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

ESD14084

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National Energy Technology Laboratory

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

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Presentation Outline

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 develops a unique methodology for hydraulic fracturing visualization in the laboratory and uses its results to test a highly adaptive numerical modeling tool for fracture propagation in heterogeneous and anisotropic rock.

The project provides better understanding and predictive capabilities for the complex interactions between preexisting weaknesses (fractures) and textures in shale and hydraulic fractures, an important prerequisite for improved and optimized reservoir stimulation.

Project Overview:
Goals and Objectives

Project Goals and Objectives

Combined laboratory and modeling studies to
(1) Obtain improved understanding and a "fact check"–dynamic visualization experiments—of how initial rock heterogeneity affects hydraulic fracturing
(2) Develop an improved and tested numerical simulation capability for coupled, fluid flow and fracture propagation processes
→A predictive tool

- Fundamental understanding of hydraulic fracture propagation in complex, anisotropic, and heterogeneous rock (shale)
- Hydraulic fracturing modeling and predictions

Program Goals and Objectives

- Fracturing operation optimization
- Efficient and sustainable oil and gas production
- Mitigation of seal breach and fault activation

Success Criteria (milestones & deliverables)

- Development of new visualization experiment setups
- Laboratory data showing complex hydraulic fracturing behvior
- Development of predictive numerical simulation capability
- Simulation results validated by lab and available field data

EARTH & ENVIRONMENTAL SCIENCES

BERKELEY LAB

Benefit to SubTER

Mastering the Subsurface

Adaptive Control of Subsurface Fractures and Flow

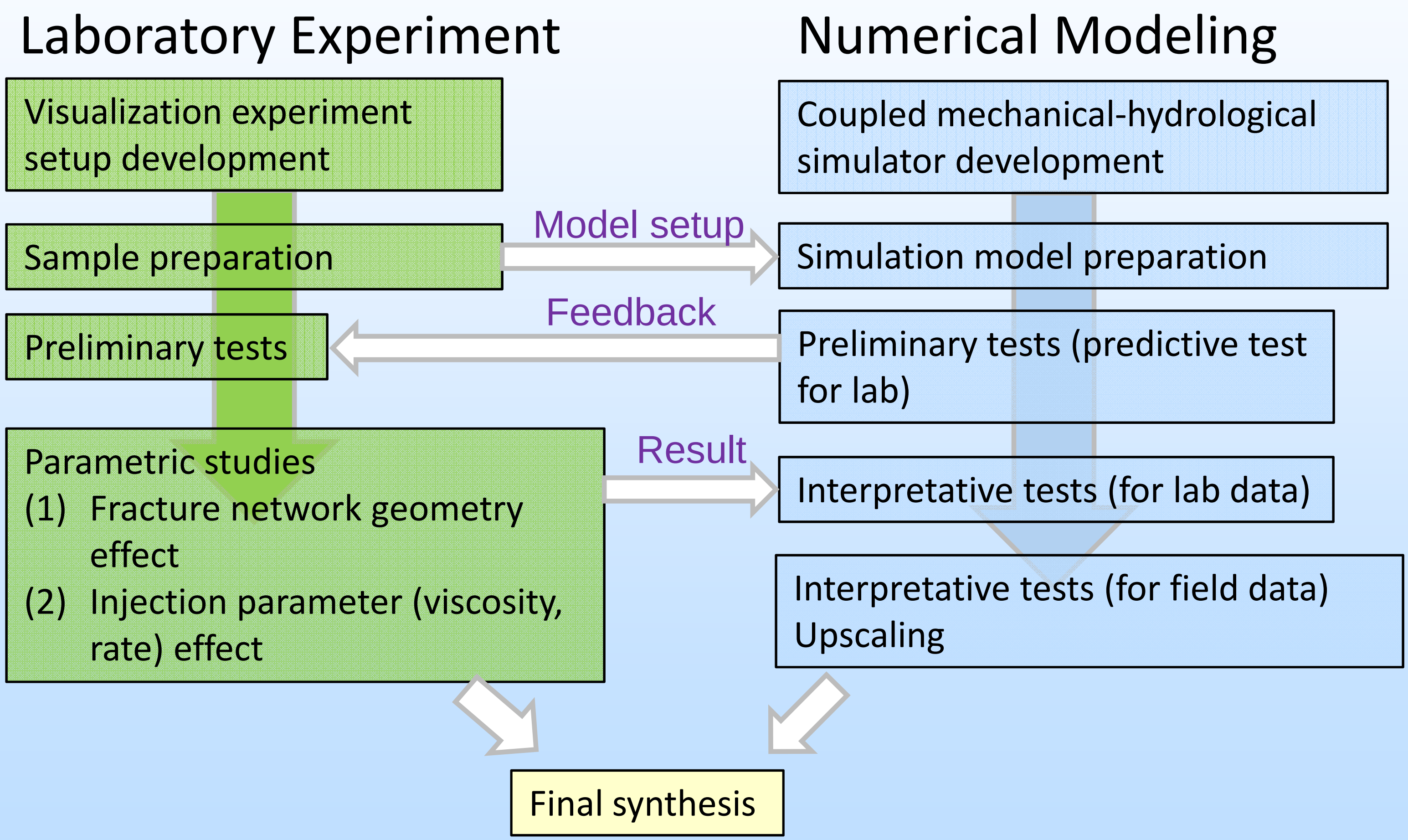
Intelligent Wellbore Systems	Subsurface Stress & Induced Seismicity	Permeability Manipulation	New Subsurface Signals
Improved well construction materials and techniques	Measurement of stress and induced seismicity	Physicochemical fluid-rock interactions	New sensing approaches
Autonomous completions for well integrity modeling	Manipulation of stress and induced seismicity	Manipulating flowpaths	Integration of multi-scale, multi-type data
New diagnostics for wellbore integrity	Relating stress manipulation and induced seismicity to permeability	Characterizing fractures, dynamics, and flows	Adaptive control processes
Remediation tools and technologies	Applied risk analysis of subsurface manipulation	Novel stimulation methods	Diagnostic signatures and critical thresholds
Fit-for-purpose drilling and completion tools (e.g. anticipative drilling, centralizers, monitoring)			
HT/HP well construction / completion technologies			

