Role of anisotropy during hydraulic fracturing true triaxial experiments in shales

Prof. Giovanni Grasselli & Dr. Aly Abdelaziz

- University of Toronto -

ARMA Symposium 2025 - Large Block Hydraulic Fracturing in the Laboratory

with contributions by J. Ha, F. Nasseri, M. Li, E. Magsipoc and P. Wu

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- BSc. in Civil-Structural Engineering at Benha University, Cairo - Egypt (2007).
- About 10 years professional experience in Geotechnical Engineering (Laboratory and In-situ Testing/Instrumentation) in the United Arab Emirates.
- Joined Prof. Giovanni Grasselli Group at the University of Toronto in 2015 and earned my PhD. in 2023.
- About 12 peer-reviewed journal articles and 13 conference publications.
- Currently a Senior Completions Design and Geomechanics Engineer at Petronas Canada.

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Professional and Academic Career

Outline

- Introduction
- Characterizing Anisotropy
- True Triaxial Sample Preparation and Test Procedure
- Results
- Findings
- Conclusions and Limitations

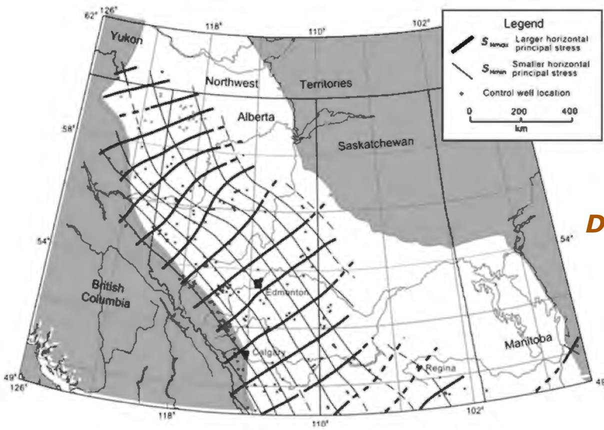
Image Source: Suarez-Rivera, R., et al. "Optimizing lateral landing depth for improved well production: Presented at the Unconventional Resources Technology Conference." *URTeC–2460515* (2016).

Unconventional Reservoir - Bedding Planes

The Montney Formation is the largest unconventional hydrocarbon play in Canada.

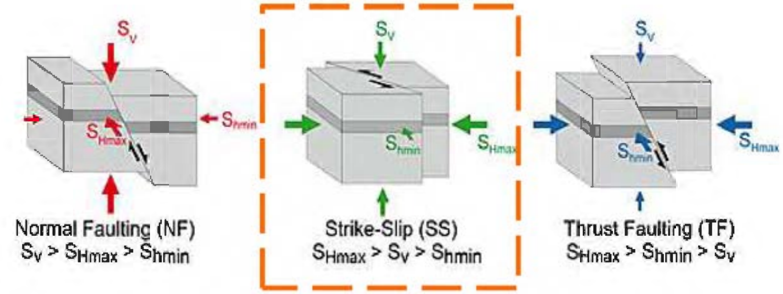
To date, there has been no studies on the hydromechanical characterization under true triaxial conditions for the Montney shale. In fact, these are non-existent for deep reservoirs.

There is very limited publicly available data for the mechanical properties of shale samples at depth. This is true for almost any fragile and water sensitive rock at depth.



Extent of Montney Development

Stress Regimes

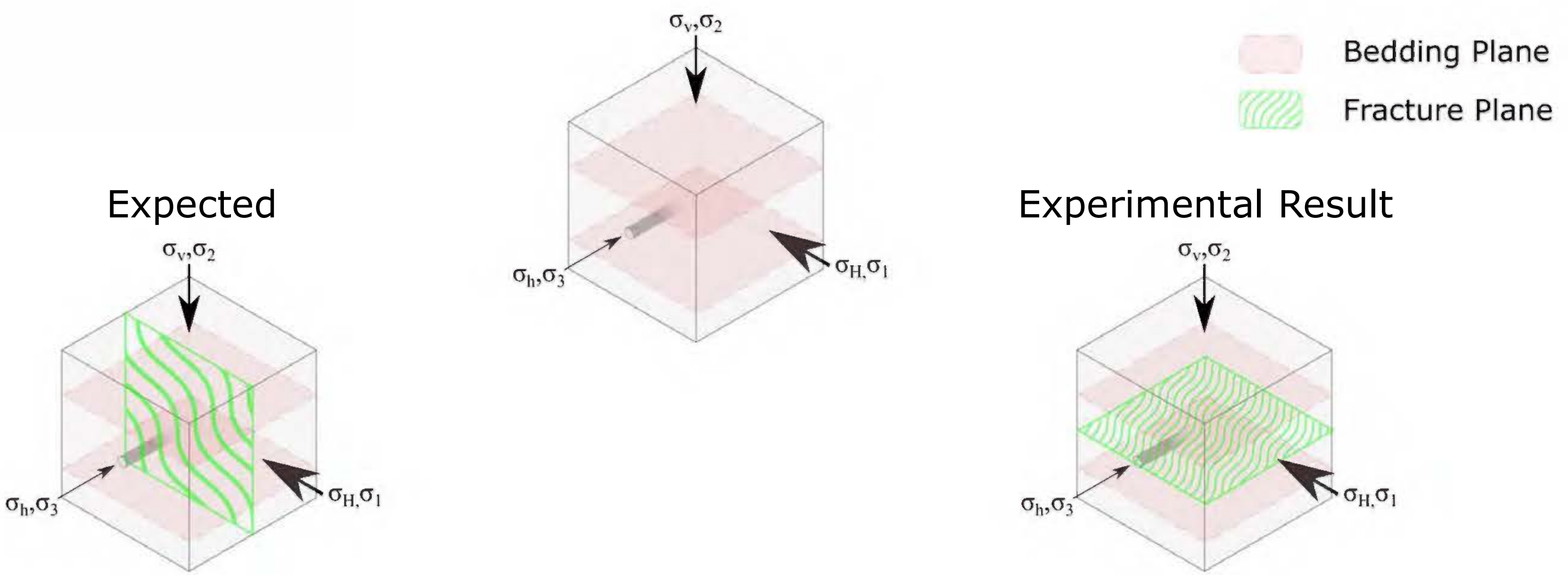


Source: http://www.world-stress-map.org/data/

Montney Formation

Given a strike-slip stress regime, with a horizontal wellbore. The expected failure is against the least principal stress (σ_3).

Additionally, the fracture reopening pressure and the shut-in pressure are close to σ_3.



And can the shut-in pressure tell us more than just the magnitude of the principal stress.

Motivation and Obstacles

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Outcrop

At depth

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Montney Samples

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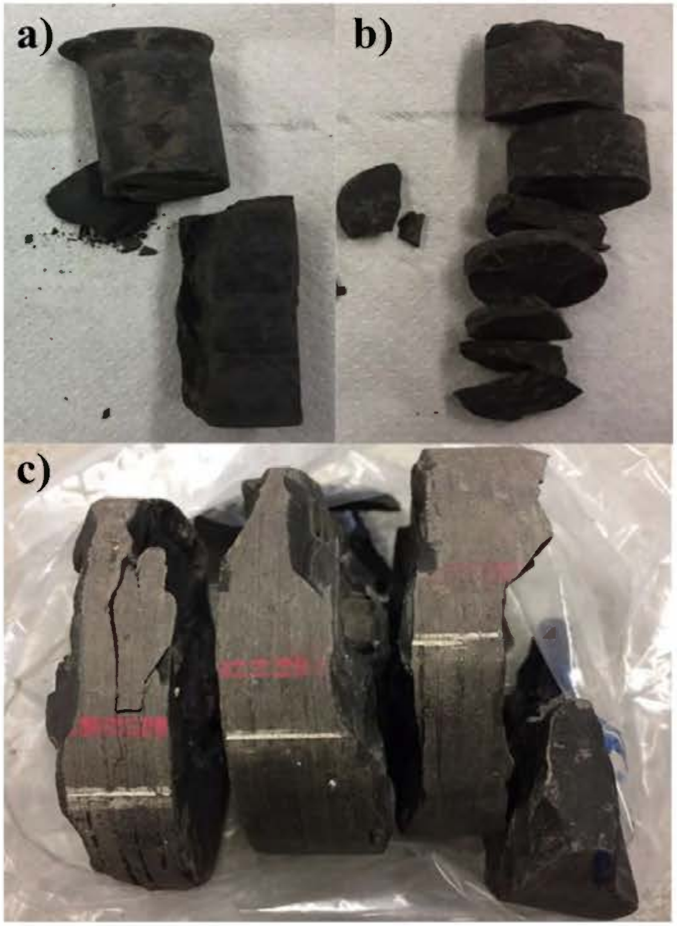
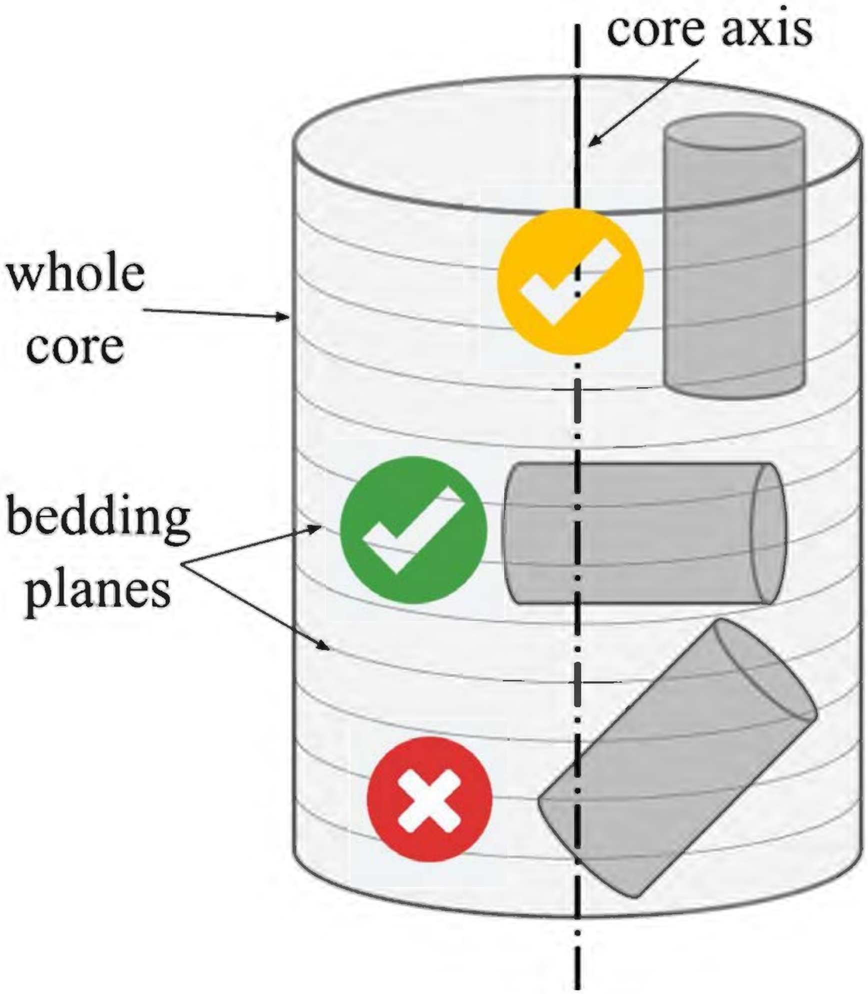
Outline

Because of the unexpected results, we are now met with additional obstacles:

1. Limited laboratory testing due to difficulties arising from sampling procedures.
2. Absence of laboratory testing results that assess anisotropy.
3. Variability of the results for similar samples across testing laboratories and testing machines.



Additional Obstacles



Perpendicular to bedding
Limited Success Rate

Parallel to bedding
High Success Rate

Angle to bedding
Rare Success

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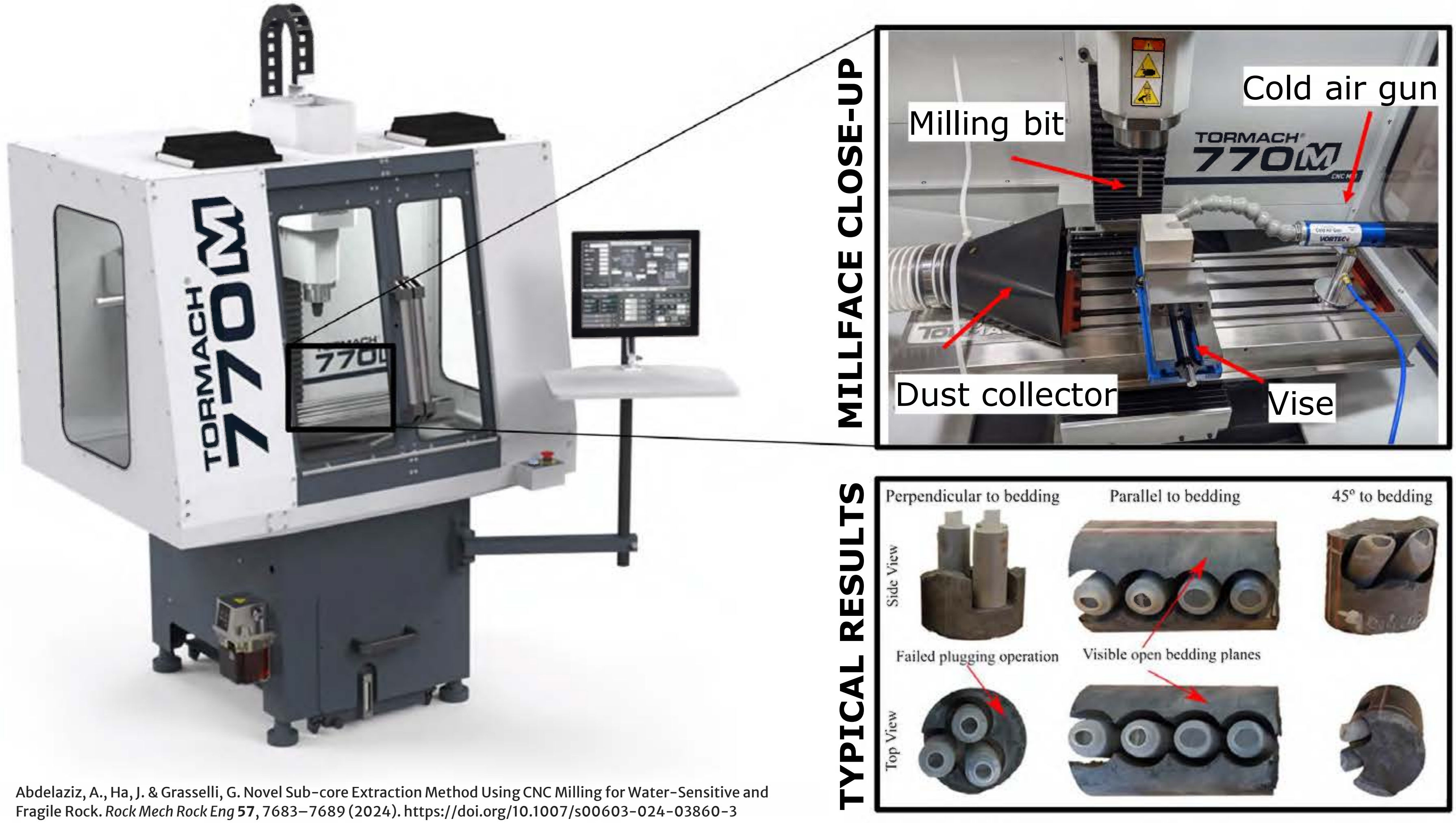

