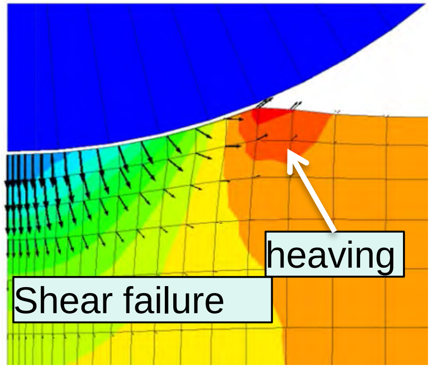
- Based upon Mohr-Coulomb plastic model (shear failure).
- The **strength parameters (C, μ) may be back-calculated** from lab measured load-displacement curves and indentation geometry
- Short-term indentation creep can be modeled using the Burger creep model, but long-term prediction may **require longer term creep experiments**



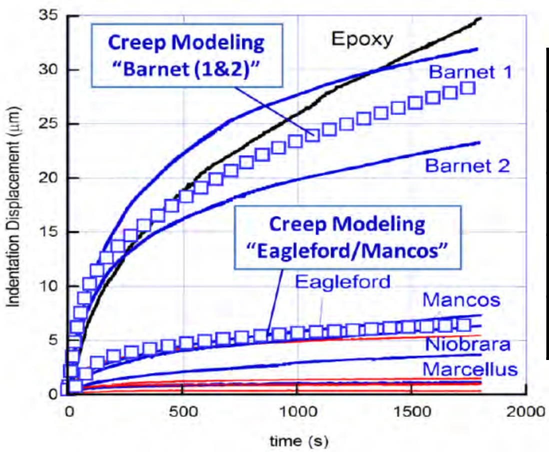

Indentation test




Indentation geometry




Indentation creep test

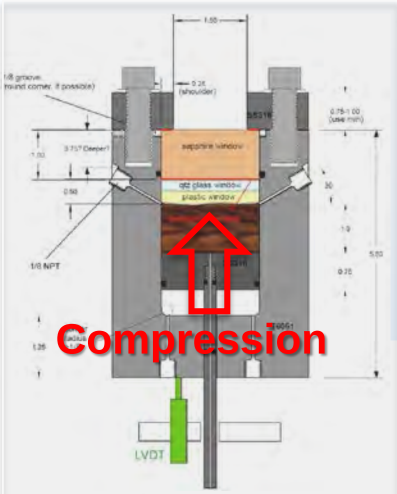


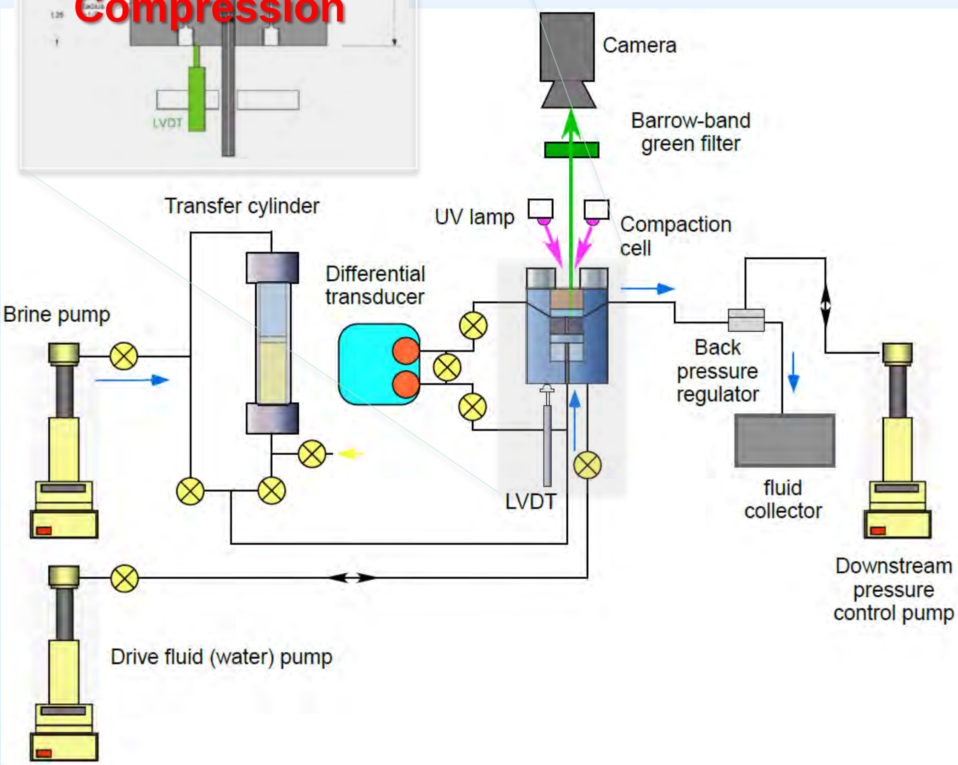

Burger Parameters

| |
|---|
| Bulk Modulus (Pa) |
| Kelvin Shear Modulus (Pa) |
| Kelvin Viscosity (Pa·s) |
| Maxwell Shear Modulus (Pa) |
| Maxwell Viscosity (Pa·s) |

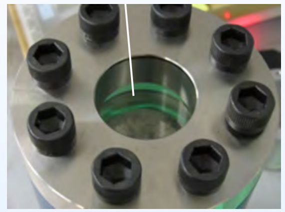
# Results So Far

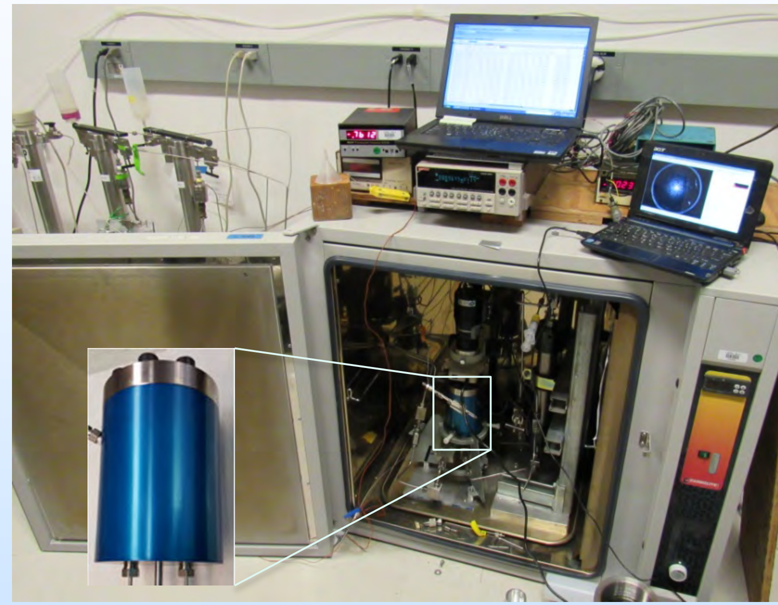
## Fracture closure and proppant crushing/embedment visualization experiment




sapphire window





Current test conditions

Axial effective stress: 3,920 psi (27 MPa)

Pore pressure: 1,500 psi (10.3 MPa)

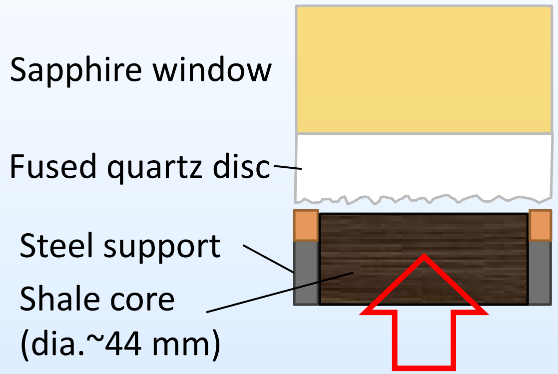
Test temperature: Ambient and 60˚C

Fluid: Brine (5%wt NaCl aq.)

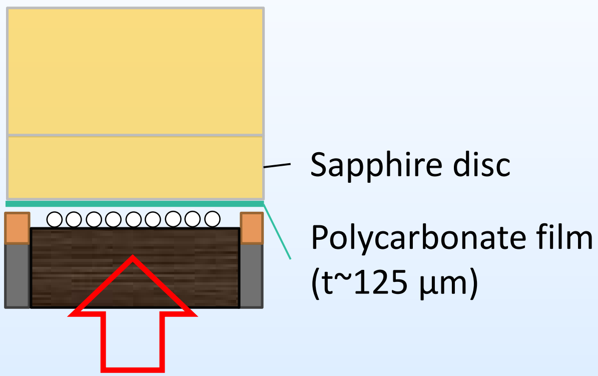
# Results So Far

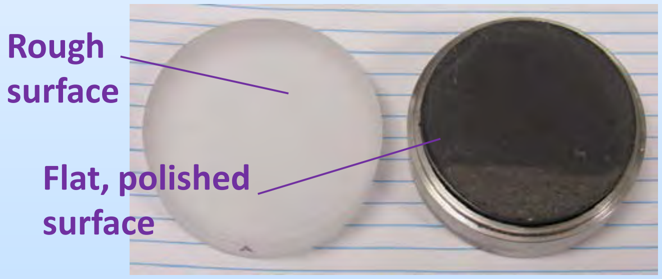
## Fracture closure and proppant crushing/embedment visualization experiment

**Tests without proppant (bare fracture)**

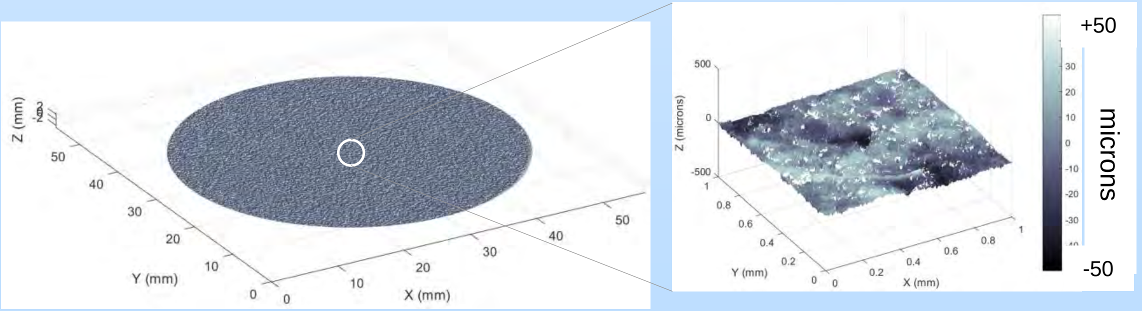



**Tests with proppant (sparse monolayer)**




- Glass models for fracture upper half
- Circular core cross section
- Laterally confined sample

