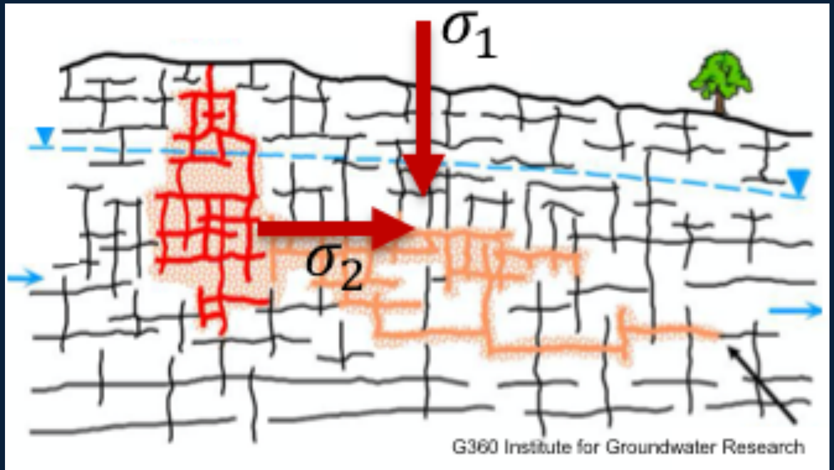
Earth Resources Laboratory

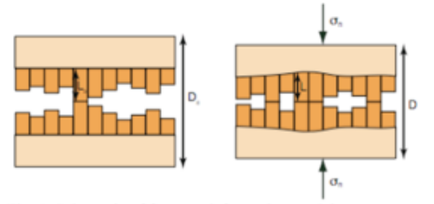
Experimental Study of Flow in Fractured Media

Rafael Villamor Lora, Hao Kang
GRADUATE STUDENTS [CIVIL AND ENVIRONMENTAL ENGINEERING]

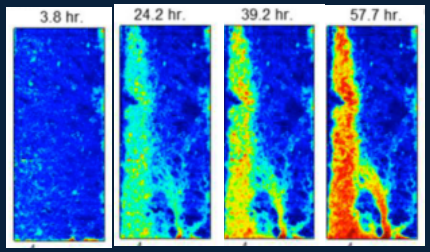
Supervised by Prof. Herbert Einstein, in collaboration with Wei Li

Introduction

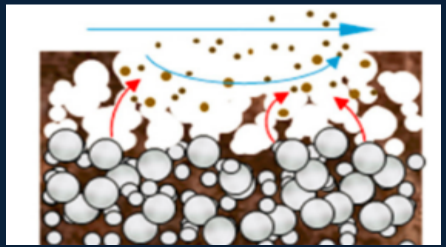




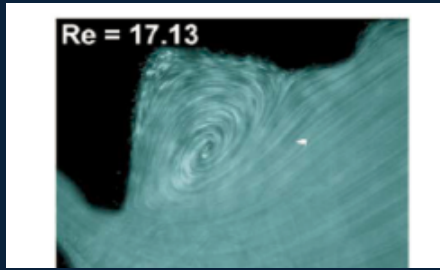
Detwiler & Morris. (2014)



Deng et al. (2015)



Deng et al. (2015)



Lee et al. (2015)

Mechanical deformation

Dissolution

Surface erosion

Non-linear flow

Coupled Processes

Key Points

- Fracture flow is affected by a series of coupled processes → Experimental results may be difficult to interpret

- Better understanding through experiments in which:
  - Processes can be separated
  - Processes can be observed directly (e.g. visually)

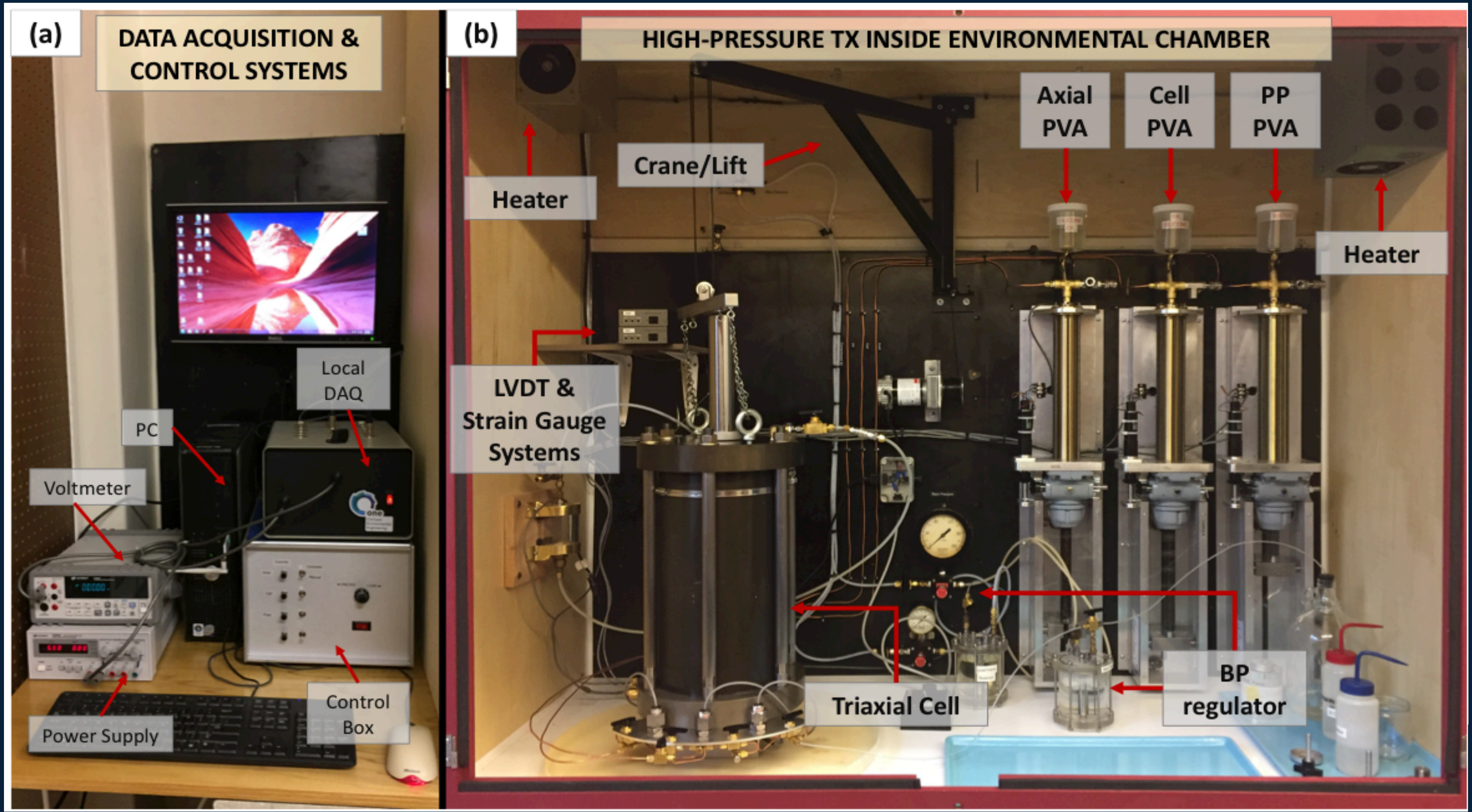
- Will lead to more accurate models, and validation of existing ones.