Abdelaziz, A., Ha, J. & Grasselli, G. Novel Sub-core Extraction Method Using CNC Milling for Water-Sensitive and Fragile Rock. *Rock Mech Rock Eng* **57**, 7683–7689 (2024). https://doi.org/10.1007/s00603-024-03860-3

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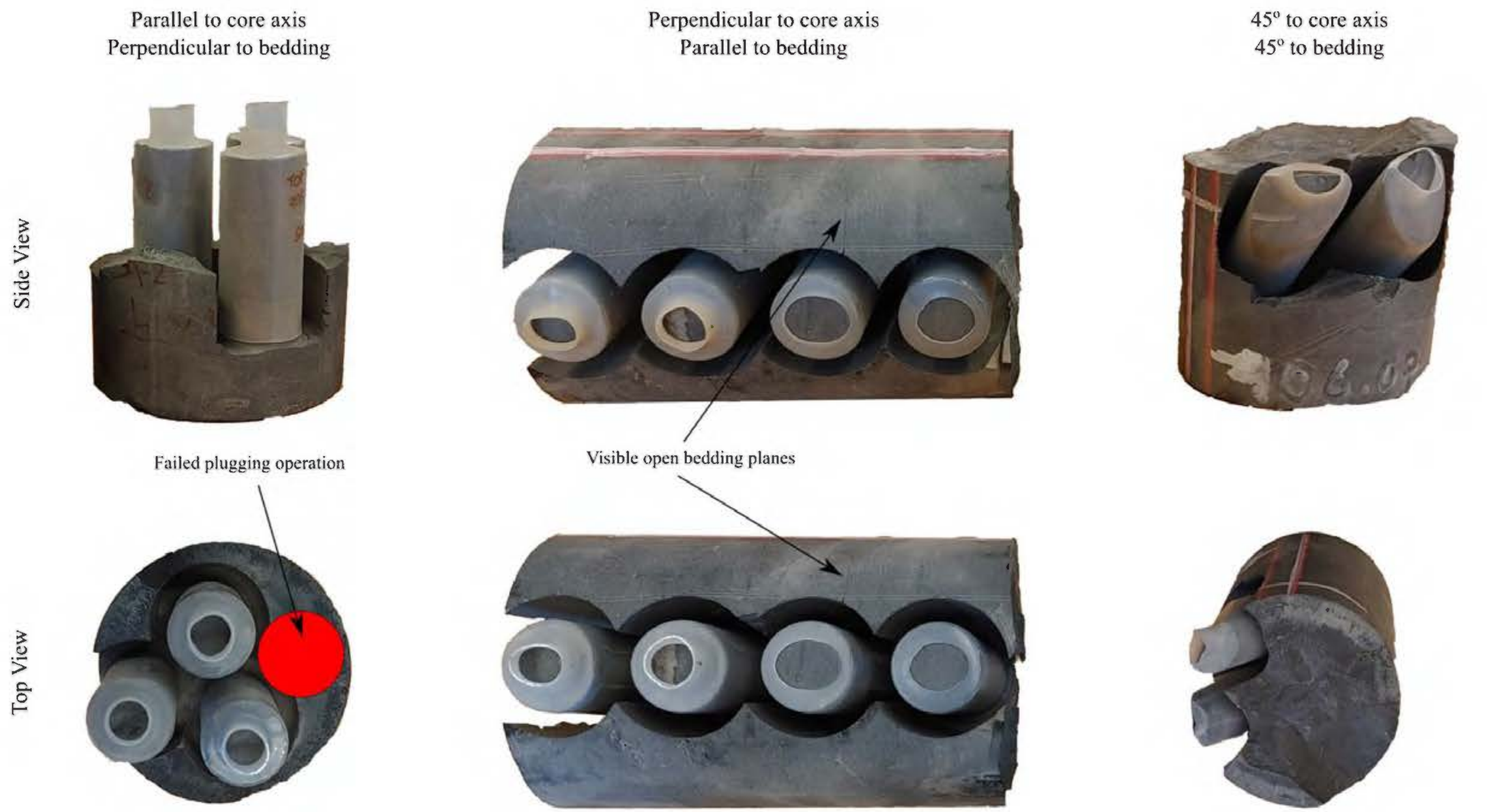
Schematic of CNC Milling Operations



Milling Results

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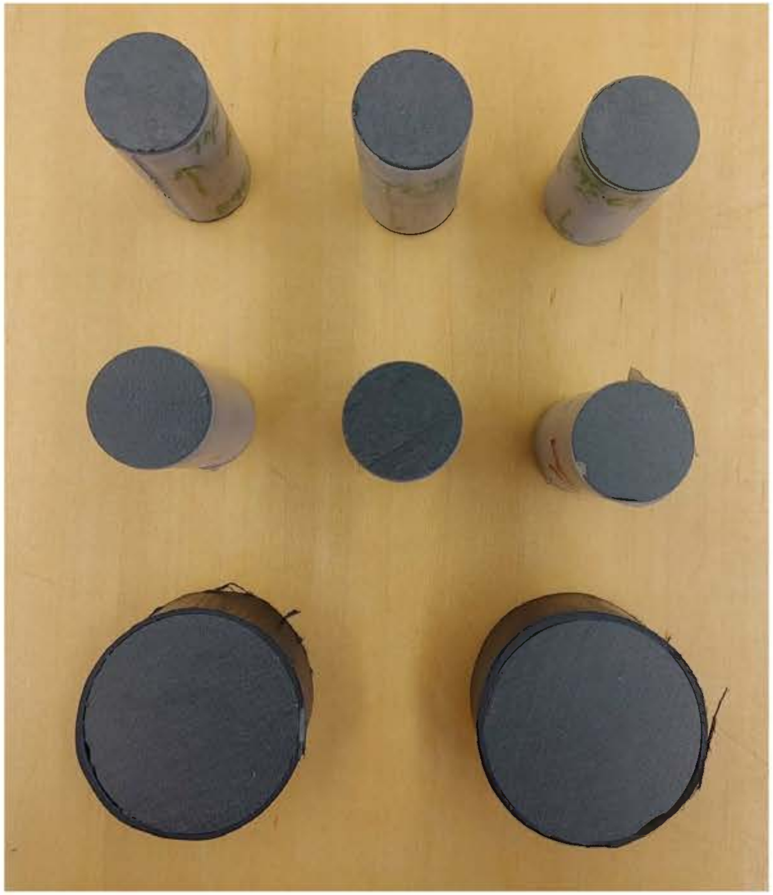

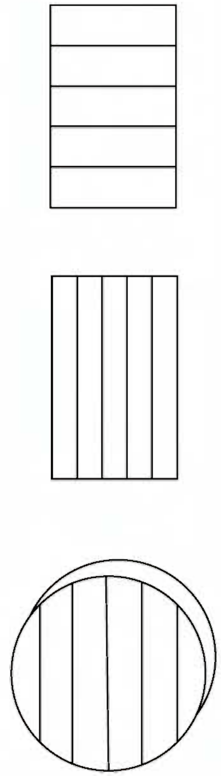

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Example of Extracted Plugs

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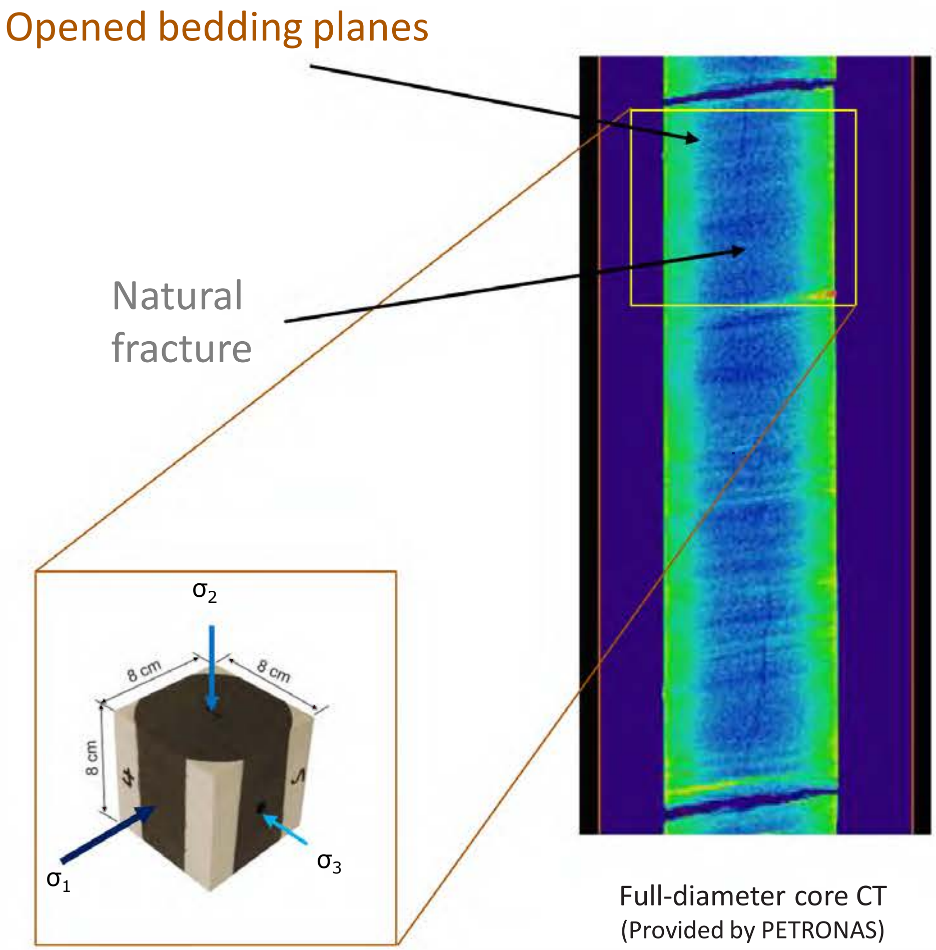

Full-diameter core CT
(Provided by PETRONAS)

3D Rendering of the Core at Depth Sample

True Triaxial Tests – Sample Preparation

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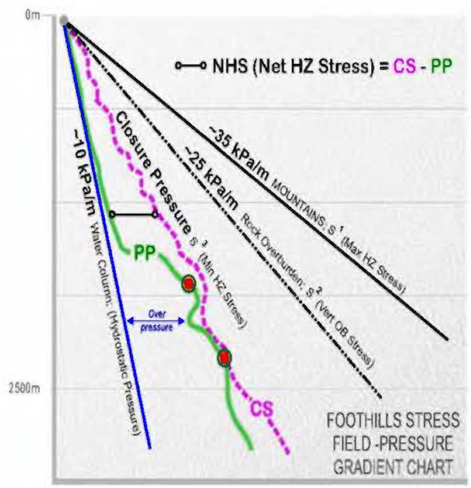
Input Parameters for True Triaxial Testing

Input Parameters

Montney 1D MEM



Source: Khair and Adams 2019

- DFIT (Pore Pressure) Data Point
- Petrophysical Model: PP (Pore Pressure)*
- Petrophysical Model: CS (Closure Pressure)*

Reservoir Rock

Injection Fluids

True Triaxial Testing Cell

True principal stresses can be applied to the sample prior to hydraulic stimulation replicating reservoir stresses

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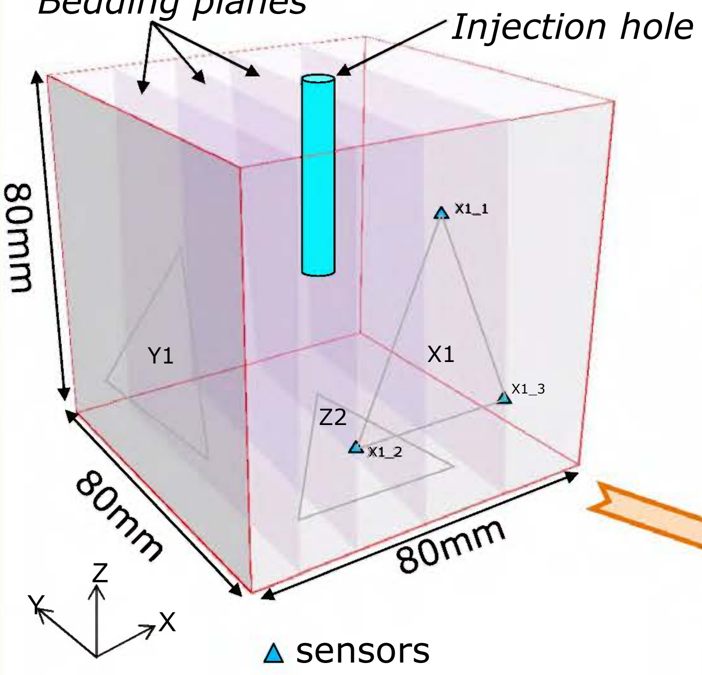
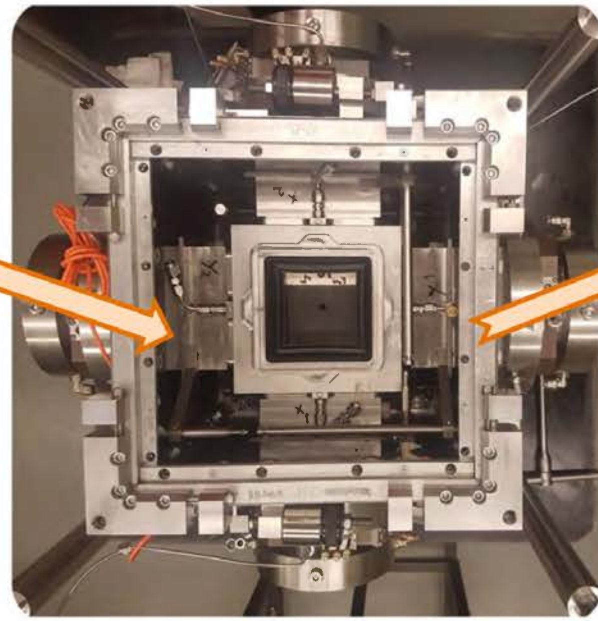


