Sustainability of Hydraulic Fracture Conductivity in Ductile and Expanding Shales

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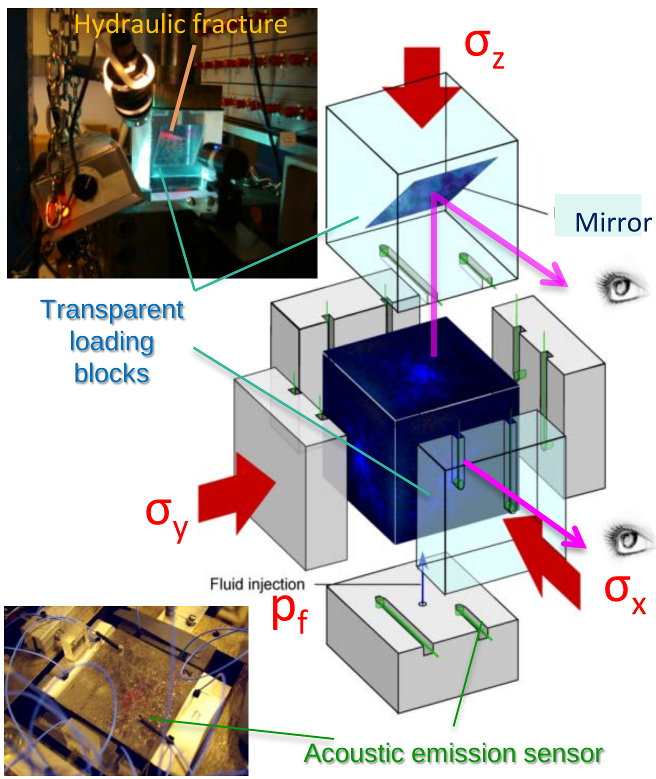
Presentation Outline

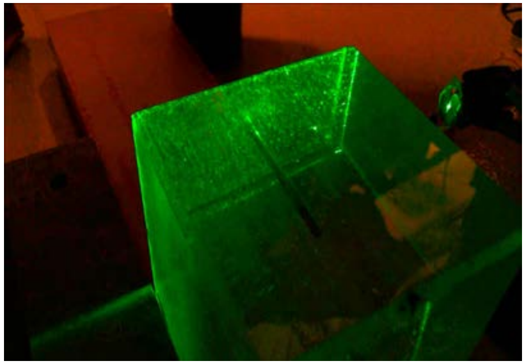
- Technical Status
  - FY2015-2016 Results
  - Motivation & Background
  - Goal and Objectives
  - Anticipated Products and Impacts
  - Project Tasks and Activities
  - **Laboratory Experiment Tasks**
  - **Numerical Modeling Tasks**
- Accomplishment to Date
- Lesson Learned
- Synergy Opportunities
- Project Summary

FY2015-2016 Results

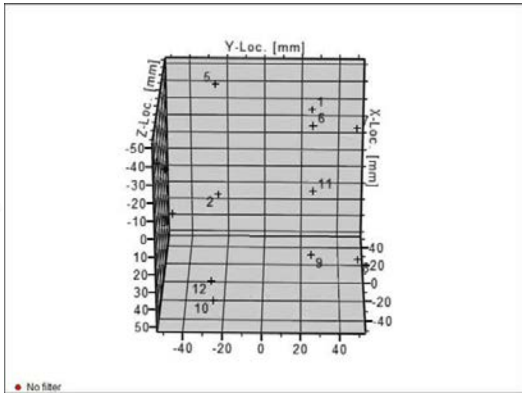
"Laboratory and Numerical Investigation of Hydraulic Fracture Propagation and Permeability Evolution in Heterogeneous and Anisotropic Shale"

True-triaxal hydraulic fracturing + real-time optical +AE visualization tests



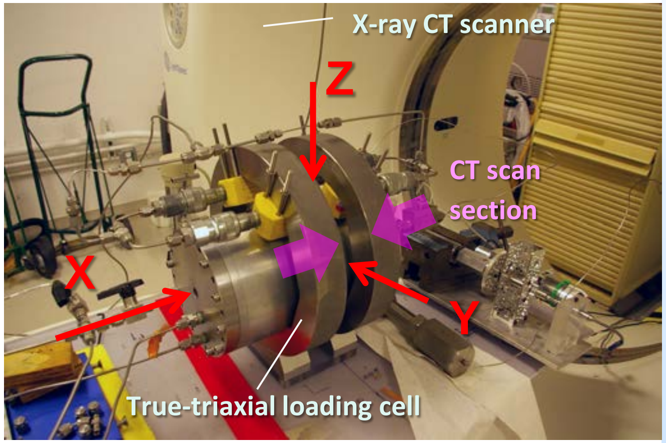


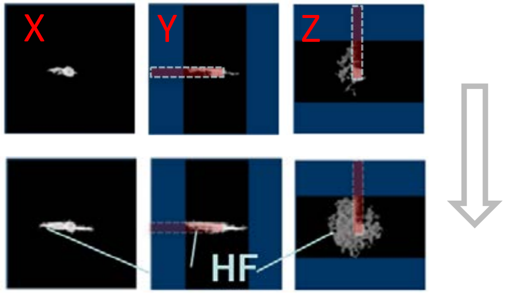
Optical visualization



AE visualization

X-ray CT imaging of hydraulic fracturing in anisotropic shale



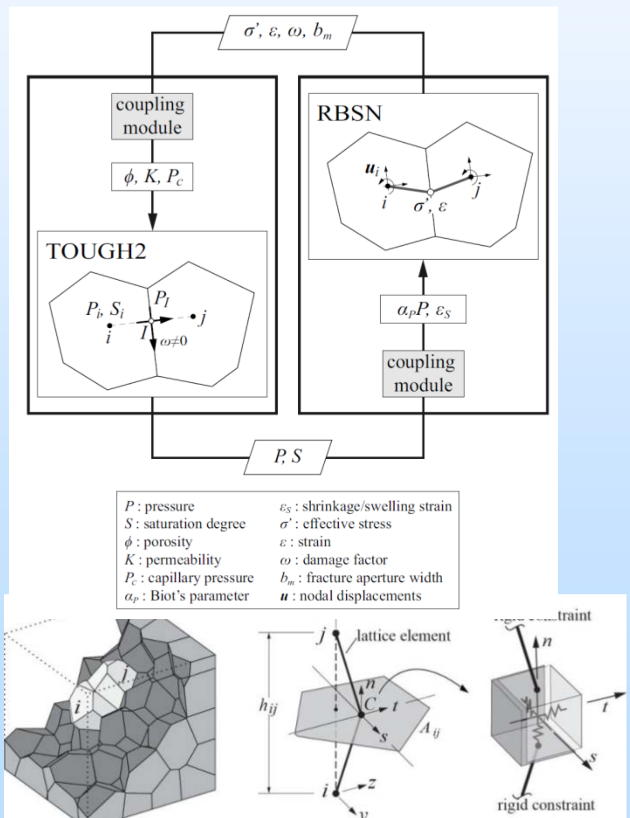


X-ray CT visualization

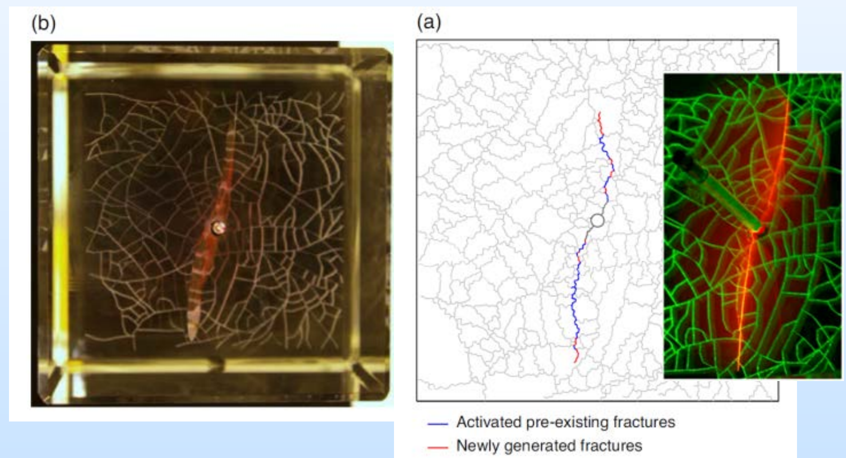
FY2015-2016 Results

"Laboratory and Numerical Investigation of Hydraulic Fracture Propagation and Permeability Evolution in Heterogeneous and Anisotropic Shale"

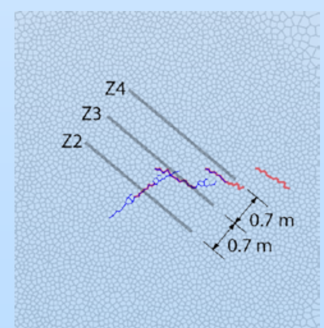
A TOUGH-RBSN code for hydraulic fracturing problems