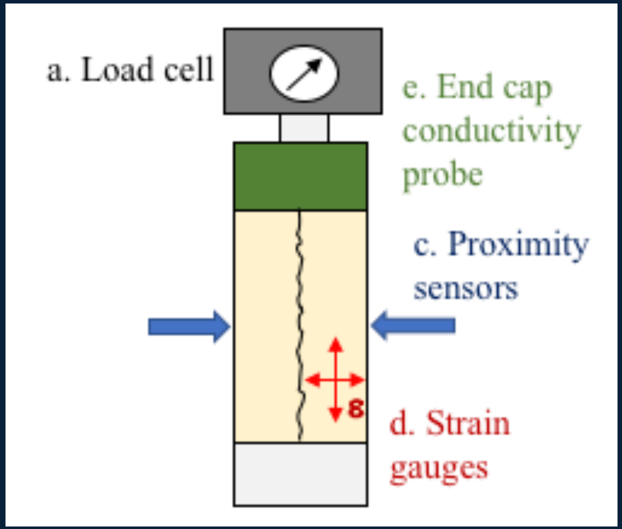
Earth Resources Laboratory

Outline

- Laboratory Equipment
- Fracture Replica [Acrylic/Silicone]
- Real Rock [Limestone]
- Conclusions

Laboratory Equipment

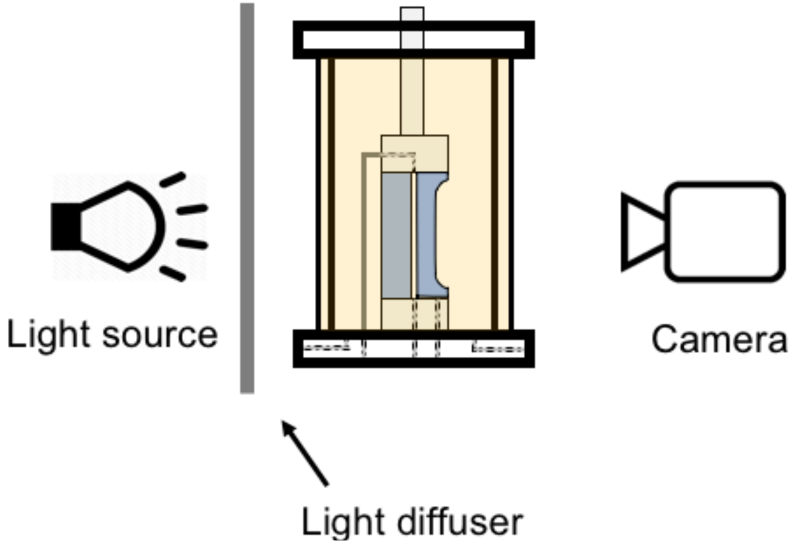




- Low-Pressure TX
- Medium-Pressure TX
- Materials

Investigation using Idealized Fracture Models

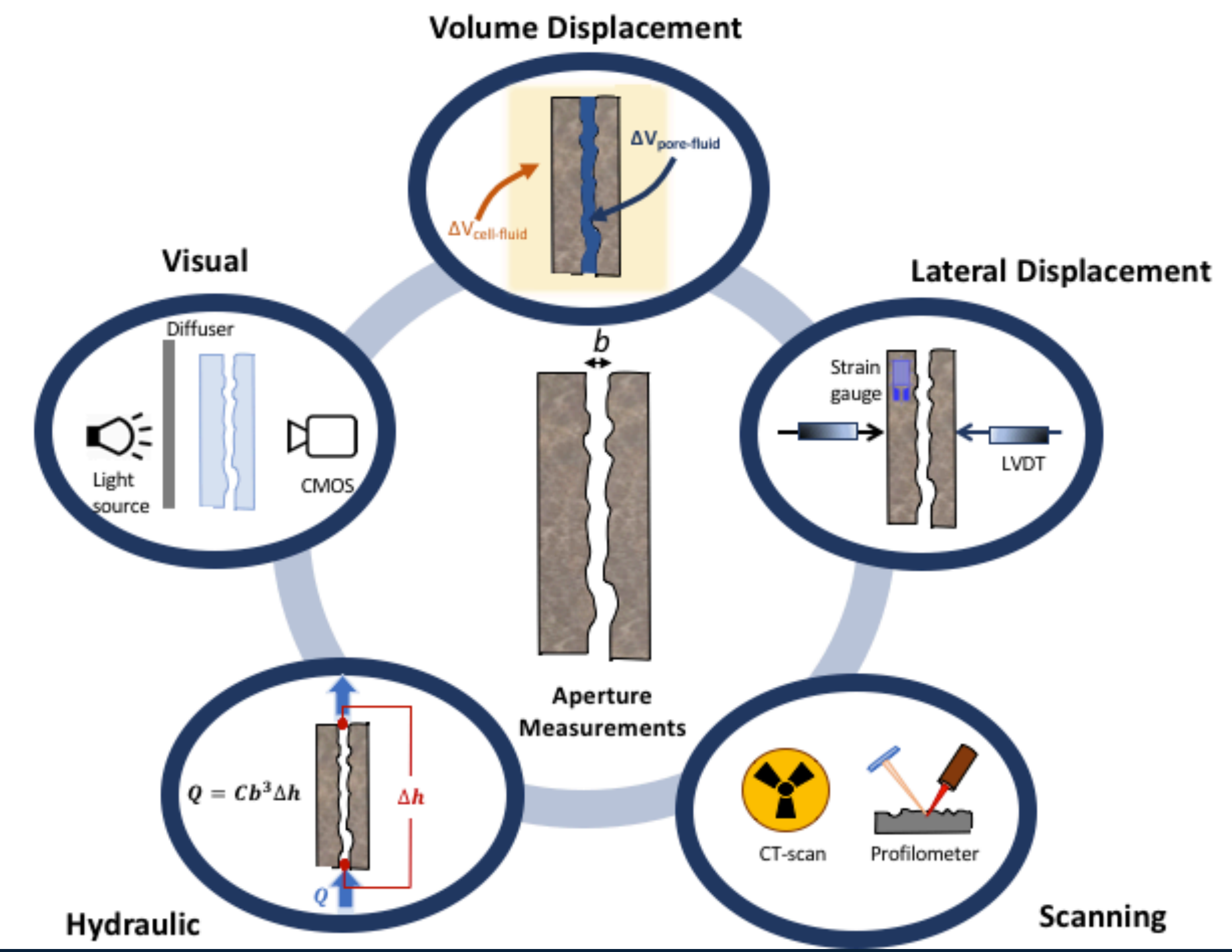
Fracture Replica and Technique



Investigation using Idealized Fracture Models

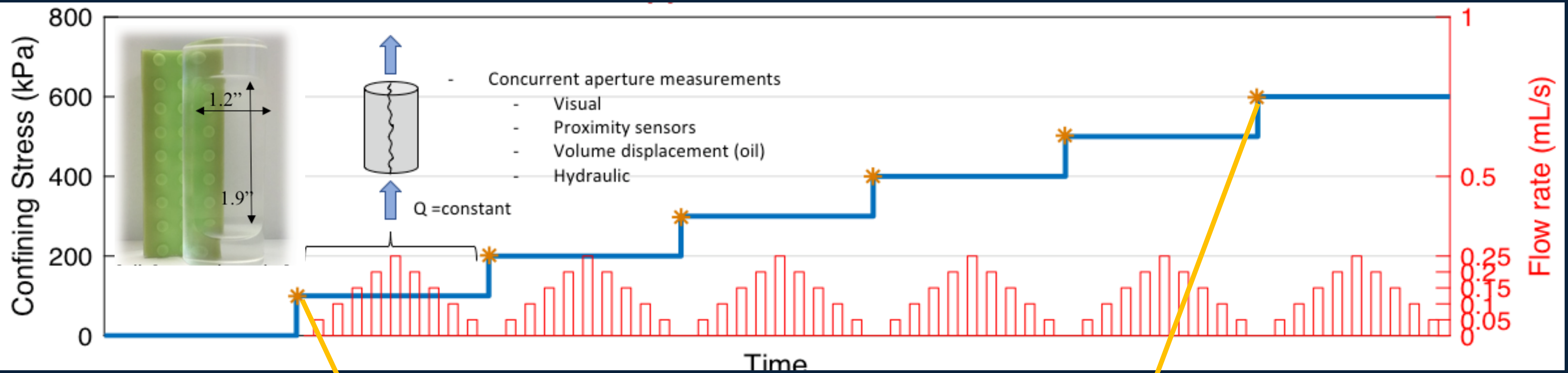
Applications

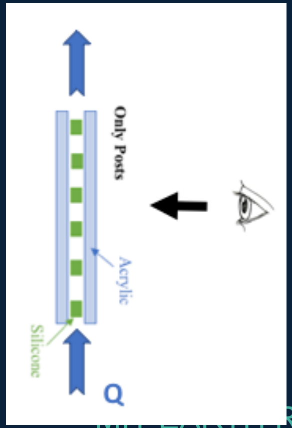
- Equipment/Technique Development
- Validation of Flow Models
- Investigations of Coupled Processes