- 3-axes (X,Y,Z) 3-Comp (P,S1,S2) velocity survey
- Sampled at 10 MHz and 12-bit resolution

- Independently applied σ_1, σ_2, σ_3
- 3 LVDT X,Y,Z directions
- 6 x 3 AE sensor
- 20 kHz – 1.2 MHz broad bandwidth resonant frequency



Test sample assembly (Top view)

True triaxial (polyaxial) machine (Side view)

The True Triaxial Vessel

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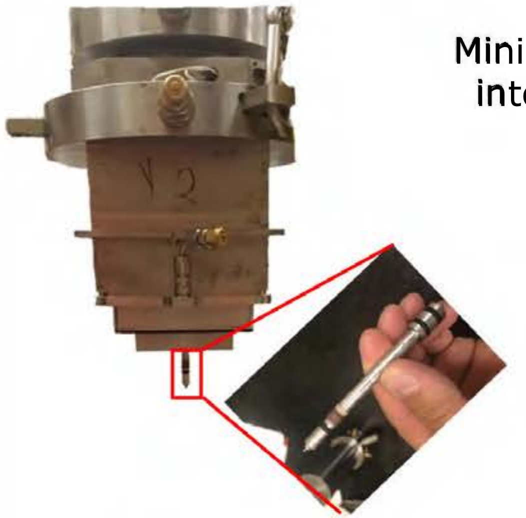
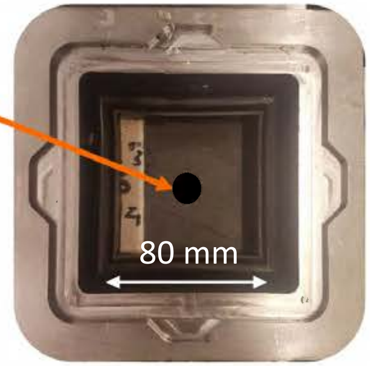
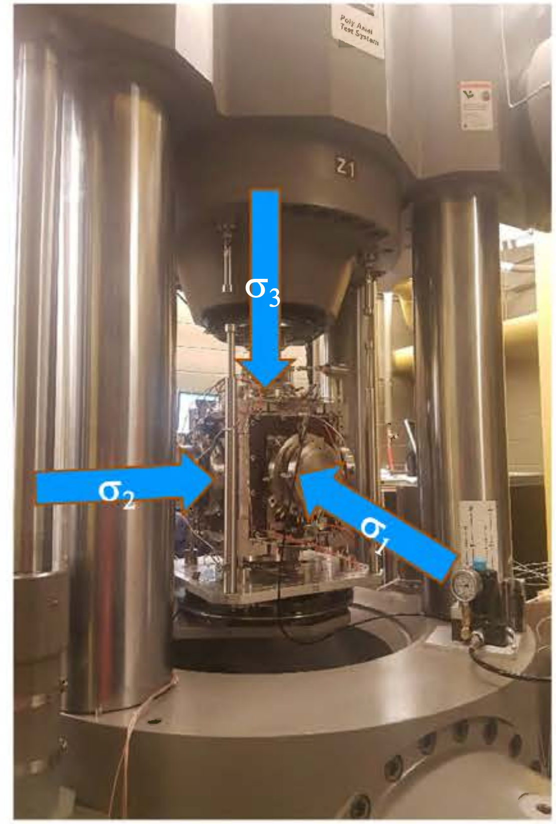
Mini-packer inserted into injection hole



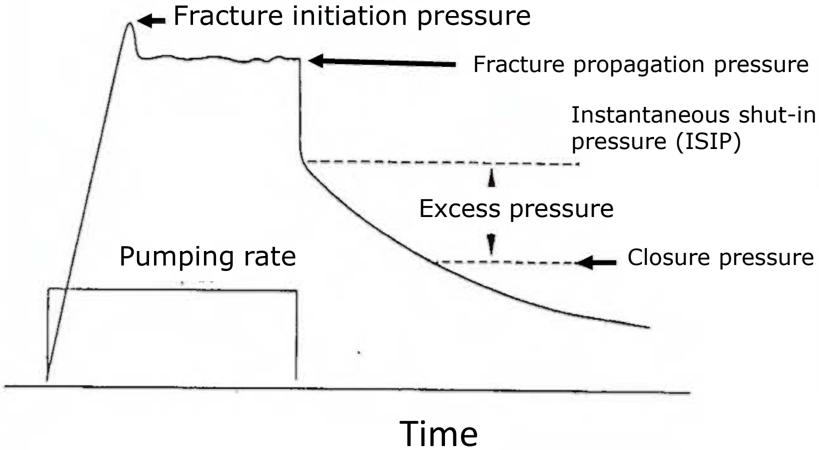
Mini-well
Mini-packer

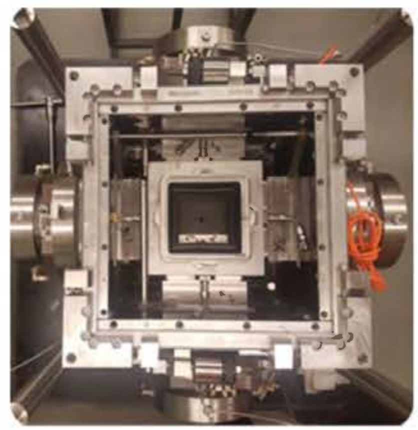
Post-test





Polyaxial frame





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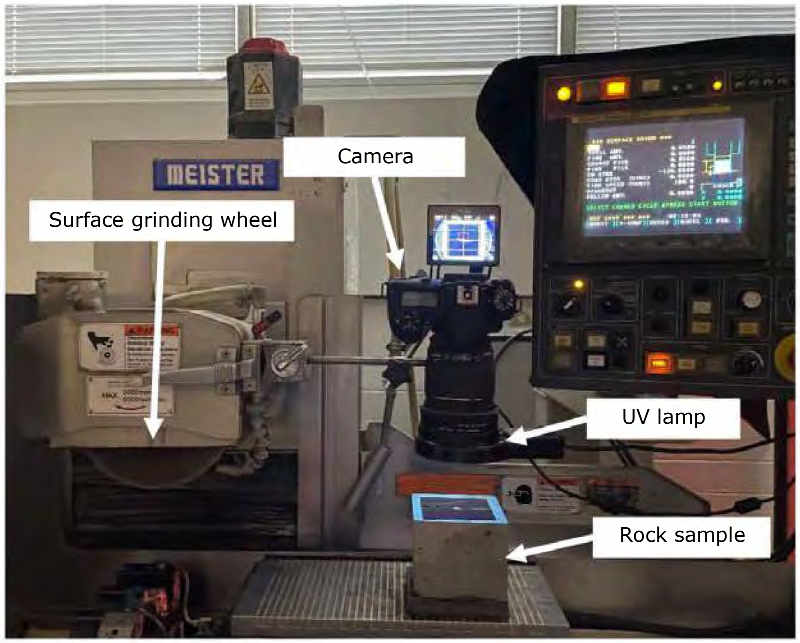
Hydraulic Fracturing Facility Under True Triaxial (Polyaxial) Conditions

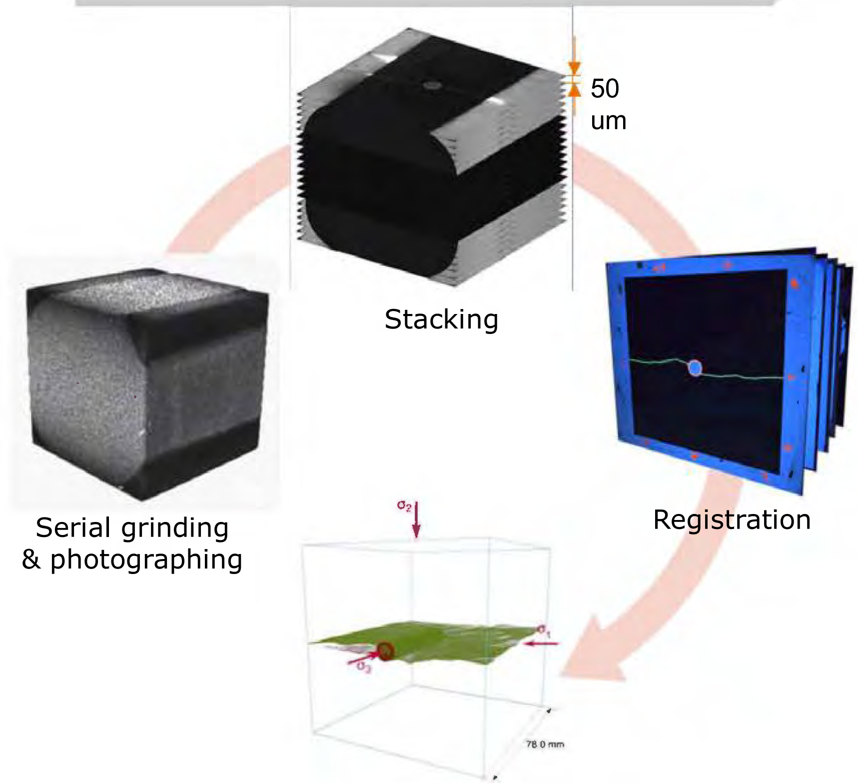
Experimental Setup



Sample size:
8 x 8 x 8 cm^3

Imaging Resolution:
26.5 x 26.5 x 50 um^3

3D serial-sections reconstruction



Li et al. "Mapping Fracture Complexity of Fractured Shale in Laboratory: Three-dimensional Reconstruction From Serial-section Images." Rock Mechanics and Rock Engineering (2021): 1-12.

Serial Sectioning

- Introduction
- Characterizing Anisotropy
- True Triaxial Sample Preparation and Test Procedure
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Outline

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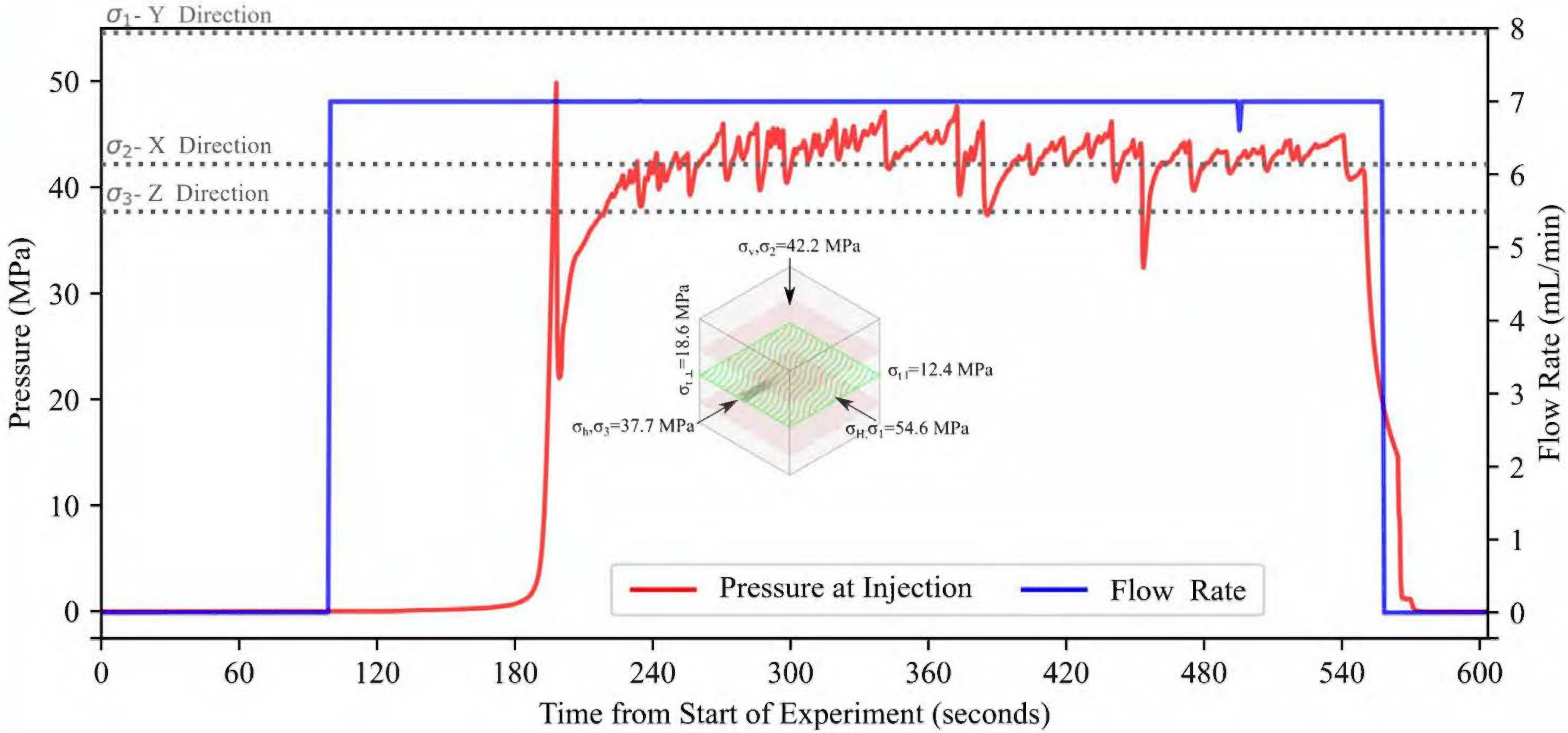

