ERL, MIT
16th July Mon. 2pm

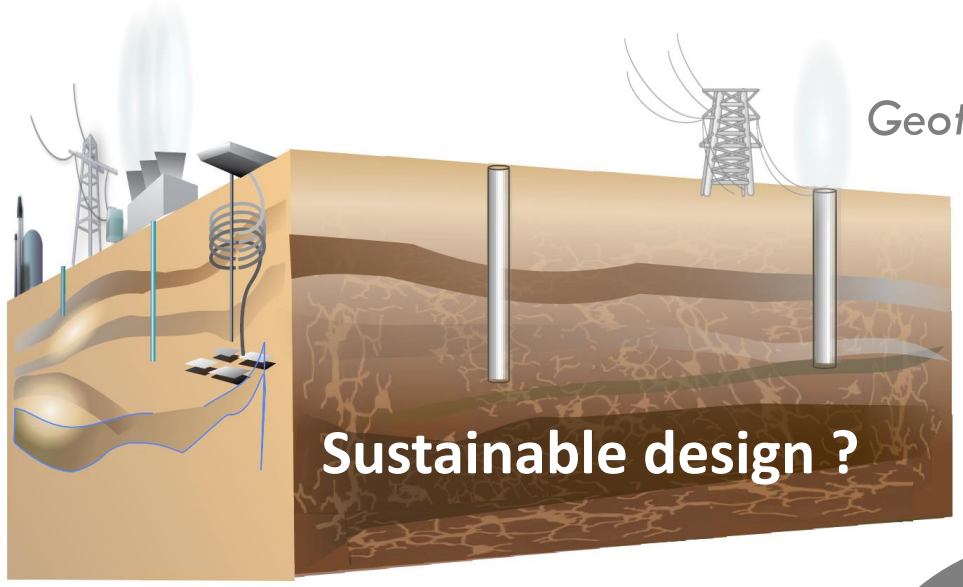
Inverse analysis of fracture structures and flow for designing geological energy systems

Anna Suzuki

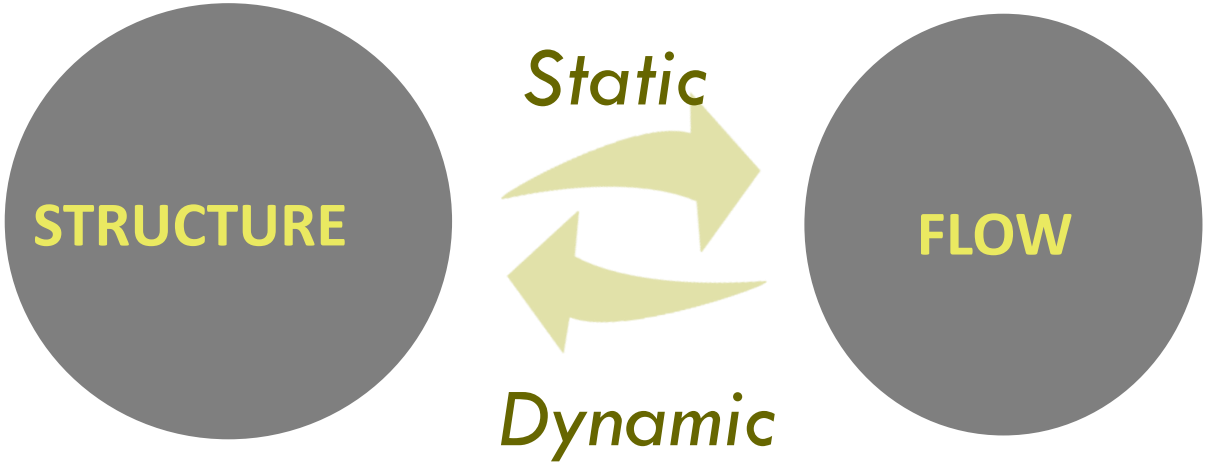
Design of Structure and Flow in the Earth Lab
Institute of Fluid Science, Tohoku University

2007.4-2014.6	Undergrad~Ph.D. (Mechanical Eng/Environmental Studies, Tohoku U)
2014.6-2016.10	Postdoc (Geothermal group, Stanford)
2016.11-present	Tenure track assistant professor (Fluid Science)

Design of Structure and Flow in the Earth Lab

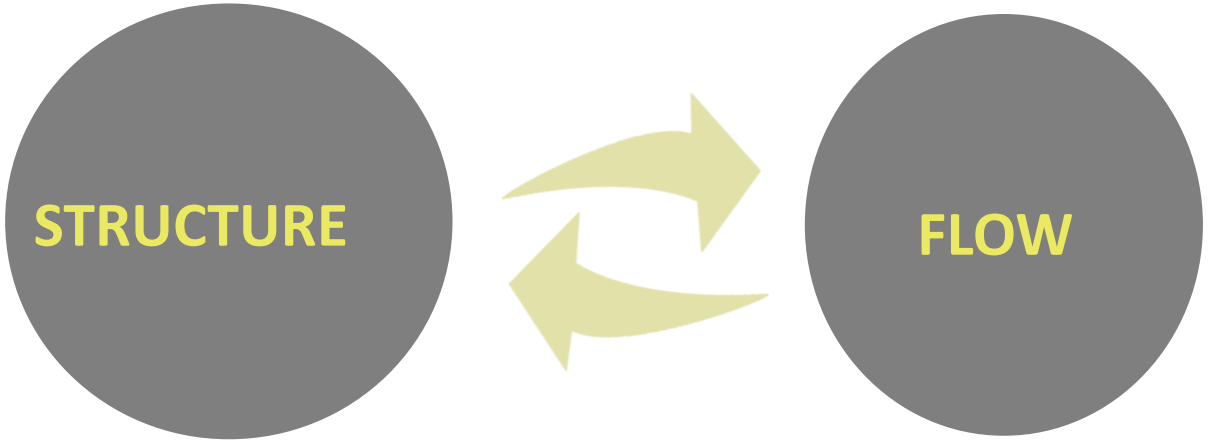


Geothermal energy



QUESTION

1) How do structure and flow interact each others?
2) How to quantify fracture patterns?
3) Can we estimate structure or flow from the other data?



DATA

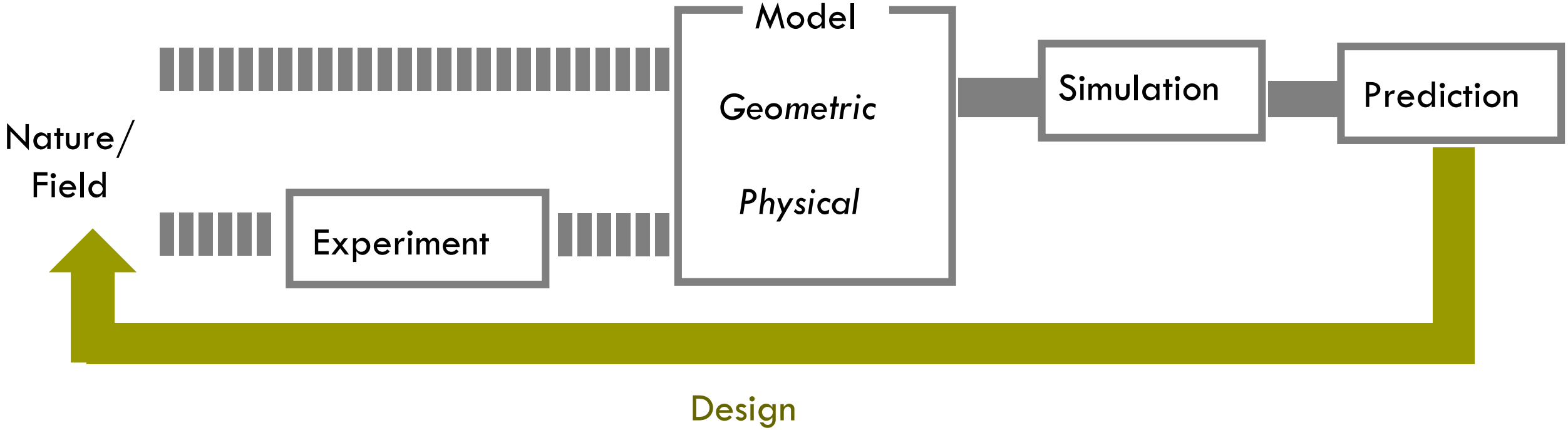
Fracture patterns

Tracer
Thermal response
Electrical resistivity etc.

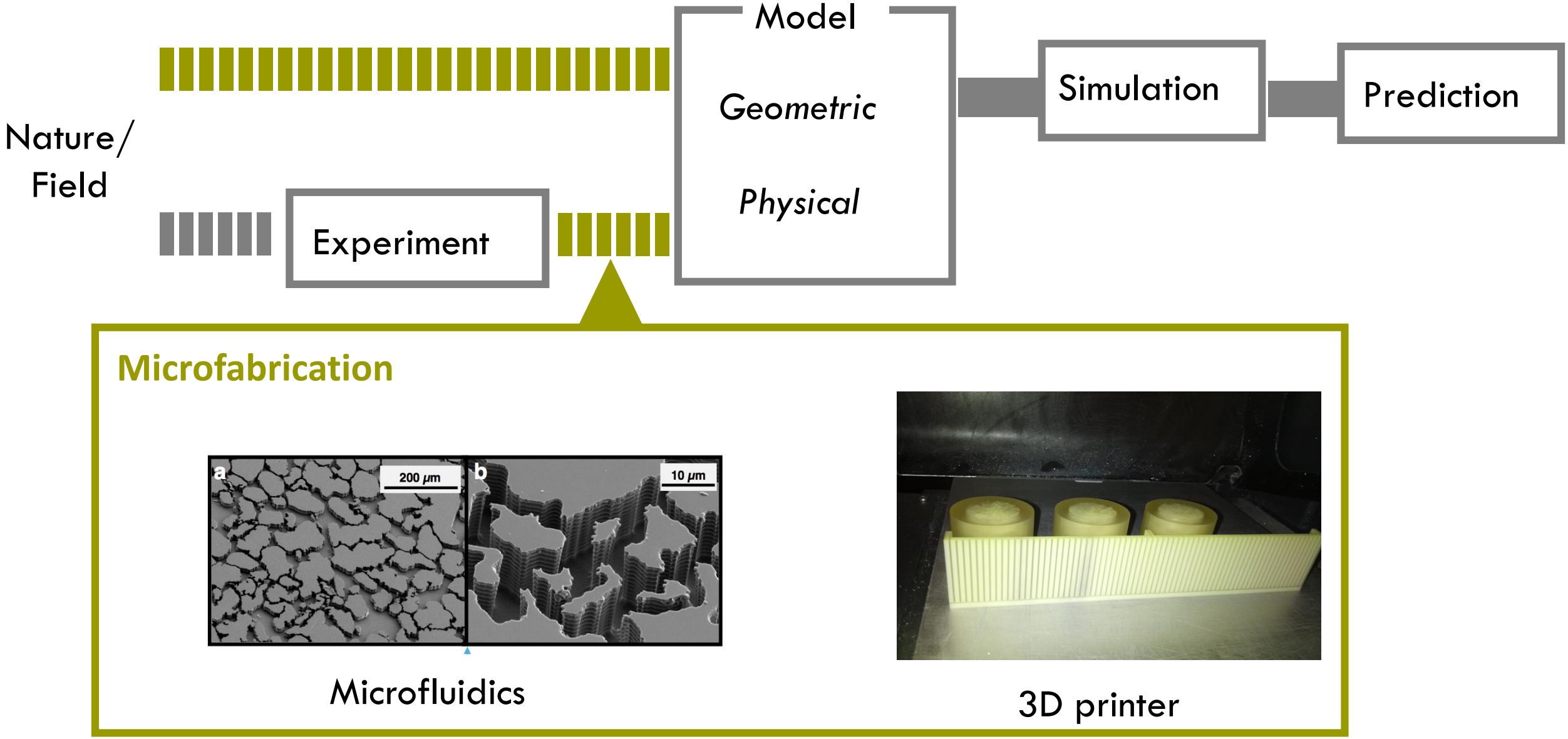
QUESTION

1) How do structure and flow interact each others?

RESEARCH TO FIELD DESIGN

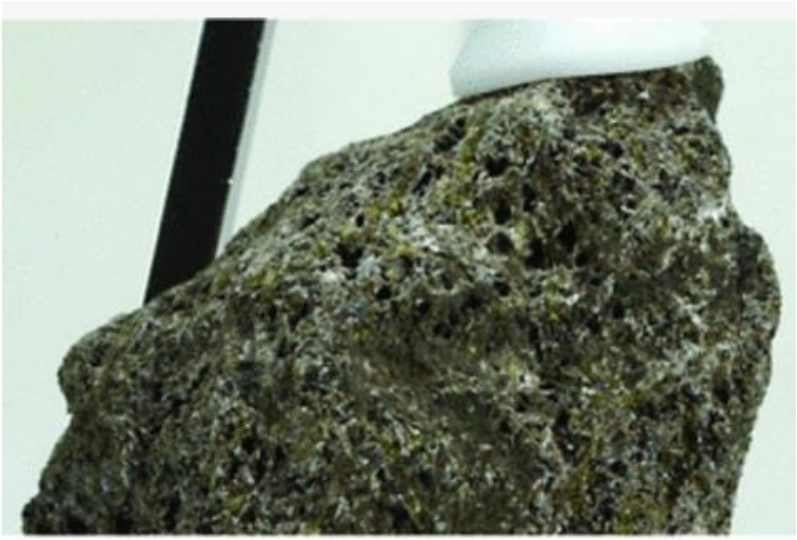


MICROFABRICATION APPROACH

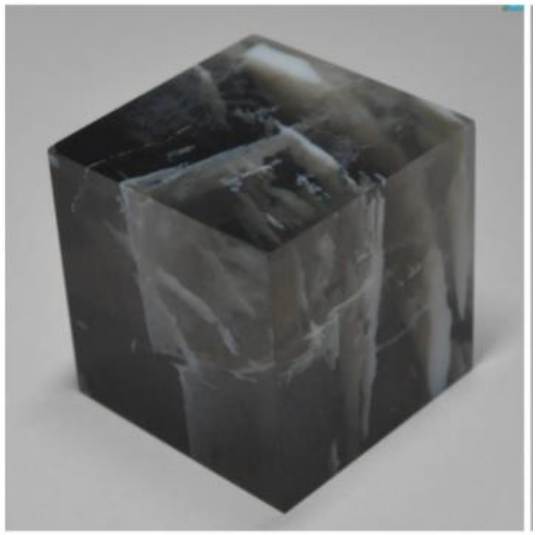


3D PRINTING ROCKS

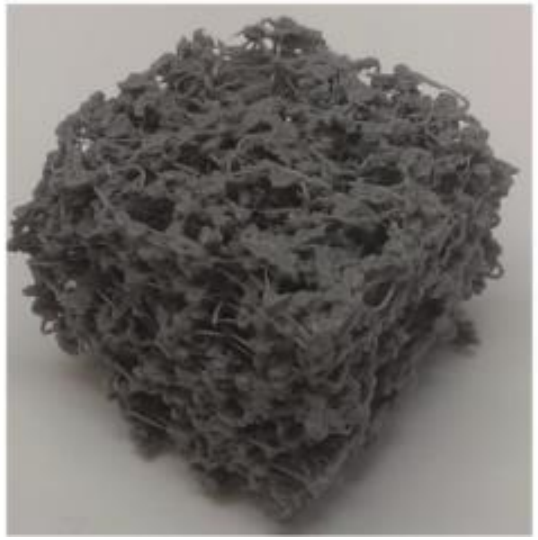
Core scale



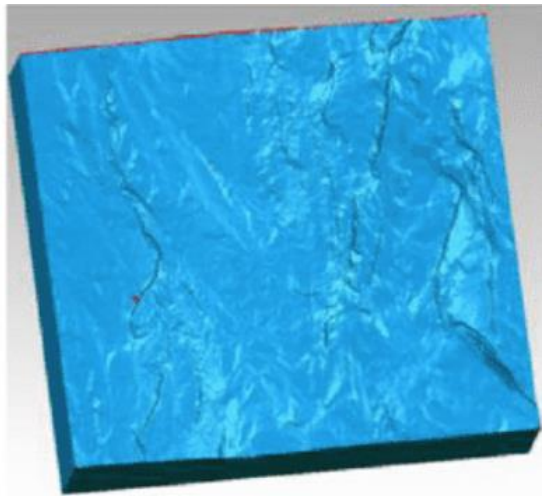
Moon rock
(Holloway, 2012)



Coal rock
(Ju et al., 2014)

