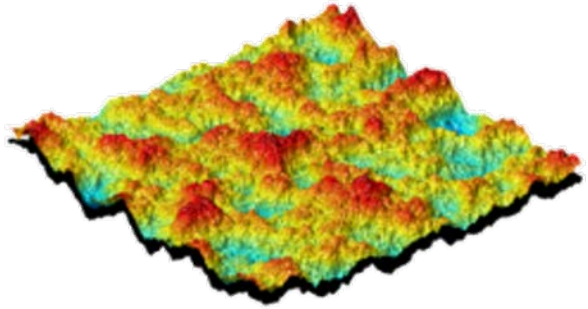
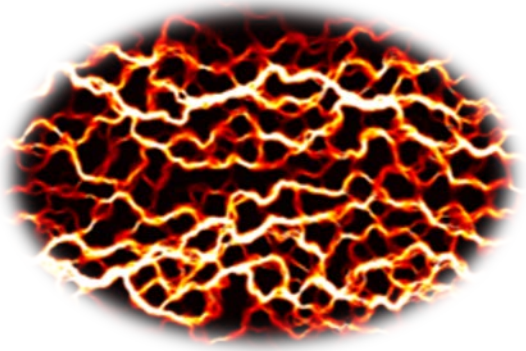
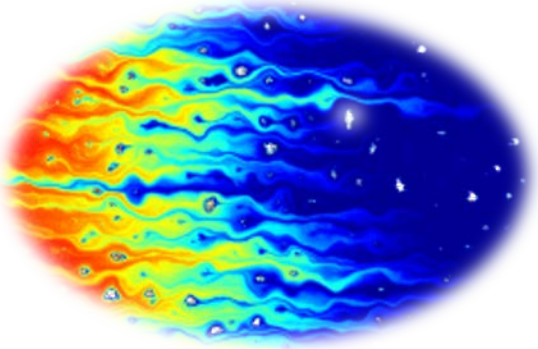
Experimental Investigations of Flow and Mass Transport in Stressed Rough Fractures







Rafael Villamor-Lora

PhD Student, Civil & Environmental Engineering

In collaboration with Herbert H. Einstein

May 25, 2022

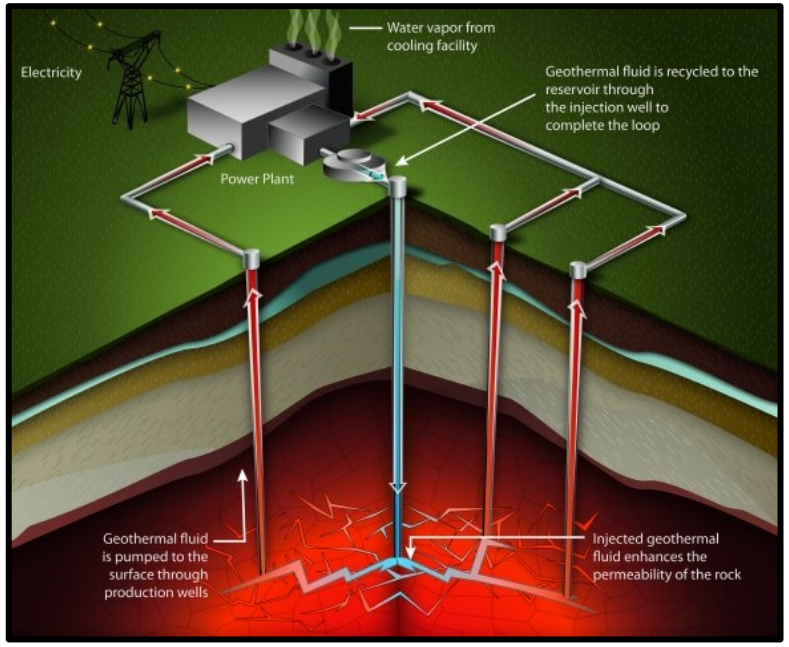
MIT Earth Resources Laboratory
Annual Founding Members Meeting 2022

Civil and Environmental Engineering

Motivation

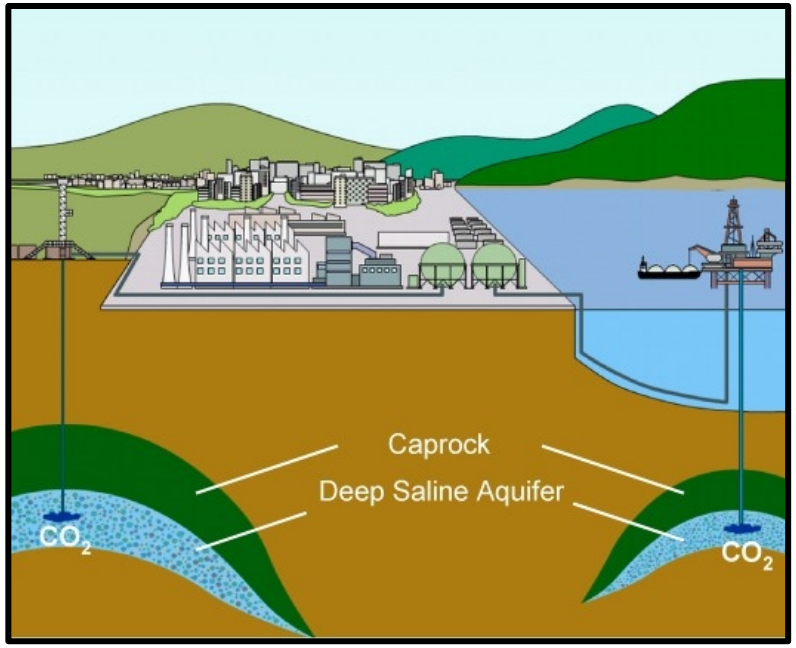
Flow in Rough Fractures. Applications

Geothermal Energy



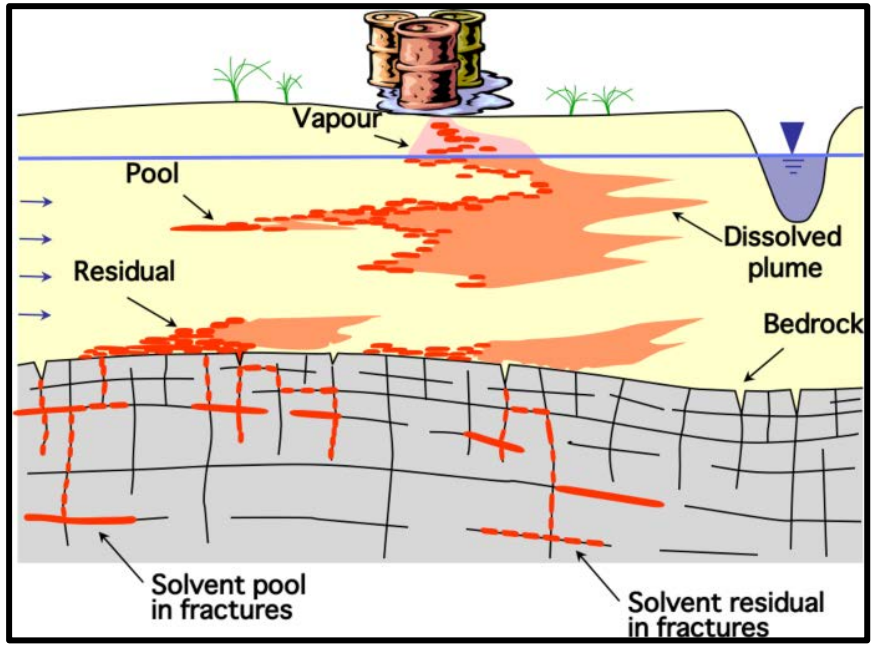
Source: Department of Energy

CO2 Sequestration



Source: Yohanes Nuwara

Contaminant Transport

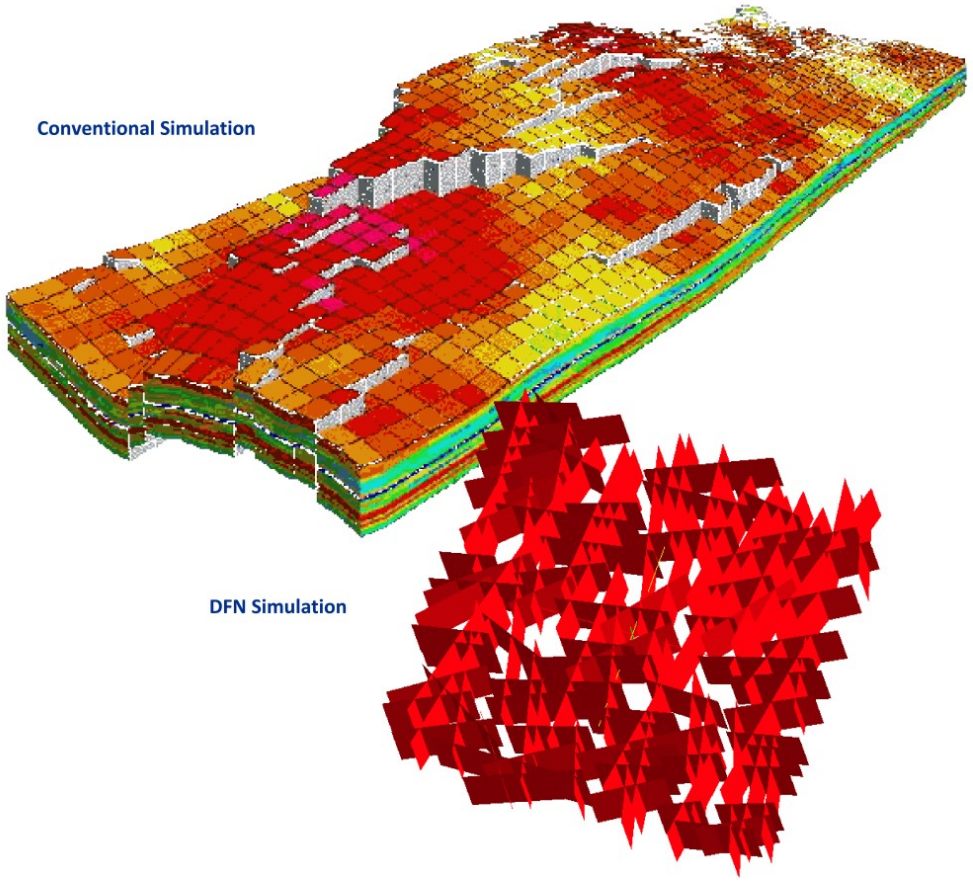


Source: Leharne (2019), *ChemTexts*

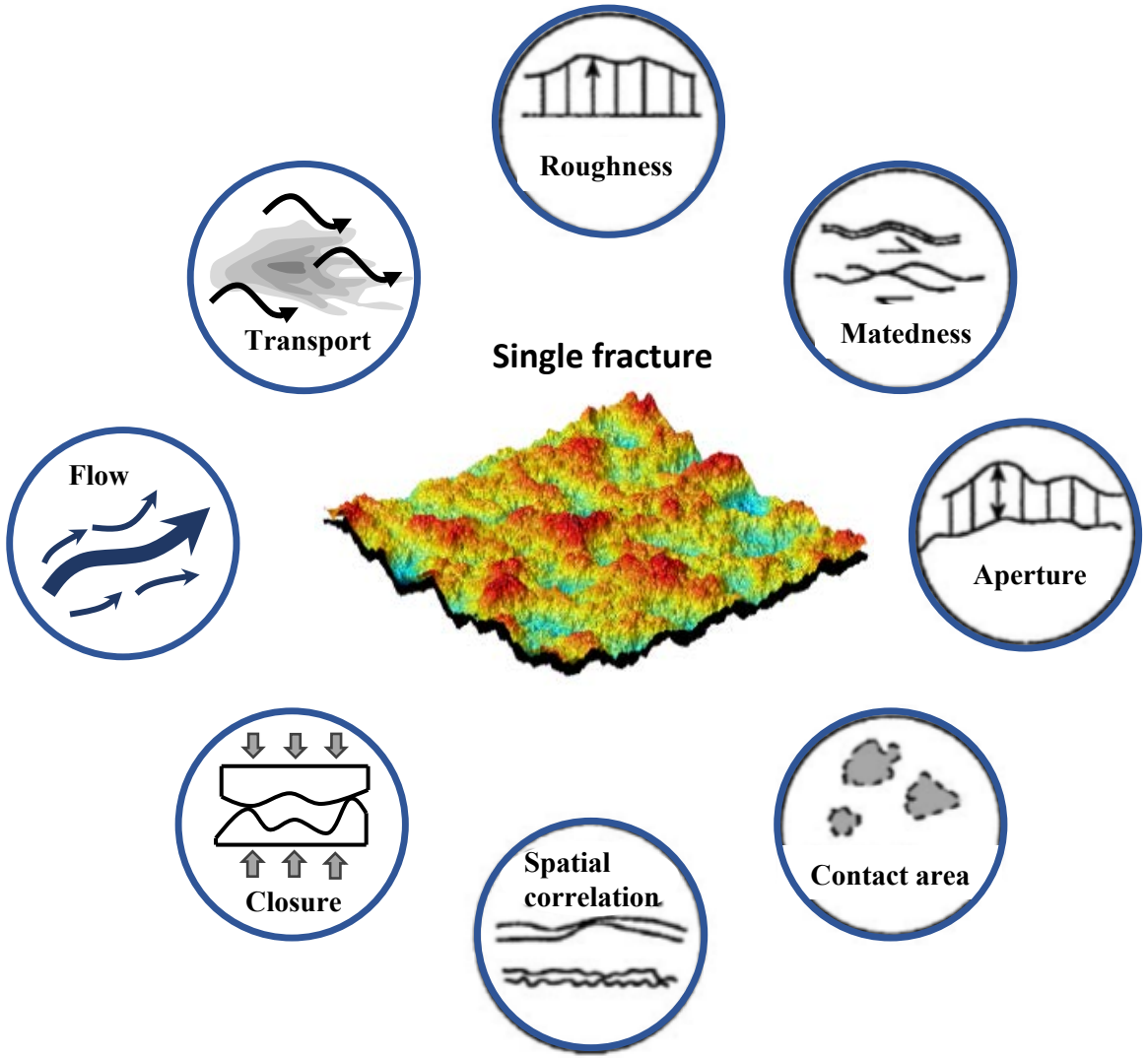
Others: Oil & Gas, Biotechnology, etc.