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Outcrop Sample

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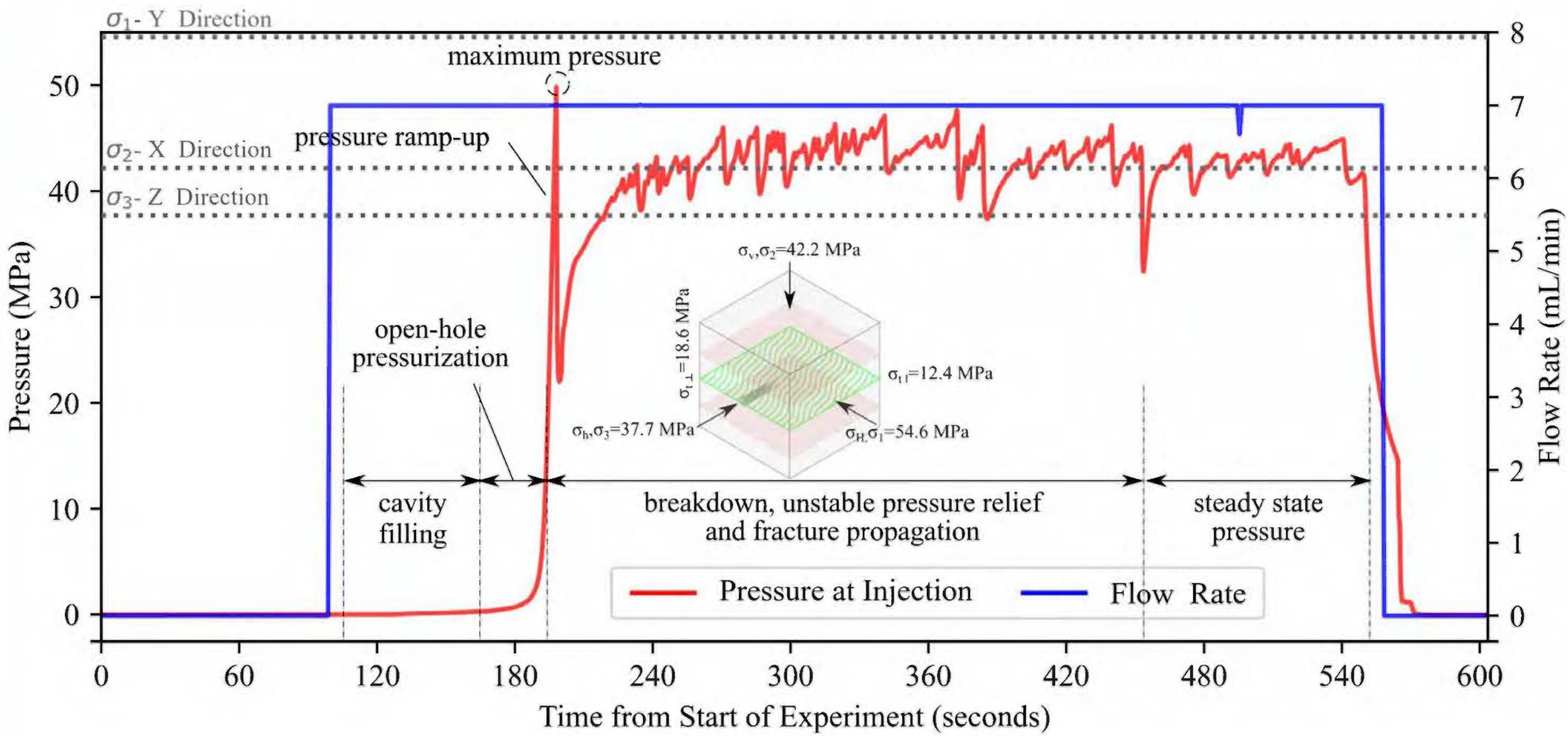

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Outcrop Sample

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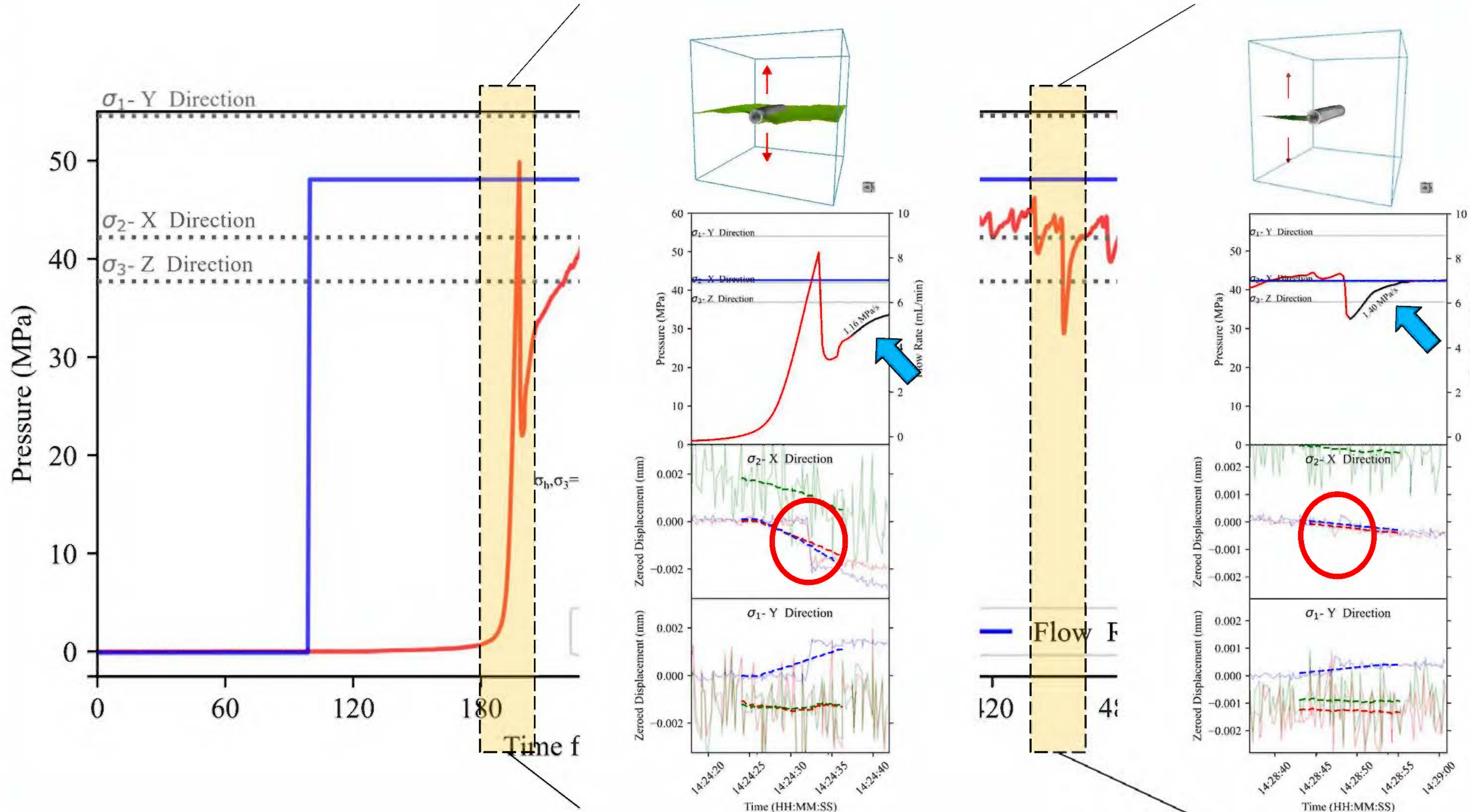

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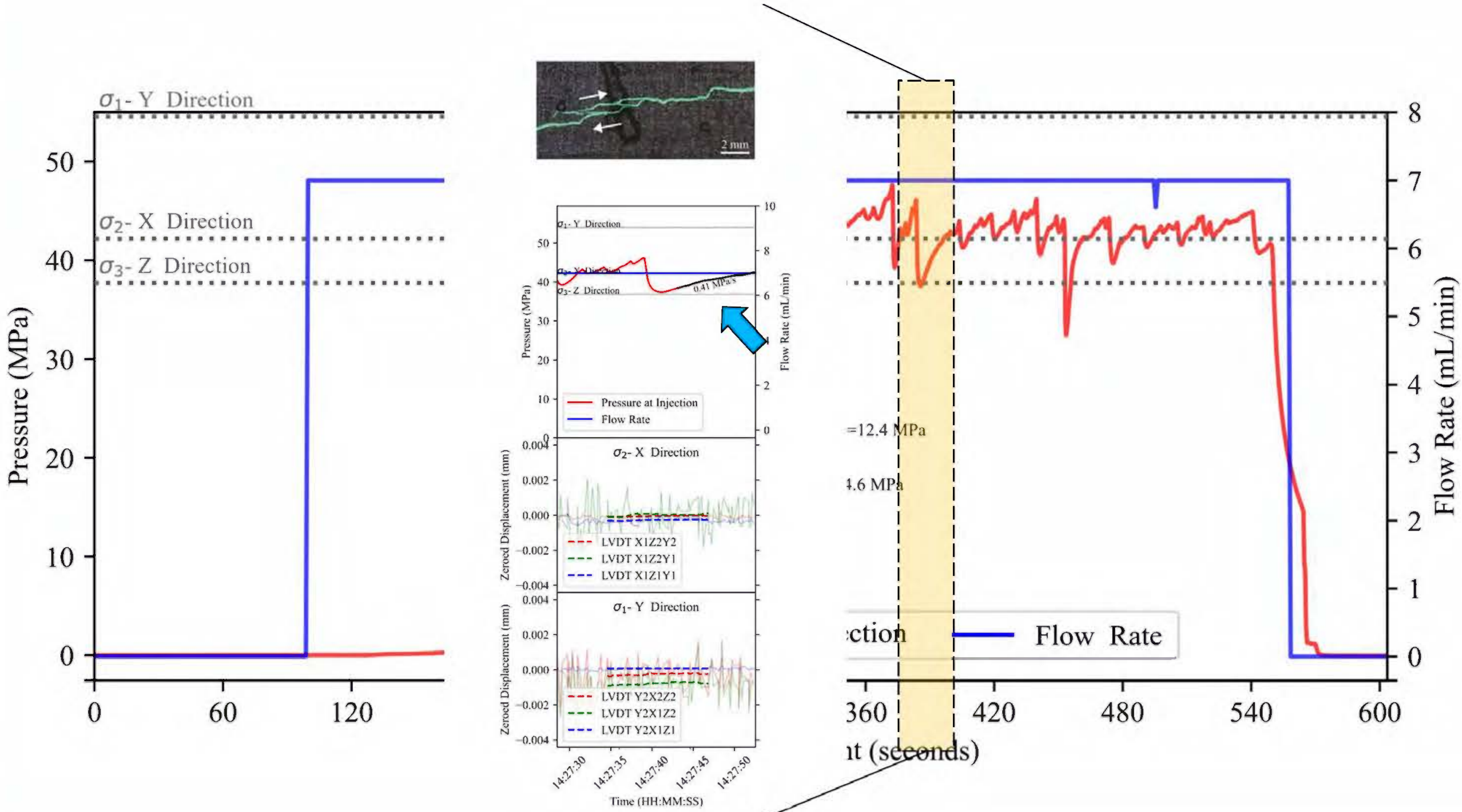
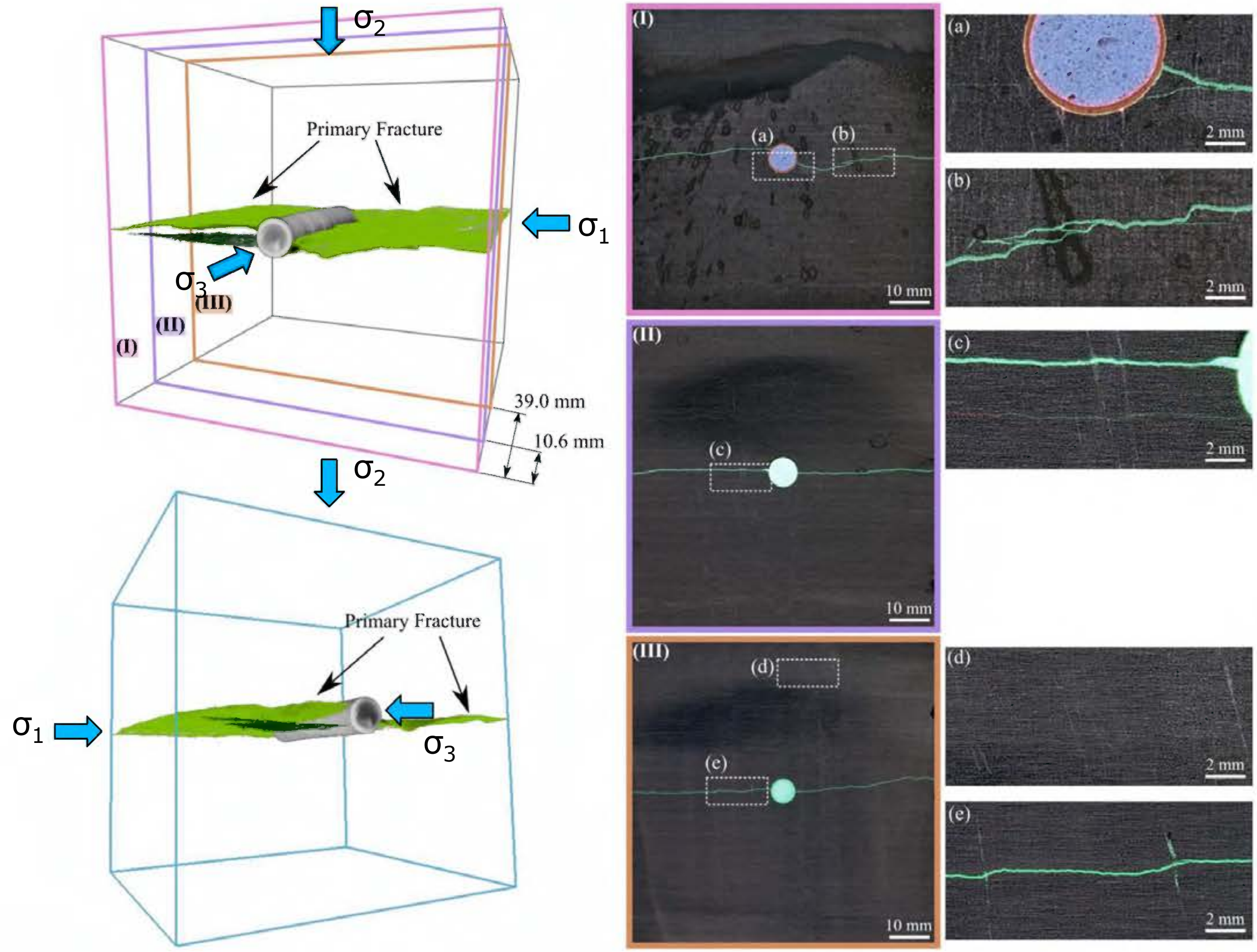
Outcrop Sample – Tensile Signature



