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

ESD14084

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Presentation Outline

1. Benefit to Program
2. Project Overview
3. Technical Status
   1. Project Framework
   2. Laboratory Visualization Experiments
   3. TOUGH-RBSN Numerical Modeling
4. Accomplishments to Date
5. Synergy Opportunities
6. Summary
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 behavior
- Development of predictive numerical simulation capability
- Simulation results validated by lab and available field data
## Benefit to SubTER

### Mastering the Subsurface
Adaptive Control of Subsurface Fractures and Flow

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

**Fit For Purpose Simulation Capabilities**
Technical Status

Project Framework

Laboratory Experiment

- Visualization experiment setup development
- Sample preparation
- Preliminary tests
- Parametric studies
  1. Fracture network geometry effect
  2. Injection parameter (viscosity, rate) effect

Numerical Modeling

- Coupled mechanical-hydrological simulator development
- Simulation model preparation
- Preliminary tests (predictive test for lab)
- Interpretative tests (for lab data)
- Interpretative tests (for field data) Upscaling

Model setup
Feedback
Result
Final synthesis
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

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

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

Stress limit <1,500 psi (10MPa) for 4” (10cm) cubes.
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 $\Delta T$ 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)

UV-illuminated

Absorption  Emission

Pre-existing fracture model

TOP  SIDE
Technical Status

Further enhancement...

Laser sheet can “cut” the sample, allowing more clear visualization of fracture interactions.

- Green laser sheet
- Scattered light
- Laser-induced fluorescence
- Hydraulic fracture containing glycerol+fluorescent dye

H=0.25”
H=0.5”

Activated fractures
Reflections
Activated fractures

Branching and activation of existing fractures
Matrix fracturing

Color filter
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
  - Flow channels/branches
  - Plane fracture
  - Flow channels/branches
Fast injection produced different fluid/pressure distribution within propagating hydraulic fractures
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
RBSN code development specifically for shale hydraulic fracturing

Local stiffness and strength matrix rotation $\rightarrow$ anisotropic behavior

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

Variation of bulk elastic modulus
TOUGH-RBSN Modeling of Laboratory Hydraulic Fracturing Experiments

- 2D lab fractures
- Digitization
- Voronoi tessellation
- 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.
- Borehole damage has a large impact on the breakdown pressure and the rate/stability of post-breakdown fracture growth.

**TOUGH-RBSN Modeling**

- Undamaged borehole wall
- With an initial notch

**Laboratory Experiment**

- Undamaged
- Increasing initial flaw size

*2cP fluid
Technical Status

- 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?

*Material properties specified based upon glycerol-based characterization tests
Technical Status

Application to Larger-Scale Experiment

Mont Terri Underground Rock Laboratory

Mont Terri

Security Gallery

Opalinus Clay

2011
2009
2004
2003
1998
1996
Technical Status

Application to Larger-Scale Experiment

Mont Terri URL Experiment (Opalinus Shale/Clay)

- Suspected fracture stepping

TOUGH-RBSN Modeling

- Bedding texture
- Preexisting fracture/fault
- Hydraulic Fracture
- Injection point

1. Initially HF follows the bedding plane
2. HF deviates, affected by a preexisting fracture
3. HF turns back along the bedding plane

Injection point

$0.7 \text{ m}$
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).

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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

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<tbody>
<tr>
<td></td>
<td>Q1</td>
<td>Q2</td>
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<tr>
<td><strong>Task 1: Management and Planning</strong></td>
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<td><strong>Task 2: Laboratory experiments</strong></td>
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<tr>
<td>Subtask 2.1: Preparation of true triaxial test setups</td>
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<td>Subtask 2.2: Preparation of rock samples containing complex heterogeneities</td>
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<td>Subtask 2.3: Preliminary hydraulic fracturing experiment</td>
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<td>Subtask 2.4: Hydraulic fracturing visualization I: Stress and texture anisotropy effect</td>
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<td>Subtask 2.5: Hydraulic fracturing visualization II: Fluid viscosity/injection rate effect</td>
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<td><strong>Task 3: Numerical modeling</strong></td>
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<td>Subtask 3.1: Code modification and verification of TOUGH-RBSN hydraulic fracturing algorithms</td>
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<td>Subtask 3.2: Numerical model setup and preliminary simulation of complex hydraulic fracturing</td>
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<td>Subtask 3.3: Model prediction of laboratory hydraulic fracturing experiments</td>
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<td>Subtask 3.4: Interpretative numerical modeling of laboratory experiments</td>
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<td>Subtask 3.5: Simulation of Mont Terri hydraulic fracturing experiment</td>
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<td><strong>Task 4.0: Final Synthesis of Experimental and Numerical Modeling Results</strong></td>
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M1-M9: Milestones (Completed at this point)
### Publications and presentations generated from the project


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