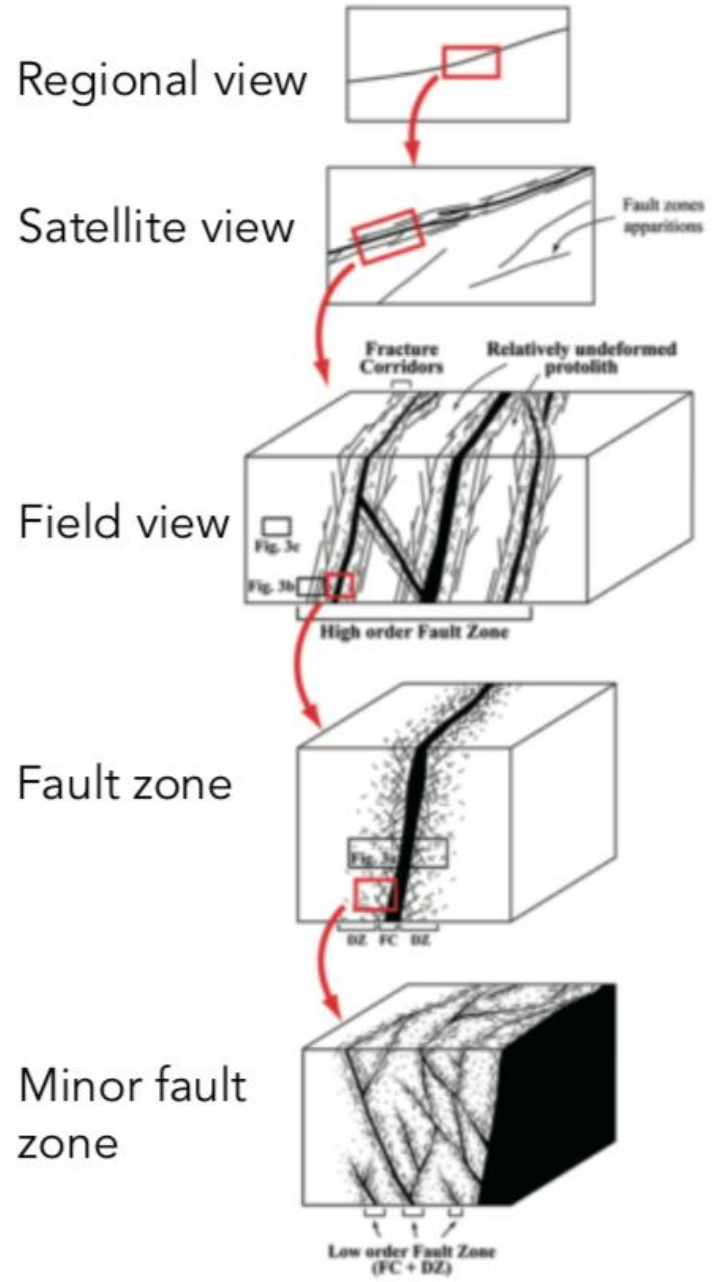


Sandstone
(Ishutov et al., 2015)



Single fracture surface
(Jiang et al., 2016)

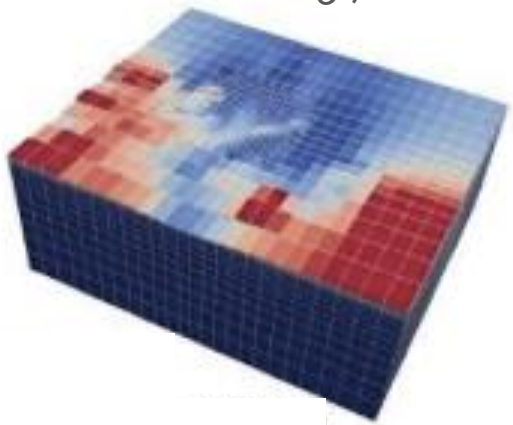
FRACTURE NETWORK



Reservoir simulation

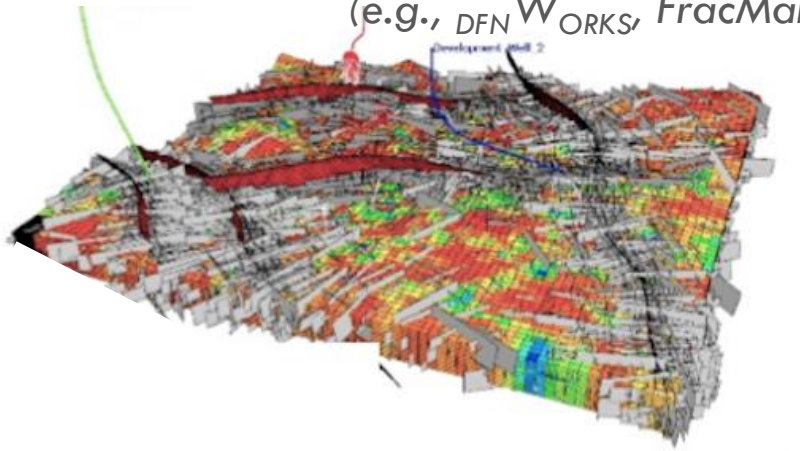
Equivalent continuum model

(e.g.,TOUGH2, FE-FLOW)



Discrete fracture network

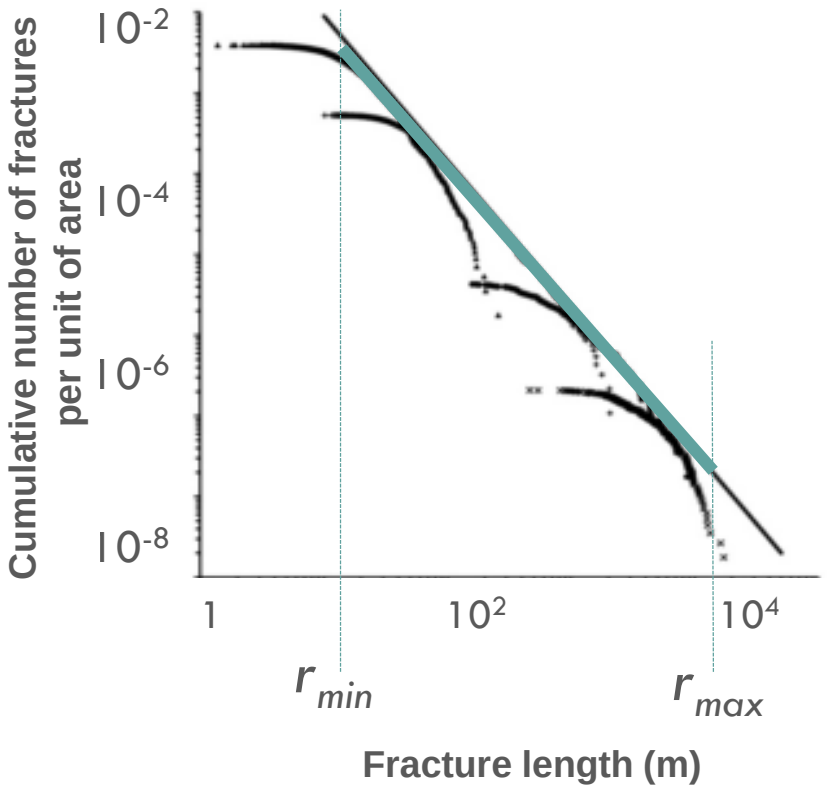
(e.g., DFNWORKS, FracMan)



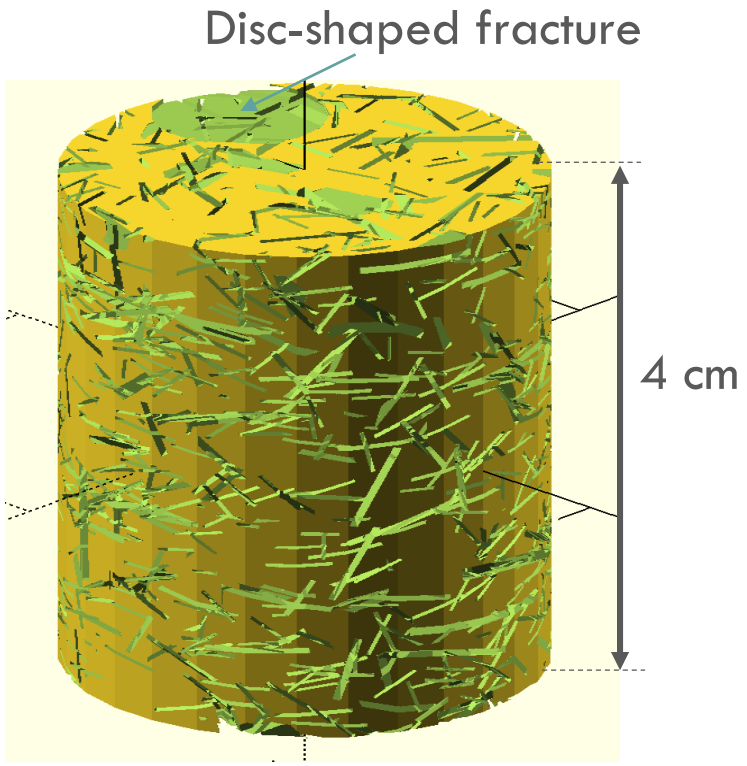
Use 3D printer for validation

FRACTURE NETWORK

Scaling of fracture systems



(Castaing et al.,1996; Odling et al., 1999)



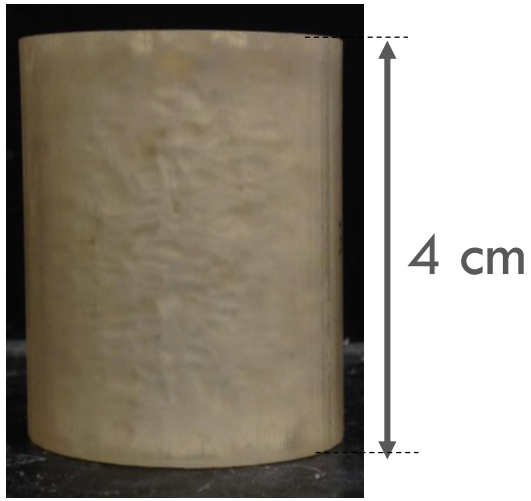
Min aperture / radius
0.2 / 1.6 mm

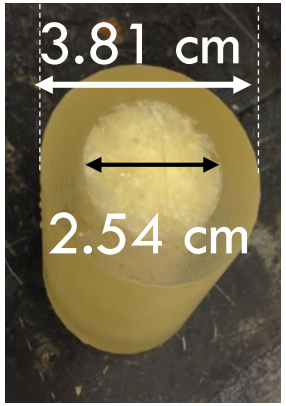
Max aperture / radius
1 / 8 mm

3D PRINTER

VisiJet ® EX200
3D Systems @Stanford 3-Dimensional Printing Facility (3D)

Base material:
UV curable acrylic plastic
Support material:
Hydrophobic wax

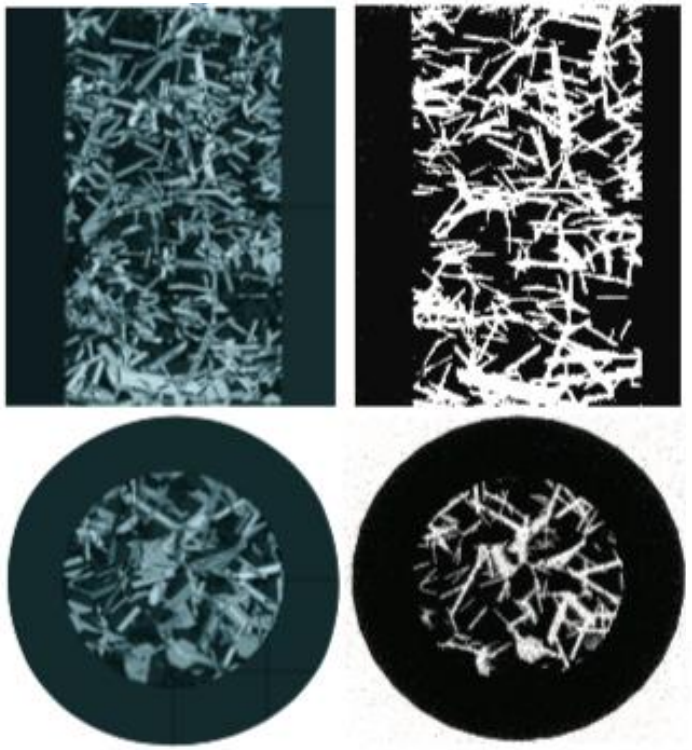




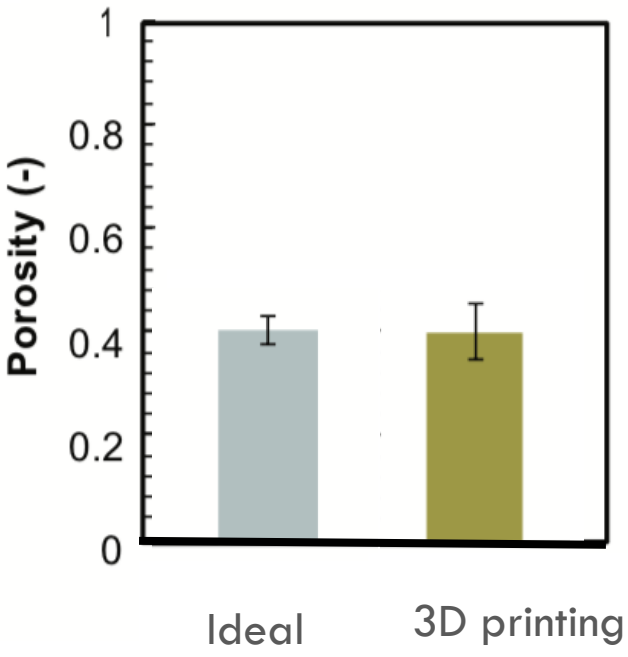
VALIDATION

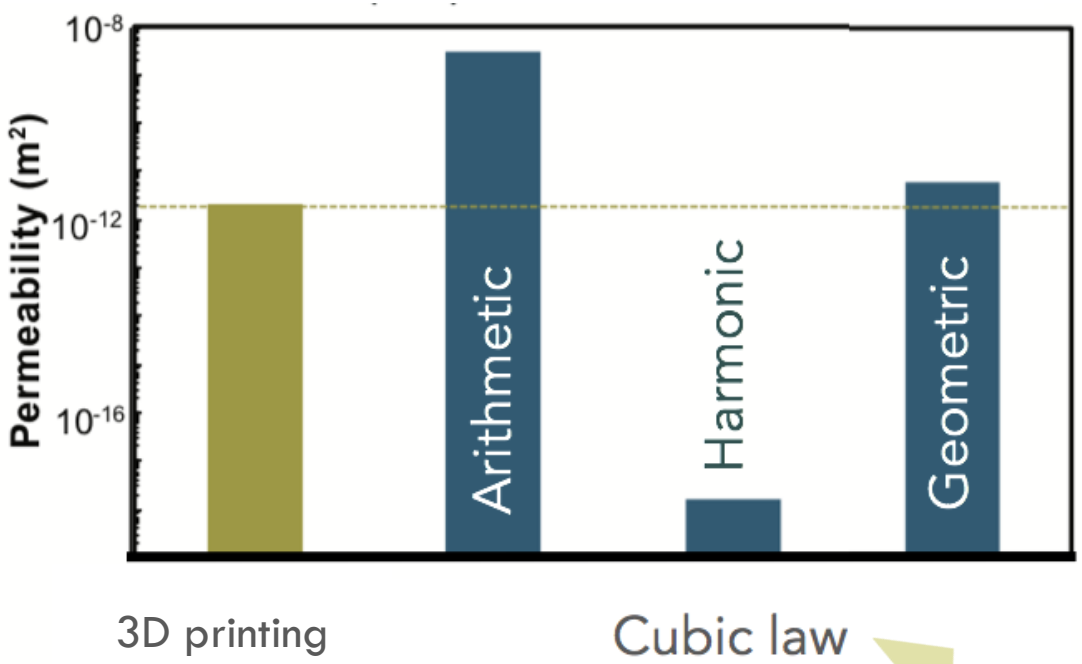
CT scanning

Ideal 3D printing



Flow experimental results



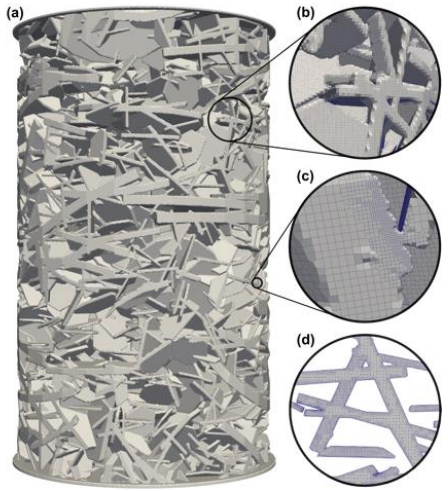


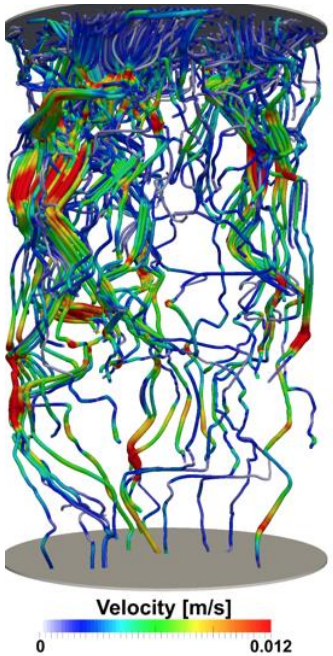
Consistent with conventional theoretical studies (Jensen, 1991)