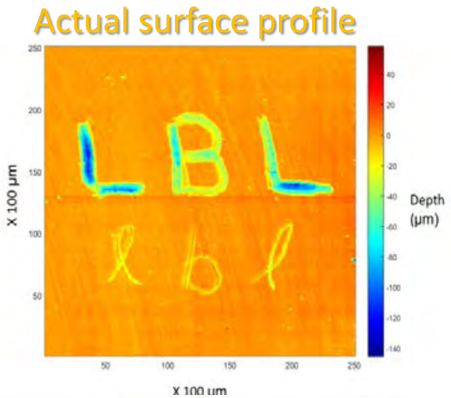


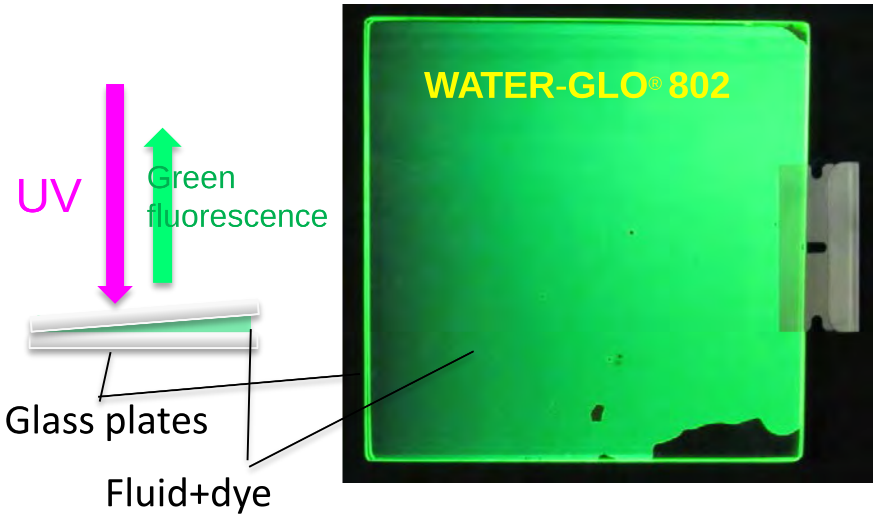
# Results So Far

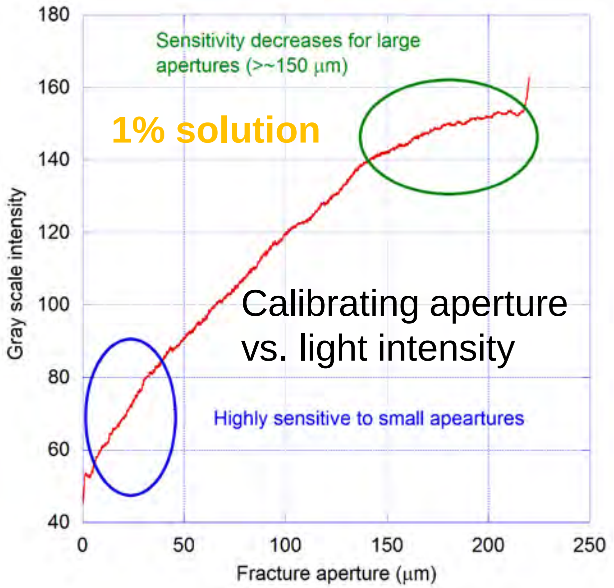
## Fracture closure and proppant crushing/embedment visualization experiment

UV-induced fluorescence is used to obtain quantitative fracture aperture distribution


a. Cover glass only b. Filled with dyed fluid c. Illuminated by UV light



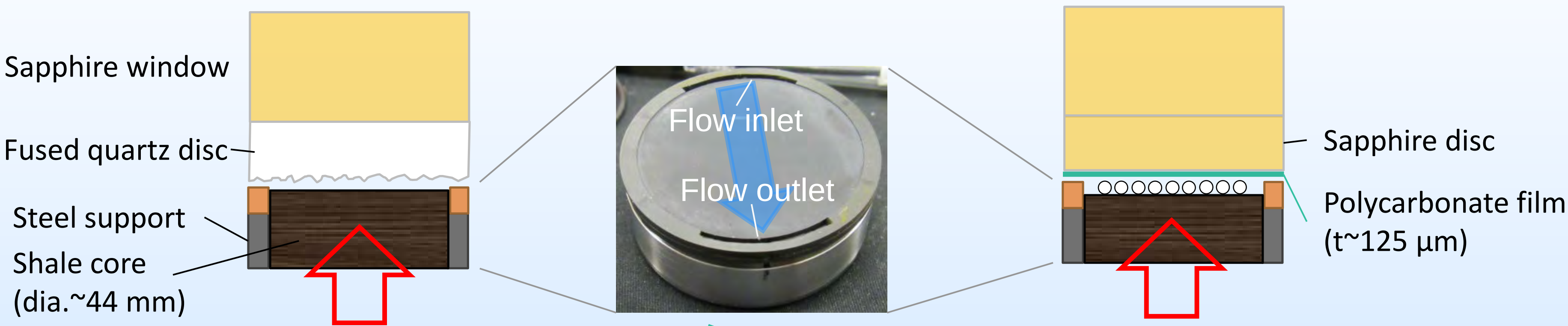



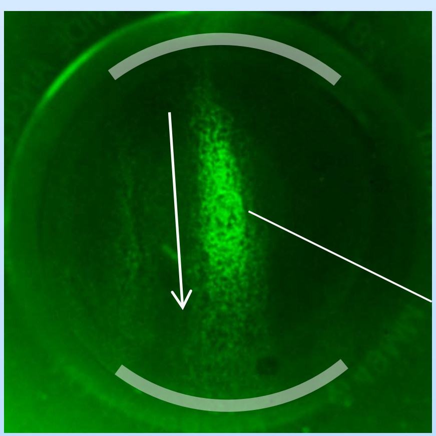



# Results So Far

## Fracture closure and proppant crushing/embedment visualization experiment

**Tests without proppant (bare fracture)** **Tests with proppant (sparse monolayer)**



- Circular core cross section
- Approximately linear flow

(max flow rate of 1 mL/min was used to avoid fine migration)

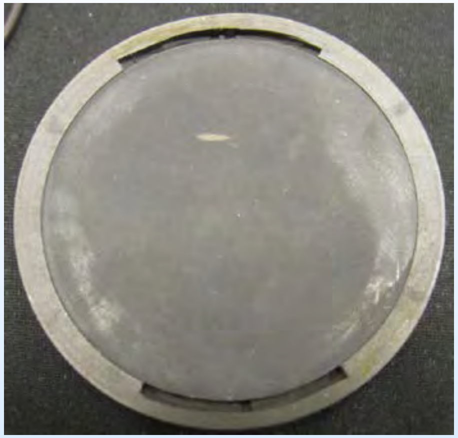
A plume of injected, dyed fluid in an open fracture under stress

# Results So Far

## Samples before and after the long-term compaction experiments

**Barnett shale (outcrop)**

**Marcellus shale (outcrop)**



No proppant

With proppant

2 weeks, 3,920 psi, 25˚C

No proppant

With proppant

2 weeks, 3,920 psi, 25˚C

# Results So Far

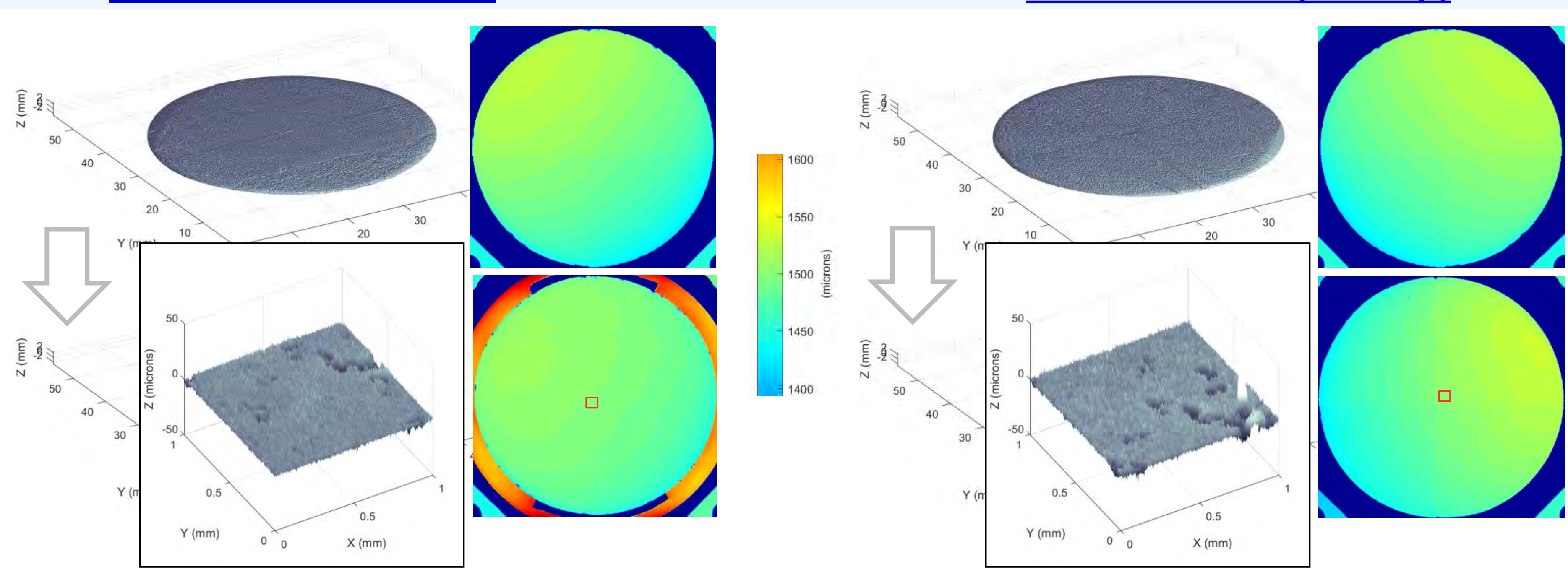
## Samples before and after the long-term compaction experiments