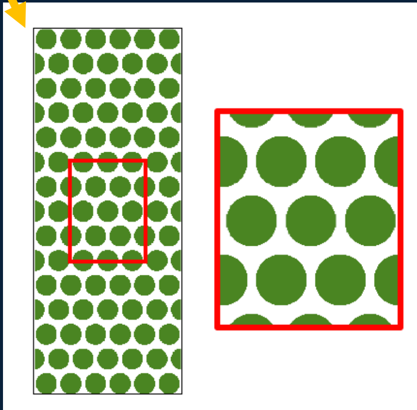


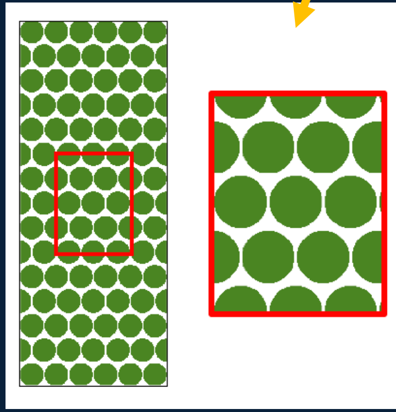
Investigation using Idealized Fracture Models

Experimental results: Linear & Non-linear Flows



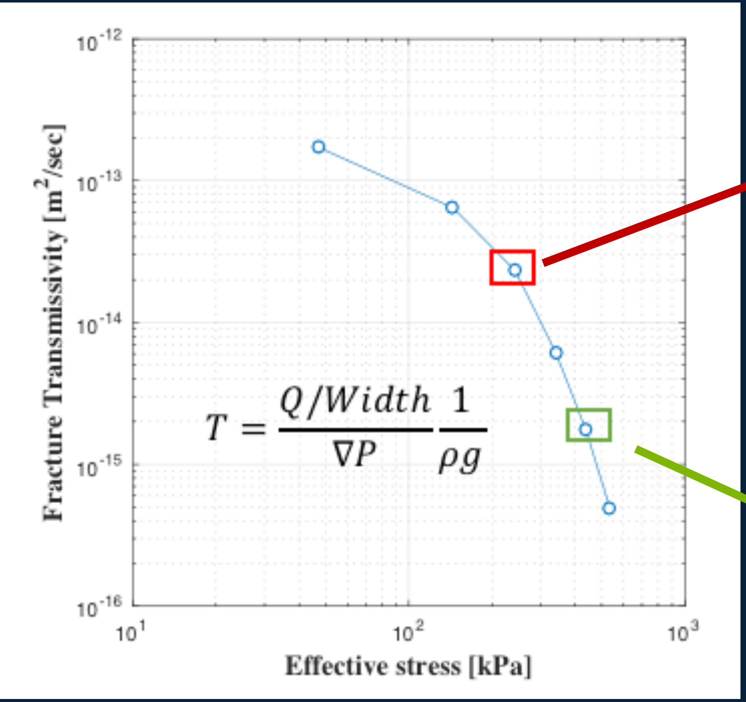


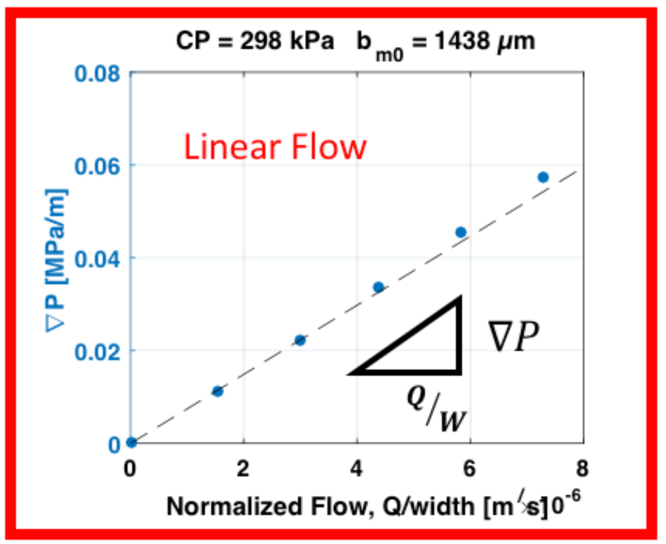




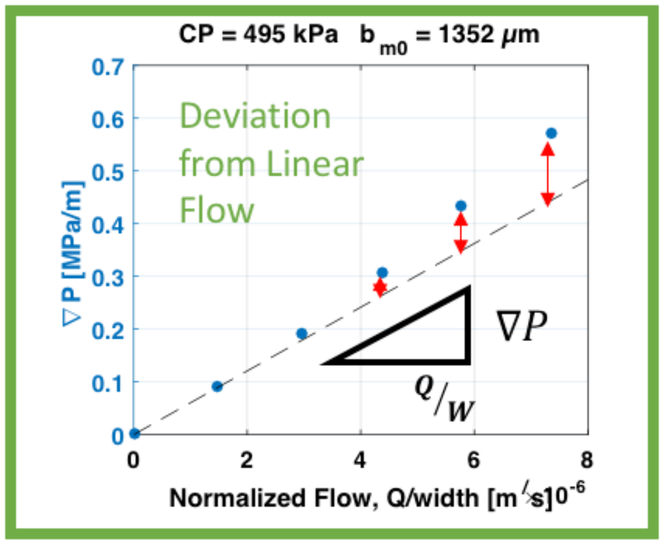
Investigation using Idealized Fracture Models

Experimental Results: Linear & Non-linear Flows





At <u>"low" confining pressure</u>: the pressure gradient is linear with flow rate even for "large" flux rates.



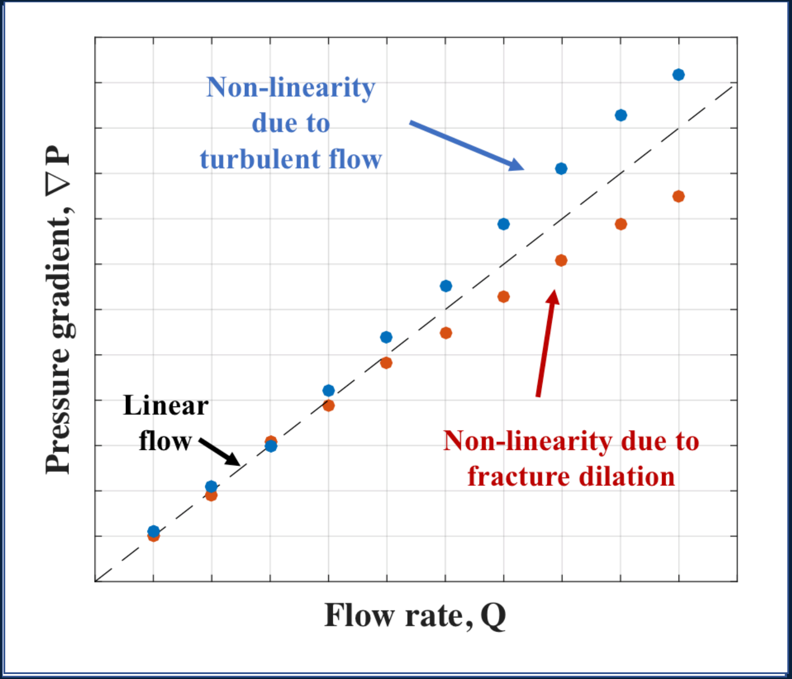
At <u>"high" confining pressure</u>: the gradient is non-linear with flow rate, especially at "large" flux rates. Also, the large pressure gradient results in fracture dilation.