Energy Field Observatories

Fit For Purpose Simulation Capabilities

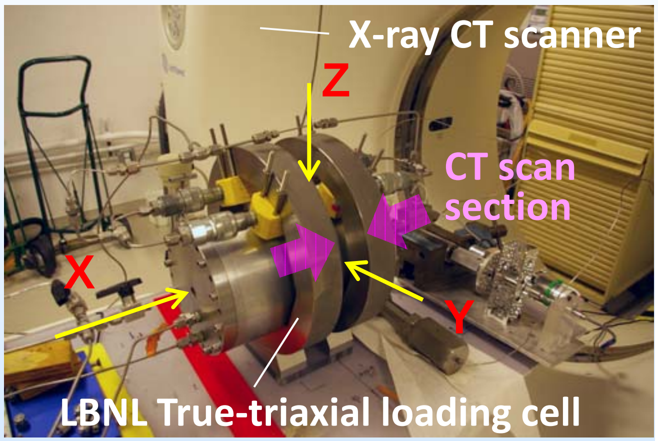
Technical Status

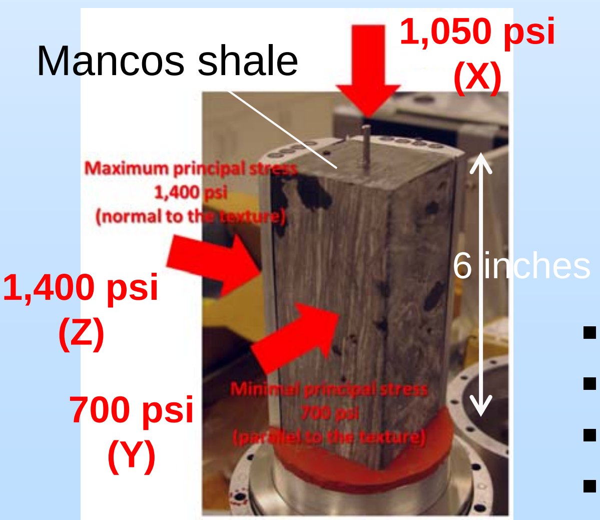
Project Framework

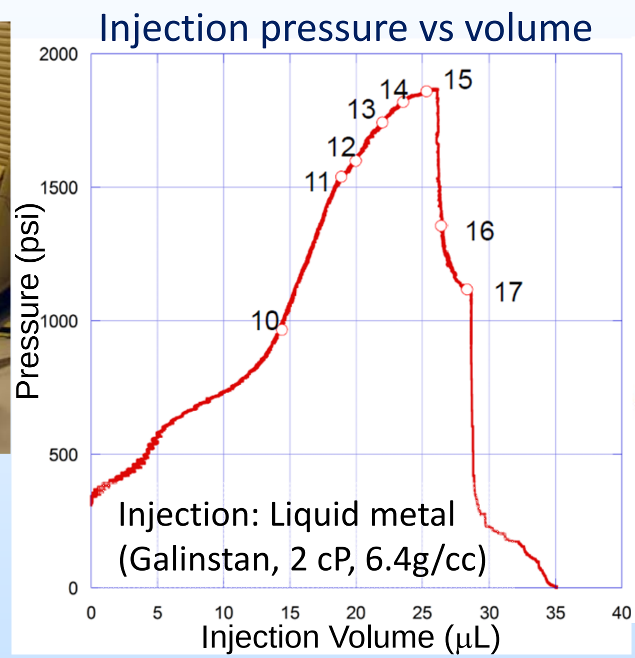


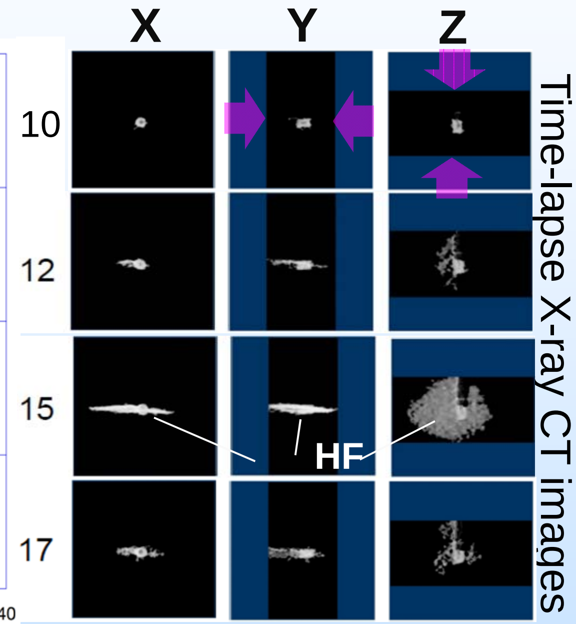
Technical Status

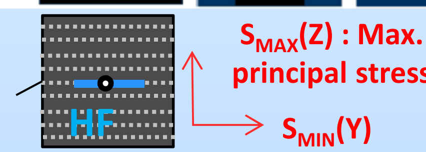
Hydraulic Fracturing (HF) Visualization Experiment via X-ray CT









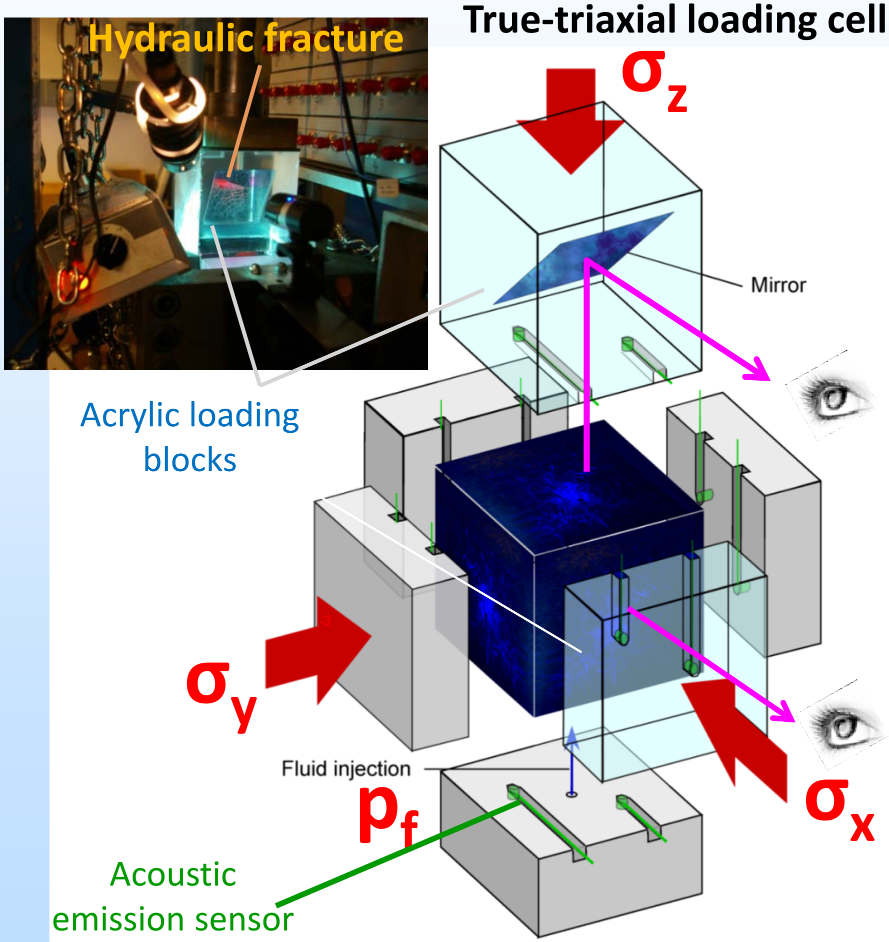


- High-density liquid metal injection helps real-time imaging
- Strong shale texture overwhelmed the stress anisotropy effect
- Thin hydraulic fractures→ Still difficult to image via medical X-ray CT
- Water-sensitive shale sample → Difficult to prepare samples

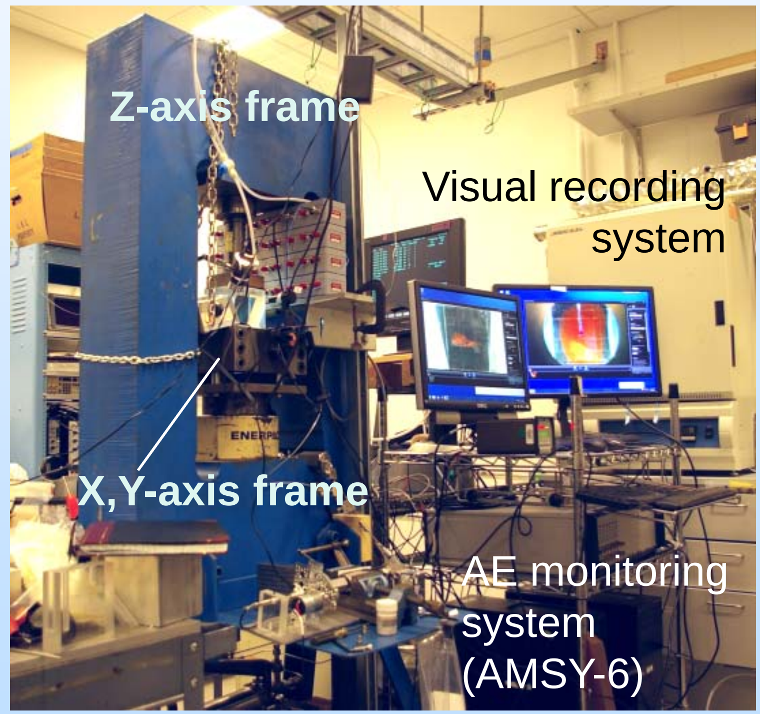
Technical Status

Optical hydraulic fracturing visualization experiment

True-triaxial loading cell



Using transparent rock analogues, optical images, mechanical/hydrological responses, and acoustic emission data can be obtained concurrently



Stress limit <1,500 psi (10MPa) for 4" (10cm) cubes

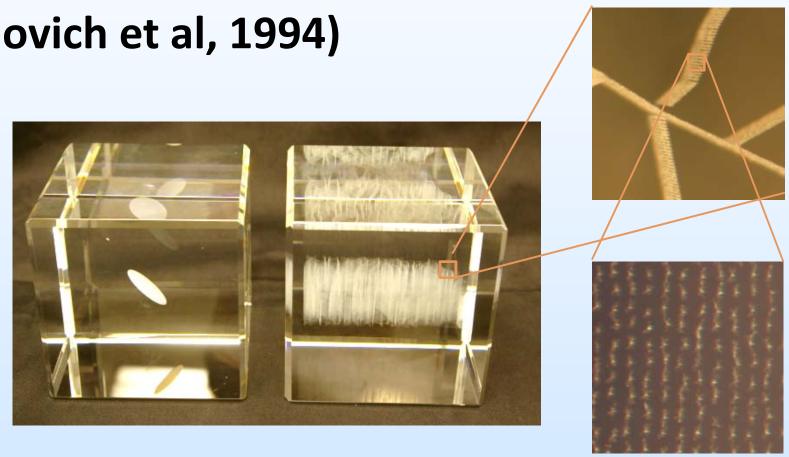
Development of hydraulic fractures can be viewed and recorded in real time

Technical Status

Glass Blocks as Transparent Analogue Fractured Rock Samples

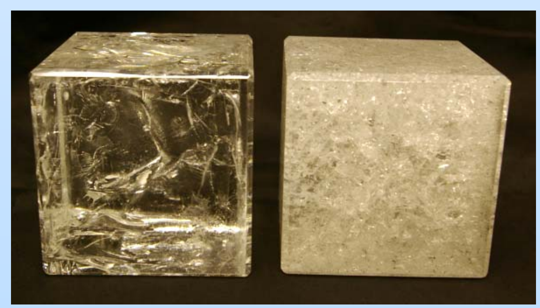
I. 3D-Laser-Engraving Method (e.g., Germanovich et al, 1994)

- Use thermal cracking by conically focused laser beam
- Fractures consist of micron-scale cracks
- Precise 3D fracture geometry
- Repeatable
- Fracture strength can be modified by changing the microcrack density



II. Thermal Contraction Method

- Use thermal contraction of soda-lime glass
- Dense and connected fracture network
- Fracture density can be modified by ΔT for thermal fracturing
- Fracture strength and permeability can be modified by re-heating

