Closing the Loop between In Situ Stress Complexity and EGS Fracture Complexity
2-2446-LLNL

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University of Pittsburgh

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Objectives and Purpose

Main objective: Combine high-fidelity simulations and true-triaxial block fracturing experiments to explore the connect between in situ stress and hydraulic fracture patterns

- **Experiment:** study influences of in situ stress, temperature, and wellbore orientation on resulting hydraulic fracture complexities
- **Simulation:** numerically study hydraulic fractures across different scales and purposes; compare with experimental and field observations to infer the in situ stress condition

Major impacts on geothermal development

- Improve the in situ stress characterization at Utah FORGE
- Offer a validated toolset in GEOS for future uses
- Demonstrate the use of a suite of hydraulic fracturing simulation tools for EGS
- Provide laboratory hydraulic fracturing experiments to identify key components of in situ stress and to assess current technologies for stress estimation

Project Overview

Task 1

Perform numerical simulations of DFITs/minifrac tests and use simulation results to interpret the observed DFIT responses

Task 2

Employ a phase-field model to capture nucleation and propagation of hydraulic fractures in the near-well region

Task 3

Conduct geomechanical simulation of far-field hydraulic fractures to characterize the far-field stress profile and rock fabrics

Task 4

Perform true-triaxial block fracturing experiments at Utah FORGE conditions

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Task 1: Methods/Approach

LLNL GEOS
Hydraulic Fracturing Module

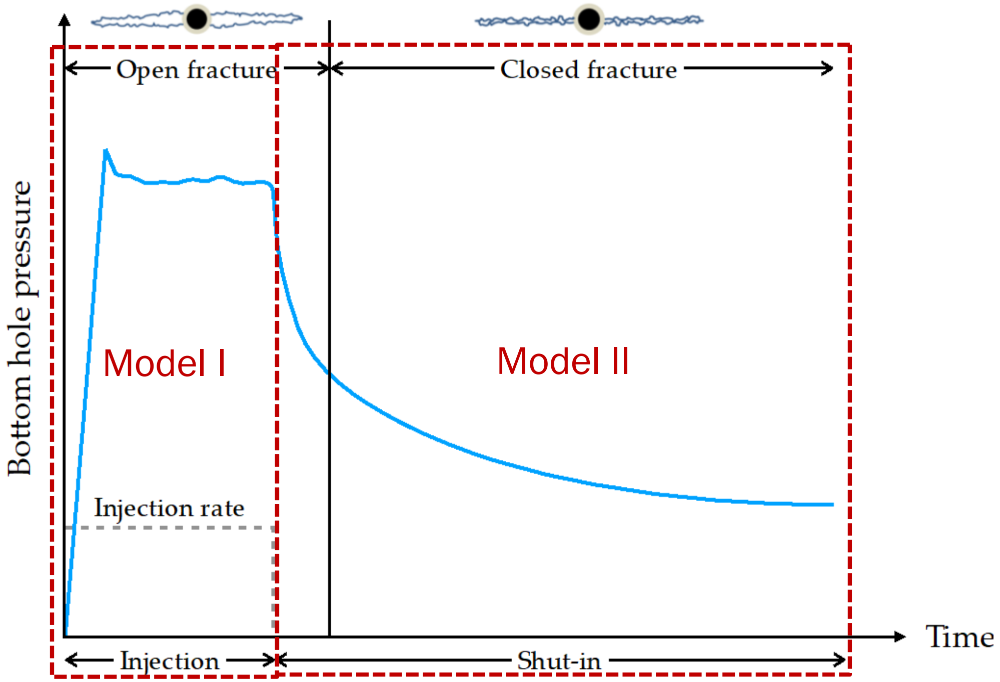
Model I: Injection stage

- Allow fracture propagation
- Planar fracture surface
- $\Delta\omega_h = \Delta\omega_m$

Modeled fracture & pressure

Model II: Shut-in stage

- No fracture propagation
- Permeable matrix to enable leakoff
- $\omega_h = f(\sigma_N)$ a nonlinear aperture model



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Task 1: Technical Accomplishments and Progress

- With S_{hmin} = 3178 psi inferred field data (Battelle's report)

Constant permeability

Pressure-dependent permeability

Simulation results infer possible pressure-dependent permeability → leakoff into natural fractures

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Task 1: Technical Accomplishments and Progress

- With S_{hmin} = 2989 psi → fracture remains open at the end

Pressure comparison

G-function comparison

Pressure curve & *G*-function derivatives well matched **but fracture remains open** → likely overestimated S_{hmin} based on field data

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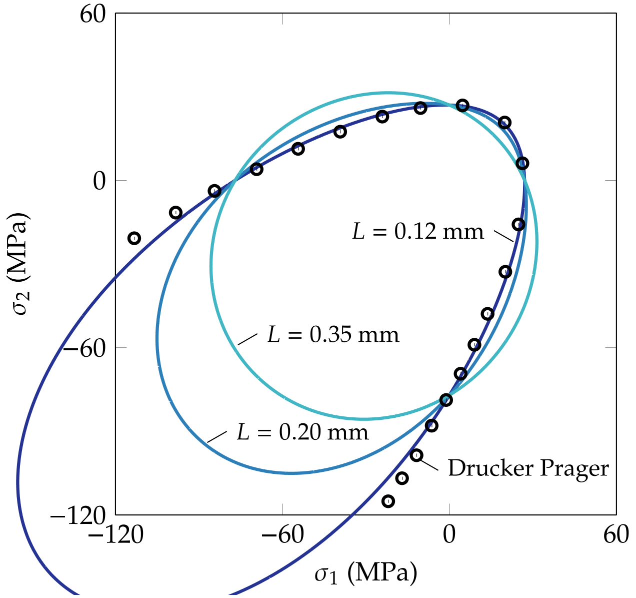
Task 2: Methods/Approach

- A novel formulation that specializes in modeling nucleation & propagation of hydraulic fractures

$$\underbrace{-2(1-d)W^e(\boldsymbol{\varepsilon})}_{\text{Release of stored energy}} - \underbrace{m'(d)bp\nabla\cdot\boldsymbol{u}}_{\text{Work done by pore pressure}} + \underbrace{m'(d)\nabla\cdot(p\boldsymbol{u})}_{\text{Work done by fracture flow}} + \underbrace{\frac{3\mathcal{G}_c}{8L}[1-2L^2\nabla^2 d]}_{\text{Fracture dissipation}} + c_e = 0.$$

- Incorporates the strength envelope of rocks as fracture nucleation criterion through c_e



Converge to the Drucker Prager yield surface as the phase-field regularization length decreases