Suzuki et al., WRR, 2017

COMPARISON

CFD simulation





Equivalent permeability model

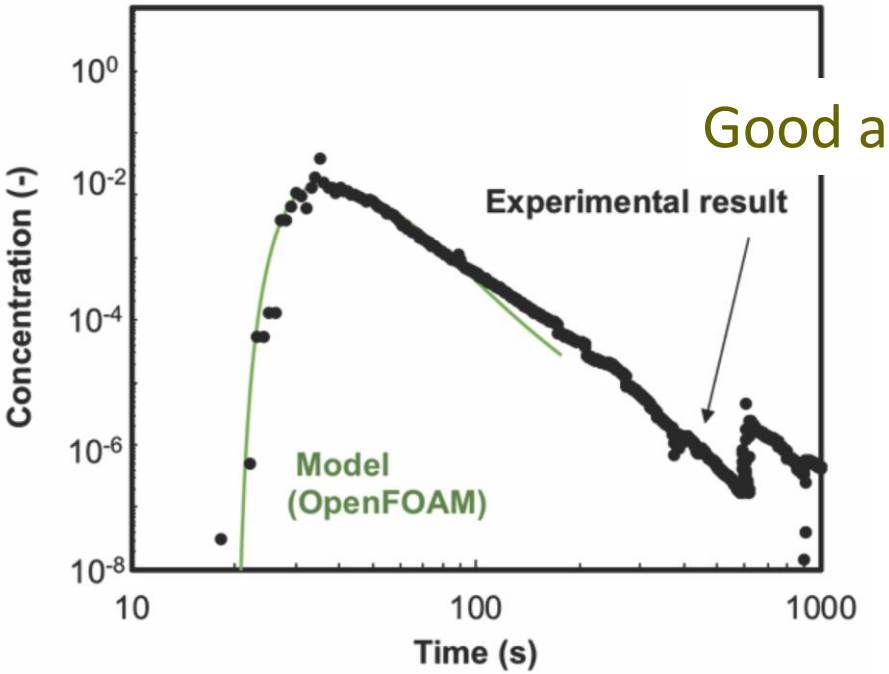
$$K_x = \sum_j \frac{\eta_j^2}{12} \frac{\eta_j L_j}{A_x}$$

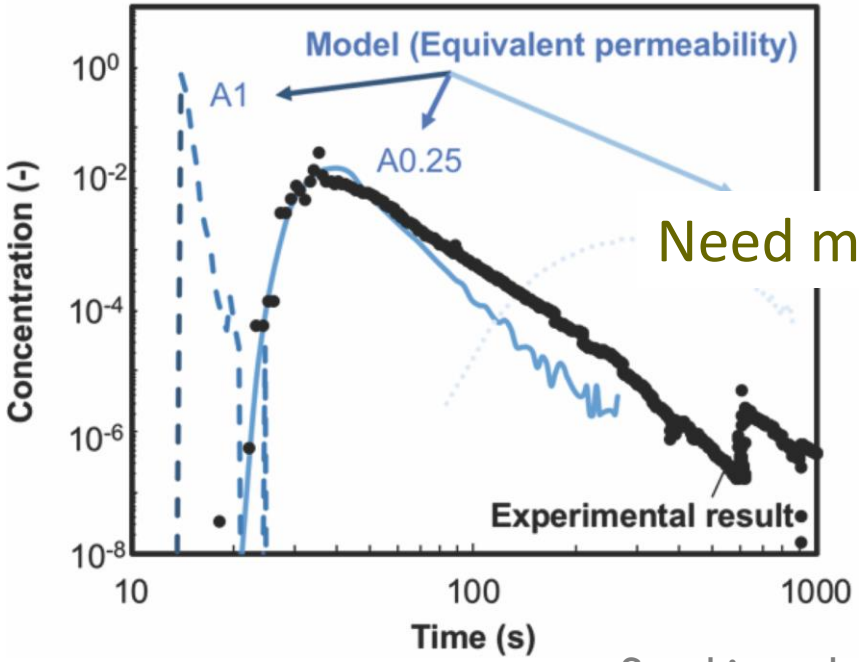
Ax: Areas of grid cell interfaces orthogonal to the x
j: Numbering of fractures
ηj : Aperture
Lj : Length of the fracture intersecting the interface of grid cells

- Calculate flow rate by using Darcy's law:

$$Q_x = A_x \frac{K_x}{\mu} \frac{\Delta P}{\Delta x}$$

ΔP/Δ: Pressure gradient
μ the viscosity of water





Suzuki et al., TiPM, submitted

QUESTION

1) How do structure and flow interact each others?

Microfabrication approach will help to understand.

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2) How to quantify fracture patterns?

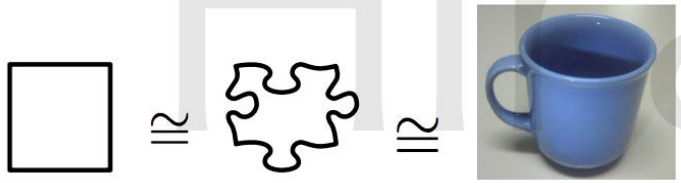
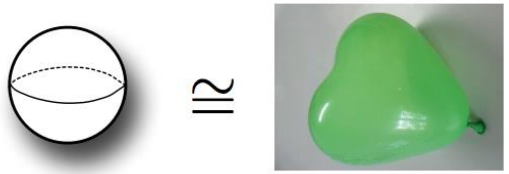
QUANTIFICATION OF FRACTURE STRUCTURES

Quantitative tools for geometry

- intensity [Mauldon et al., 2001]
- length [Bour et al., 2002]
- density [La Pointe, 1988]
- fractal dimension [Bonnet et al., 2001]
- percolation thresholds [Mourzenko et al., 2005]
- topology of networks [Sanderson and Nixson, 2015]

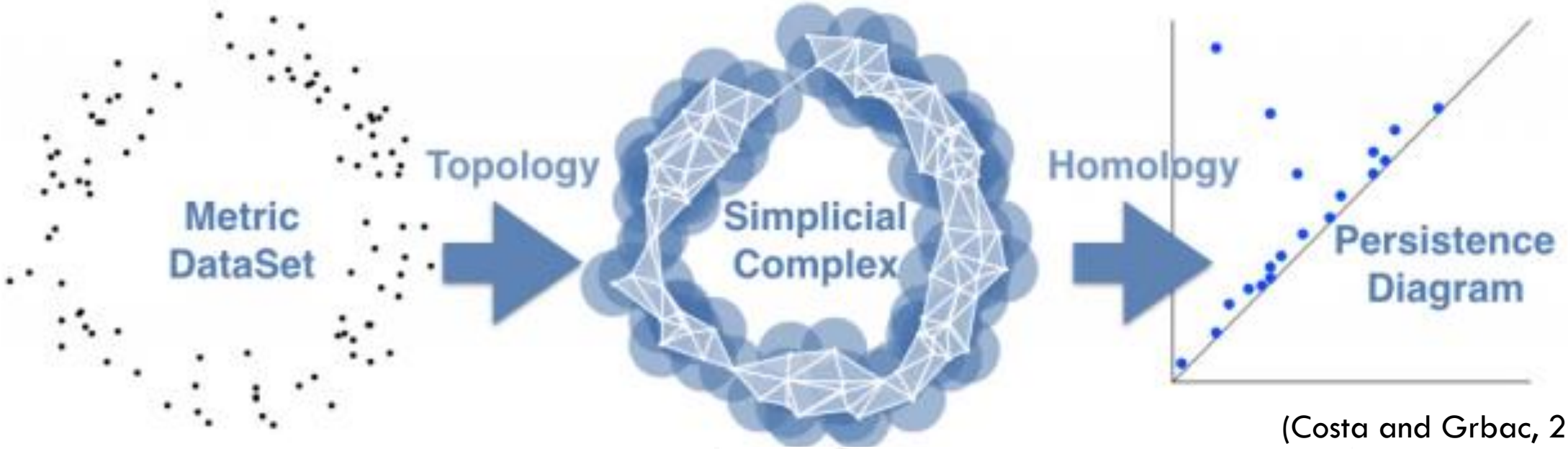
etc.

PERSISTENT HOMOLOGY

	Connected component	ring	pore
	1	0	0
	2	0	0
	1	1	0
	1	0	1

https://www.wpi-aimr.tohoku.ac.jp/hiraoka_labo/introduction_j.pdf

PERSISTENT HOMOLOGY

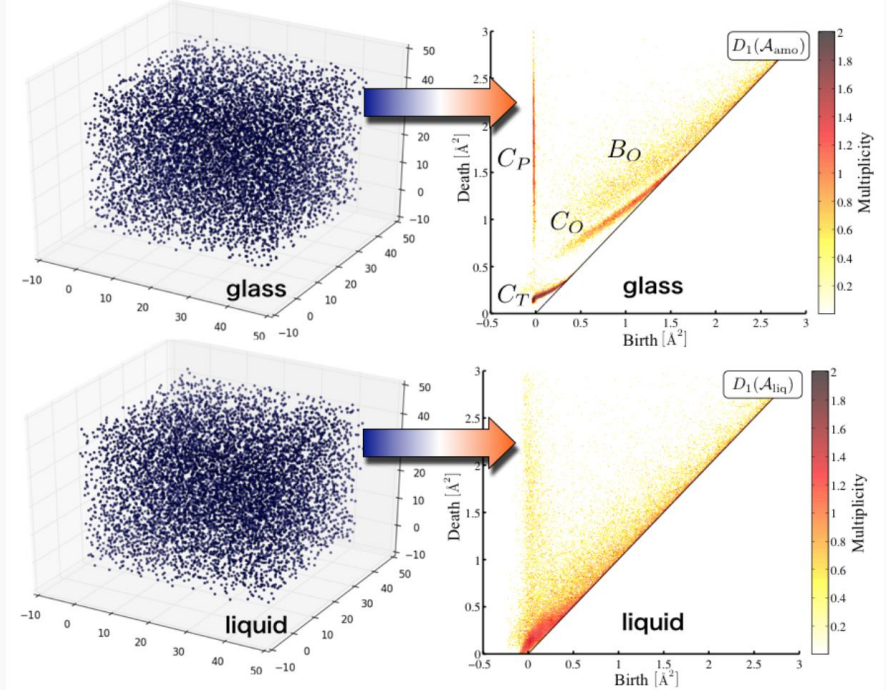


(Costa and Grbac, 2017)

Application

- material science [Hiraoka et al., 2016]
- data memory [Choudhury et al., 2012]
- RNA folding space [Mamuye et al., 2016]
- viral evolution [Chan et al., 2013]

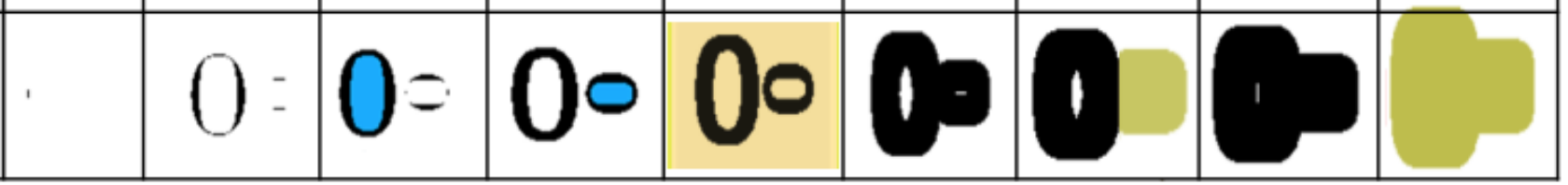
  etc.



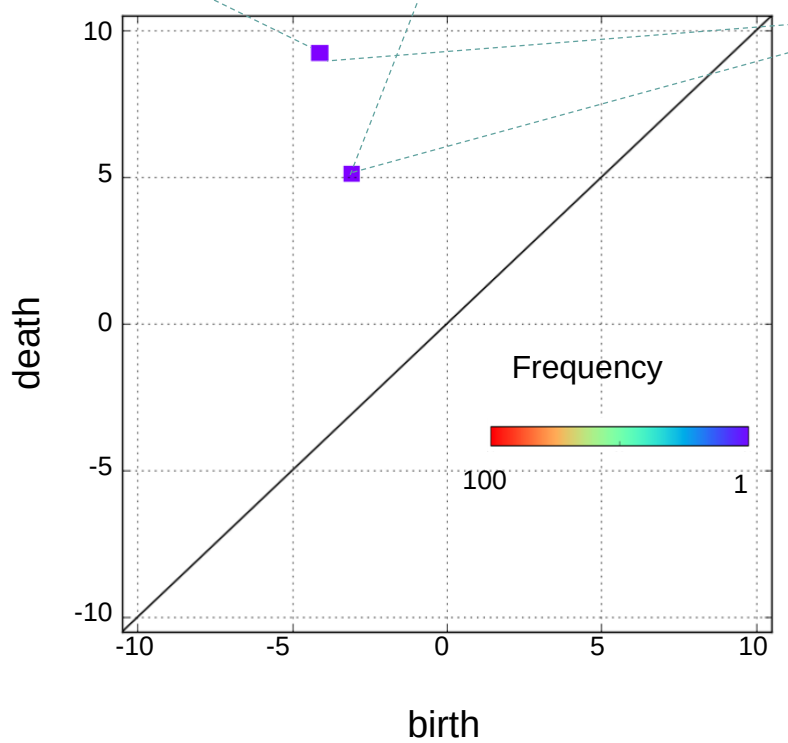
(Hiraoka et al., 2016)

PERSISTENT HOMOLOGY

Thinning ← Original → Thickening

Pixel increment /decrement	…	…	- 4	- 3	0	…	5	…	9
Image									

birth birth death death

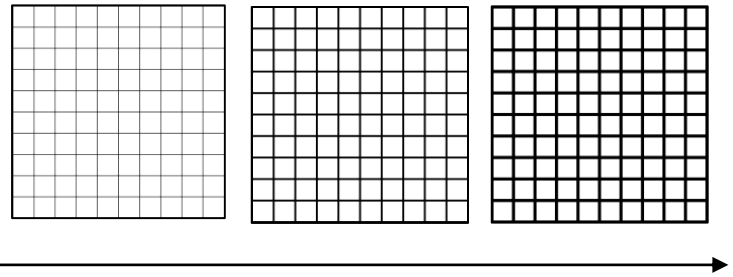


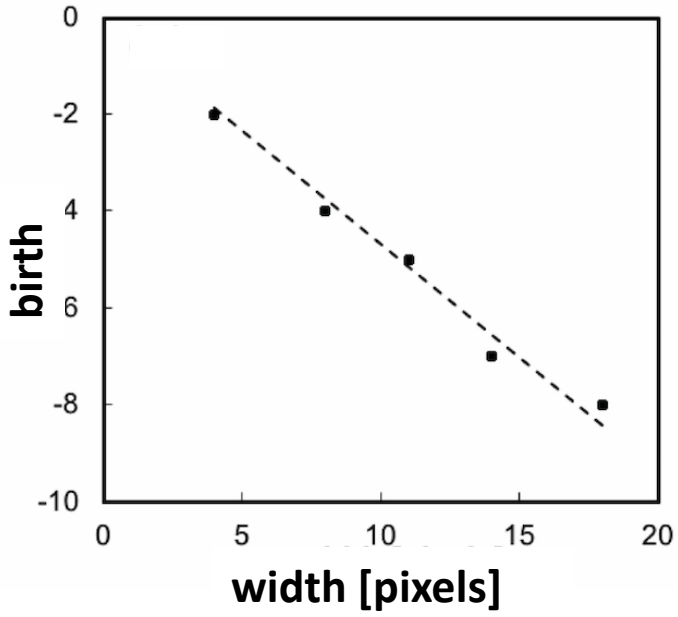
Persistence diagram

Software:HomCloud
(Hiraoka and Obayashi)

