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Lab-Scale Hydraulic Fracturing Experiments

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جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
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Acknowledgments

- HydraFrac team at KAUST
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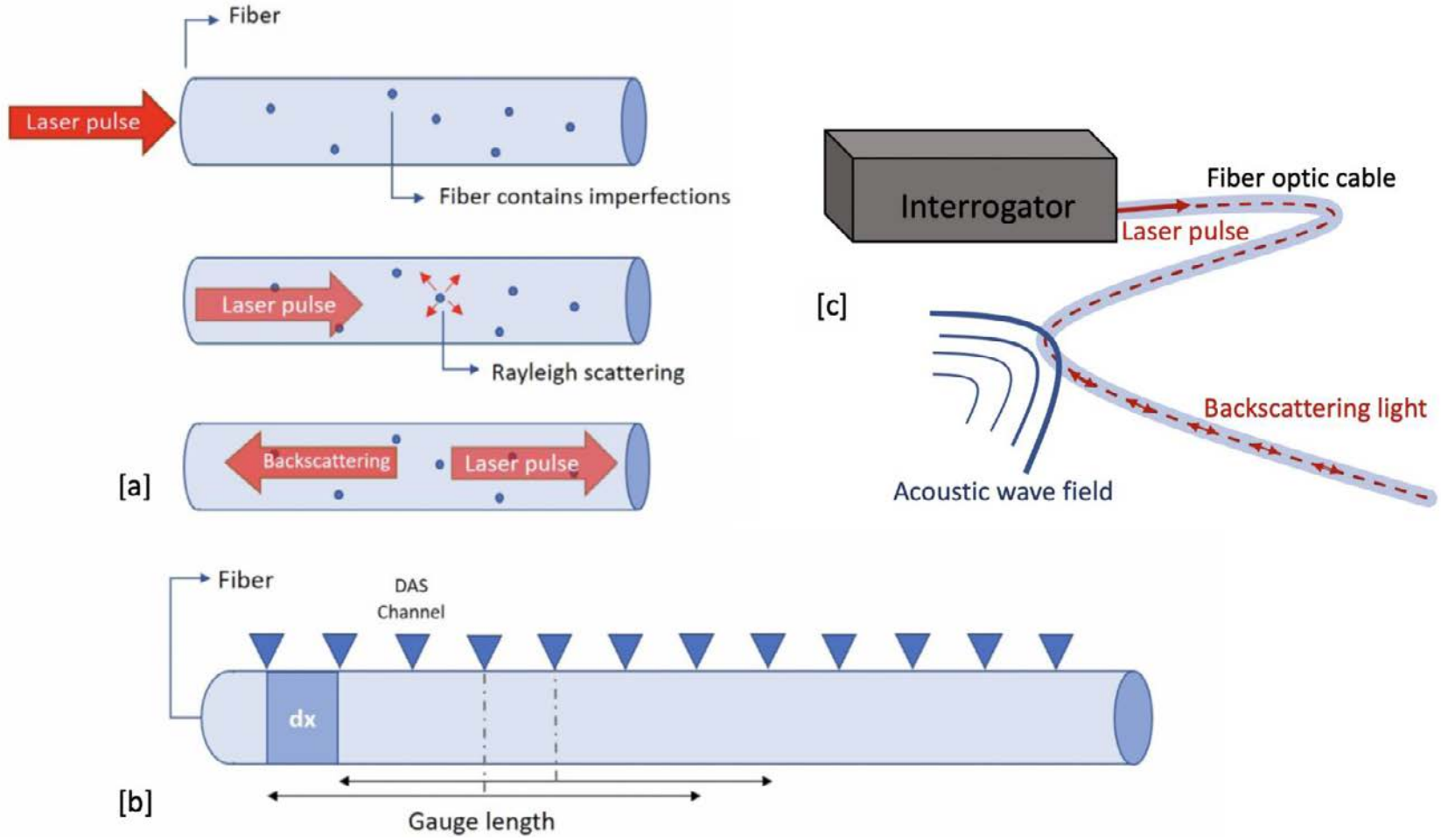
- جامعة الملك عبدالله للعلوم والتقنية
  King Abdullah University of Science and Technology

Distributed Acoustic Sensing: What is it?



- Rayleigh scattering
- Optical time domain reflectometry
- Measure strain or strain rate
- Gauge length
- Channel Spacing

Source: Nap [2020]

Distributed Acoustic Sensing

Pros

- Can be used in any orientation
- Provides more than one measurement
- High spatial and temporal resolution
- Large sensing distances
- Resistance to high pressure
- Durable – can function for years if not decades
- Adequate fiber coupling

Cons

- Less sensitivity to broadside signals
- Some inadmissible sensor subsets
- Huge streams of data

Motivation

Why large rock block-scale studies in the lab?

- Rock blocks at the decimeter scale provide **interim scale** between plug size experiments and the field

- Laboratory experiments provide a **controlled environment** to:

  - Replicate **field-relevant stress conditions**
  - Validate **monitoring techniques** such as DAS and AE
  - Study fracture **initiation, propagation, and interaction with faults**
  - Support safe and efficient design for **field-scale applications**

Project Goals

Aim

Understanding how (lab size) rock samples respond to hydraulic fracture stimulation:

- Reactivation of natural fractures and creation of new fractures.
- Understand influence of heterogeneities (e.g., stylolites)

Objectives

- **Simulate hydraulic fracturing** under controlled lab conditions.

- **Integrate DAS & AE sensors** for high-resolution HF monitoring.
  - 3D imaging & higher resolution than just AE sensors

- **Analyze microseismic data** to map fracture networks and source mechanisms.

- **Advance understanding** of rock behavior during fluid injection for energy, geothermal, and CO_2 storage applications.

Approach

1. Smaller rock blocks: 15 cm x 15 cm x 15 cm

Purpose

- Preliminary testing to **optimize experimental parameters** such as injection pressure, AE sensor placement, and fracturing conditions
- **Iteration and troubleshooting** of the experimental setup in a controlled and cost-effective manner

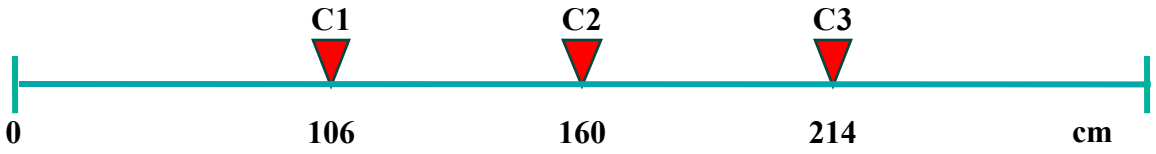
2. Larger rock blocks : 40 cm x 40 cm x 40 cm

Purpose

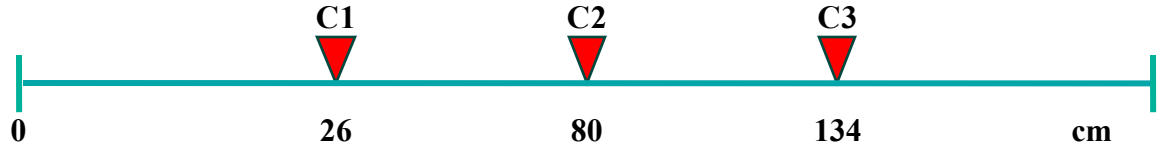
- For the **main hydraulic fracturing experiments** to simulate more realistic subsurface conditions
- Provided a **larger volume for fracture propagation**, enabling comprehensive monitoring and characterization of fracture networks
- Facilitated **integration of multiple sensing technologies** (e.g., DAS and AE)

Sensor Array For Detection

1. Two-rounds wrap (Rock Block 3; improve S/N)



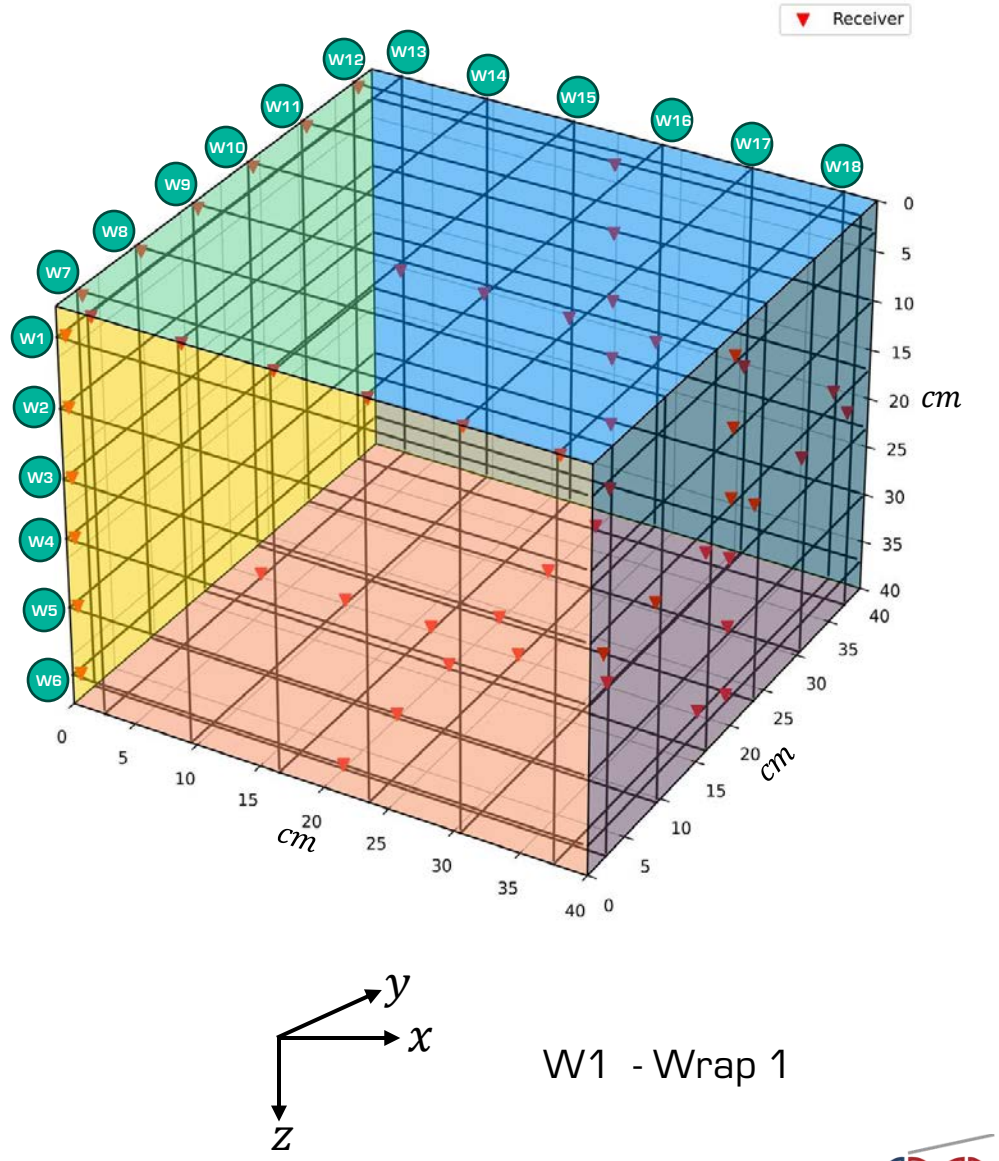
2. Single-round wrap (Rock Blocks 1, 2, & 4)



- Gauge length : 150 cm
- Channel Spacing: 54 cm

- Lines per face: 6
- Total wraps: 18
- Channels per wrap: 3
- Total Channels: 54

Channel = Receiver (sensor)