Motivation

COUPLED PHYSICAL PROCESSES IN STRESSED, ROUGH FRACTURES



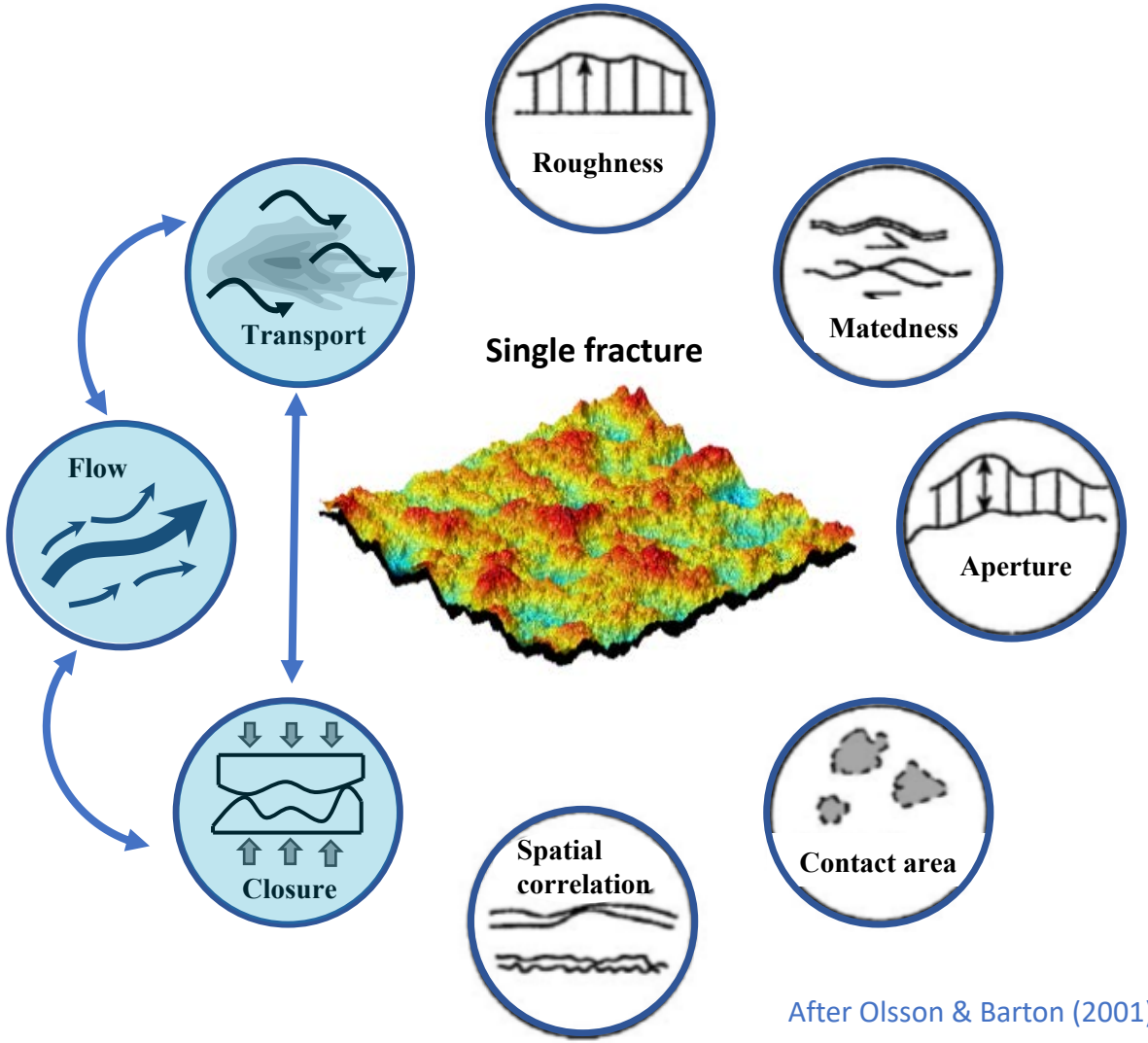
Source: iReservoir



Motivation

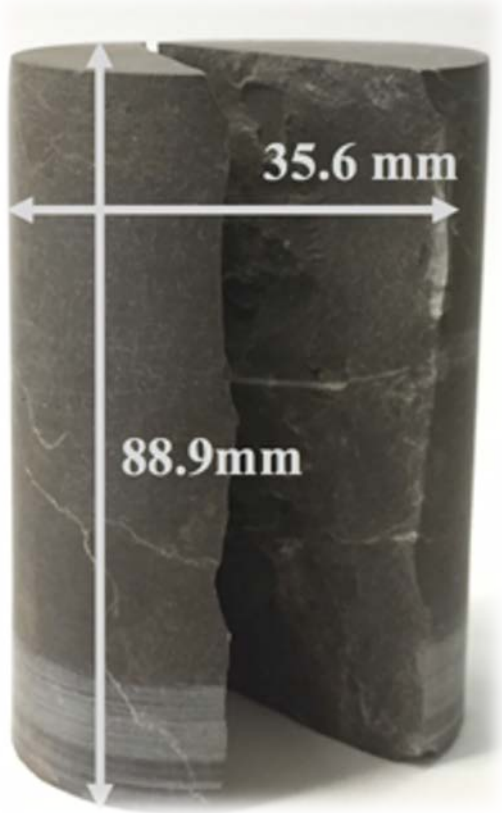
COUPLED PHYSICAL PROCESSES IN STRESSED, ROUGH FRACTURES

- Experimentally investigate the interplay between **fracture deformation** & **flow** & **mass transport**
- Develop an experimental setup that allows direct **visualization** of different physical processes **under stress** at **real time**

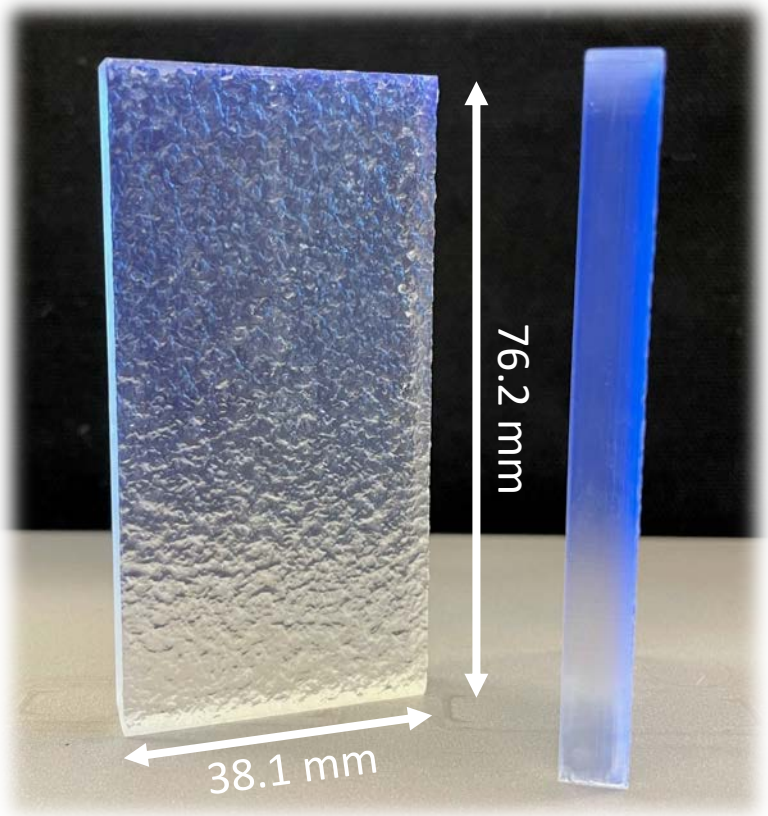


After Olsson & Barton (2001)

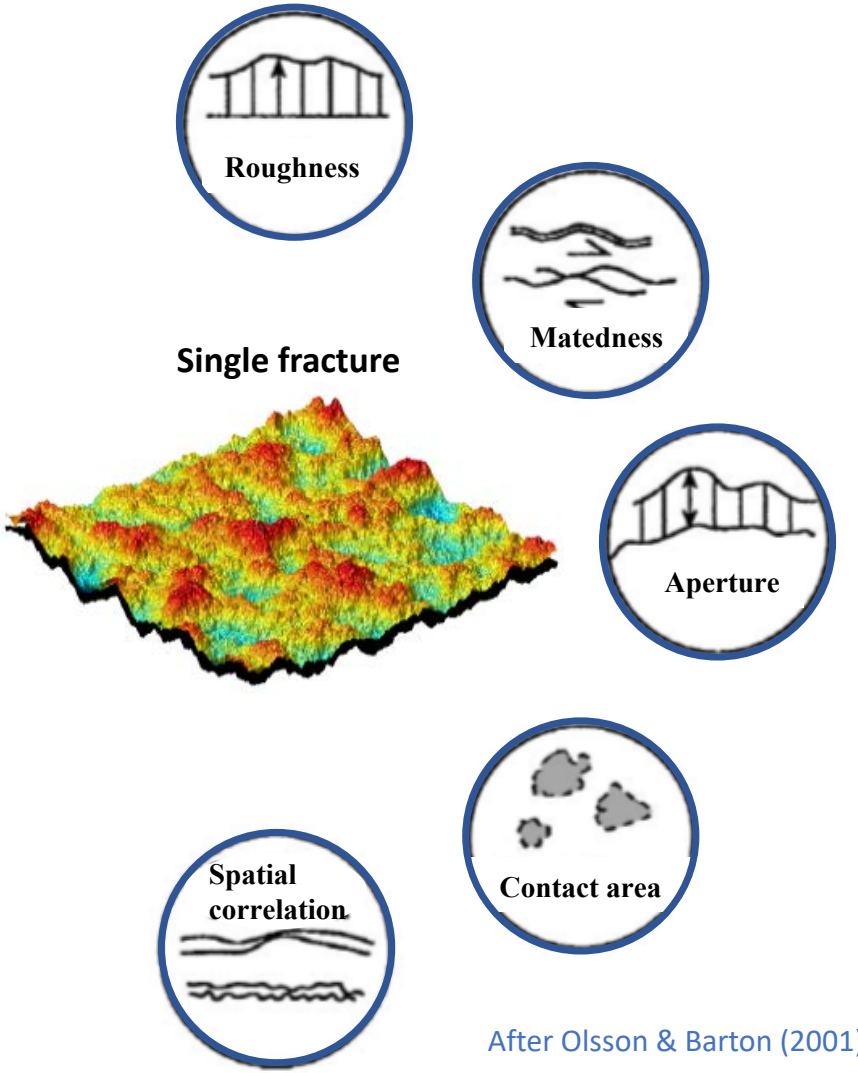
Experimental Investigations



Real rock fractures
[Musandam limestone]