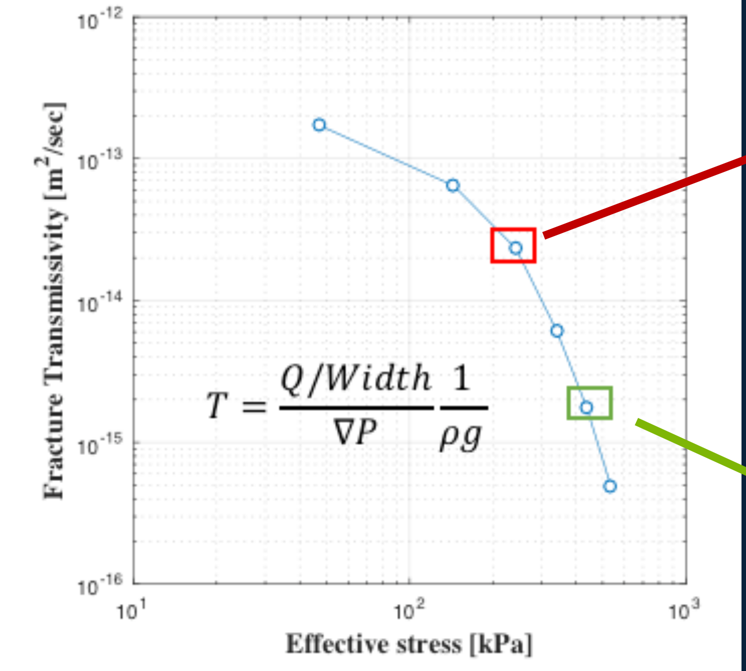
Non-linearity may be caused by a combination of turbulent flow and fracture dilation

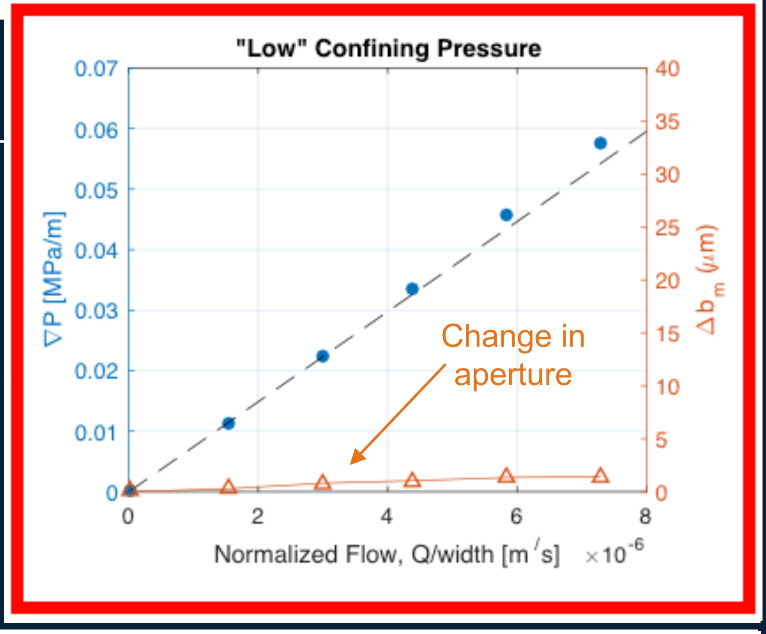
Investigation using Idealized Fracture Models

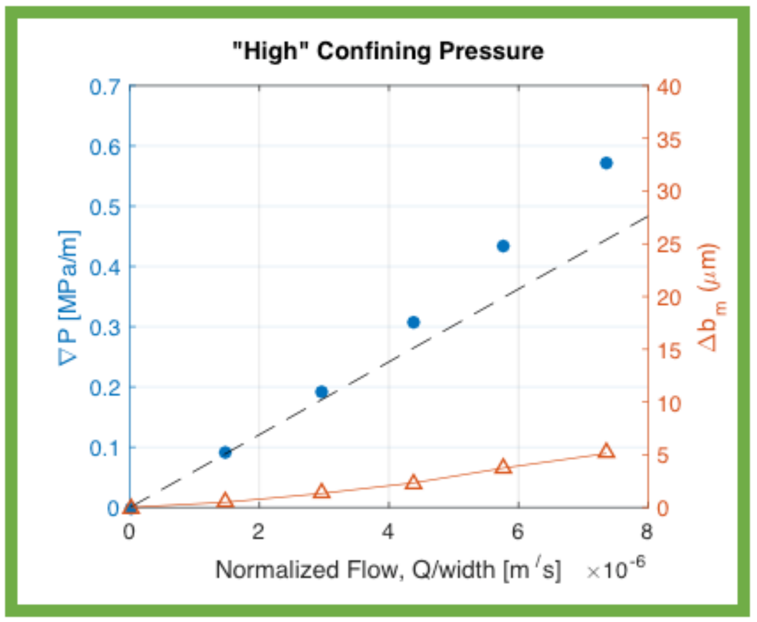
Experimental Results: Investigation of Coupled Processes

Experimental observations (e.g. Chen et al 2015)