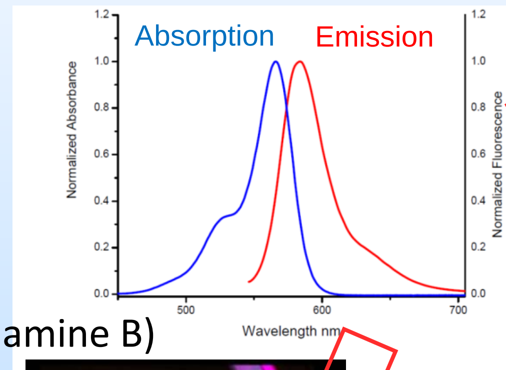


Technical Status

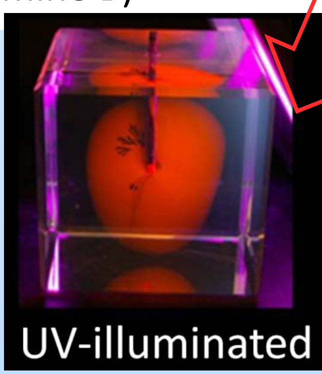
Real-time image enhancement with UV light and fluorescent dye

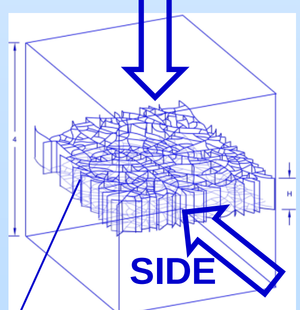
Laboratory hydraulic fractures in glass are very thin (~1µm), making visualization difficult. However, the images can be enhanced by using fluorescent dyes.

Glycerol+1%wt SRhB



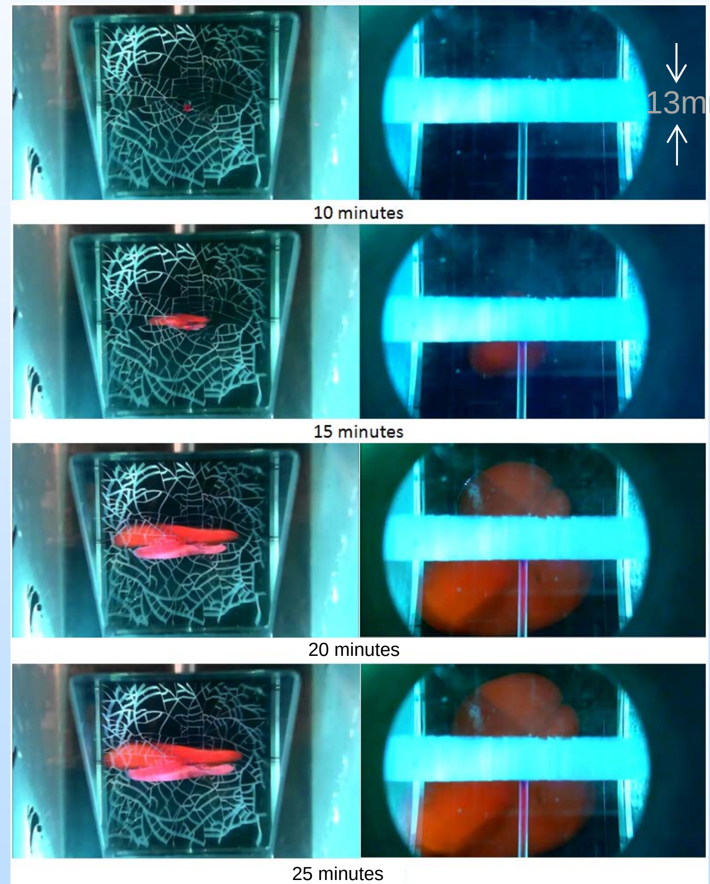
(Sulforhodamine B)





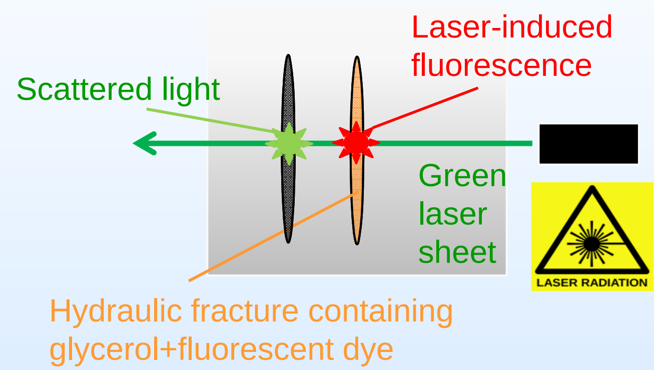
Pre-existing fracture model

TOP VIEW SIDE VIEW

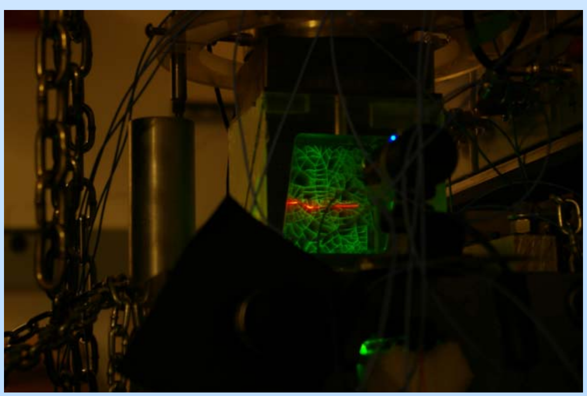


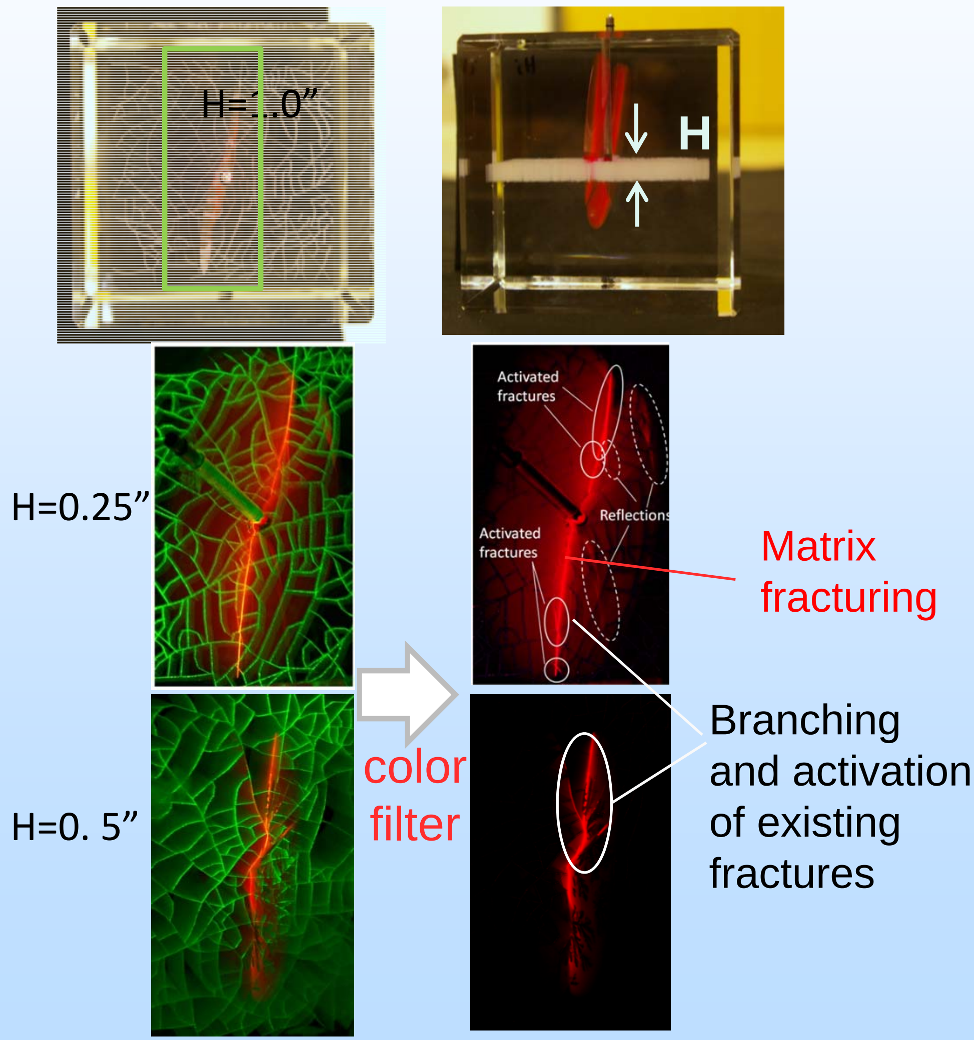
Technical Status

Further enhancement…



Laser sheet can "cut" the sample, allowing more clear visualization of fracture interactions





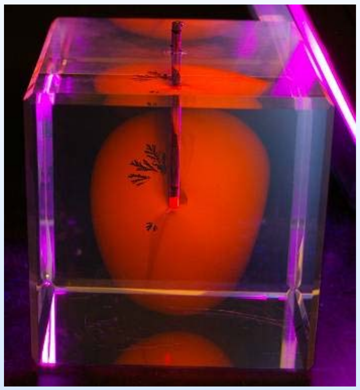
Technical Status

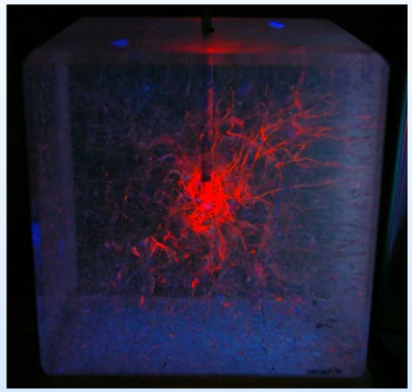
Hydraulic fracturing in more complex media (thermal contraction samples)