Outcrop Sample – Shear Signature

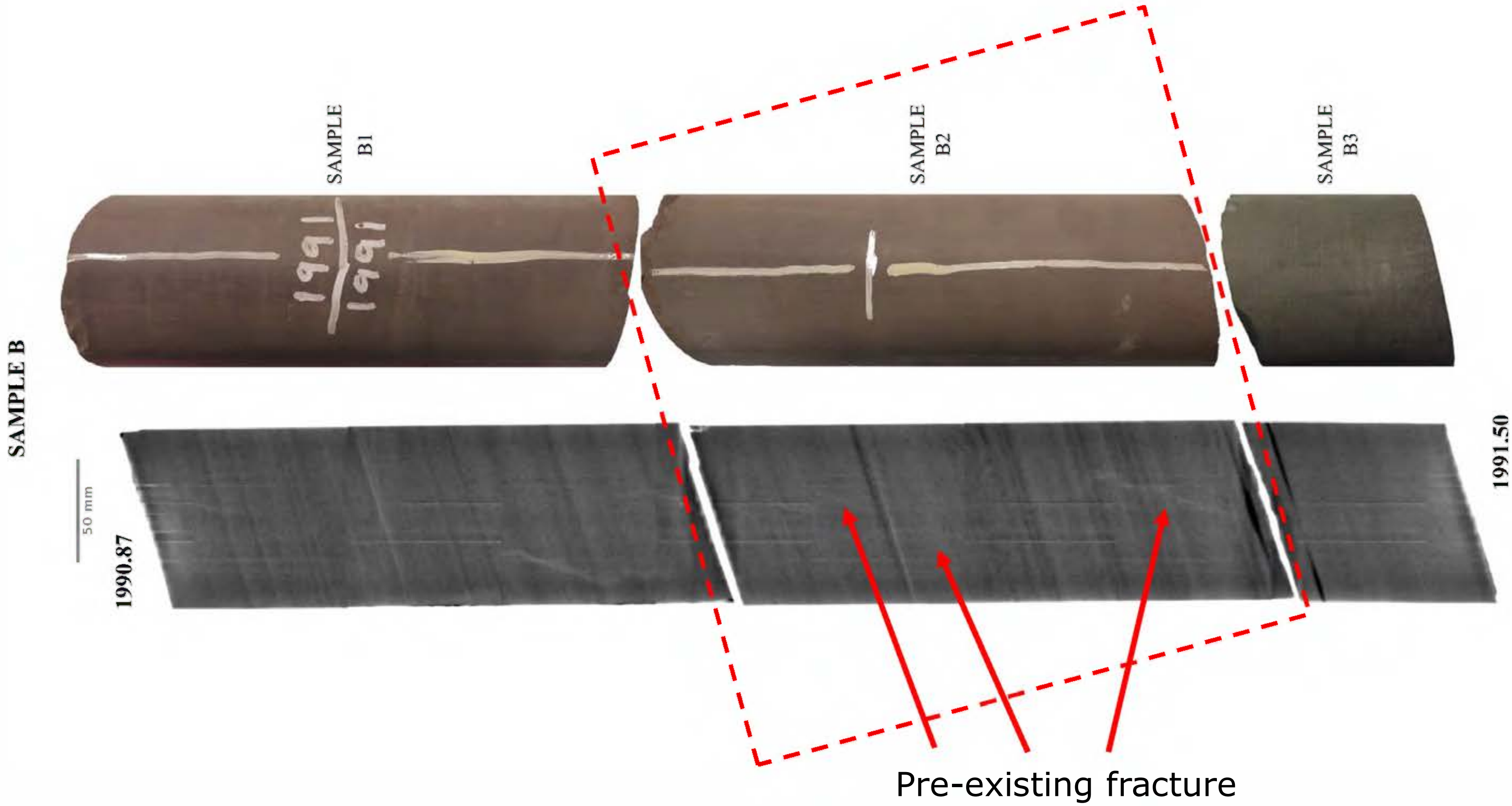


En-echelon

Horst and Graben

Horst and Graben

Outcrop Sample – Serial Sectioning Results



Whole Core Samples

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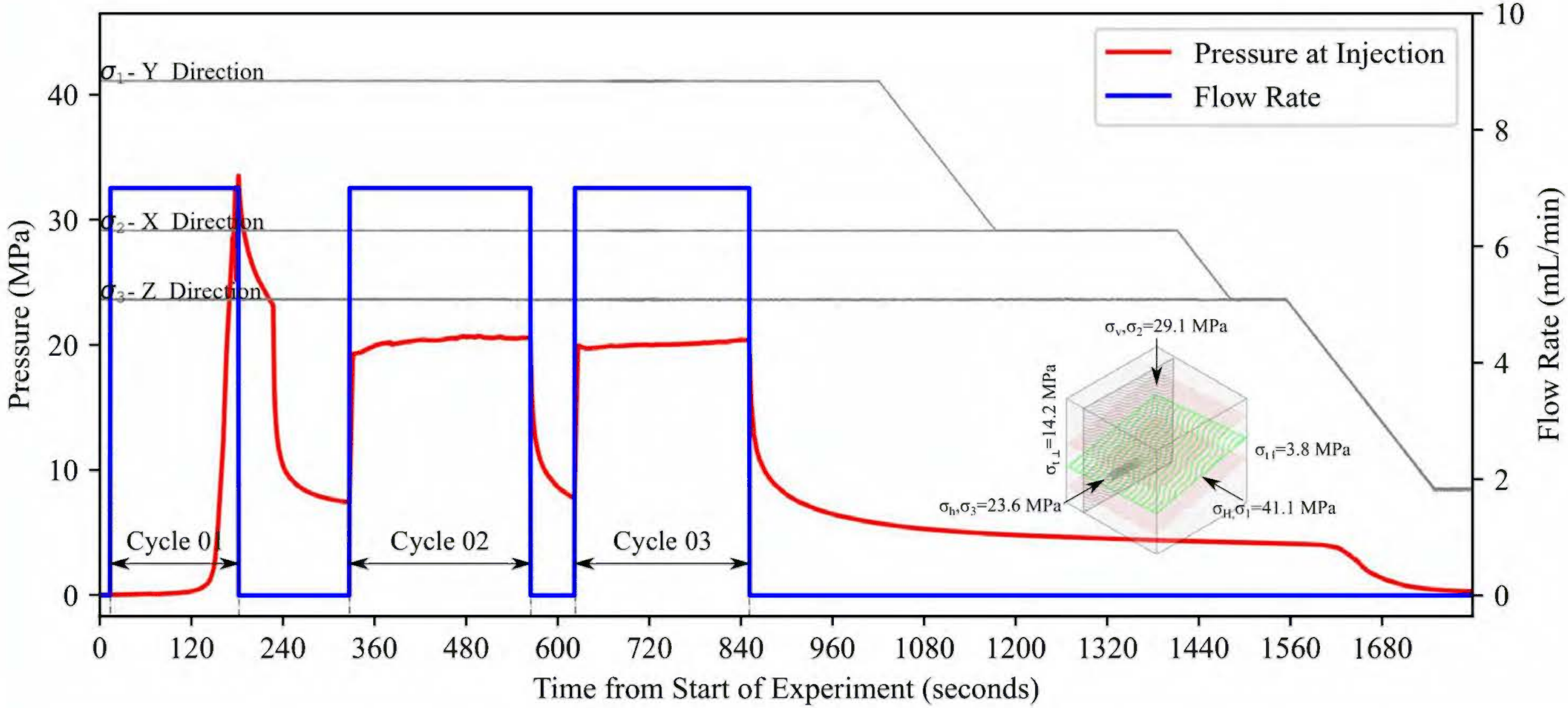