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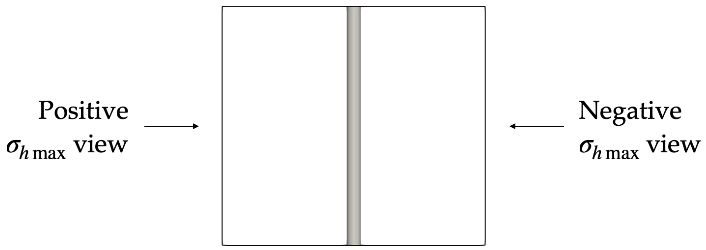
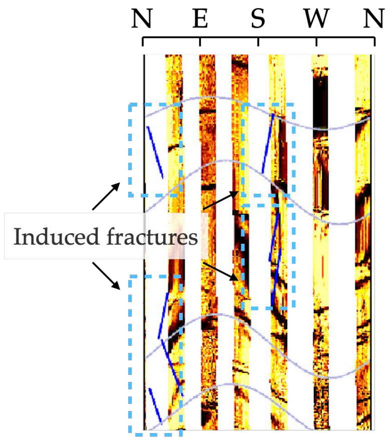
Task 2: Technical Accomplishments and Progress

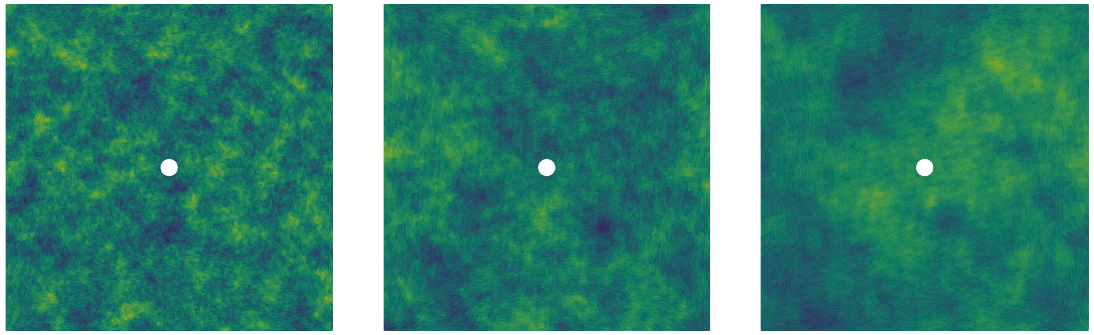
✓ **M2.3.1** Baseline phase-field model for near-well fracture/damage patterns

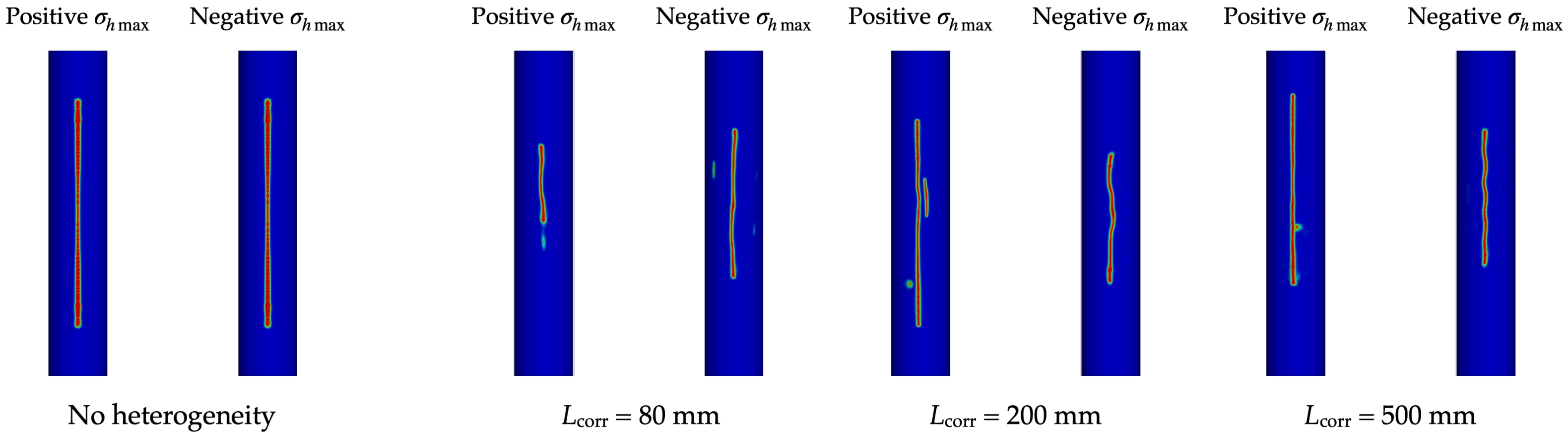
- Simulations of 16(B)78-32 minifrac test with rock heterogeneity





Post-test image log





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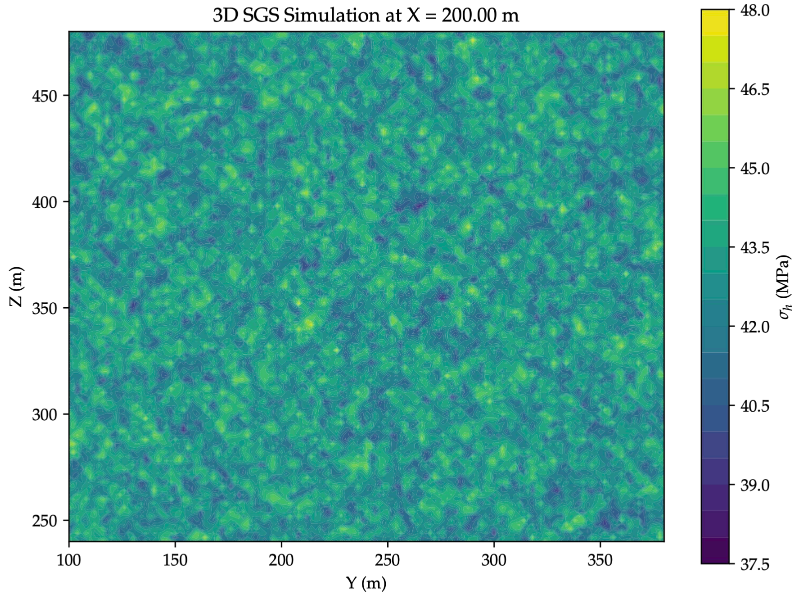
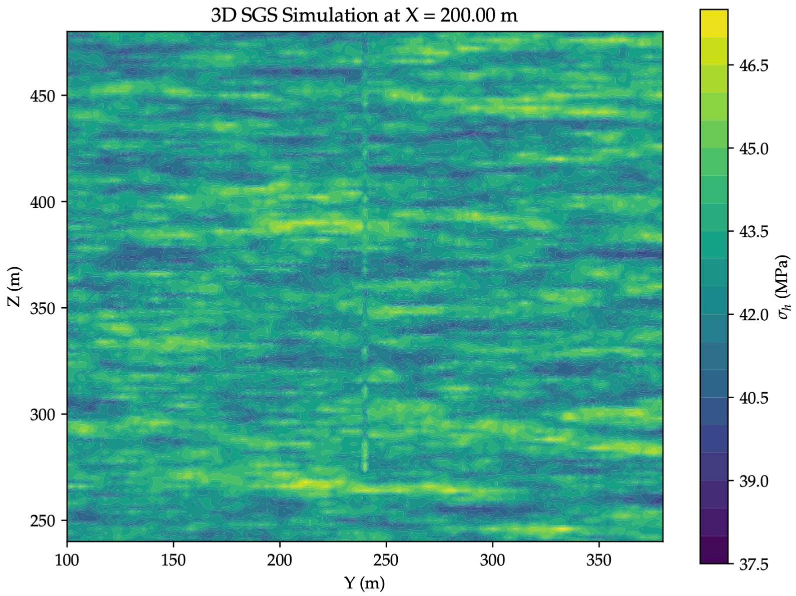
Task 3: Methods/Approach