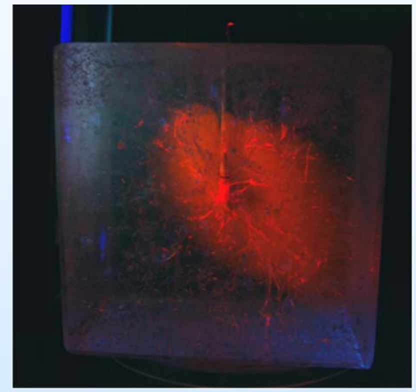
Intact block — Slow injection

Randomly fractured block (re-heated and healed) — Slow injection (0.425 μL/min); Fast injection (x20)

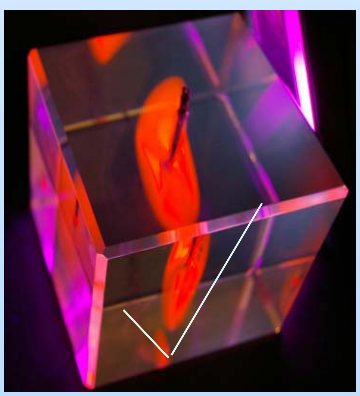
SIDE VIEW

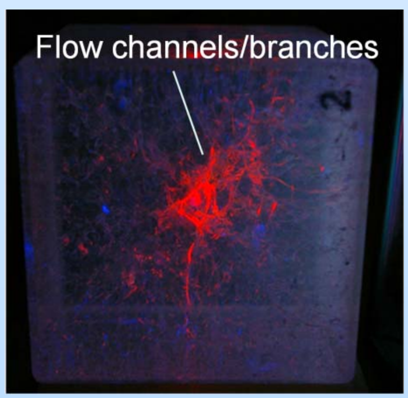


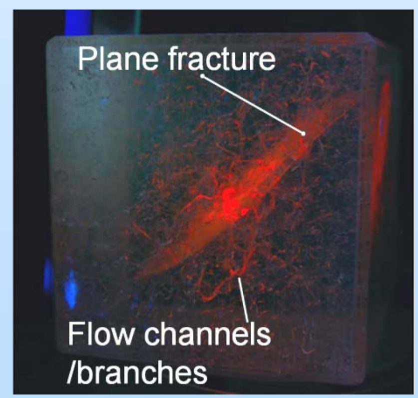




TOP (or BOTTOM) VIEW

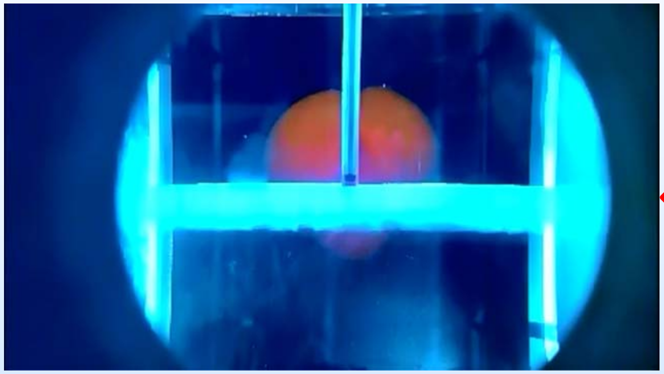




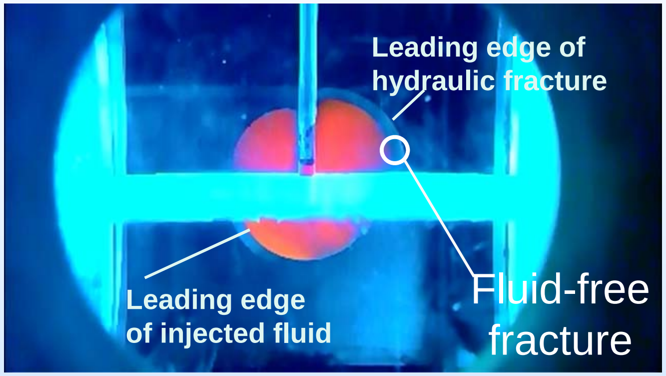


Technical Status

Slow injection experiment



Fast injection experiment (x20)

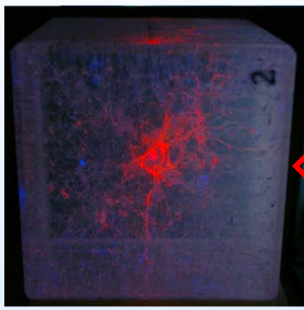


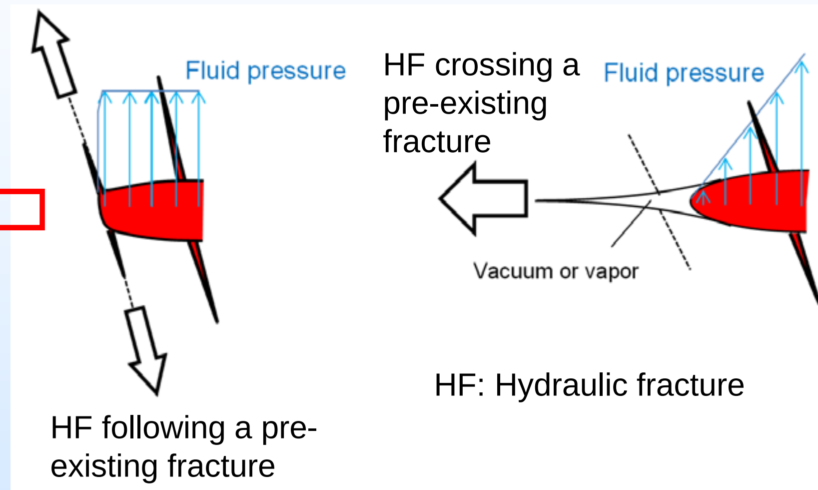
Fast injection produced different fluid/pressure distribution within propagating hydraulic fractures

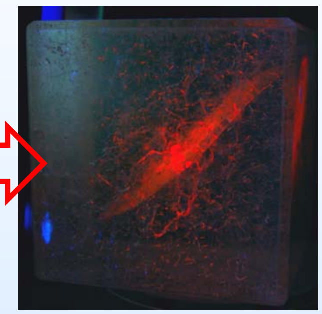
Technical Status

Slow injection experiment

Fast injection experiment (x20)





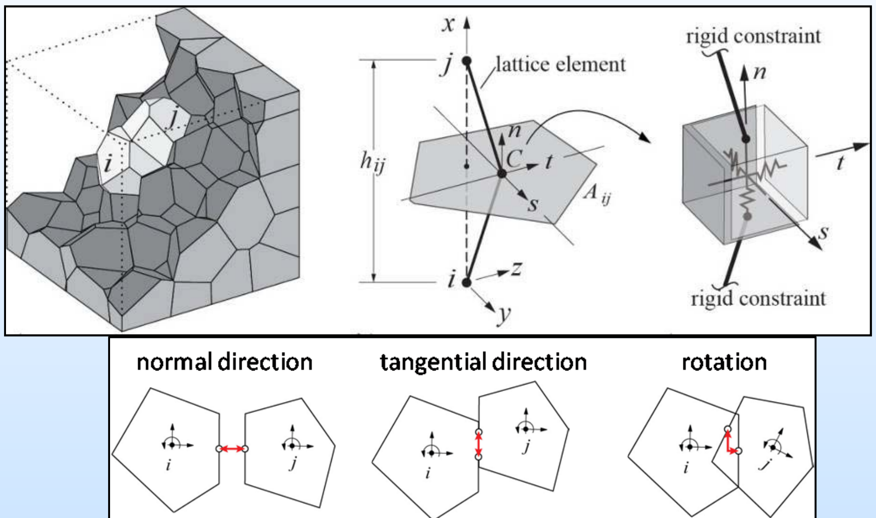


- Fast injection can create far-reaching, high-permeability hydraulic fracture with smaller footprint
- Demonstrates the effect of variable injection rates as a tool for manipulating hydraulic fracture geometry/reservoir permeability

