# Controlling Sustainability of Hydraulic Fracture Permeability in Ductile Shales

FP00008114

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U.S. Department of Energy
National Energy Technology Laboratory
2021 Carbon Management and Oil and Gas Research Project Review Meeting
August 2021

# 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

<u>Advisors and collaborators</u>

- Dr. Russ Ewy (Recently retired, Chevron Energy Technology Company)
- Prof. Mehdi Mokhtari (Univ. Louisiana/ Tuscaloosa Marine Shale Laboratory)
- Prof. Mileva Radonjic (Oklahoma State Univ./Caney Shale Laboratory)
- HFTS Project
- Adam Jew (SLAC), Joe Morris (LANL), Dustin Crandall (NETL)

# Presentation Outline

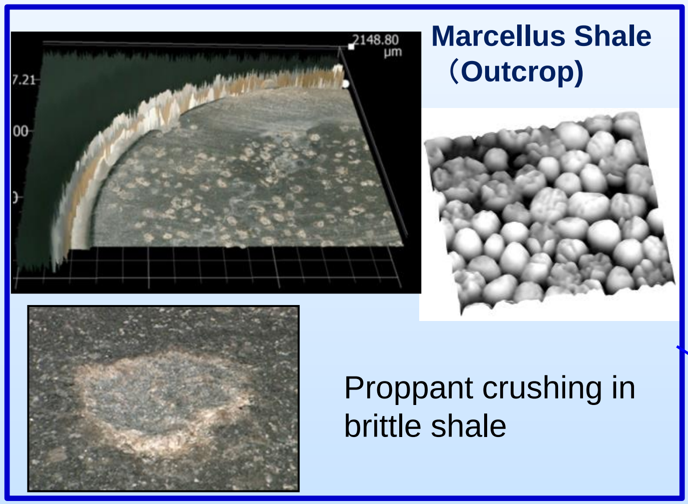
- Technical Status
  - Motivation & Background
  - Project Outline
  - **Highlights from lab experiment and numerical modeling**
- Accomplishment to Date
- Lesson Learned
- Synergy Opportunities
- Project Summary

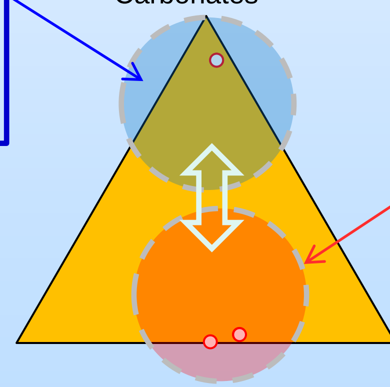
# Technical Status

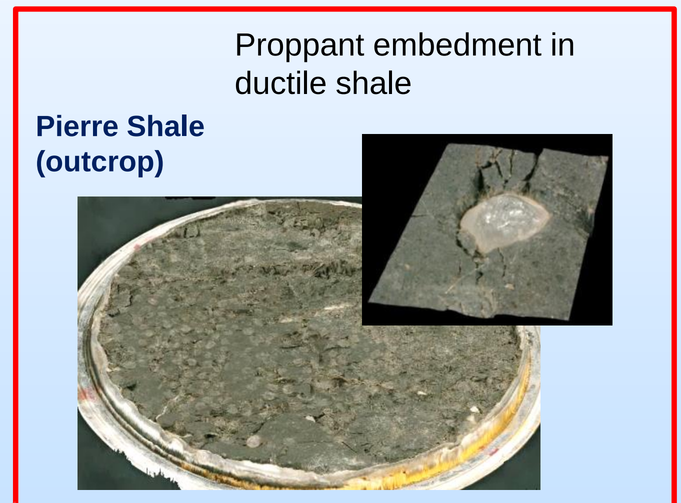
# Motivation and Objectives

Thin, near-leading-edge fractures and tributary cracks in a HF system

- Contribute to a large drainage footprint
- But are vulnerable to premature permeability declines due to **proppant crushing (brittle shale)** and **embedment (ductile shale)**



# Motivation and Objectives

## Big question/Technology goal of this project

- Can we chemically manipulate shale-proppant interaction and hydraulic fracture closure (permeability reduction)?

- If so, how do we achieve this?

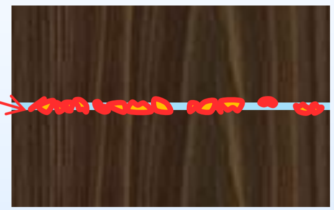
# Motivation and Objectives

## Possible method for proppant crushing reduction

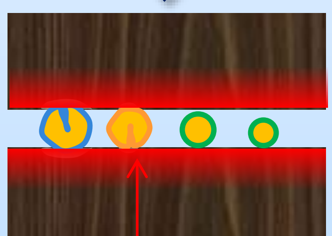
## Possible method for proppant embedment reduction

**Brittle Shale**

Crushed proppant

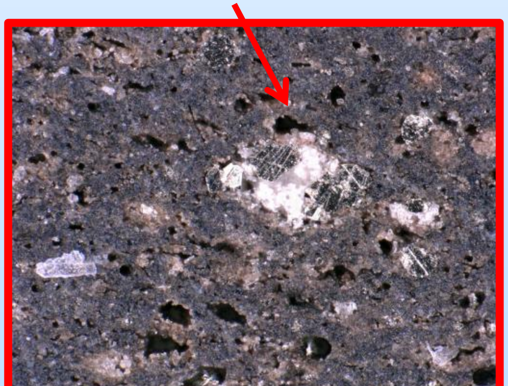


Controlled acid treatment

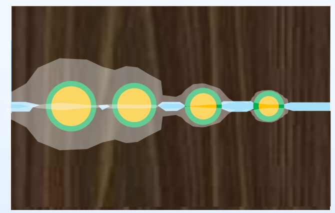


Soft zone (dissolution)

Pores from dissolved carbonate



**Ductile Shale**

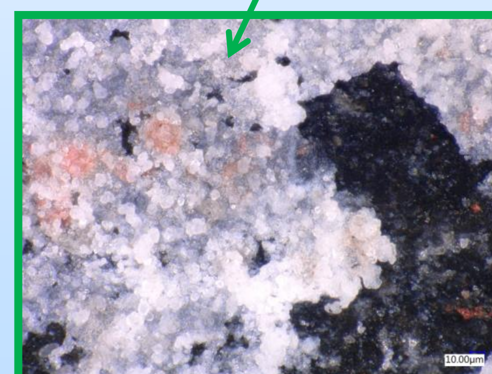


Proppant embedment

Controlled mineral precipitation

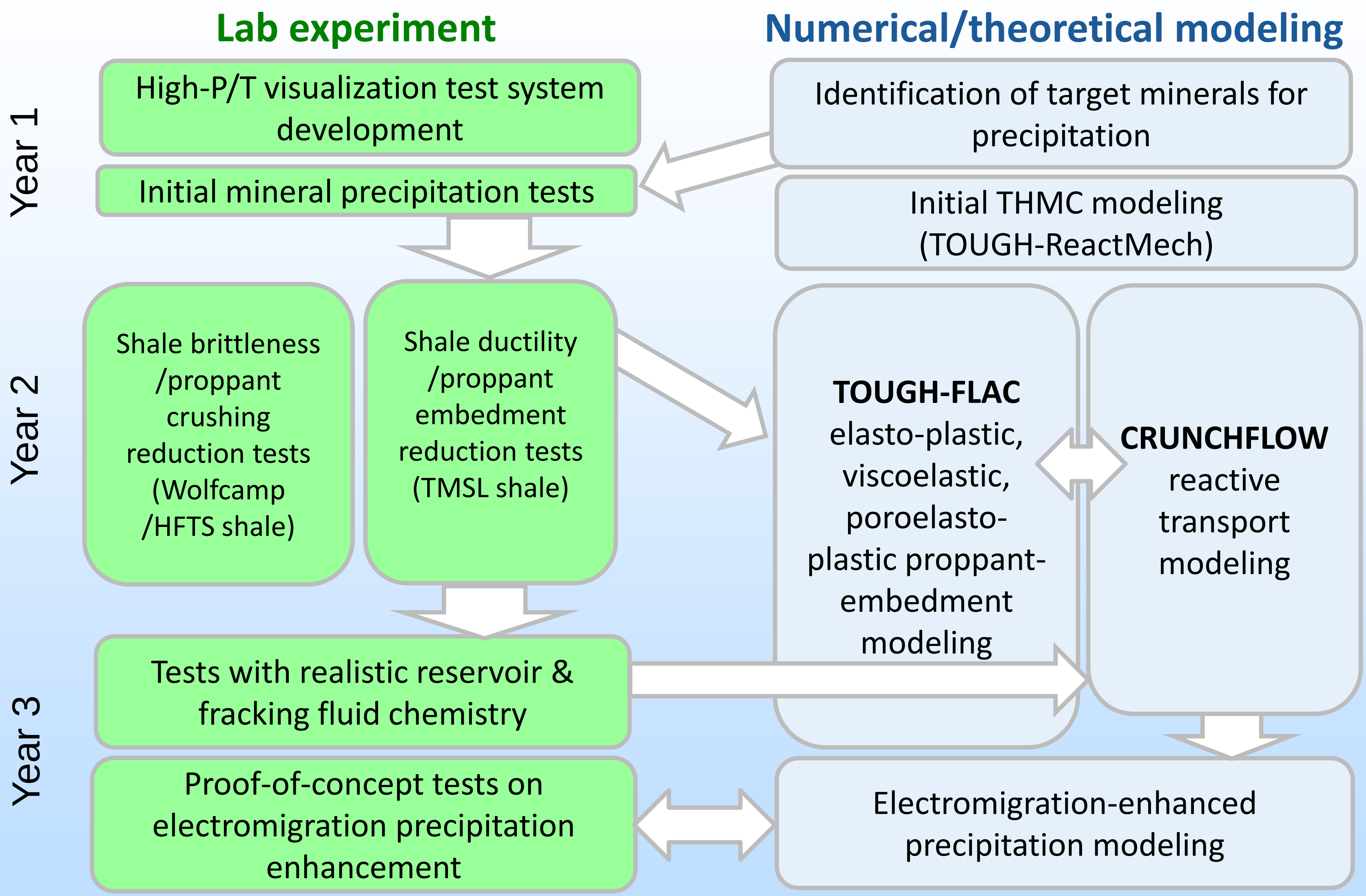
Hard zone (precipitation)