Hydraulic fracturing module in GEOS

- Loosely coupled poromechanics
- Virtual crack closure technique (VCCT) and linear elastic fracture mechanics (LEFM) for fracture growth
- Apparent anisotropic fracture toughness to describe stress roughness (presented in *Go/No-Go 2*)
- Heterogeneous stress profile (isotropic v.s. anisotropic)



Isotropic realization ($L_{\mathrm{corr},x} = L_{\mathrm{corr},y} = L_{\mathrm{corr},z}$)



Anisotropic realization ($L_{\mathrm{corr},x} = L_{\mathrm{corr},y} = 10L_{\mathrm{corr},z}$)

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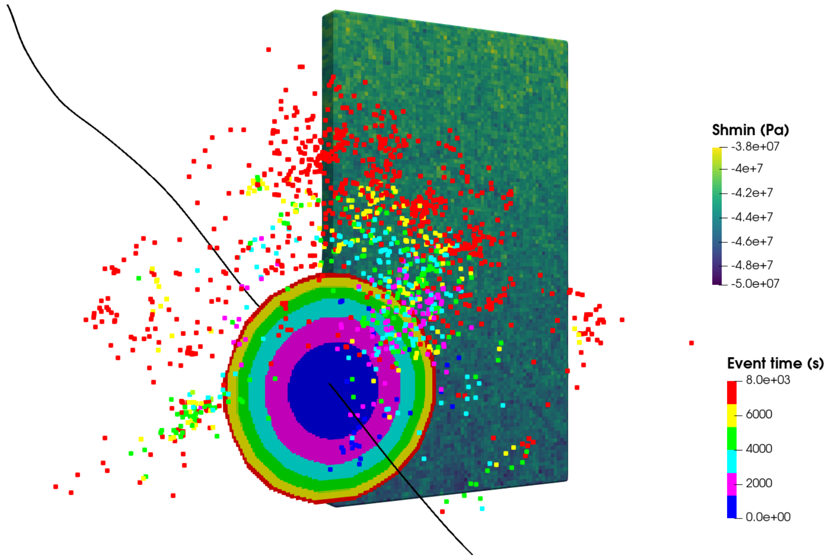
Task 4: Technical Accomplishments and Progress

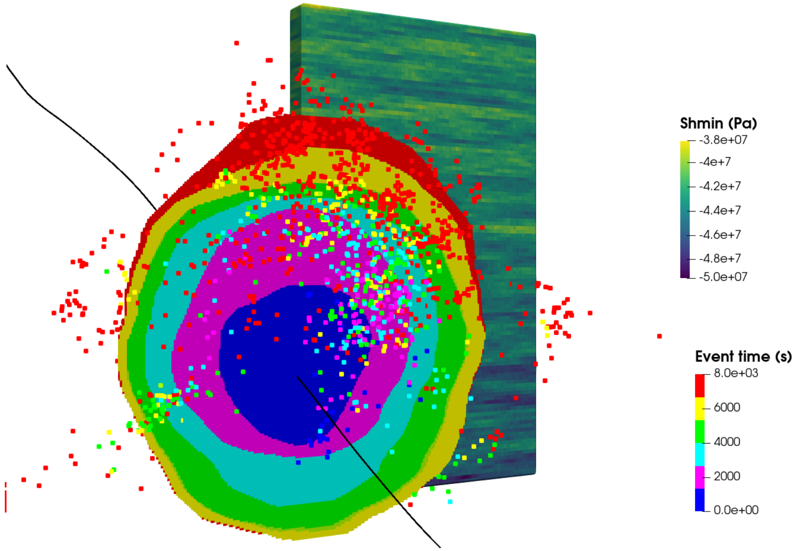
✓ **M3.3.1** Baseline GEOS model to predict far-field fracture trajectories

- Simulations of Stage 3 with stress heterogeneity

Isotropic



Anisotropic



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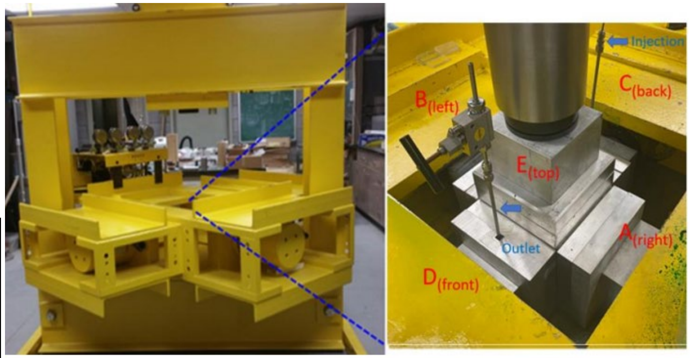
Task 4: Technical Accomplishments and Progress

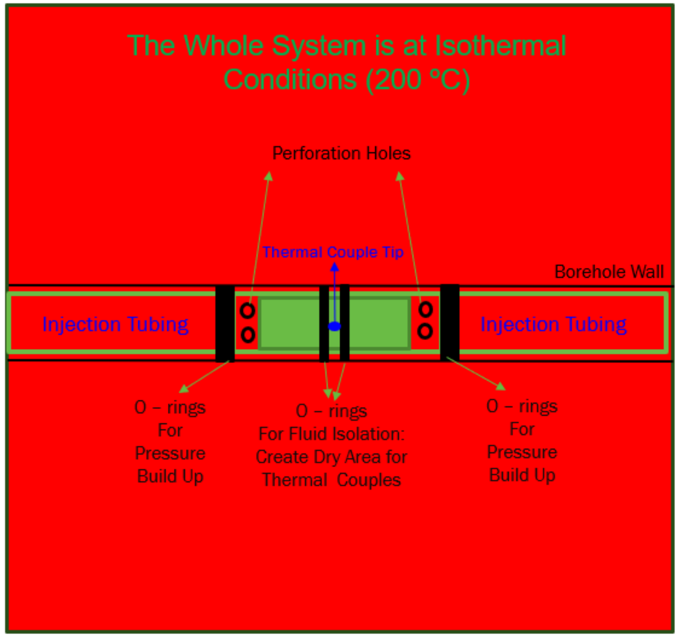
Total 21 Experiments Covering **Eight Combinations of Testing Conditions**