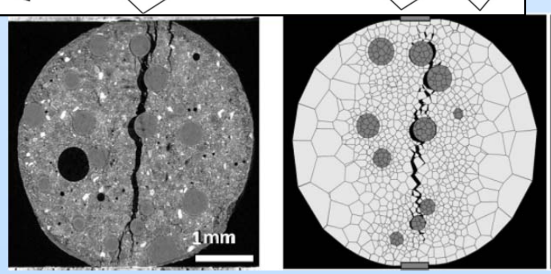
Technical Status

Modeling Effort: Hydraulic Fracturing Numerical Simulations

RBSN Method

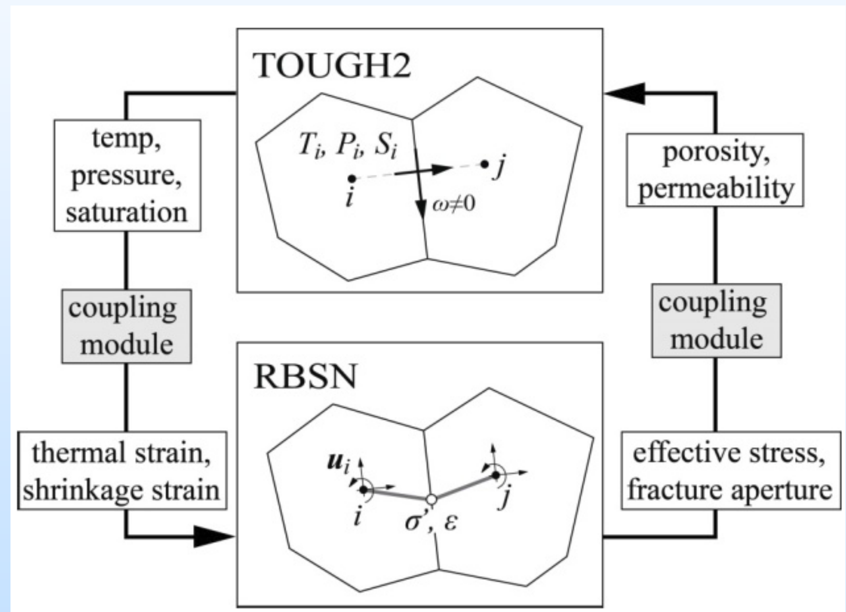


Concrete block, X-ray CT



Rigid Body Spring Network method models mechanical behavior of complex solid with interfaces (fractures) via Voronoi tessellation

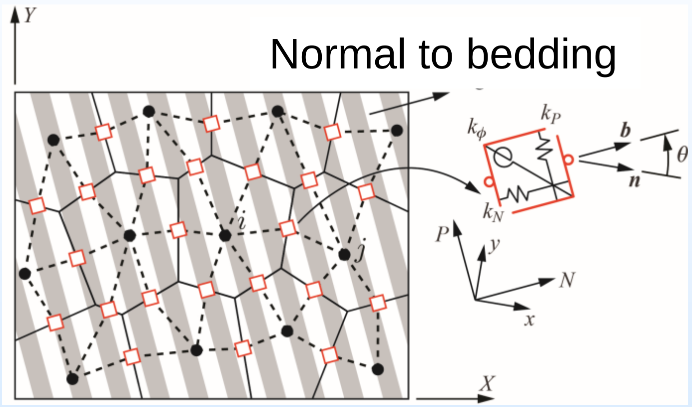
Coupling with TOUGH simulator



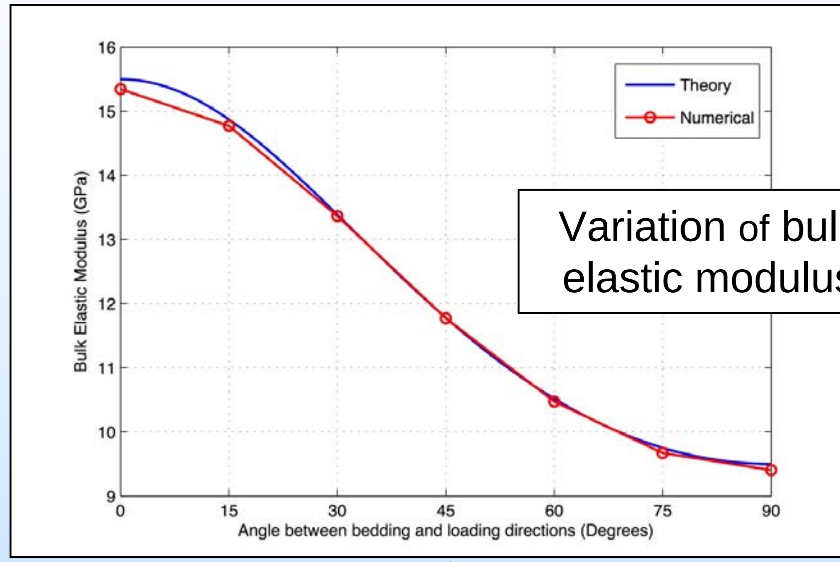
Combined with a transport simulator (TOUGH), hydraulic fracturing modeling is conducted

Technical Status

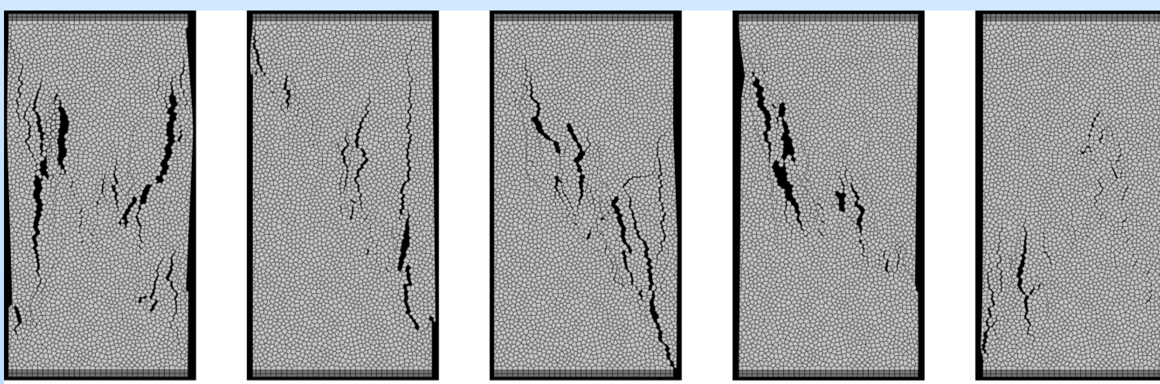
RBSN code development specifically for shale hydraulic fracturing



Local stiffness and strength matrix rotation → anisotropic behavior



Variation of bulk elastic modulus



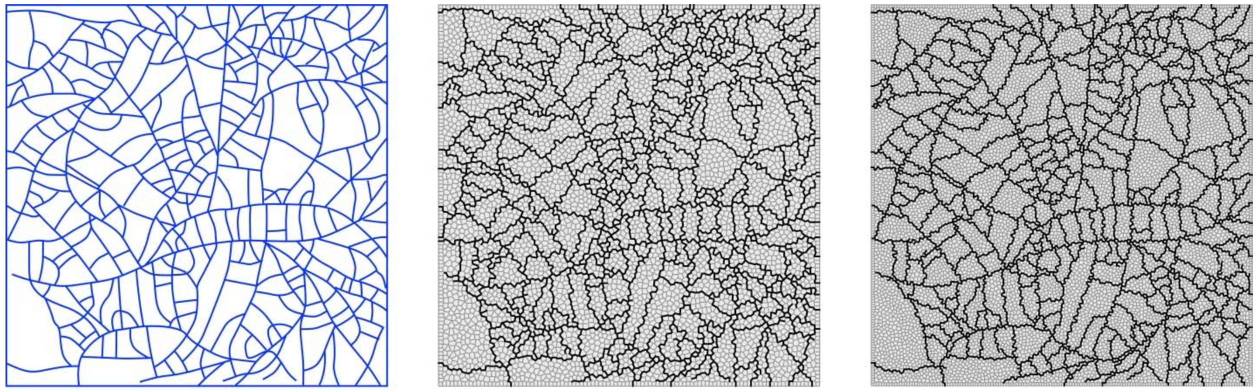
a) β=0º b) β=30º c) β=45º d) β=60º e) β=90º

A demonstration of anisotropic rock failure via 2D uniaxial compression simulations

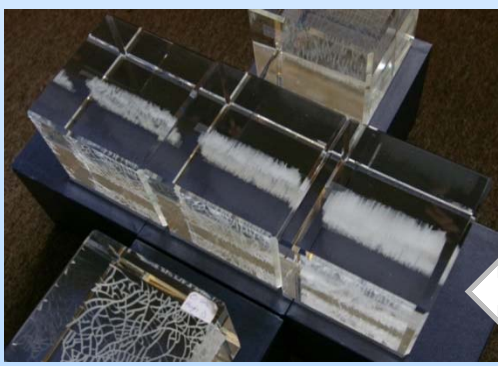
Technical Status

TOUGH-RBSN Modeling of Laboratory Hydraulic Fracturing Experiments

2D lab fractures



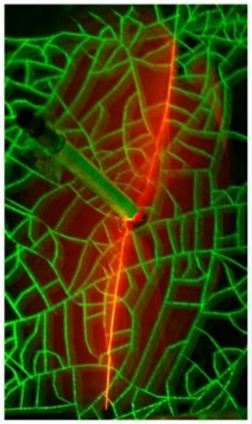
a) Digitization   b) Voronoi tessellation   c) Finer tessellation



Laser-etched 2.5D fractured reservoir model was used in 2D numerical simulations, with lab-determined material and fluid properties

Transparent fractured reservoir models with different fracture height and strength