3D-printed fracture analogs

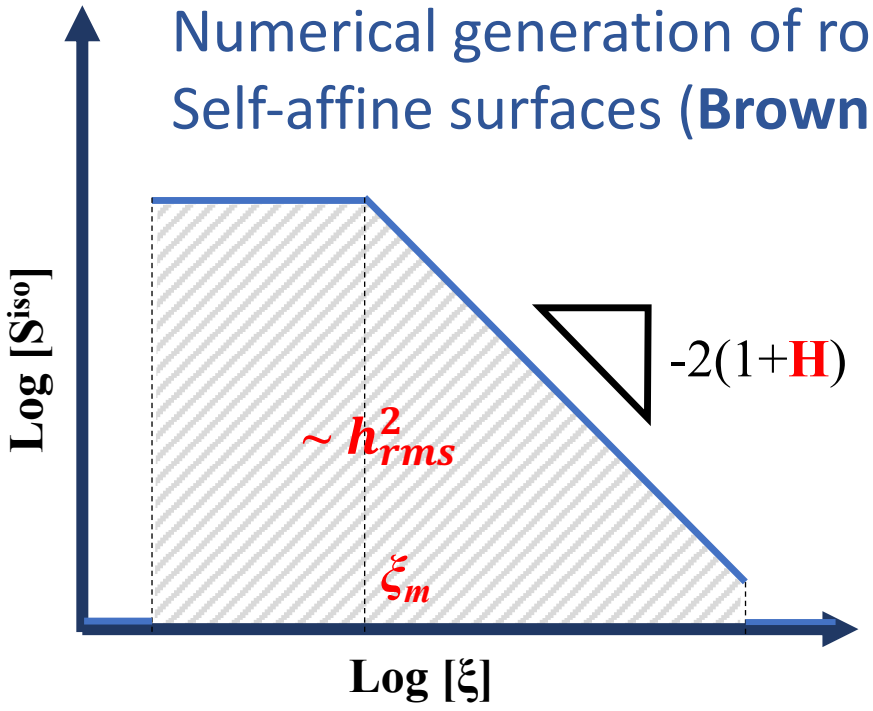


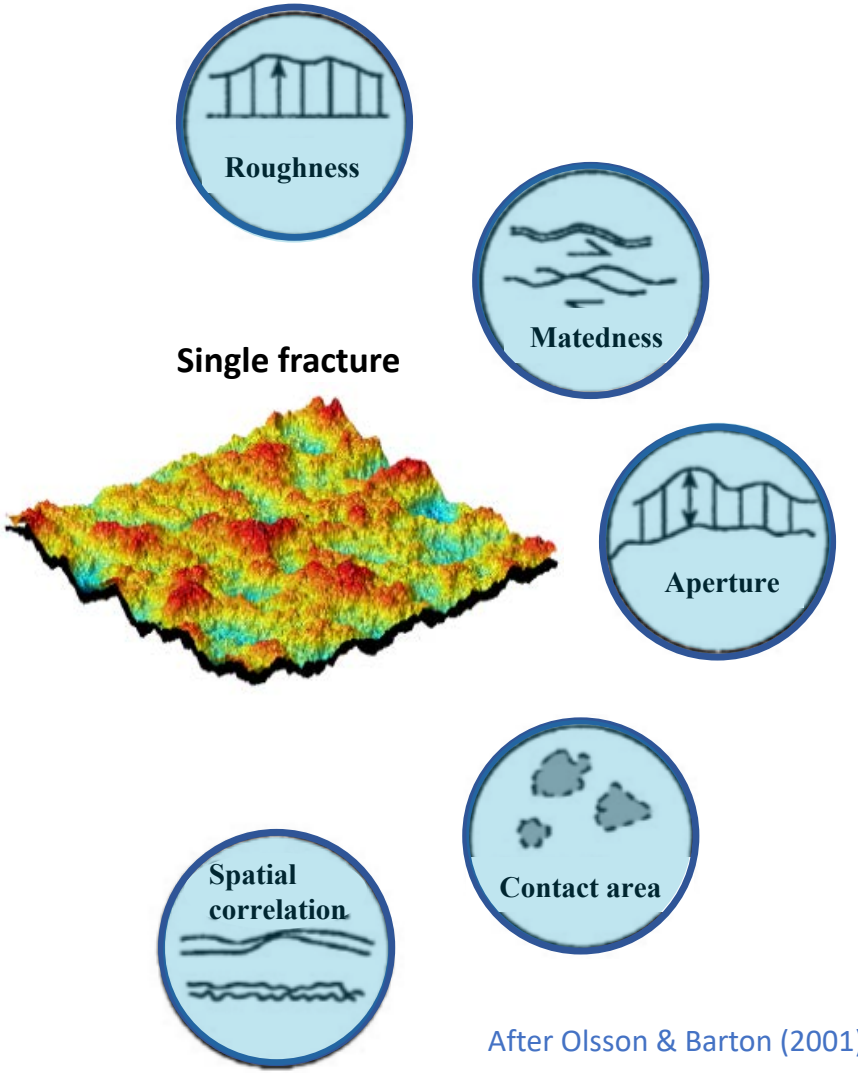
After Olsson & Barton (2001)

Experimental Investigations

DIGITAL FABRICATION OF ROUGH ROCK FRACTURES

Numerical generation of rough fractures:
Self-affine surfaces (**Brown 1995, *JGR***)





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Experimental Investigations

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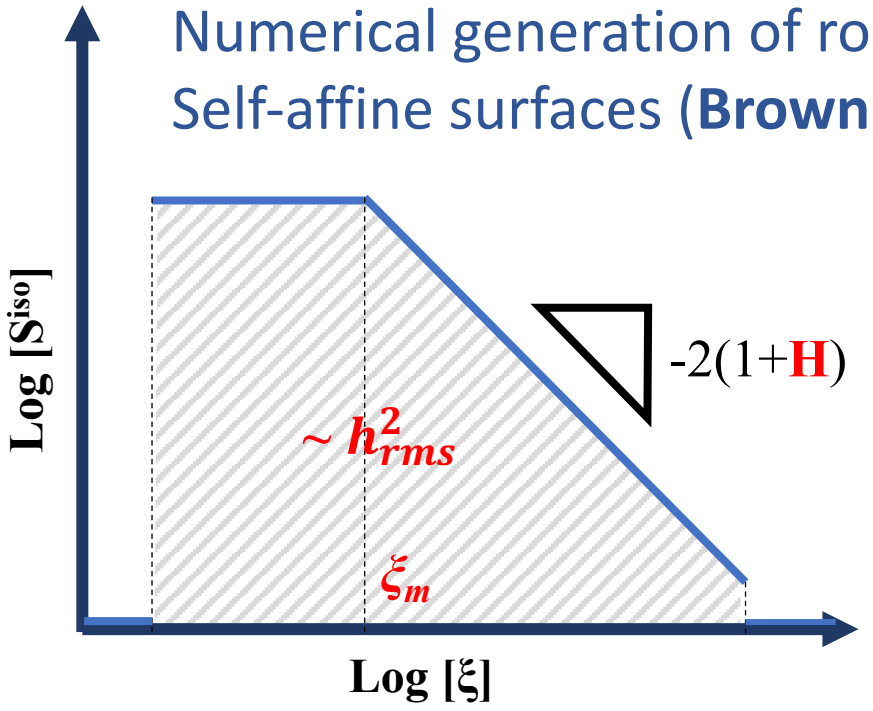
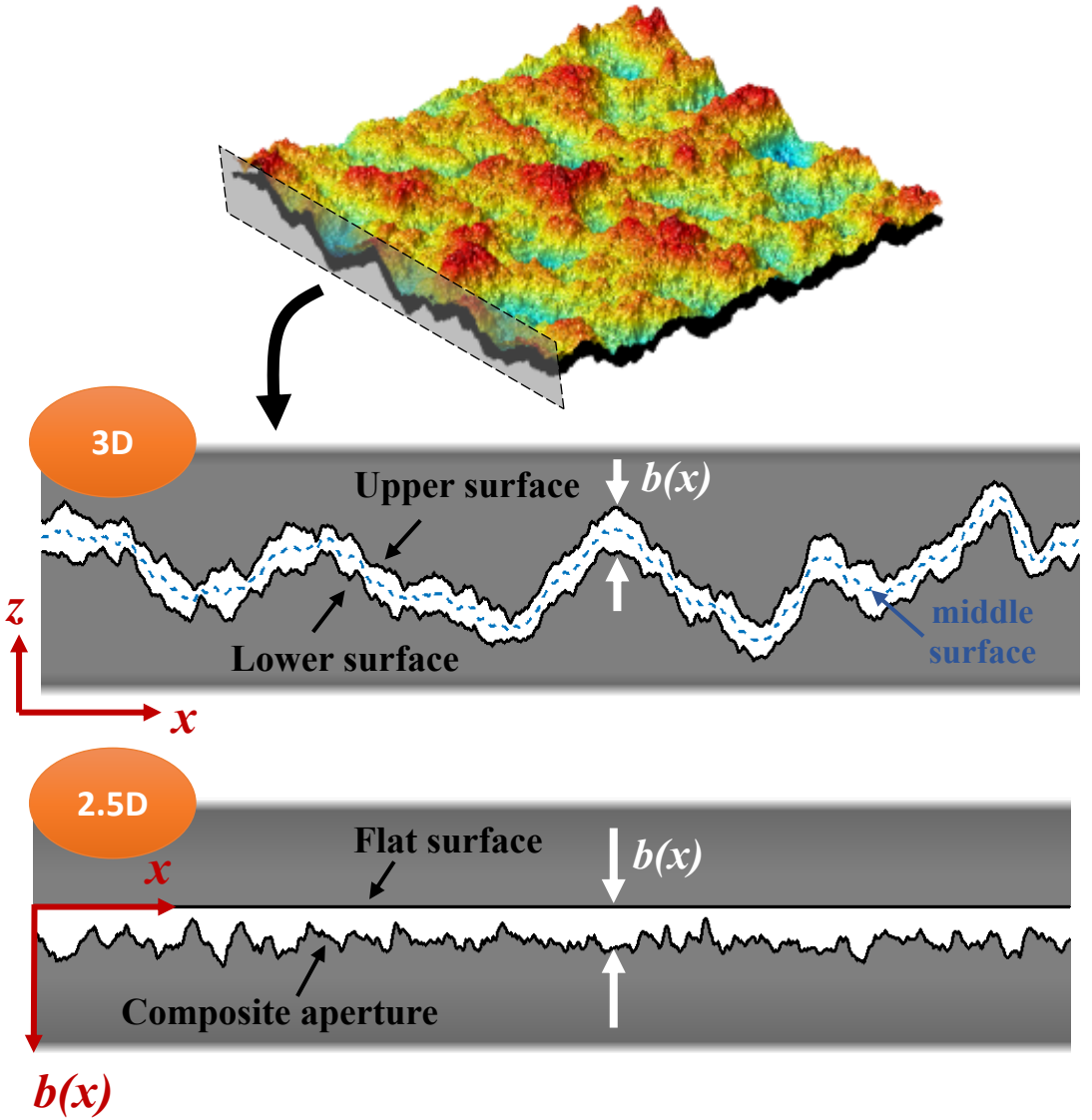