Intentionally precipitated carbonates from reservoir fluid




**Optimum propping?**

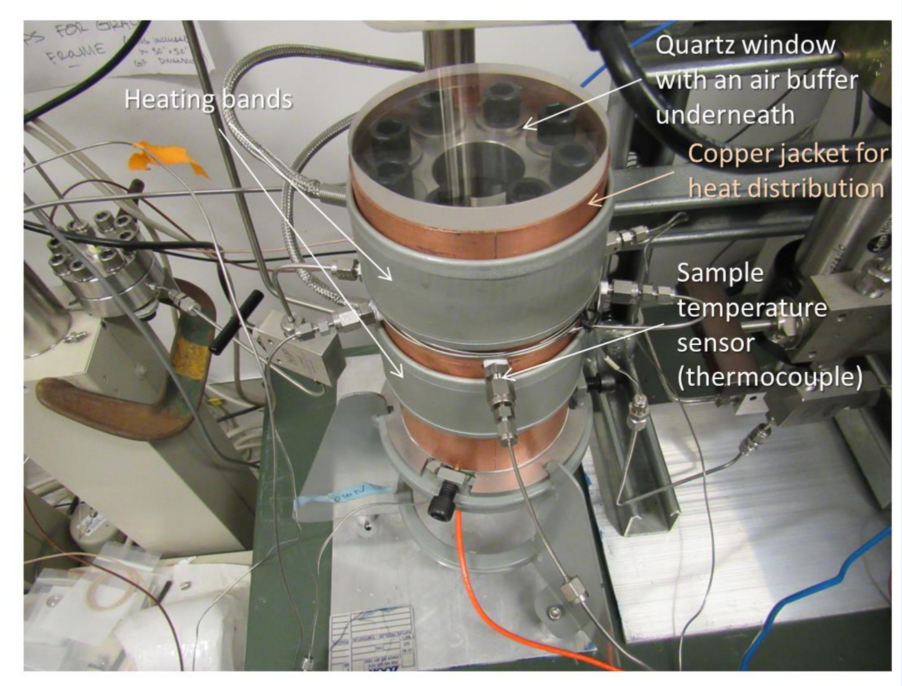
# Project Outline

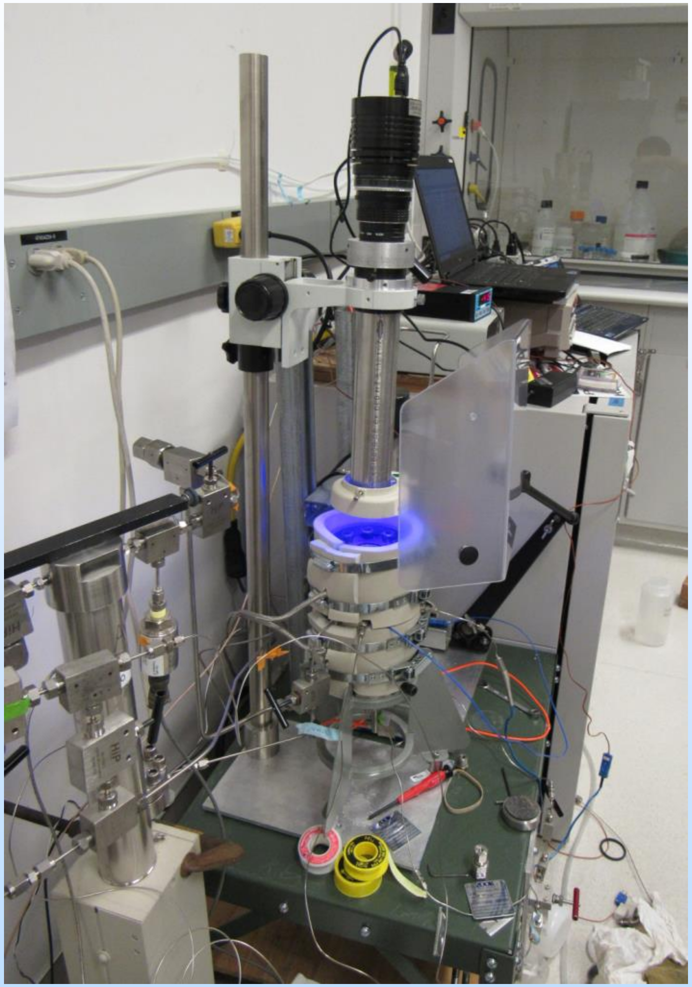


# Experimental Setup: Test System

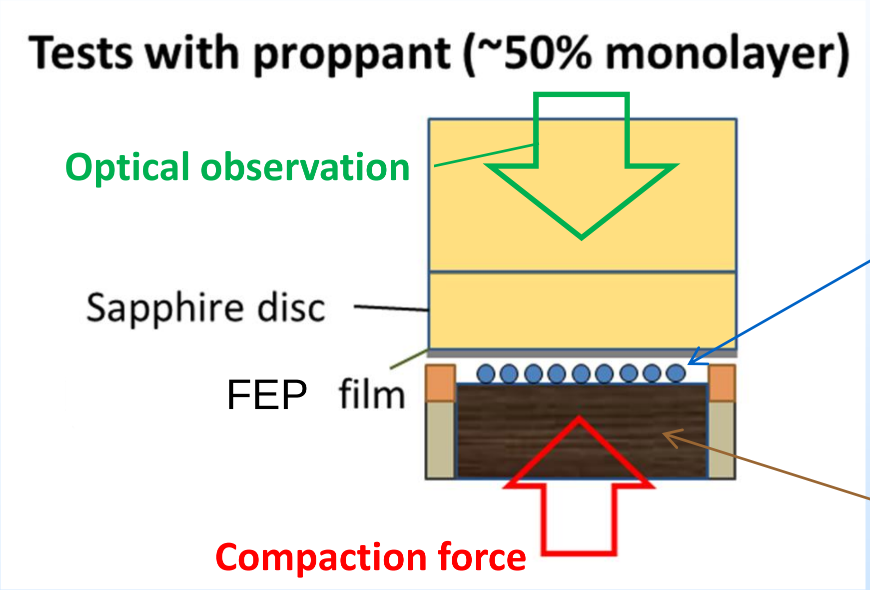
- Customized high P-T oedometric compaction cell
- Optical visualization

Actual test max effective stress: 27 MPa (3920 psi)
test temperature: 120-125˚C
test pore pressure: 10.3 MPa (1500 psi)

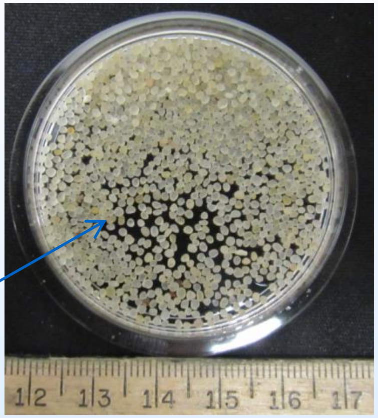


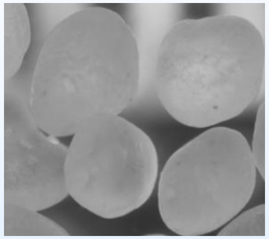



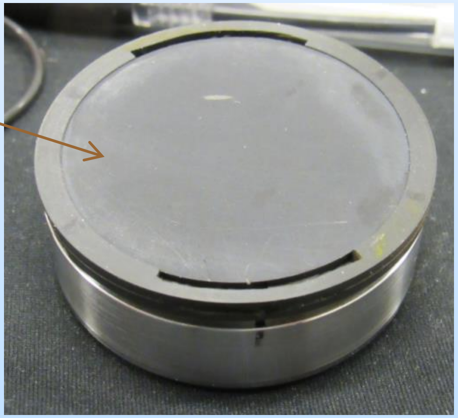
# Experimental Setup: Test System




Quartz sand (dia.1-1.5 mm)



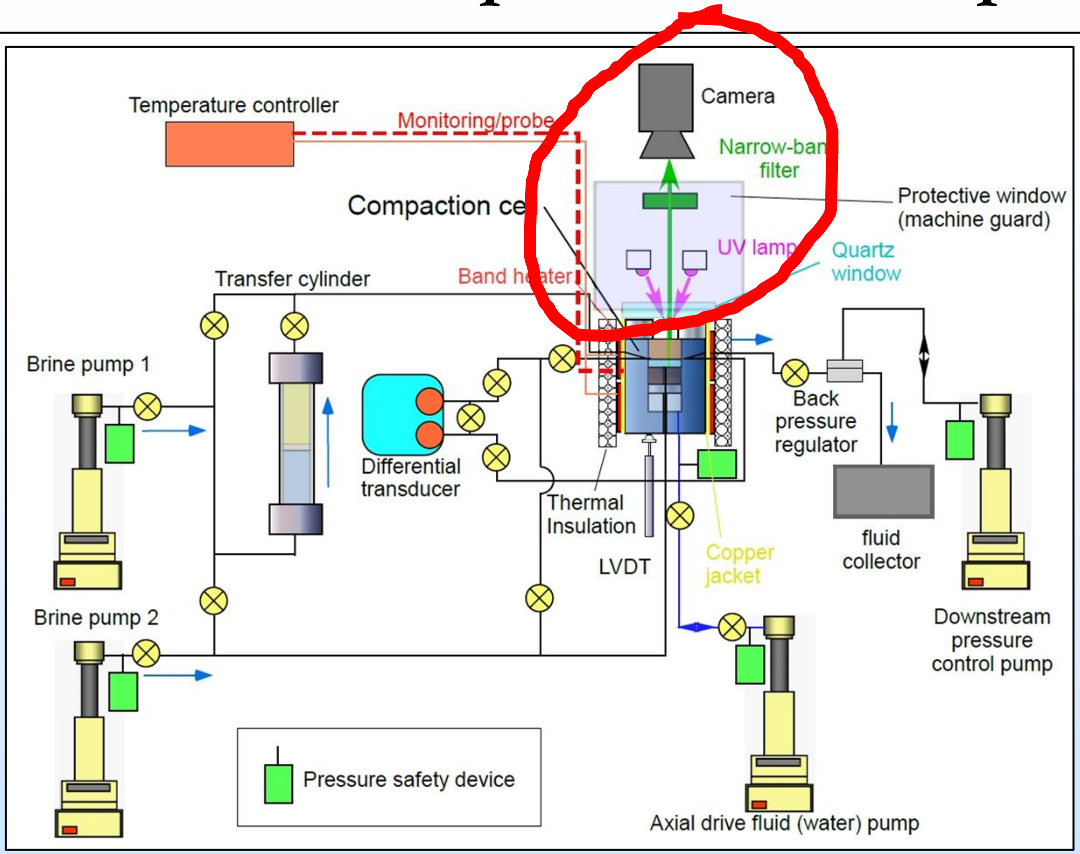


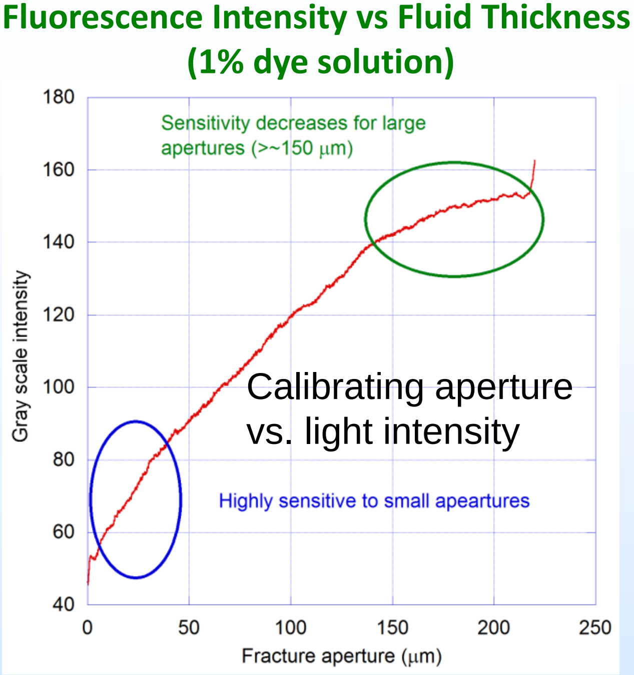


Shale disc (dia. ~44 mm)