PERSISTENT HOMOLOGY FOR FRACTURES

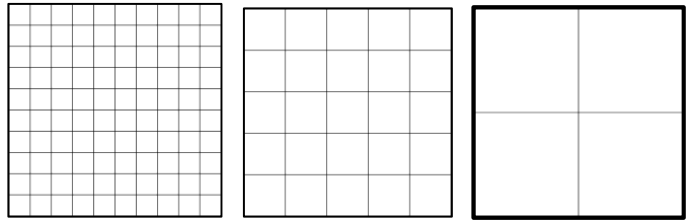
Fracture width

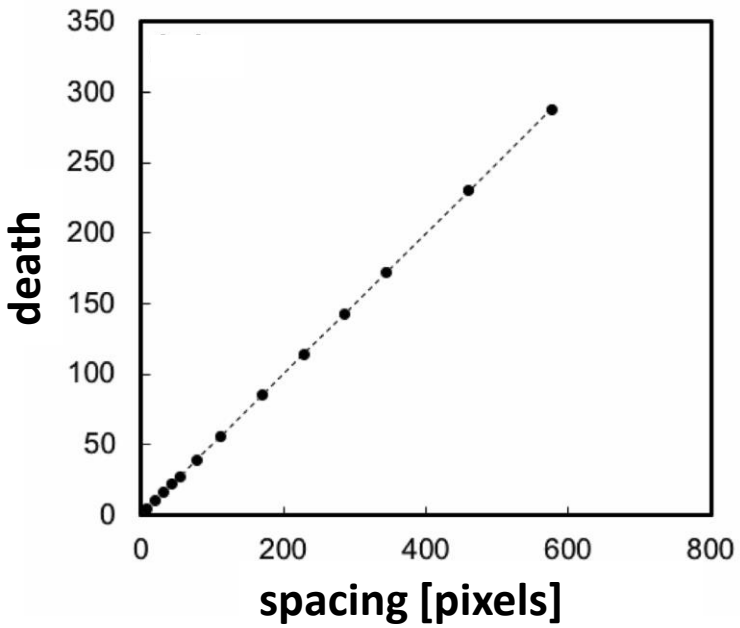




birth ∽ - width

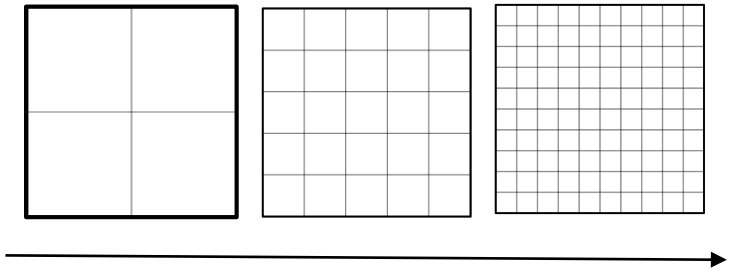
Fracture spacing

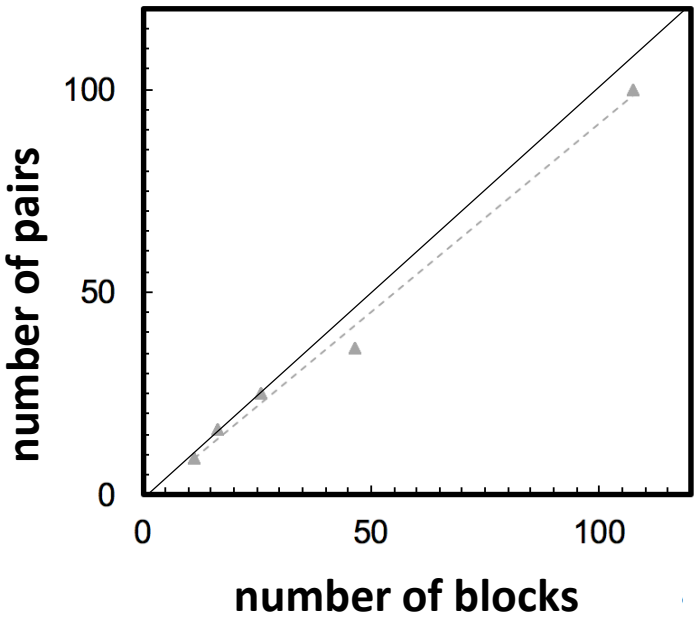




death ∽ spacing

Matrix blocks

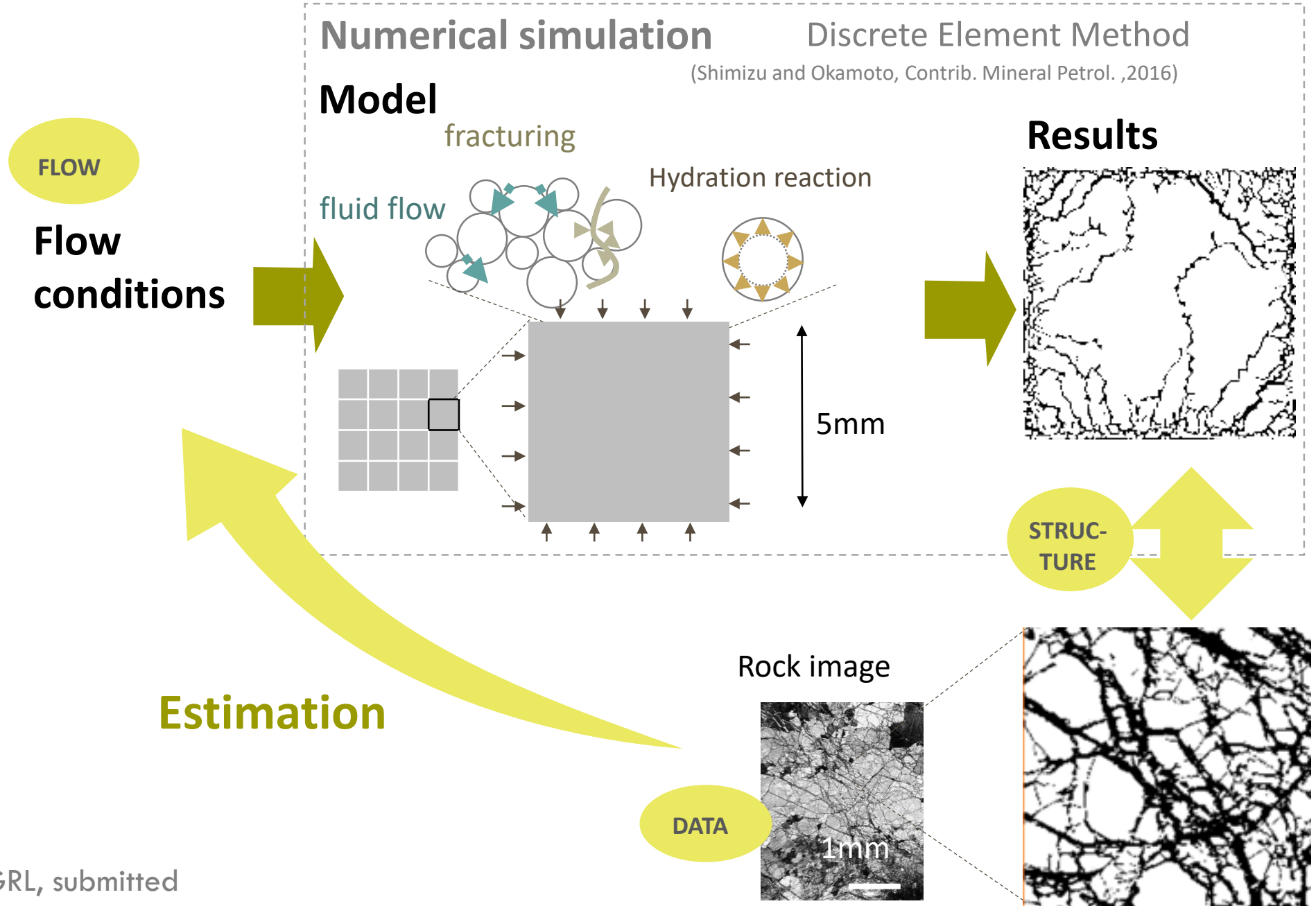




pairs = # blocks

Suzuki et al., GRL, submitted

PERSISTENT HOMOLOGY ANALYSIS

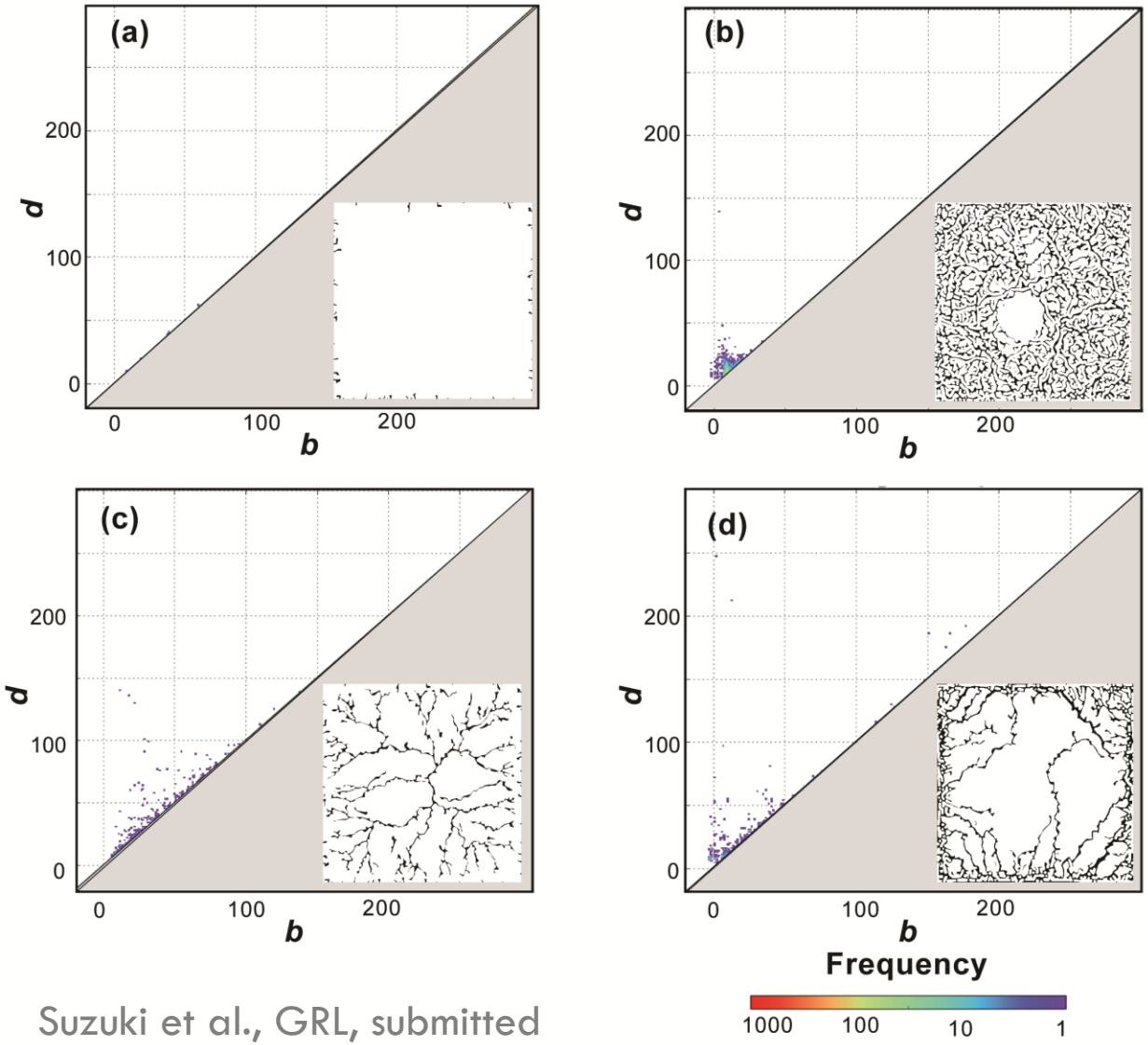


Suzuki et al., GRL, submitted

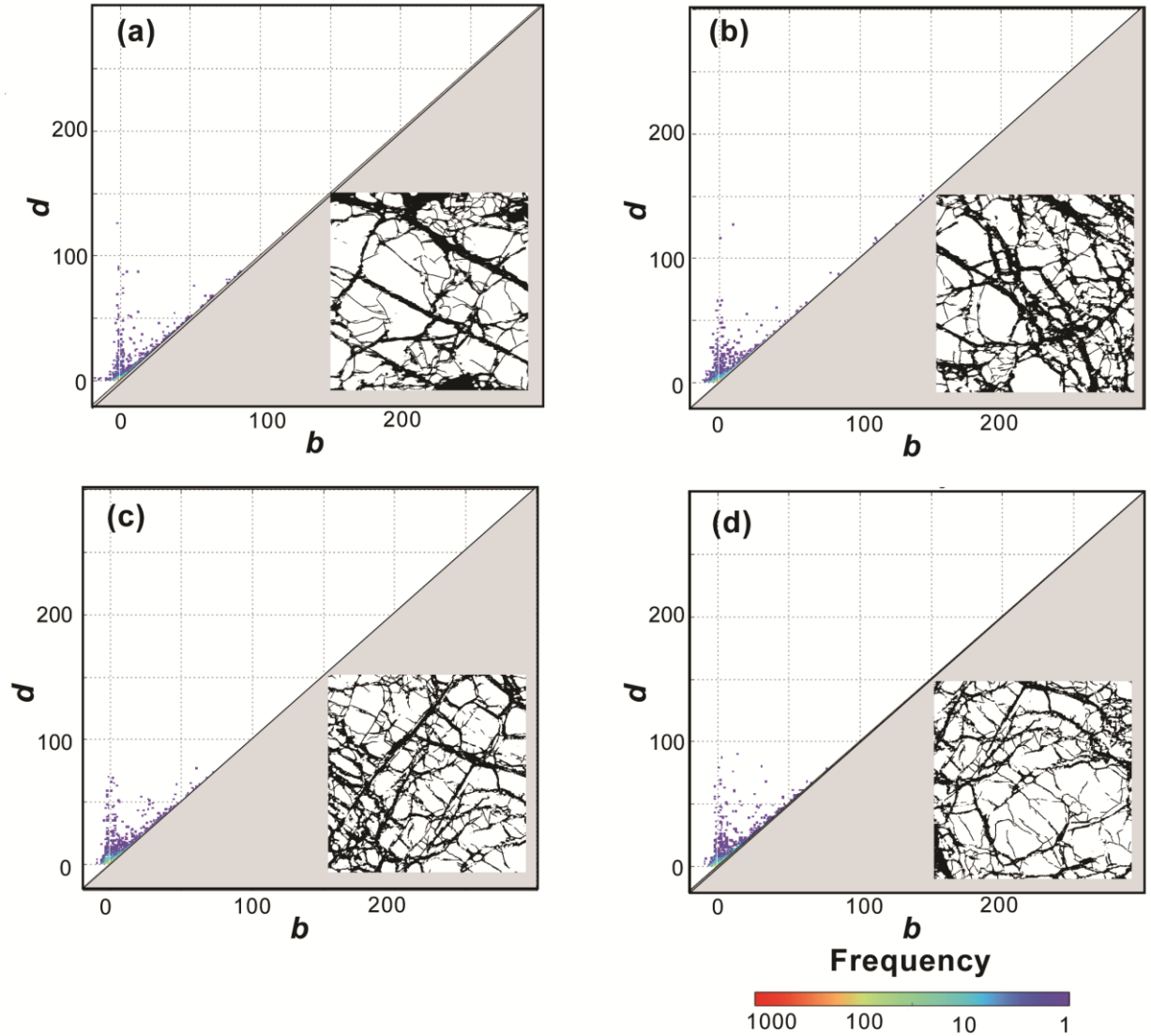
PERSISTENT HOMOLOGY ANALYSIS

b =birth, d=death

Numerical simulation

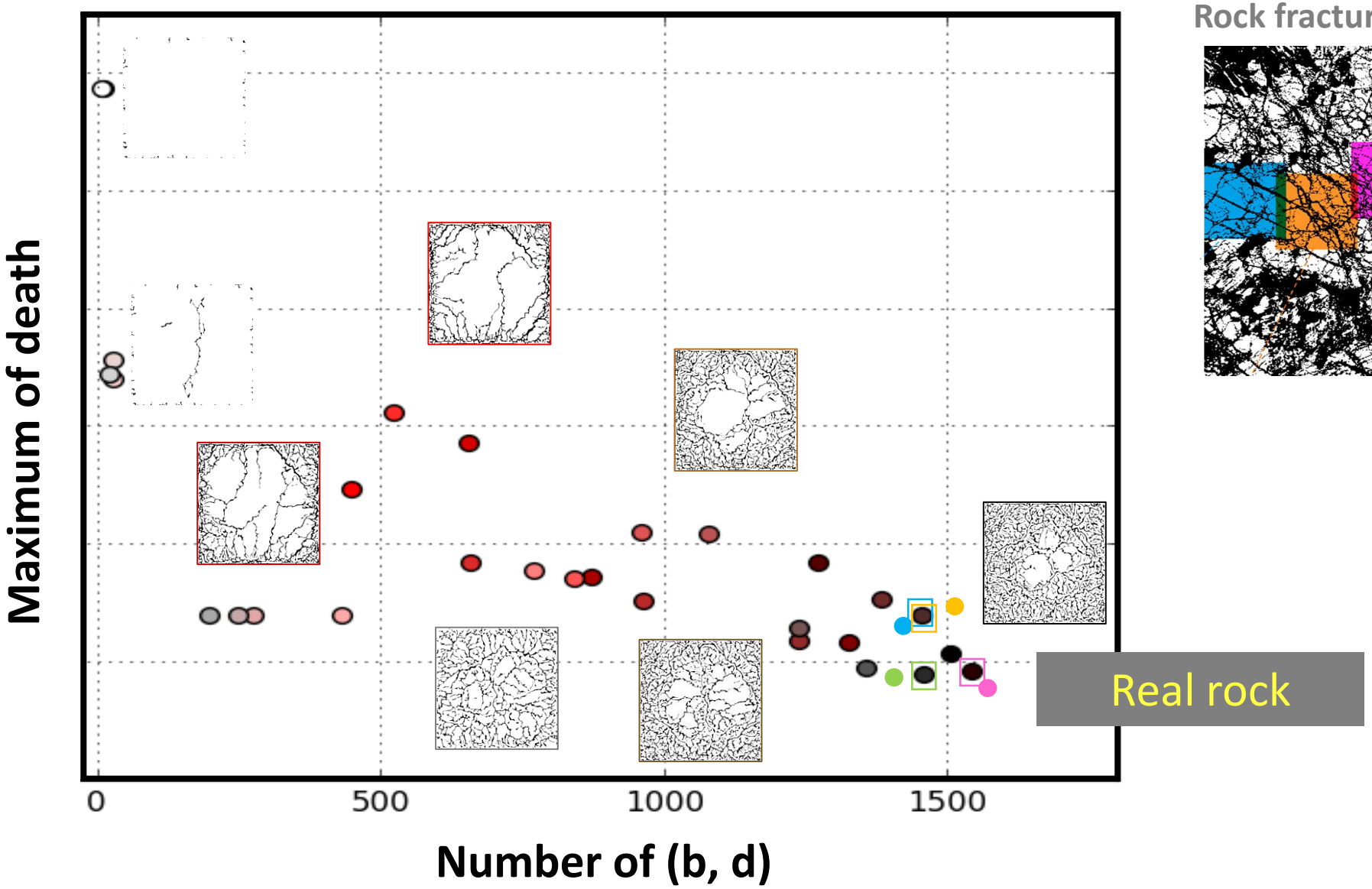


Rock fractures

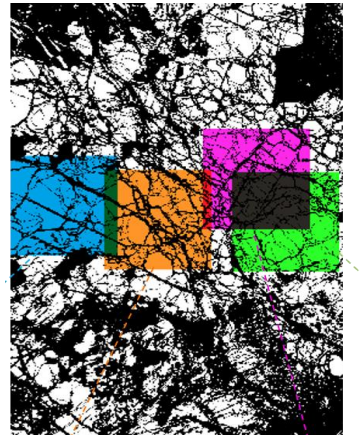


Suzuki et al., GRL, submitted

PERSISTENT HOMOLOGY ANALYSIS



Rock fractures



Suzuki et al., GRL, submitted

QUESTION

1) How do structure and flow interact each others?