— Surface profile/texture changes

**Fracture without proppant**

**Barnett shale (outcrop)**

**Marcellus shale (outcrop)**



# Results So Far

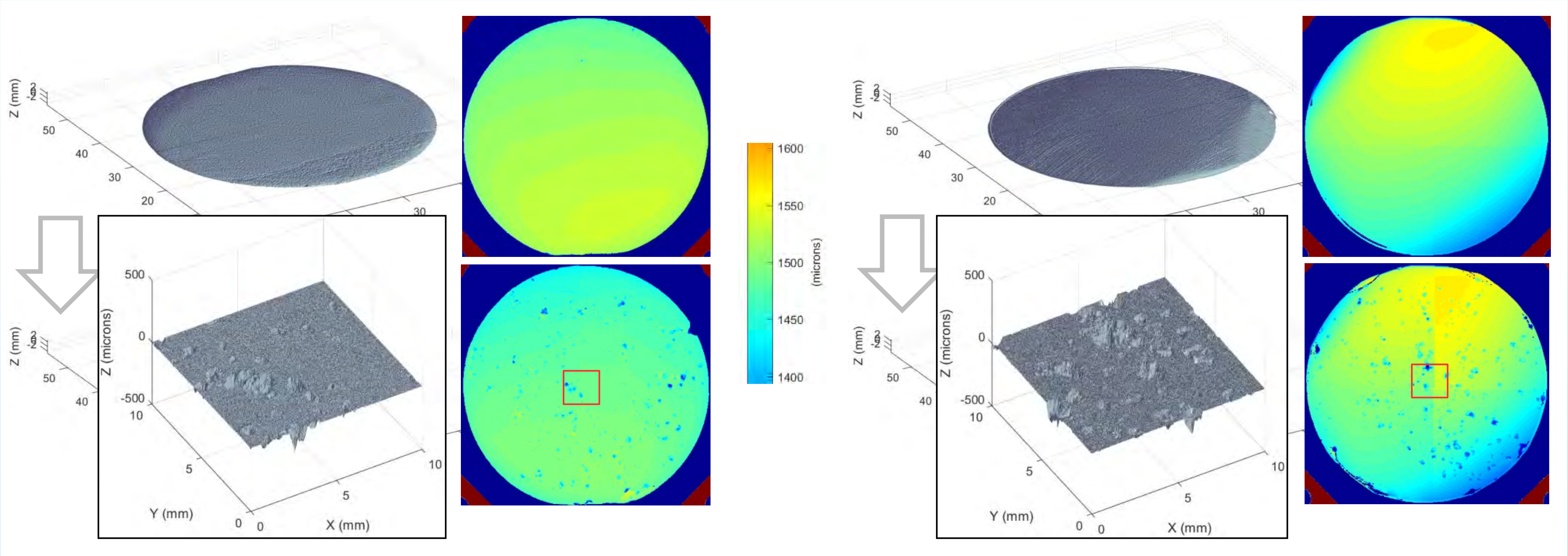
**Samples before and after the long-term compaction experiments**

— Surface profile/texture changes

**Fracture with proppant**

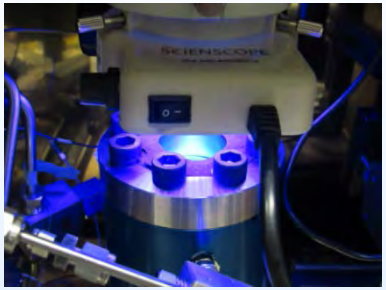
Barnett shale (outcrop)

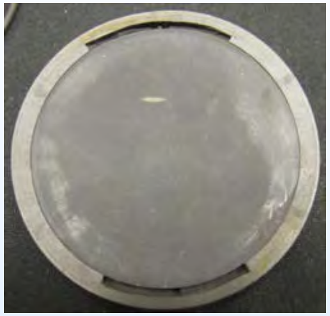
Marcellus shale (outcrop)