Testing Case	Breakdown Pressure (Mpa)	Closure Pressure (MPa) -G function-Compliance Method	Closure Pressure (MPa) -G function-Holistic	Reopening Pressure (MPa)-Reopen	Reopening Pressure (MPa) - Step Rate	Applied Vertical Stress	Applied Horizontal Maxumum Stress	Applied Horizontal Minimum Stress	Thermal Sterss Effect	Notch
VR-NTS-1	18	--		--	--	17.5	15	10	N	N
VH-NTS-1	23.2	14	7	14.2	7.8	17.5	15	10	N	N
VH-NTS-2	21.8	11	8	13.8	11.5	17.5	15	10	N	N
VH-NTS-3	22.4	13.5	11	22.5	15.8	17.5	15	10	N	N
VH-ITS-1	20.6	12	8	13.5	10	17.5	15	10	Y	N
VH-ITS-2	17.7	13	8	10	10.5	17.5	15	10	Y	N
IH-ITS-1	15.7	11.5	6.2	11	11	17.5	15	11.8	Y	N
IH-ITS-2	8.7	7	4	8.5	8.5	17.5	15	11.8	Y	N
HH-ITS-1	23.1	15	14	18	15.5	17.5	15	10	Y	N
HH-ITS-2	21.4	7.5	5.5	10	10	17.5	15	3	Y	N
HH-ITS-3	11	6	4	5	5	17.5	15	3	Y	N
HH-ITS-4	15	10	7	9	9	17.5	15	7	Y	N
HH-ITS-5	22.9	4	3	6	--	17.5	15	7	Y	N
HR-NTS-1	37.5	11	6.5	12	11	17.5	15	3	N	N
HR-NTS-2	42.5	11	7.8	14	13	17.5	15	3	N	N
HR-NTS-3	20.4	7.5	4.8	7	7	17.5	15	7	N	N
HR-NTS-4	23.2	12	9	12	11	17.5	15	7	N	N
HR-NTS-1-notch	37.8	13	9	20	13	17.5	15	7	N	2 mm
HR-NTS-2-notch	34.8	13	9	16	--	17.5	15	7	N	4 mm
HR-NTS-3-notch-shorten-injection	44.31	17.5	13.5	--	--	17.5	15	7	N	4 mm
HR-NTS-4-notch-shorten-injection	40.3	6	9	11	9	17.5	15	0.6	N	4 mm

1) Vertical well-Room temperature sample-Non-Thermal Stress (VR-NTS)
2) Vertical well-High temperature sample-Non-Thermal Stress (VH-NTS)
3) Vertical well-High temperature sample-Induced Thermal Stress (VH-ITS)
4) Inclined well-High temperature sample-Induced Thermal Stress (IH-ITS)
5) Horizontal well-High temperature sample-Induced Thermal Stress (HH-ITS)
6) Horizontal well-Room temperature sample-Non-Thermal Stress (HR-NTS)
7) Horizontal well-Room temperature sample-Non-Thermal Stress-Notched (HR-NTS-N)
8) Horizontal well-Room temperature sample-Non-Thermal Stress-Notched- Reduced Pressurization Interval (HR-NTS-N-RPI)



True-triaxial block fracturing tests in 200 Ton Poly-axial Load Frame



Details of Injection System

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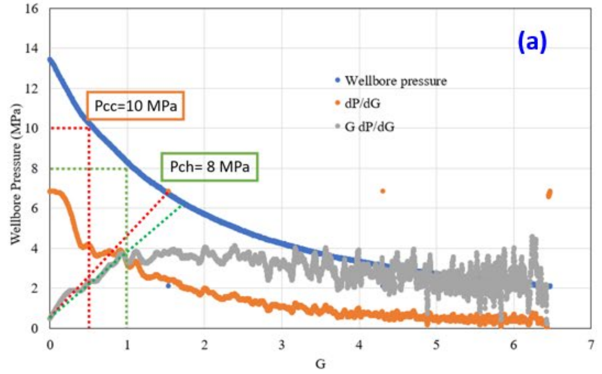
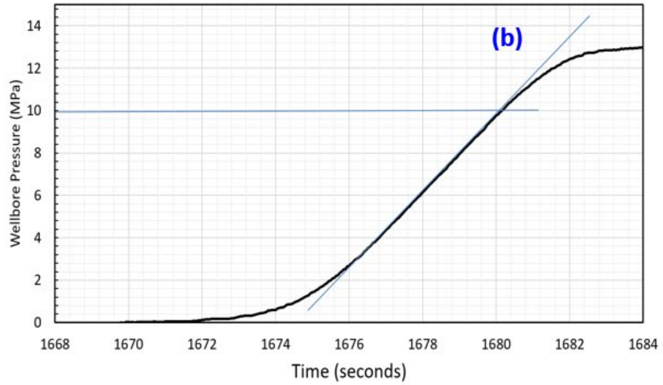
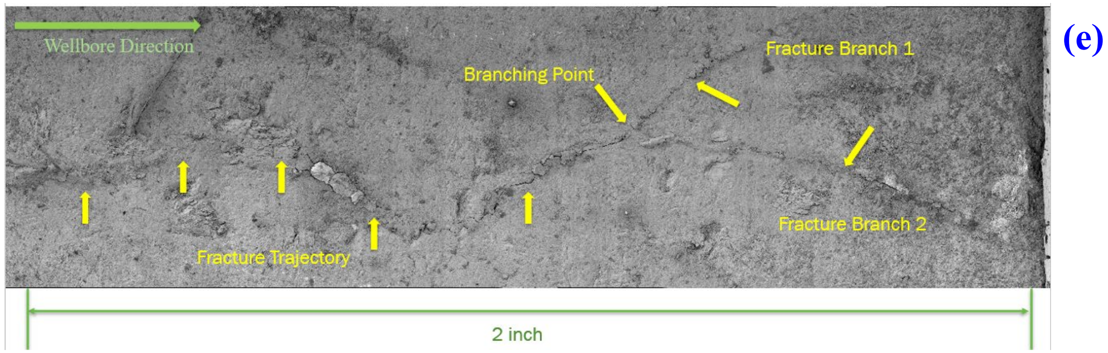
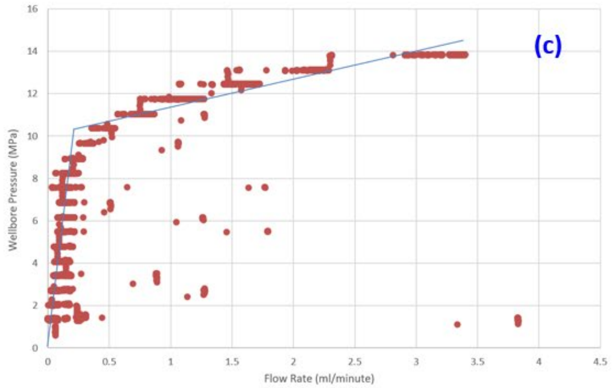
Task 4: Technical Accomplishments and Progress