Comparison of experimental and numerically modeled hydraulic fracturing



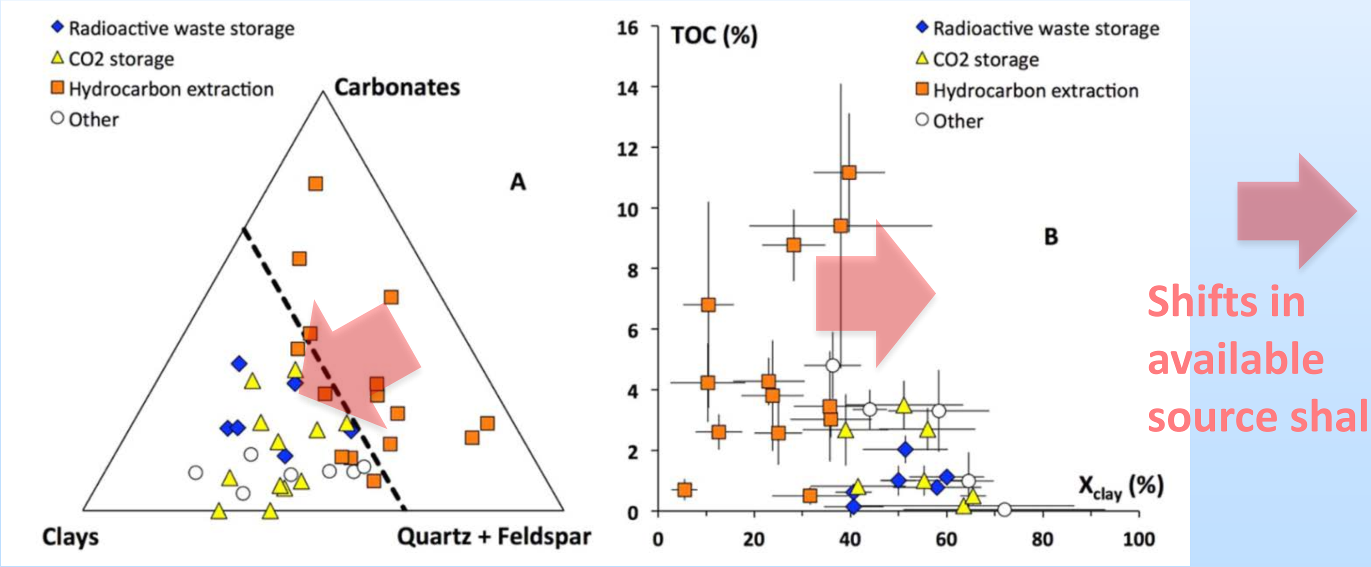
Mont Terri URL hydraulic fracturing modelling



Motivation and Background

- In the new project phase started in Oct. 2016, we have changed the focus of research from creation of fractures (hydraulic fracturing) to sustenance of fractures in shale.
- Pristine, high-TOC, low-clay-content oil and gas shale formations are being depleted

  →Increasing needs to produce from 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



Shifts in available source shale

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

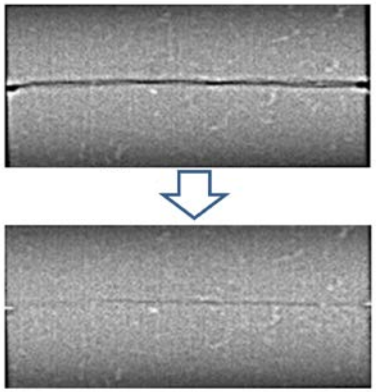
To investigate and understand

(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.

- **Core-scale laboratory visualization** experiments under (moderately) elevated temperature and stress
- **Various natural shale samples** with different ductility and clay compositions, fluid chemistry
- **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

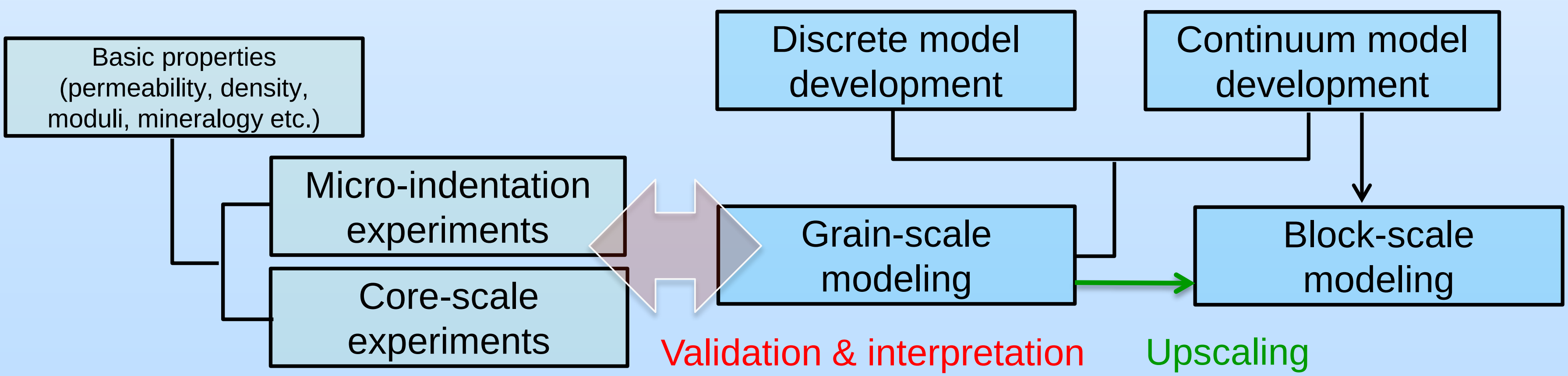
- **New experimental tool** (fracture/proppant compaction visualization system) **and methodology** for measuring and visualizing time-dependent compaction of a fracture in ductile shale
- **Numerical tools and the simulation methodology** based upon TOUGH-FLAC and TOUGH-RBSN codes for predicting long-term behavior of hydraulic fractures in ductile and swelling shales
- Laboratory and modeling **data correlating shale properties, time-dependent compaction, permeability changes**
- 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

<u>**Anticipated impacts (our ultimate goals)**</u>

- 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)