Microfabrication approach will help to understand.

2) How to quantify fracture patterns?

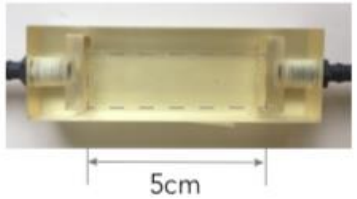
Persistent homology will help.

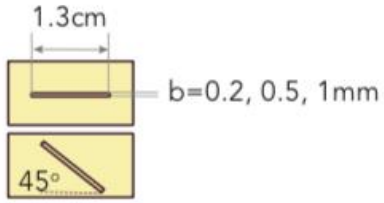
CURRENT WORK

New 3D printer

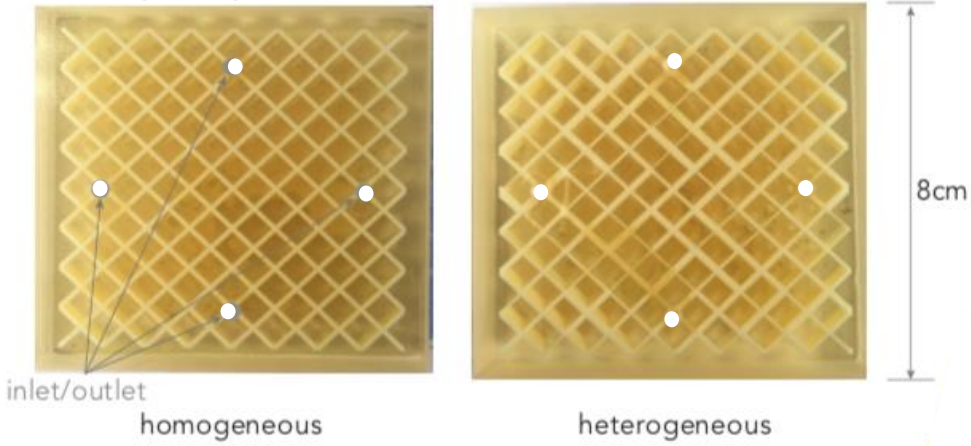
KEYENCE
AGILISTA -3200

Parallel plate

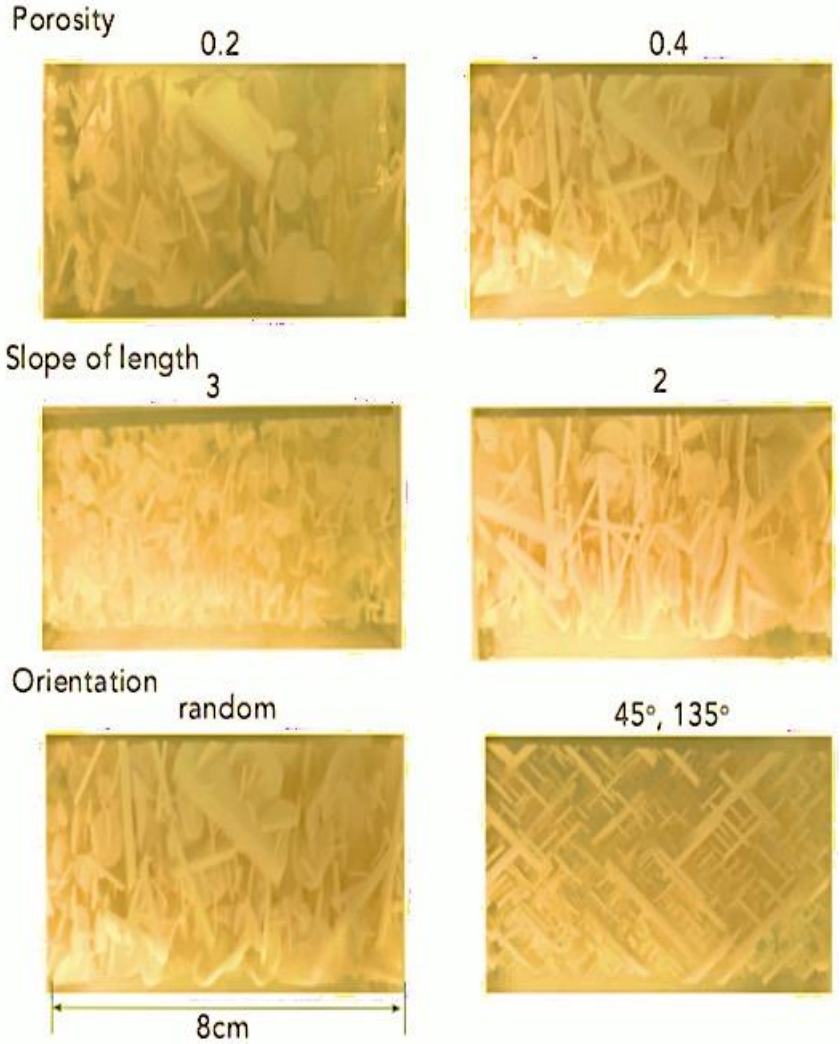




2D network

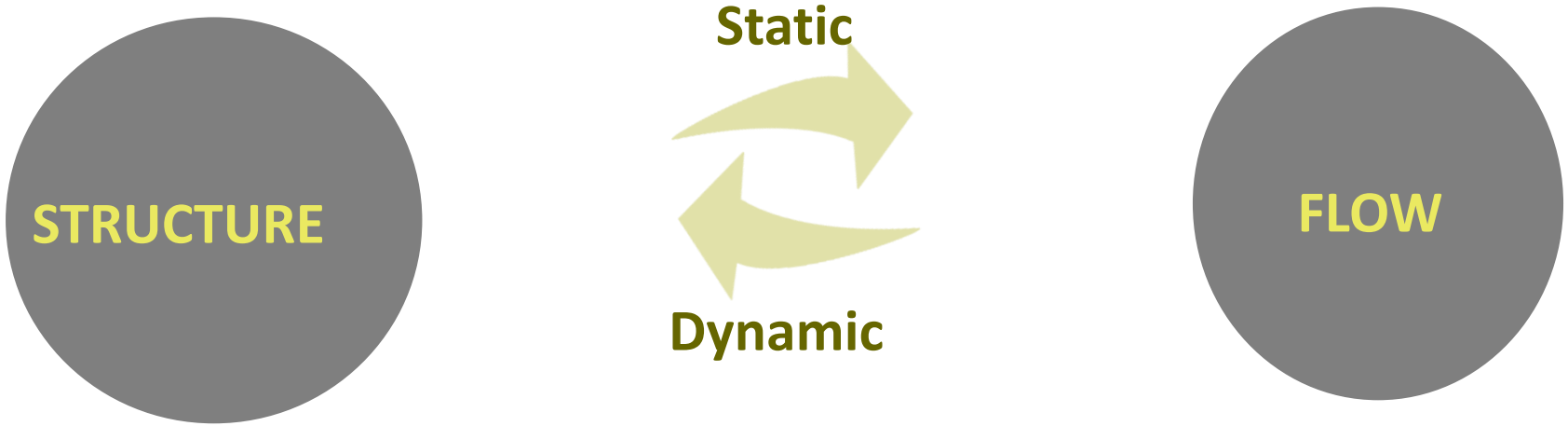


3D network



Base material:
UV curable acrylic plastic
Support material:
Hydrophilic plastic

NEXT STEP



Micro-fabrication

Measurement data

- Tracer
- Thermal response
- Electrical resistivity etc.

Multiphysics

- Chemical reaction (Precipitation/dissolution)
- Anisotropic stress field

Topological analysis

QUESTION

1) How do structure and flow interact each others?

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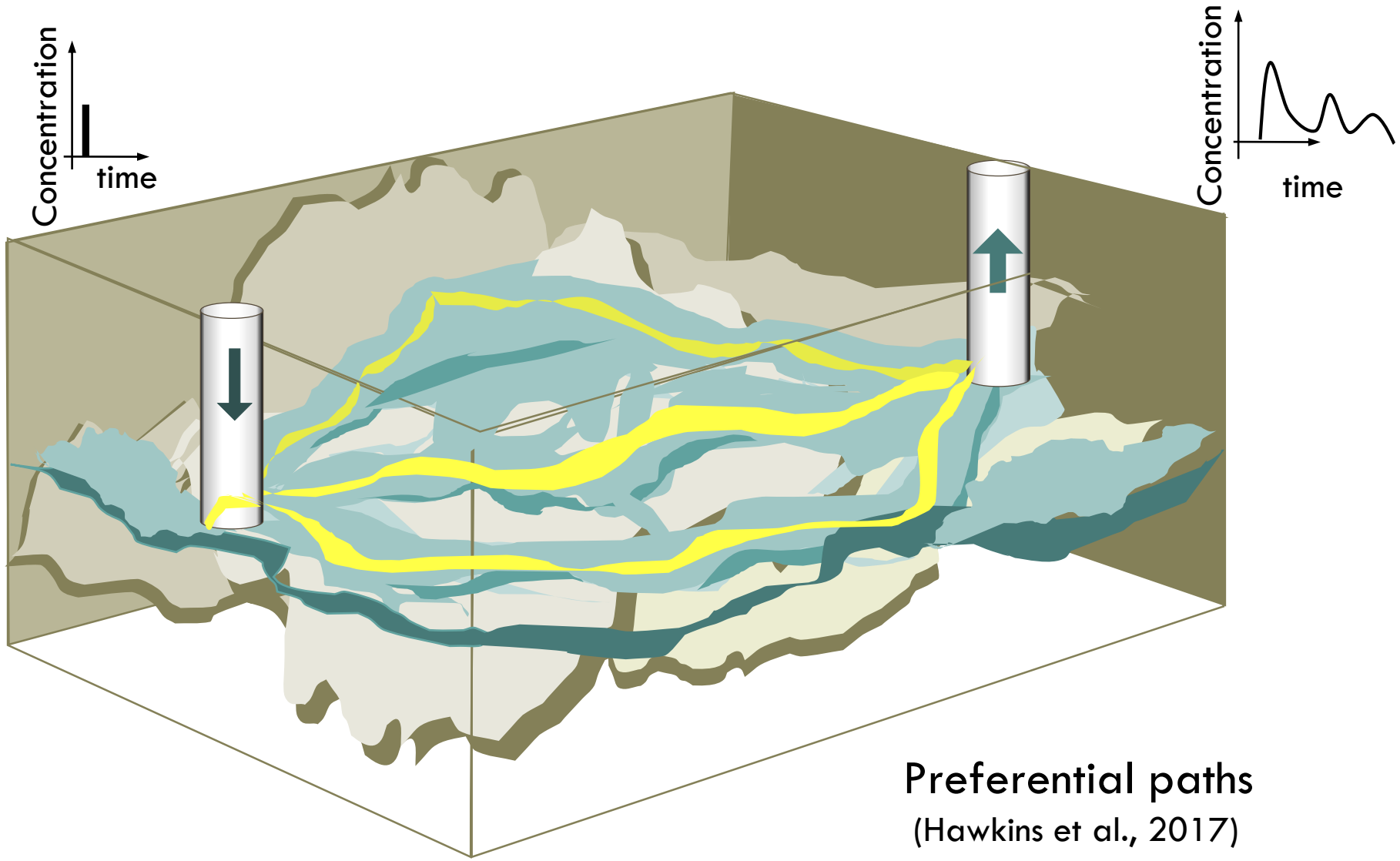
3) Can we estimate structure or flow from the other data?

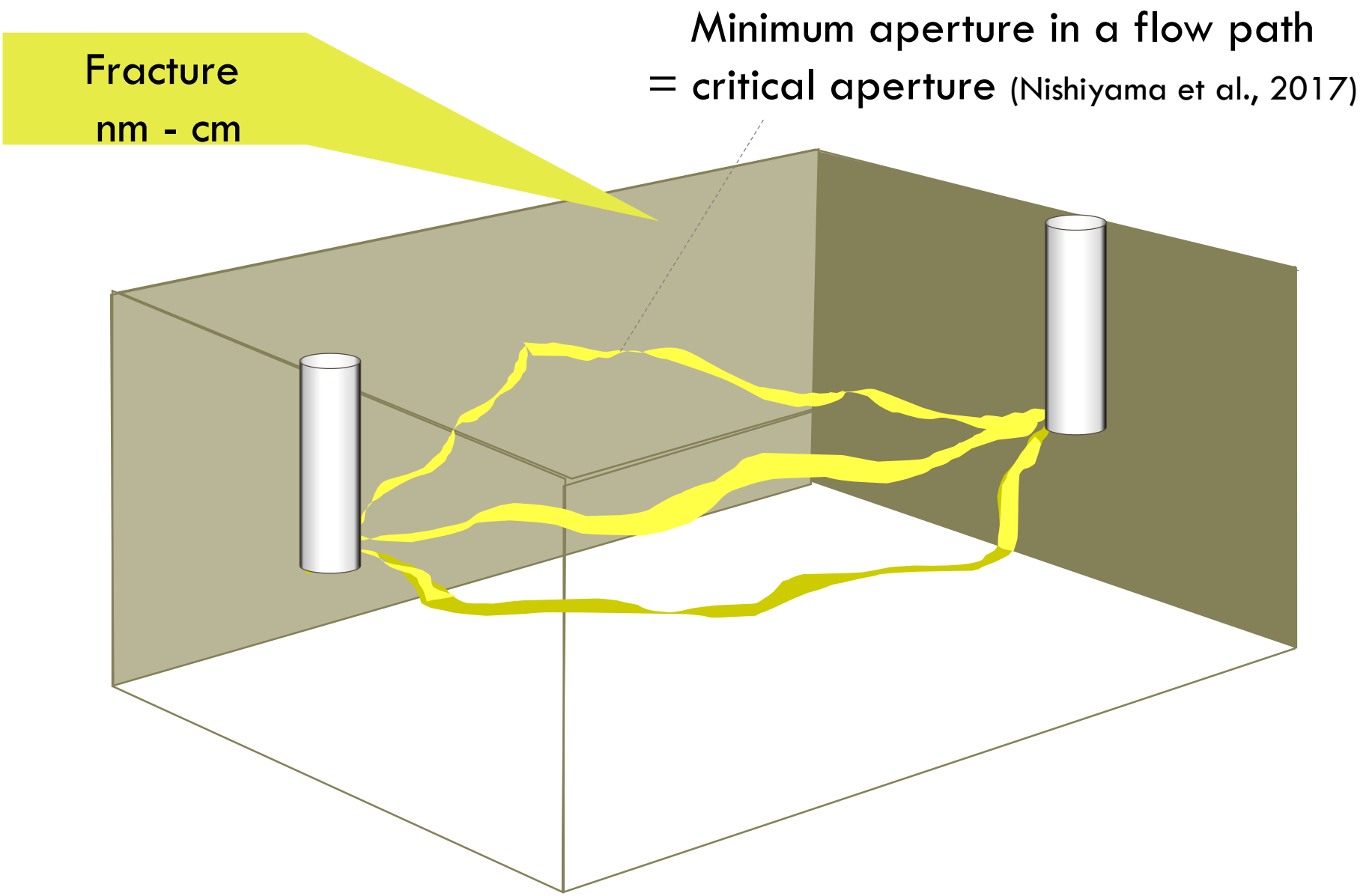
FRACTURE APERTURE ESTIMATION

Tracer test solute tracer (e.g., dyes, radioactive, …)



Preferential paths
(Hawkins et al., 2017)