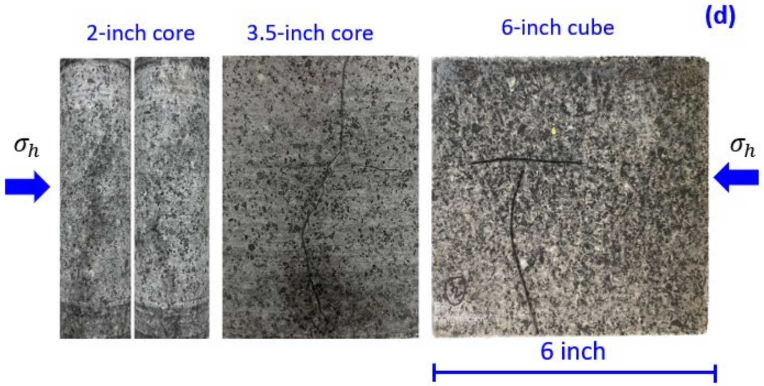
For each experiment, by extending the experimental protocol through the post-peak hydraulic fracturing processes, the tests obtained **laboratory-derived G-functions** with analysis from both **holistic** and **compliance** methods, **step-rate** results, and **fracture reopening** measurements.











(a) G-function plot displaying fracture closure pressure obtained using the fracture compliance method (orange) and the holistic method (green);

(b) zoom-in view and detailed pressure records during the fracture reopening test;

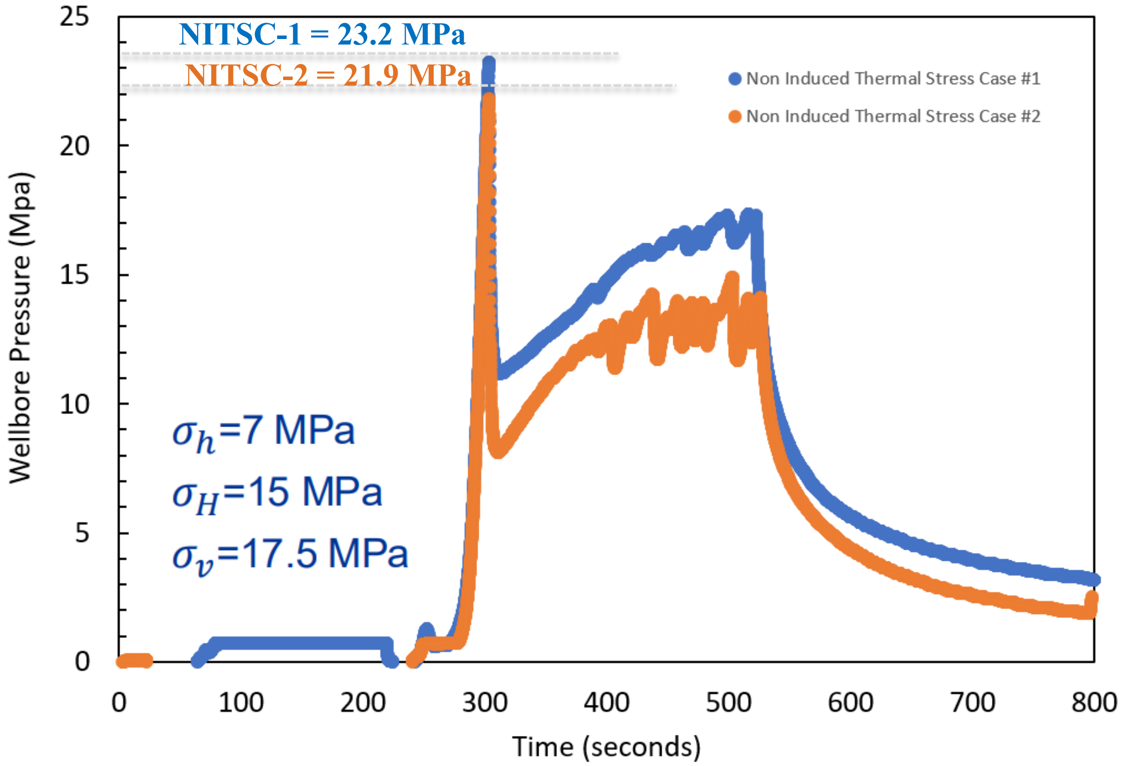
(c) pressure and flow rate records during the step rate pressure test;

(d) fracture identifications and observations from the 2-inch core surface, 3.5-inch core surface, and 6-inch cubic surface (from left to right)

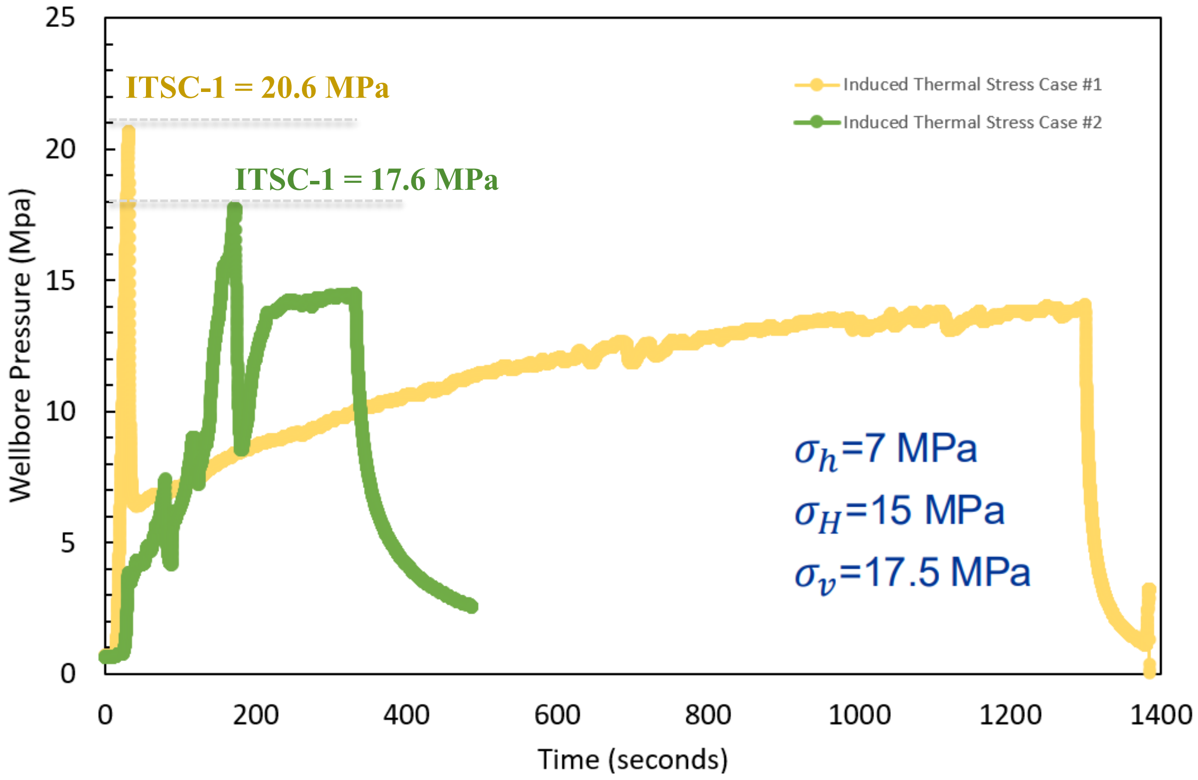
(e) Wellbore fractures under SEM

Task 4: Key Observations (1/3)