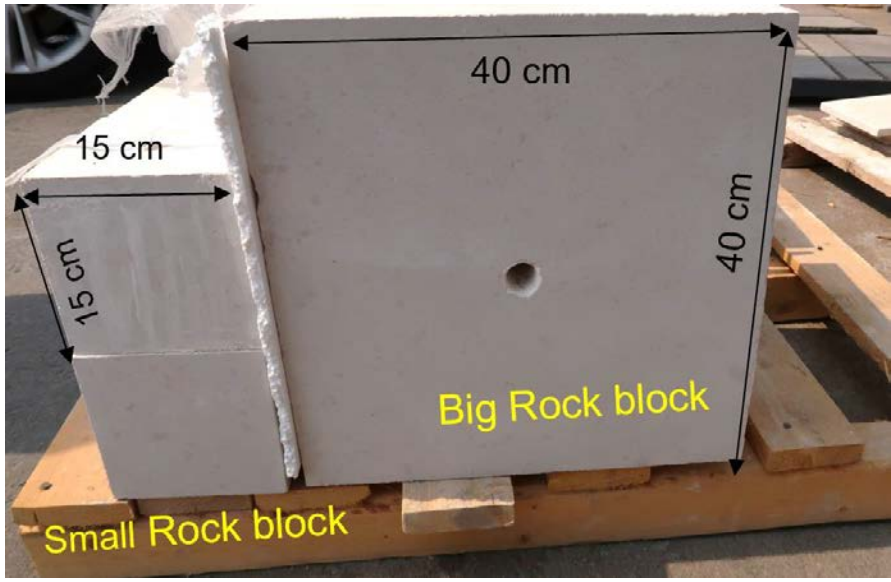


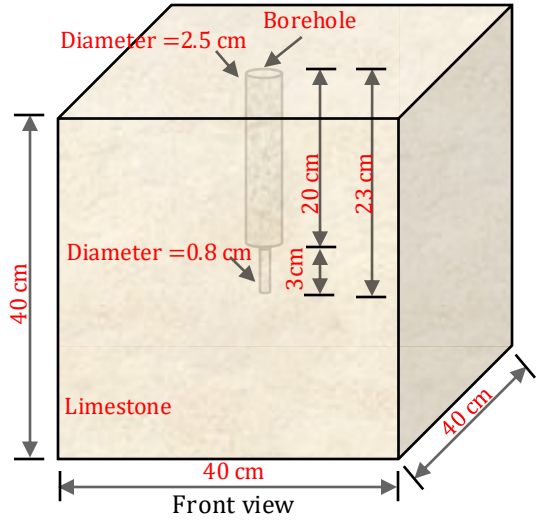
W1 - Wrap 1

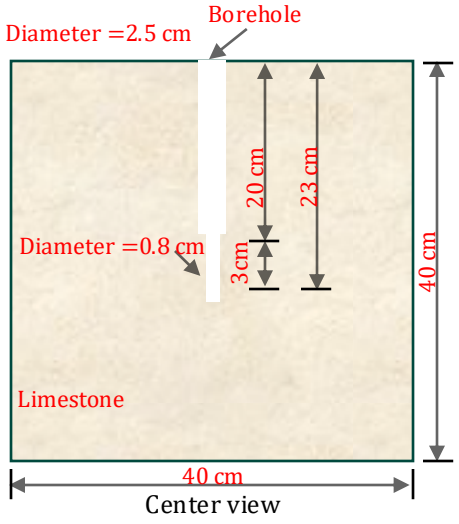
Rock Blocks

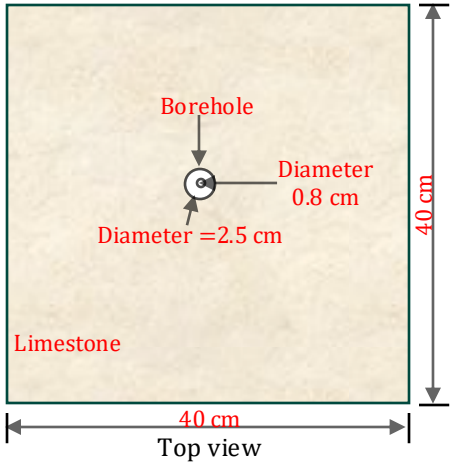

Limestone
Marble
Rock quarry

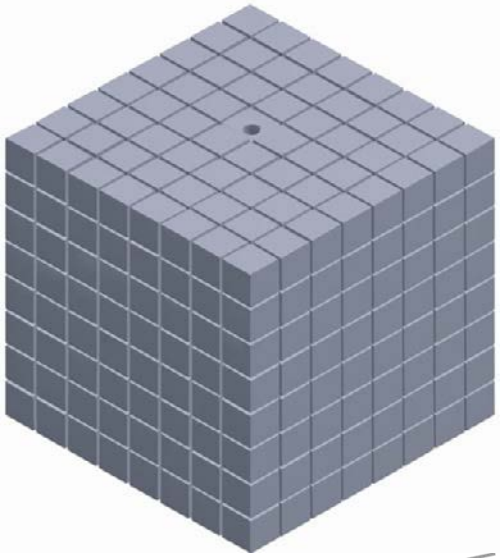

Cutting machine
Saw
Rock


40 cm
15 cm
15 cm
40 cm
Big Rock block
Small Rock block

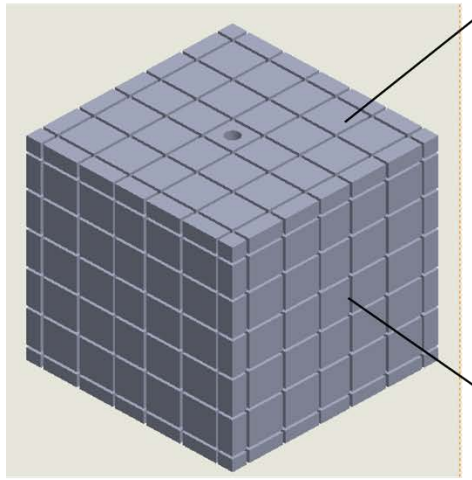

Diameter =2.5 cm
Borehole
20 cm
23 cm
Diameter =0.8 cm
3cm
40 cm
Limestone
40 cm
40 cm
Front view

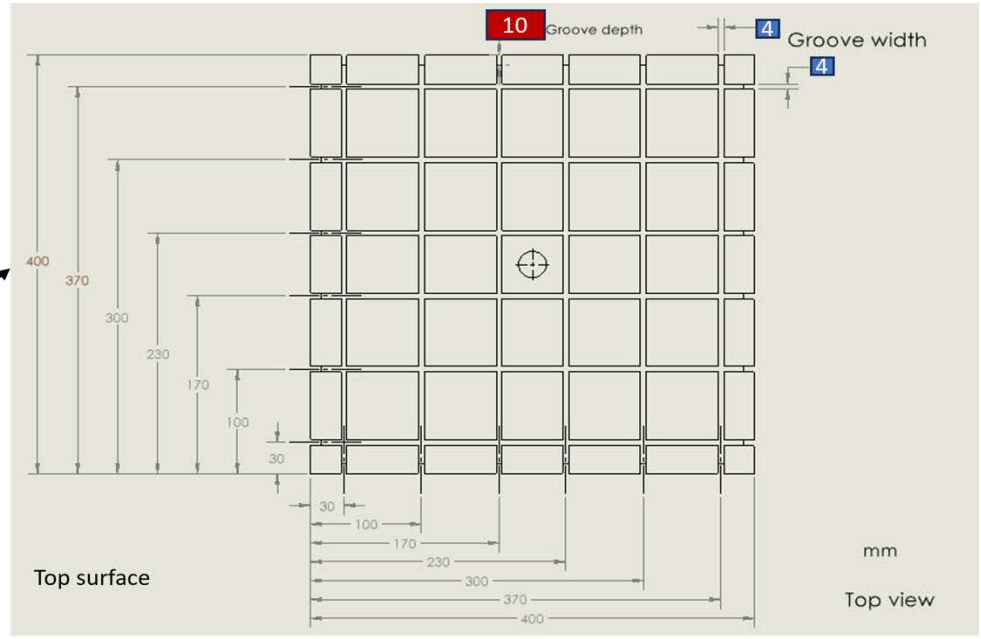

Diameter =2.5 cm
Borehole
20 cm
23 cm
Diameter =0.8 cm
3cm
40 cm
Limestone
40 cm
Center view

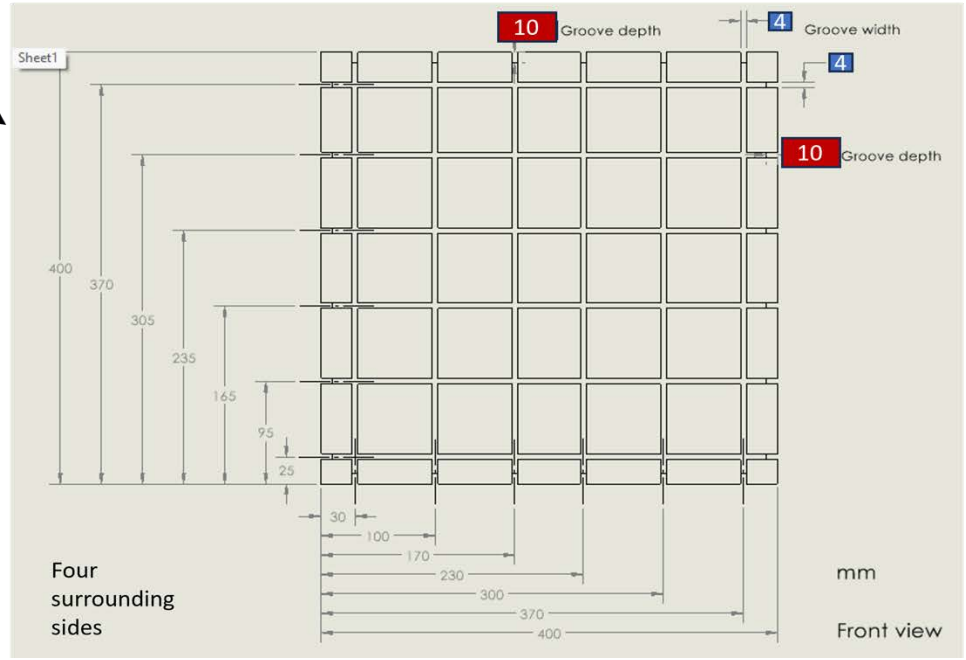

Borehole
Diameter
0.8 cm
Diameter =2.5 cm
40 cm
Limestone
40 cm
Top view



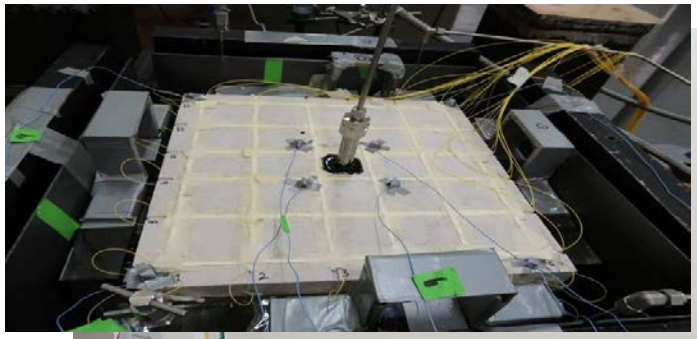
Groove Dimensions







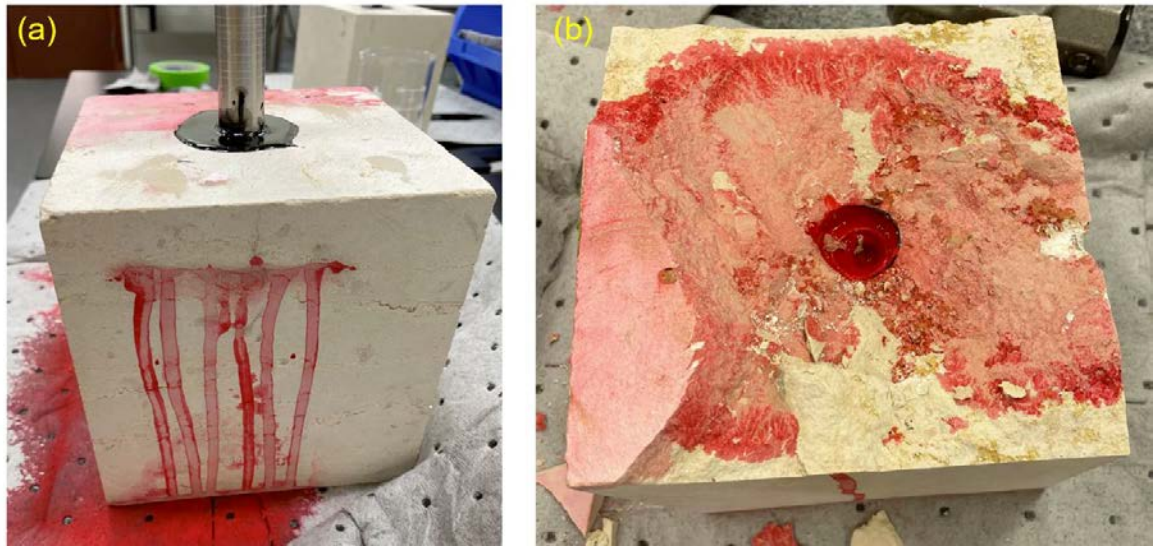
Experimental Setup



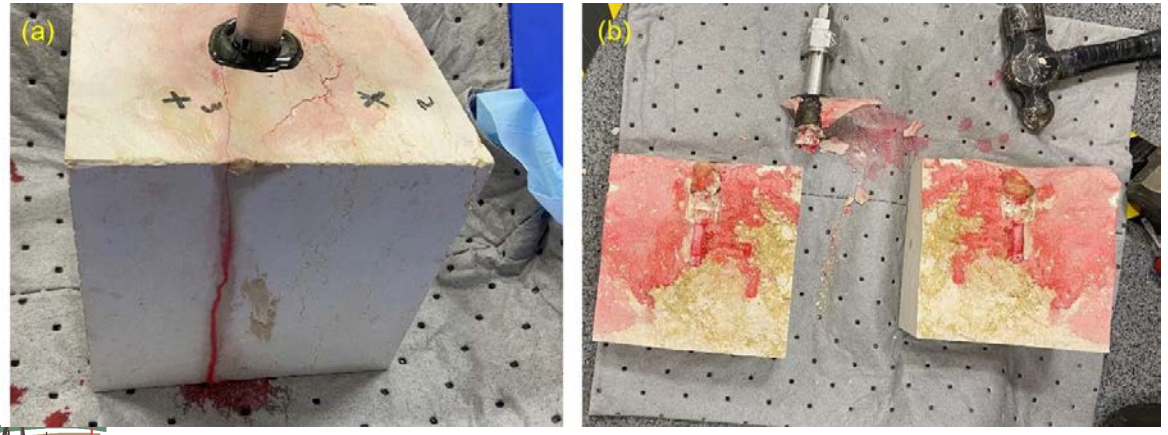
- Rock is wrapped with FO cables and mounted in triaxial frame.
- AE transducers and fiber optic cables for DAS
  - Coupling of FO cables to rock
- Isco-pumps for confining pressure applied & fluid injection.
- AK-Sens interrogator:
  Measurement: Differential intensity
  Gauge length: 1.5 m
  Channel spacing: 0.54 m