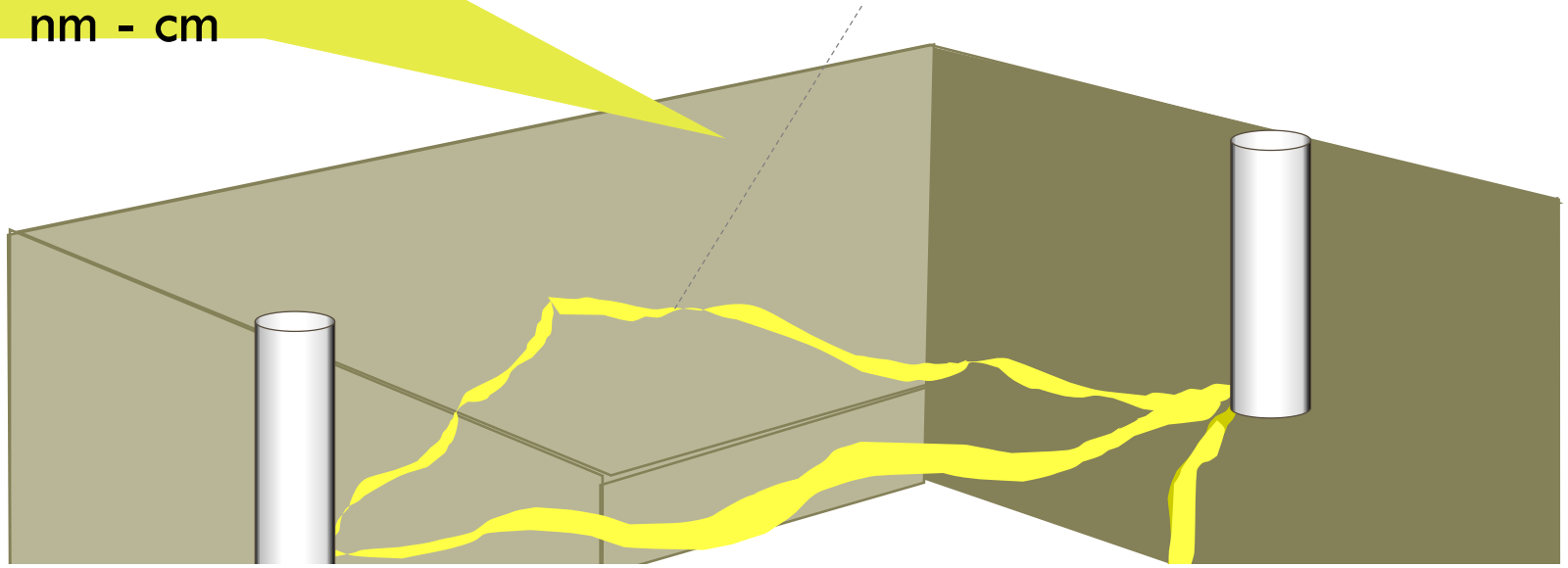
FRACTURE APERTURE ESTIMATION



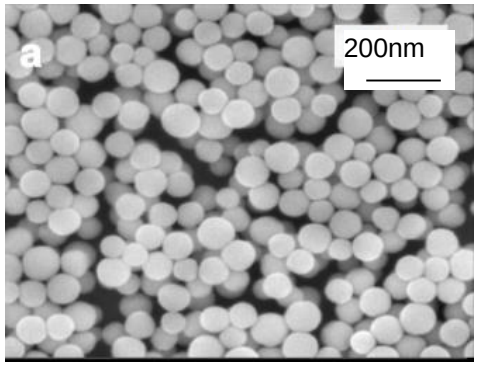
FRACTURE APERTURE ESTIMATION

Fracture
nm - cm

Minimum aperture in a flow path
= critical aperture (Nishiyama et al., 2017)



Nano-/microparticle tracers



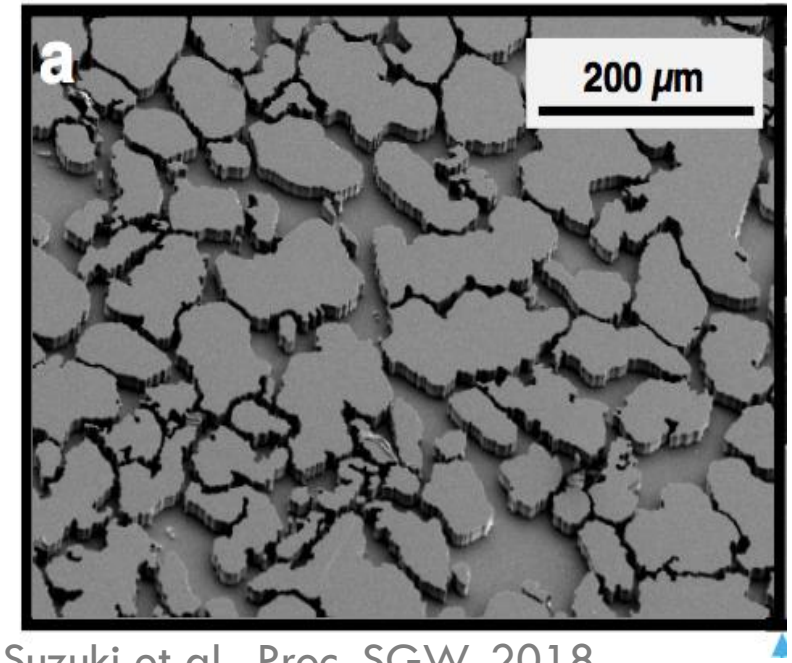
- **DNA-embedded particles**
  → make barcode

* **Various materials**
→ Use in Extreme environments

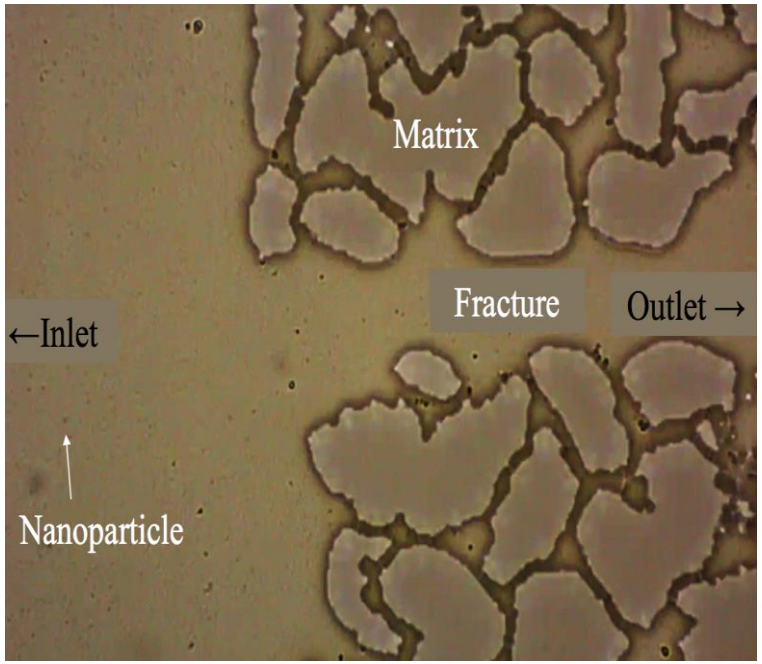
* **Small devices**
→ possibility ∞

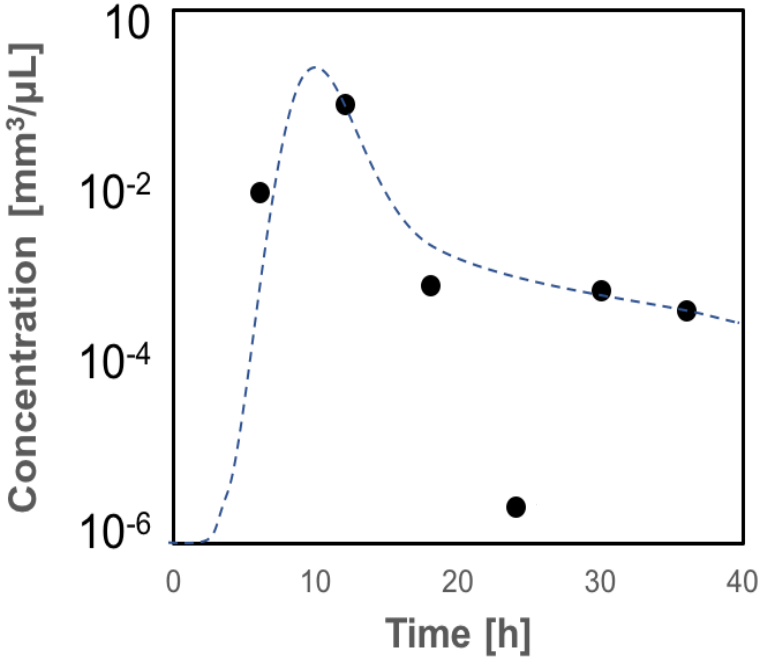
EXPERIMENT

1. Preparing particles
2. Creating micro structures
3. Flow test under microscope
4. Measuring particle concentration

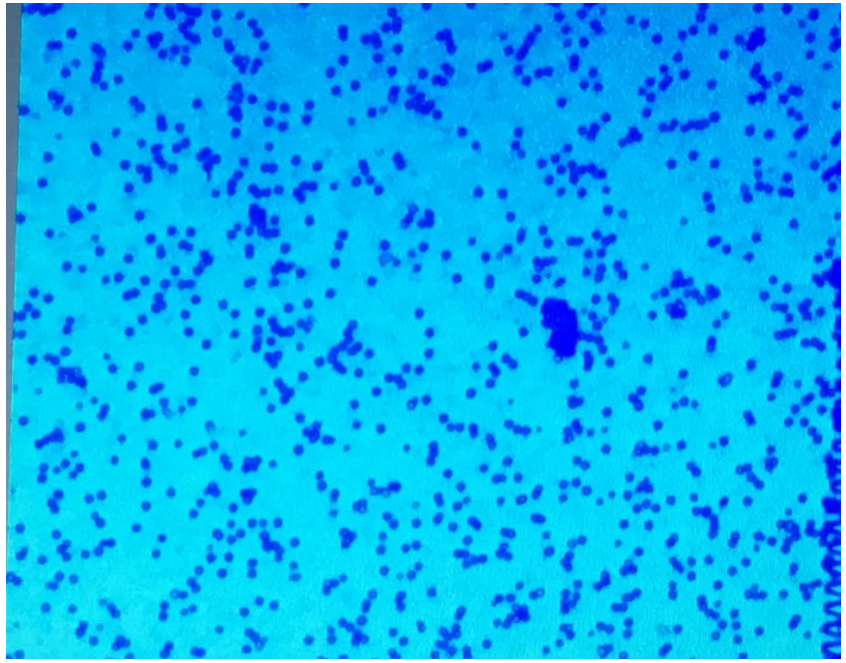


Suzuki et al., Proc. SGW, 2018





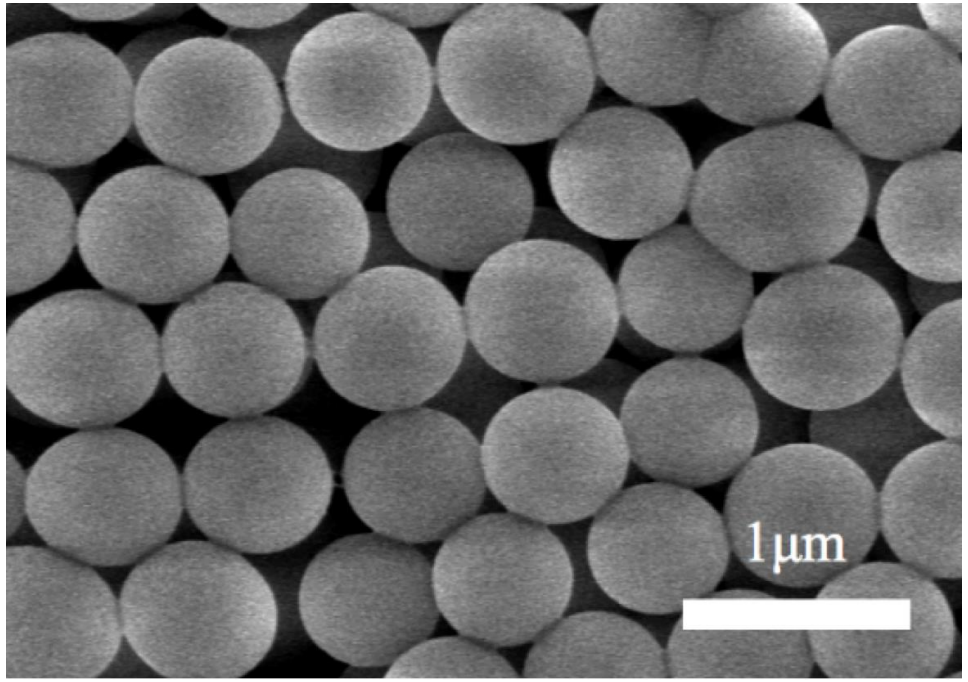
Fluorescent nano-/microparticles



500 nm green fluorescent
(Corpuscular Inc., New York, USA)