Non Induced Thermal Stress Group



Induced Thermal Stress Group



Under the same conditions, thermal stress can reduce the wellbore breakdown pressure from 10% to 30%

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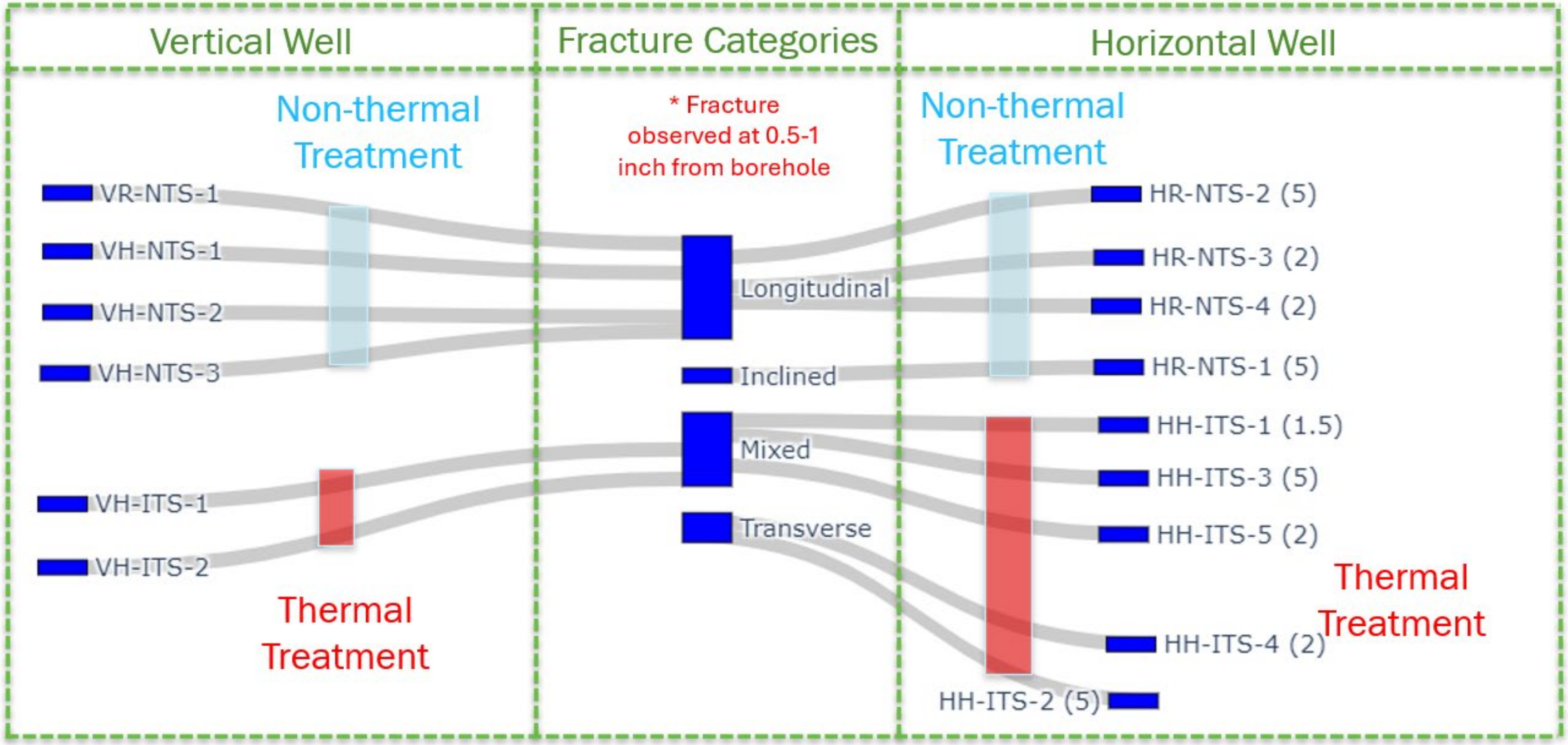
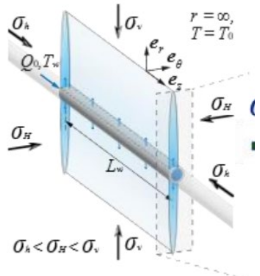
Task 4: Key Observations (2/3)

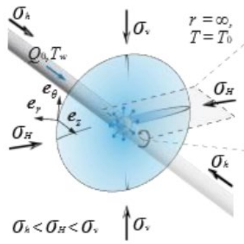
Effects of Wellbore Direction and Thermal Treatment on Observed Fracture Categories from Unnotched Case

* The number in parentheses following the horizontal well notation represents the ratio of maximum in-situ stress to minimum in-situ stress.





Longitudinal Fracture



Transverse Fracture

Mixed: Transverse and Longitudinal exist at the same time

Inclined: Fracture angles with wellbore drilling direction range from 10 to 45 degrees.

Controlling time and temperature to promote transverse initiation and reduce near-wellbore tortuosity