Small Rock Block Experiments

Small Rock Block 1



Small Rock Block 2

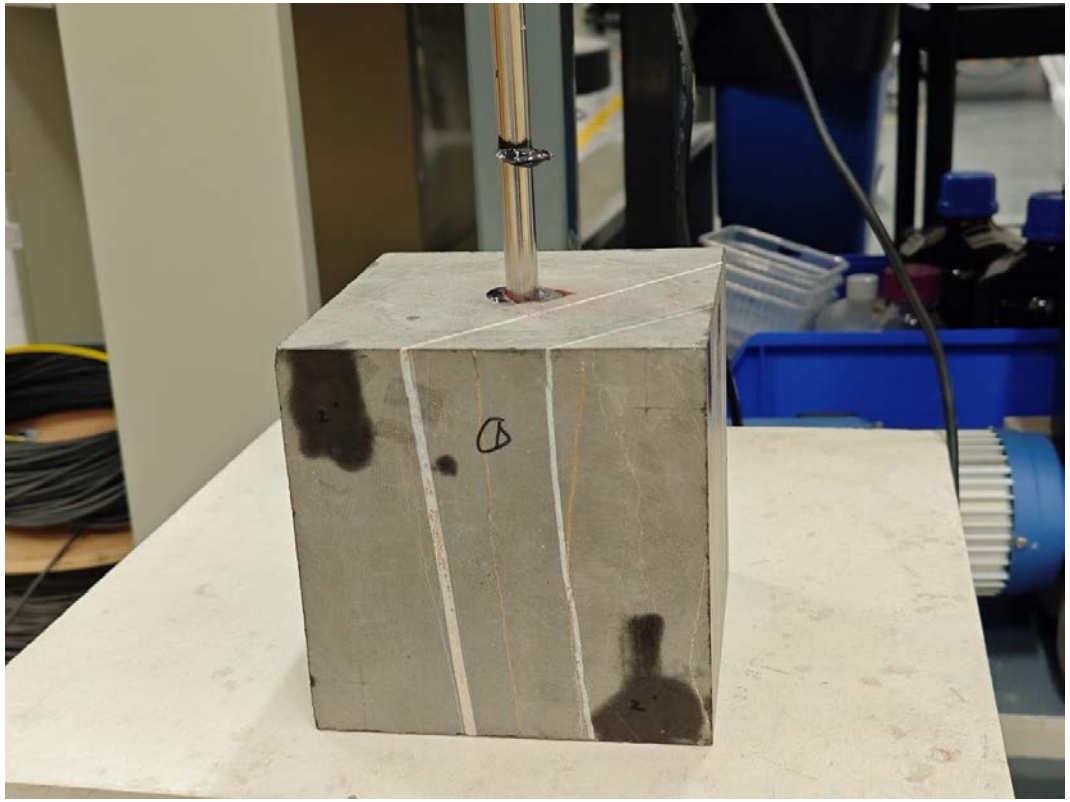


Small Rock Block 3

- Tests on small rock blocks.
- Limestone fractures
- Marble required pre-conditioning with LN_2

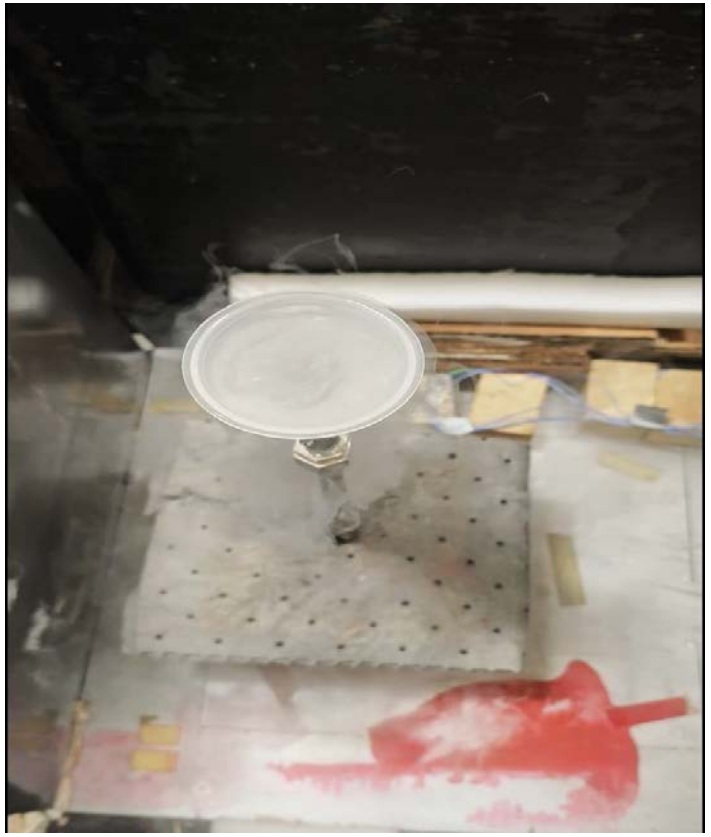
Small Rock Block Experiment: Marble

Initial HF injection failed



- Peak pressure reached: 4,000 psi (27.6 MPa)
- Tubing came off!

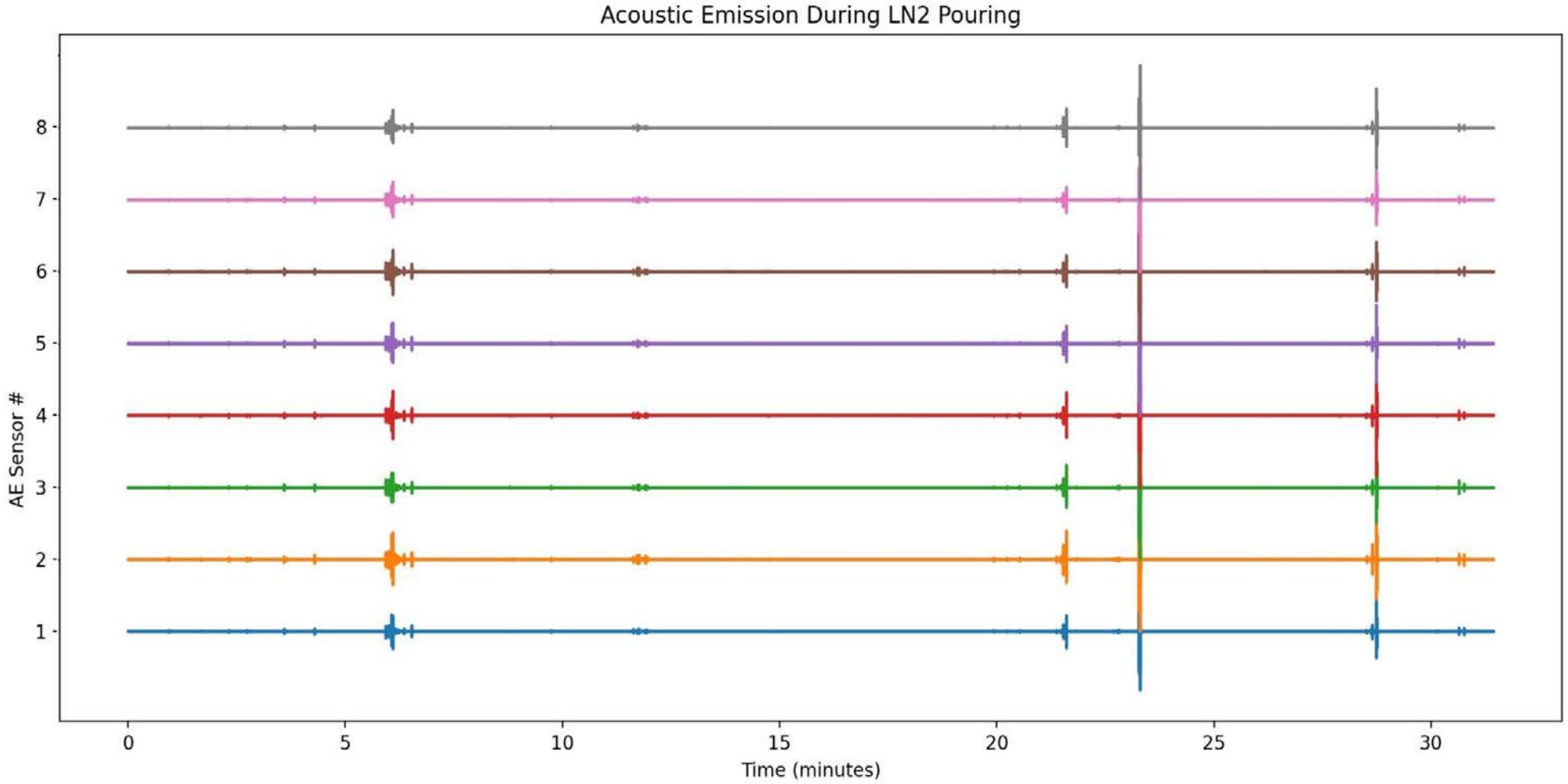
So, we precondition with LN_2



- 3L of LN_2 at room temp. & pressure
- Duration: 32 mins.
- AE sensors installed