silica (2.0 g/cm^3)
0.25 mg/ml

SEM images

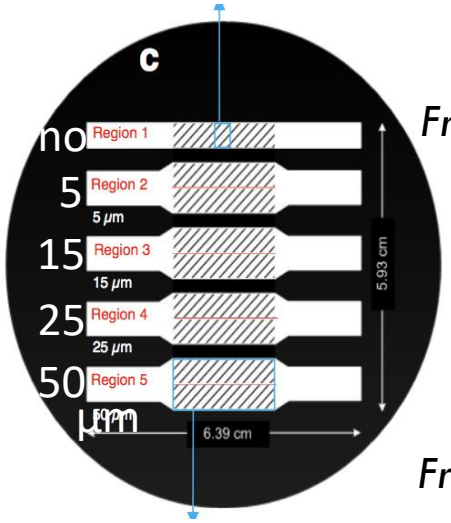


Suzuki et al., Proc. SGW, 2018

2D micromodel

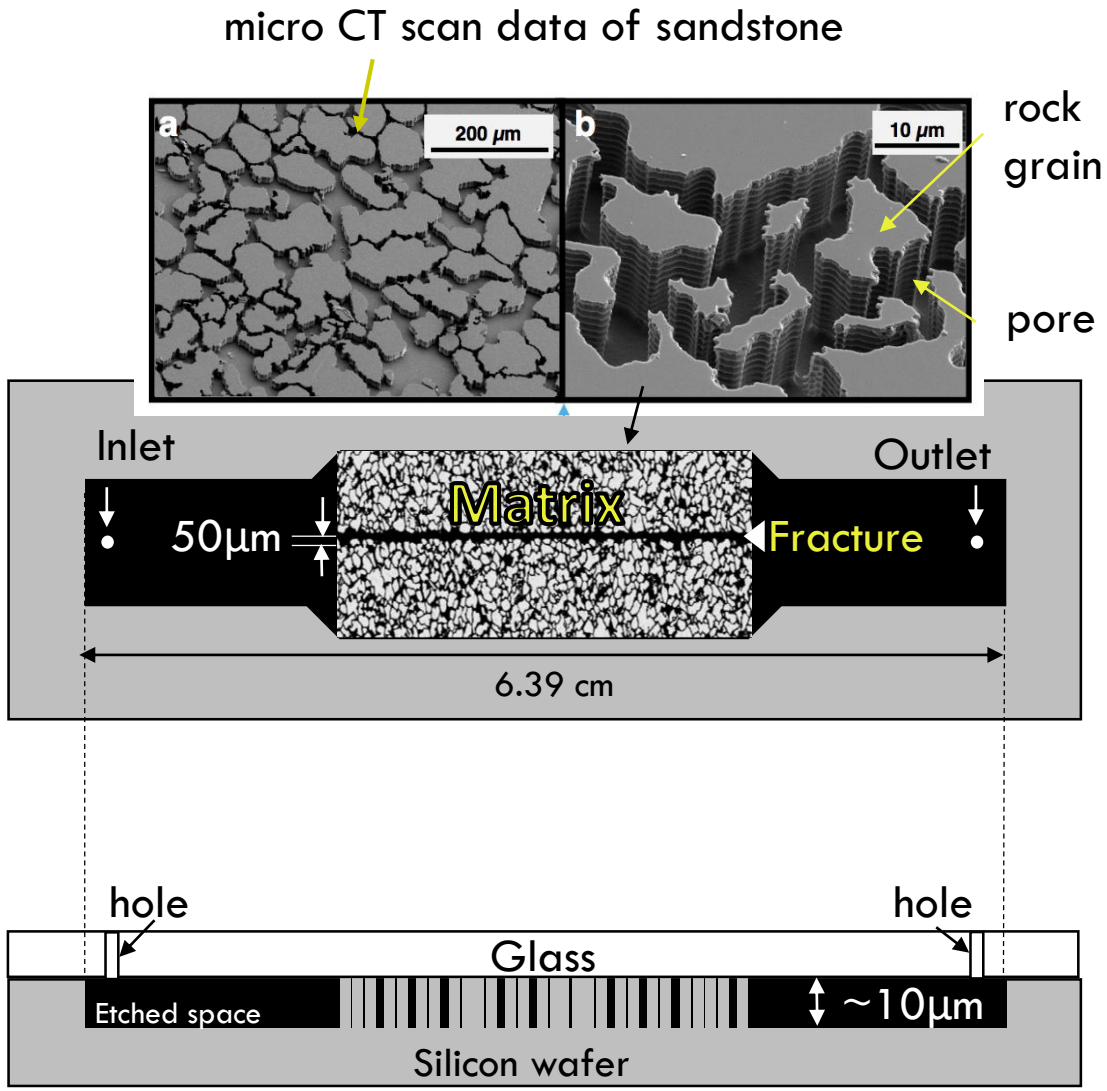
4-inch
Silicon wafer

1 Create mask
2 Etch silicon wafer
3 Cover glass



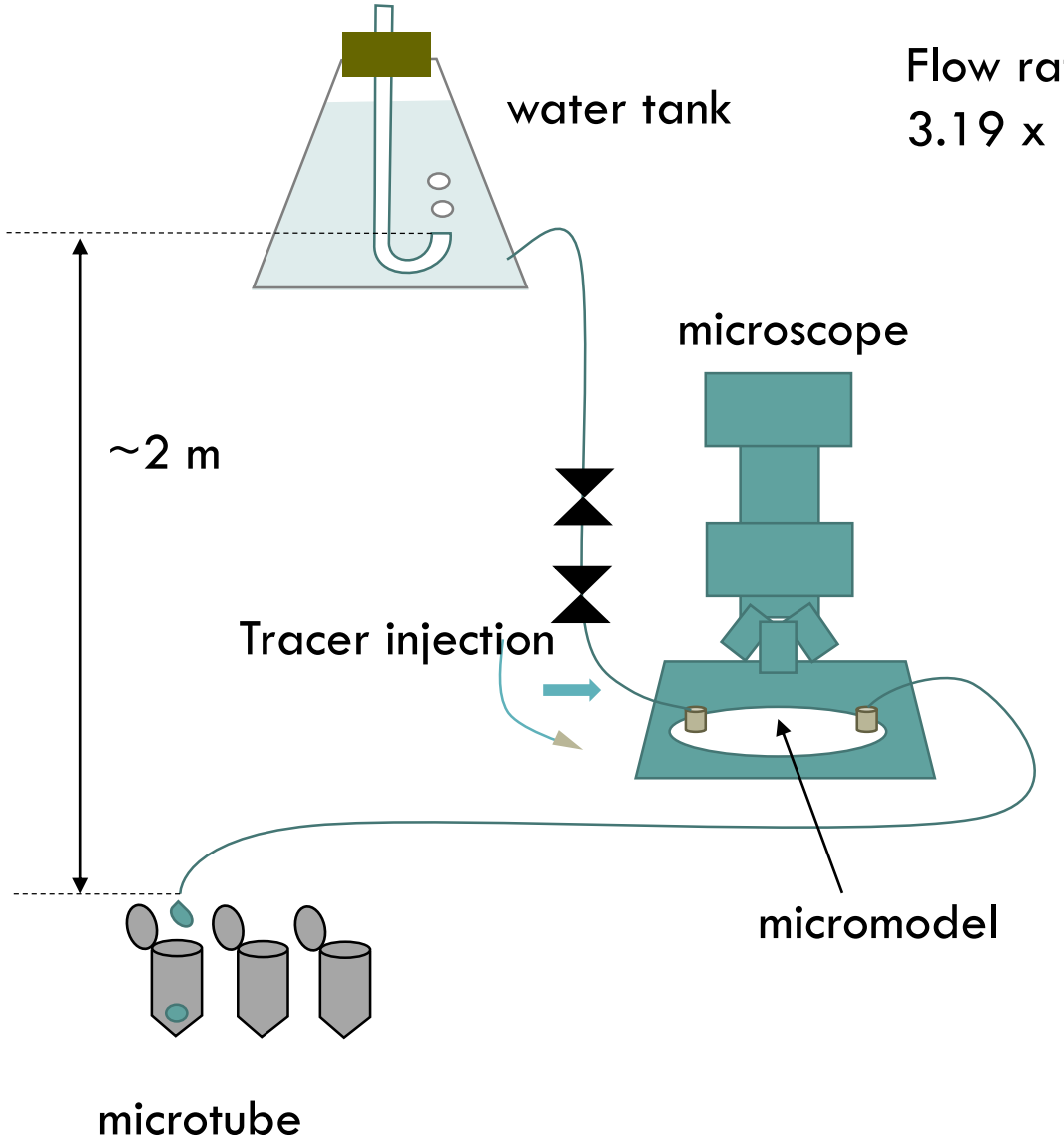
From top

From side



(Alaskar et al., Proc. SGW,. 2013)

Apparatus



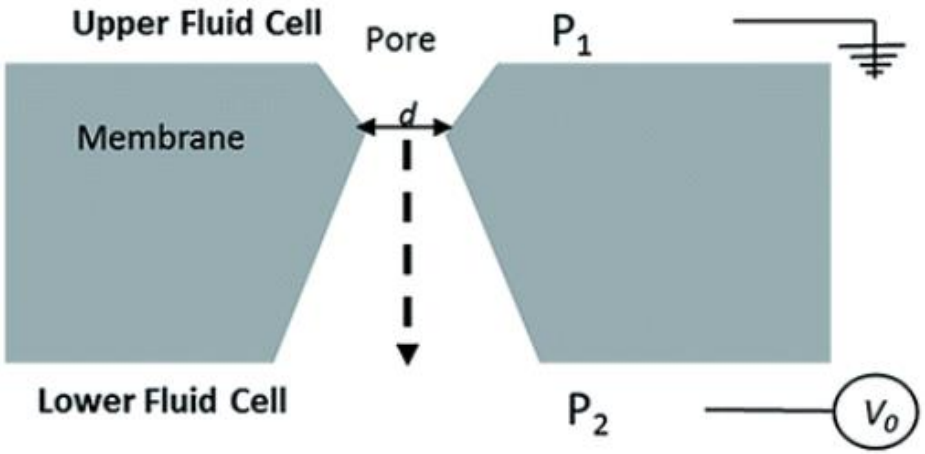
Flow rate
3.19×10^{-4} cm^3/s

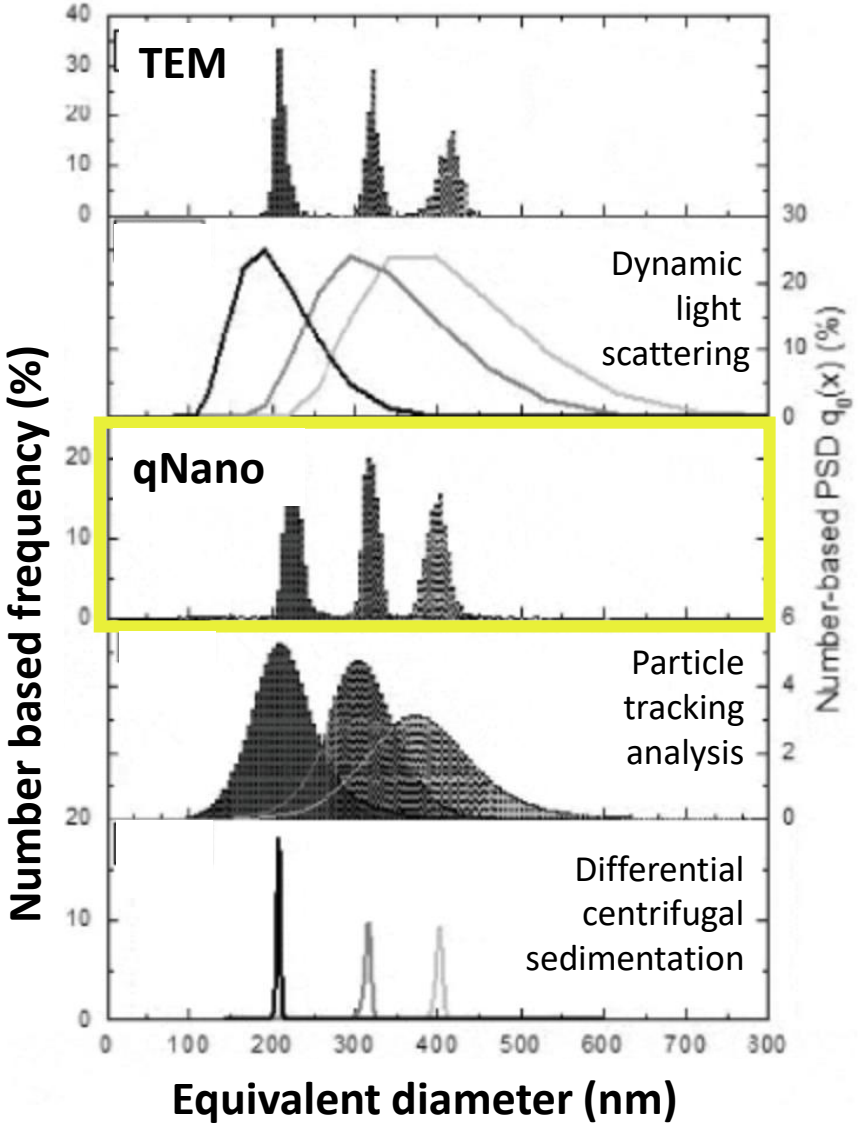
Suzuki et al., Proc. SGW, 2018

Tunable resistive pulse sensor: qNano (Izon Science Inc.)

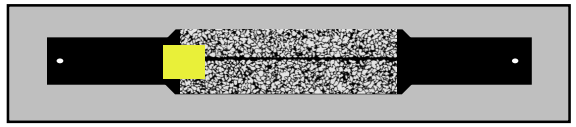
(Platt et al., 2012)

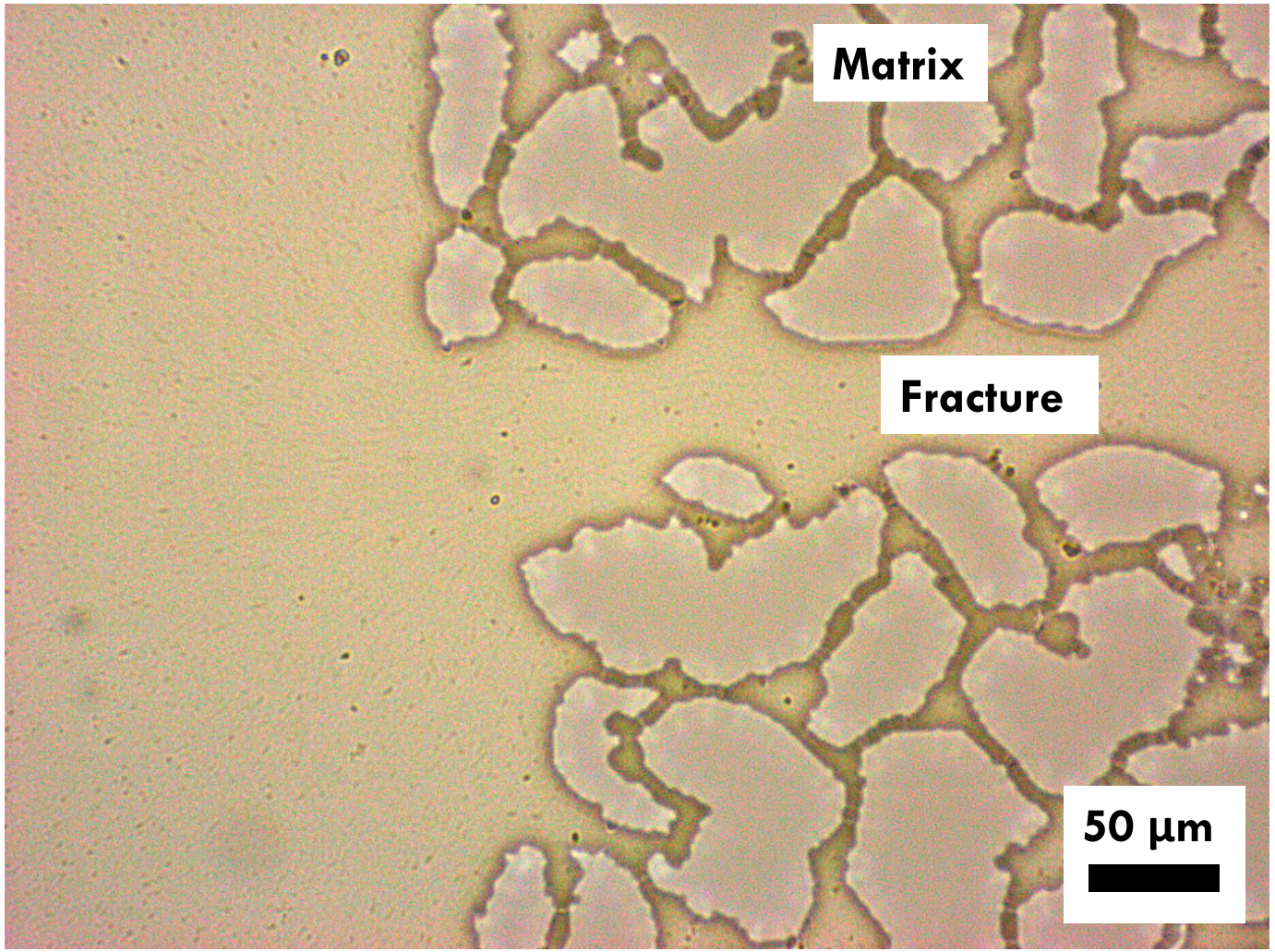
* particle diameter, volume, effective surface charge, Zeta potential