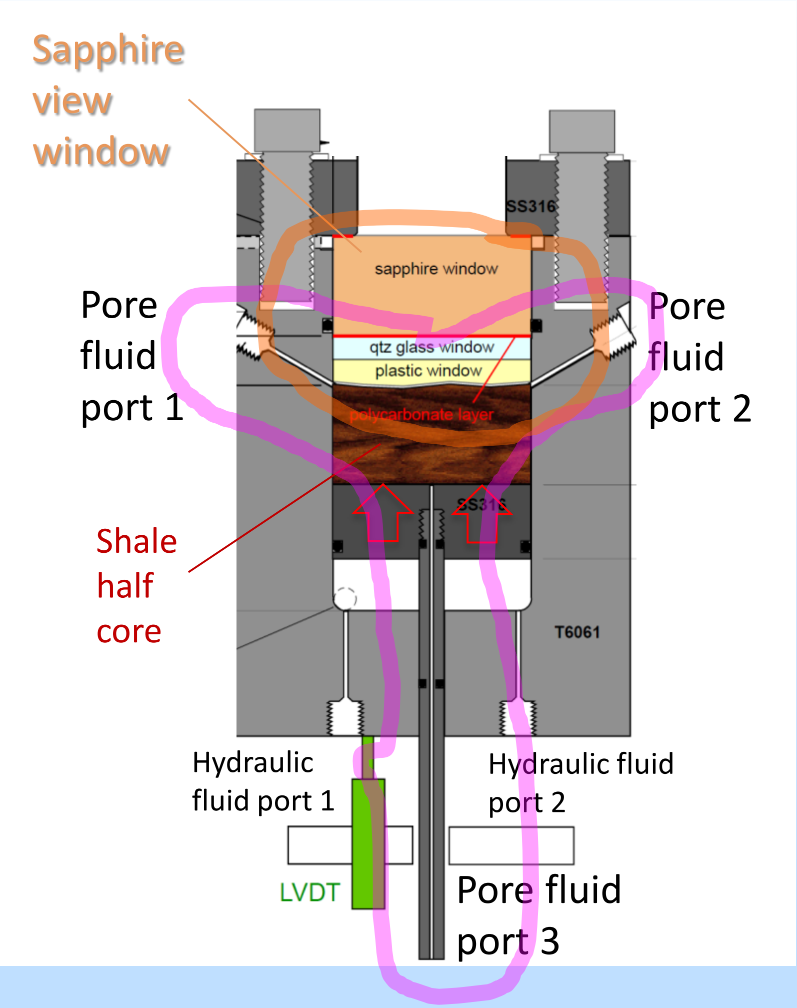
Project Tasks and Activities

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

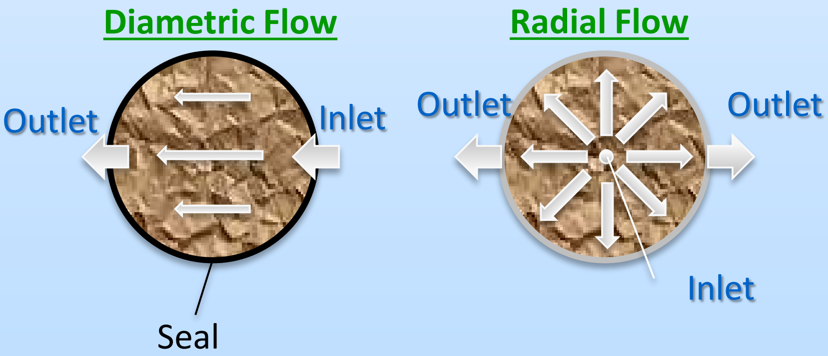


Laboratory Experiments: Core-scale experiment

Designing and fabrication of shale fracture test cell



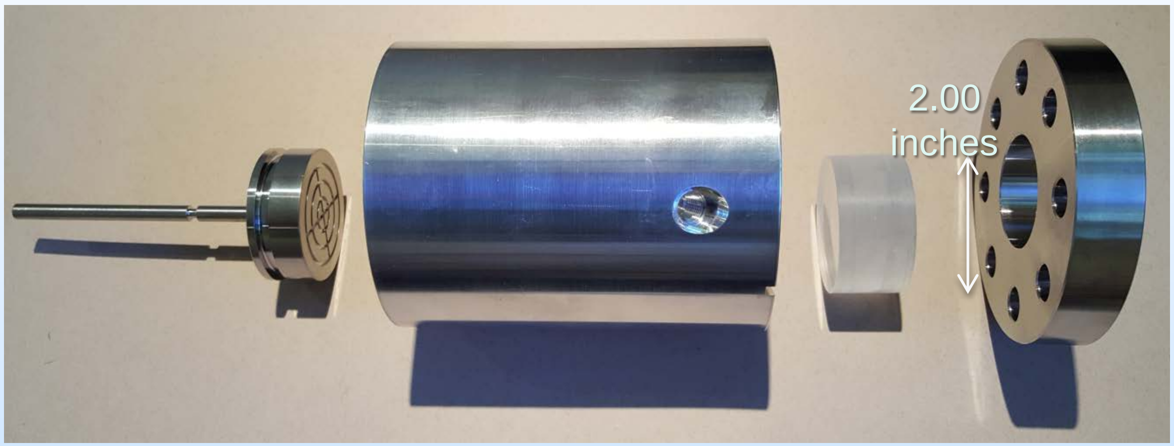
- Optical view window (sapphire, 1.5-inch viewable diameter)
- T6061 Aluminum wall (Low X-ray absorption)
- Max. 2-inch diameter core
- Max. axial stress (MAWP) 5,220 psi, overpressure safety factor (SF)=4
- Max. Pore pressure up to MAWP
- Both diametric flow and radial flow options
- Axial deformation measured via LVDT

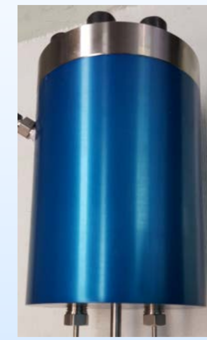


Laboratory Experiments: Core-scale experiment

Designing and fabrication of shale fracture test cell

Shale fracture compaction visualization cell (“CVC”) –Fabrication finally completed

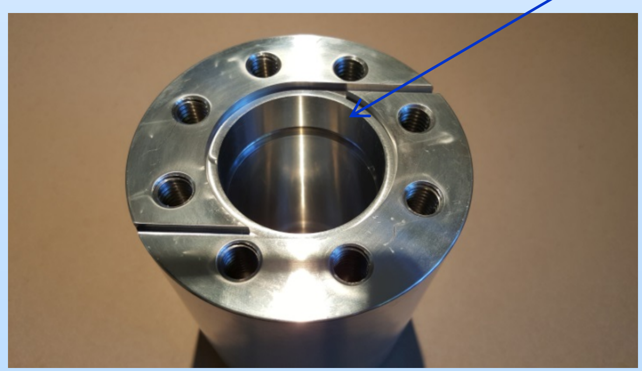


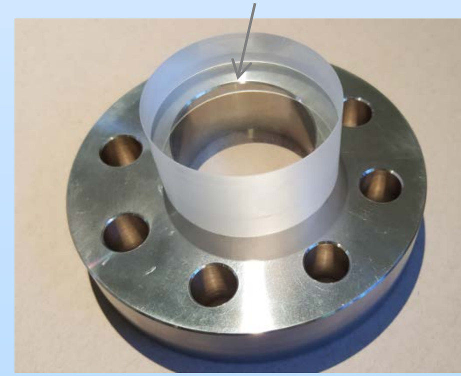


Anodized....

Electroluminescent wire

Sapphire window

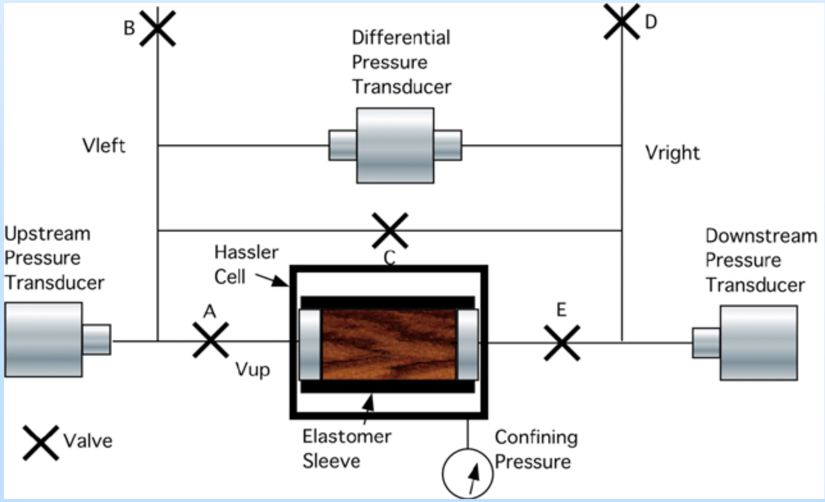


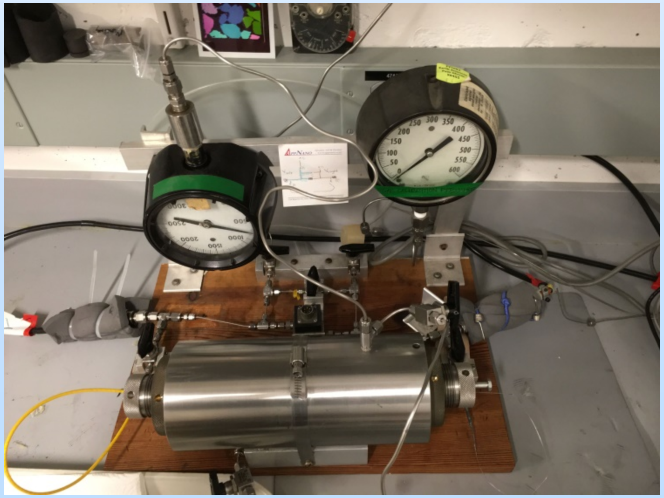


Laboratory Experiments: Permeability Measurements

Shale matrix permeability measurement

- Permeability measurement is done using LBNL's pressure-decay permeameter (Finserle & Persoff, 1977)
- Use either gas or liquid to flow through shale core samples (dia. 1 inch)
- Use inverse modeling with iTOUGH2 to estimate permeability, porosity, and Klinkenberg Parameter
- For high permeability sample, steady-state measurement is also possible





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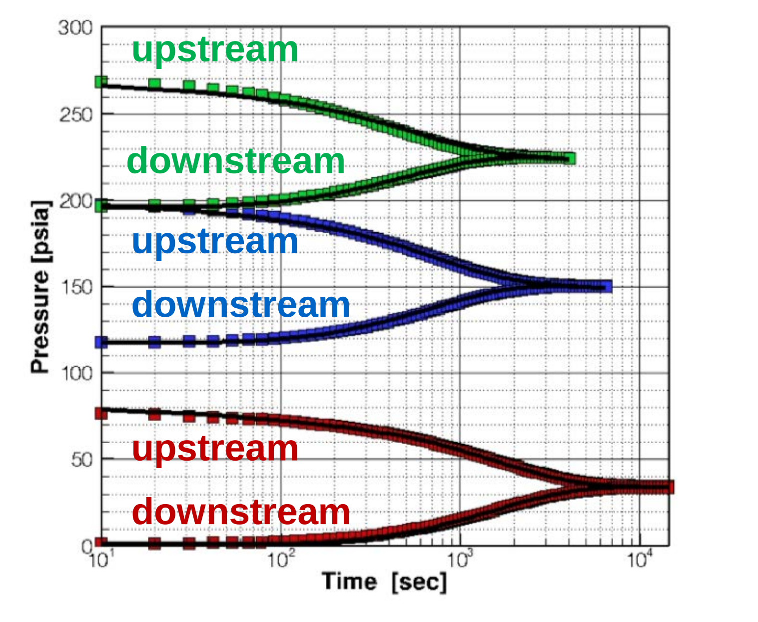


Sample	Permeability $\log_{10}(k_{abs}$ [m²])	Klinkenberg Parameter $\log_{10}$ (b [Pa])	Porosity f [%]
Montney	-17.99±0.005	5.46±0.015	6.5±0.2
Barnett 1	-19.9±0.7	7.1±0.7	0.9±0.2
Barnett 2	-19.6±0.6	7.3±0.6	1.4±0.1
Barnett 3	-19.0±0.2	6.5±0.2	1.5±0.2
Barnett 3 reversed	-20.5±0.8	7.5±0.8	3.6±0.3