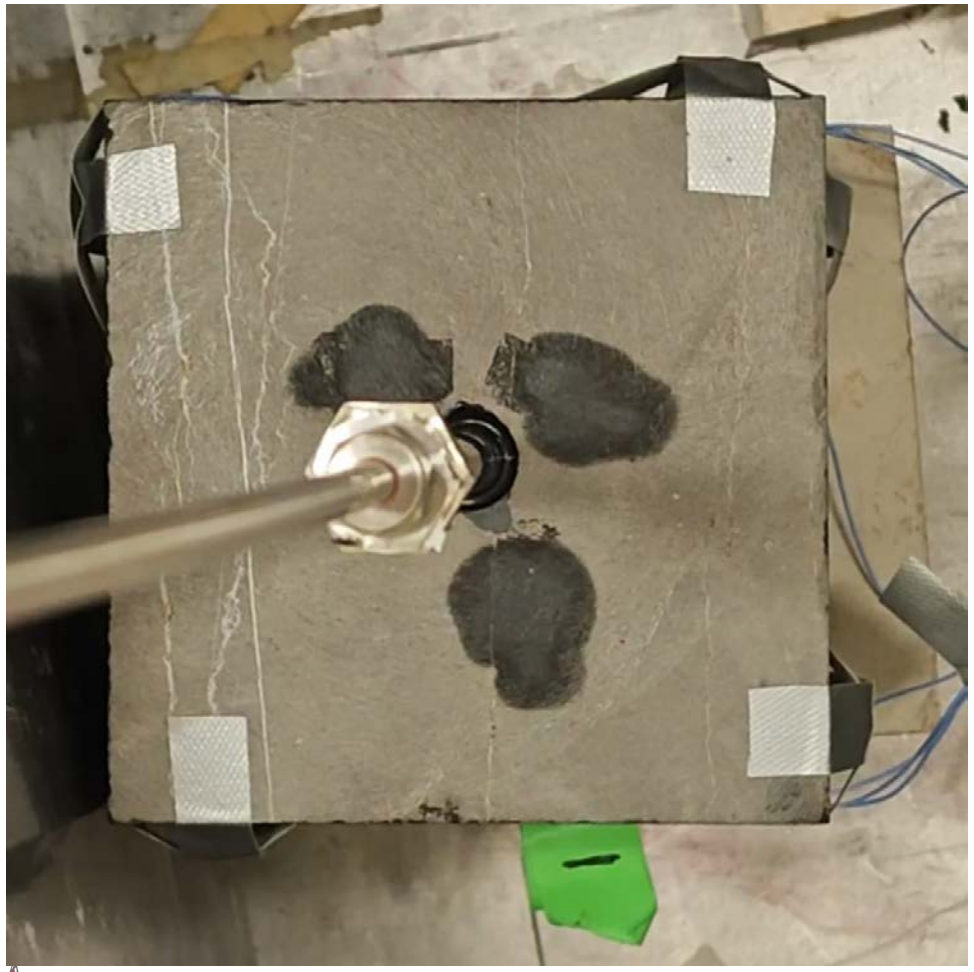
Small Rock Block Experiment: Marble

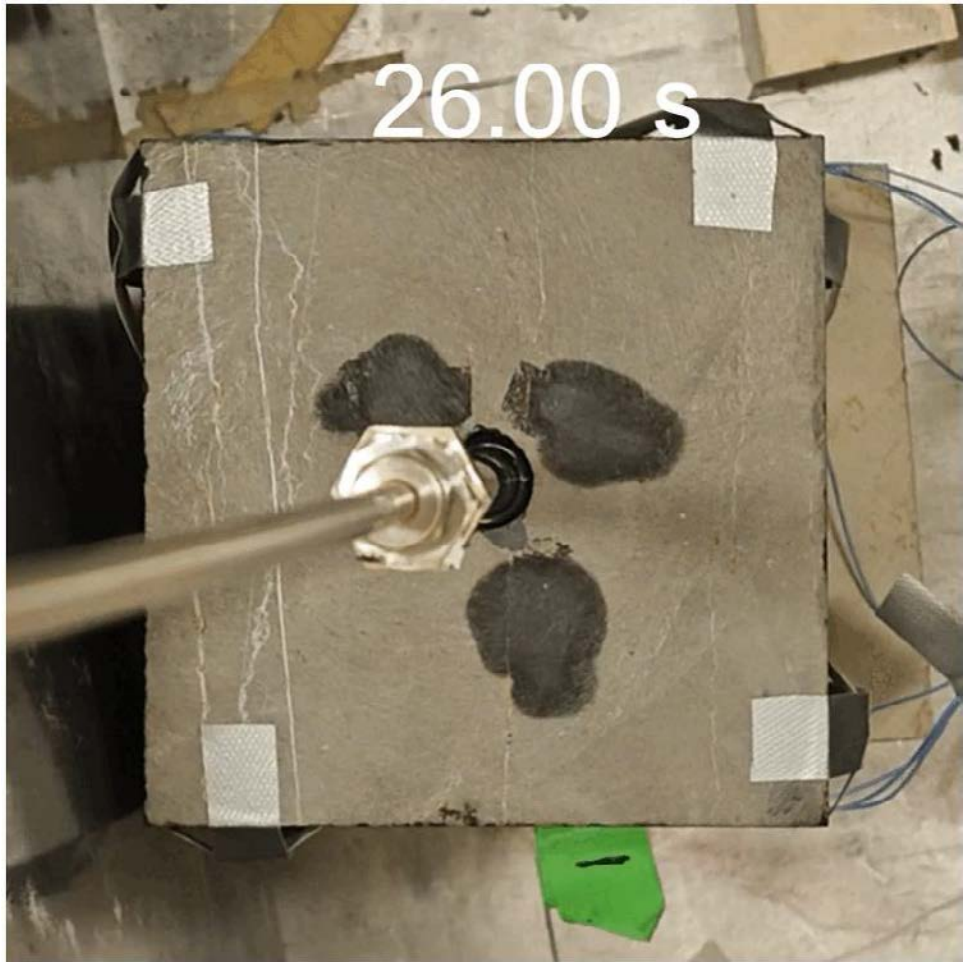
LN_2 initiates fractures



Small Rock Block Experiment: Marble

HF conducted 2 hours after pre-conditioning with LN_2

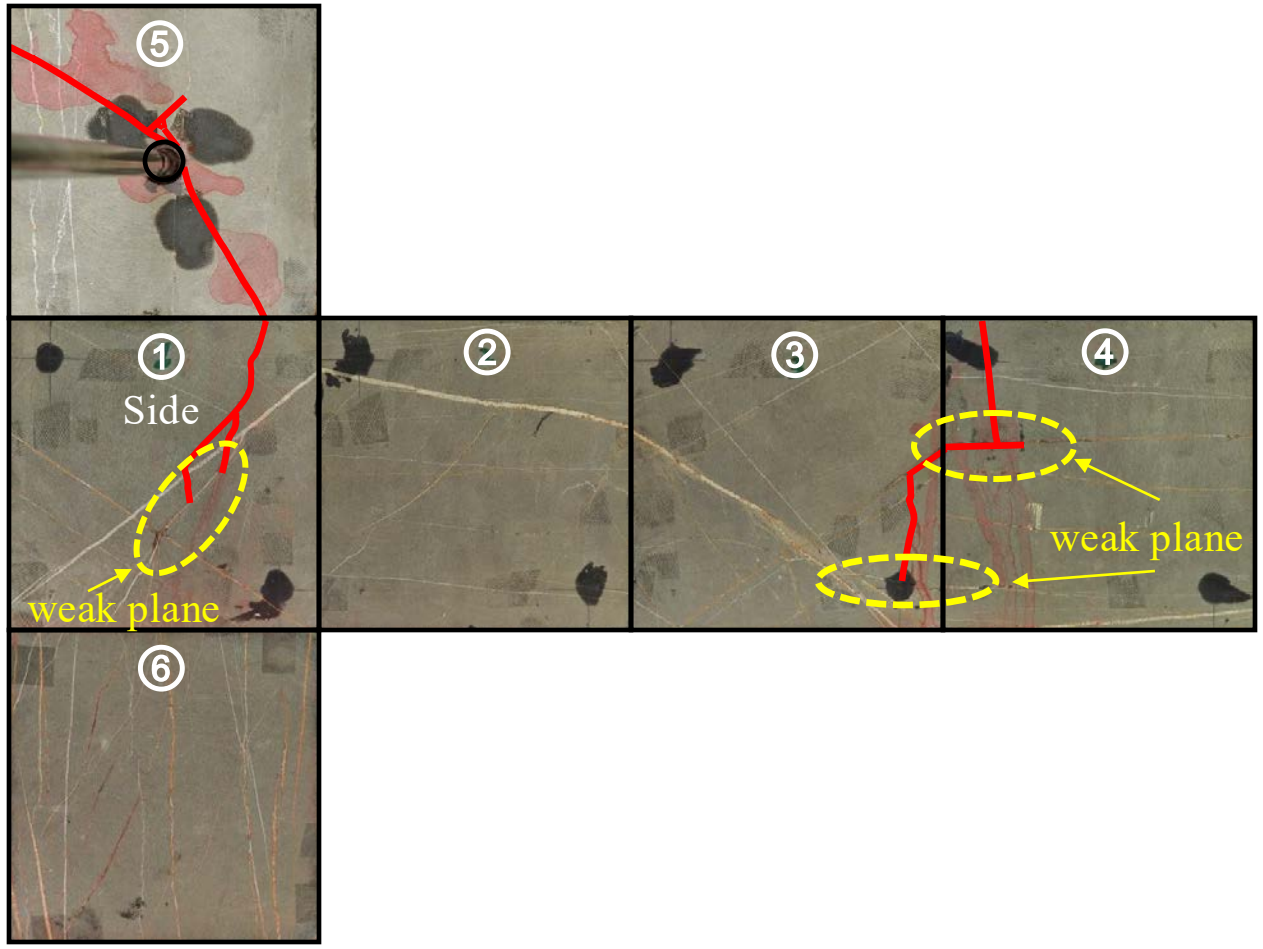




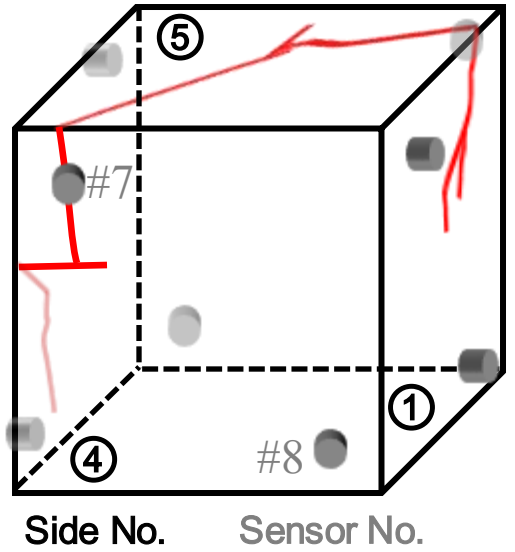
Playback at 0.02 s intervals

Small Rock Block Experiment: Marble

HF conducted 2 hours after pre-conditioning with LN_2



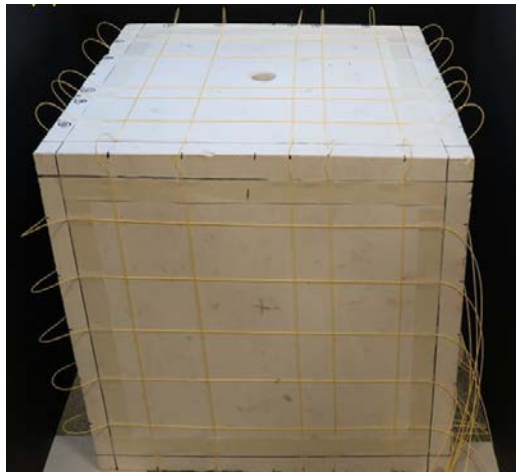
Unrolled view of the marble rock



3D display of surface cracks

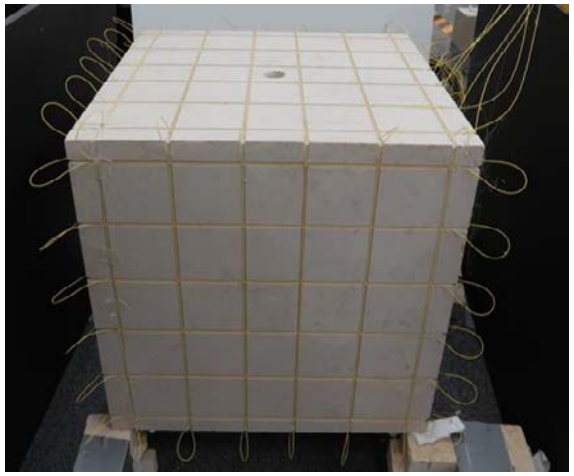
Four Large Rock Blocks: Before HF Experiment

Rock Block 1



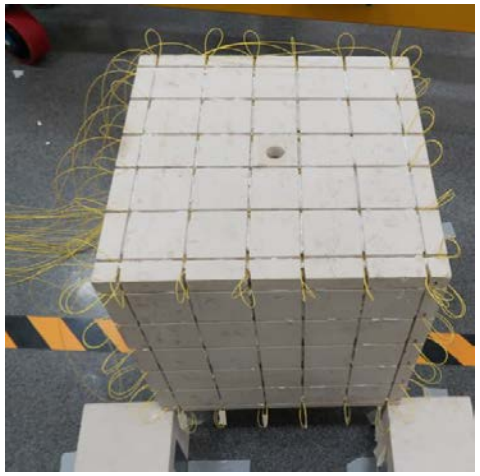
Type: Limestone
Vp: 5,260 m/s
FO lines: 5/face
Conf. Pres: 0.21–0.11 MPa

Rock Block 2



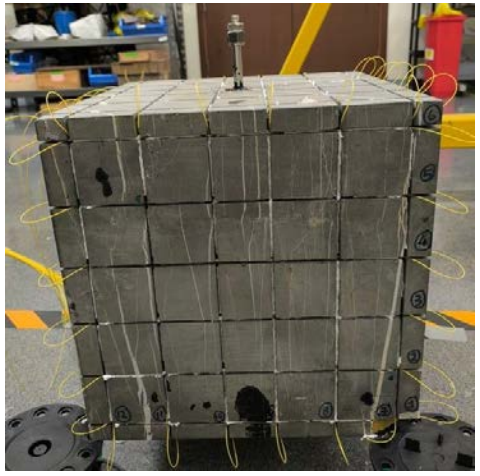
Type: Limestone
Vp: 5,260 m/s
FO lines: 6/face
Conf. Pres: 0.21–0.11 MPa

Rock Block 3



Type: Limestone
Vp: 5,282 m/s
FO lines: 6/face
Conf. Pres: 0.2 –0.11 MPa

Rock Block 4

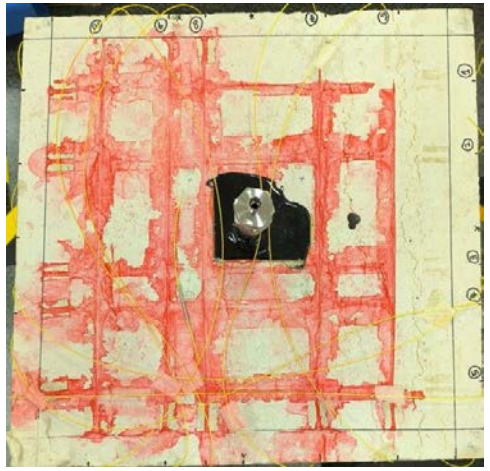


Type: Marble
Vp: 6,752 m/s
FO lines: 6/face
Conf. Pres: 0.18–0.10 MPa

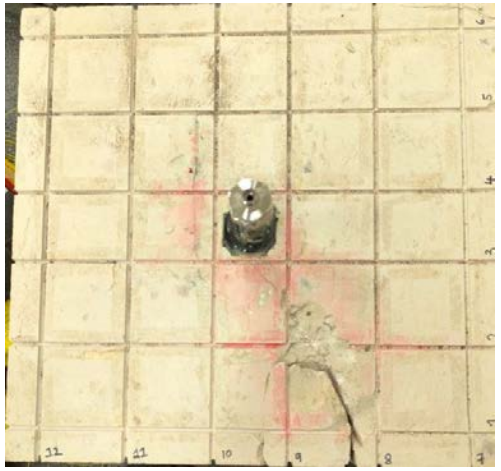
- All rock blocks measured 40cm x 40 cm x 40 cm
- Rock Block 3 had double wrap to improve signal-to-noise ratio
- Rock Block 4 was preconditioned with 8L of liquid N_2 36 hours prior to stimulation

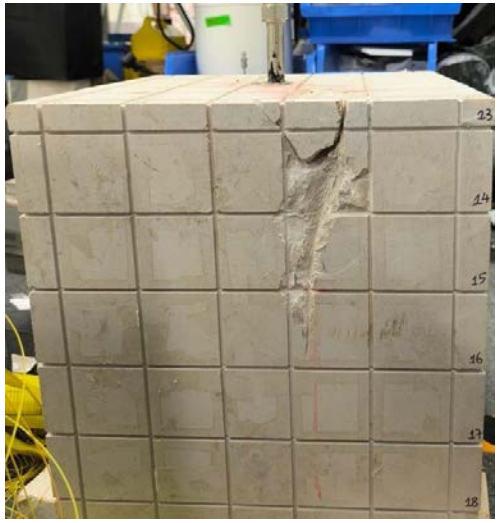
Experiment: Four Large Rock Blocks after HF Experiment