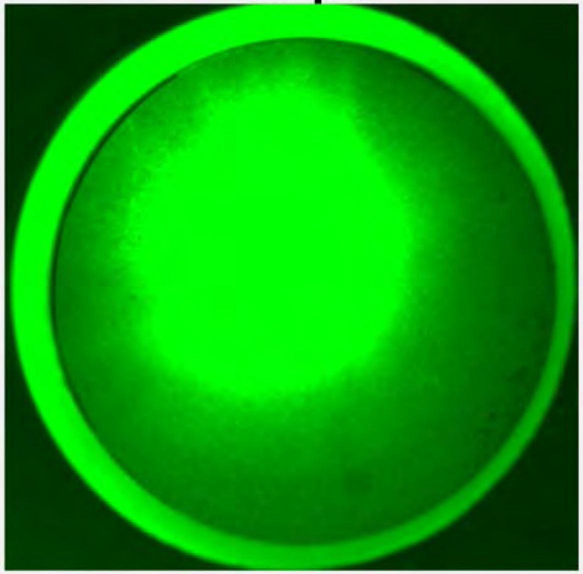
# Results So Far

## Fracture closure visualization experiment



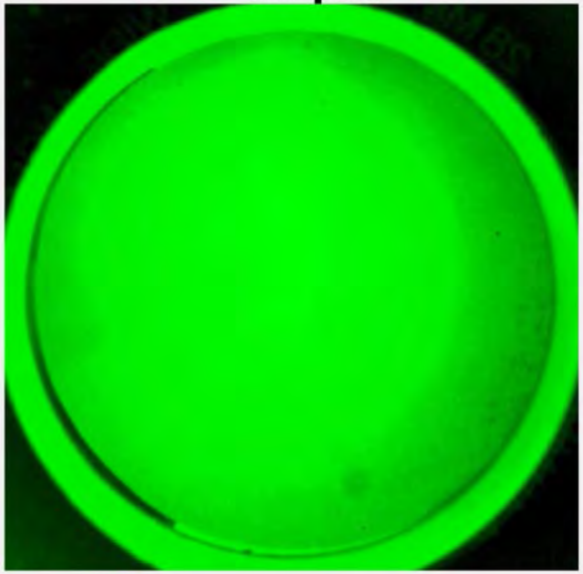


10 psi



Barnett shale
No proppant

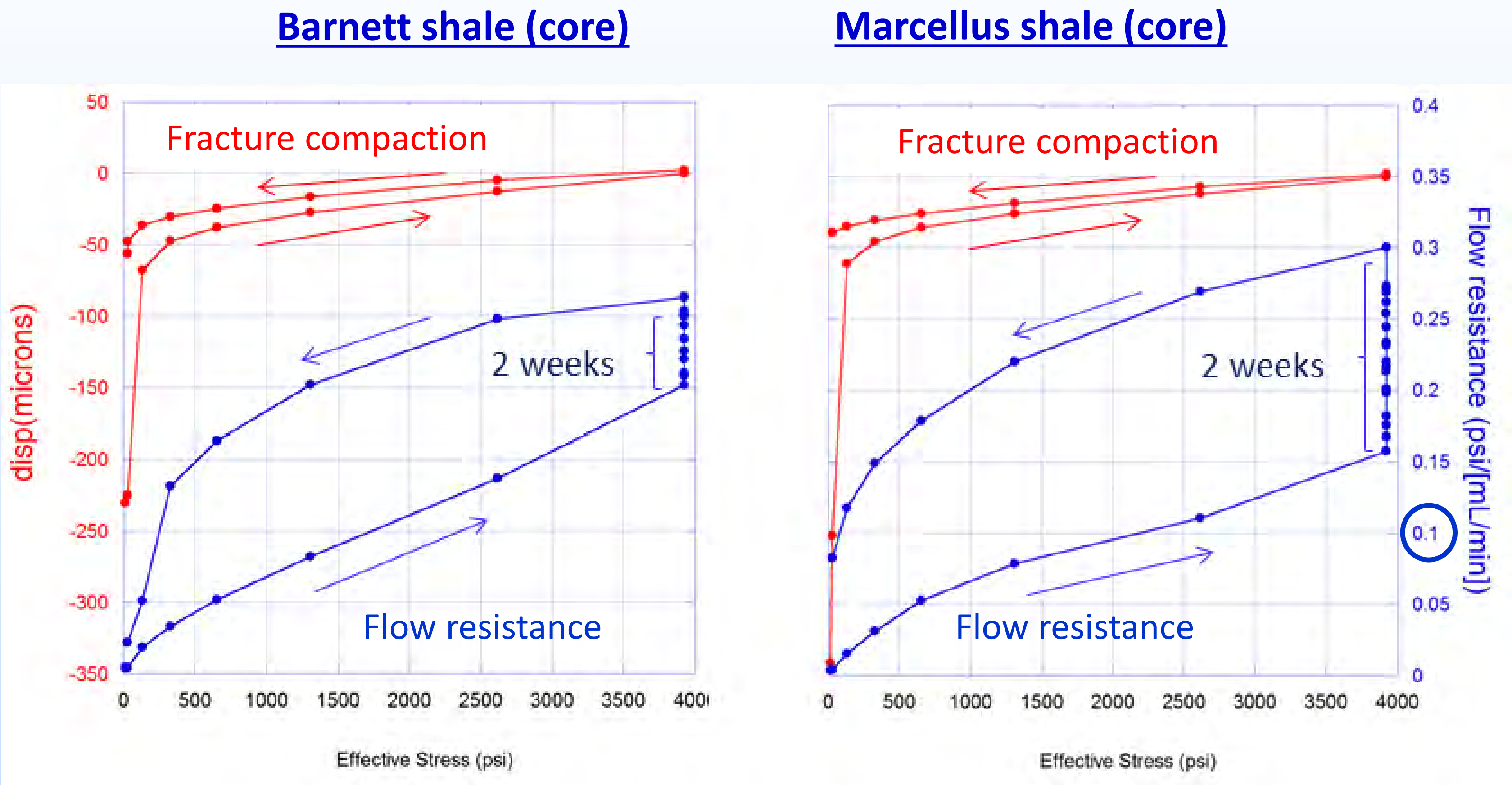
13 psi



Marcellus shale
No proppant

# Results So Far

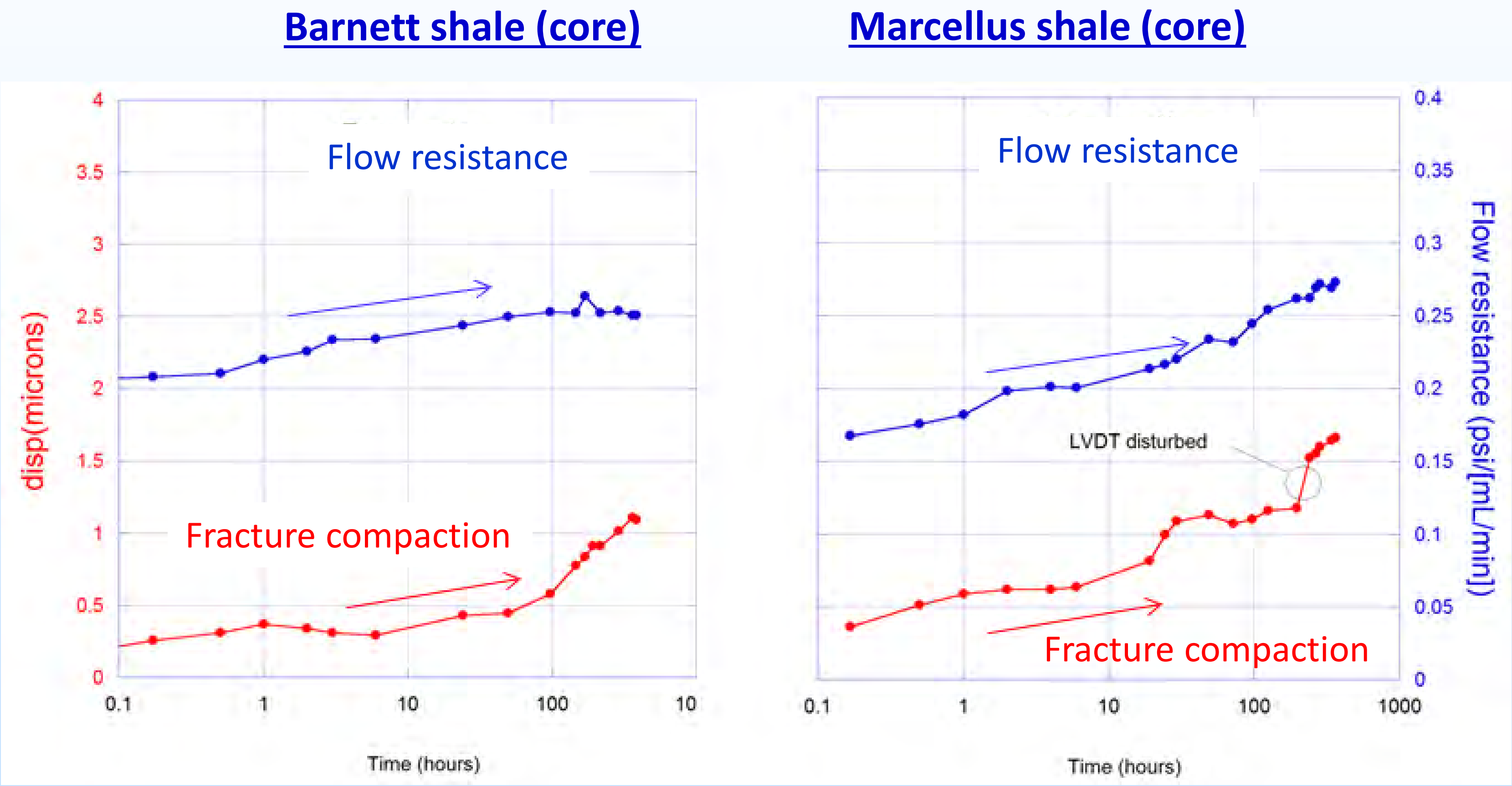
## Short-term (loading-unloading) changes




- Small hysteresis and time-dependent changes in fracture deformation
- Much larger changes in fracture conductivity
  (Flow resistance 0.1 psi min/mL→ ~70 μm hydraulic aperture)

# Results So Far

## Long-term changes

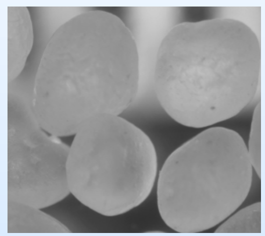



- Small hysteresis and time-dependent changes in fracture deformation
- Much larger changes in fracture conductivity

  (Flow resistance 0.1 psi min/mL→ ~70 µm hydraulic aperture)

# Results So Far

## Fracture closure and proppant crushing/embedment visualization experiment

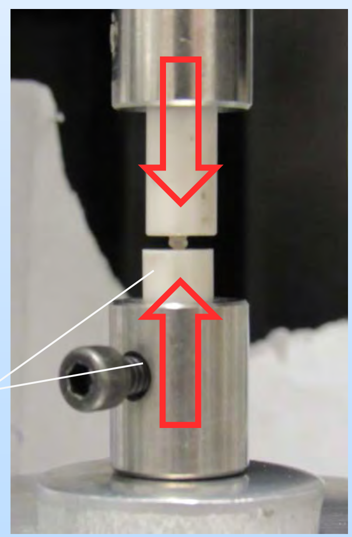



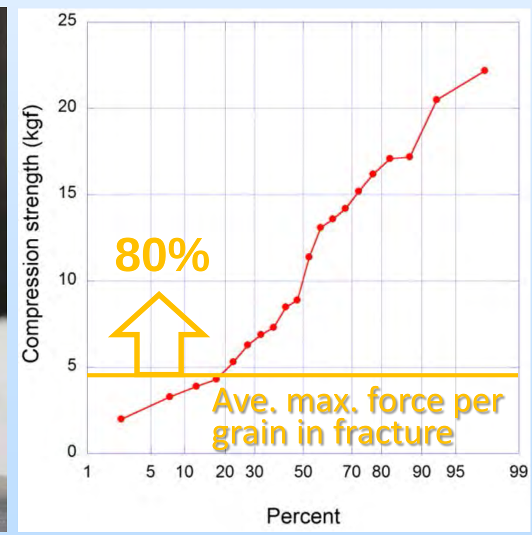
**Proppant**

- Round quartz sand
- D~1 mm (16/20)
- Surface coverage=45.6%
- Single-grain crushing strength
  Ave.=10.9 kgf, std.dev=6.0 kgf