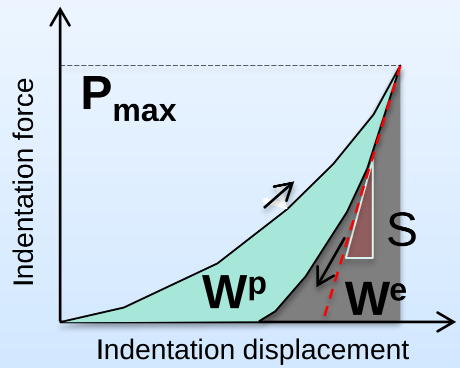
-18→1 μD

-20→10 nD

Laboratory Experiments: Moduli & Nonelastic Property Measurements

Shale ductility measurement via micro indentation tests

- **Instrumented indentation tests** can be used for mechanical property measurements of small samples ([reduced] Young's modulus, hardness, ductility parameter)



Oliver & Pharr (2004)

S : Contact stiffness ⇒ E_{eff}: Reduced Young's modulus

A: Contact x-sec. area

H: Hardness ($H=P_{max}/A$)

W^p : Plastic (or permanent) work

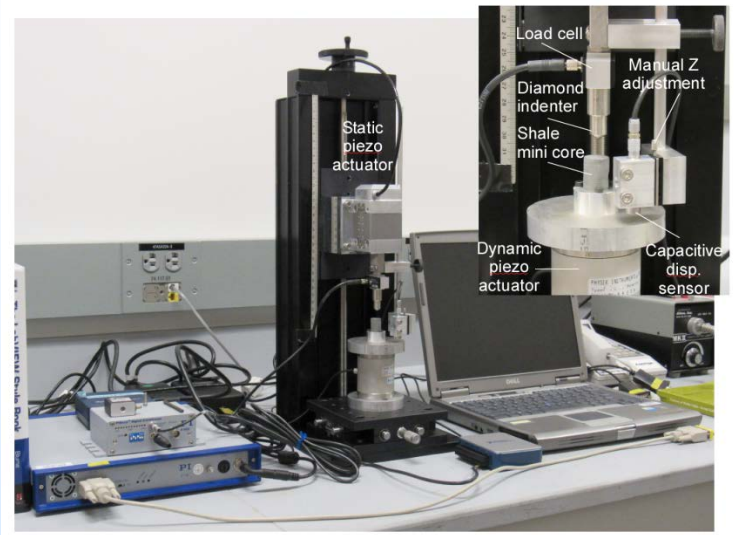
W^e : elastic work

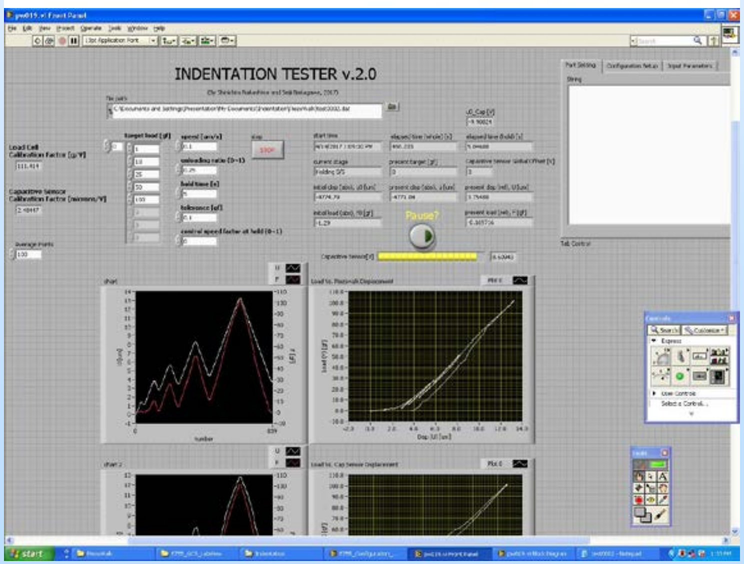
(One) Ductility parameter

$W^{p*}=W^p/(W^e+W^p)$

- Nano-indentation tests are gaining popularity for obtaining shale elastic properties and hardness from very small samples (e.g., Benett, 2015; Liu, 2016)
  - ❑ Sample availability (side-wall cores, chips (for nano))
  - ❑ Less preparation time (fluid saturation, chemical diffusion)
  - ❑ Less experimental time

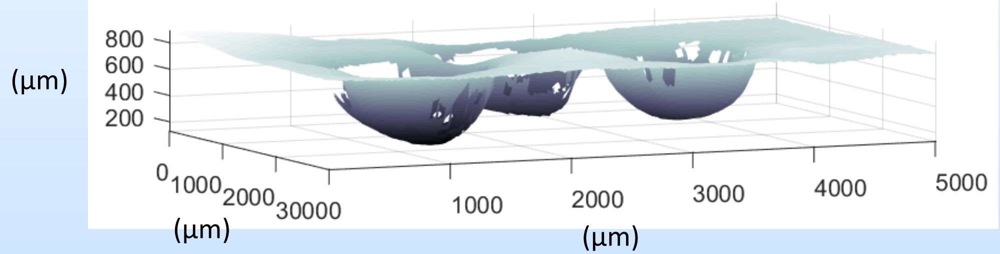
Laboratory Experiments: Moduli & Nonelastic Property Measurements

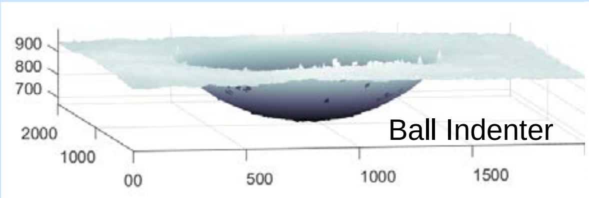


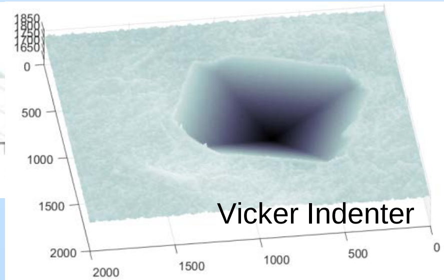


- In-house, mid-range instrumented micro indentation test system (high-resolution micro indentation system) has been developed
- Control software developed (LabView)
- Possibilities for future expansion (non-commercial system)

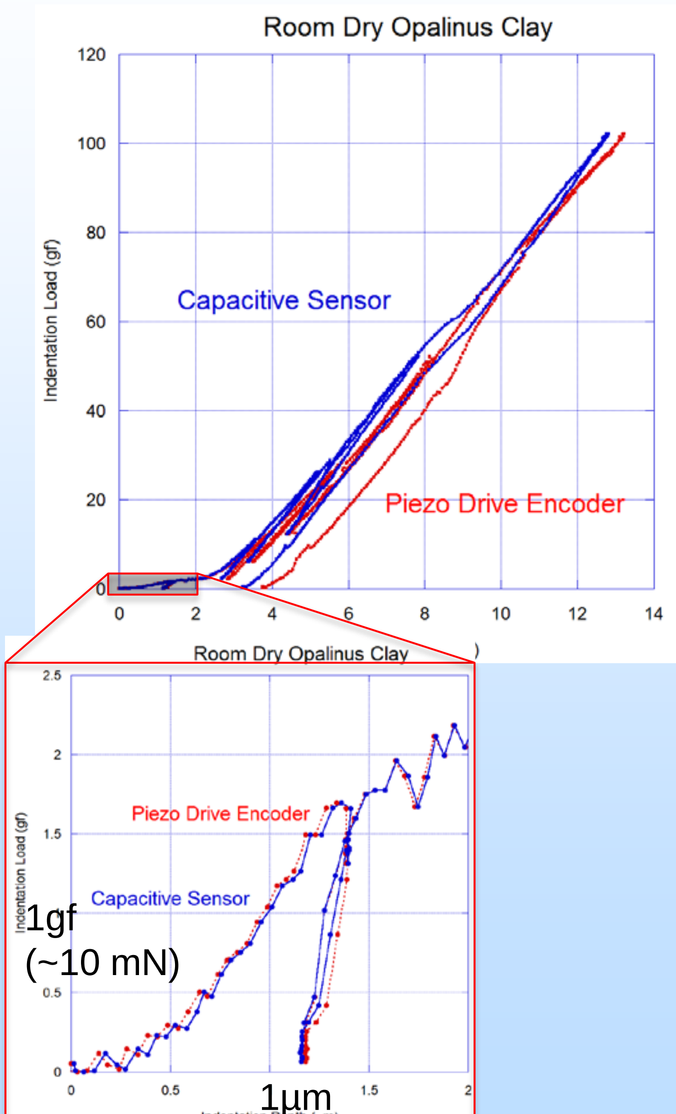
Impressions of ~1mm silica sand (proppant) on soft metal