Rock Block 1
Limestone

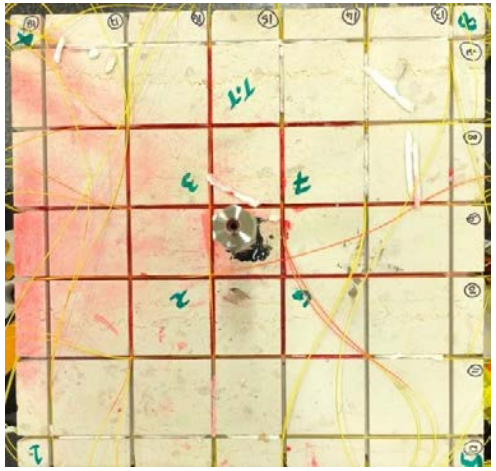


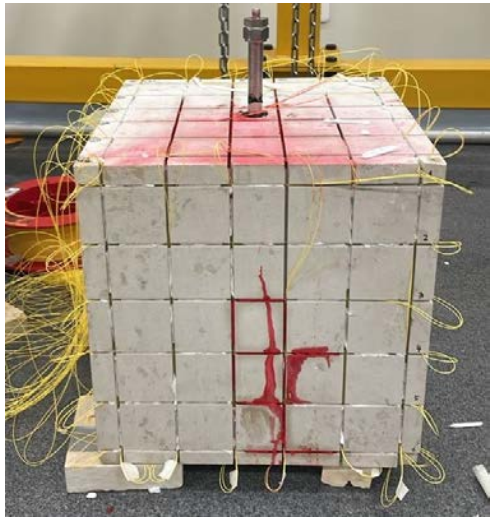
Rock Block 2
Limestone



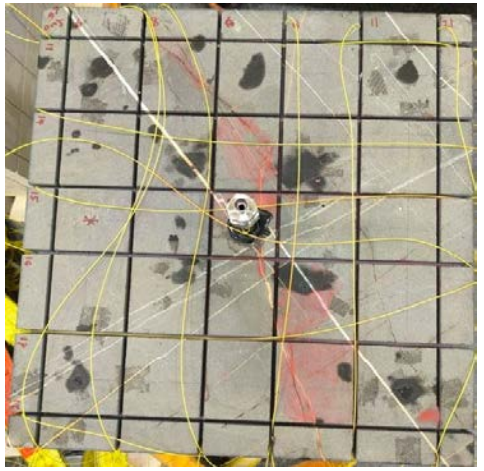


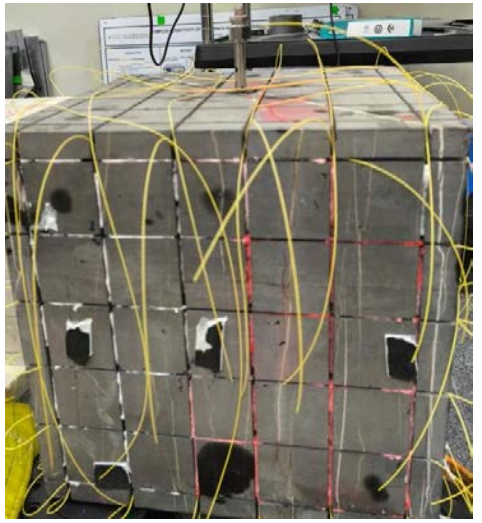
Rock Block 3
Limestone





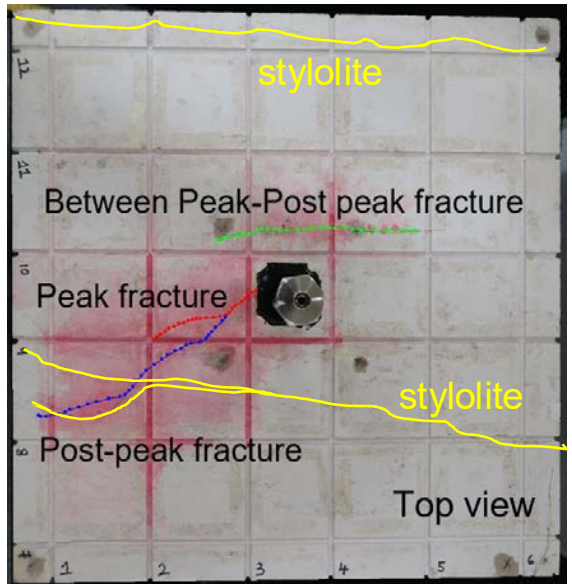
Rock Block 4
Marble, LN_2

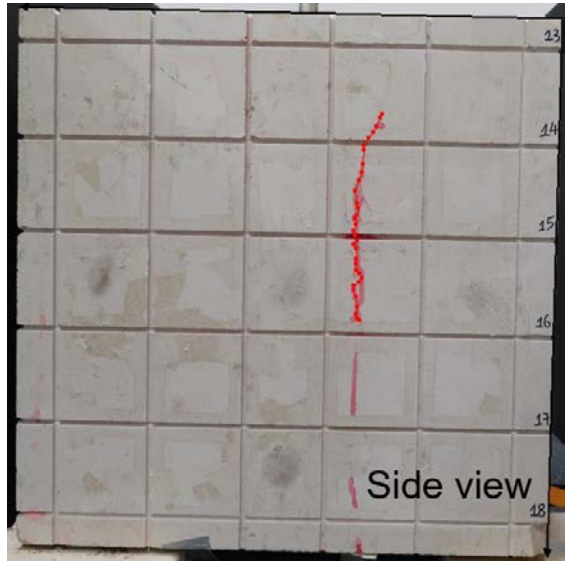




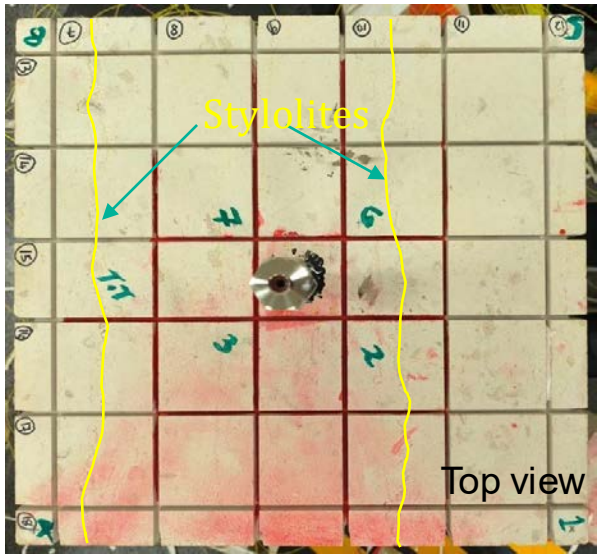
Experiment: Fracture and Stylolite Visualization