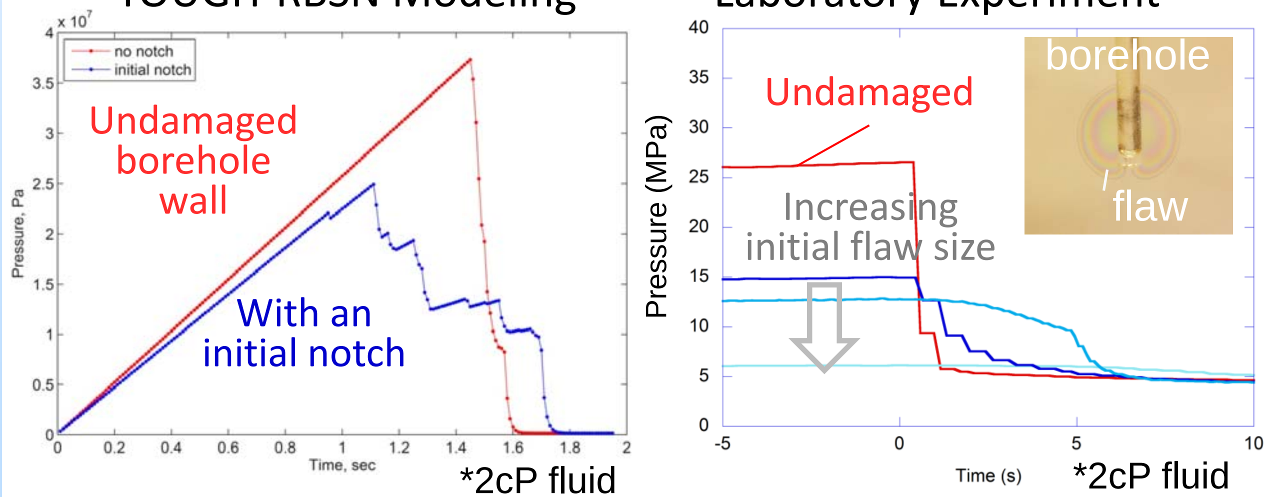
Technical Status



- Fracturing patterns from the lab experiments and numerical simulations show reasonably good agreement
- Propagating fractures in the lab tests tend to be less affected by preexisting fractures

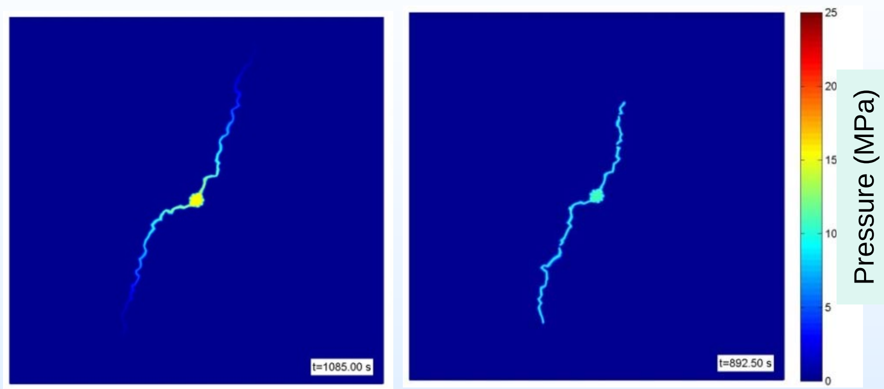
TOUGH-RBSN Modeling

Laboratory Experiment



- Borehole damage has a large impact on the breakdown pressure and the rate/stability of post-breakdown fracture growth

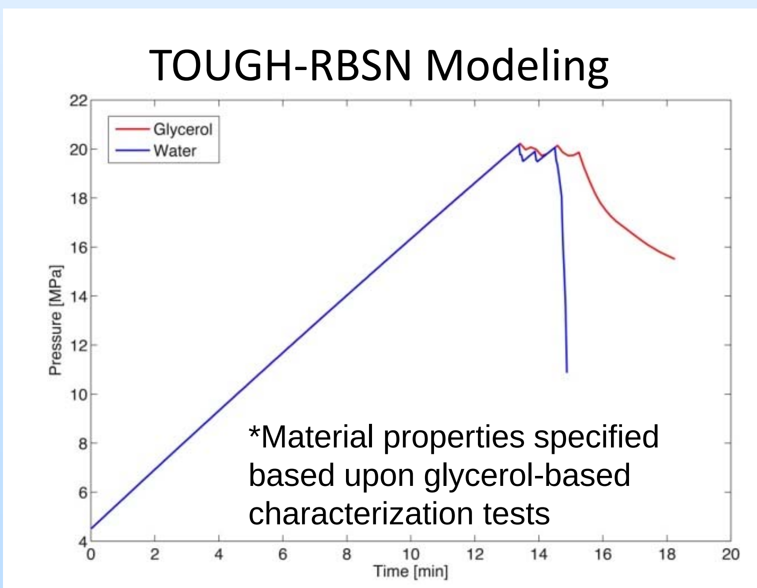
Technical Status

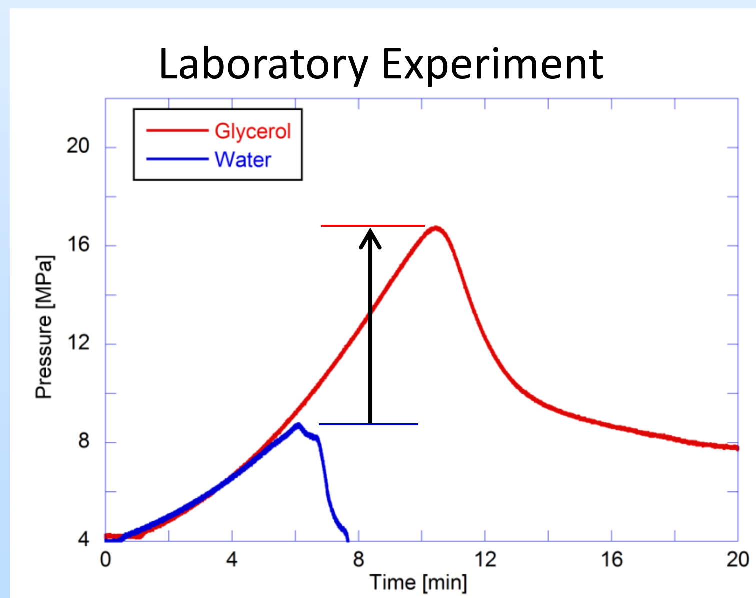


Glycerol Water

- However, breakdown pressure increases by viscous fracturing fluid (Glycerol, 1,000 cP vs Water, 1 cP) were not well captured by the numerical model

→ Insufficient representation of the delayed viscous fluid infiltration into developing microcracks?