Per grain force at maximum effective stress (3,920 psi)⟶ 4.75 kgf per grain

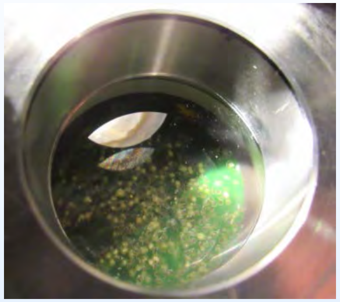
Zirconia rods

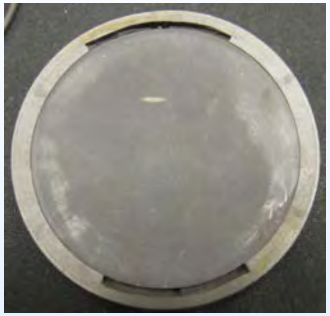


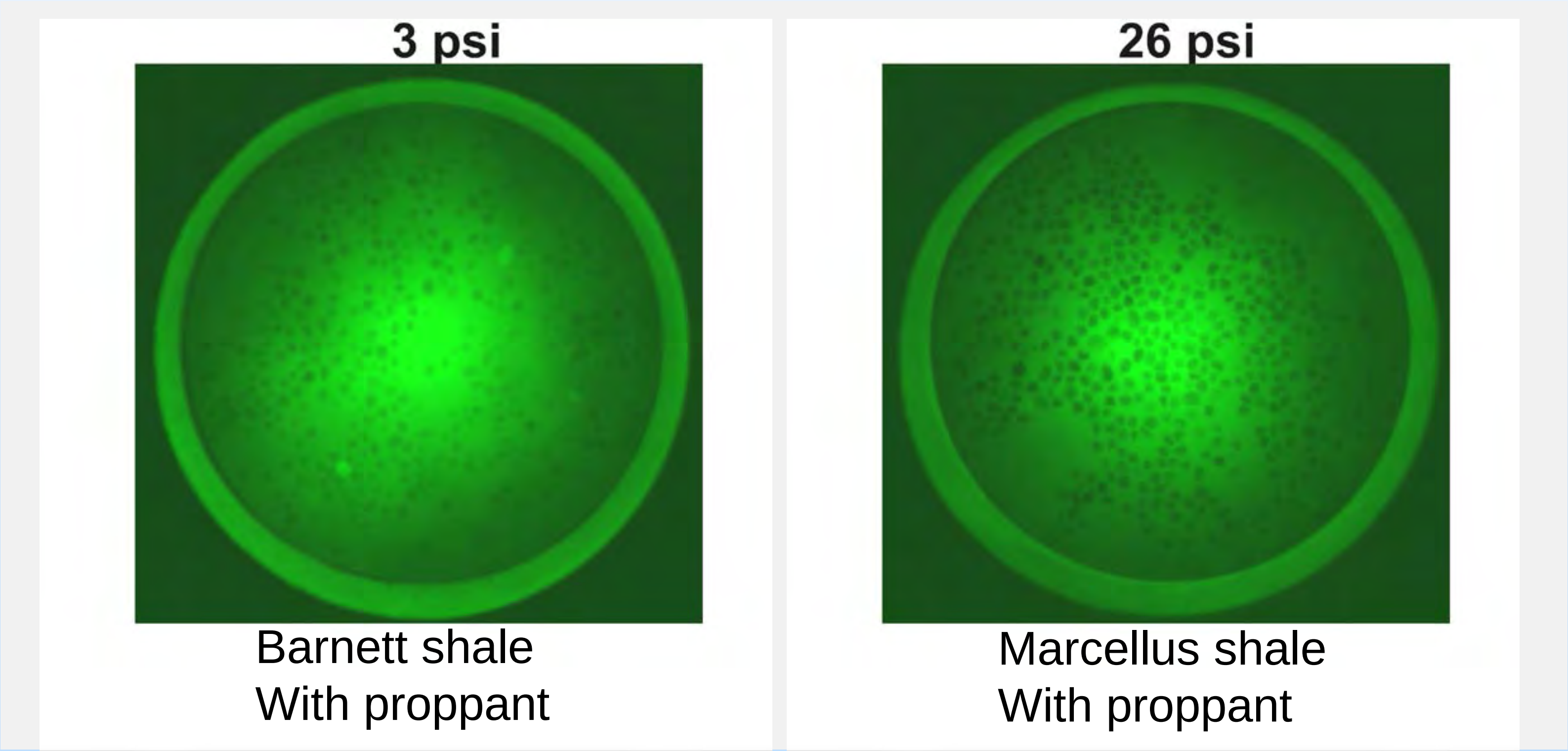


# Results So Far

## Fracture closure and proppant crushing/embedment visualization experiment

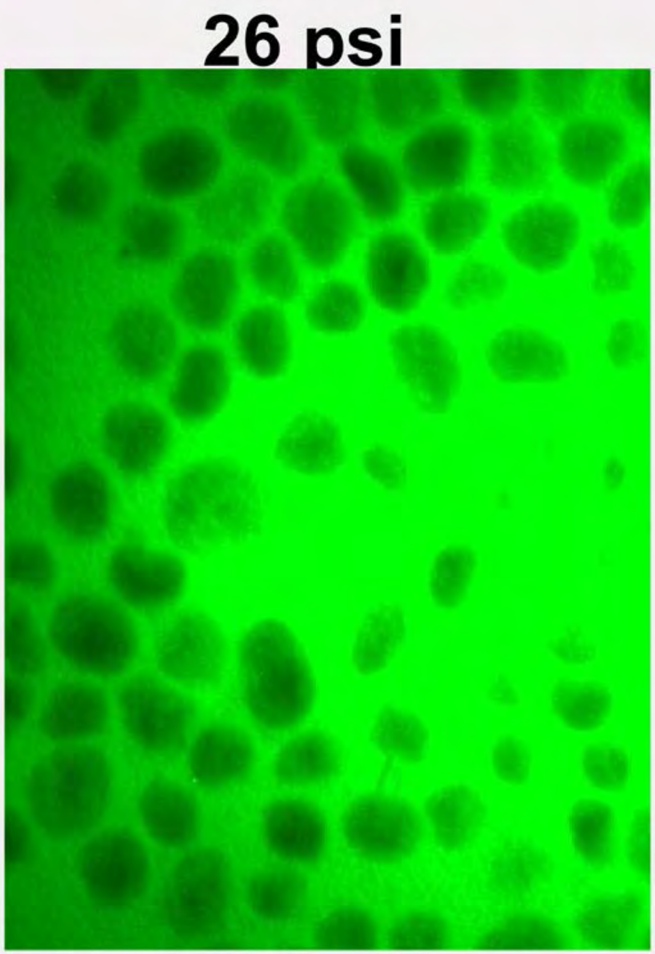


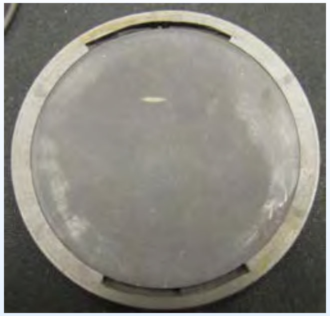


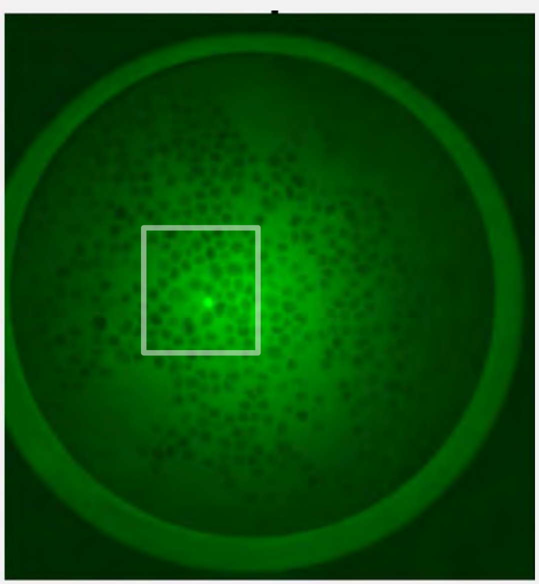


# Results So Far

## Fracture closure and proppant crushing/embedment visualization experiment



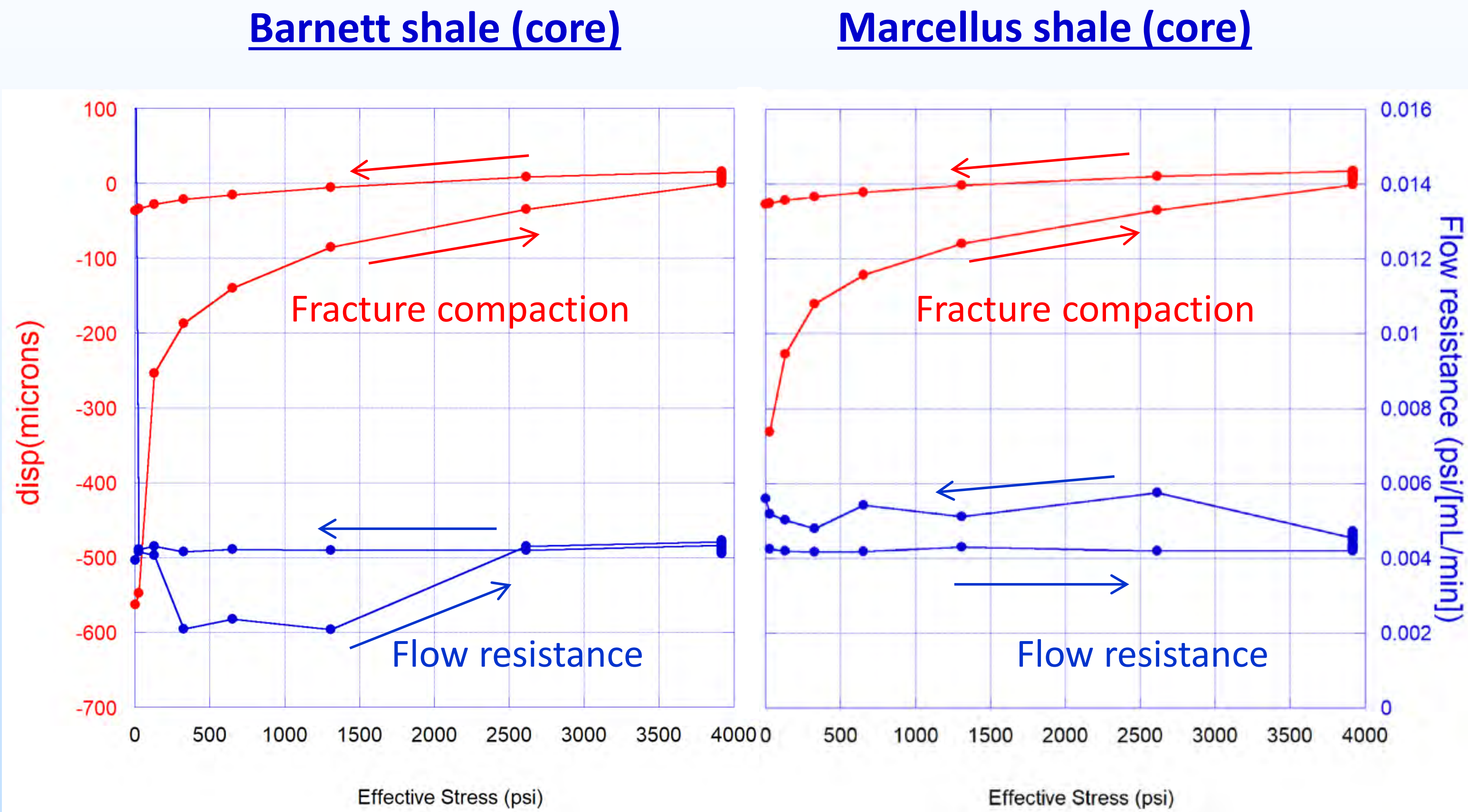





Marcellus shale
With proppant

# Results So Far

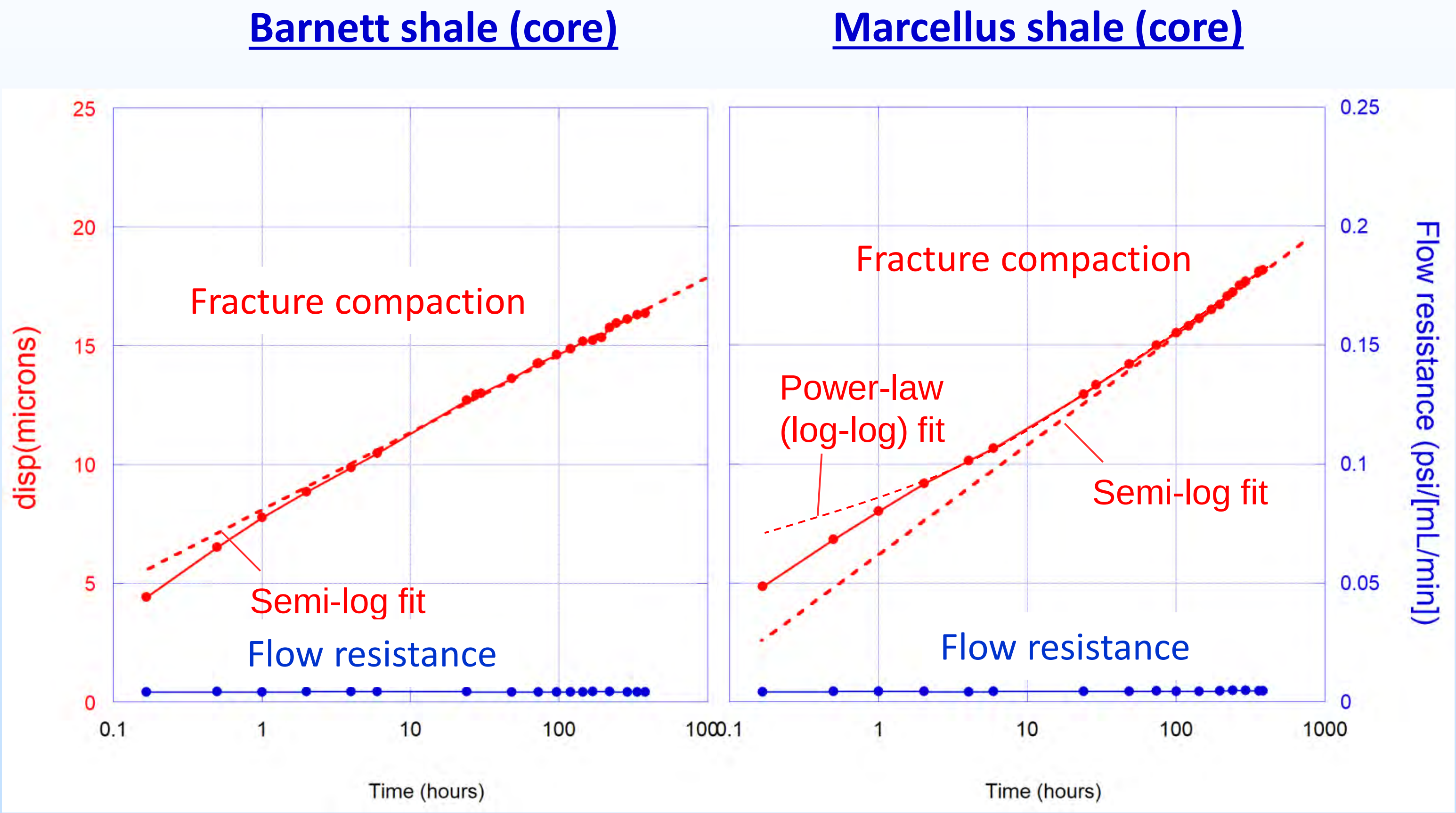
## Short-term (loading-unloading) changes