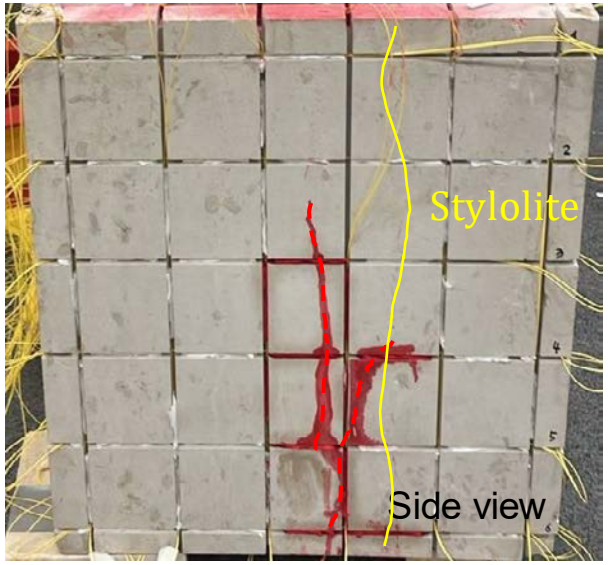
Rock Block 2



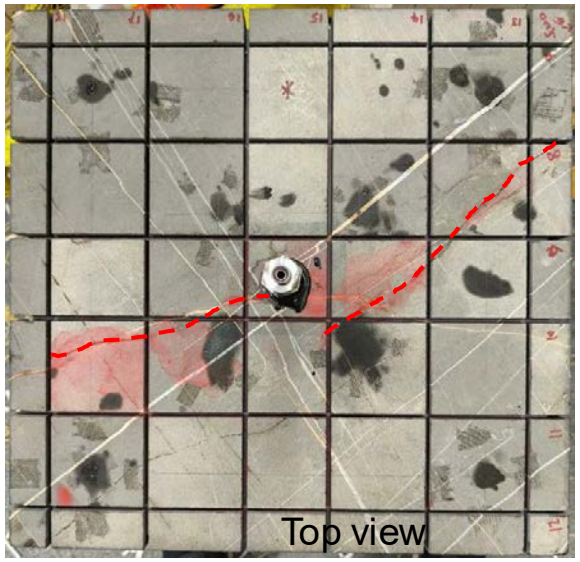


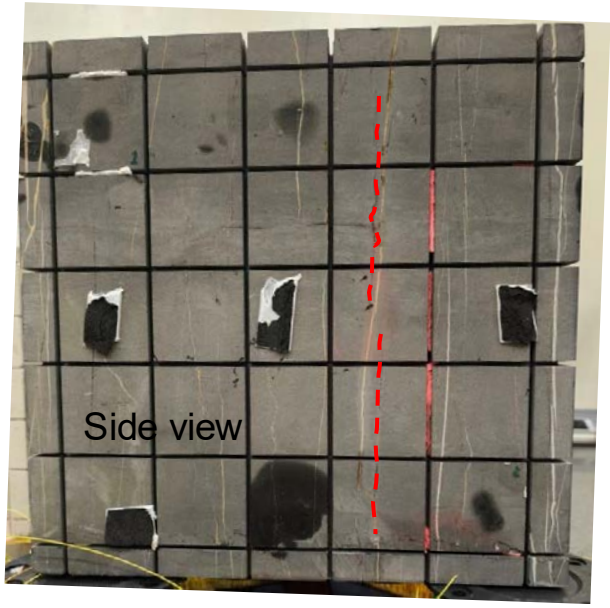
Rock Block 3





Rock Block 4

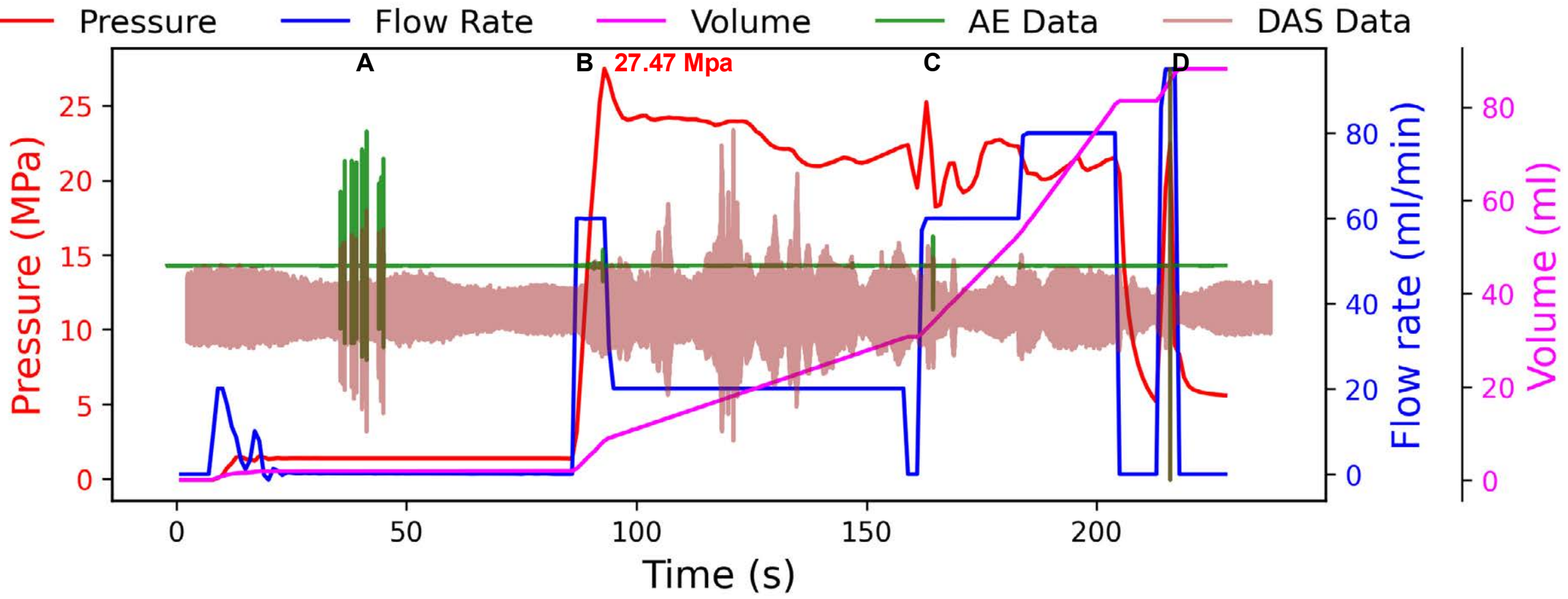




Results from Rock Block 3

Signal Processing and Imaging

Pump Statistics & Waveform Signal



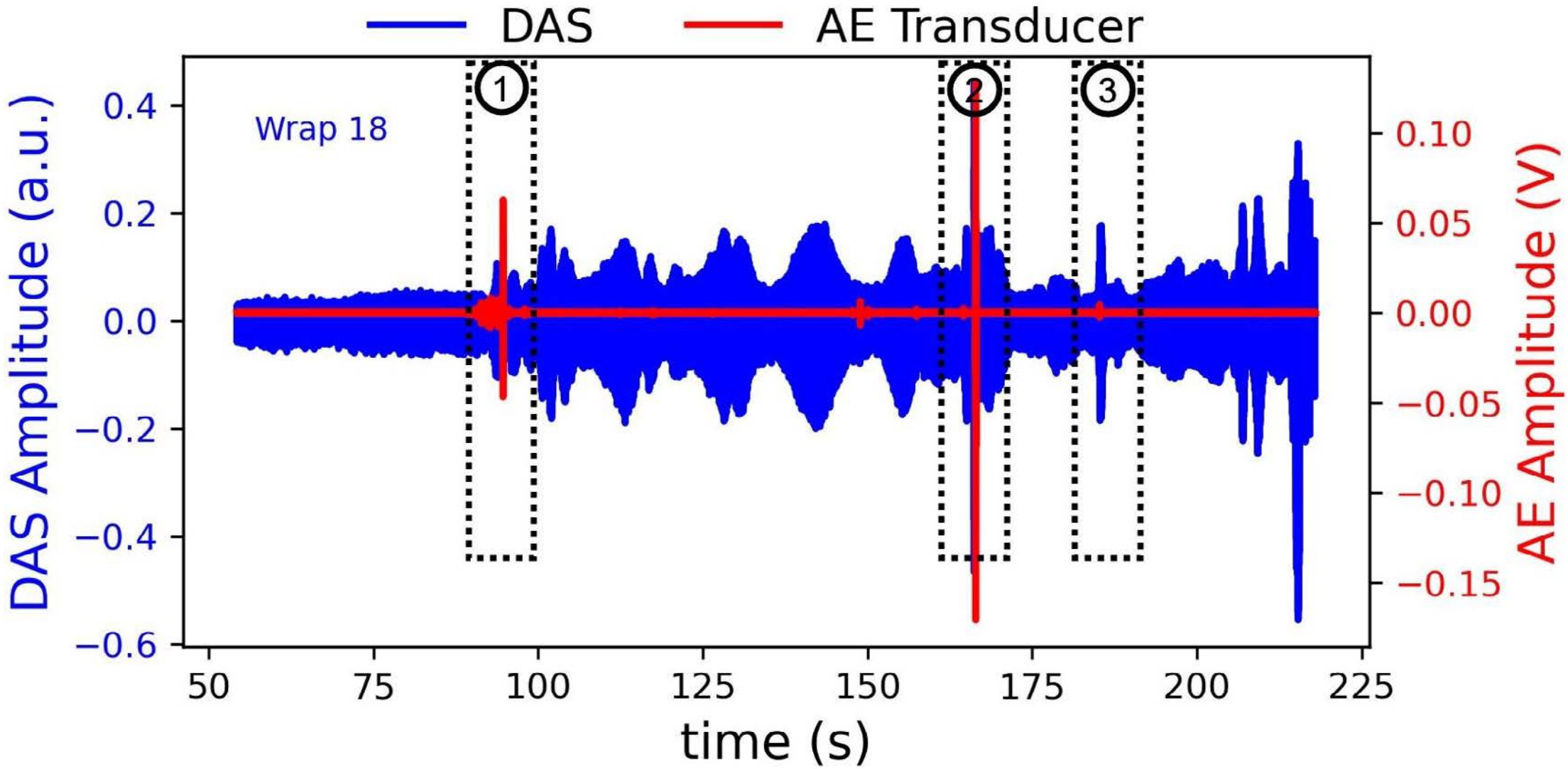
A: Tappings

B: Breakdown

C: second failure (breakdown of additional fracture?)

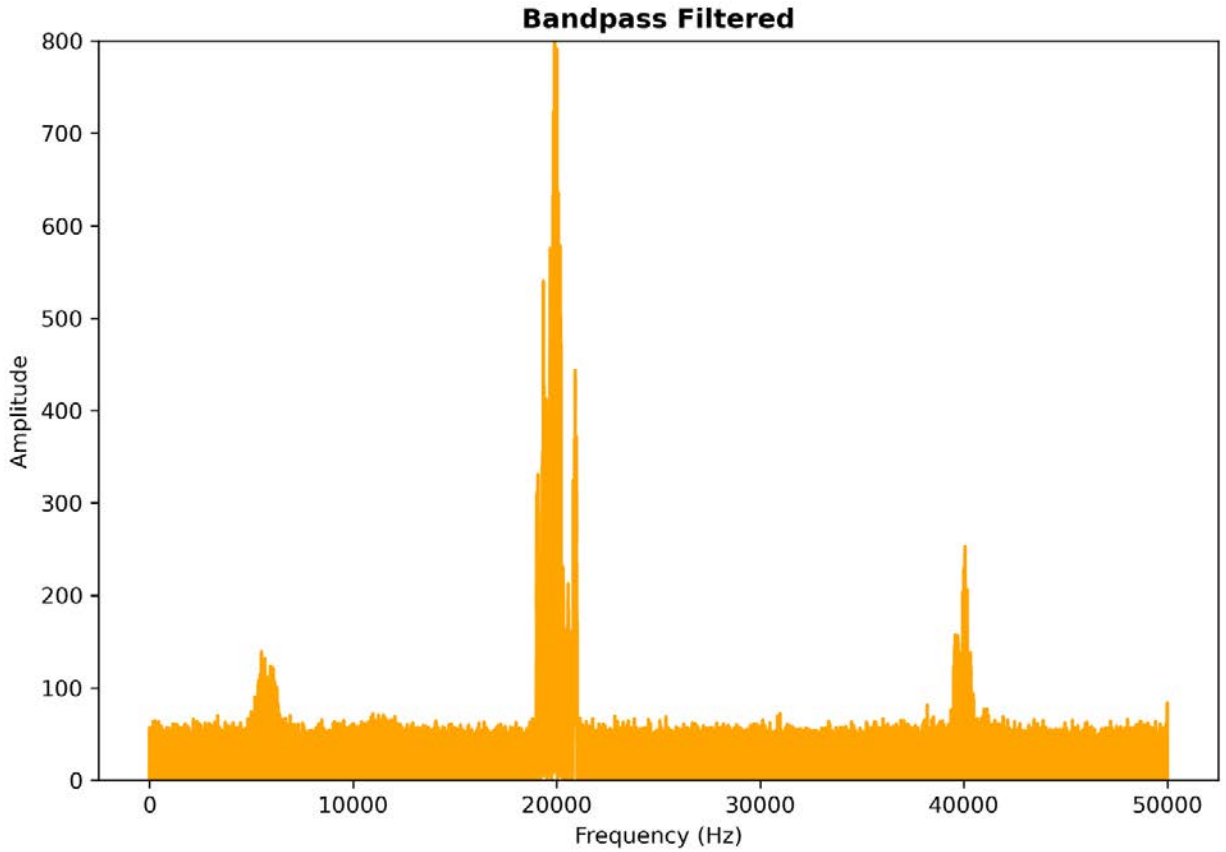
D: Tubing (well casing) detached and "ejected" from the rock block

Overlay of DAS and Transducer Events Sections

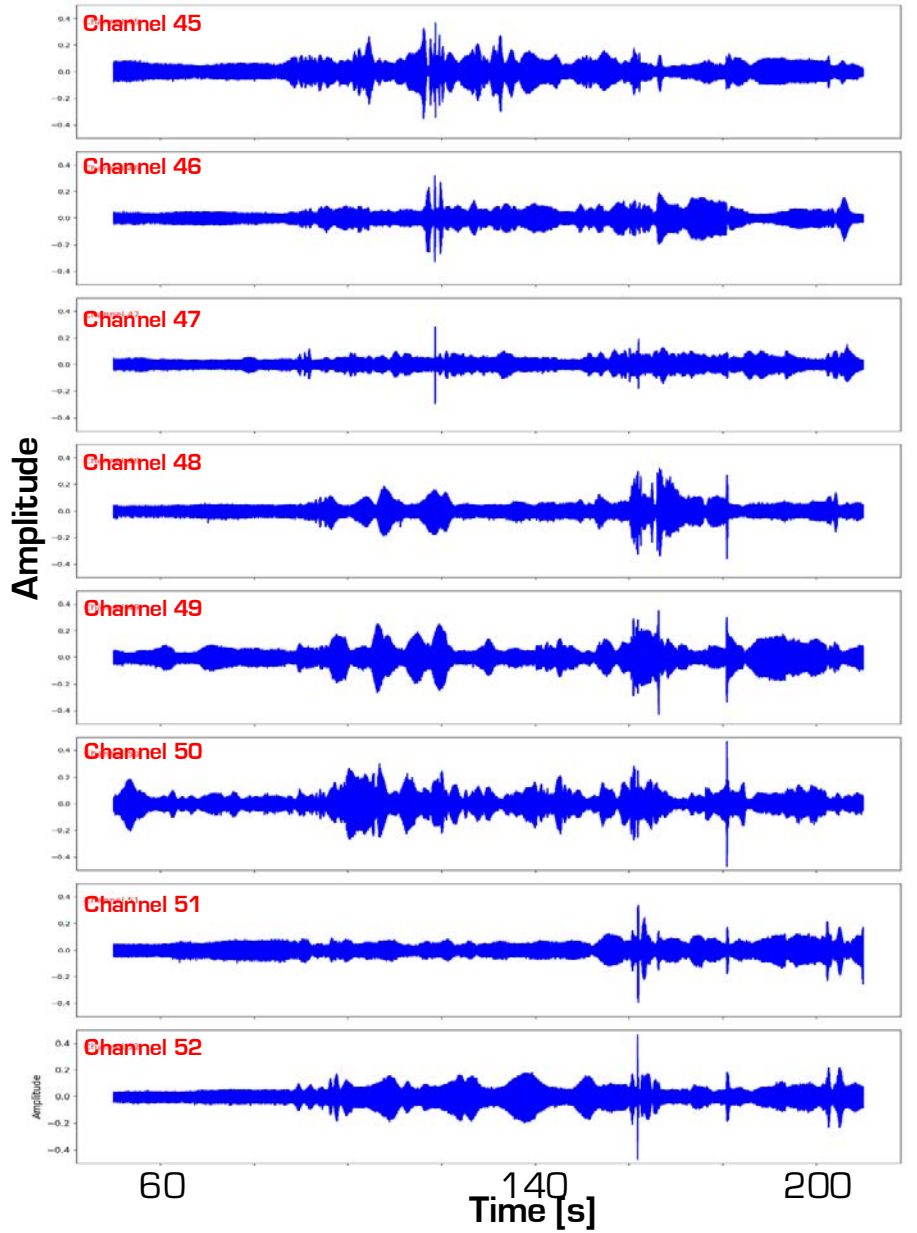


Imaging Challenges

Frequency Spectrum of DAS



Sample Processed DAS Records

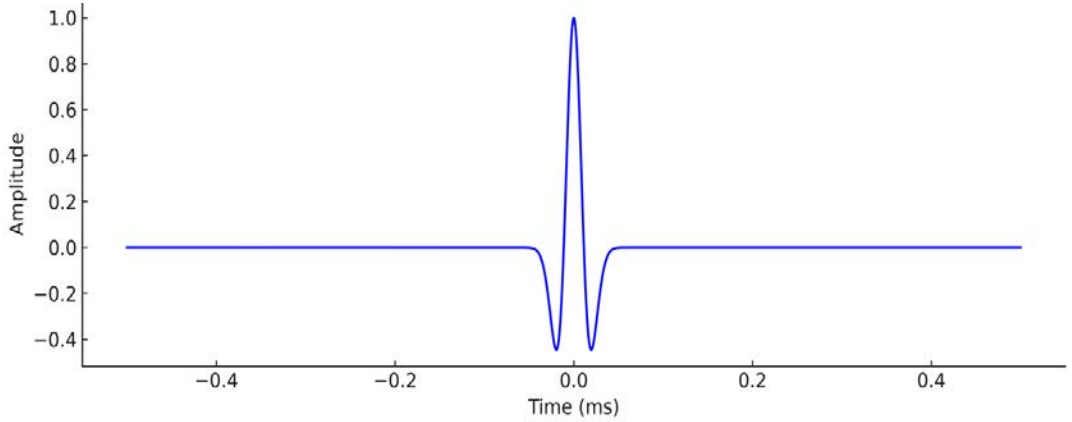


Imaging Challenges

1. Source wavelet unknown

Solution:

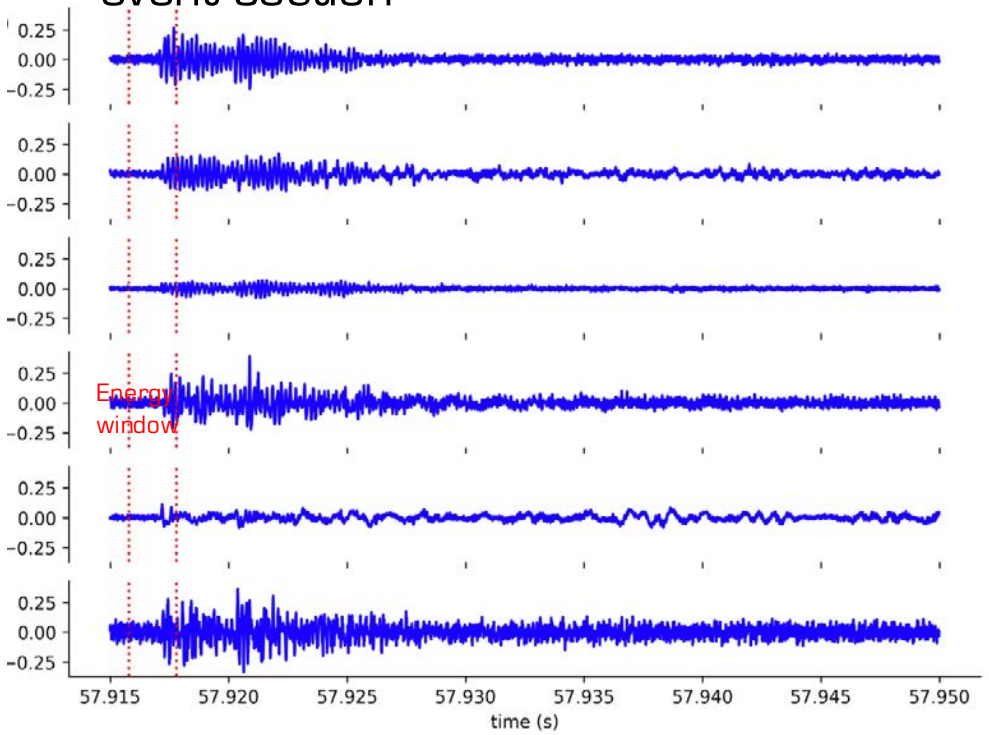
- Assume a zero-phase 20 kHz Ricker wavelet.
- Wavelet spectrum based on frequency spectrum of recorded events



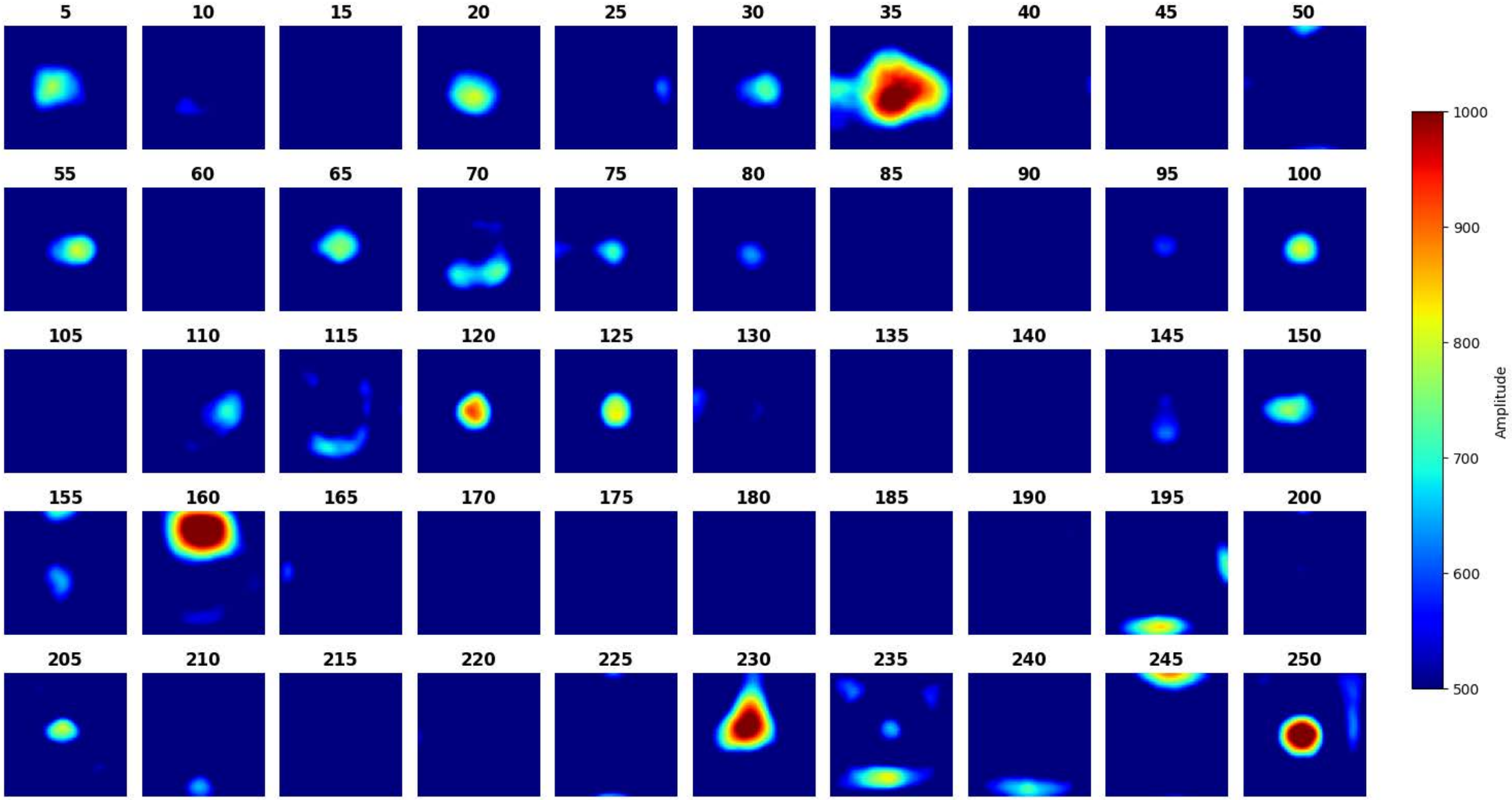
2. Origin time unknown

Solution

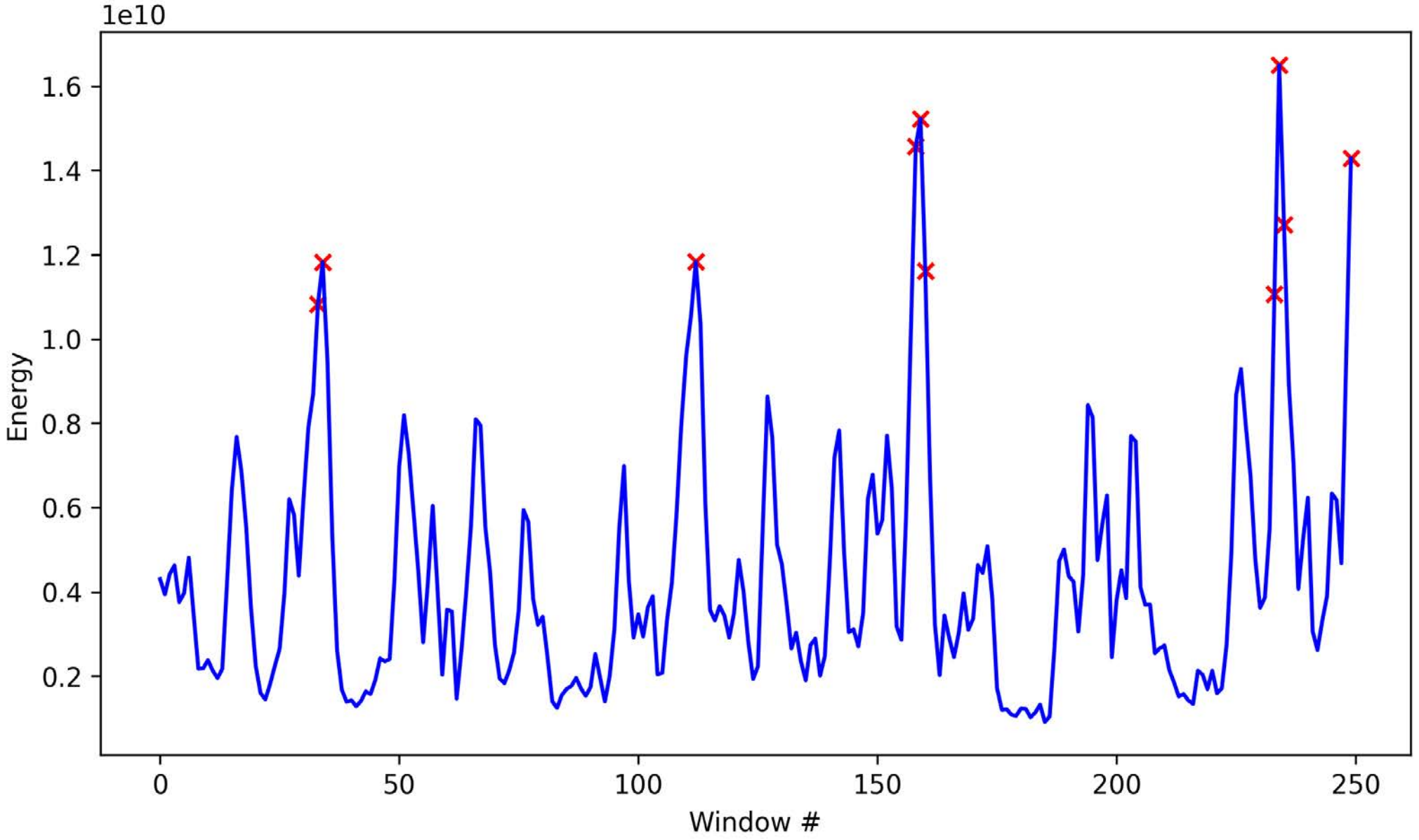
- Sliding window analysis around expected arrival time to capture and calculate energy concentration → 250 window positions along event section