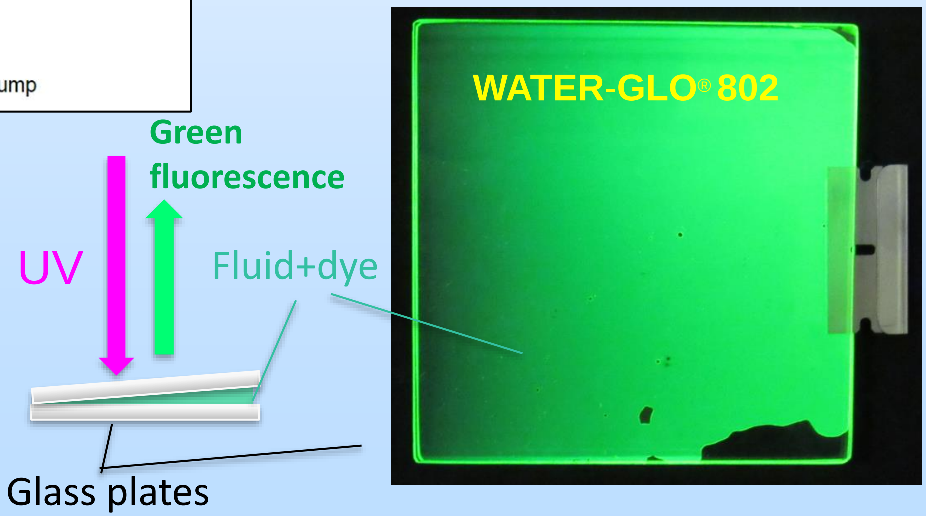
- Monolayer/sub-monolayer proppant is pressed against the surface of a shale disc
- Top half of the “fracture” is a transparent, sapphire window

# Experimental Setup: Test System




- Visualization is facilitated by the UV-fluorescence technique
- Semi-quantitative measurement of fracture aperture and proppant geometry

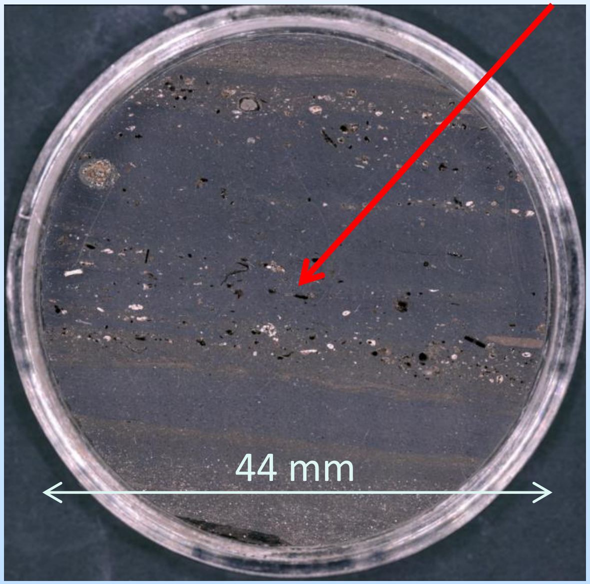


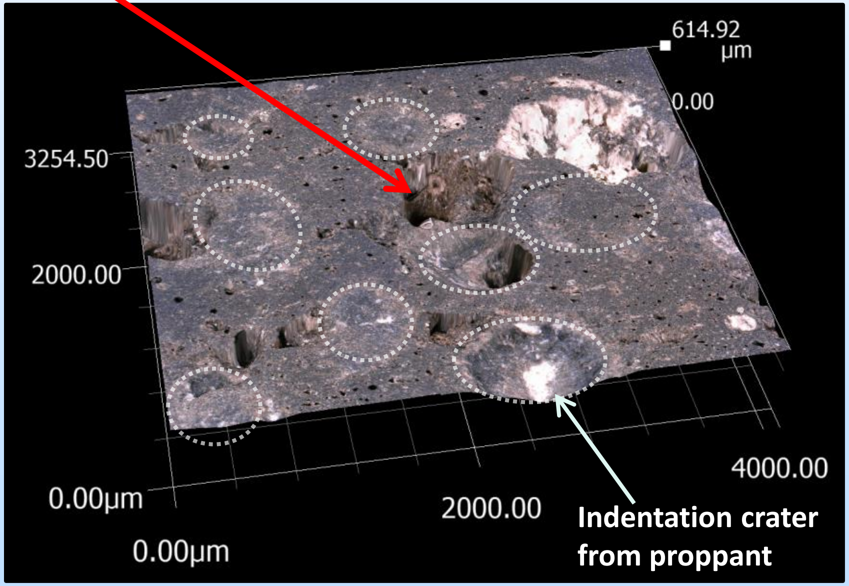
# Result: Brittleness Reduction (Wolfcamp/HFTS shale)

- Examined the impact of acid treatment ("acid spearhead") on clay and carbonate rich shales (Wolfcamp shale, HFTS project)
- Conducted long-term (~2 weeks) in-situ visualization experiments

Effective stress: 27 MPa
Temperature: 123˚C
Pressure: 10.3 MPa
Duration :2 weeks
Acid pretreatment: 15% HCl (room T)

**Carbonate-dissolution-induced porosity**

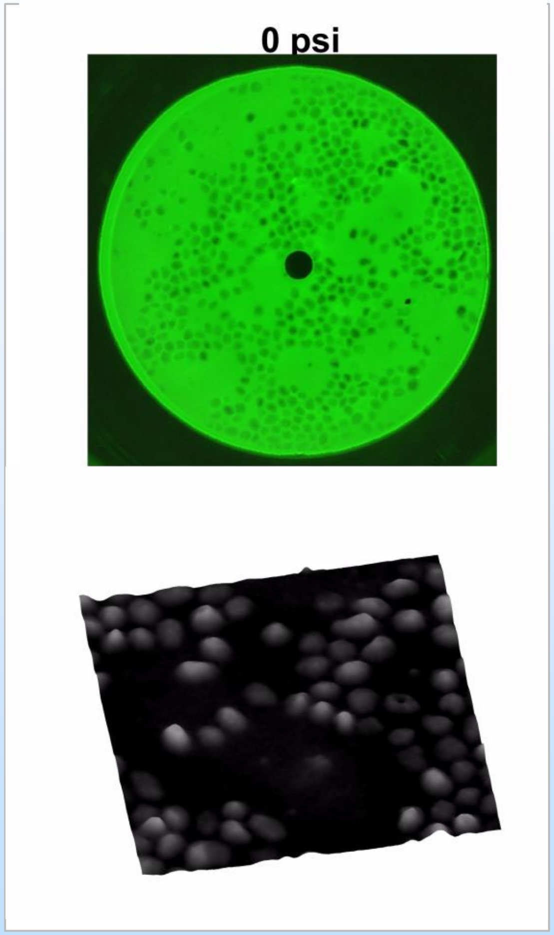


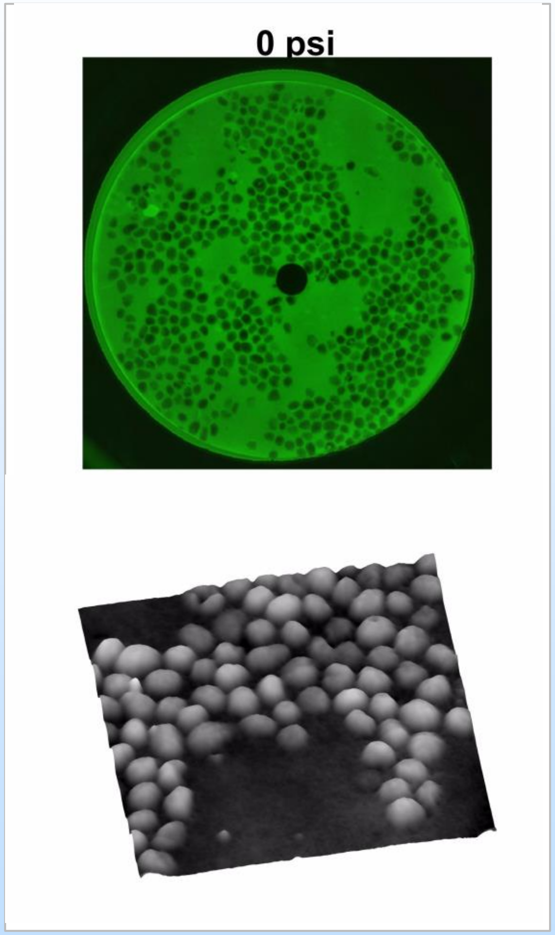

Carbonate-rich, heterogeneous Wolfcamp shale

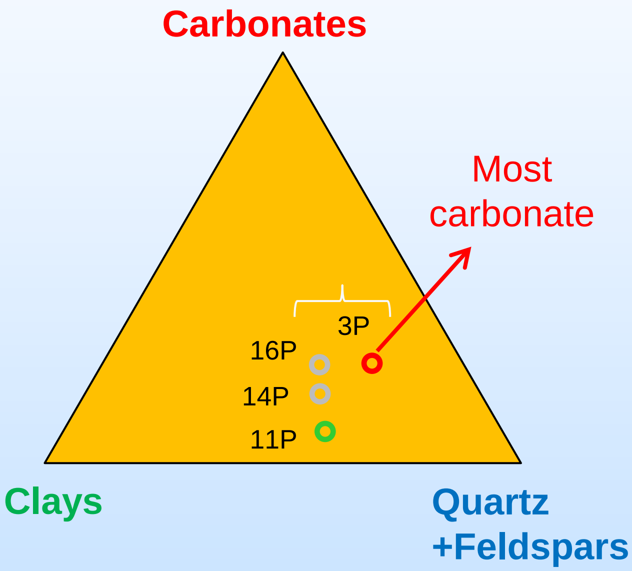
# Result: Brittleness Reduction (Wolfcamp/HFTS shale)