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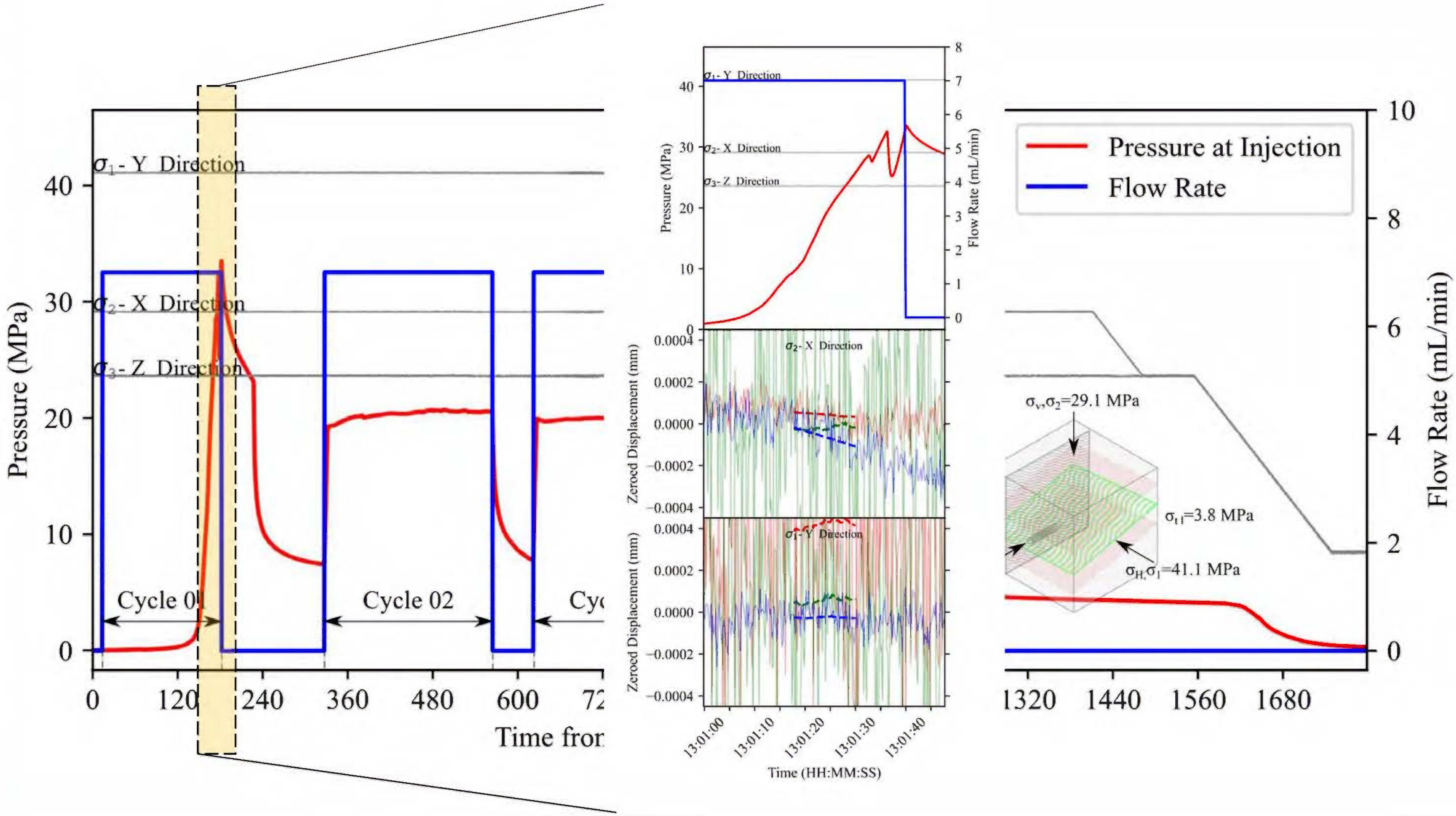
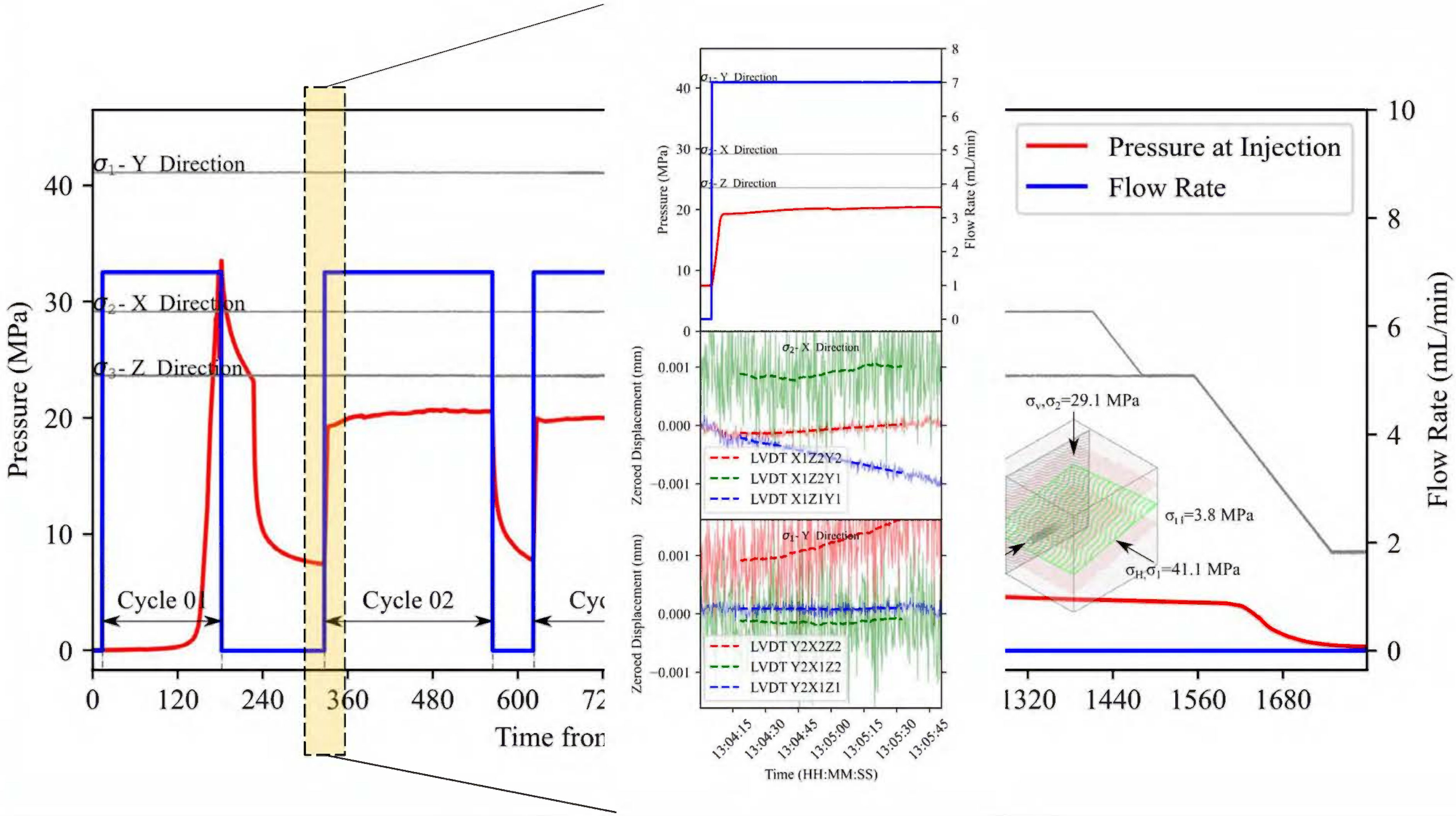
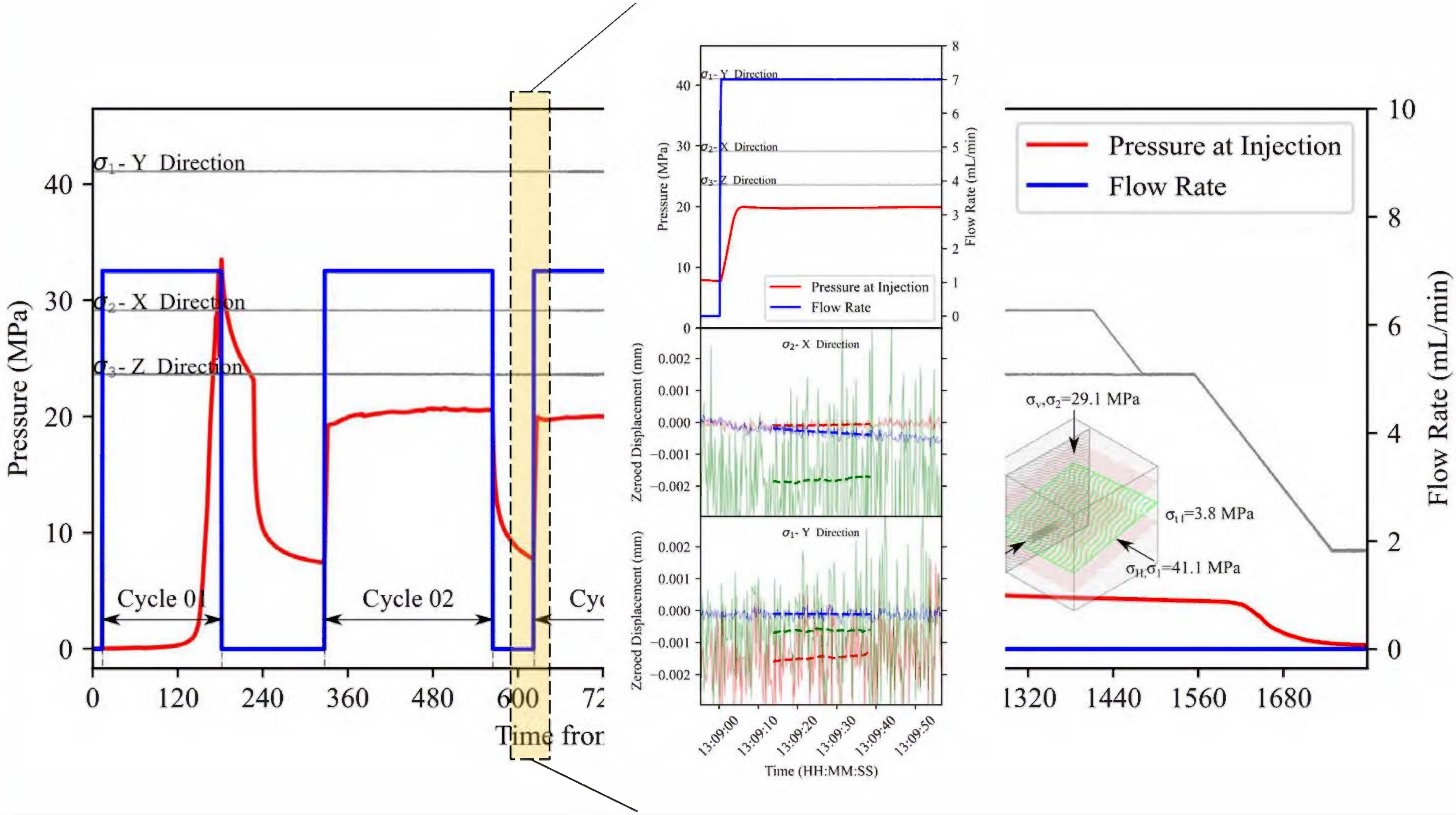
Sample B2-01 – Low Viscosity



Sample B2-01 – Low Viscosity



Sample B2-01 – Low Viscosity



Sample B2-01 – Low Viscosity

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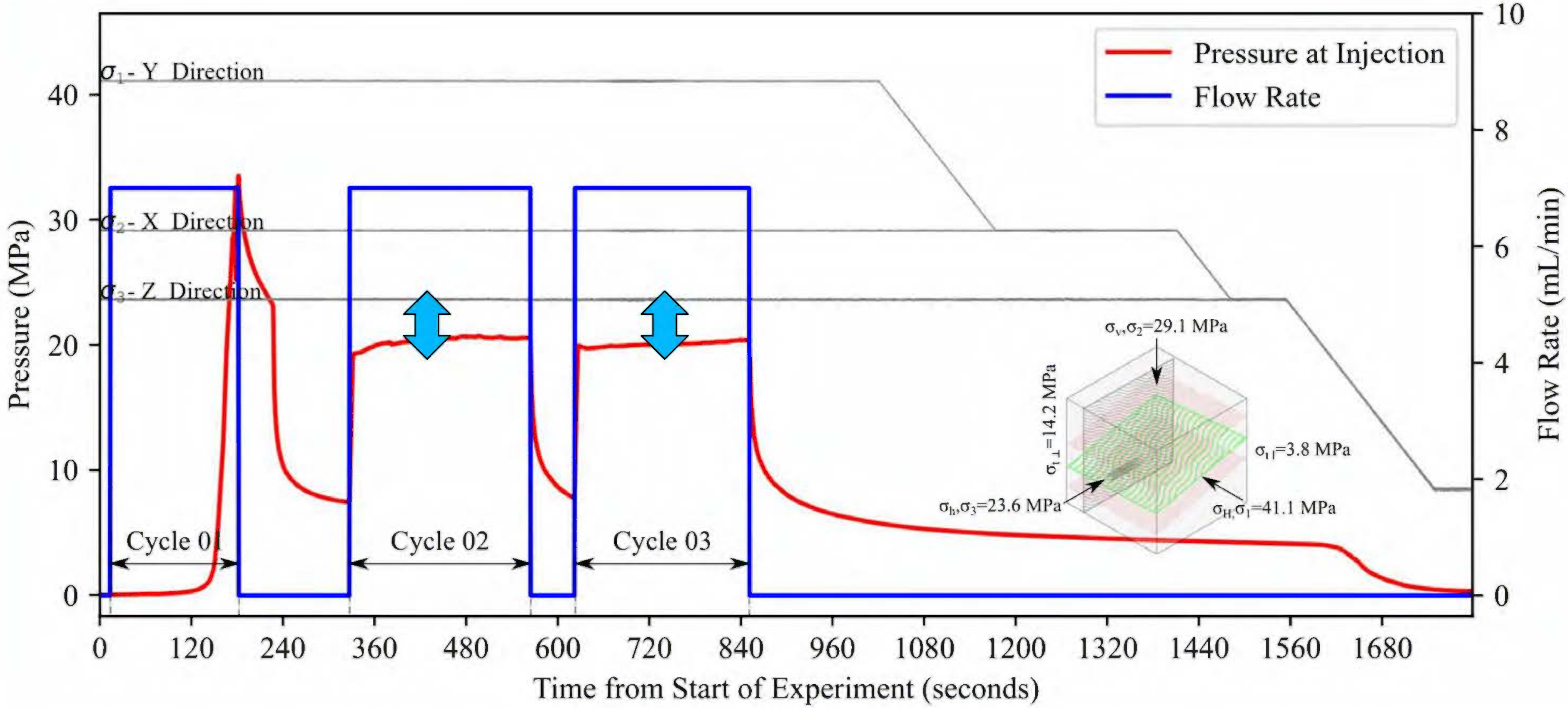

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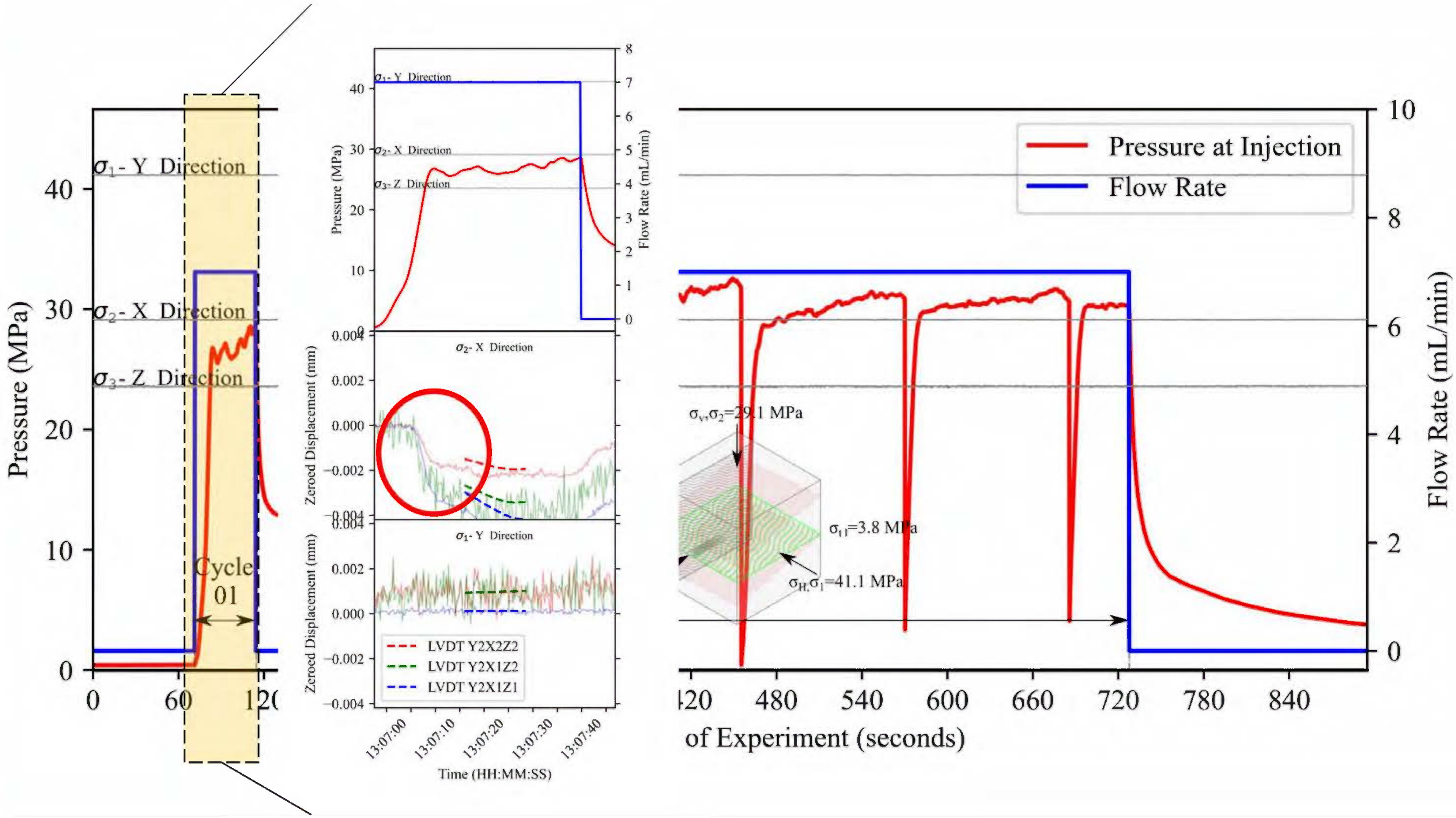
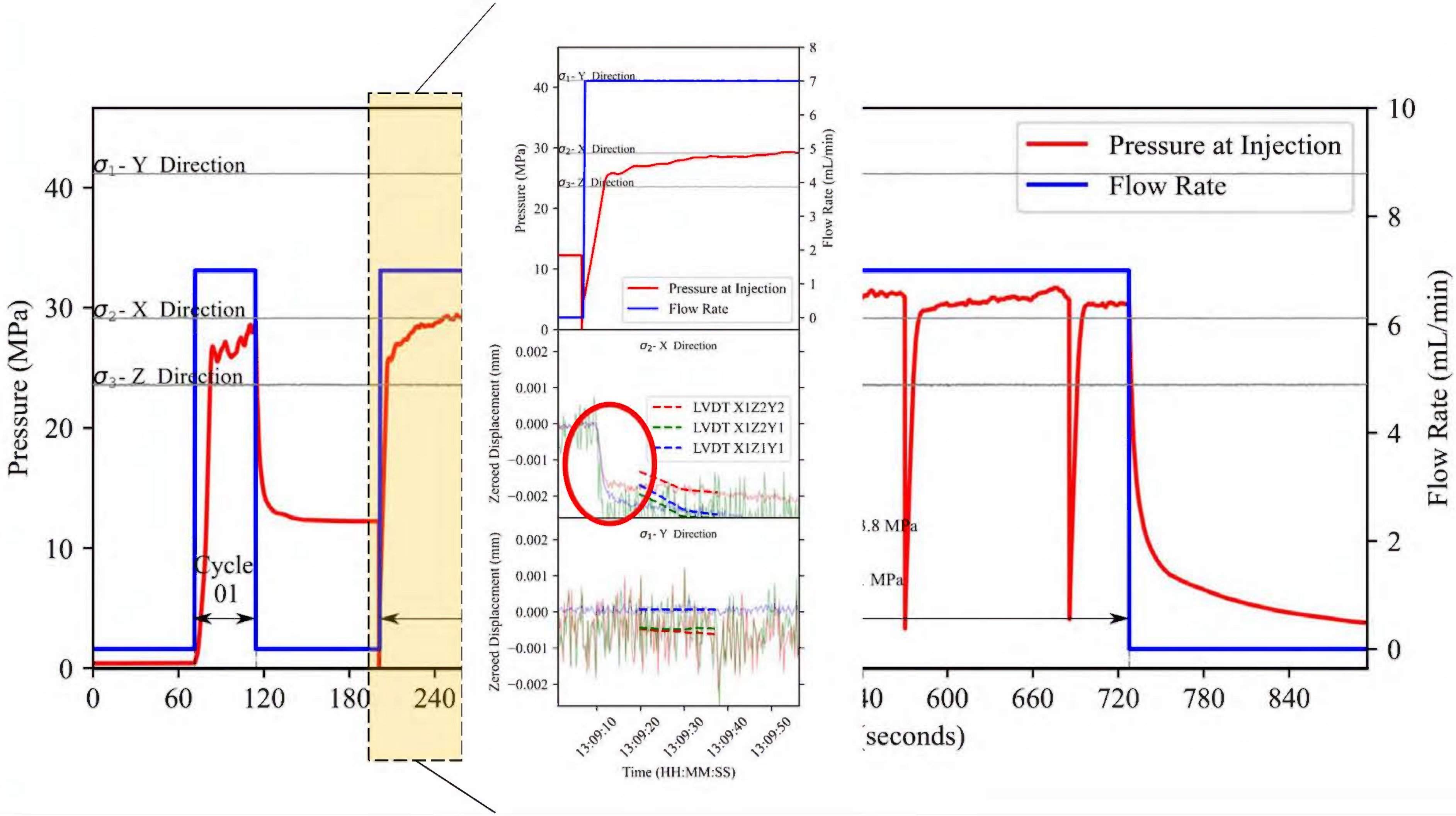
Sample B2-01 – Low Viscosity