Laboratory Experiments: Moduli & Nonelastic Property Measurements



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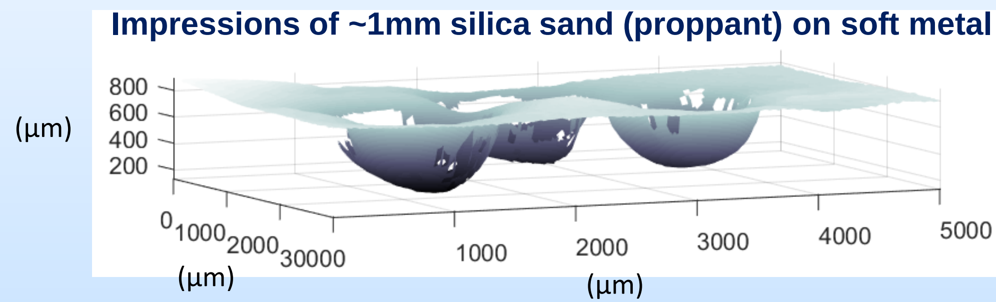
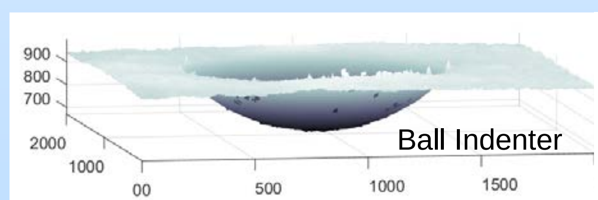
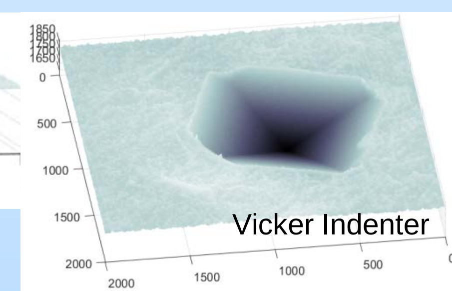
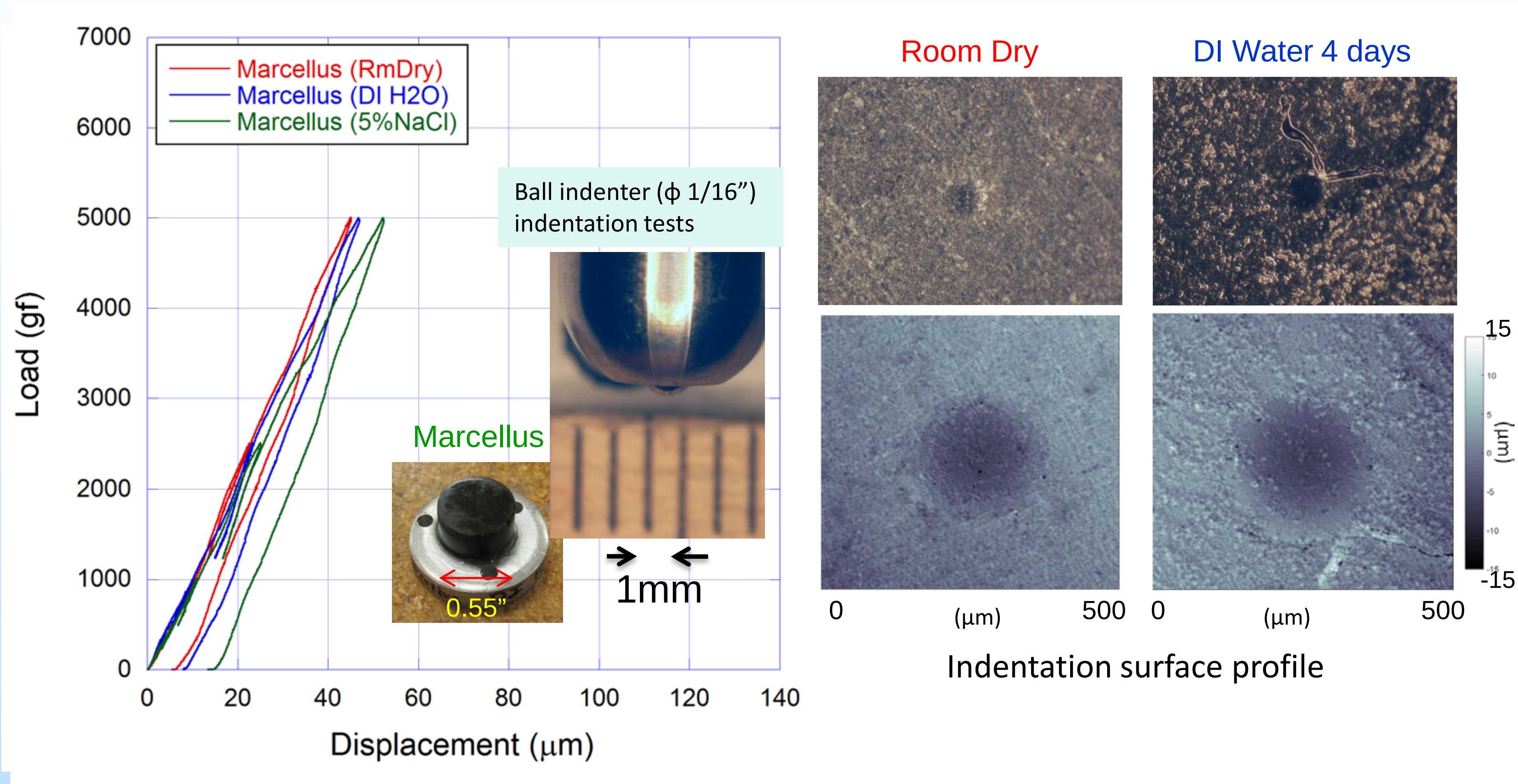