Carbonate-rich shale, no acid




Carbonate-rich shale, with acid

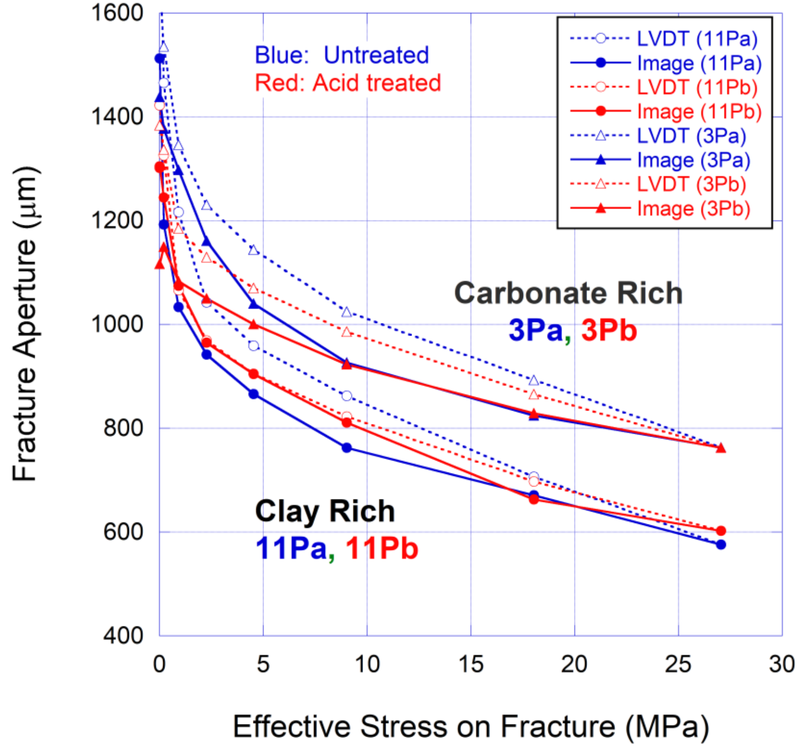


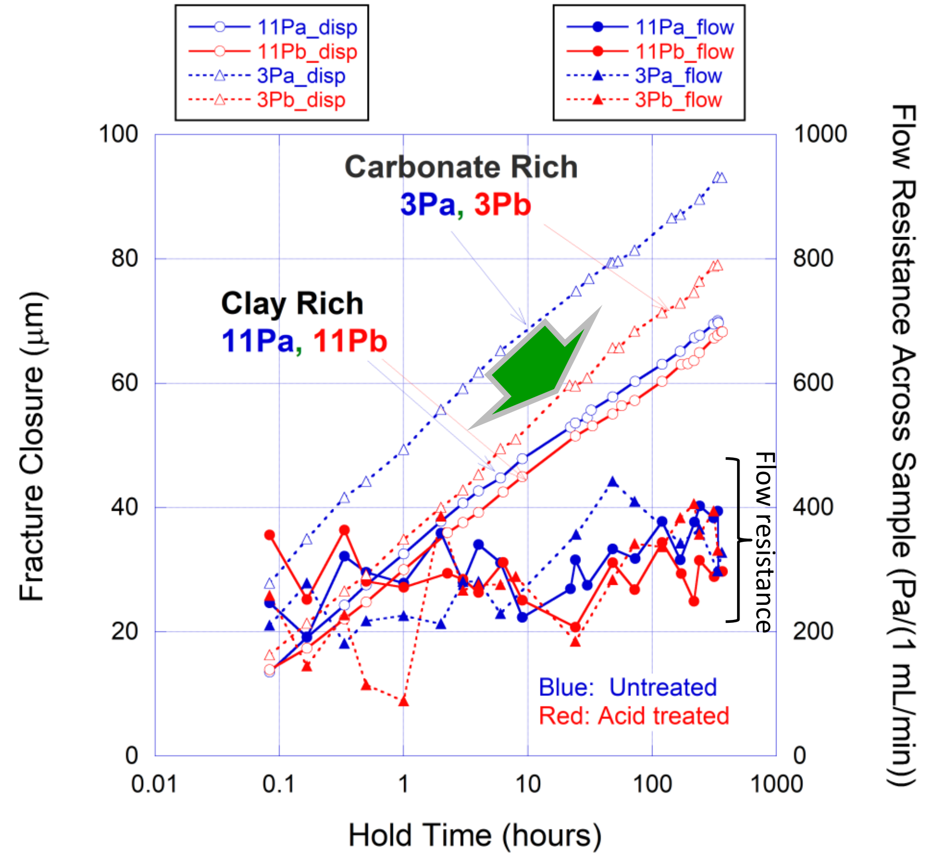




- Severe proppant crushing was observed for both cases

# Result: Brittleness Reduction (Wolfcamp/HFTS shale)

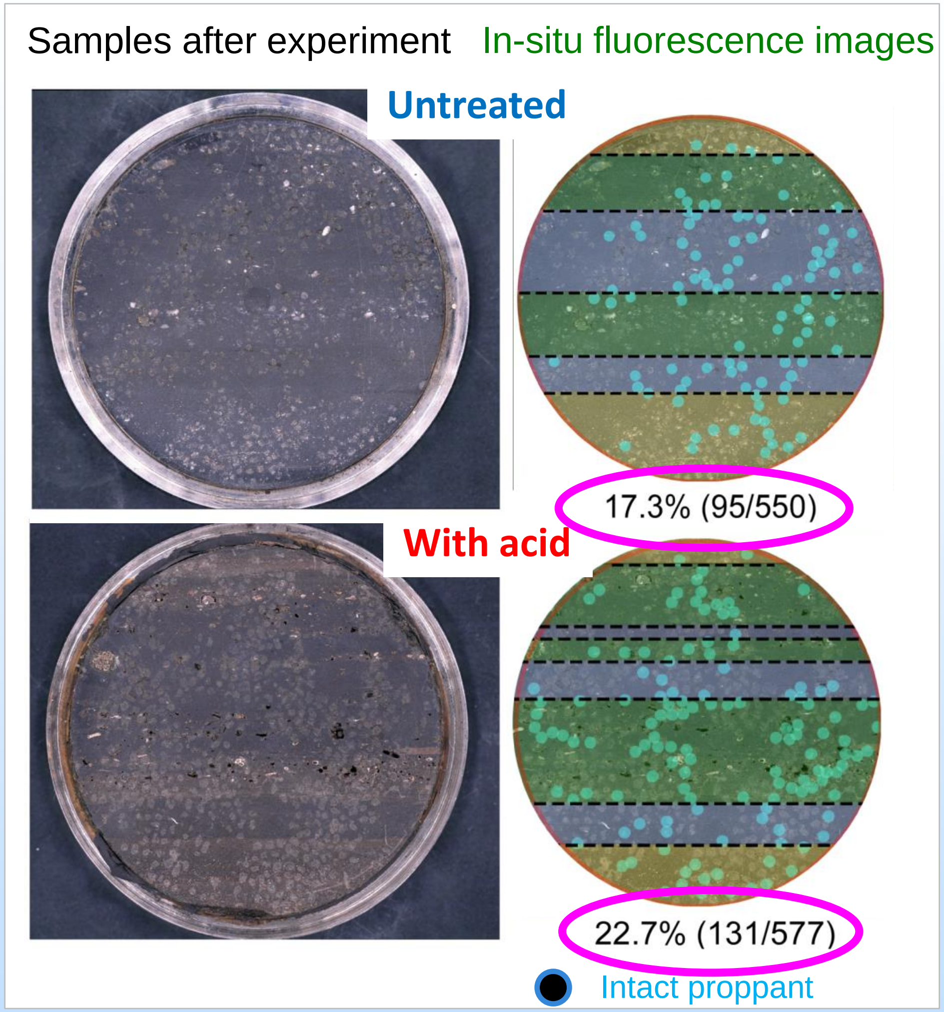
**[Initial, short-term compaction (<1hr)]** **[Long-term creep compaction (<2 weeks)]**



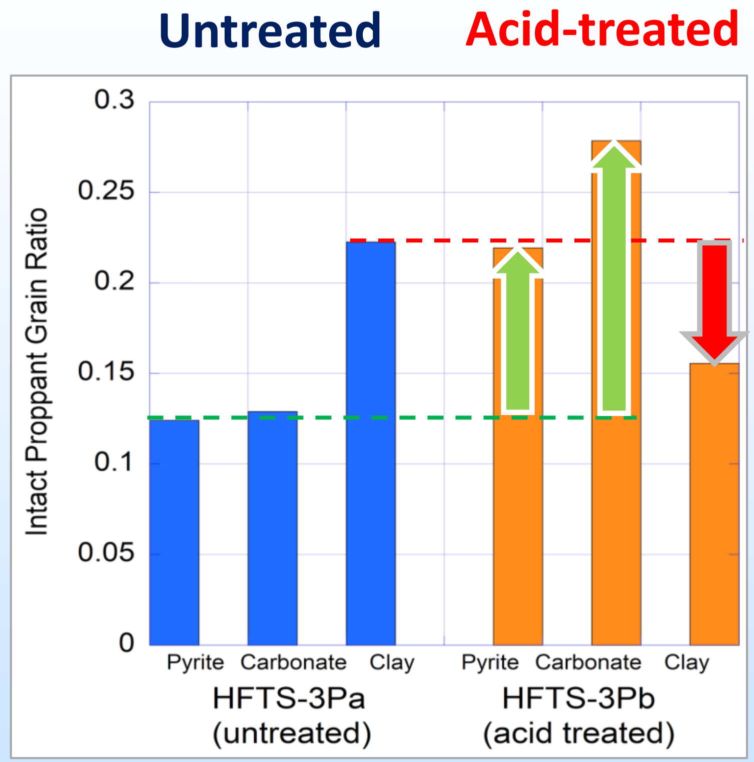




- Acid-induced softening effect was not obvious for this shale

# Result: Brittleness Reduction (Wolfcamp/HFTS shale)



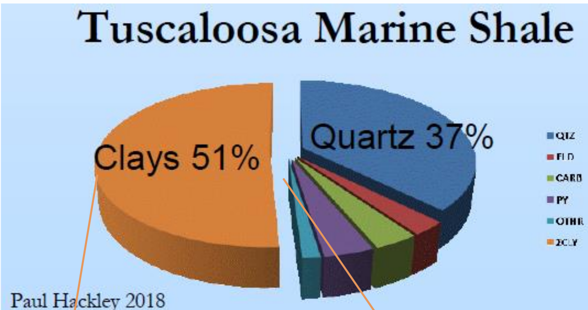

**Clay-rich (blue)**
**Carbonate-rich (green)**
**Pyrite (and carbonate)-rich**

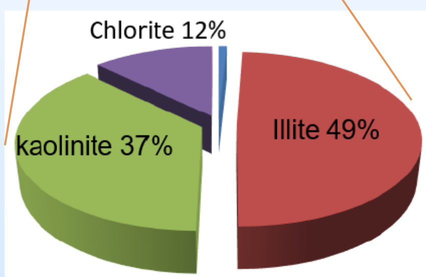



- From direct in-situ observations, proppant "survivability" is determined

$$[\text{Survivability}] \equiv \frac{\left[\begin{array}{l}\text{\# of intact and}\\ \text{load-bearing grains}\end{array}\right]}{[\text{\# of all the grains}]}$$