Sample B2-02 – High Viscosity



Sample B2-02 – High Viscosity

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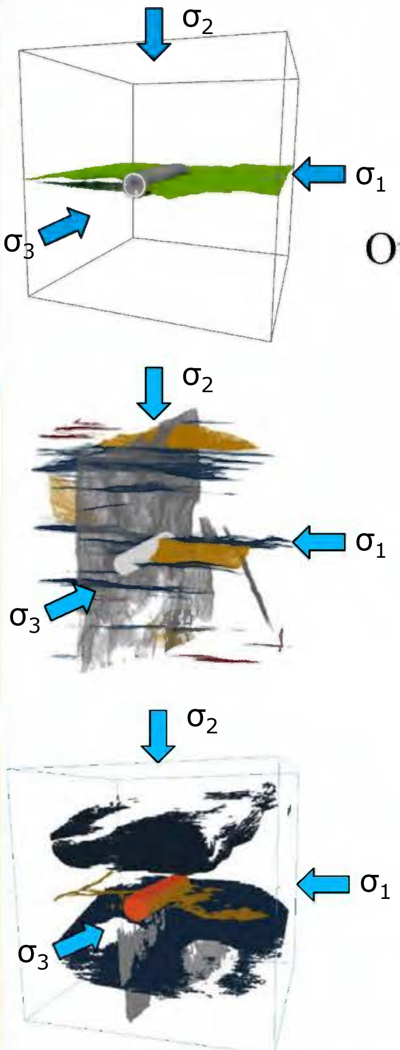
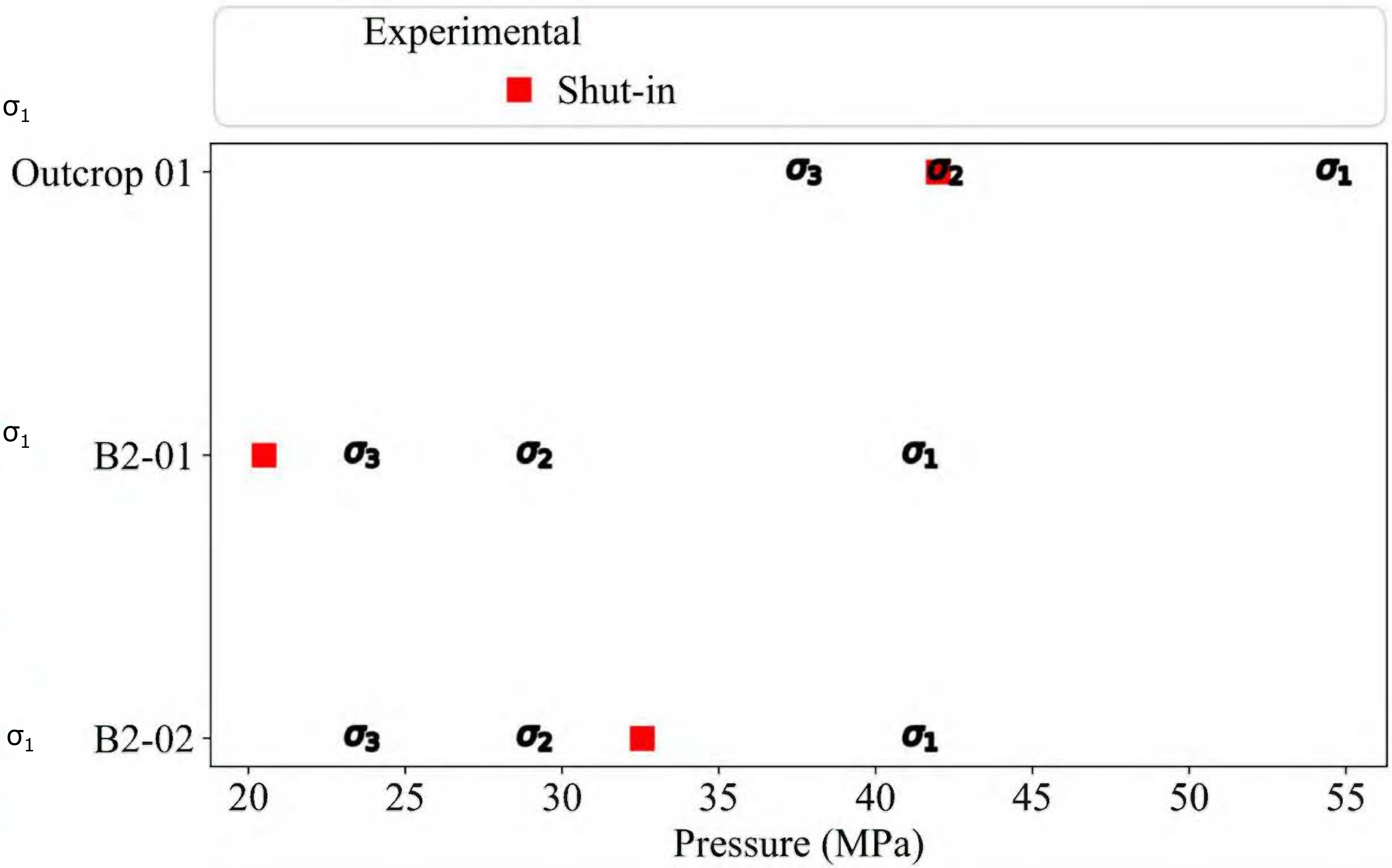
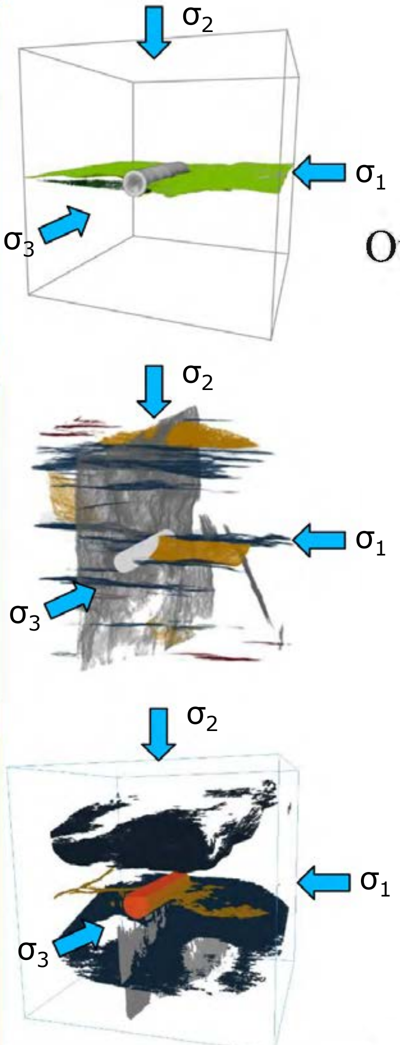
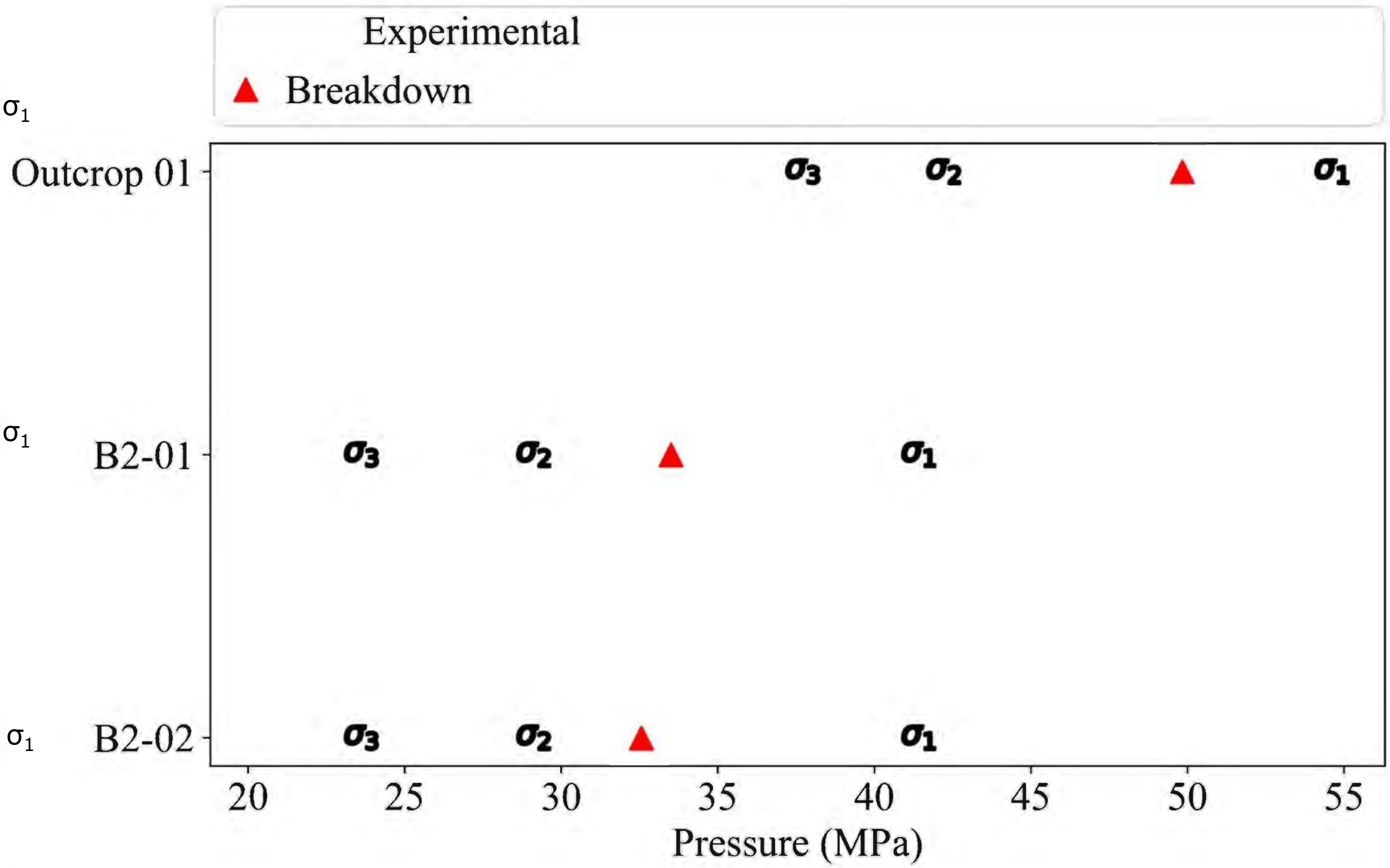
Outline