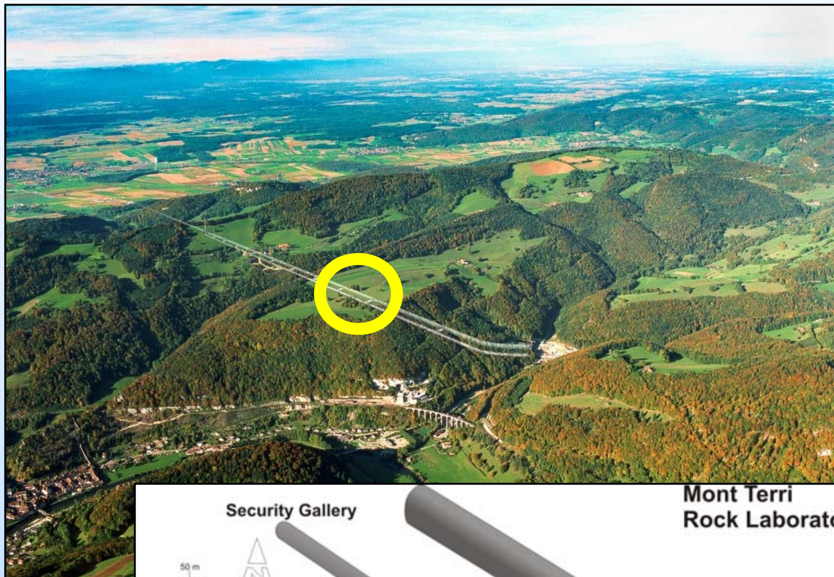


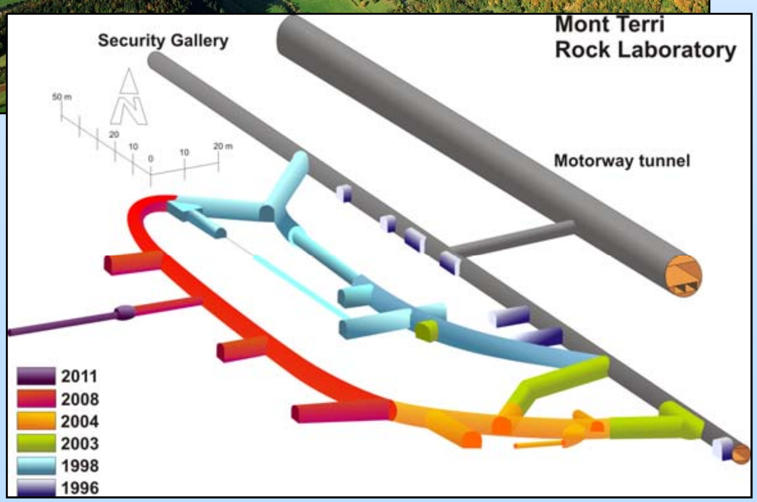


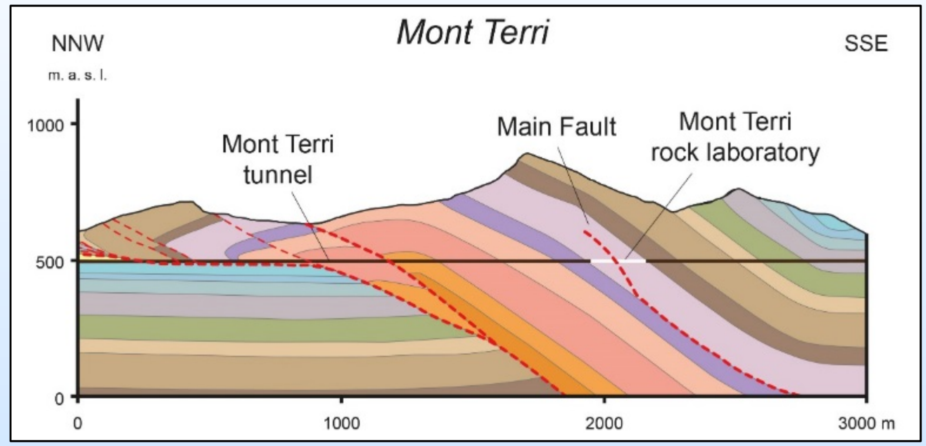
Technical Status

Application to Larger-Scale Experiment

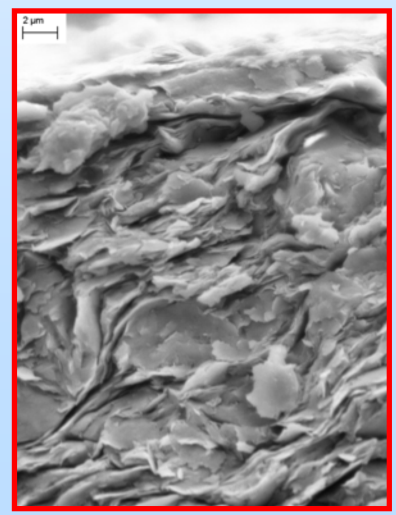
Mont Terri Underground Rock Laboratory







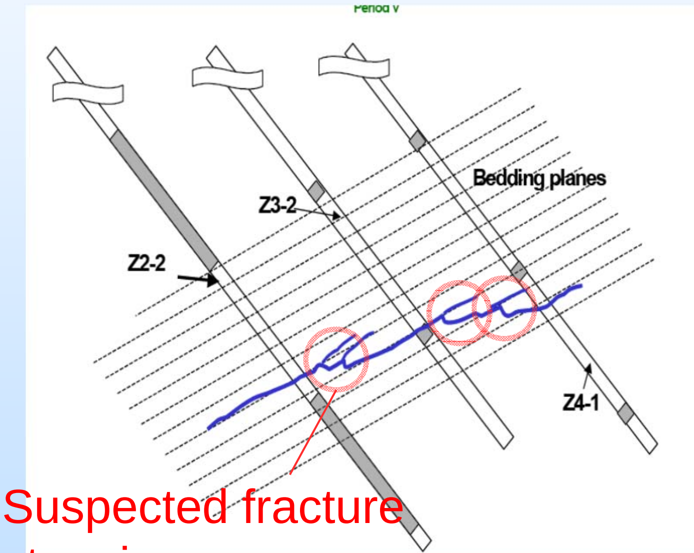
Opalinus Clay



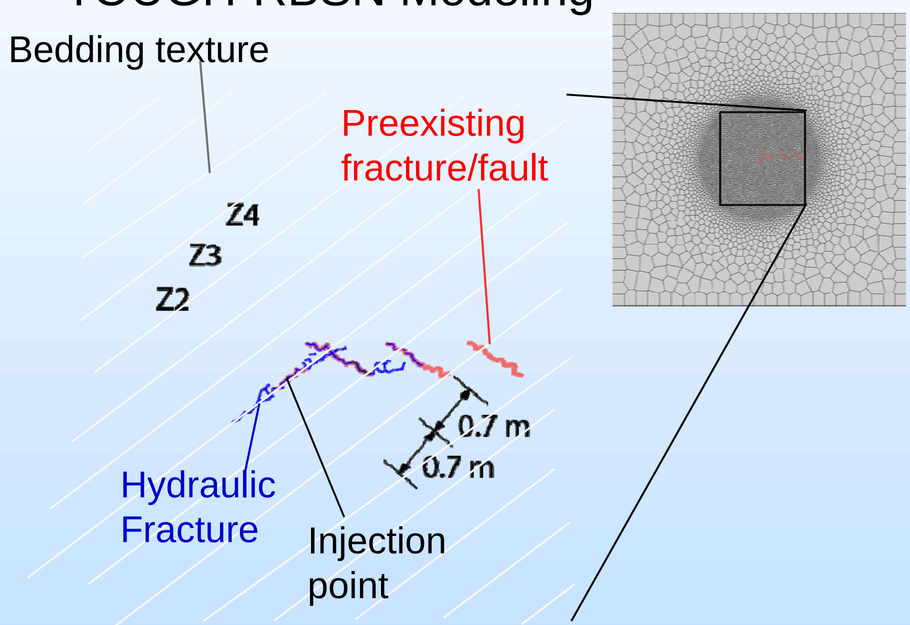
Technical Status

Application to Larger-Scale Experiment

Mont Terri URL Experiment
(Opalinus Shale/Clay)



TOUGH-RBSN Modeling



i. Initially HF follows the bedding plane
ii. HF deviates, affected by a preexisting fracture
iii. HF turns back along the bedding plane

Accomplishments to Date

- **All planned milestones and deliverables completed (incl. final report)**
- **All funding spent according to the approved budget (June 2016)**

- New analogue fractured-rock-sample fabrication methods developed
- New optical hydraulic fracturing visualization system developed
- Laboratory parametric studies on fracture geometry and fluid injection scheme (injection viscosity and rate) completed
- Real-time visualization of hydraulic fracturing (both optical and x-ray CT) correlated to injection data completed
- TOUGH-RBSN code for hydraulic fracturing developed and validated
- Simulation of the laboratory experiments conducted and compared to the lab results
- Numerical simulations and interpretation of field hydraulic fracturing experiment completed

Synergy Opportunities

Key Points for collaboration…..

Lab visualization experiments

- ❑ Provide insights regarding hydraulic fracturing in complex reservoir rock
- ❑ Provide data sets that can be used for testing/validating other numerical modeling methods
- ❑ Provides imaging methods for further testing of shales and analogs

Coupled, discrete hydraulic fracturing modeling

- ❑ Provides a tool for examining impact of various field variables on hydraulic fracturing at a high speed and low cost
- ❑ Provides a unique numerical method which can participate in cross validation between different numerical methods available for hydraulic fracturing simulation

Summary

Take Home Messages:

- ❑ Hydraulic fracture network geometry can strongly depend upon the interactions between the propagating and preexisting fractures, and even more importantly, on the fluid injection scheme
- ❑ The newly developed, coupled mechanical-hydrological simulator (TOUGH-RBSN) can model discrete fracture propagation in complex media including anisotropic and fractured rock

Lessons Learned:

- ❑ Even with high density contrast fluid, imaging of hydraulic fractures in the laboratory using medical X-ray CT is difficult
- ❑ The current TOUGH-RBSN code reproduces most of the experimental findings, but not all (e.g., the breakdown pressure difference between fracturing fluids with different viscosity)

Future Work

The project focus in the next phase will be on laboratory studies and modeling of the local, time-dependent, coupled hydro-mechanical behavior and sustainability of hydraulic fractures in ductile, expanding shale.

- Experiments on various ductile vs non-ductile, swelling vs non-swelling shales
- Laboratory visualization of shale fracture closure, rock-proppant interactions, with permeability measurements.
- Near-fracture fluid/gas transport imaging (via X-ray CT)
- Coupled, discrete and continuum modeling of fracture-proppant interactions and time-dependent shale deformation using TOUGH-RBSN and TOUGH-FLAC codes.

Appendix

Organization Chart

Project Team

Lab Experiment Team

Seiji Nakagawa (PI)
–Hydraulic fracturing experiment. Optical visualization –
Tim Kneafsey
– X-ray CT imaging –

Numerical Modeling Team

Jonny Rutqvist (Co-PI)
–Modeling strategizing and supervising Lab/Field data interpretation –
Kunhwi Kim
–TOUGH-RBSM coding and numerical simulation execution–

Jens Birkholzer
– Facilitation of Mont Terri field fracturing test data use –

Lab/numerical modeling coordination / Field data

Gantt Chart

	Phase 1 (Oct./2014-June/2015)			Phase 2 (July/2015-March/2016)		
Quarter	Q1	Q2	Q3	Q4	Q5	Q6
Task 1: Management and Planning						
Task 2: Laboratory experiments						
Subtask 2.1: Preparation of true triaxial test setups		M1				
Subtask 2.2: Preparation of rock samples containing complex heterogeneities		M2				
Subtask 2.3: Preliminary hydraulic fracturing experiment			M4			
Subtask 2.4: Hydraulic fracturing visualization I: Stress and texture anisotropy effect				M6		
Subtask 2.5: Hydraulic fracturing visualization II: Fluid viscosity/injection rate effect				M6		
Task 3: Numerical modeling						
Subtask 3.1: Code modification and verification of TOUGH-RBSN hydraulic fracturing algorithms		M3				
Subtask 3.2: Numerical model setup and preliminary simulation of complex hydraulic fracturing		M3				
Subtask 3.3: Model prediction of laboratory hydraulic fracturing experiments			M5			
Subtask 3.4: Interpretative numerical modeling of laboratory experiments				M7		
Subtask 3.5: Simulation of Mont Terri hydraulic fracturing experiment					M8	
Task 4.0: Final Synthesis of Experimental and Numerical Modeling Results						M9

M1-M9: Milestones (Completed at this point)

Bibliography

Publications and presentations generated from the project

Kim, K., Rutqvist, J., Nakagawa, S., and J. Birkholzer, J., TOUGH-RBSN modeling of hydraulic fracture propagation within discrete fracture networks, Computers & Geosciences, In preparation.