# Result: Ductility Reduction (Tuscaloosa Marine shale)



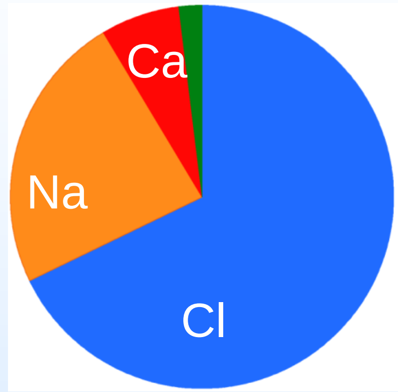




Cray-rich and ductile
(with some water sensitivity)

Water-cut core

Oil (OMS)-cut core

Solid composition of TMS in-situ brine




Key Ingredients of Lab Brine

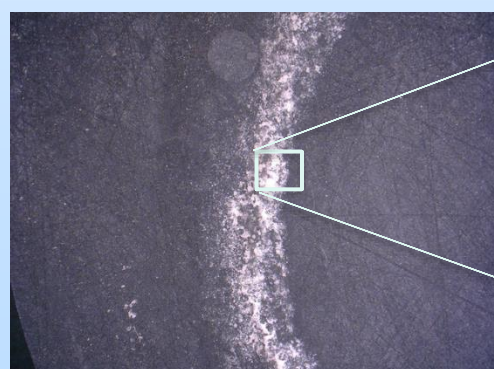
| | |
|---|---|
| NaCl | 9.66 g/100g |
| $CaCl_2 \cdot 2H_2O$ | 4.03 g/100g |

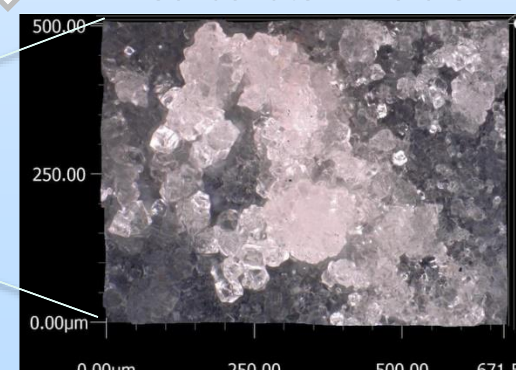
(More alistic brine used in later study)

$$CaCl_2 + 2NaHCO_3\,(aq) \rightarrow CaCO_3\downarrow + 2NaCl(aq) + H_2O + CO_2\uparrow$$

**Bi-carbonate additive to proppant/fracking fluid**

Carbonate minerals

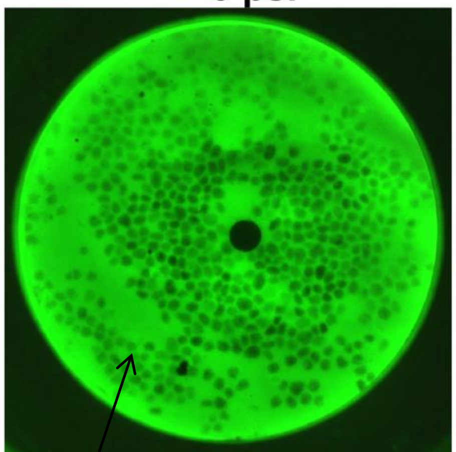




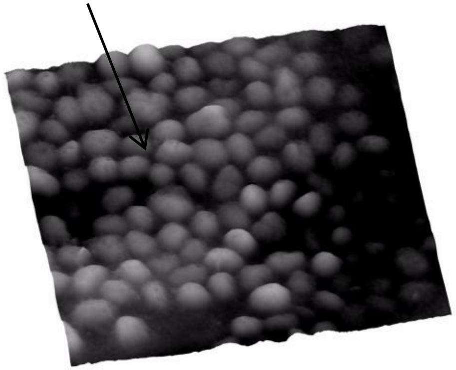
# Result: Ductility Reduction (Tuscaloosa Marine shale)

**“Uniform” proppant**
**No additives**

**0 psi**

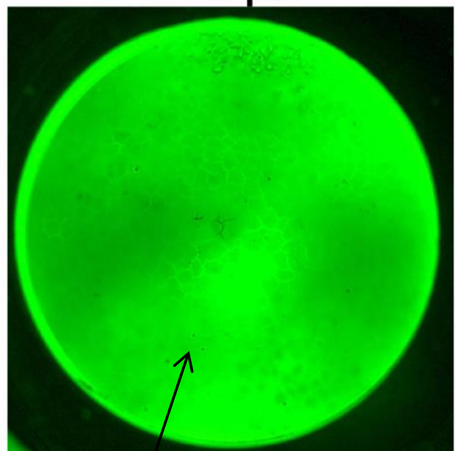


Clouding due to produced shale fines



**“Uniform” proppant**
**With additives**

**0 psi**



Precipitated minerals on the window surface

Test conditions

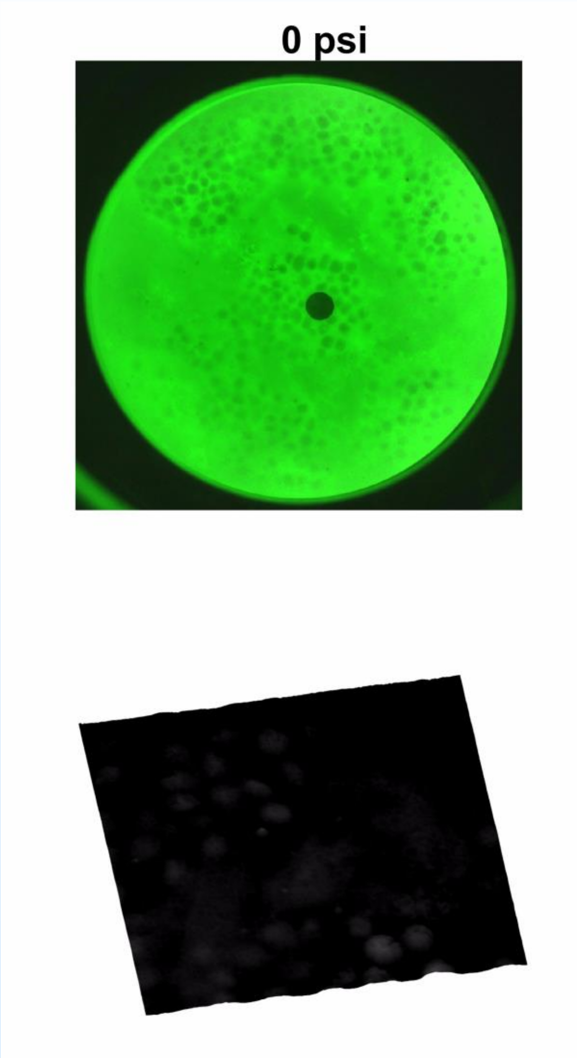
- Pre-saturation with “realistic” brine (7 days)
- Temperature 120˚C
- Max. effective stress 27 MPa (3920 psi)
- Fluid pressure 10.3 MPa(1500 psi)

Proppant + fracking fluid

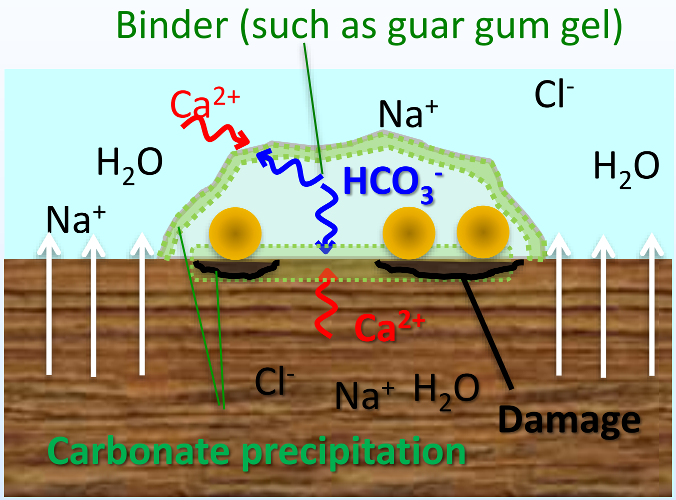
- pH 9.2
- Guar gum
- K metaborate (crosslinker)
- Ammonium persulfate (delinker)
- Na bicarbonate (powder)
- 1-1.5mm D quartz sand

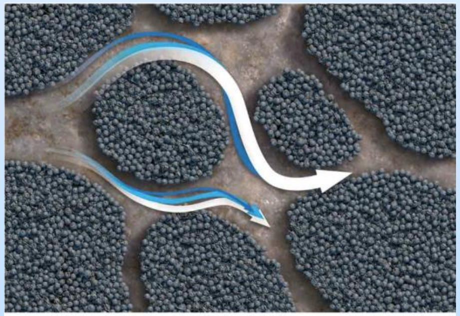
# Result: Ductility Reduction (Tuscaloosa Marine shale)

**"Clustered" proppant With additives**




Clustered proppant with bicarbonate additive, bound by high concentration guar gum