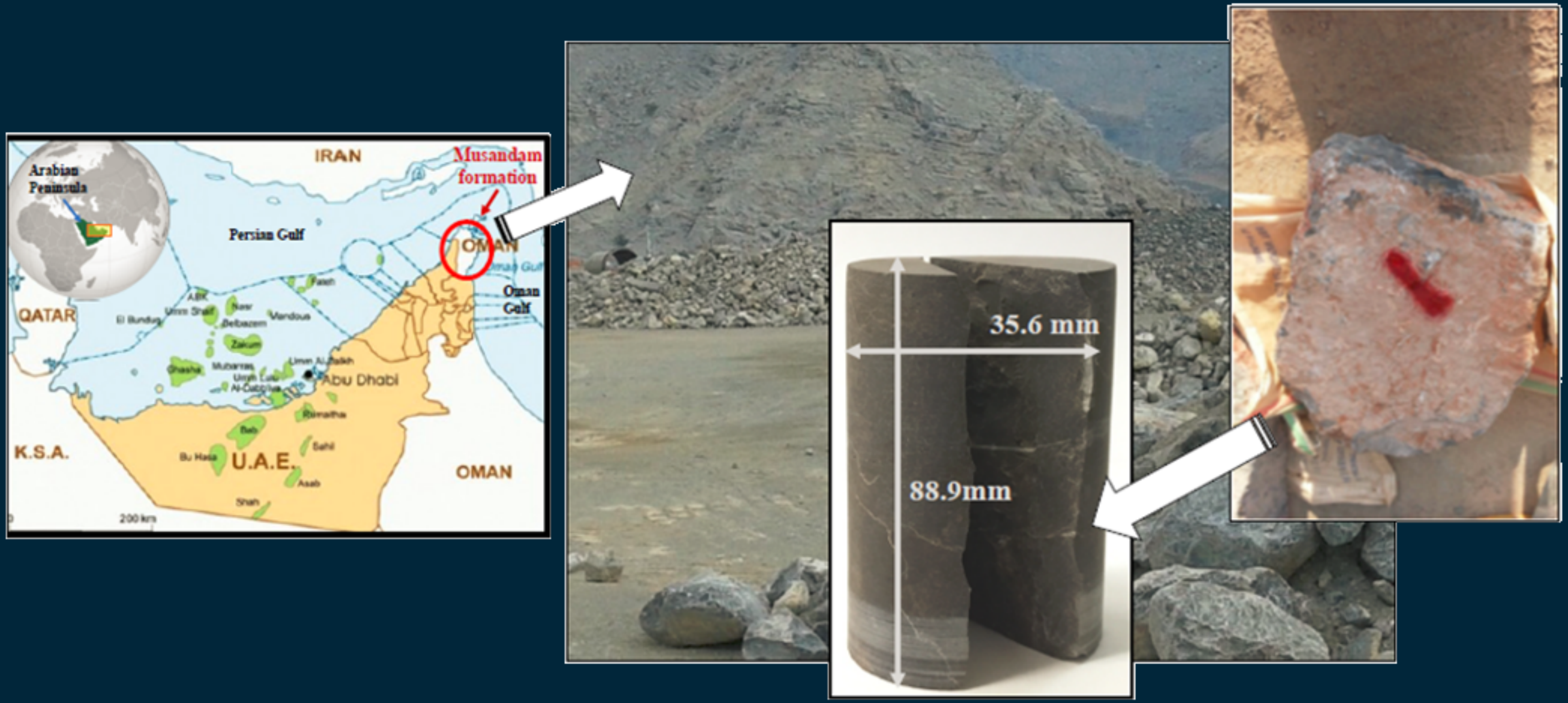




Increasing CP → Nonlinearity ∇P vs. Q → Turbulence & Fracture dilation

Investigation using Real Rocks

Musandam Limestone Specimens



Investigation using Real Rocks

Motivation

- The hydro-mechanical properties of Musandam limestone have not been well characterized
  - *Evolution of fracture aperture over time* √
  - *Evolution of fracture aperture over cyclic loading*
  - *Effect of minerology and solubility*

- Important both regarding civil infrastructure and hydrocarbon reservoirs

Investigation using Real Rocks

Methodology

FACTORS ON HYDRAULIC APERTURE CHANGING WITH TIME

- In each test, fix the confining pressure and flowrate. Measure the hydraulic aperture changing with time.
- From test to test, vary the confining pressure or flowrate or surface geometry. Study the effect of the above mentioned factors

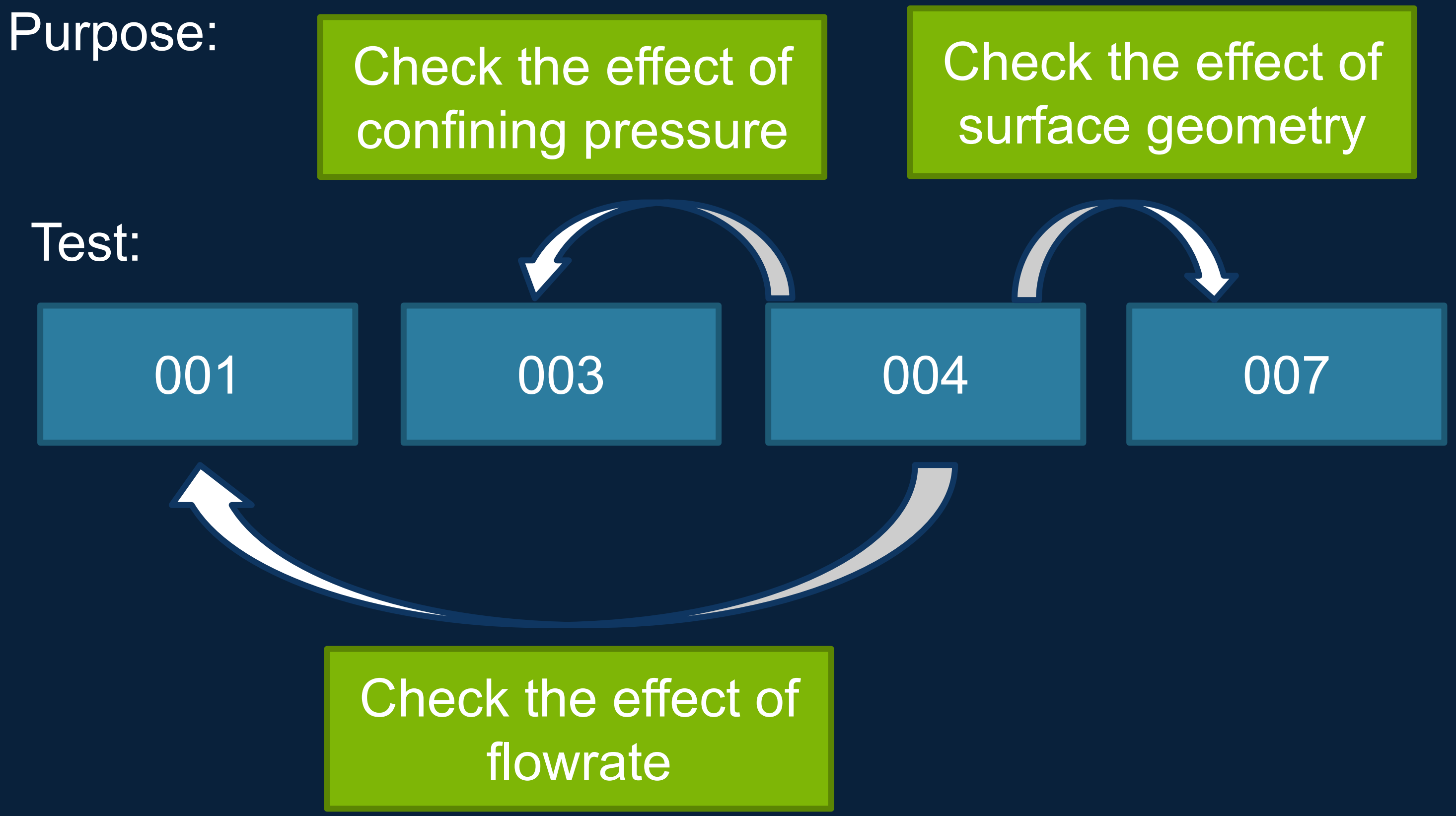
APERTURE CALCULATION

- The surface profiles before and after the flow test were scanned.
- The aperture distribution fields are calculated based on three-point contact assumption.