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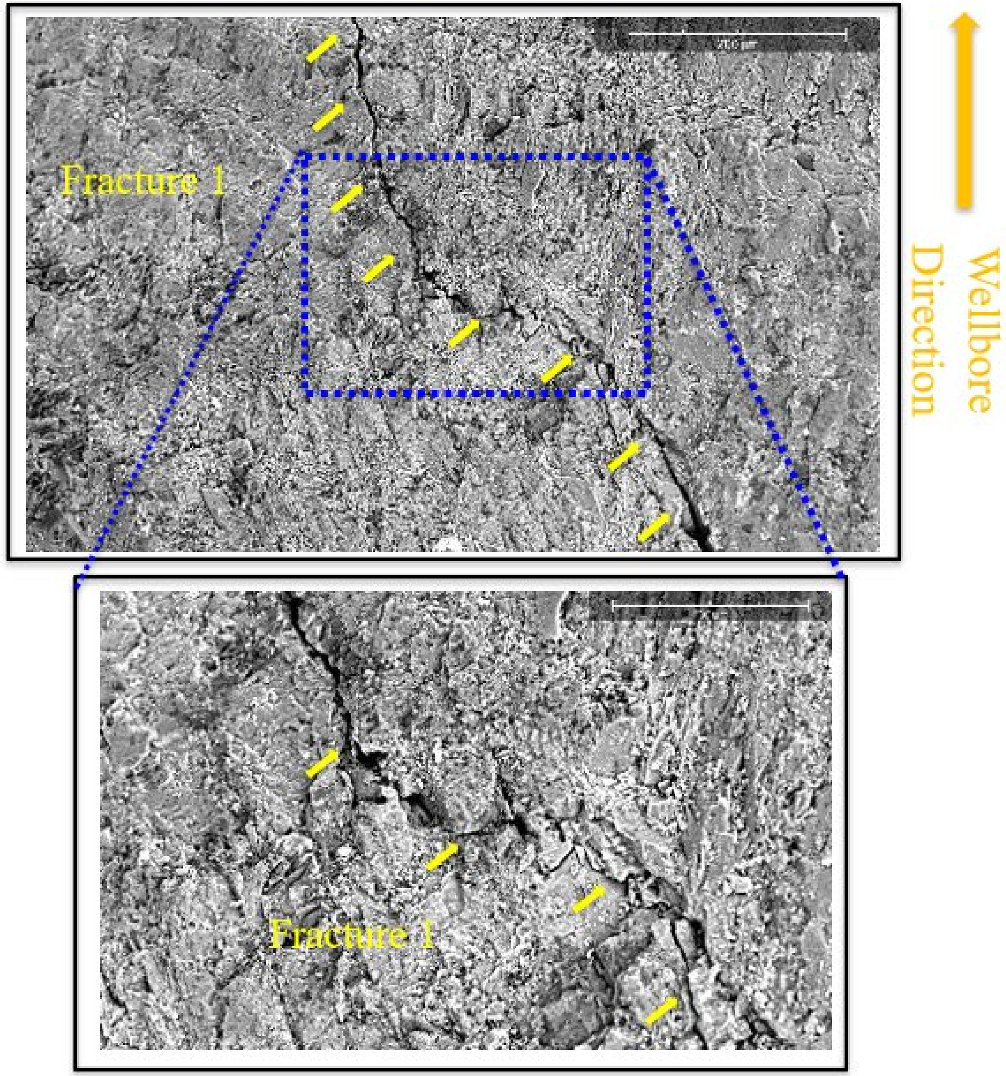
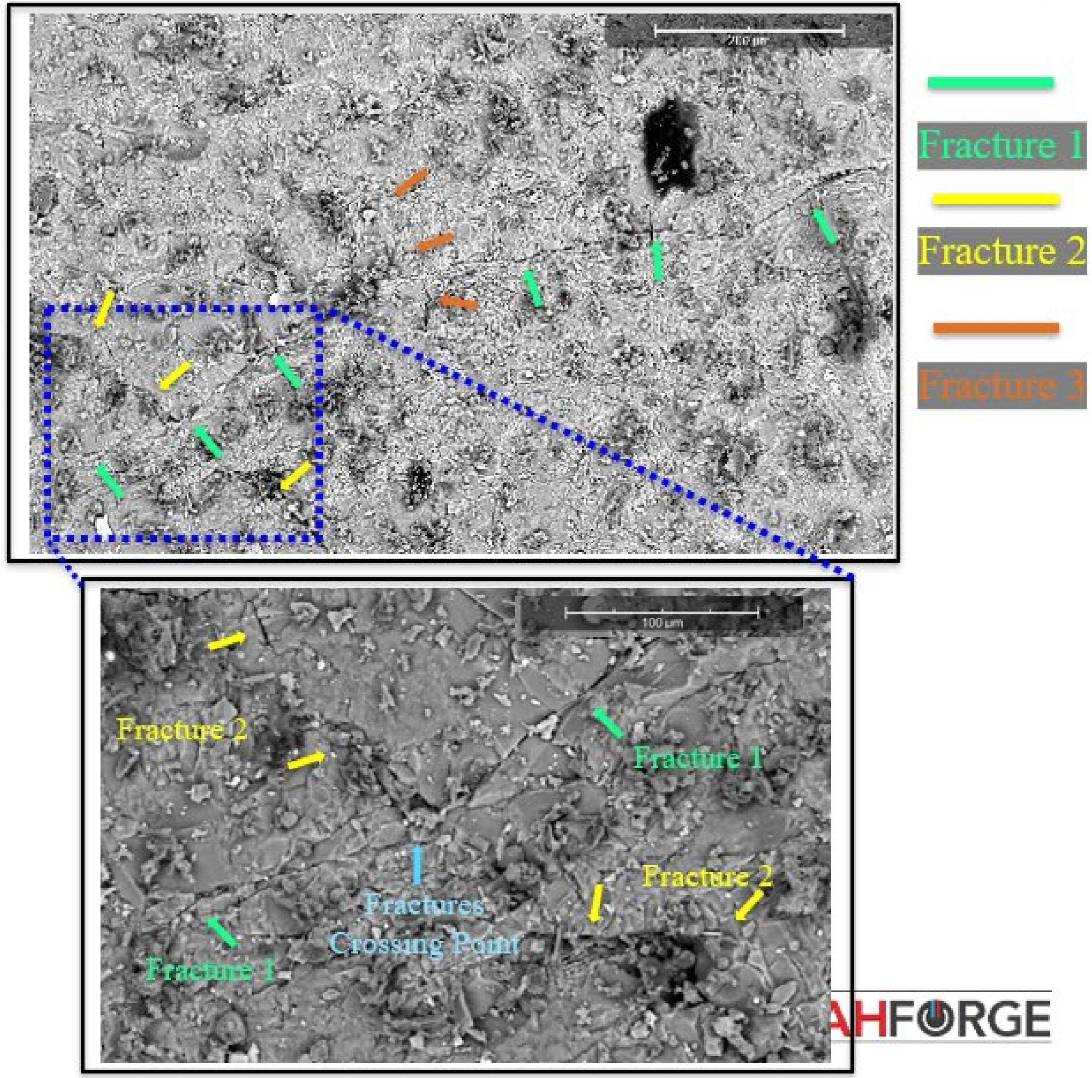
Controlling time and temperature to promote transverse initiation and reduce near-wellbore tortuosity – SEM Observations