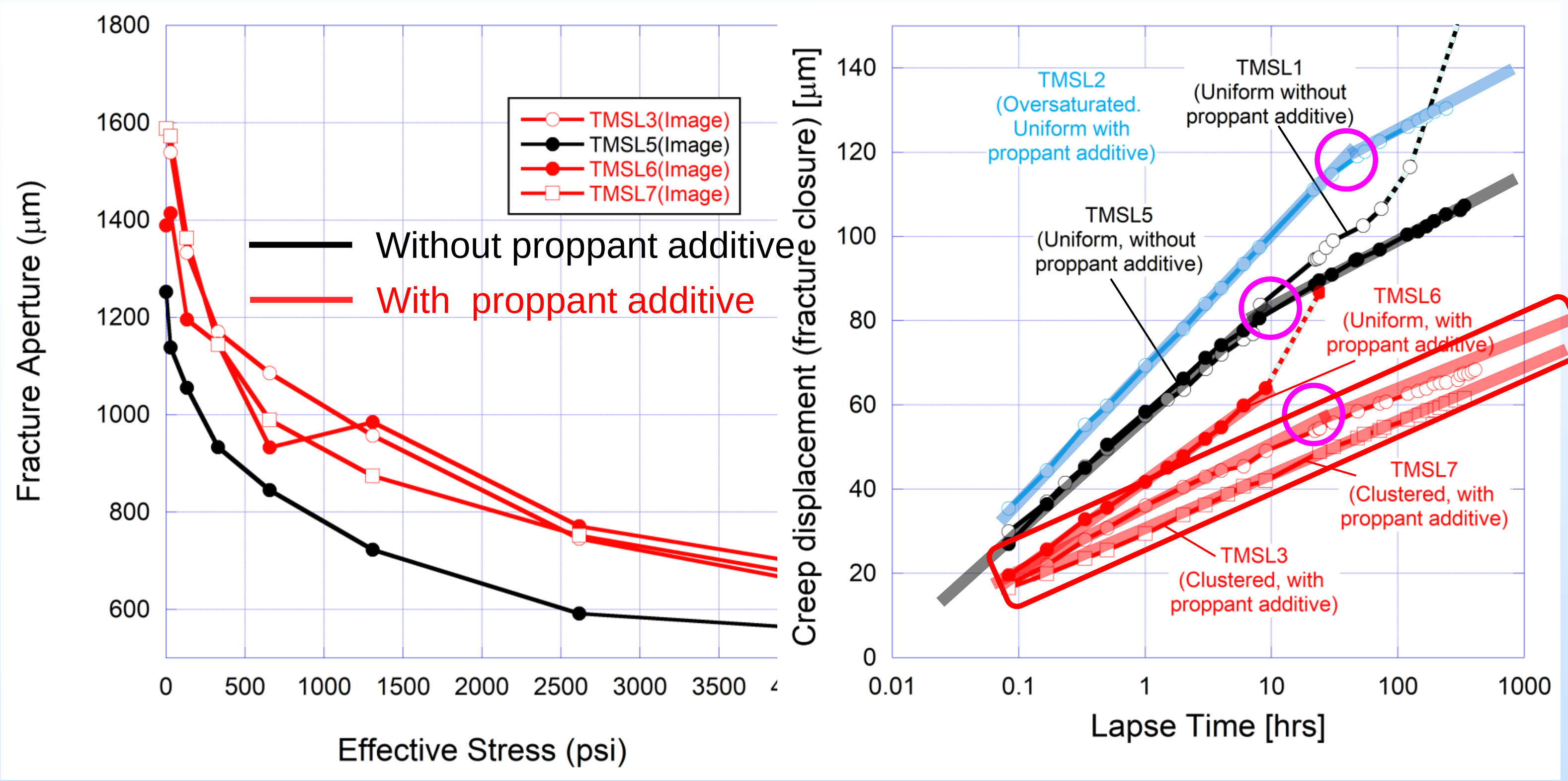
**HiWAY (Schlumberger)**

**Flow-channel fracturing technique**

Maximize oil and gas flow through hydraulic fractures by creating infinite-conductivity channels in your proppant pack.

# Result: Ductility Reduction (Tuscaloosa Marine shale)

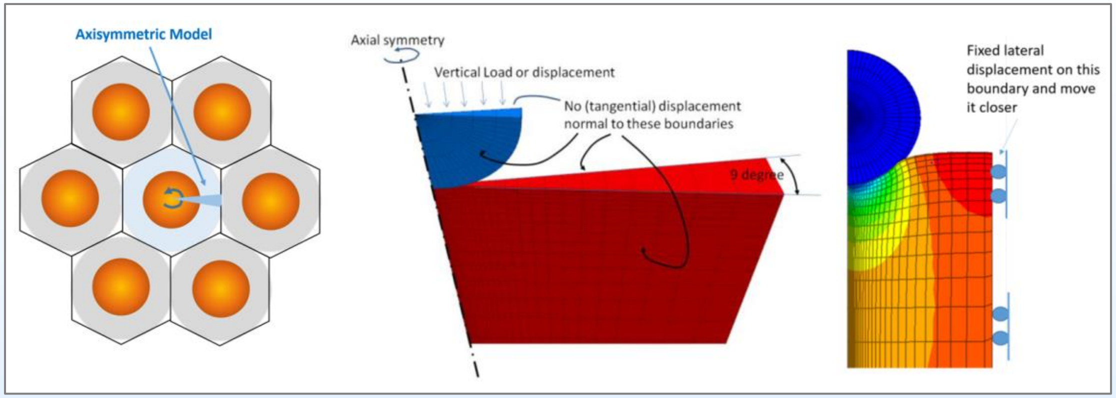
**[Initial, short-term compaction (<1hr)]** **[Long-term creep compaction <2 weeks)]**




- Precipitation reduced both short and long-term fracture compaction and proppant embedment
- Clustered proppant distribution is more effective
- Repeatedly observed and confirmed linear and bi-linear log(t) behavior

# Result: Ductility Reduction (Tuscaloosa Marine shale)

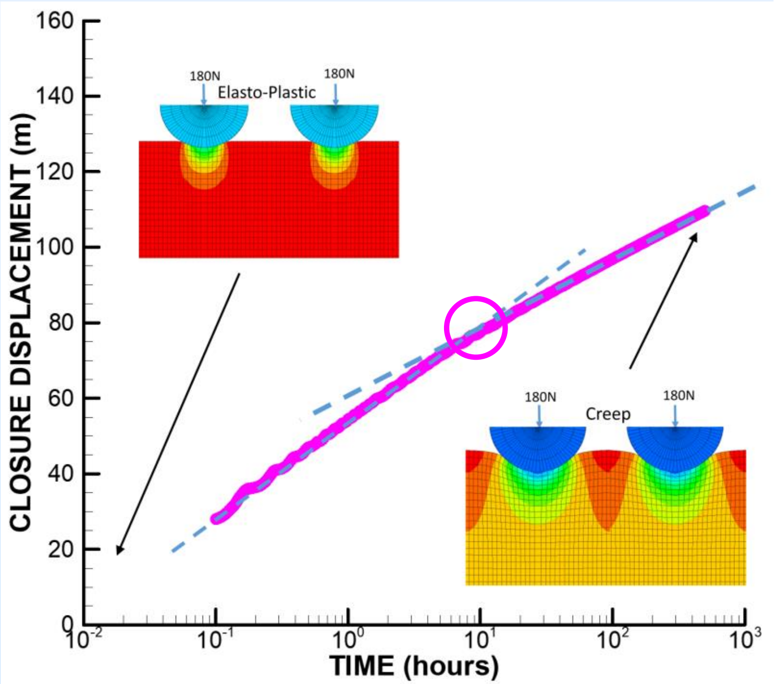
## TOUGH-FLAC modeling of proppant embedment

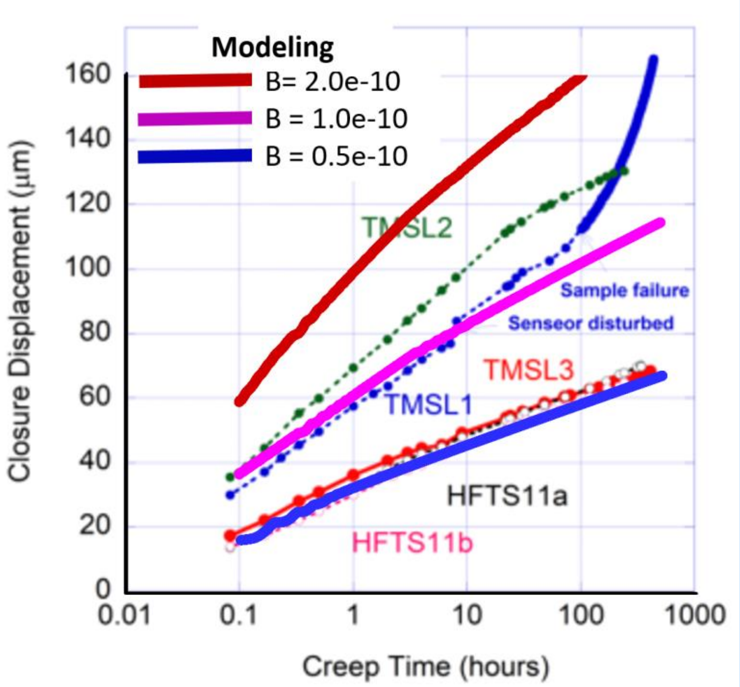



- Time-dependent creep law (empirical)

$$\varepsilon_{creep} = A + B\log(t + t_0)$$
$$\dot{\varepsilon}_{creep} = B/(t + t_0)$$

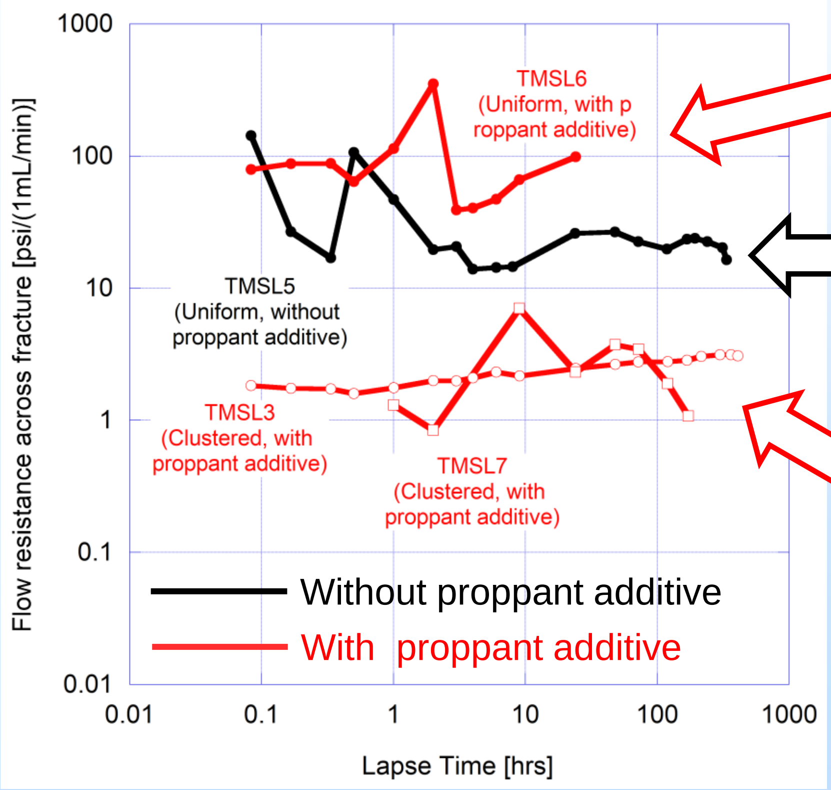
- Interference between neighbors seems to lead to a “kink”

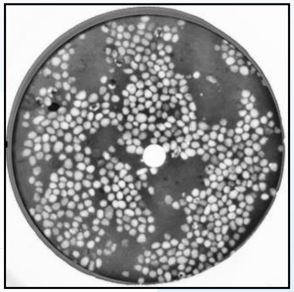


# Result: Ductility Reduction (Tuscaloosa Marine shale)

## [Long-term flow resistance changes]

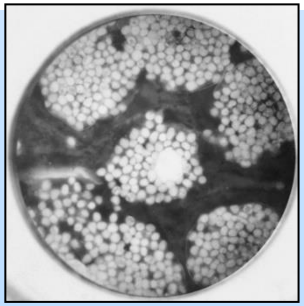


[Uniform proppant]
Precipitated minerals clog proppant packs

[Uniform proppant]
Proppant embedment+matrix “heaving” reduces permeability

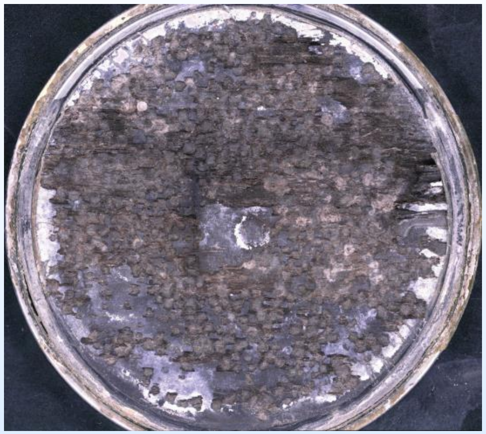
[Clustered proppant]
Permeability preserved in spite of mineral precipitation