Kim, K., J. Rutqvist, S. Nakagawa, J. Houseworth, and J. Birkholzer. 2015. Discrete modeling of hydraulic fracturing processes in a complex pre-existing fracture network, Fall American Geophysical Union Meeting, MR41A-2626, San Francisco December 14-18.

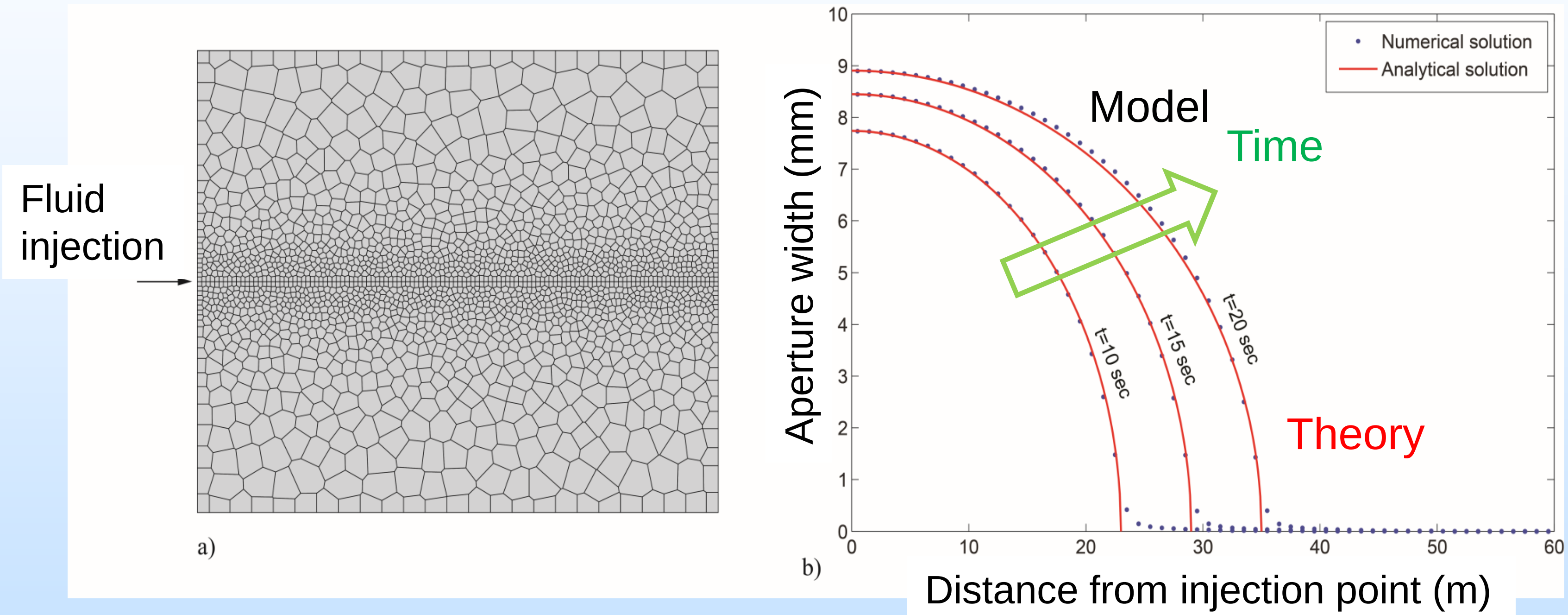
Kim, K, J. Rutqvist, S. Nakagawa, J. Houseworth, and J. Birkholzer. 2015. Simulations of fluid-driven fracturing within discrete fracture networks using TOUGH-RBSN, TOUGH Symposium 2015, Berkeley, September 28-30.

Nakagawa, S., T.J. Kneafsey, and S. Borglin. 2015. Laboratory Visualization of Hydraulic Fracture Propagation and Interaction with a Network of Preexisting Fractures, Fall American Geophysical Union Meeting, MR41A-2615, San Francisco, December 14-18.

Backup

Technical Status

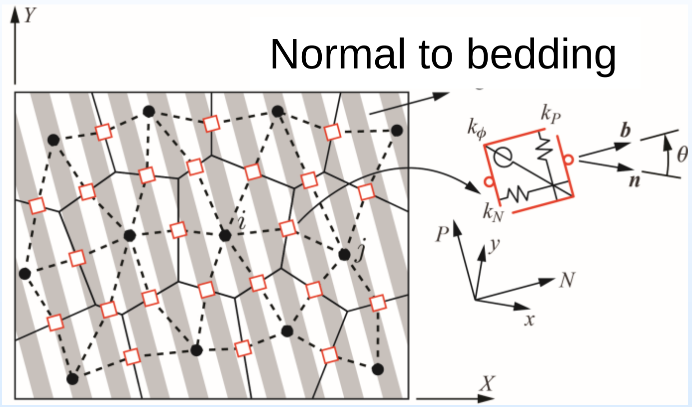
TOUGH-RBSN code initial validation

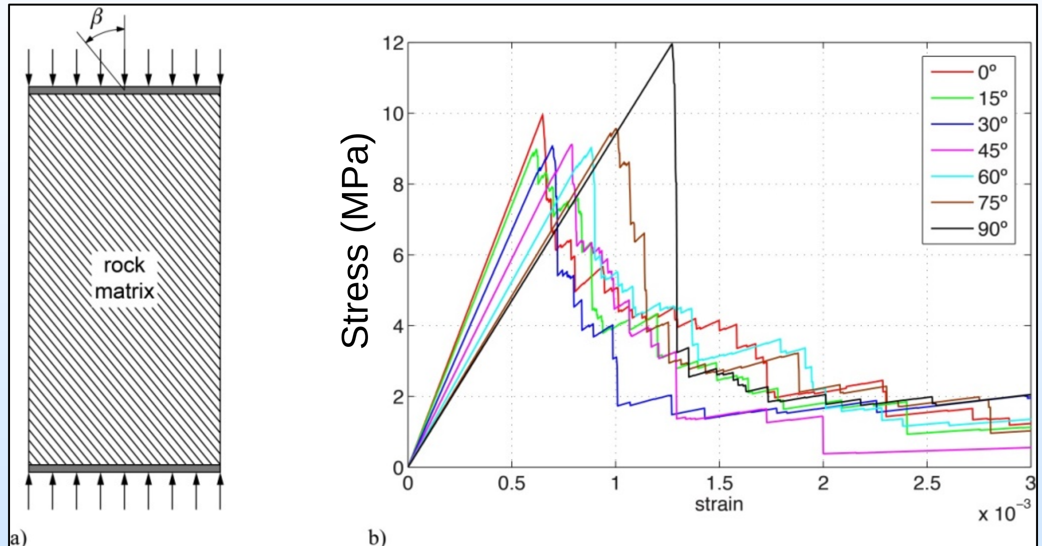


Basic code performance validation was done using known analytical 2D hydraulic fracturing solutions (Khristianovic-Geertsma-de Klerk (KGD) model)

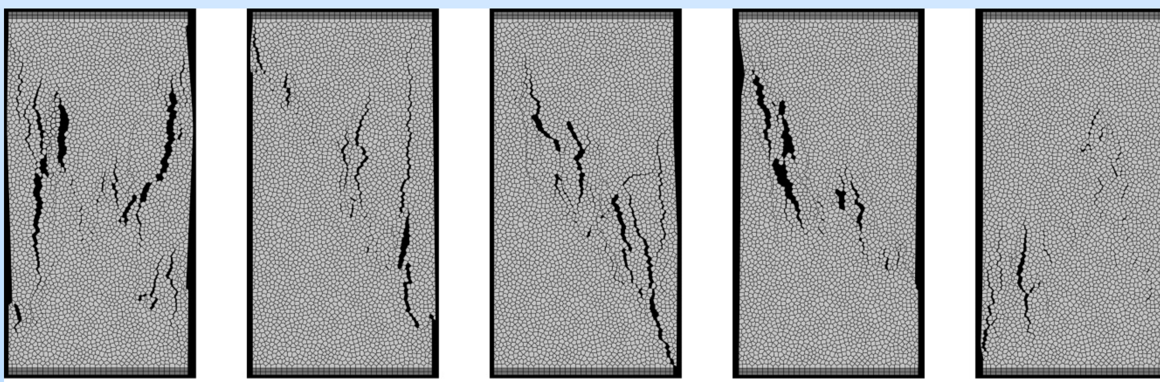
Technical Status

RBSN code development specifically for shale hydraulic fracturing





Local stiffness and strength matrix rotation → anisotropic behavior



a) β=0° b) β=30° c) β=45° d) β=60° e) β=90°

A demonstration of anisotropic rock failure via 2D uniaxial compression simulations