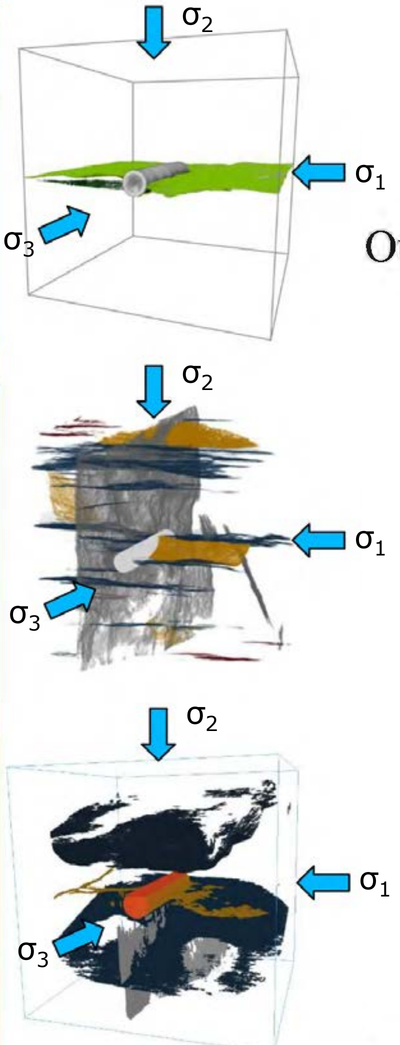


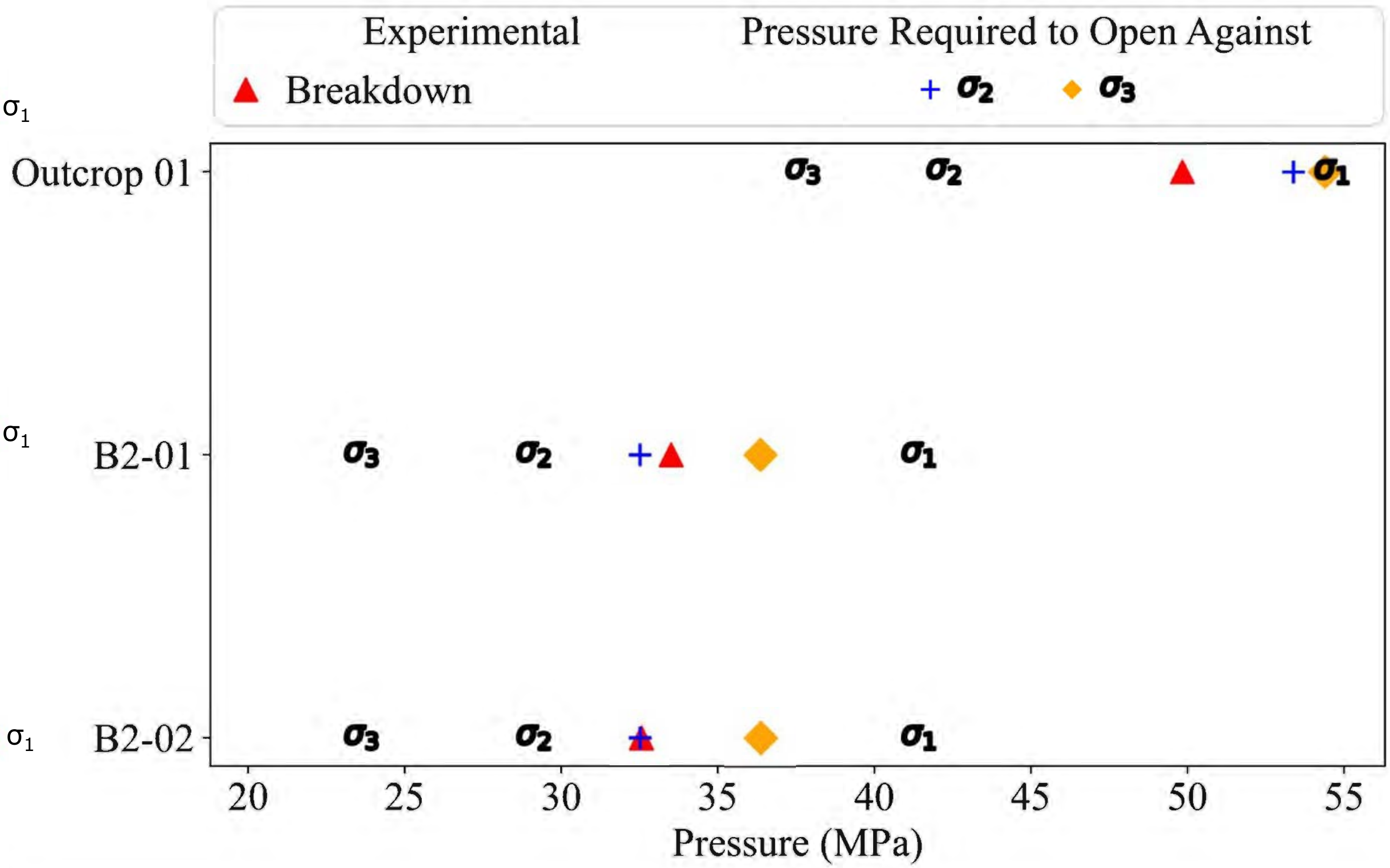
Comparison of Results – Shut-in





Comparison of Results – Breakdown





Comparison of Results – Breakdown Model

- Introduction
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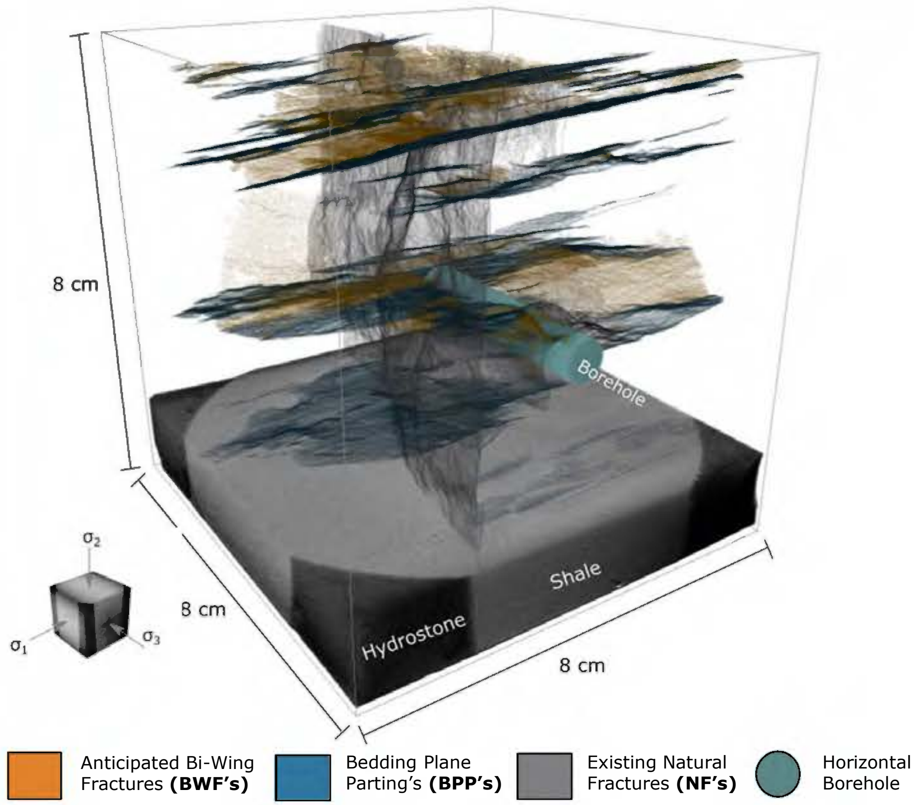
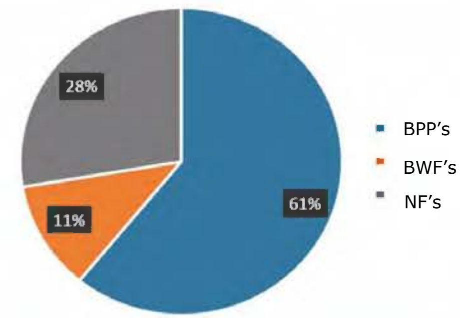
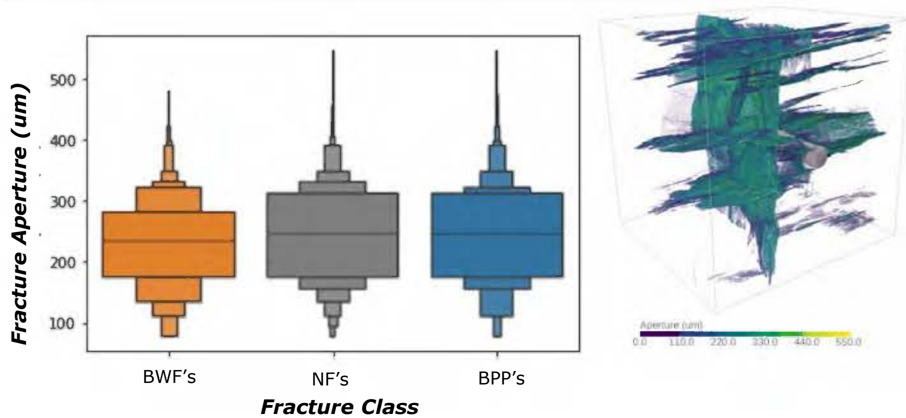
SRV Cube



Fracture Class Volume

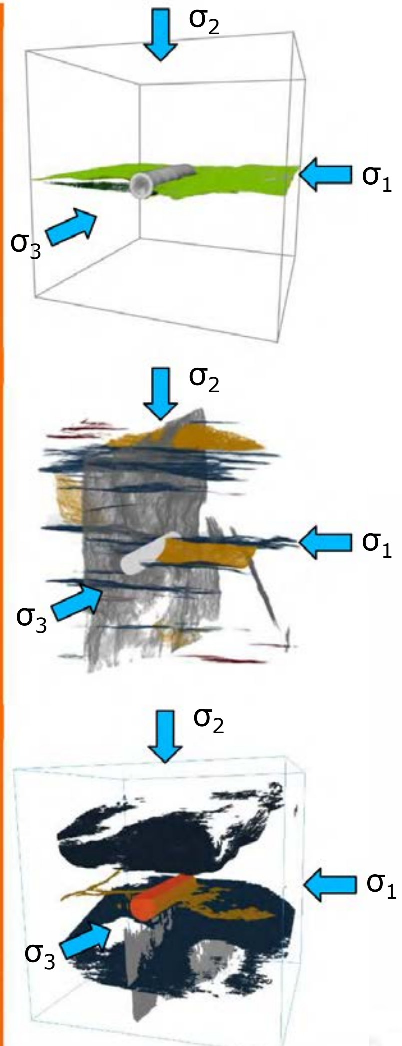


Aperture of Each Fracture Set



The majority of the Stimulated Rock Volume (SRV) is dominated by bedding plane partings, while bi-wing fractures have smaller aperture and volume, connecting the SRV

Fracture Geometry is Complex



- Proposed a breakdown model that captures the in-situ stress contrast and the rock strength anisotropy:

$$P_b = \min(\sigma_{in\text{-}situ(\theta)} + \sigma_{t\,(\theta)}) - P_o\,;\ \textit{when}\ \min(\sigma_{in\text{-}situ(\theta)} + \sigma_{t\,(\theta)}) < \sigma_\theta$$

- Unique breakdown signature.
  - Tensile shows an abrupt change in the strain response that initiations before breakdown.
  - There is a lag in the abrupt change when using high viscosity fluids.
  - The strain response is very subtle during shear.

- The shut-in pressure can be used as a proxy to determine the complexity of the fracture. Planar fracture will usually resolve to the magnitude of a principal stress.

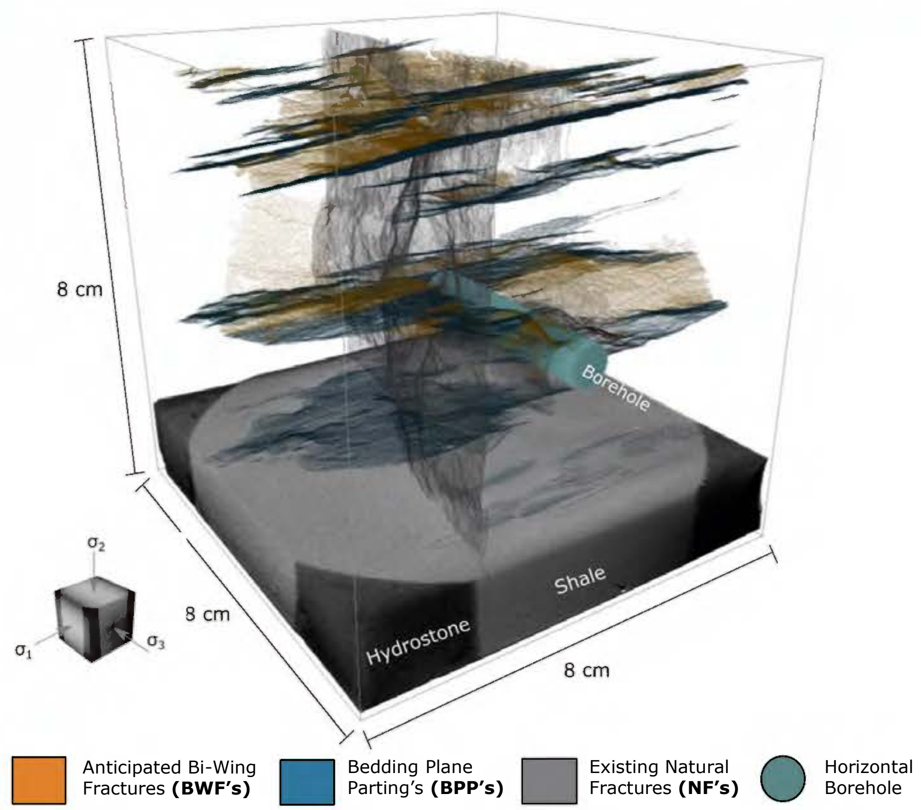
- **High viscosity** leads to a hydraulic fracture and limits interaction with pre-existing weakness and discontinuities.

What we Learned

Limitations and Topics not addressed

- While this experiment can be a proxy for near wellbore behaviour and tortuosity, it highly the significant role that strength anisotropy plays in dictating the fracture trajectory.
- Although acoustic emissions (AE) were monitored, there has been limited findings till date.
- The influence of pore-pressure was not addressed in this work.

SRV Cube



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- Rock fabric not principal stress dictates SRV: The Story of how a ~70 Year-old discounted data point still plagues our industry and how true triaxial testing finally confirms it. Giovanni Grasselli, Matthew G. Adams, and Aly Abdelaziz. Unconventional Resources Technology Conference, 13–15 June 2023. August 2023, 199-208

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