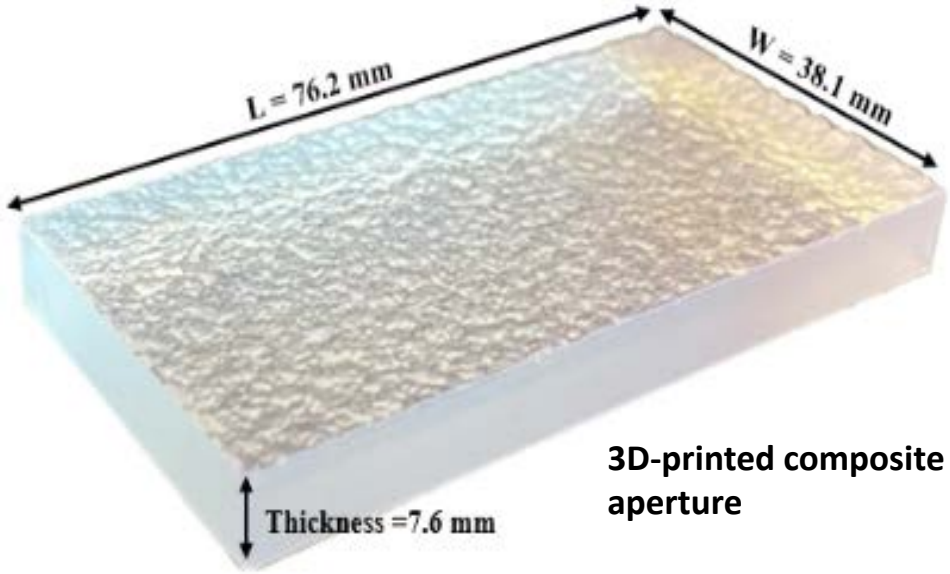


Experimental Investigations

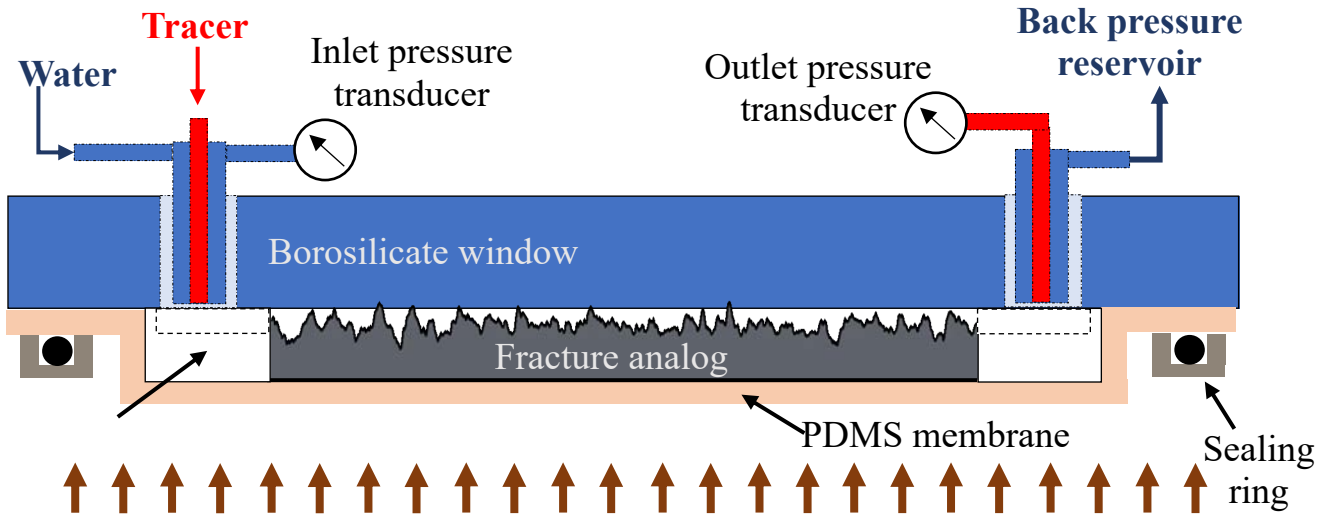
PRESSURE-CONTROLLED HELE-SHAW CELL

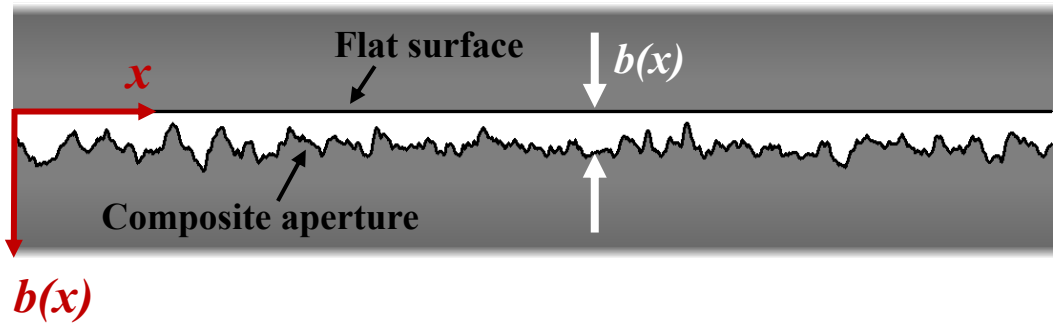
Lab-Field scaling

$$\sigma_{lab} / E_{lab} \sim \sigma_{field} / E_{field}$$



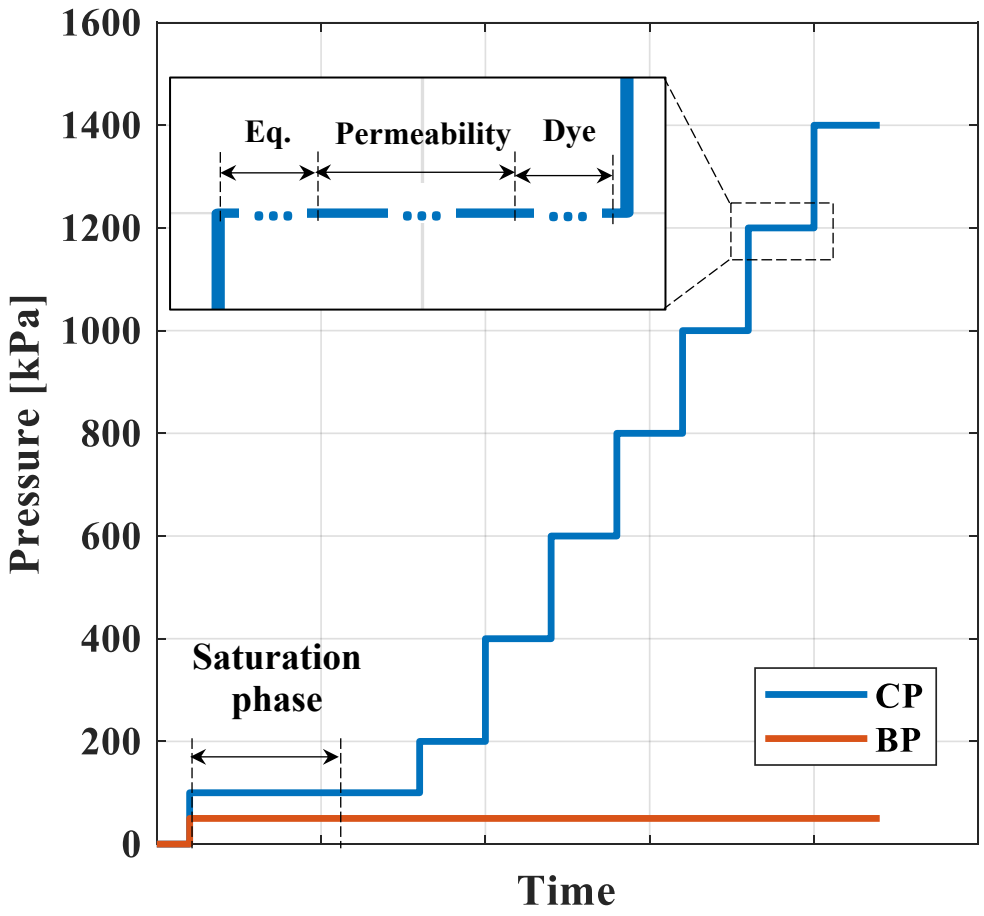
3D-printed composite aperture

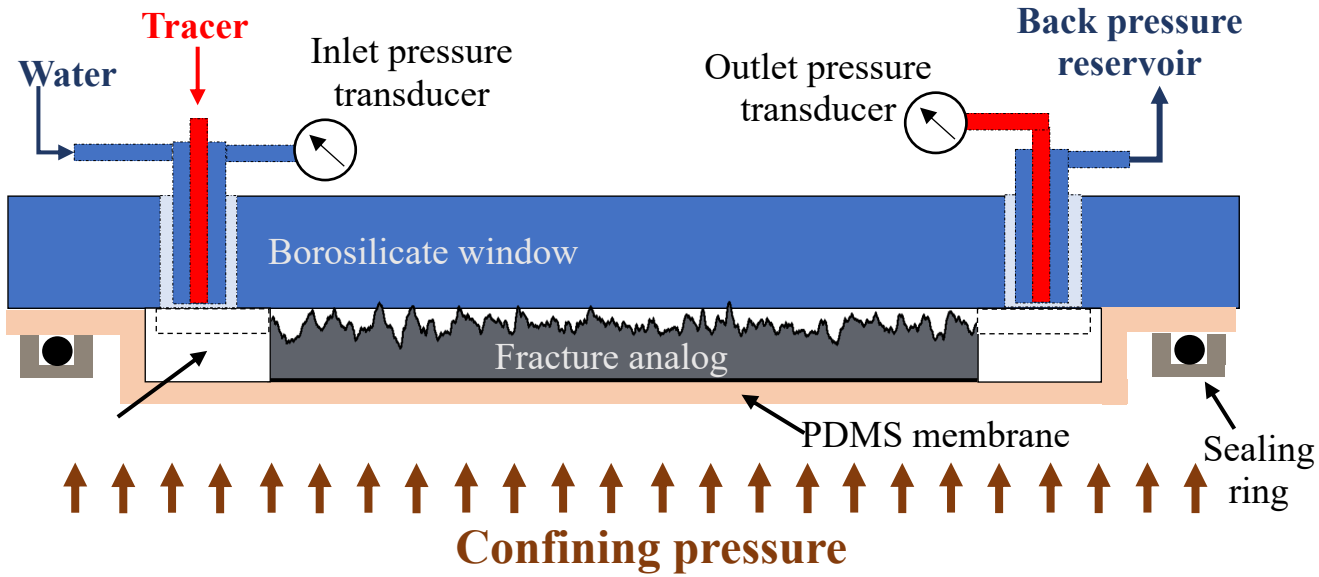




Experimental Investigations

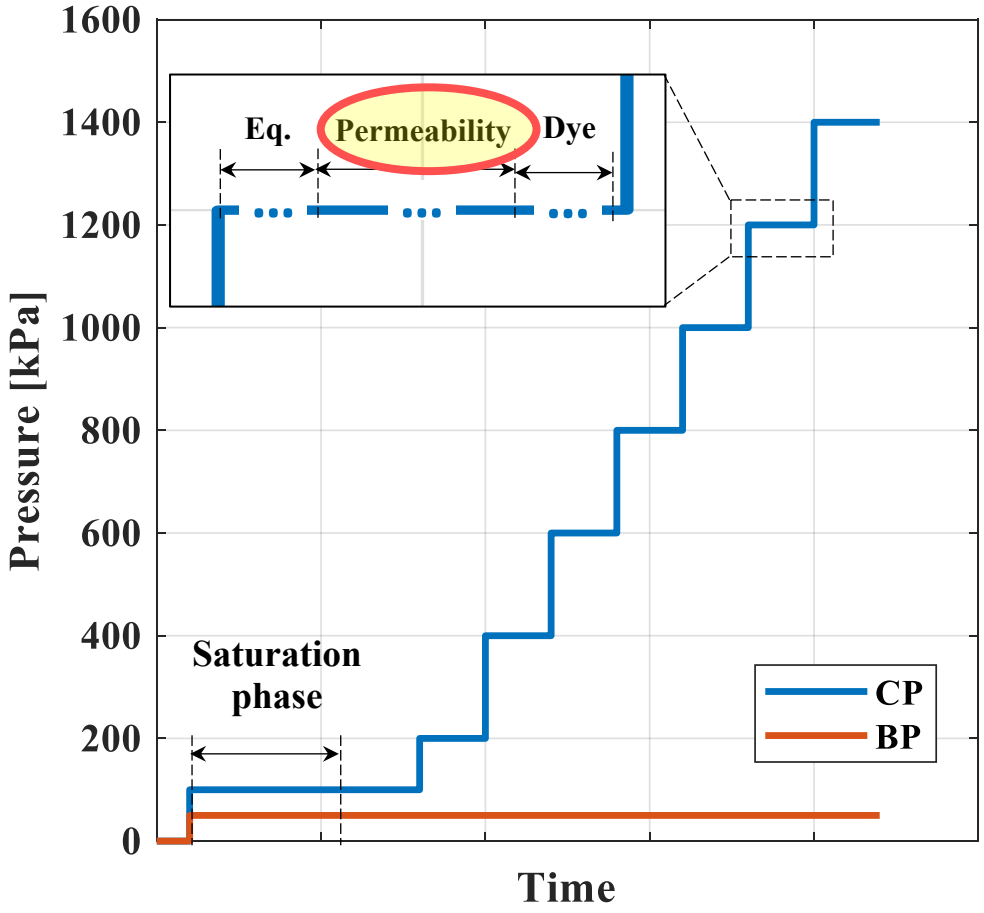
EXPERIMENTAL PROTOCOL

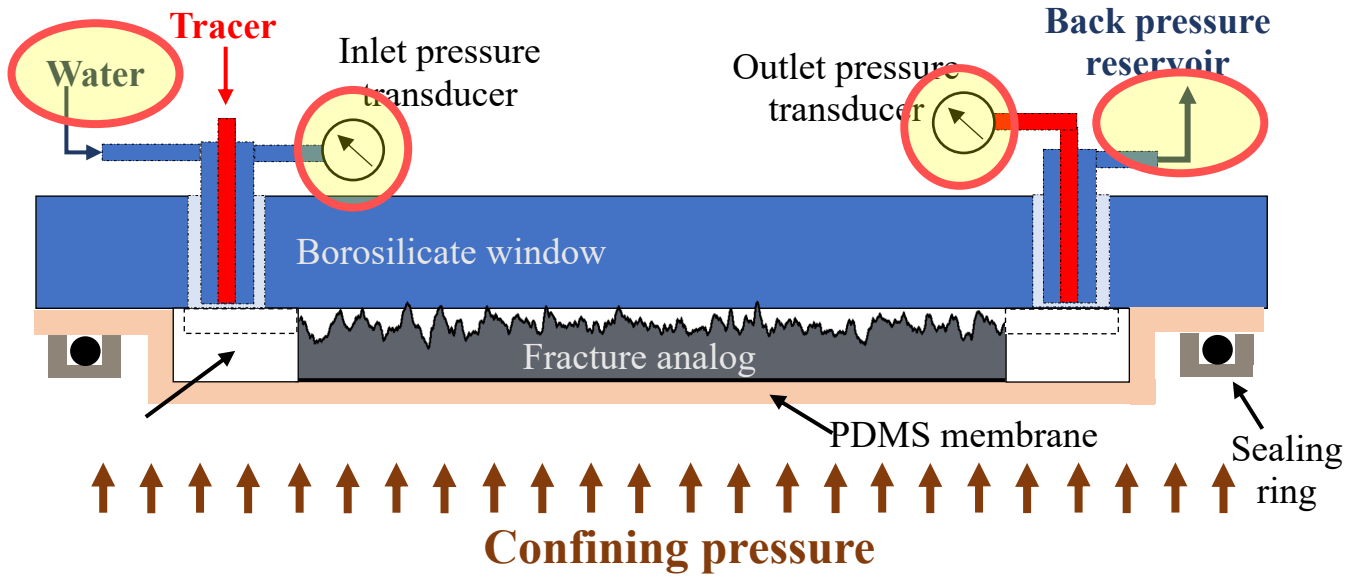




Experimental Investigations