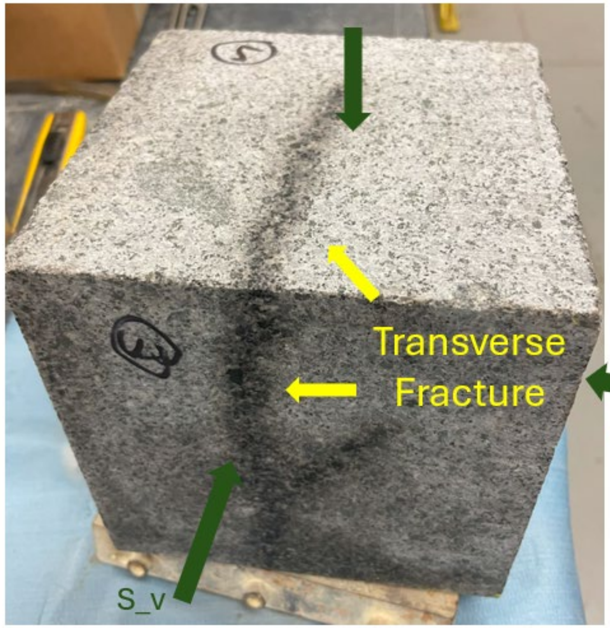
SEM Images of Hydraulic Fractures (No Thermal Effects – Single Fracture)



SEM Images of Hydraulic Fractures (With Thermal Effects – Conjugate Fractures)



Task 4: Key Observations (3/3)

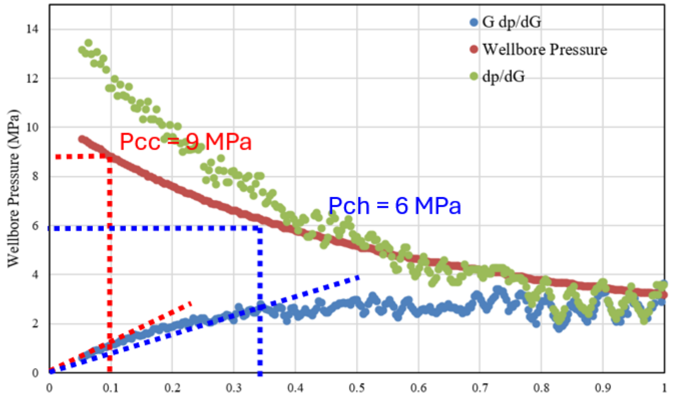


$\sigma_v = 17.5\ MPa$

$\sigma_H = 15\ MPa$

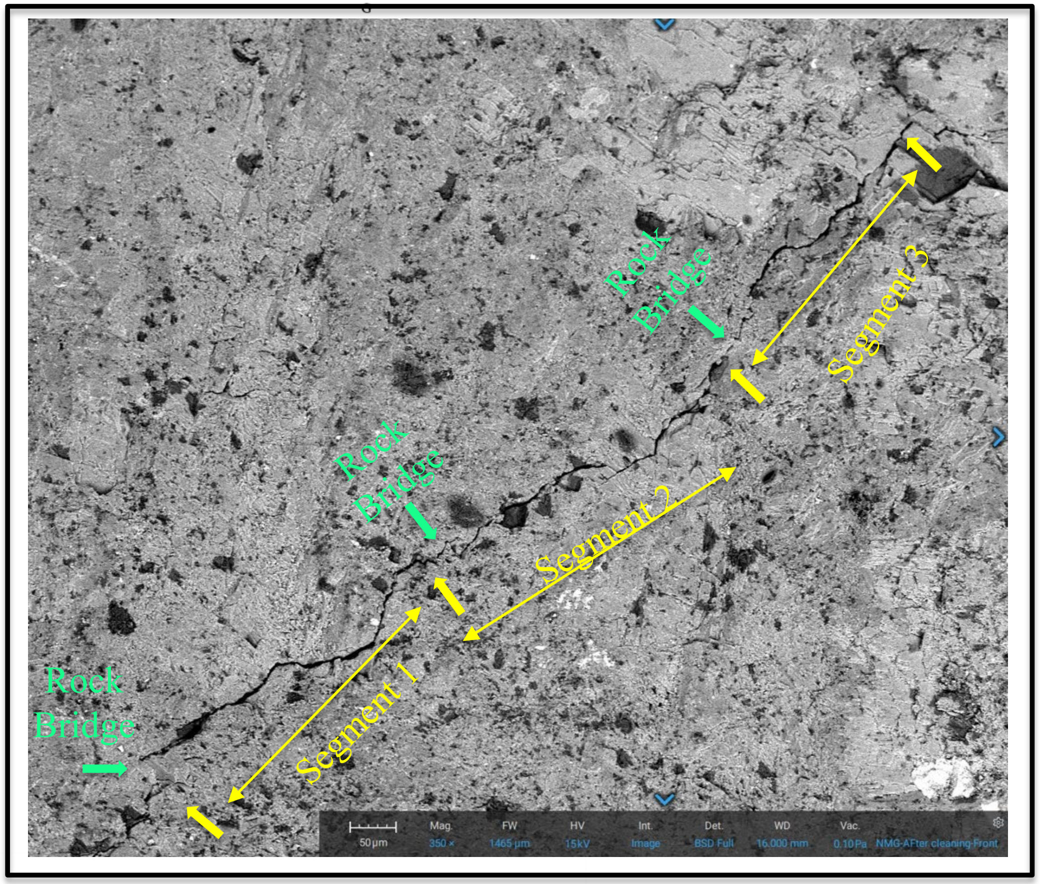
$\sigma_h = 0.6\ MPa$

2 inch over-core



G-function from shut-in pressure data based on compliance and holistic method

Neither method yields accurate estimation of horizontal minimum stress



The Segmentation and Rock Ridges Effects: the mineral grains still hold strong between fractures are created could influence fracture reopening, closure, and stress estimation

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Technological Advancement and Data Dissemination

- A complete numerical toolset for hydraulic fracturing simulations in an open-source framework available for future EGS applications
- Numerical capabilities demonstrated for hydraulic fractures with various scales and purposes at FORGE conditions, including DFITs/minifrac tests, near-well hydraulic fractures, and far-field hydraulic fractures.
- Comprehensive dataset for hydraulic fracturing experiments including fracture patterns, recorded pressure curves, and SEM images

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Summary

Task 1

- Pressure-dependent fluid leakoff behavior → potential influence from natural fractures
- Possibility that fracture remains open at the end of test → S_{hmin} may be overestimated

Task 2

- Simulation of laboratory tests for validation and form an integrated dataset
- Simulation of field injection tests to predict complex near-well fracture patterns

Task 3

- Simulation of Stage 3 hydraulic fracturing with stress heterogeneity
- Results indicate potential anisotropy of the in situ stress profile in the field

Task 4

- Effects of thermal stress on breakdown pressure & fracture patterns observed
- Effects of micro-cracks & rock bridges observed
- Limitation of existing stress estimate methods

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Future Work

Modeling:

- Continue DFIT modeling of MF2 Cycle 1 test on the 16(B)78-32 well by adding thermal effects
- If time allows, apply the far-field hydraulic fracture model to more recent stimulations on 16(A) or 16(B)
- Prepare data submission and publications

Experiment (if time and budget allow):

- Revisit *G*-function theory and incorporate fracture segmentation effects
- Use high-temp acoustic emission sensors to capture damage during pre-circulation cooling
- Study how thermal stresses and thermally induced micro-cracks affect fracture patterns

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