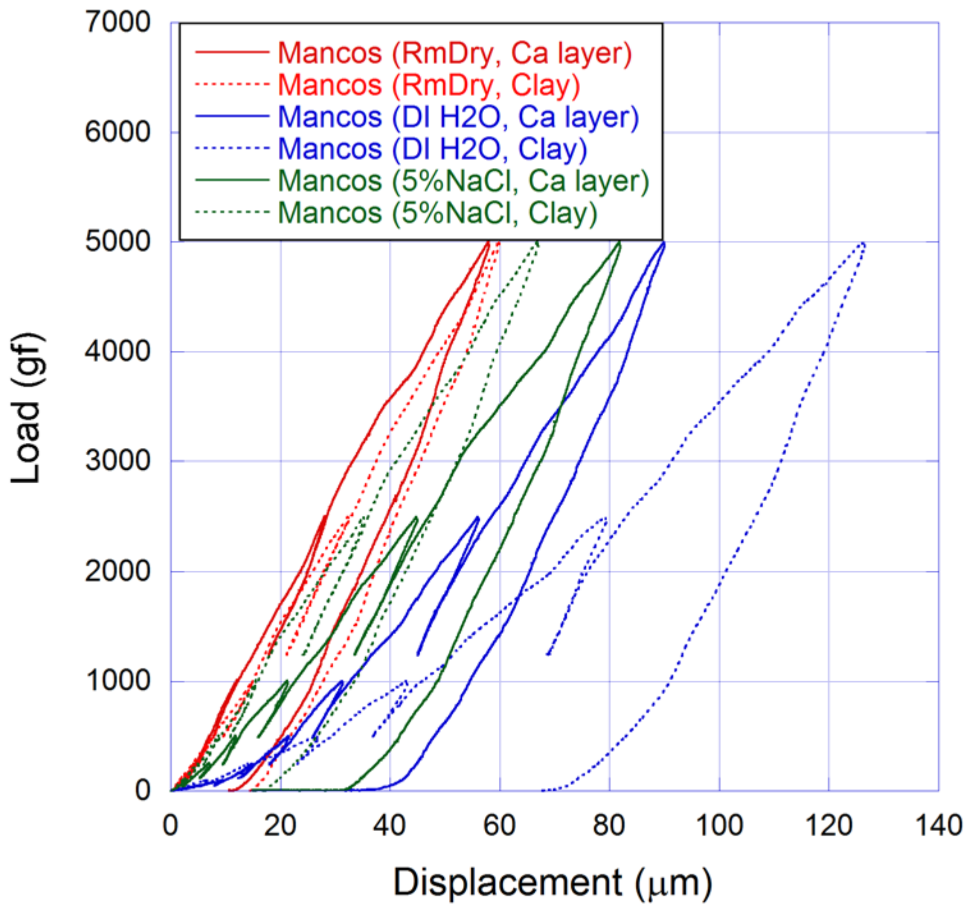


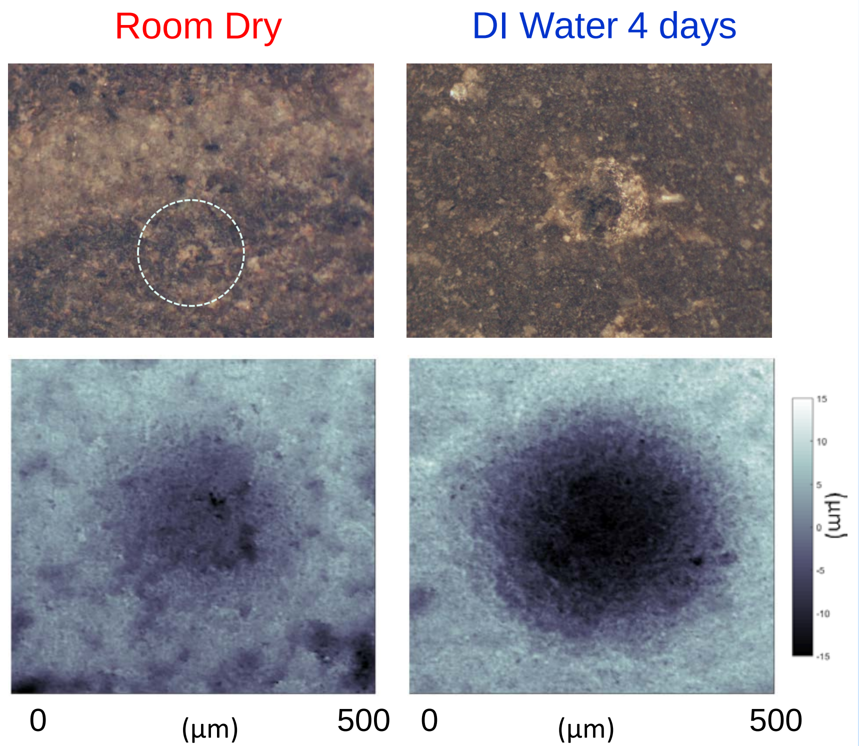


Laboratory Experiments: Moduli & Nonelastic Property Measurements

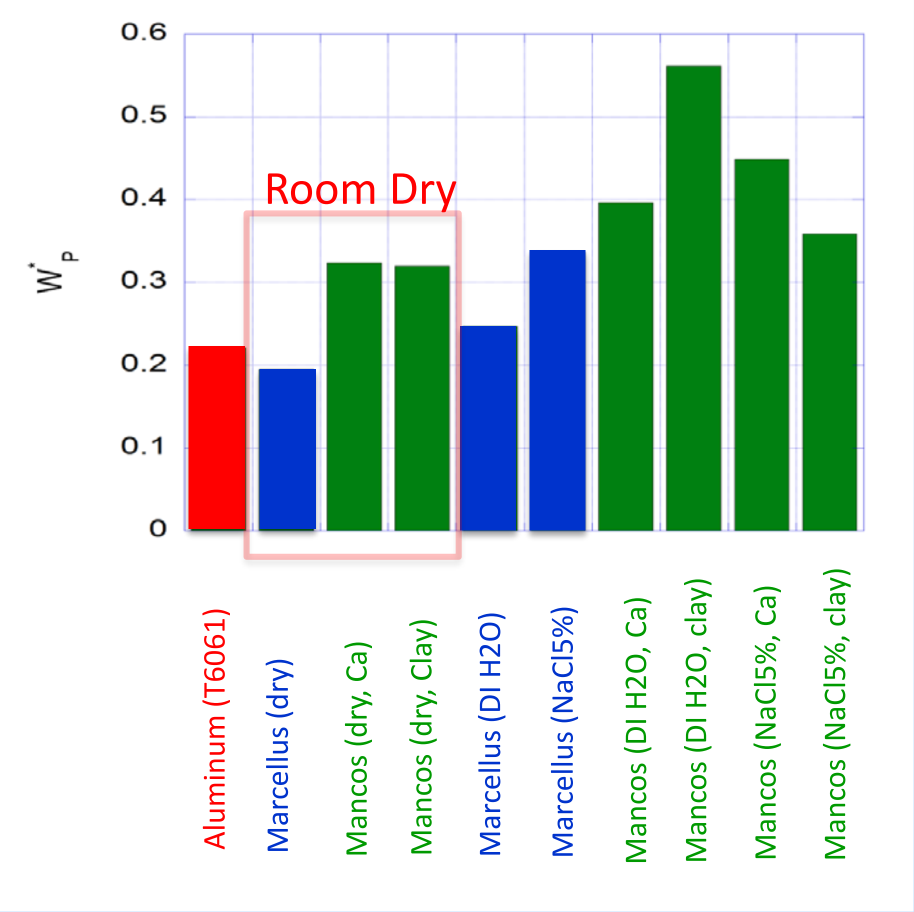


Laboratory Experiments: Moduli & Nonelastic Property Measurements





Laboratory Experiments: Moduli & Nonelastic Property Measurements

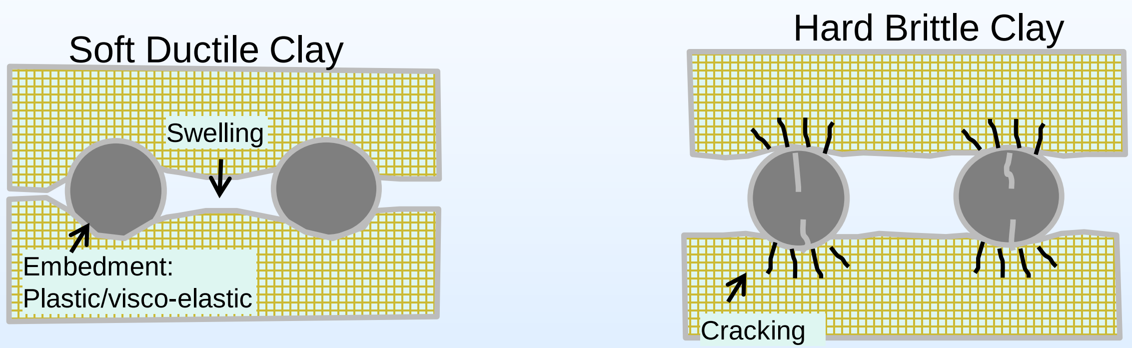


Ductility Parameter

$$W^{p*} = W^p / (W^e + W^p)$$

- Mancos shale generally exhibited larger ductility and water sensitivity
- Need a large number of measurements to get good statistics
- Mineralogical analysis will be performed in parallel

Numerical Modeling: Approaches



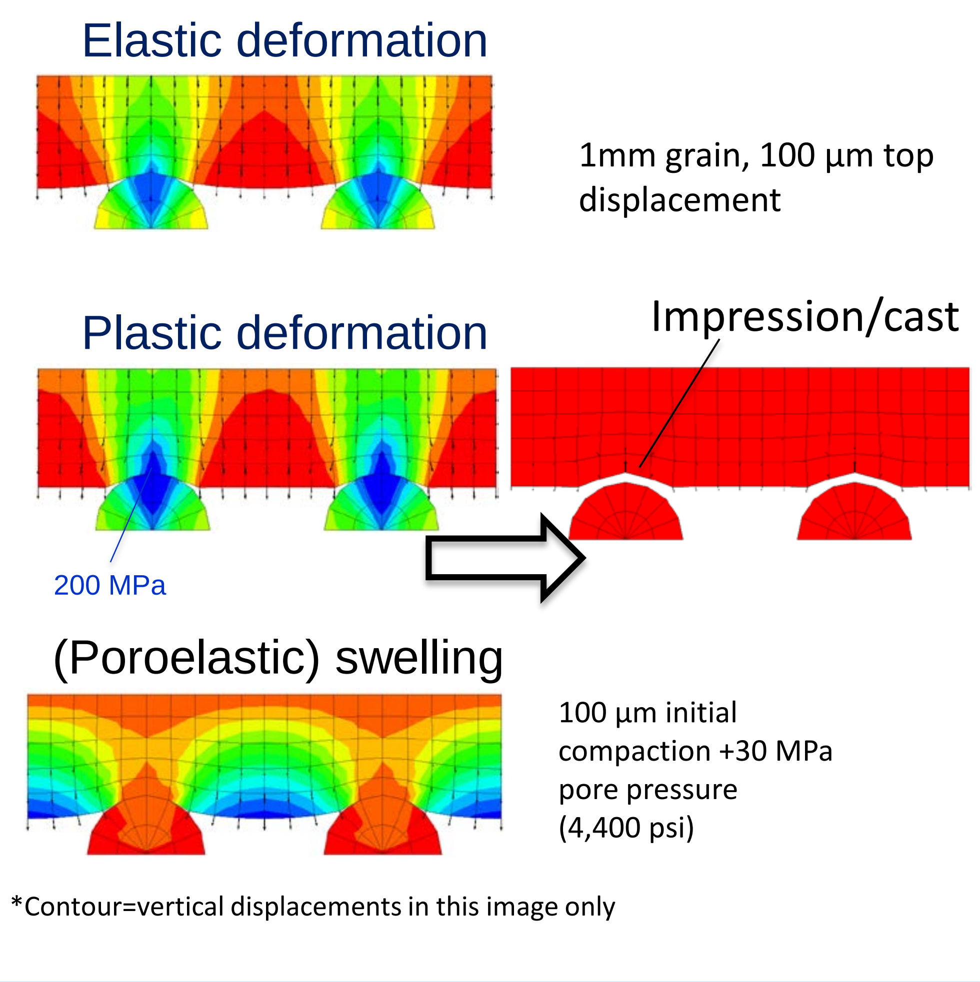
- Modeling the whole spectrum of shale behavior (ductile to brittle) using a single modeling method is difficult and perhaps not necessary
- We adopt a two-prong approach focusing the poro-viscoelastic/plastic deformation of shale matrix (proppant embedment problem) and the elastic-brittle failure of proppant grains (proppant crushing problem)

Numerical Modeling: Continuum Approach

Grain-scale modeling with TOUGH-FLAC

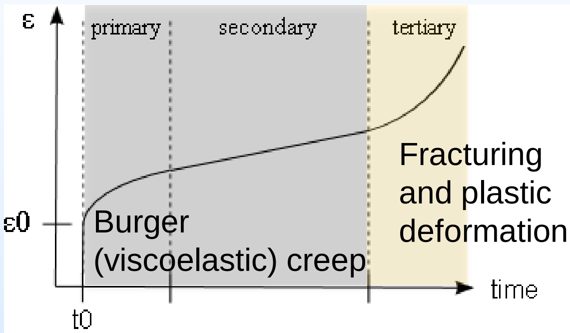
- Approach for proppant embedment in ductile, soft and swelling shale (higher clay content)
- Continuum with discrete particles and progressive contact development under large deformation
- Special considerations needed for grain-matrix contacts

Opalinus Clay (Mont Terri URL)
Young's modulus 5 GPa
Poisson's ratio 0.3
Cohesion 5 MPa
Friction angle 25 degrees
Tensile strengh 2 MPa.