Investigation using Real Rocks

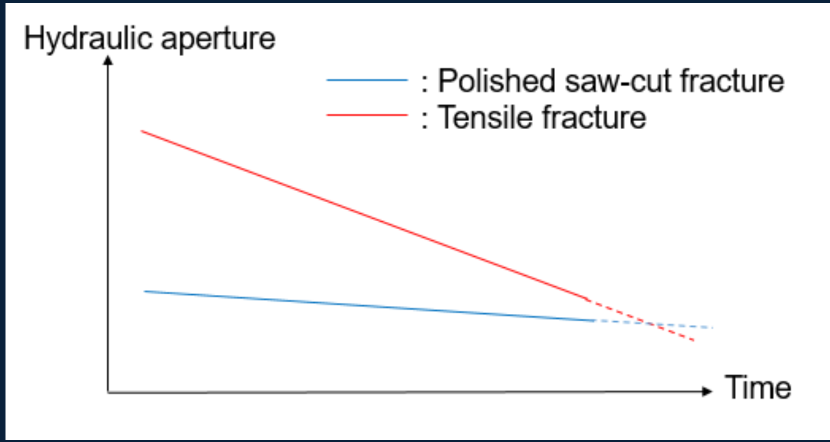
Methodology

Specimen	Fracture type	Confining pressure (kPa)	Flowrate (μL/s)
001	Tensile	300	10
003	Tensile	500	2.5
004	Tensile	300	2.5
007	Saw-cut (polished)	300	2.5

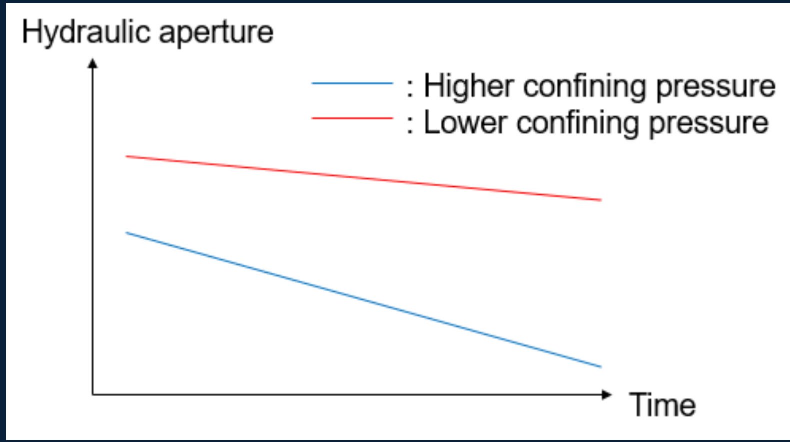


Investigation using Real Rocks

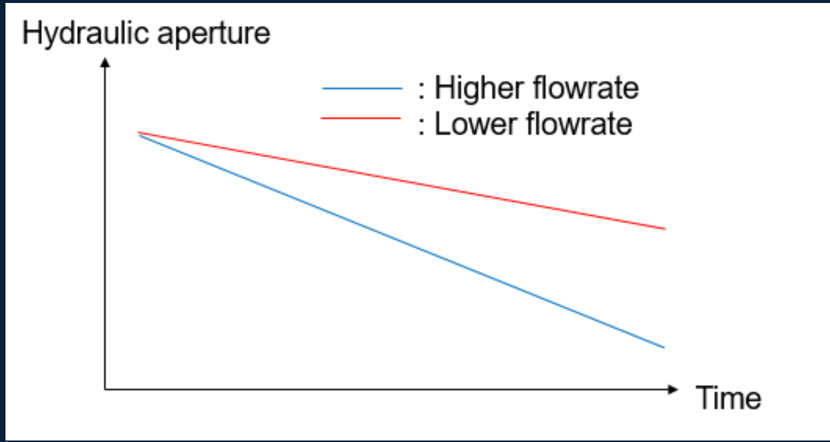
Schematic – Effect of Different Factors



Effect of surface roughness



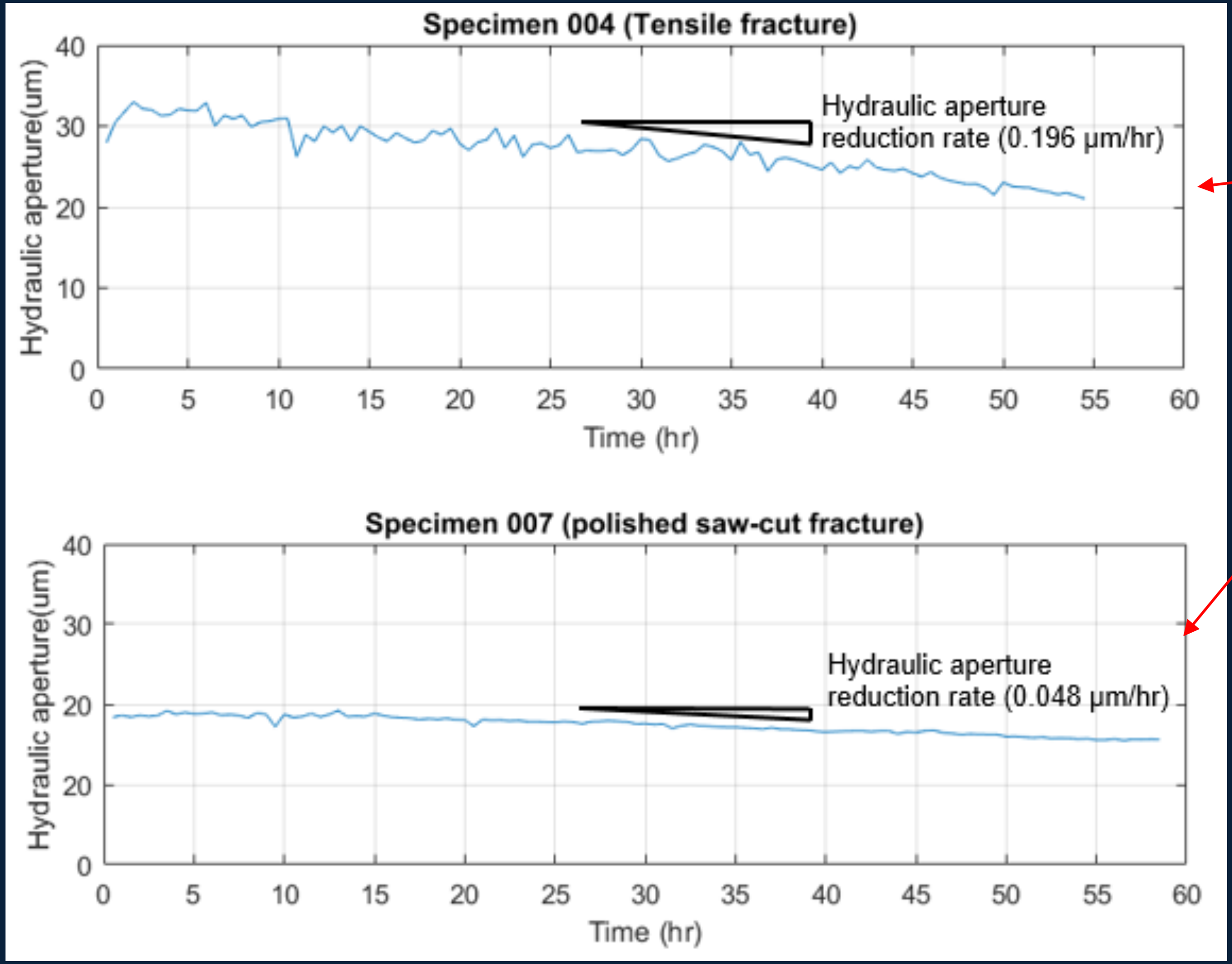
Effect of confining pressure



Effect of flowrate

Investigation using Real Rocks

Example: effect of surface roughness on hydraulic aperture change



Comparison:

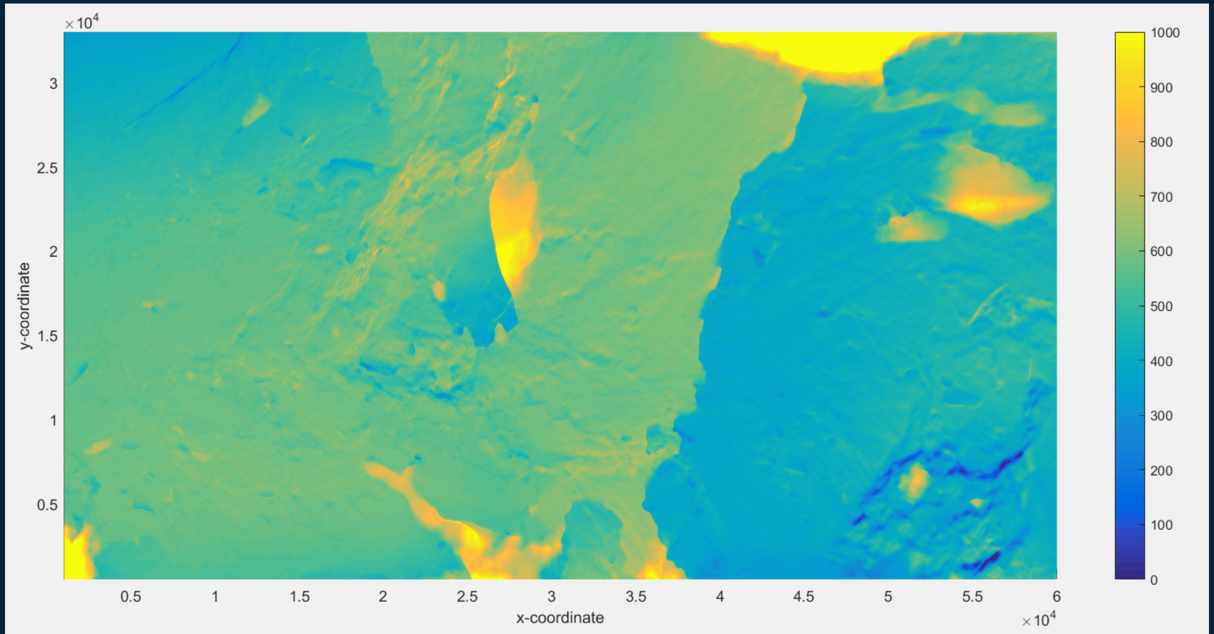
- Tensile fracture (specimen 004)
- Polished saw-cut fracture (specimen 007)

Summary:

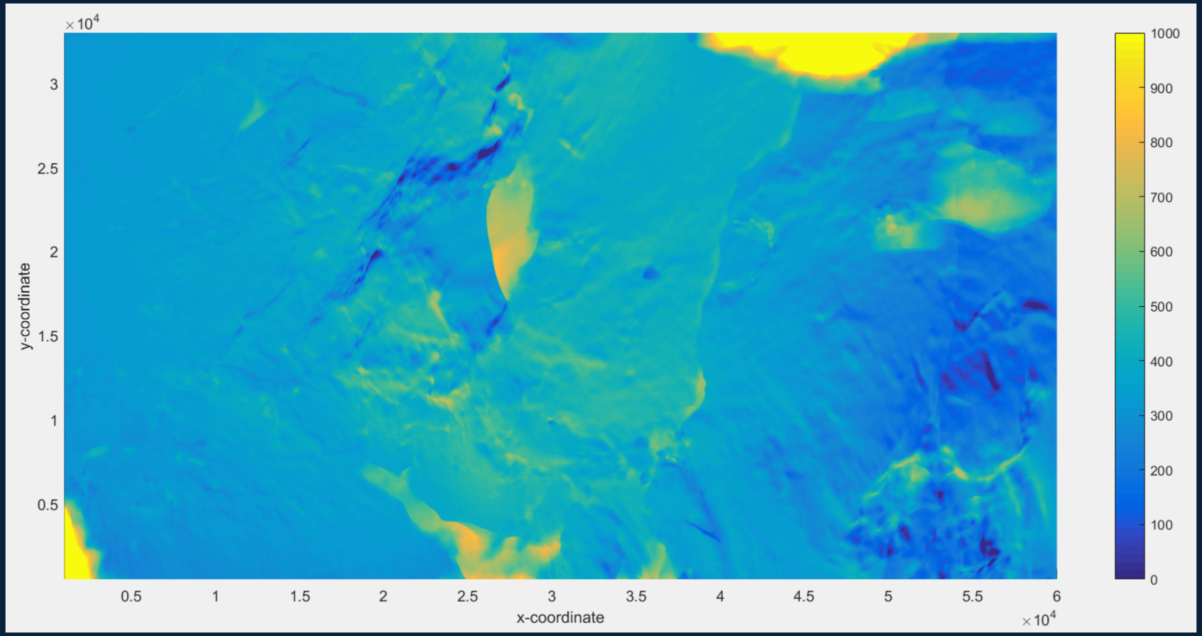
- Initial hydraulic aperture: tensile > polished saw-cut
- Hydraulic aperture reduction rate: tensile > polished saw-cut

Investigation using Real Rocks

Example: effect of surface roughness on mechanical aperture change (tensile)



Tensile fracture: before testing



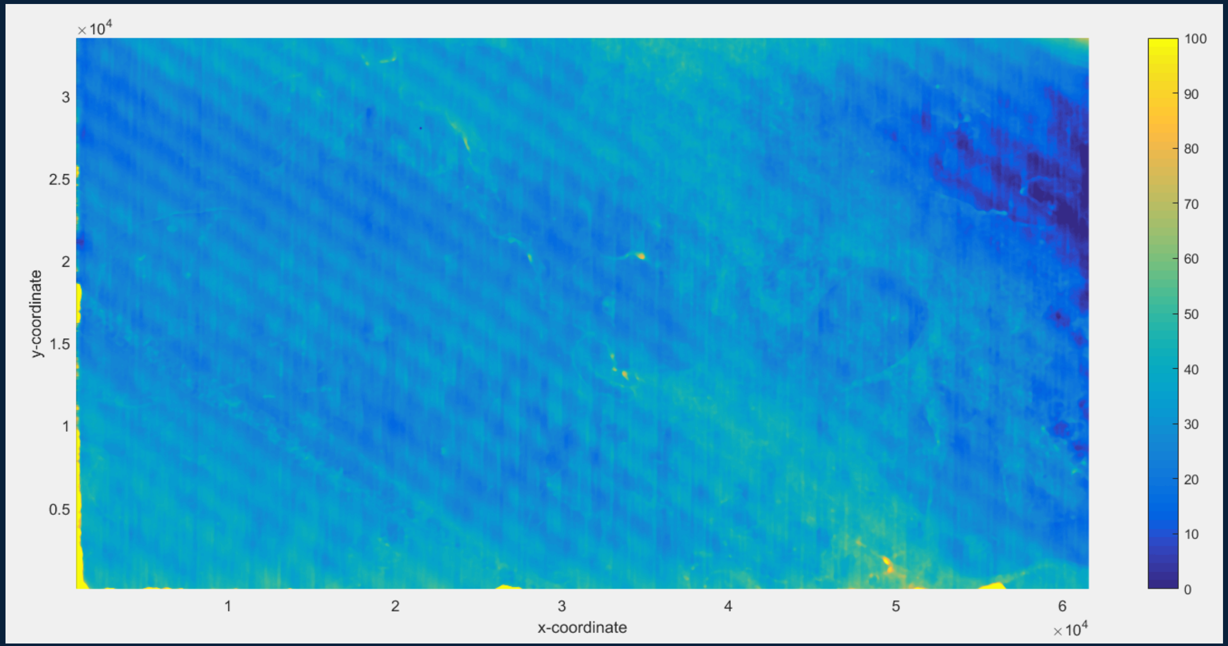
Tensile fracture: after testing

	Averaged mechanical aperture (μm)
Before test	330.39
After test	228.20 (reduced by 30.90%)