- Very large hysteresis in the fracture compaction (non-elastic proppant embedment)
- Permeability still too large to be affected by the fracture closure (large proppant grains)

# Results So Far

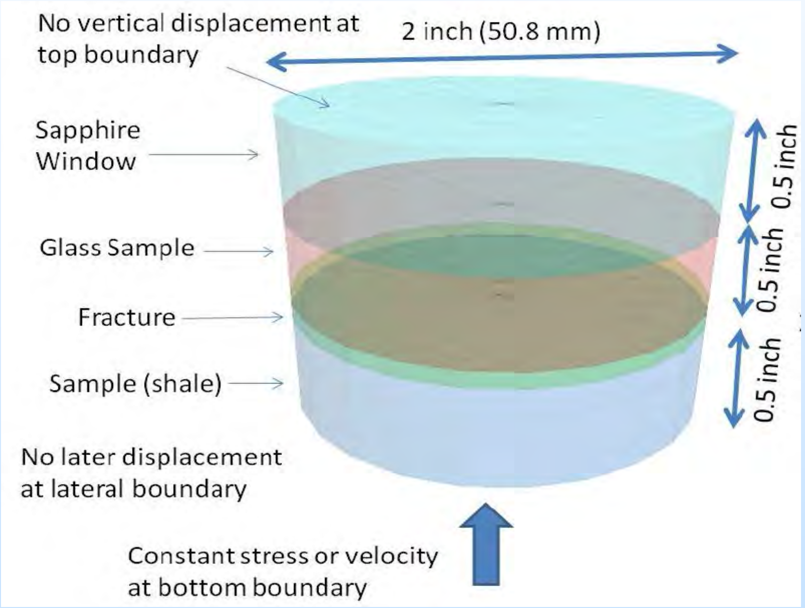
## Long-term changes



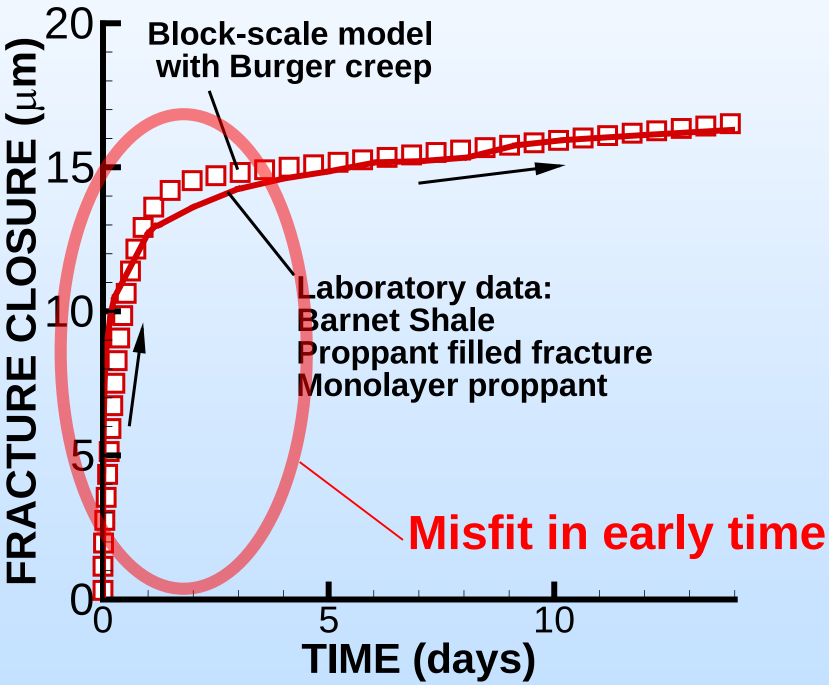

- Very large hysteresis in the fracture compaction (non-elastic proppant embedment)
- Permeability still too large to be affected by the fracture closure (large proppant grains)

# Results So Far

## TOUGH-FLAC modeling of fracture compaction/proppant embedment



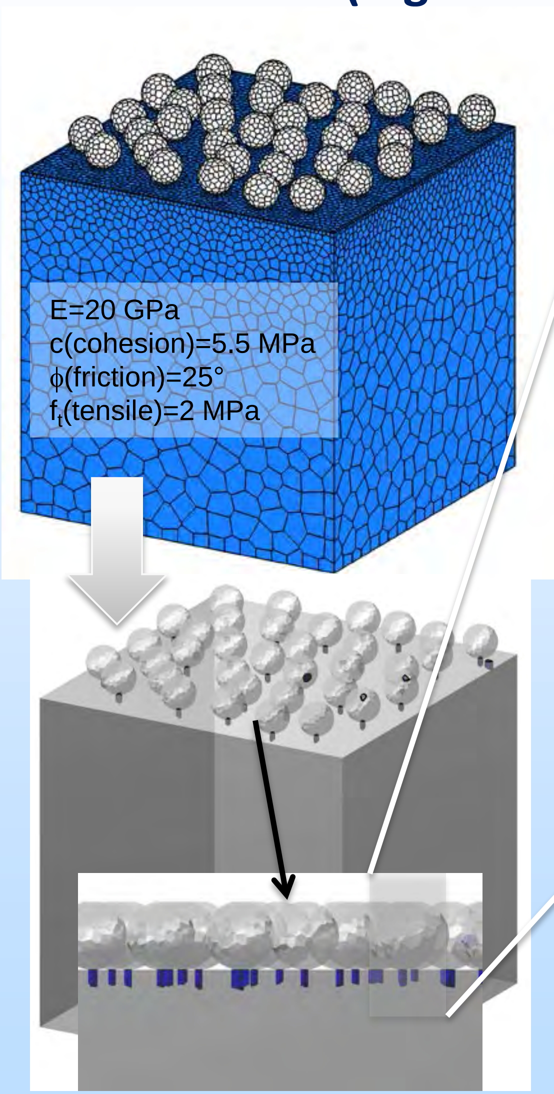

Barnett shale (core) fracture with proppant



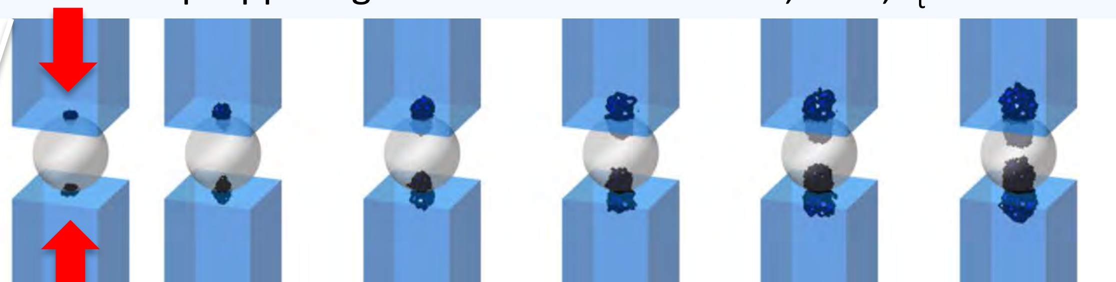

Proppant geometry effect?
Proppant crushing effect?