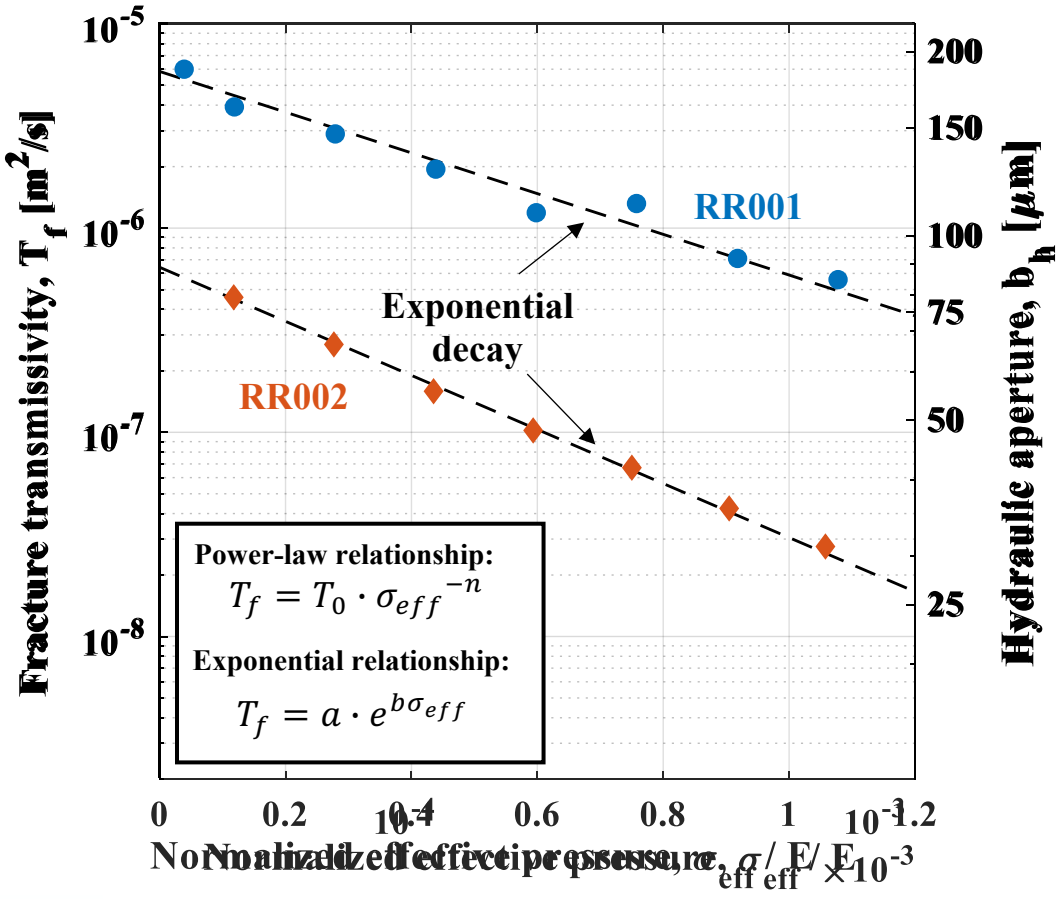
HYDRAULIC MEASUREMENTS (PERMEABILITY)





Experimental Investigations

HYDRAULIC MEASUREMENTS (PERMEABILITY)



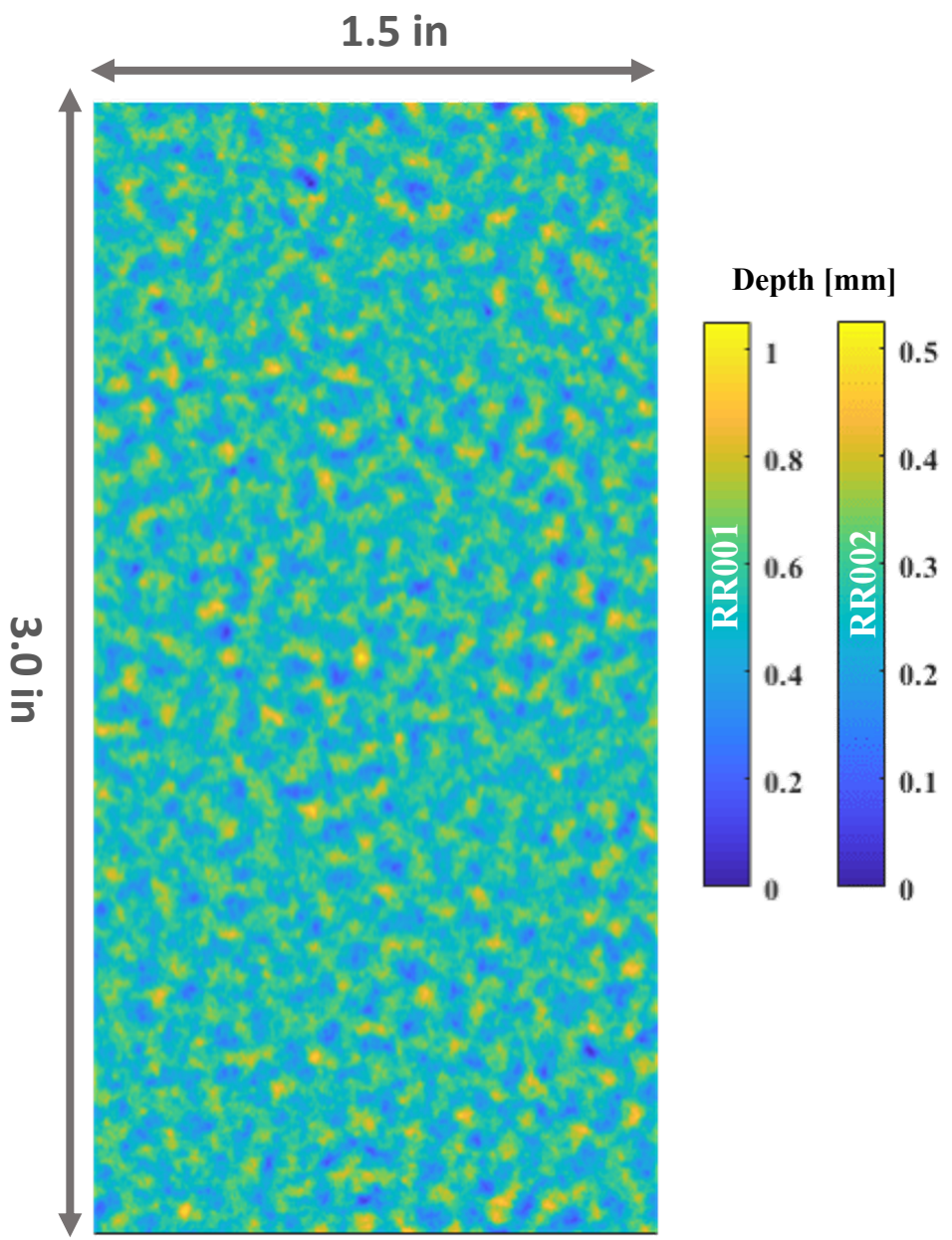
Fracture transmissivity

$$T_j = \rho g \frac{Q}{\Delta P} \frac{L}{W}$$

Hydraulic aperture

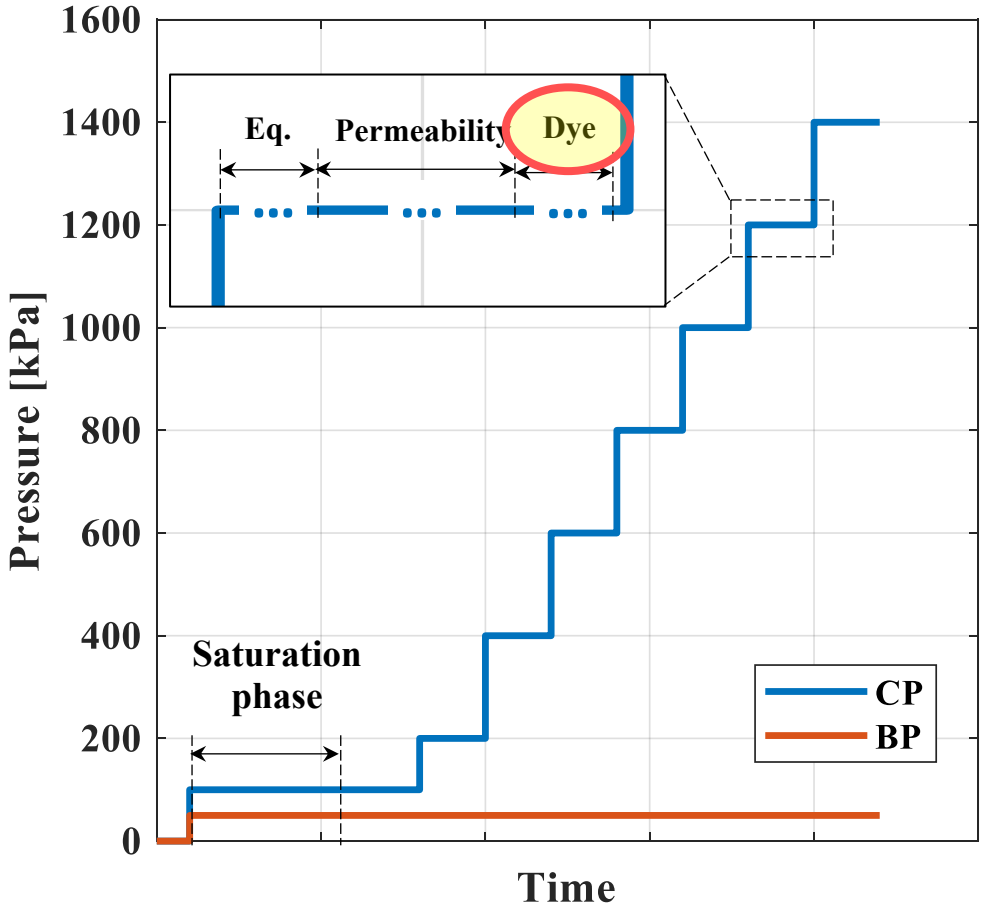
$$b_h = \sqrt[3]{12\mu \frac{Q}{\Delta P} \frac{L}{W}}$$

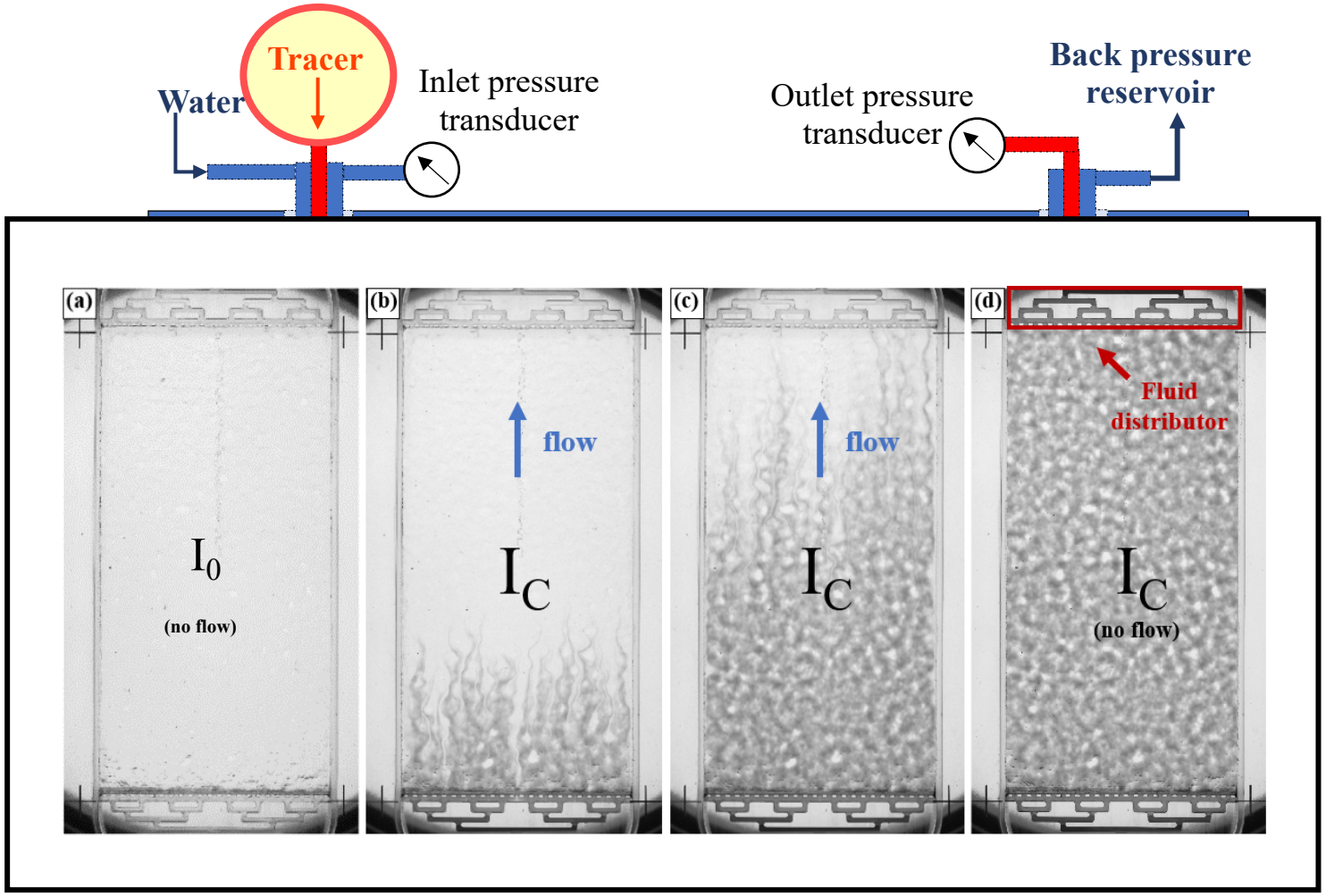
ρ	Fluid density
g	Gravity acceleration
Q	Flow rate
ΔP	Pressure drop
L	Fracture length
W	Fracture width