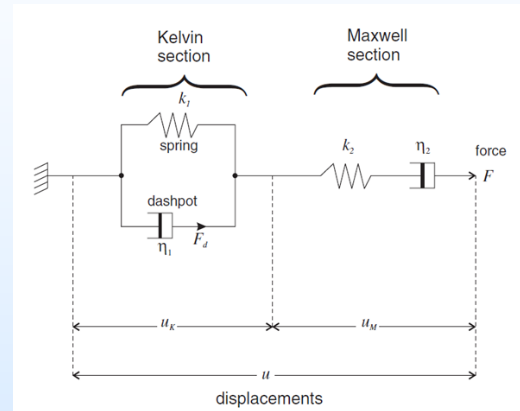


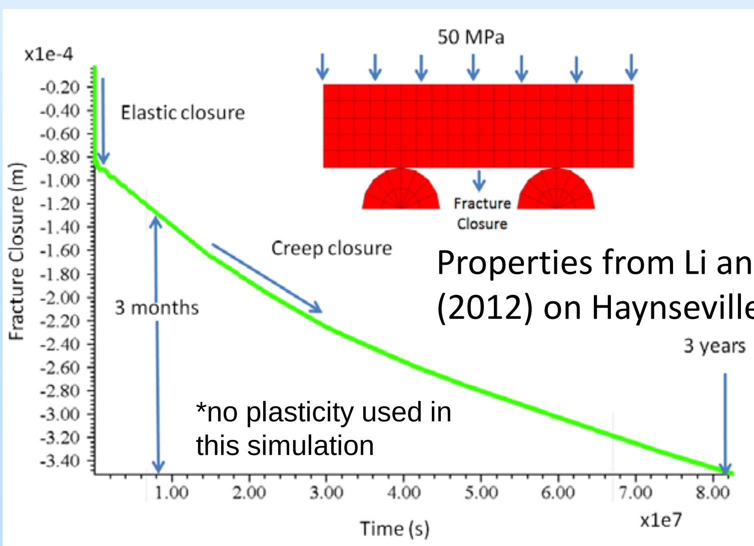
Numerical Modeling: Continuum Approach

Creep modeling of proppant-fracture interaction using TOUGH-FLAC

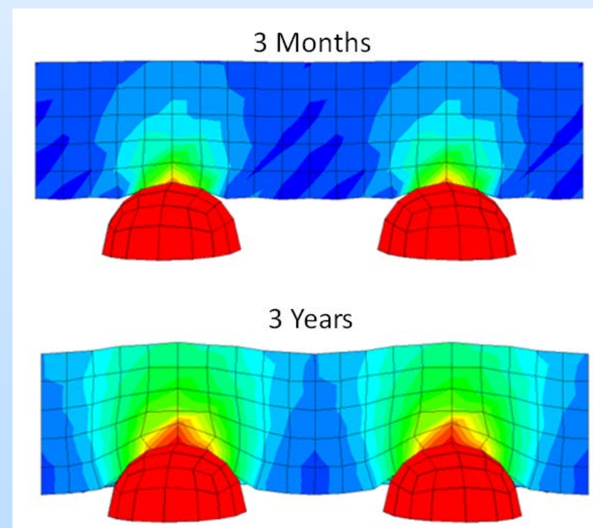


Burgers viscoelastic creep model



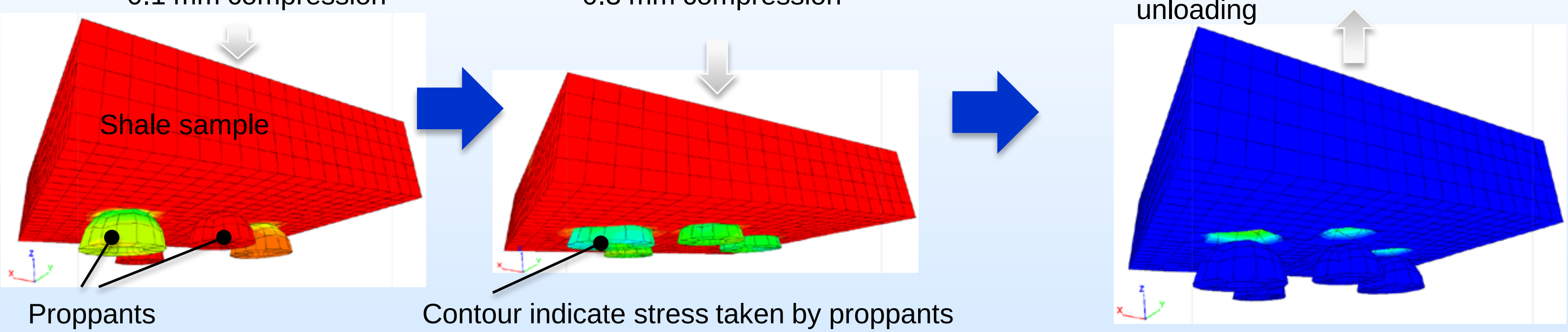


Properties from Li and Ghassemi (2012) on Haynseville Shale



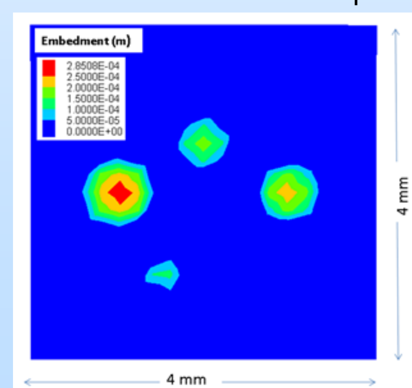
Numerical Modeling: Continuum Approach

Increasing the scale to sub-core fracture scale: 3D elasto-plastic modeling



Opalinus Clay (Mont Terri URL)
Young's modulus 5 GPa
Poisson's ratio 0.3
Cohesion 5 Mpa
Friction angle 25 degrees
Tensile strengh 2 MPa.

Plane view of embedment depths

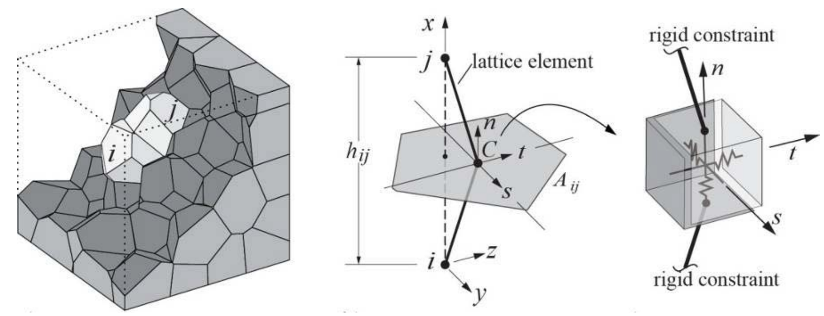


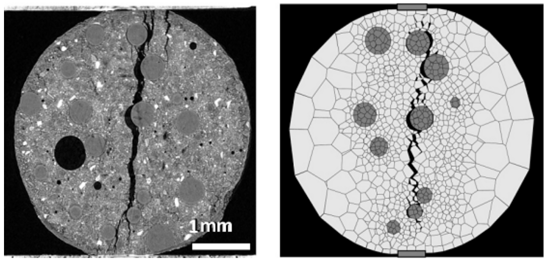
Numerical Modeling: Discrete Approach

Grain-scale modeling with TOUGH-RBSN

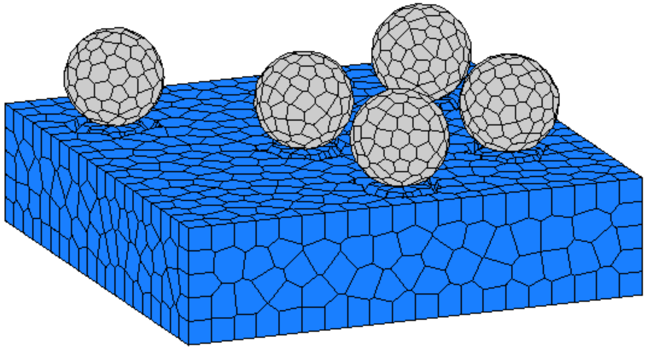
- Approach for embedment by shale and grain crushing in more brittle shale (lower clay content)
- Models discrete damage (fracturing) in both proppant grains and brittle shale matrix using rigid-body-spring network (RBSN)
- Built upon the hybrid TOUGH-RBSN code developed in the previous budget period for hydraulic fracturing modeling