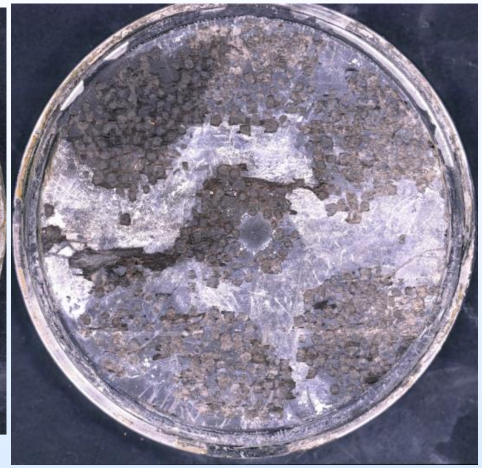
# Result: Ductility Reduction (Tuscaloosa Marine shale)

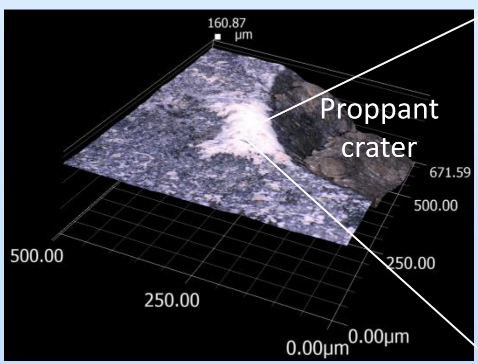
## Surface Precipitation

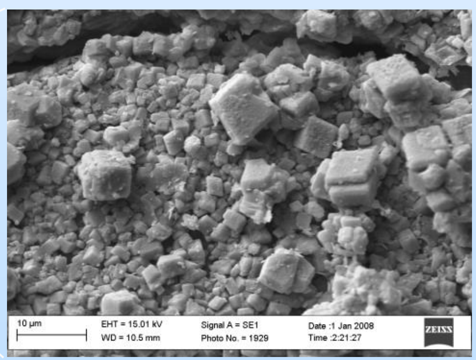
[Uniform w/additive]



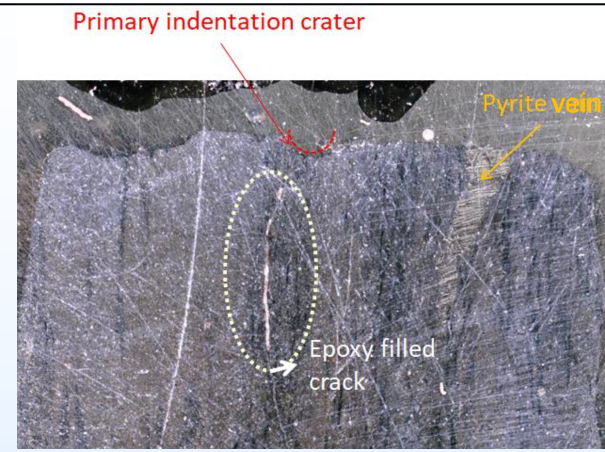
[Clustered w/additive]

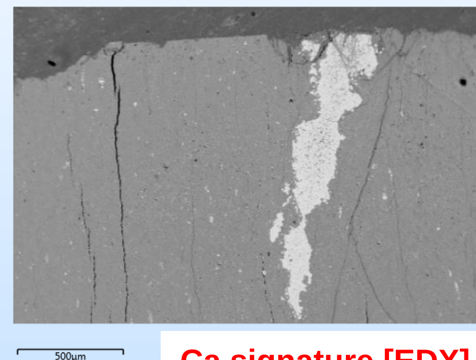




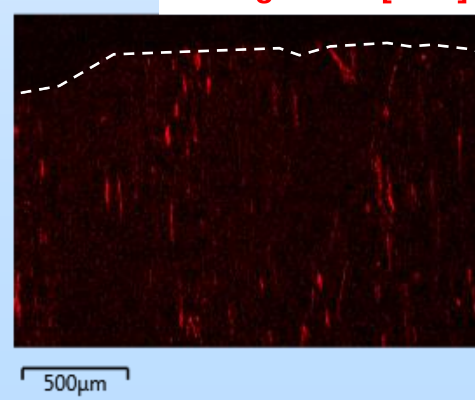




## Vertical cross section



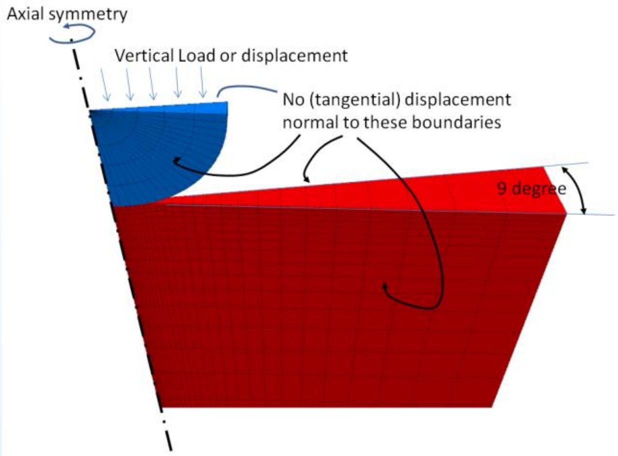



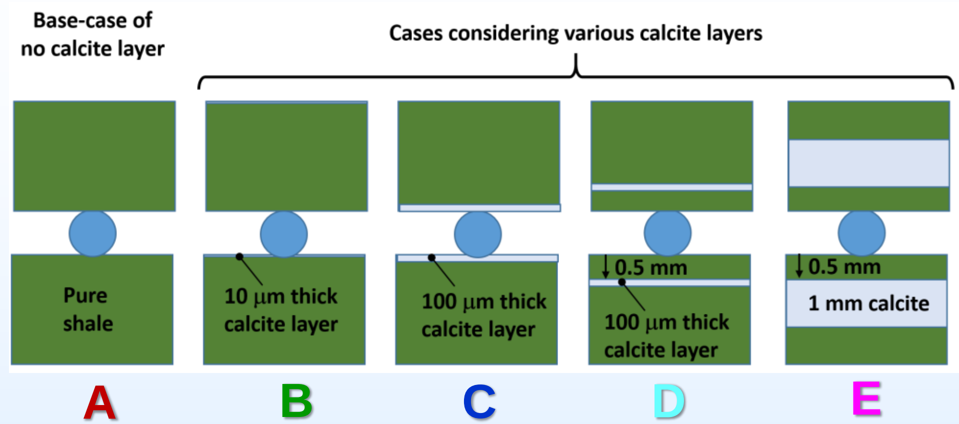

Ca signature [EDX]



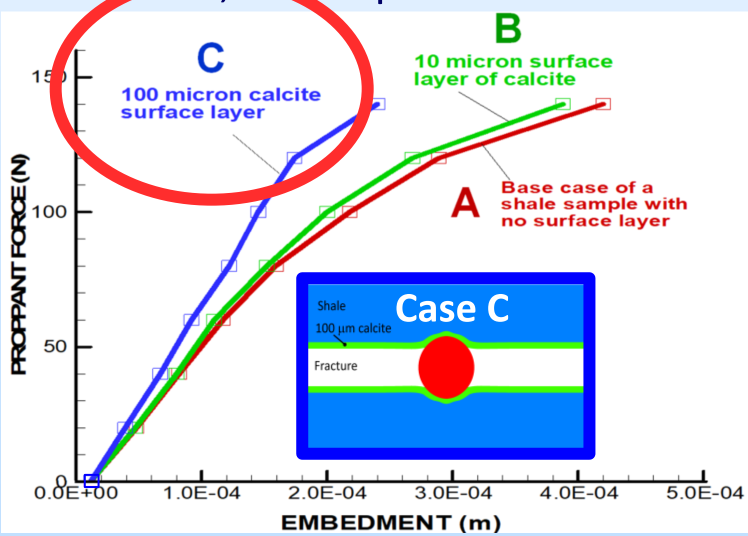

- Clear, abundant carbonate precipitation on the surface
- But little precipitation signatures within the shale matrix