Experimental Investigations

FRACTURE DEFORMATION & MASS TRANSPORT

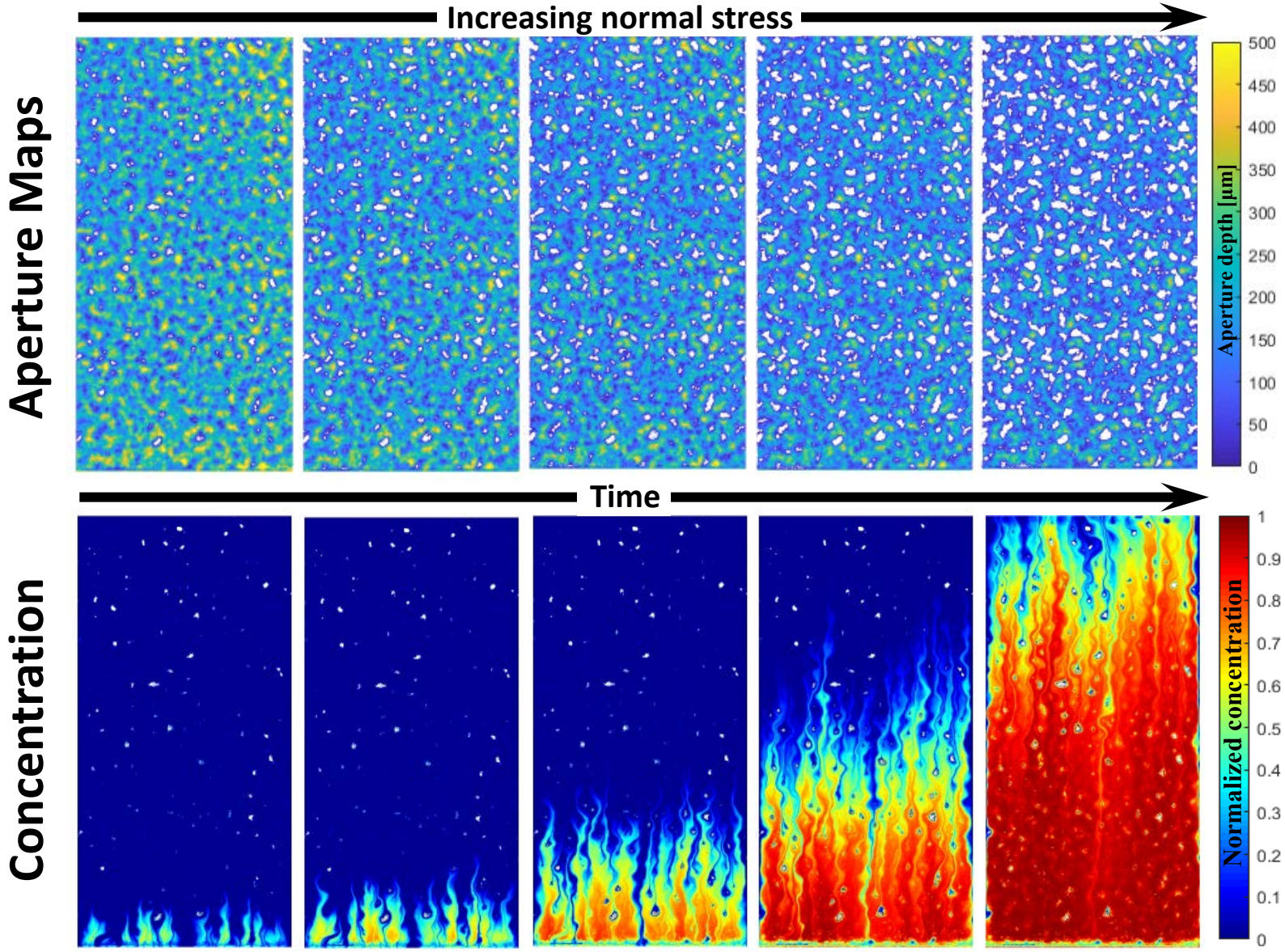


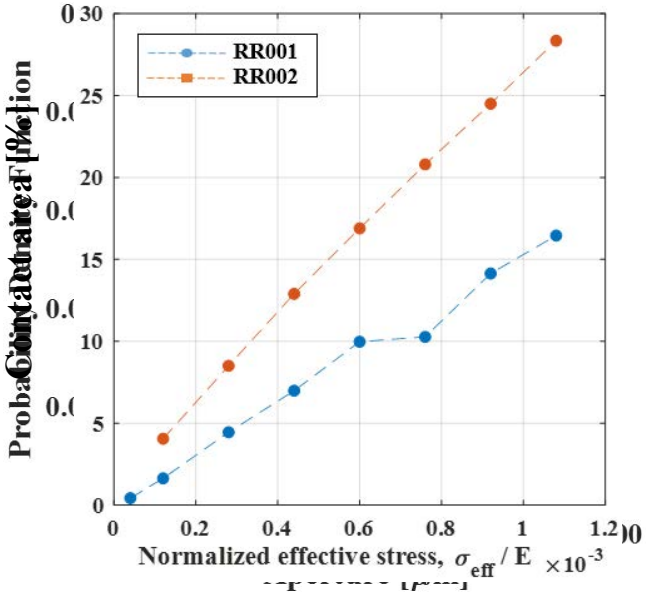


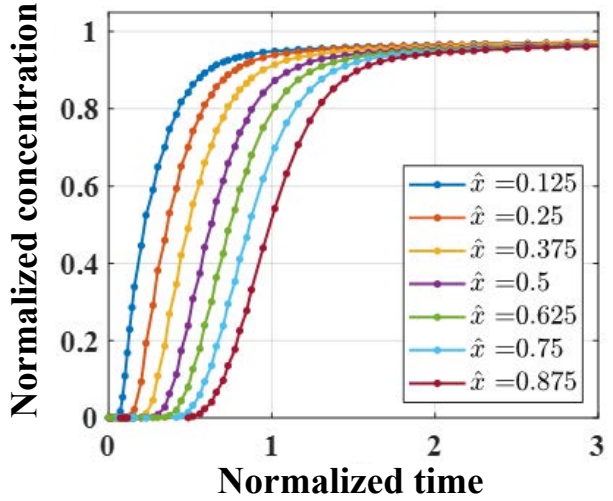
Light intensity → Beer-Lambert Law → **Aperture & Concentration maps**