# Results So Far

## RBSN (Rigid-Body-Spring-Network) modeling of proppant crushing

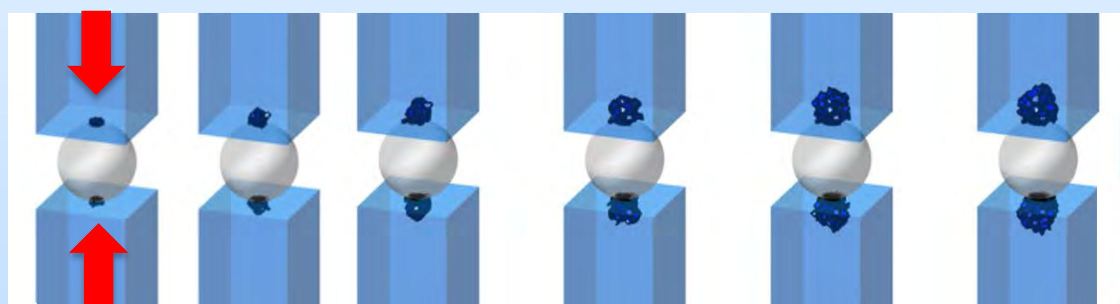


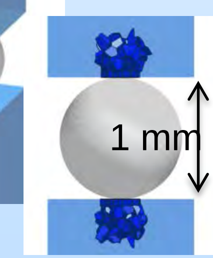

Weaker proppant grains c=7.5 MPa, f=25, $f_t$=5 MPa



Δ=20μm

Stronger proppant grains c=15.5 MPa, f=30, $f_t$=10 MPa



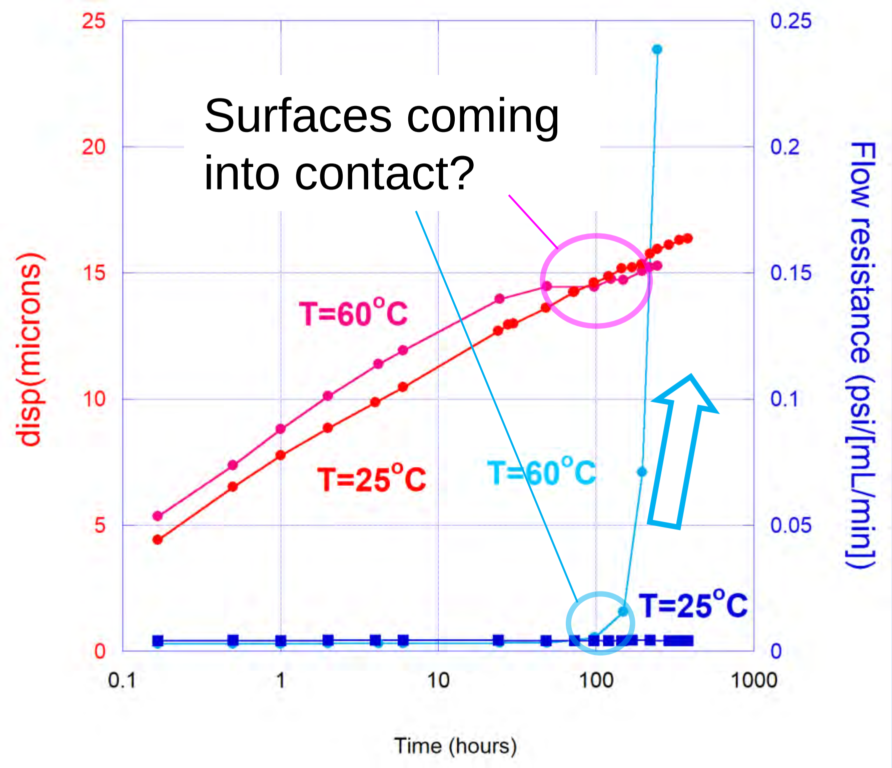


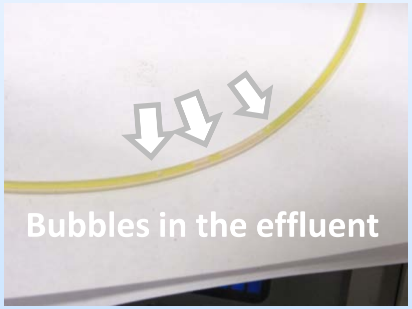

- Relative strength of proppant results in proppant crushing
- Weak tensile strength of shale has a large impact→Matrix fracturing always seems to happen

# Results So Far

## Temperature effect?

Barnett shale (core)




Degassing of shale?

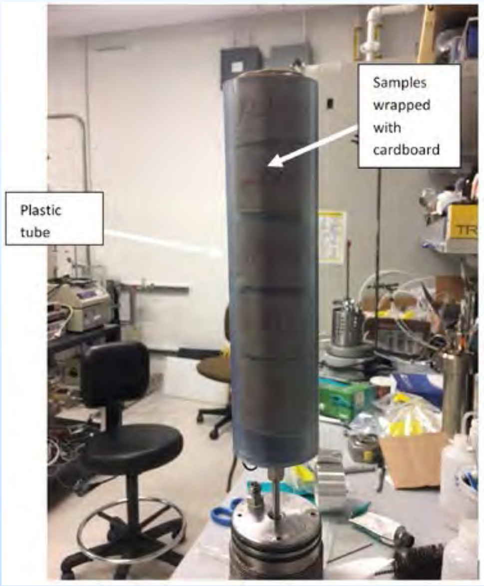
- Initial slightly faster fracture closure (Barnett with proppant) with the higher T test
- Sudden behavior changes at T~100 hours
- Contacting surfaces? Mixed gas & fluid in fracture? O-ring failure?

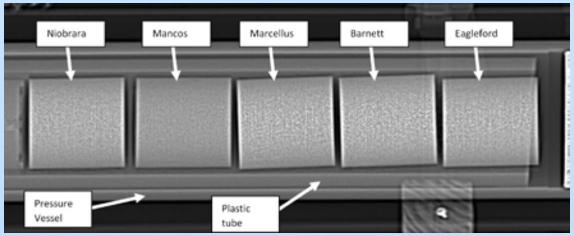
# Results So Far

## Imaging of gas transport in partially saturated shale matrix

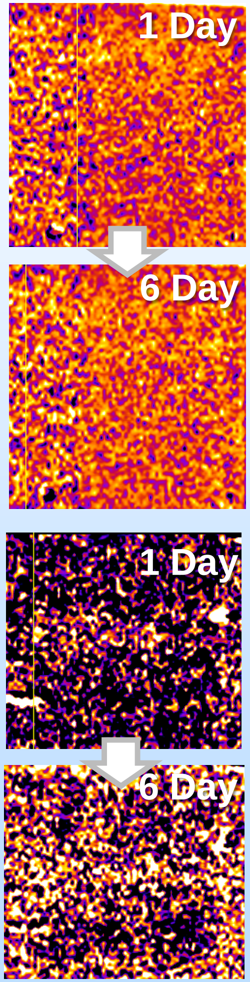
—Preliminary tests on the use of heavy gas (Kr) using (medical X-ray CT)

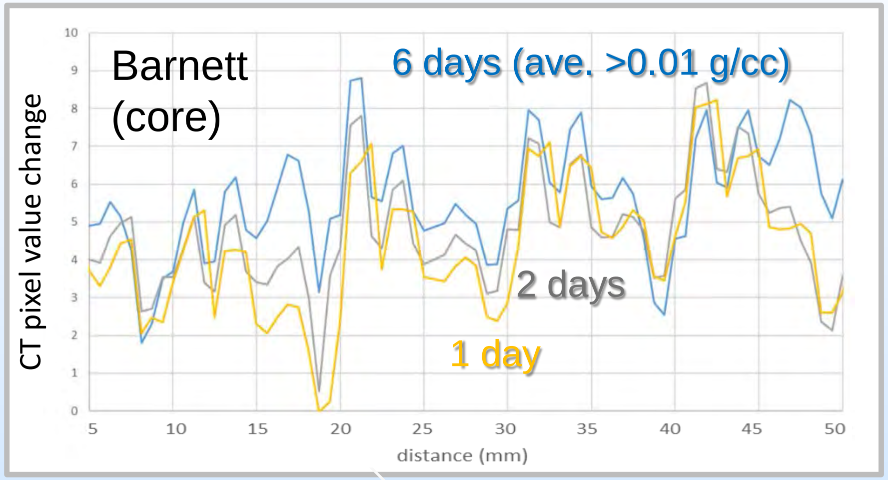
Kr 'Soaking' test at 1,000 psi

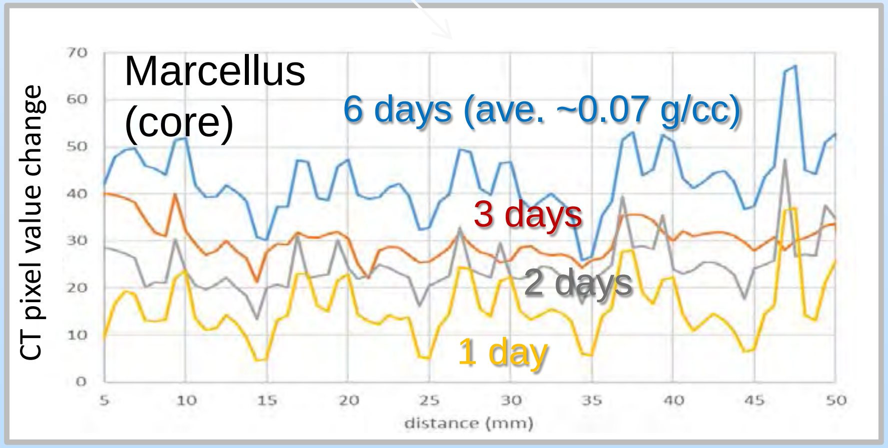



(X-ray CT images)

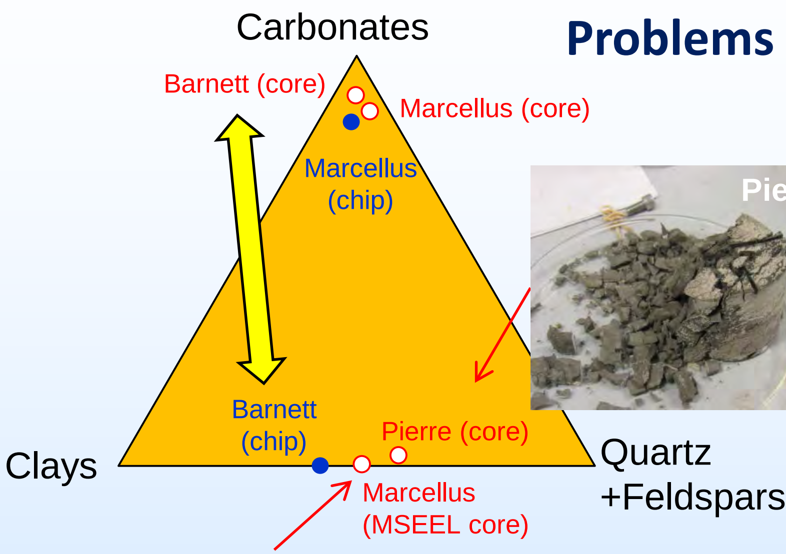


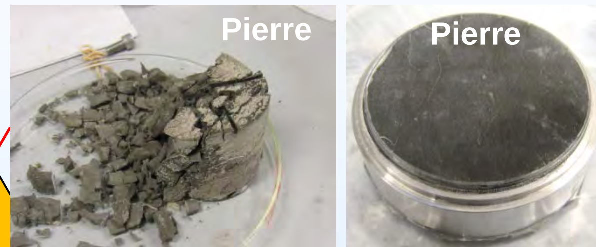



# Results So Far

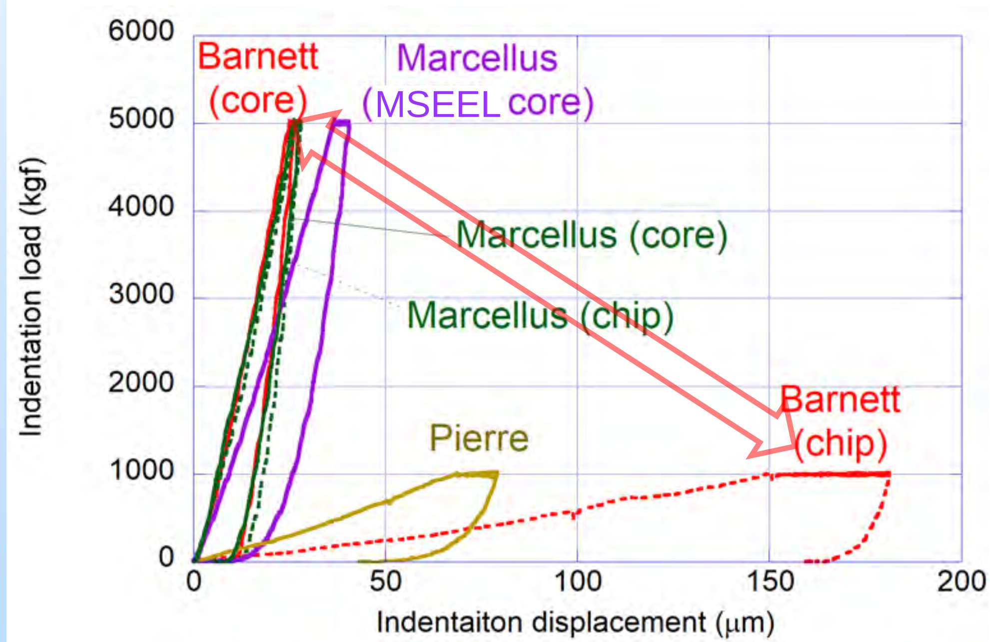
## Problems with "good" shale samples (chips vs cores)