# Result: Ductility Reduction (Tuscaloosa Marine shale)

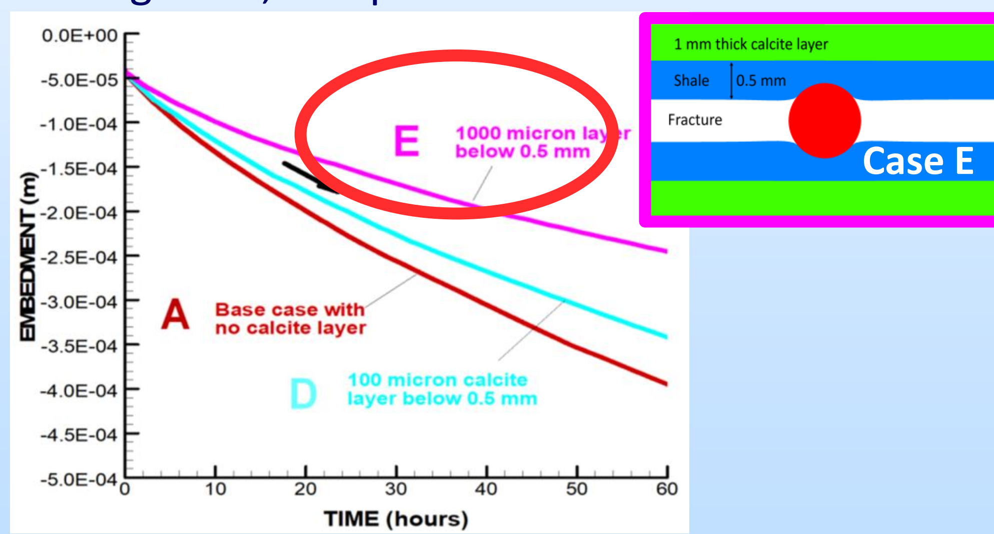



Short-term, elasto-plastic embedment



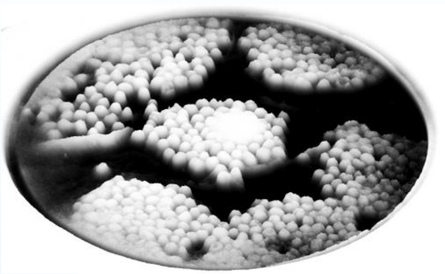

Long-term, creep embedment



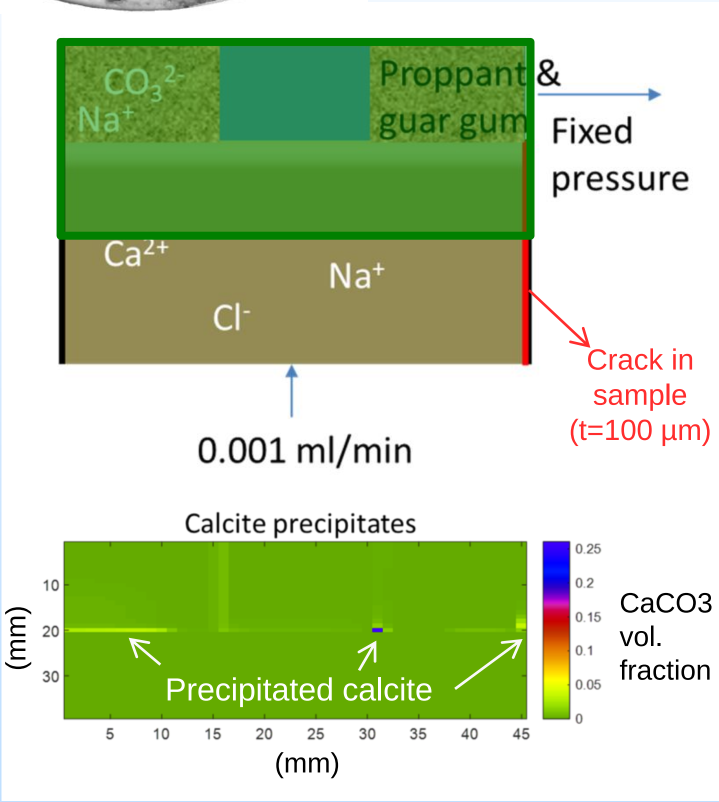

**Surface precipitation is most effective**

**In-matrix precipitation is most effective**

# Next Step: Ductility Reduction



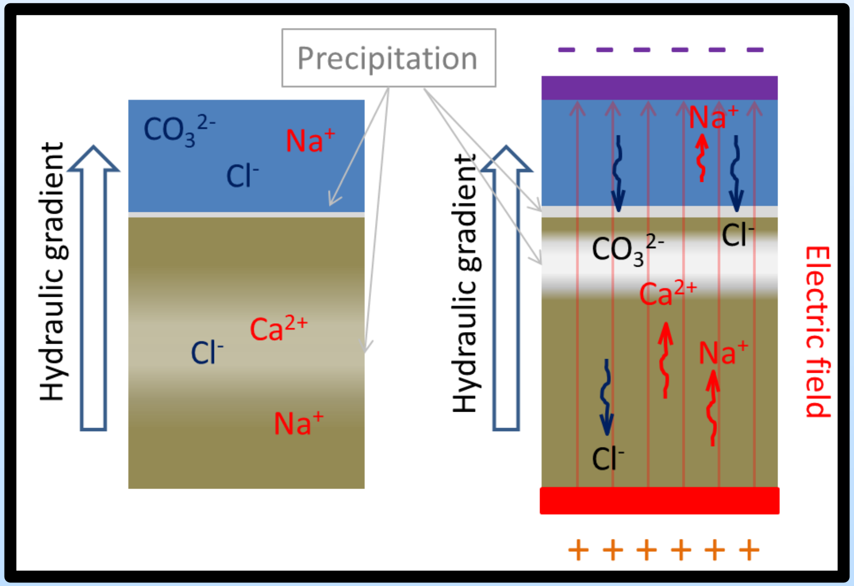
- Reactive-transport modeling (CRUNCHFLOW) also predicts little precipitation with the shale matrix




120°C, 120 hours (5 days)

Next (and the final) phase of the project

**Proof-of-concept studies of the electro-migration-enhancement of precipitation**



# Accomplishments to Date

- Long-term (2-week) experiments have been conducted on fractures in reservoir shales under realistic stress, temperature conditions and fluid chemistry
- Time-lapse dataset correlating optical images of fracture aperture distribution, average fracture closure, and fracture permeability (hydraulic aperture) has been obtained.
- **Acid treatment of carbonate-rich shale has been shown to reduce proppant crushing** by increased surface ductility
- **Mineral precipitation** from Ca-rich fluid and bi-carbonate additive **has been shown to reduce proppant embedment**
- **Again, the tests revealed very robust, (bi-)linear semi-logarithmic fracture closure deformation behavior** with lapse time, for realistic oil & gas reservoir conditions.

# Lessons Learned

- Acid treatment of carbonate-rich shale may need to be rather aggressive for having significant impact on proppant survivability
- Ductility reduction of clay-rich shale via mineral precipitation needs to be combined with heterogeneous proppant emplacement to avoid proppant pack clogging
- More effective ductility/proppant embedment reduction requires enhancement of mineral precipitation on and near the fracture surface

# Synergy Opportunities

- Field-scale behavior of hydraulic fractures in ductile shale: Collaboration with Tuscaloosa Marine Shale Laboratory (TMSL Consortium/University of Louisiana [PI. Prof. Mehdi Mokhtari]) and Carney Shale Laboratory (Oklahoma State University [PI. Prof. Mileva Radonjic])
- Field-scale behavior of hydraulic fractures in brittle shale: Collaboration with Hydraulic Fracture Testing Site (HFTS)/ Multiscale Modeling Project (MMP)
- Micron-scale shale-proppant interactions: Collaboration with synchrotron X-ray CT imaging of proppant embedment study (LBNL research, M. Voltolini, PI: Matt Reagan [LBNL] )

# Project Summary

- A new high-temperature & pressure laboratory test system involving in-situ optical visualization technique for shale fracture compaction/ proppant embedment experiment has been developed and demonstrated
- Correlated datasets of time-lapse proppant crushing/embedment images and fracture deformation and permeability changes for different types of shales have been built
- Effect of acid dissolution for shale brittleness and proppant crushing reduction for carbonate-rich shale has been demonstrated
- Effect of controlled mineral precipitation for shale ductility and proppant embedment reduction for clay-rich shale has been demonstrated

# 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 investigates the possibility of *manipulation the sustainability of hydraulic fractures in ductile shales*—particularly through alteration of proppant-embedment behavior—*using chemical means*. If successful, the knowledge gained and technology developed by this project will help economical production of hydrocarbons from normally avoided, resource-rich but difficult-to-develop , ductile shale formations.

# Project Overview
## Goals and Objectives

### Project Goals and Objectives

The primary objectives of the proposed research are
(1) to understand the behavior of fractures in clay-rich, ductile (and sometimes swelling) shales and
(2) to begin to develop technologies for efficient and economical production from such shales.

(1) Identification of proppant-shale-fluid (P-S-F) combination for proppant embedment behavior in a ductile shale fracture
(2) Laboratory demonstration of the reductions in fracture-closure-induced permeability reduction of a shale fracture
(3) Predictable numerical modeling tool development based upon coupled use of thermal-hydrological-mechanical-chemical codes (TOUGH-FLAC+CRUNCHFLOW)

**Research Activity and Products**

### 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**

- Demonstrate chemical reaction can be used to modify compaction behavior of proppant/fracture, improving sustainability of hydraulic fractures in ductile shale
- Identify their combinations effective for practical use

# Organization Chart

## Project Team

**Reed Helgens** –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**
–TOUGH-FLAC modeling–

**Hang Deng**
–CRUNCHFLOW modeling–

### Industry Advisor

**Russell Ewy**
Retired, ex.Chevron ETC

### Field Lab Collaborators

**Prof. Mehdi Mokhtari** U. Louisiana (TMSL)
**Prof. Mileva Radonjic** Oklahoma State U., (Caney Shale Lab)

**HFTS Project**

### National Lab Collaborators

**Adam Jew** SLAC, **Joe Morris** LLNL, **Dustin Crandall** NETL

# Gantt Chart

(Year-3 project extension)

| Tasks | Year 1 (Oct.2018-Sep.2019) Q1 | Q2 | Q3 | Q4 | Year 2 (Oct. 2019-Sep.2020) Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|---|---|---|---|
| **Task 1 Project Management and Planning** | | | | | | | | |
| **Task 2 Laboratory experiments** | | | | | | | | |
| Subtask 2.1 Acquisition of shale core samples and baseline sample property characterization | | | | | | | | |
| Subtask 2.2 Partial modification of the fracture compaction visualization system for THMC experiment | | M1 | | | | | | |
| Subtask 2.3 Fabrication of a new fracture compaction visualization cell | | | M3 | | | | | |
| Subtask 2.4 Medium-temperature, short-term shale fracture compaction/proppant embedment tests | | | | M4 | | | | |
| Subtask 2.5 Preliminary proppant/shale-fluid reaction tests | | | | M5 | | | | |
| Subtask 2.6: Higher-temperature, long-term shale fracture compaction/proppant embedment tests | | | | | M7 | M9 | | M10 |
| **Task 3 Numerical modeling** | | | | | | | | |
| Subtask 3.1 Initial selection of proppant, shale, fluid combinations and THMC model setup | | M2 | | | | | | |
| Subtask 3.2 Single indenter/proppant-scale THMC modeling of shale deformation using TREACTMECH* | | | | M6 | | | | |
| Subtask 3.3 Multi-grain/asperity simulations of proppant-embedment/asperity deformations | | | | | | M8 | | |
| Subtask 3.4 THMC modeling of laboratory-observed fracture closure | | | | | | | | M11 |

| Tasks | Year 3 (Oct.2020-Sep.2021) Q1 | Q2 | Q3 | Q4 |
|---|---|---|---|---|
| **Task 1 Project Management and Planning** | | | | |
| **Task 2 Laboratory experiments** | | | | |
| Subtask 2.1 Test sample preparation/characterization | | | | |
| Subtask 2.2 High-P/T share-proppant-fluid interaction tests under realistic fluid chemistry | | M1 | | |
| Subtask 2.3 Ductility reduction enhancements via electrokinetic migration of minerals | | | M2 | |
| | | | | |
| | | | | |
| | | | | |
| **Task 3 Numerical modeling** | | | | |
| Subtask 3.1 CRUNCHFLOW modeling of electrokinetic precipitation enhancement effect | | | | M5 |
| Subtask 3.2 TOUGH-FLAC modeling of mineral precipitation in complex fluid systems | | M3M3, M4 | | |
| | | | | |
| | | | | |

M2 delayed

M5 completed

# Bibliography

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- Nakagawa, S. , M. Voltolini, S. E. Borglin, and A. Jew (2021) Chemically Induced Reduction of Fracture Closure for Shale Fractures Containing Sub-Monolayer Proppant, ARMA Paper #1602, 55th US Rock Mechanics /Geomechanics Symposium, Houston, TX, June 20-23; Presentation.
- Nakagawa, S., M. Voltolini, S.E. Borglin, and T.J. Kneafsey (2021) Manipulation of shale ductility and proppant embedment via controlled mineral precipitation, in preparation.
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