Experimental Investigations

FRACTURE DEFORMATION & MASS TRANSPORT

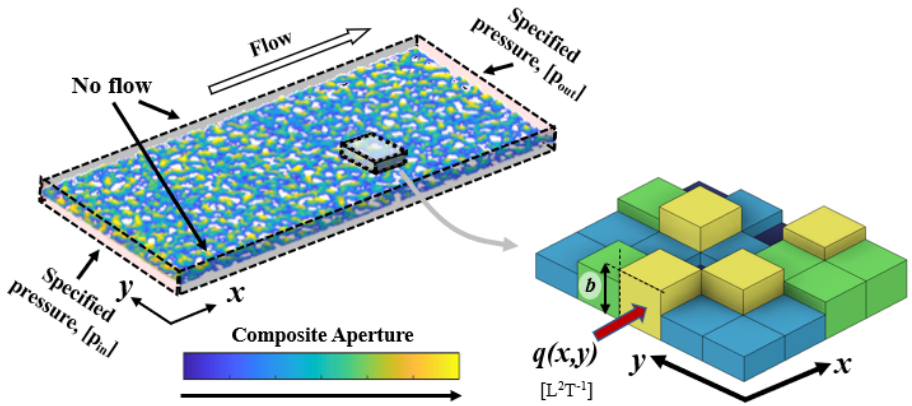






Flow simulations

DETERMINATION OF THE FLOW FIELD: LOCAL CUBIC LAW



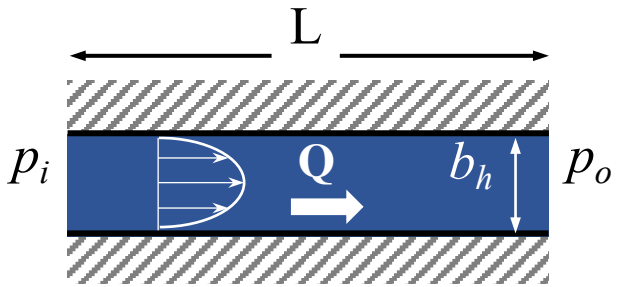
Local Cubic Law: LCL

$$\nabla \cdot \vec{q} = 0$$

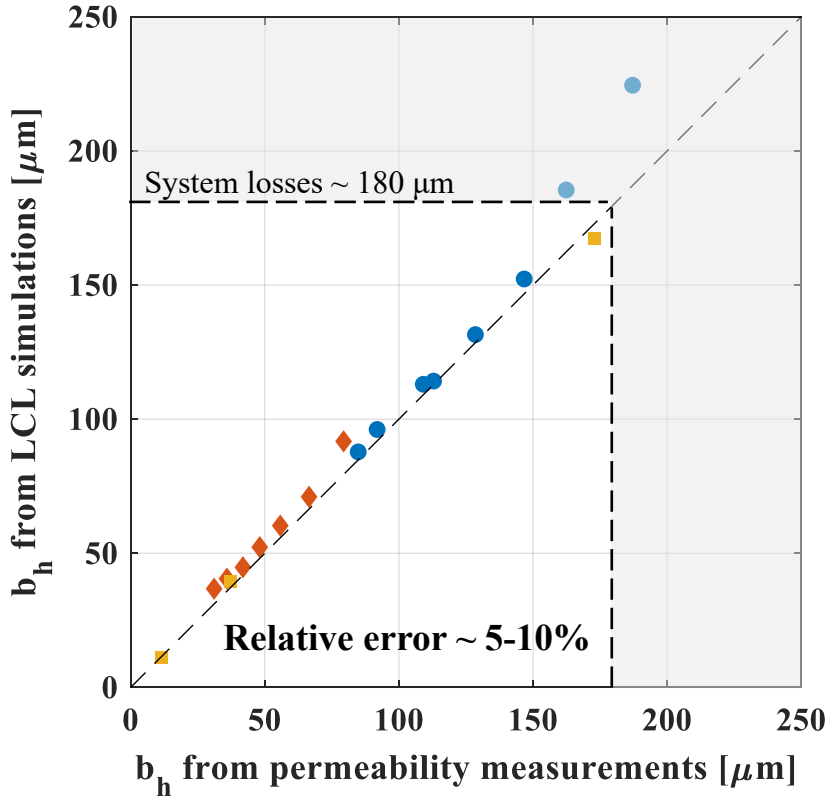
$$\vec{q} = \frac{b^3}{12\mu}\nabla p$$

q : local flux

b : local aperture



Simulations vs. Experiments

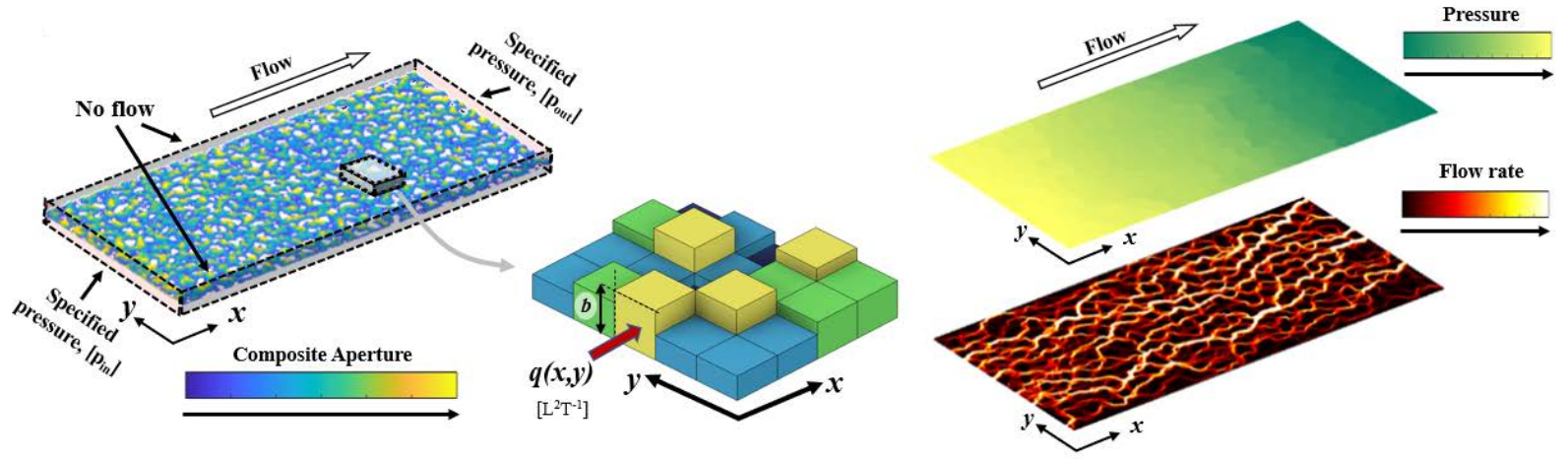


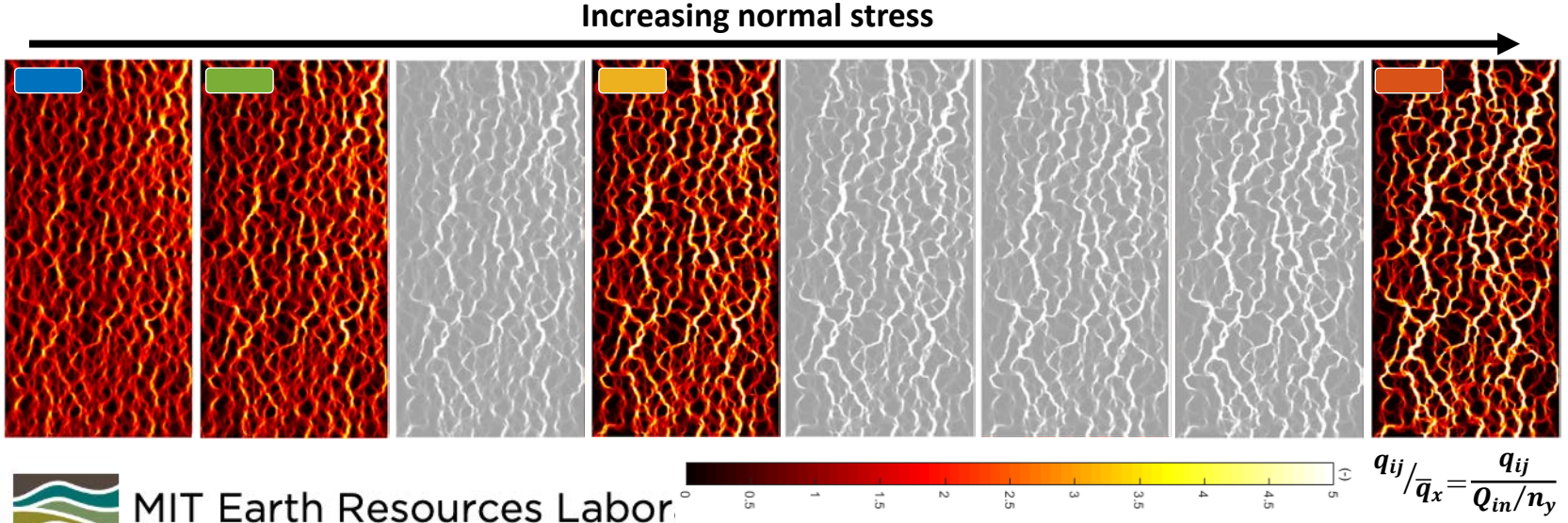
Hydraulic aperture

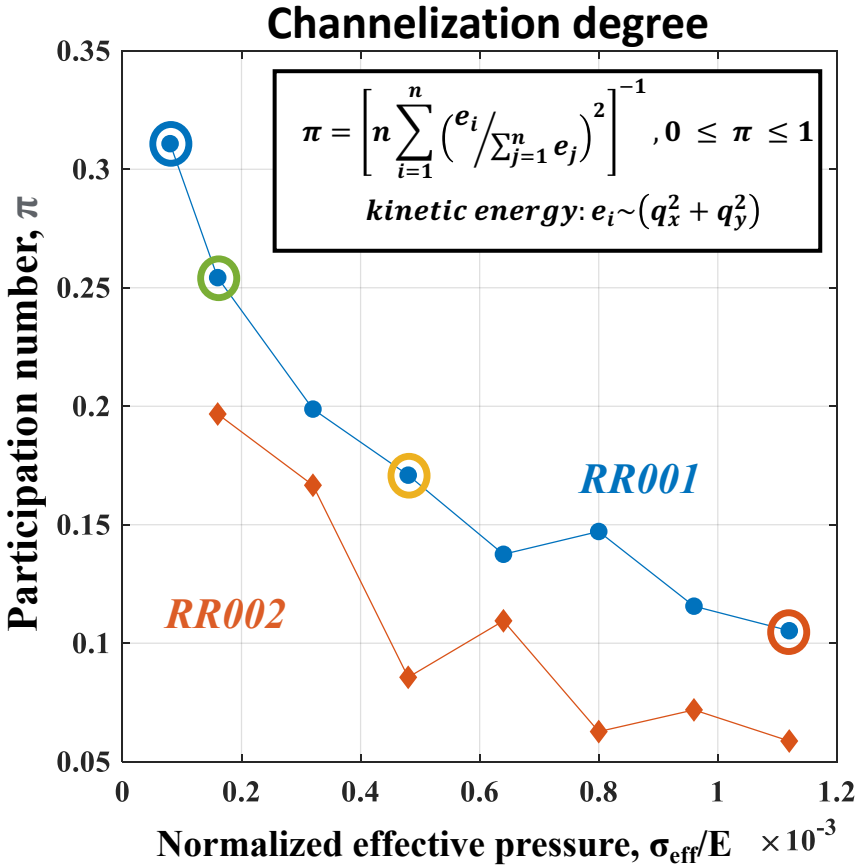
$$b_h = \sqrt[3]{12\mu \frac{Q}{\Delta P}\frac{L}{W}}$$

Flow simulations

DETERMINATION OF THE FLOW FIELD: LOCAL CUBIC LAW



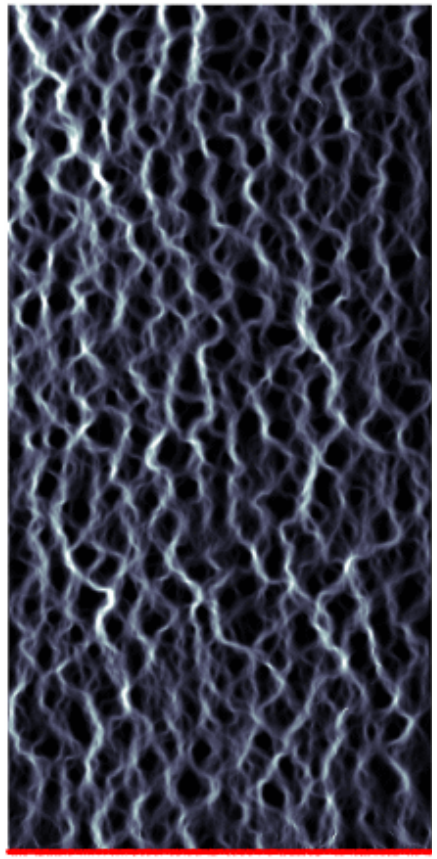


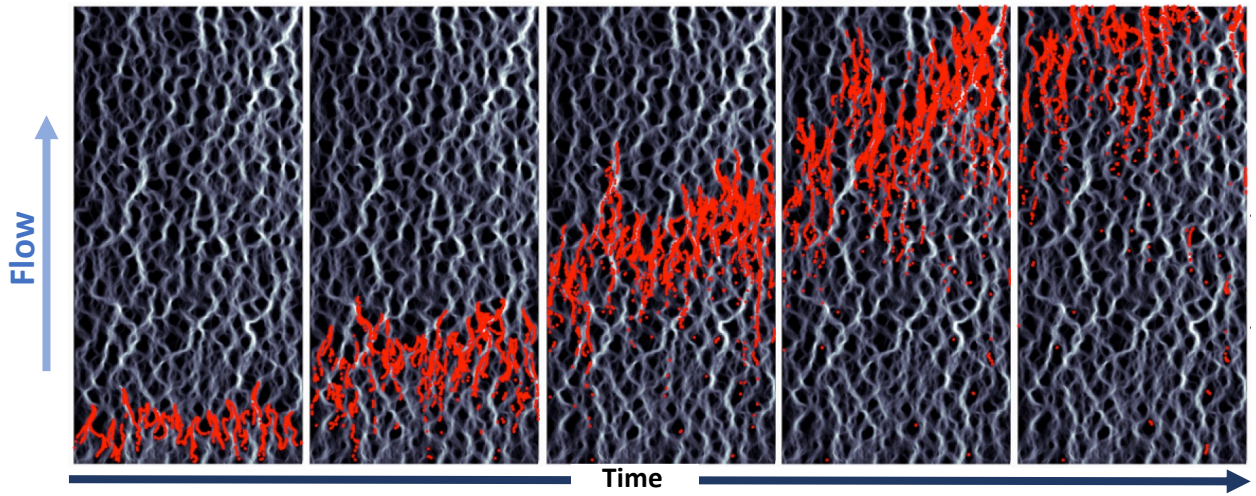


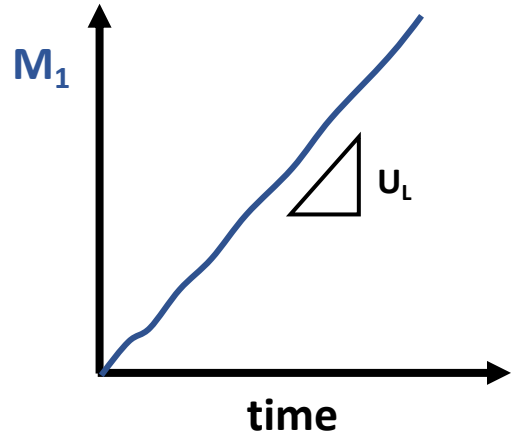
Conservative Transport

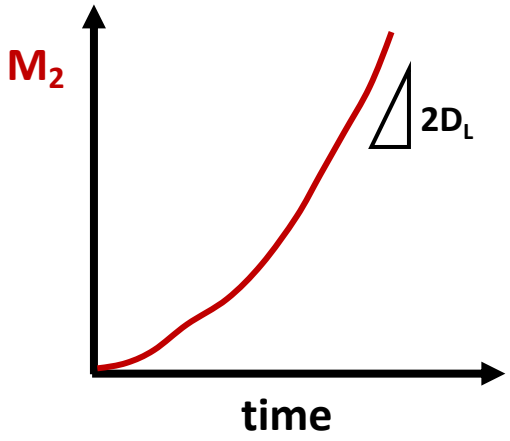
PARTICLE TRACKING SIMULATIONS

U_L Average velocity (longitudinal dir.)
D_L Dispersion coefficient (longitudinal dir.)