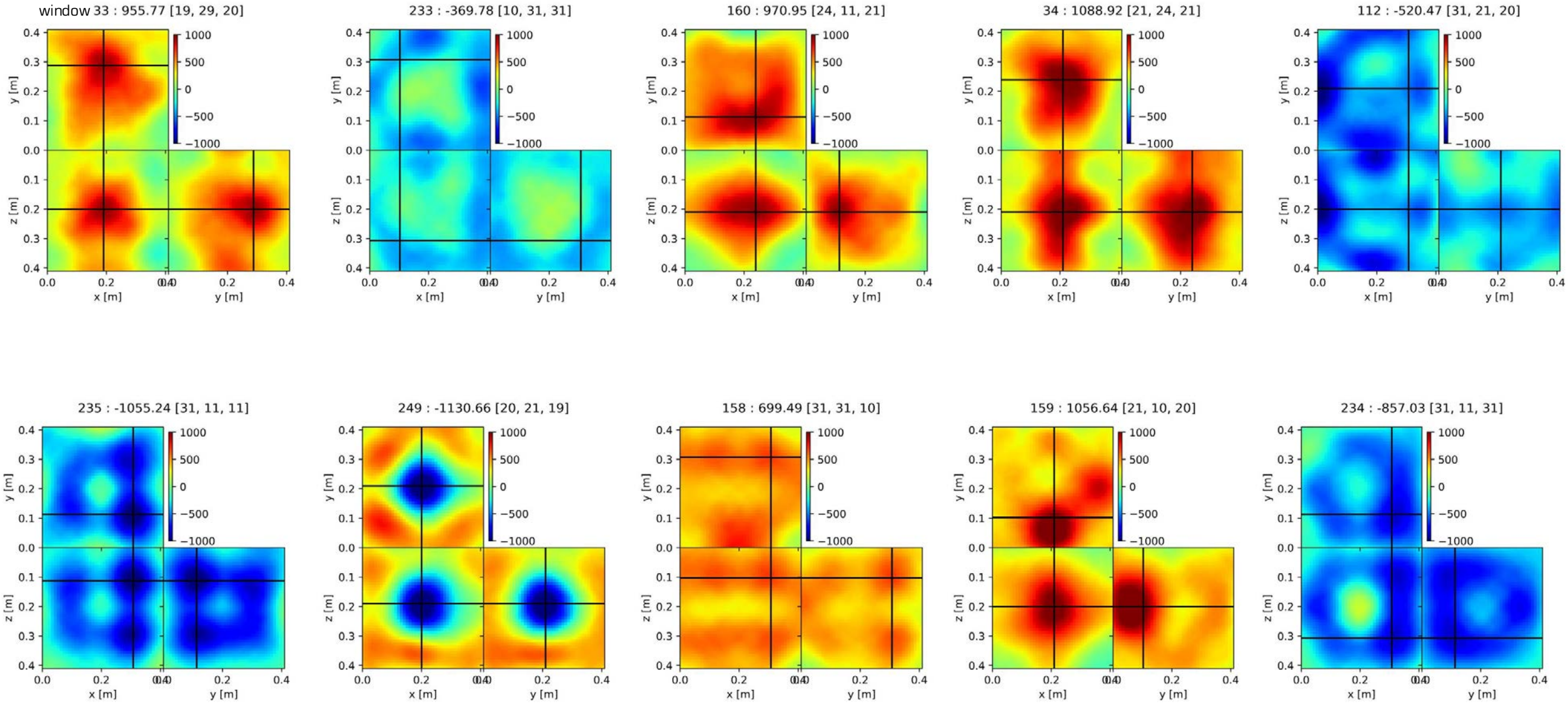
Travel-time Migration Results



Top 10 High Energy Windows

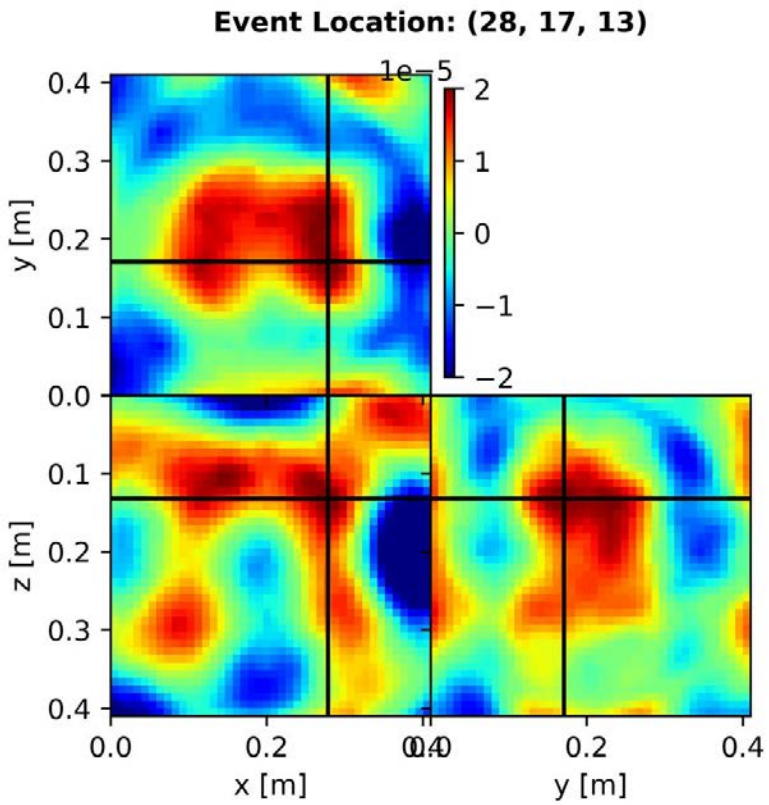


Travel-time Cubes

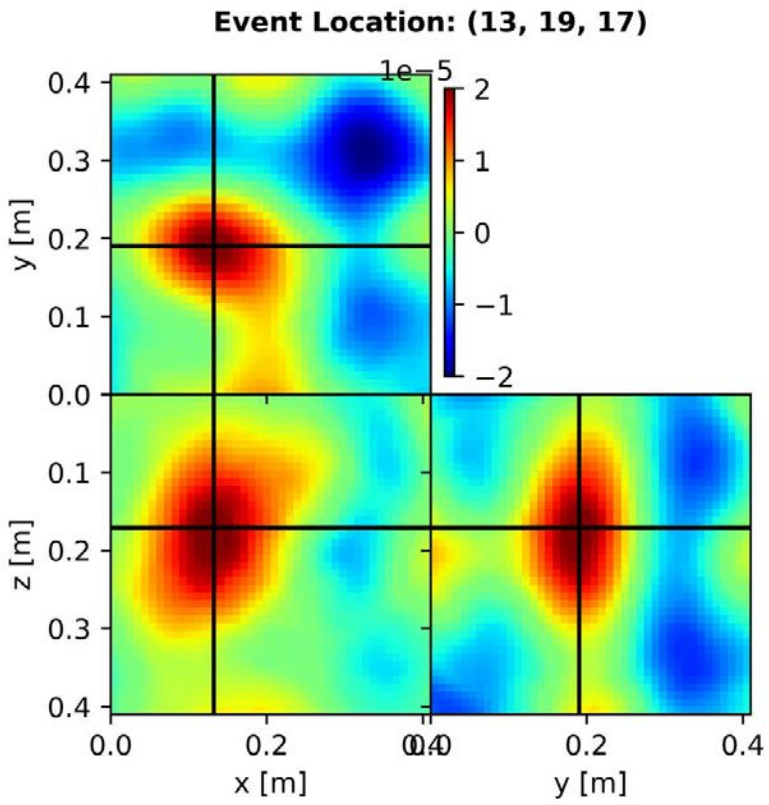


Inverted Fracture Locations

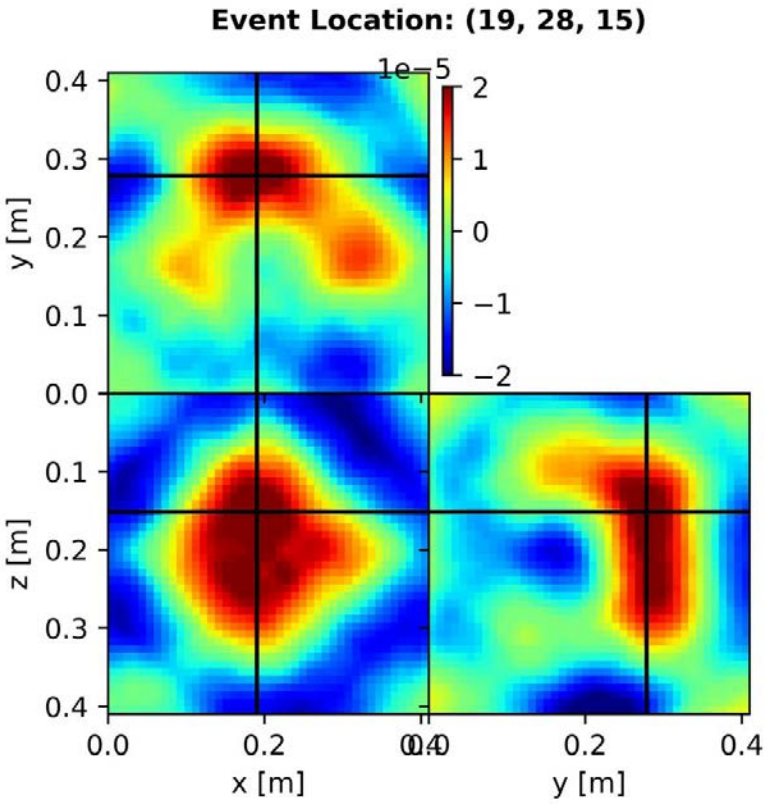
Event 1



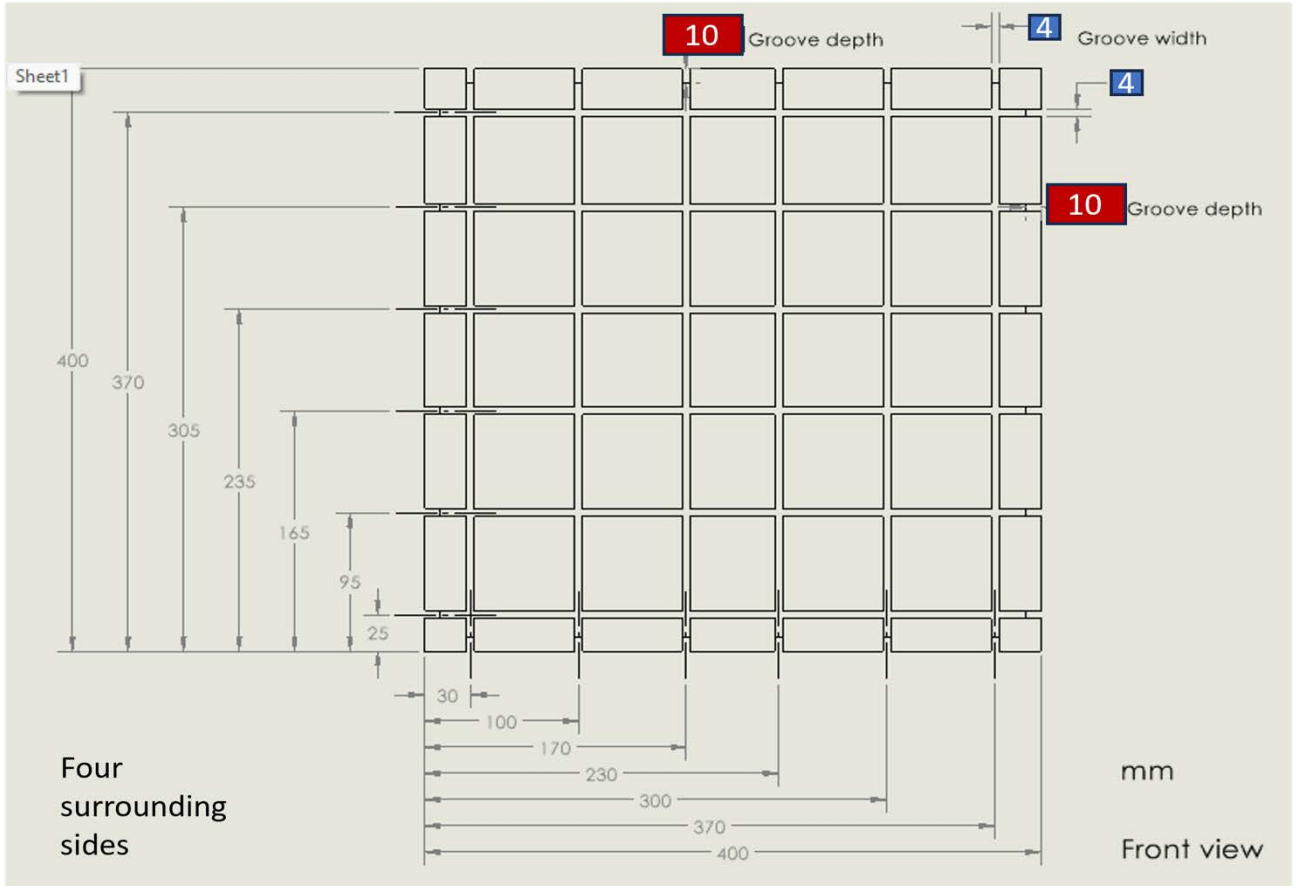
Event 2



Event 3



Inverted Fracture Locations

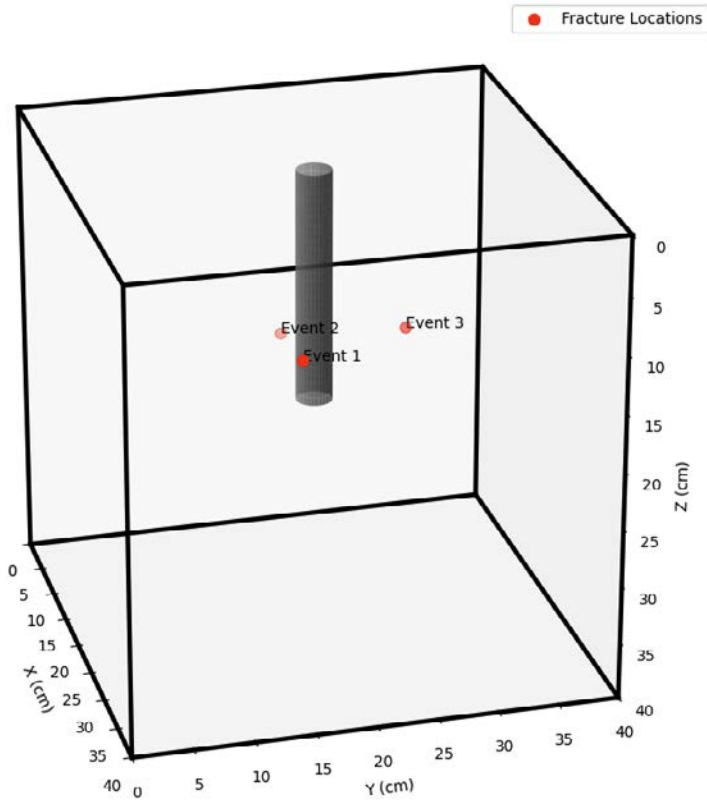


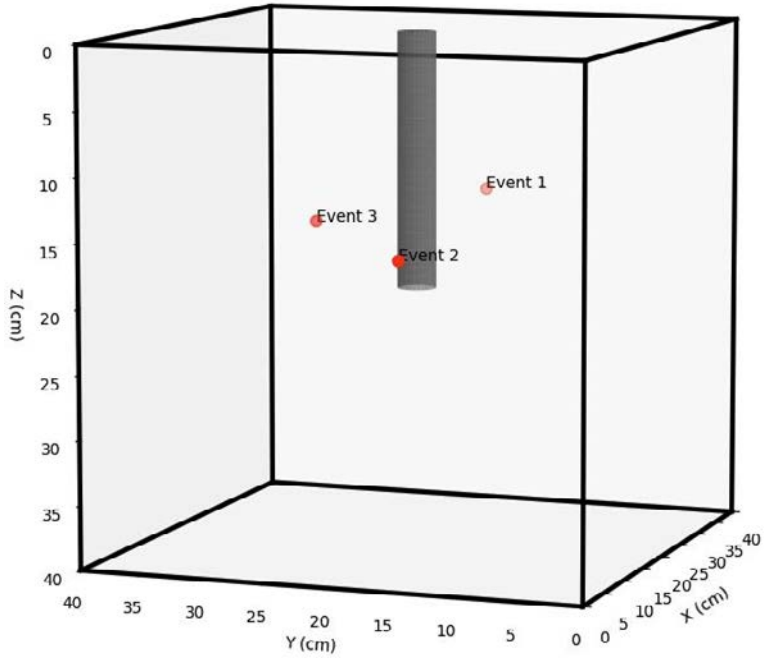
Inverted Fracture Locations

Event 1 : (28, 17, 13)

Event 2 : (13, 19, 17)

Event 3: (19, 28, 15)





Conclusions

- Four lab-scale hydraulic fracturing experiments have been conducted on cubic rock blocks measuring 40 cm × 40 cm × 40 cm.
- Additionally, three smaller-scale blocks (15 cm × 15 cm × 15 cm) were tested to explore parameter sensitivity and refine instrumentation protocols.
- A cryogenic pre-fracturing process using about 8 liters of liquid nitrogen was done on rock block 4, causing thermal shock and helping to initiate fractures before injecting fluid.
- DAS and AE data were collected from all large block experiments.
- Detection and localization of fractures in Rock Blocks 2 and 3 have been done using both DAS and AE data.

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Thank you for listening!

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