**Short-term (30 min hold) indentation creep tests**

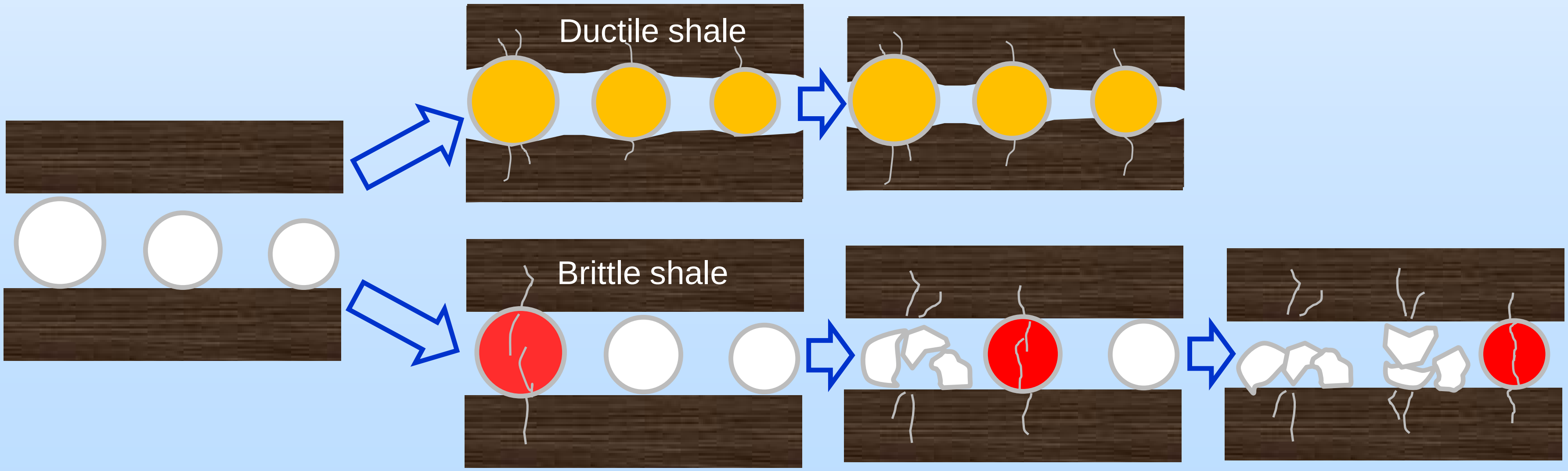


# Accomplishments to Date

- Microns-to-a-millimeter-scale **instrumented indentation system** was built. Elastic and non-elastic parameters of 5 different types of shales (outcrop samples) were determined.
- A new experimental tool (**fracture/proppant compaction visualization system**) was designed and fabricated, and a methodology for measuring and visualizing time-dependent compaction of a fracture in ductile shales has been established.
- **Multiple long-term (~2 week) experiments** have been conducted on fractures in two types of shale (Barnett shale and Marcellus shale), with and without proppant. Time-lapse dataset correlating optical images of fracture aperture distribution, average fracture closure, and fracture permeability (hydraulic aperture) has been obtained.
- Numerical tools and the simulation methodology based upon TOUGH-FLAC and TOUGH-RBSN codes have been developed
- TOUGH-FLAC code has been used on lab indentation test results for extracting parameters necessary for shale deformation tests. Related issues and a solution have been identified.

# Lessons Learned

- For sparse, monolayer proppant, the layer strength can be much smaller than expected from the strength of individual grains due to "weakest-link" effect (or "zipper" effect). Some ductility in the shale actually would help increasing the layer strength because of the redistribution of the stress within and between proppant grains
- For predicting long-term fracture closure and permeability loss, long-duration lab experiments (and modeling requiring parameters determined from them) seem essential at this point



# Synergy Opportunities

- Micro-scale shale fracture deformation and proppant embedment characterization via micro CT imaging
- "Foot-size" proppant transport visualization experiment
- Chemical & Mineralogical analysis and interpretation of shale

→ *Investigations for Maximization of Production from Tight/Shale Oil Reservoirs: From Fundamental Studies to Technology Development and Evaluation*

(M. Voltolini, PI: M. Reagan [LBNL])

- Future experiments and modeling will focus on the impact of shale-proppant-fluid interactions on the fracture closure in ductile shale

→ *Possible collaboration with NETL (*A. Hakala, D. Crandall*) and SLAC (*J. Bargar*)*

# Project Summary

- Development of both grain-scale and core-scale laboratory tools (experimental test cell, micro indentation test system) and modeling tools (TOUGH-FLAC and TOUGH-RBSN models) were completed for grain and core-scale shale fracture/proppant behavior study
- A series of long-term (~2-week) visualization experiments have been conducted with concurrent fracture permeability and compaction measurements, on both bare fracture and proppant-filled fractures
- Our Barnett shale samples, which was expected to be highly ductile from the baseline characterization tests in Year 1, turned out to be actually quite brittle. The experiment is being repeated using high-clay-content shales which are confirmed to be ductile (Pierre shale and Marcellus shale cores from NSEEL thanks to NETL). Additional cores (Hainesville shale) are being obtained through our industry contact (Chevron ETC).

# Appendix

# Benefit to the Program

**Program Goals**

- Identify and accelerate development of economically-viable technologies to more effectively locate, characterize, and produce natural gas and oil resources, in an environmentally acceptable manner
- Characterize emerging oil and natural gas accumulations at the resource and reservoir level and publish this information in a manner that supports effective development
- Catalyze the development and demonstration of new technologies and methodologies for limiting the environmental impacts of unconventional oil and natural gas development activities

## Project Benefits

This research project aims to develop laboratory and numerical modeling tools and collect data, for understanding and predicting the time-dependent permeability reduction of hydraulic fractures in ductile and expanding shales. If successful, this project provides better understanding and predictive capabilities for the complex interactions between proppant and the shale matrix, which lead to optimized and economical reservoir stimulation within shales which are currently considered difficult for stimulation and resource recovery.

# Project Overview
## Goals and Objectives

Project Goals and Objectives

This projects aims to conduct combined laboratory and modeling studies to
(1) Obtain improved understanding and data for time-dependent changes of hydraulic fractures in clay-rich, ductile and expanding shales through laboratory visualization experiment
(2) Develop an improved and tested numerical simulation capability for coupled, fluid flow and fracture/proppant deformation processes
(3) Address currently lacking upscaling knowledge and methodology from grain scale to core scale to reservoir scale shale fractures →Development of predictive tools

- o Fundamental understanding the process of hydraulic fracture closure in ductile and expanding shales (incl. brittle shale with proppant crushing)
- o Fracture permeability reduction modeling and predictions

**Gained knowledge**

Program Goals and Objectives

- ▪ Fracturing and re-fracturing operation optimization
- ▪ Efficient and sustainable oil and gas production
- ▪ Development of under-utilized shale resources

Success Criteria

- Experimental data from baseline property measurements and fracture compaction tests for at least 4 to 5 different types of shales
- Correlations between the baseline experiments and the time-dependent fracture deformation experiments for various shale samples.
- Numerical modeling capability to predict the long-duration (1-2 weeks) laboratory fracture closing behavior calibrated by the baseline shale properties

# Organization Chart

## Project Team

**Helen Prieto**
–Administrative Assistance–

### Lab Experiment Team

**Seiji Nakagawa (PI)**
–Mechanical and hydrological testing. Optical imaging–

**Tim Kneafsey**
– Hydrological testing and X-ray CT imaging –

**Sharon Borglin**
- Laboratory assistance -

### Numerical Modeling Team

**Jonny Rutqvist (Co-PI)**
–TOUGH-FLAC modeling–

**Kunhwi Kim**
–TOUGH-RBSM modeling–

### Industry Advisor

**Russell Ewy**
Chevron ETC

# Gantt Chart

| Tasks | Year 1 (Oct.2016-Sep.2017) | | | | Year 2 (Oct. 2017-Sep.2018) | | | |
|---|---|---|---|---|---|---|---|---|
| | Q1 | Q2 | Q3 | Q4 | Q1 | Q2 | Q3 | Q4 |
| **Task 1: Management and Planning** | | | | | | | | |
| **Task 2: Laboratory experiments** | | | | | | | | |
| Subtask 2.1: Designing and fabrication of shale fracture test cell | | M1 | M3 | | | | | |
| Subtask 2.2: Test sample acquisition and preparation | | | | | | | | |
| Subtask 2.3: Shale property characterization & ductility measurements | | | | M4 | | | | |
| Subtask 2.4: Fracture closure experiments I: w/o proppant | | | | | | M6 | | |
| Subtask 2.5: Fracture closure experiments II: w/ proppant | | | | | | | M8 | |
| Subtask 2.6: Gas/liquid transport experiment | | | | | | | | M10 |
| **Task 3: Numerical modeling** | | | | | | | | |
| Subtask 3.1: Develop grain-scale modeling approaches based on TOUGH-FLAC/TOUGH-RBSN | | | M2 | | | | | |
| Subtask 3.2: Develop block-scale modeling approaches | | | M2 | | | | | |
| Subtask 3.3: Indentation experiment modeling and material parameterization | | | | M5 | | | | |
| Subtask 3.4: Modeling fracture closure experiments I: w/o proppant | | | | | | M7 | | |
| Subtask 3.5: Modeling fracture closure experiments II: w/ proppant | | | | | | | M9 | |
| Subtask 3.6: Modeling Gas/liquid transport experiment | | | | | | | | M11 |

- M1-M11: Milestones

# Bibliography

For the current research project, publications are still in preparation

To be submitted:


- Nakagawa, S., S. Borglin, T.J. Kneafsey, and M. Voltolini (2018?) Laboratory visualization of fracture closure and permeability loss in fractures in ductile shales with and without proppant, to be submitted to Int. J. Rock Mech.
- Rutqvist, J. and K. Kim (2018?) Grain-scale modeling of proppant embedment and fracture closure in soft shale, to be submitted to JSPE.