Spatial Moments

$$M_1 = \langle x(t) \rangle = \frac{1}{N} \sum_{i=1}^{N} x_i(t)$$ → Center of mass

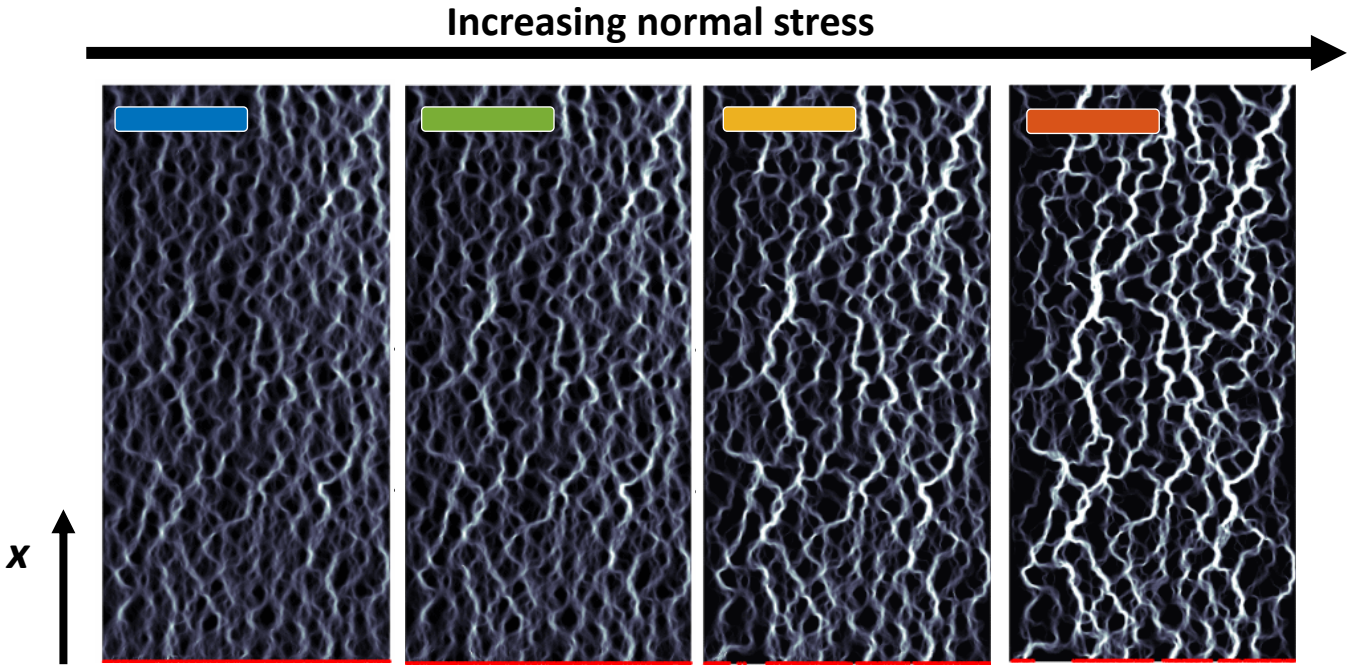
$$M_2 = \langle |x(t) - M_1|^2 \rangle = \frac{1}{N} \sum_{i=1}^{N} |x_i(t) - M_1|^2$$ → Spread around the center of mass

$x(t)$ Particle position

N Number of particles

Conservative Transport

PARTICLE TRACKING SIMULATIONS



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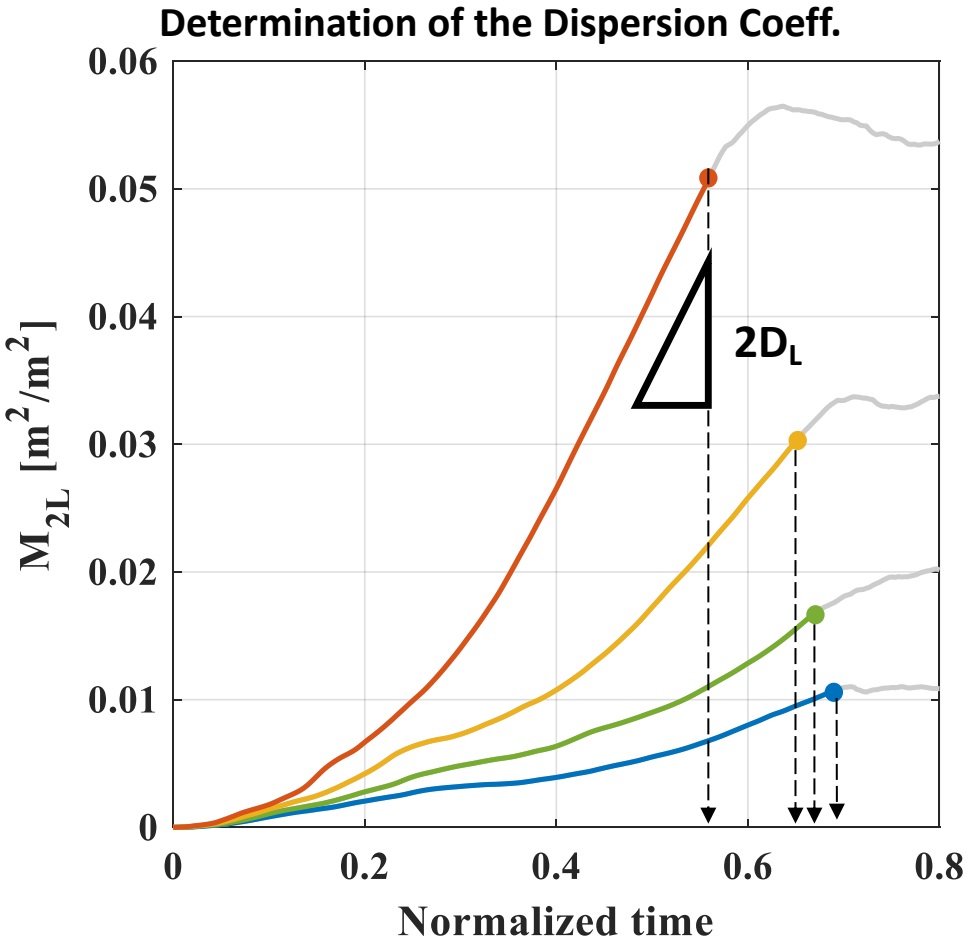
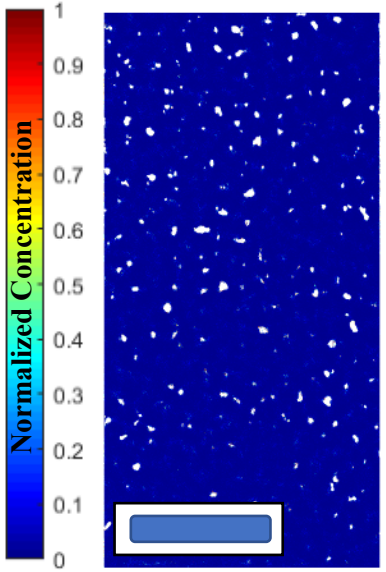
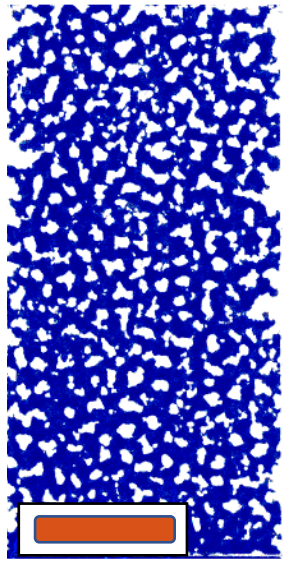
x(t) : particle position

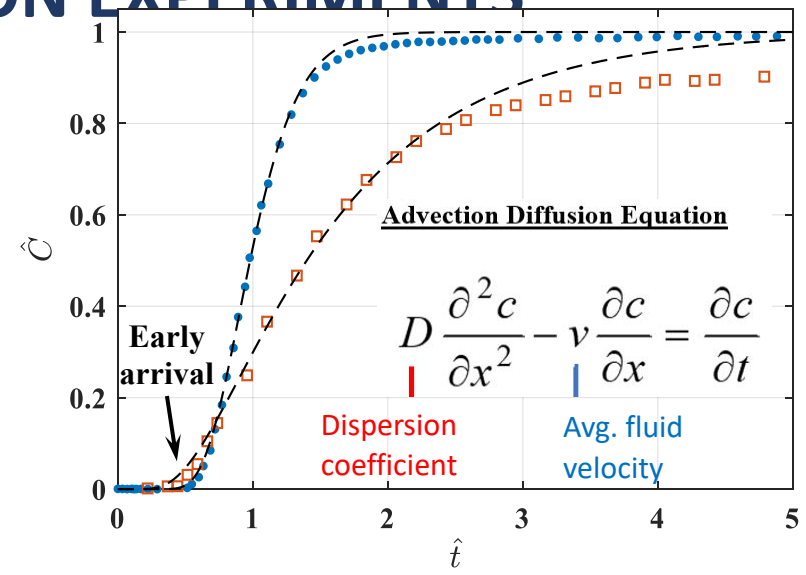


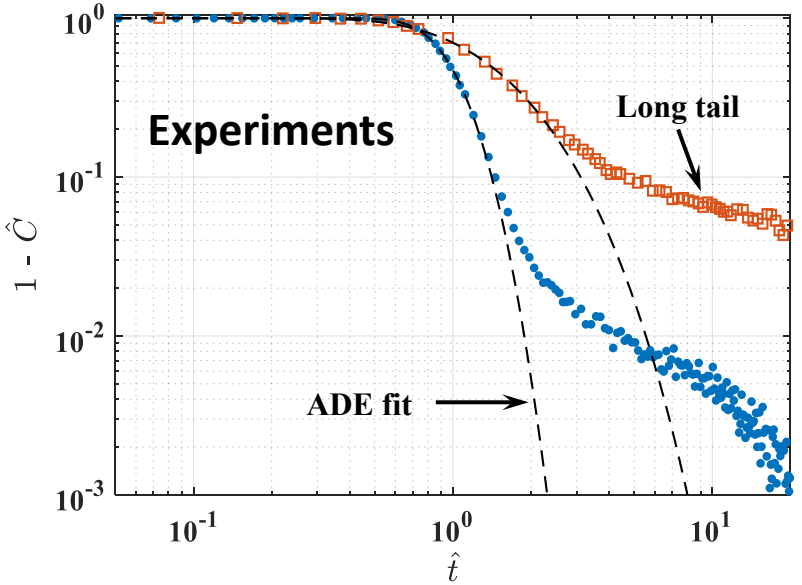
Conservative Transport

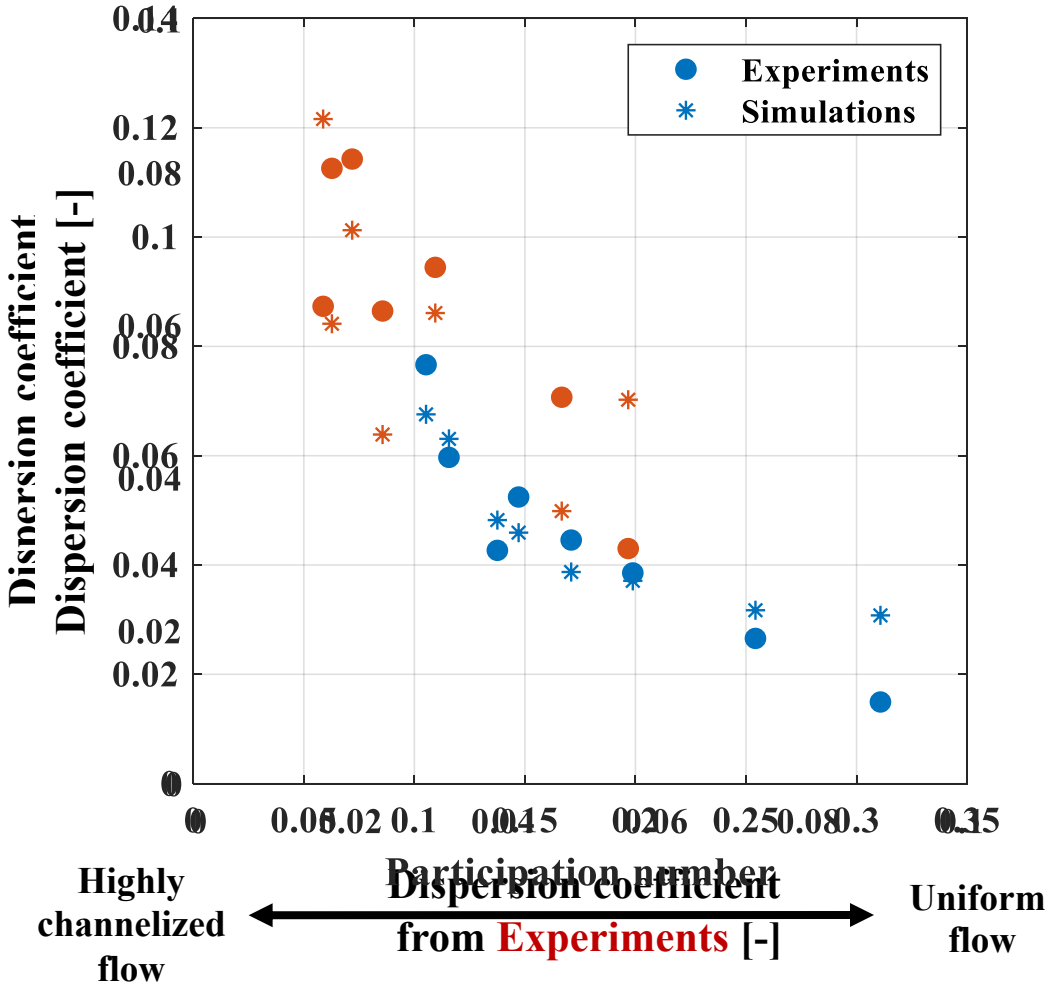
TRACER INJECTION EXPERIMENTS











Conclusions

- Developed new experimental methodology combining digital fabrication of rock analogs and a novel pressure-controlled Hele-Shaw cell.
- In-situ measurement of aperture maps + geometric characteristics
- Stress-dependent permeability + flow field topology
- Evolution of mass transport dynamics