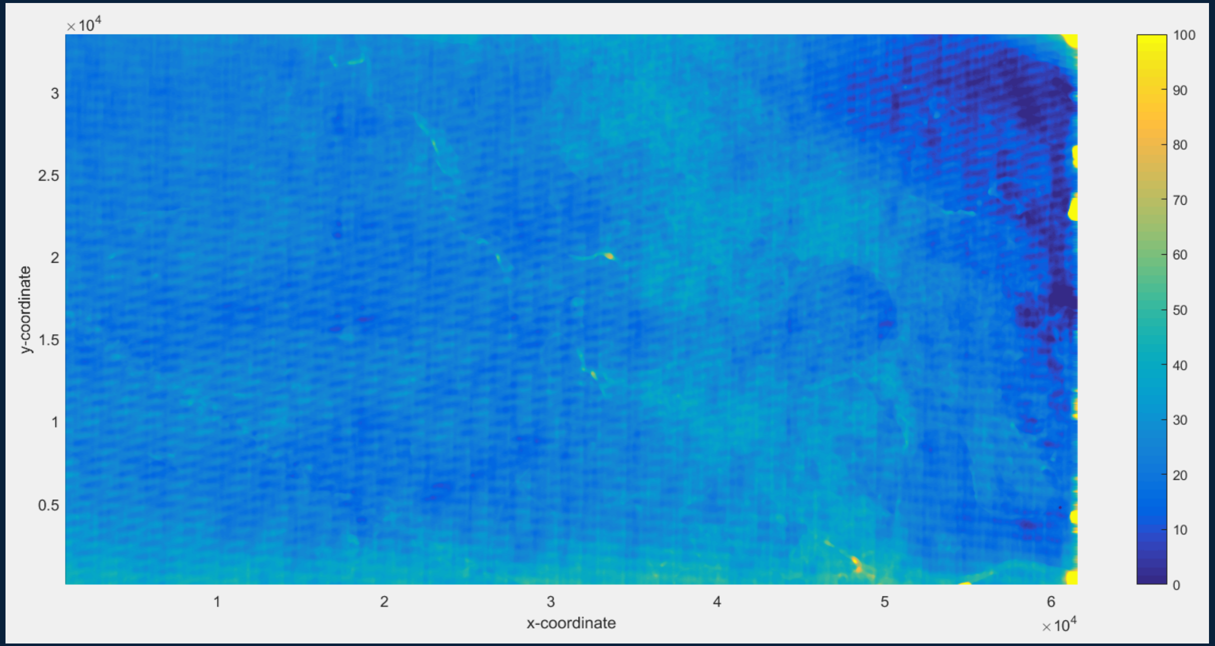
- Significant decrease in averaged mechanical aperture.

Investigation using Real Rocks

Example: effect of surface roughness on mechanical aperture change (polished saw-cut)



Polished saw-cut fracture: before testing



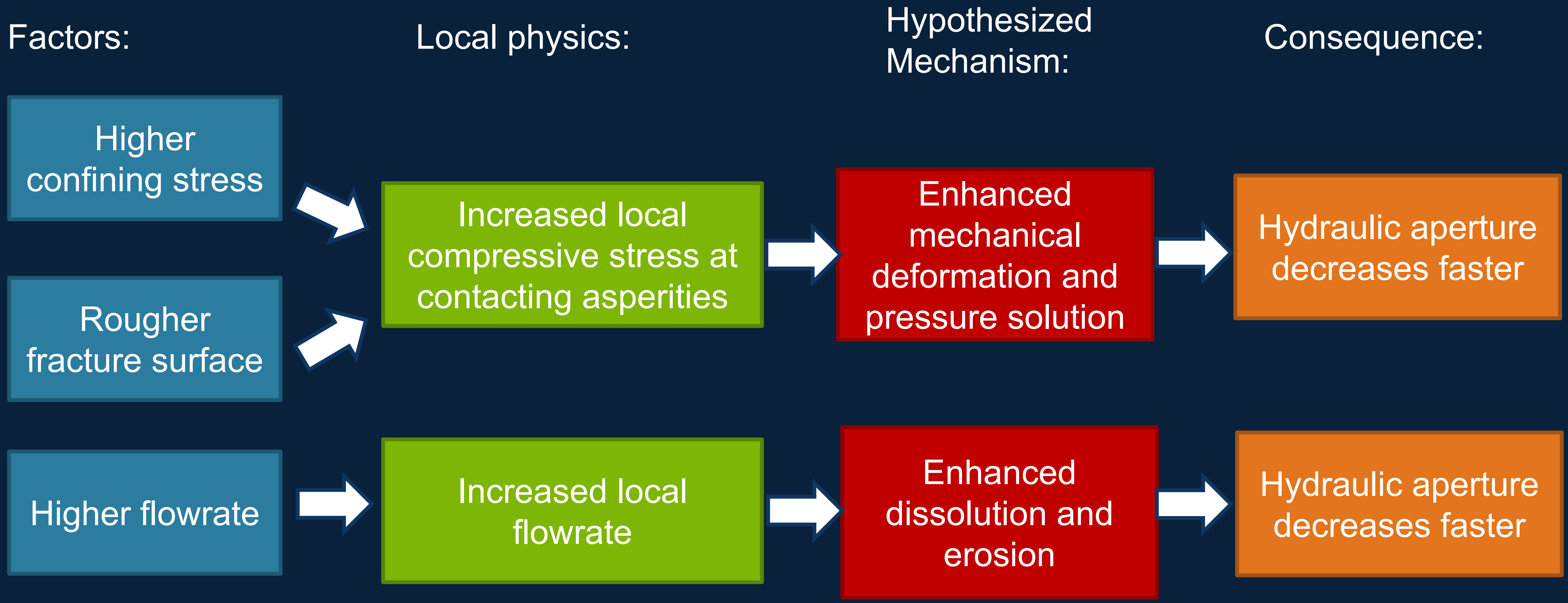
Polished saw-cut fracture: after testing

	Averaged mechanical aperture (μm)
Before test	29.81
After test	24.52 (reduced by 17.75%)

- Compared with tensile fracture, the aperture reduction for polished saw-cut fracture is smaller.
- Compared with tensile fracture, the initial averaged aperture is also smaller, and the contact area is larger.

Investigation using Real Rocks

Result Discussion



Investigation using Real Rocks

Ongoing Research

Purpose:	Check the effect of pressure solution	Check the effect of dissolution on fracture closure	Check the effect of dissolution and erosion on fracture closure	
Test:	Dry	Saturated limestone solution but no flow	Distilled water but no flow	Distilled water flow
Hypothesized mechanism:	Mechanical compression	Mechanical compression + pressure solution	Mechanical compression + pressure solution + dissolution	Mechanical compression + pressure solution + dissolution + erosion

Conclusions

- External stresses may produce important changes in the fracture geometry leading to nonlinear flow.
- Experiments with fracture replica help to separate different processes (e.g. effect of mechanical closure)
- When the time duration is less than 60 hours, under flow condition, the hydraulic aperture decreases with time. Higher confining stress, higher flowrate or rougher surface will lead to larger hydraulic aperture reduction.
- Compared with polished saw-cut fracture, the averaged mechanical aperture of tensile fracture is larger. During flow tests, the mechanical aperture reduction of tensile fracture is larger.

Acknowledgement

- Thanks for the support of ADNOC and MIT ERL!

Back-up slides

Selected Results Summary

Specimen	Fracture type	Confining pressure (kPa)	Flowrate (µL/s)	Hydraulic aperture (µm)		Averaged hydraulic aperture change percentage (%)
				Beginning	End	
001	Tensile	300	10	28.1	16.1	42.7
003	Tensile	500	2.5	16.0	5.5	65.6
004	Tensile	300	2.5	32.1	21.5	33.0
007	Saw-cut (polished)	300	2.5	18.5	15.7	15.1

Investigation using Real Rocks

Result Discussion

	Factors affecting hydraulic aperture reduction rate					
	Fracture surface roughness		Confining pressure		Flowrate	
Relative magnitude	Rougher	Smoother	Smaller	Larger	Smaller	Larger
Hydraulic aperture reduction rate	Larger	Smaller	Smaller	Larger	Smaller	Larger