*RBSN=Rigid Body Spring Network





Concrete block, X-ray CT



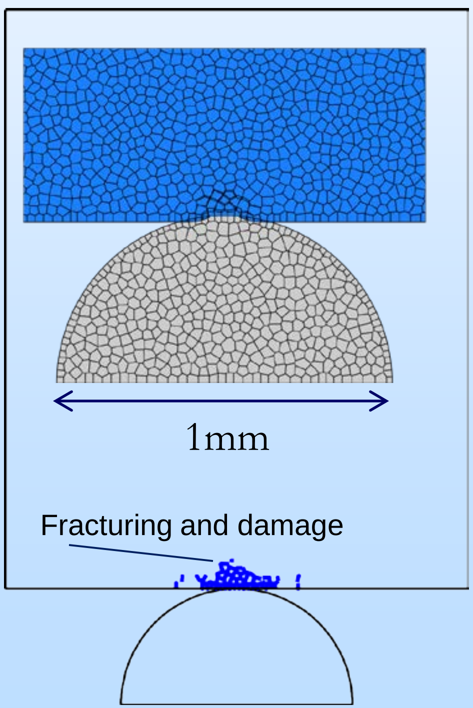
Numerical Modeling: Discrete Approach

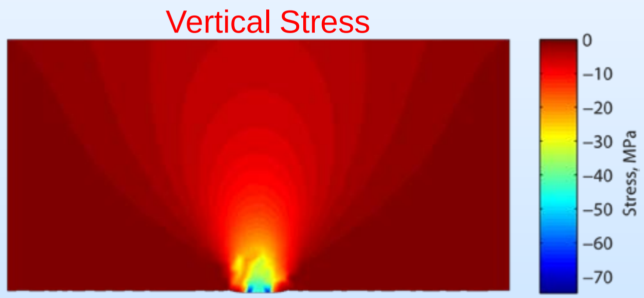
2D Case I: Stronger proppant

- E=70GPa, f_t=10 MPa; c=15.5 MPa; φ=30°
- Failure in the matrix near contact
- No proppant failure (elastic)

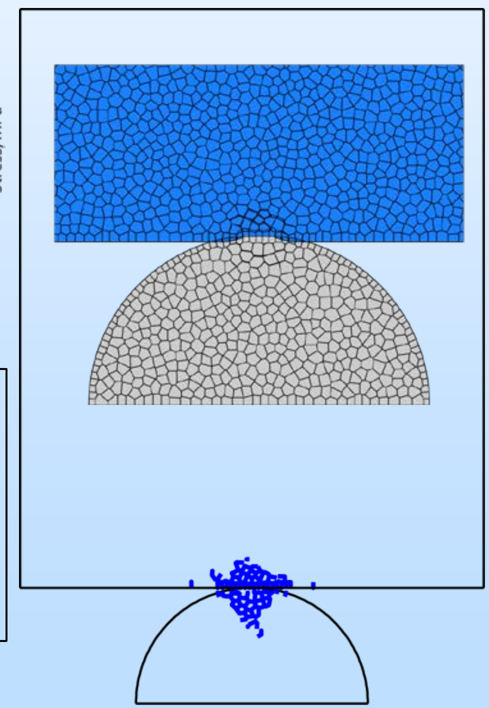
2D Case II: Weaker proppant

- E=70GPa, f_t=5 MPa; c=7.5 MPa; φ=25°
- Failure occurs both in the matrix and the proppant
- Partial crushing of the proppant grain observed





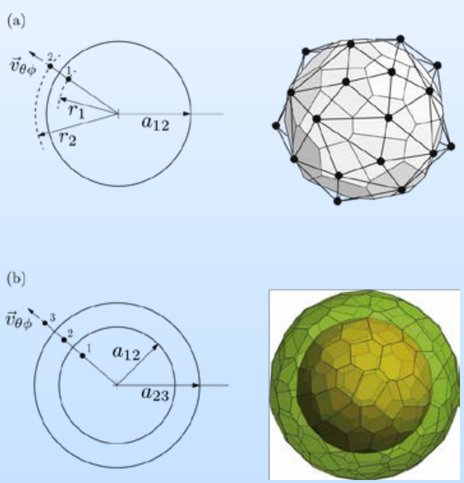
Matrix :
Young's modulus: 20 GPa
Strength parameters of Opalinus Clay
(Mohr-Coulomb criterion
f_t=2 MPa; c=5.5 MPa; φ=25°)



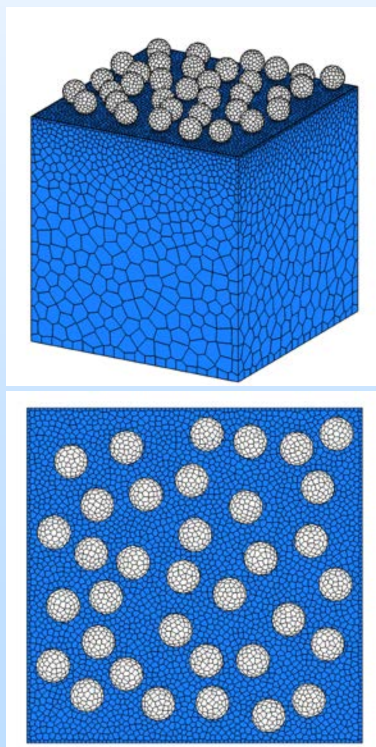
Numerical Modeling: Discrete Approach

3D simulations with multiple grains

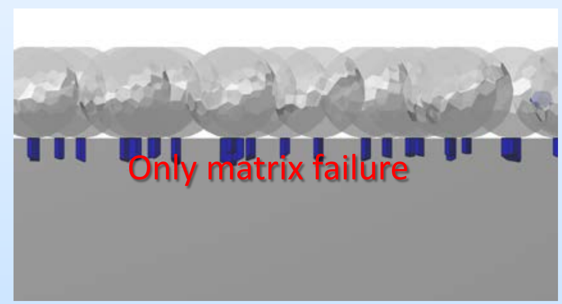
- Implemented an automated procedure to place grains randomly on the matrix block
- 35 spherical grains with an identical diameter (2 mm)
- 20 mm cubic matrix (substrate) block discretized with graded mesh density



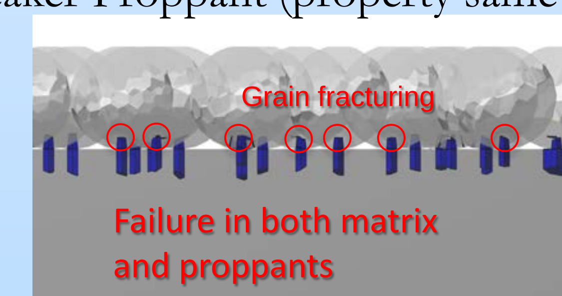
RBSN Volonoi grid representation of a spherical proppant grain



<u>Case I:</u> Stronger Proppant (property same as 2D)



<u>Case II:</u> Weaker Proppant (property same as 2D)



Accomplishments to Date

- A new shale fracture compaction visualization test cell has been designed, and its fabrication has been completed
- Fabrication and initial testing of in-house high-resolution micro indentation system completed
- TOUGH-FLAC modeling methodology for proppant embedding in plastic and viscoelastic shale formulated and tested
- TOUGH-RBSN modeling methodology for proppant/matrix fracturing formulated and tested

Lessons Learned

The project with a new focus is still at its early stage

- "Available" shale samples tend to be too competent (Ca and Si rich), exhibiting relative small ductility and swelling
- Some issues with the development of in-house micro indentation system (e.g., broken sensors, difficulties in implementing dynamic moduli measurement component)

Synergy Opportunities

- Comparison of characterized shale properties (esp. permeability)

→ *Understanding Water Controls on Shale Gas Mobilization into Fractures* (PI: Tetsu Tokunaga [LBNL])

- Micro-scale shale fracture deformation and proppant embedment characterization via micro CT imaging
- "Foot-size" proppant transport visualization experiment

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

(PI: George Moridis [LBNL])

Project Summary

- The Year 1(Budget Period 1) of the project was designed as the staging step to develop and validate tools for conducting the main tasks in Year 2.
- Both laboratory tools (experimental test cell, micro indentation test system) and modeling tools (TOUGH-FLAC and TOUGH-RBSN models) have been developed for the planned tasks of grain and core-scale shale fracture/proppant behavior study
- Key scientific knowledge and data will be produced through the experiments and modeling in Year 2.
- Stay tuned…..

Appendix

Benefit to the Program

Program Goals

"Address critical gaps of knowledge of the characterization, basic subsurface science, and completion/stimulation strategies for tight oil, tight gas, and shale gas resources to enable efficient resource recovery from fewer, and less environmentally impactful wells"

–DOE-FE/NETL FUNDAMENTALS OF UNCONVENTIONAL RESERVOIRS RESEARCH CALL, 05-01-2014

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

- Fundamental understanding the process of hydraulic fracture closure in ductile and expanding shales (incl. brittle shale with proppant crushing)
- 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
- M2 & M3 will be reported in Q3 report in July 2017

Bibliography

(For the research performed in the previous budget period)

- Journal:
  - Kim, K., J. Rutqvist, S. Nakagawa, and J. Birkholzer. 2017. TOUGH–RBSN simulator for hydraulic fracture propagation within fractured media: Model validations against laboratory experiments, Computers & Geosciences, In Press. https://doi.org/10.1016/j.cageo.2017.05.011
- Publication:
  - Nakagawa, S. 2017. Laboratory visualization of hydraulic fracture propagation induced by variable-rate fluid injection within analogue rock samples containing preexisting fractures, Paper#17-928, 51th US Rock Mechanics Symposium/ARMA Meeting, San Francisco, June 25-28
  - Kim, K., J. Rutqvist, S. Nakagawa, and J. Birkholzer. 2017. Discrete modeling of fluid-driven fracture processes in anisotropic rock formations, Paper#17-382, 51th US Rock Mechanics Symposium/ARMA Meeting, San Francisco, June 25-28