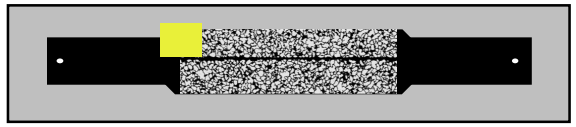


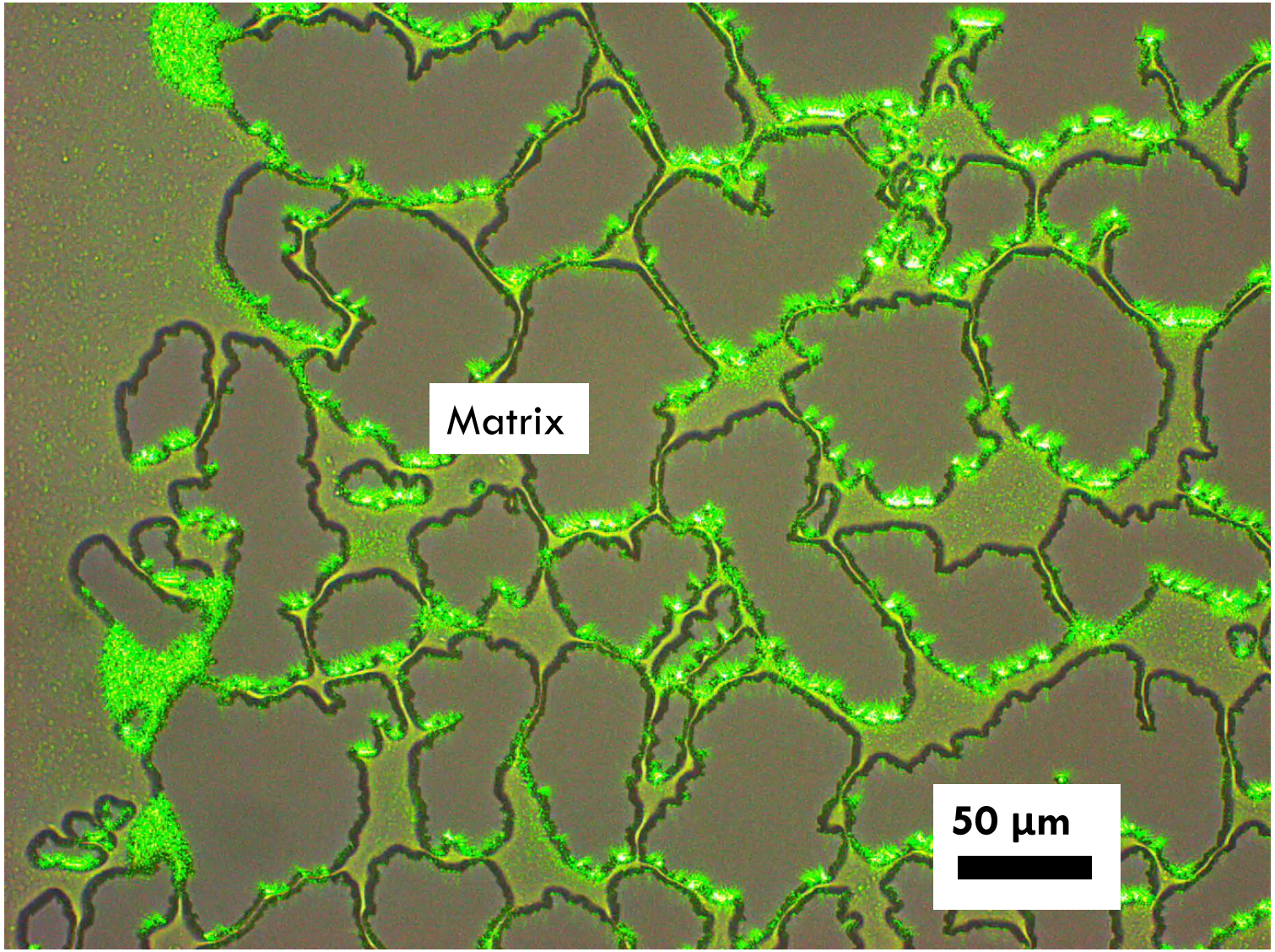
EXPERIMENTAL RESULTS





EXPERIMENTAL RESULTS



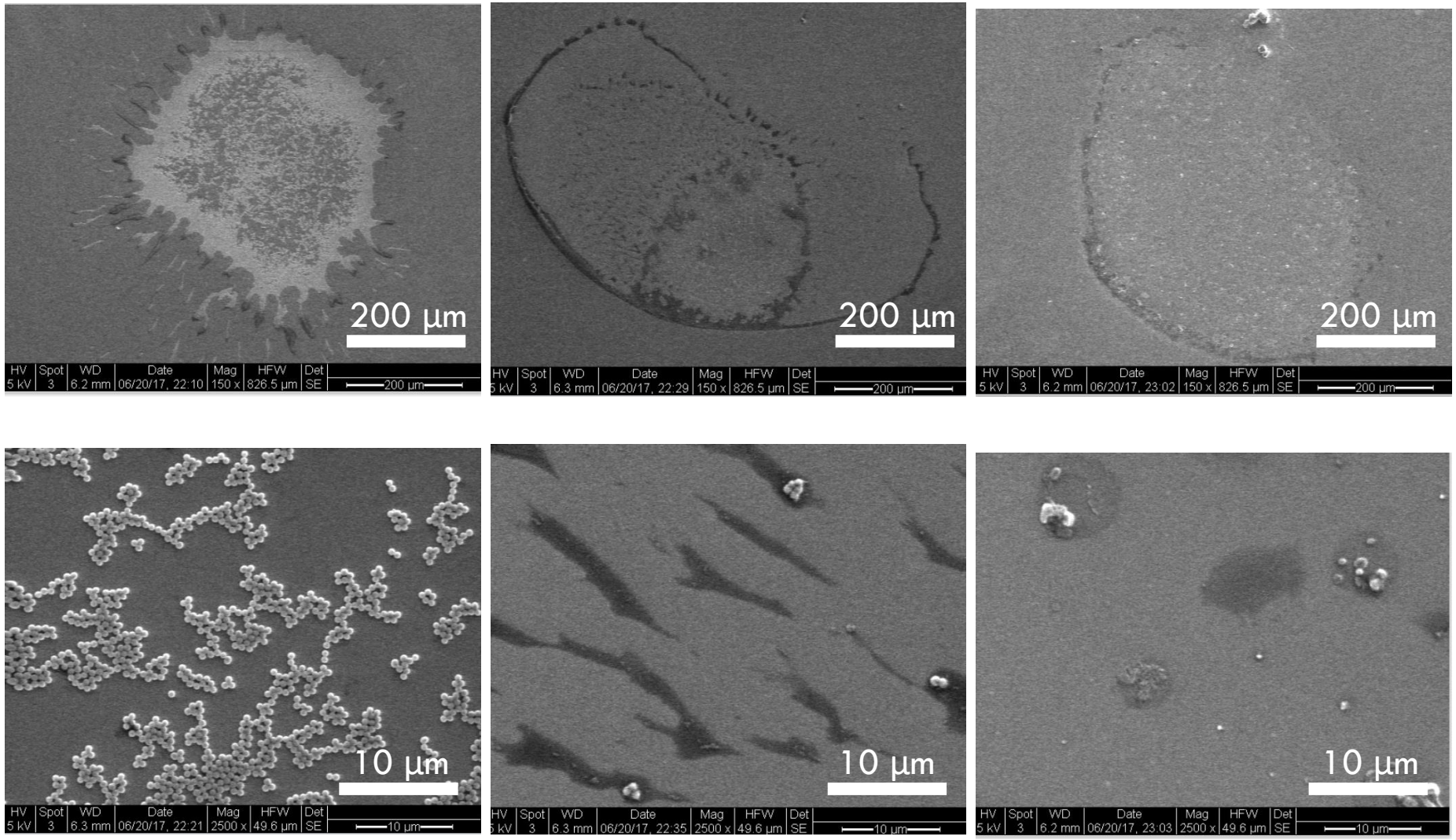


Suzuki et al., Proc. SGW, 2018

EXPERIMENTAL RESULTS

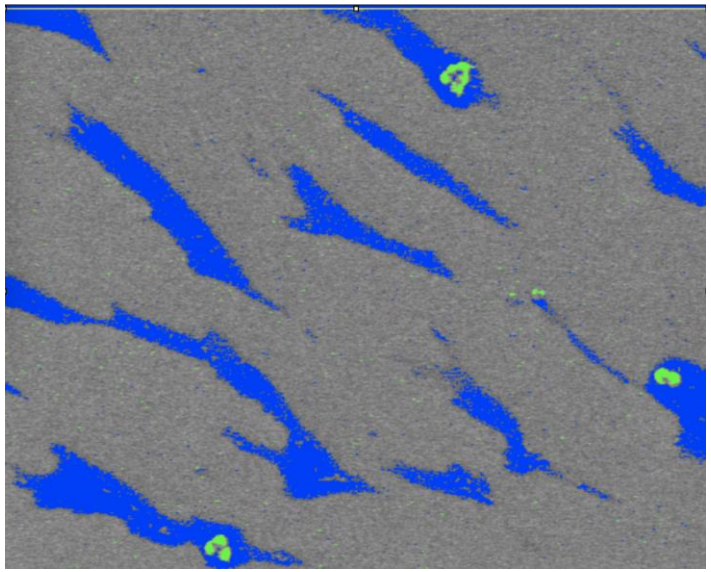
SEM images of droplets at outlet

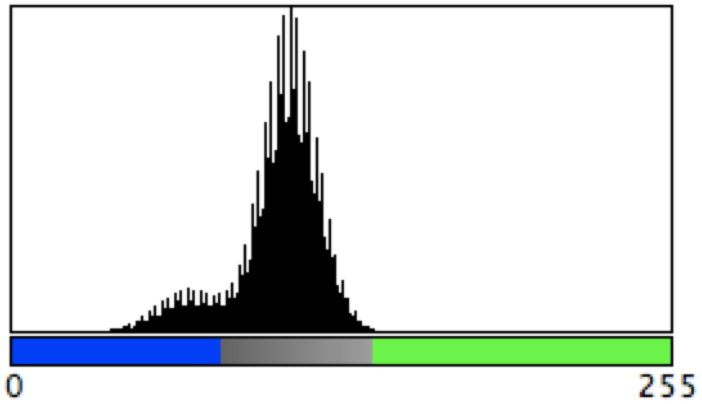
TIME: 12 h | TIME: 18 h | TIME: 36 h

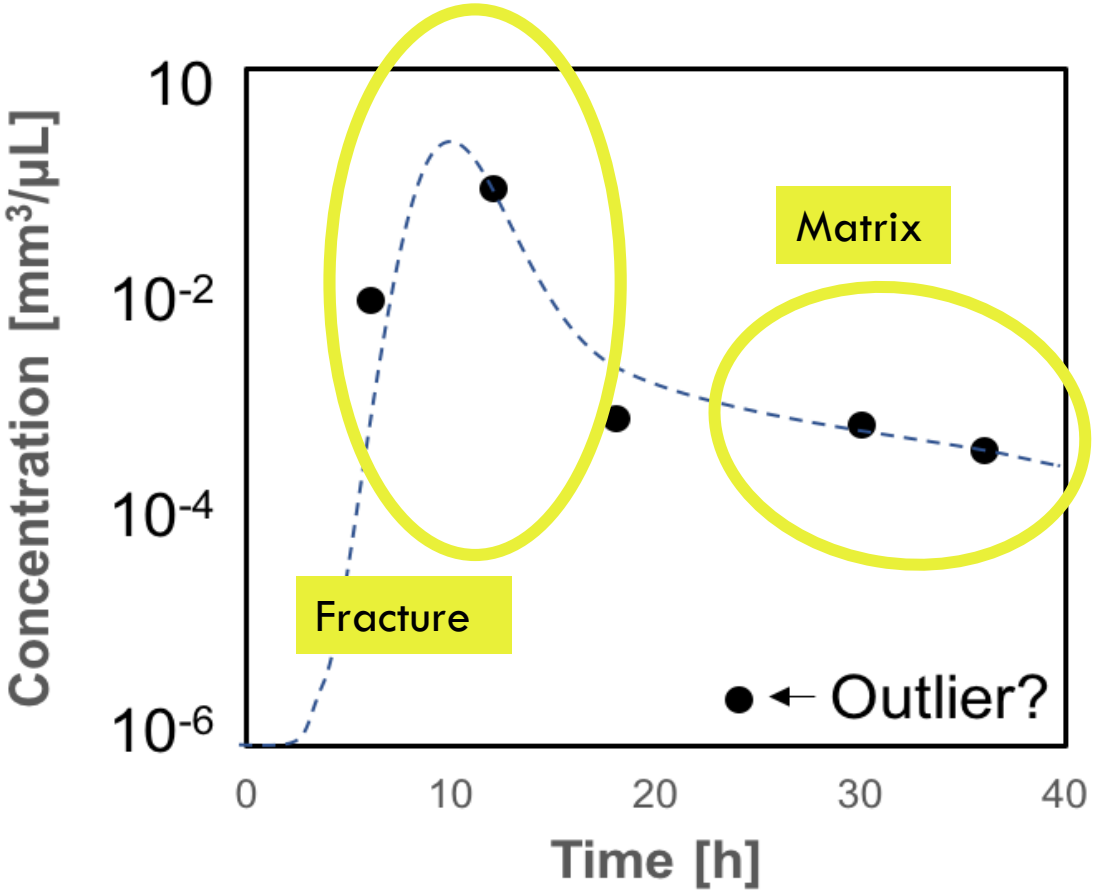


Suzuki et al., Proc. SGW, 2018

Estimation of concentration from SEM images





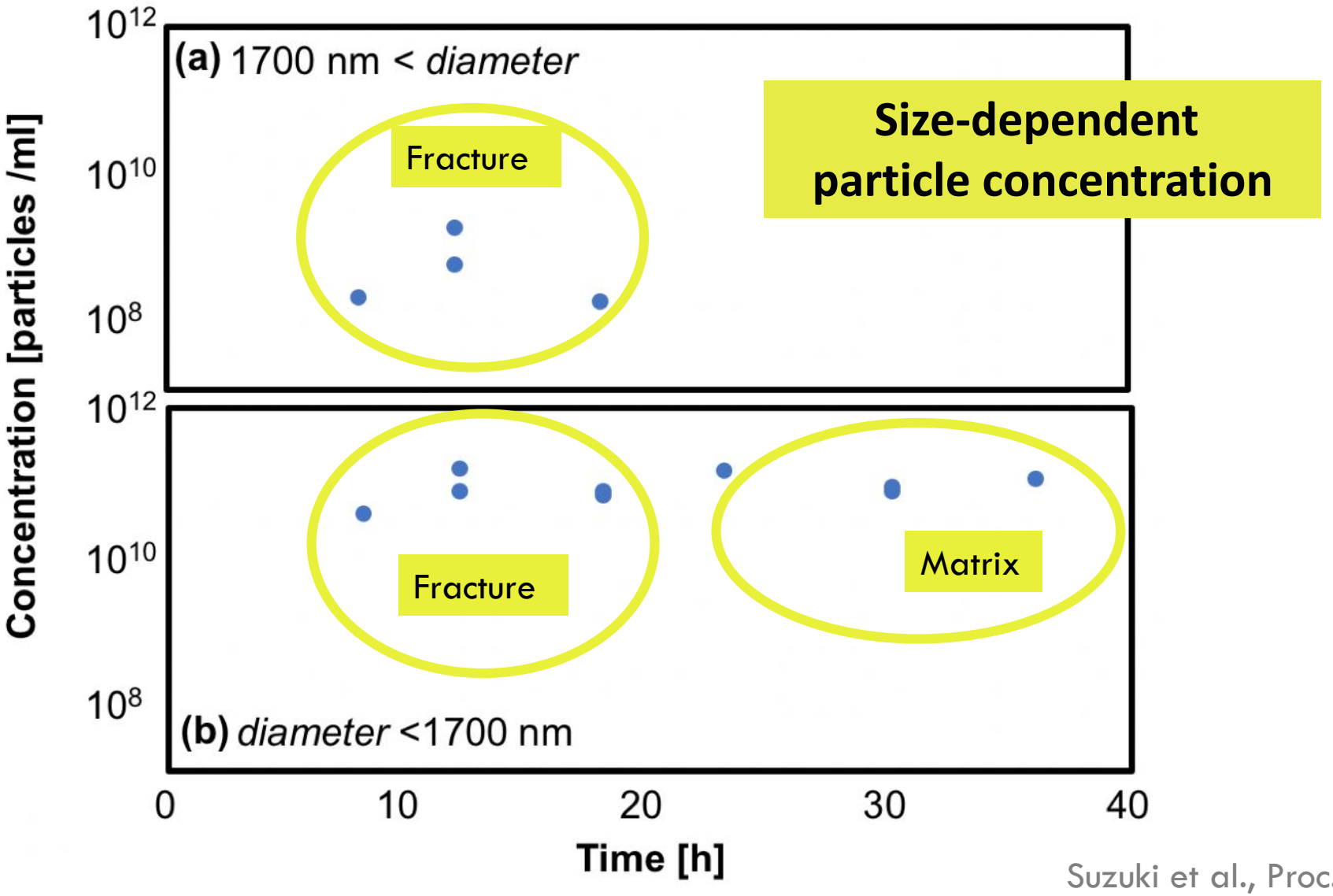


$$\text{Concentration} = \frac{\text{Green}}{\text{Green} + \text{Blue}}$$

Suzuki et al., Proc. SGW, 2018

EXPERIMENTAL RESULTS

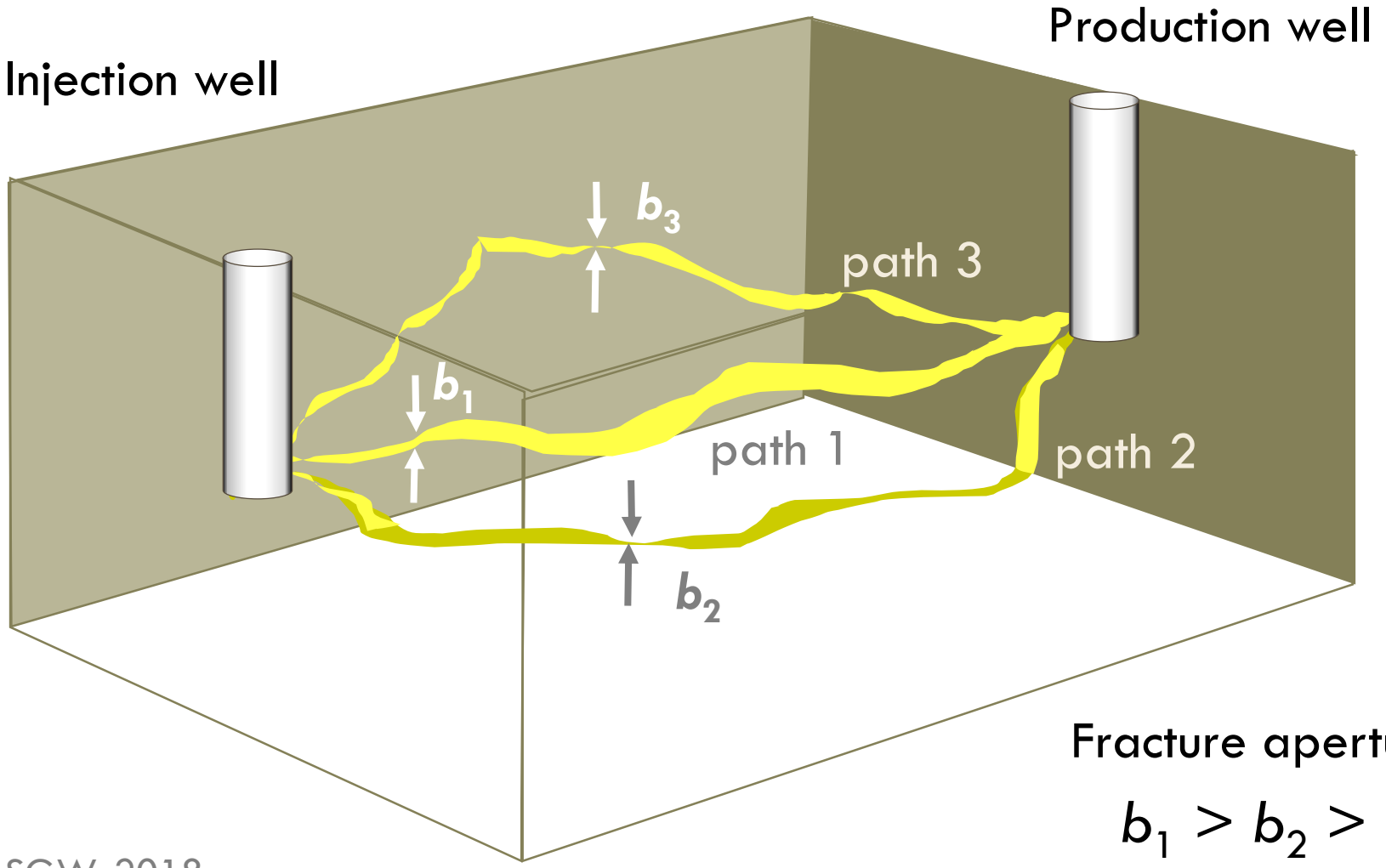
Tracer response obtained from qNano



Suzuki et al., Proc. SGW, 2018

PROPOSED METHOD

Estimation method for critical aperture

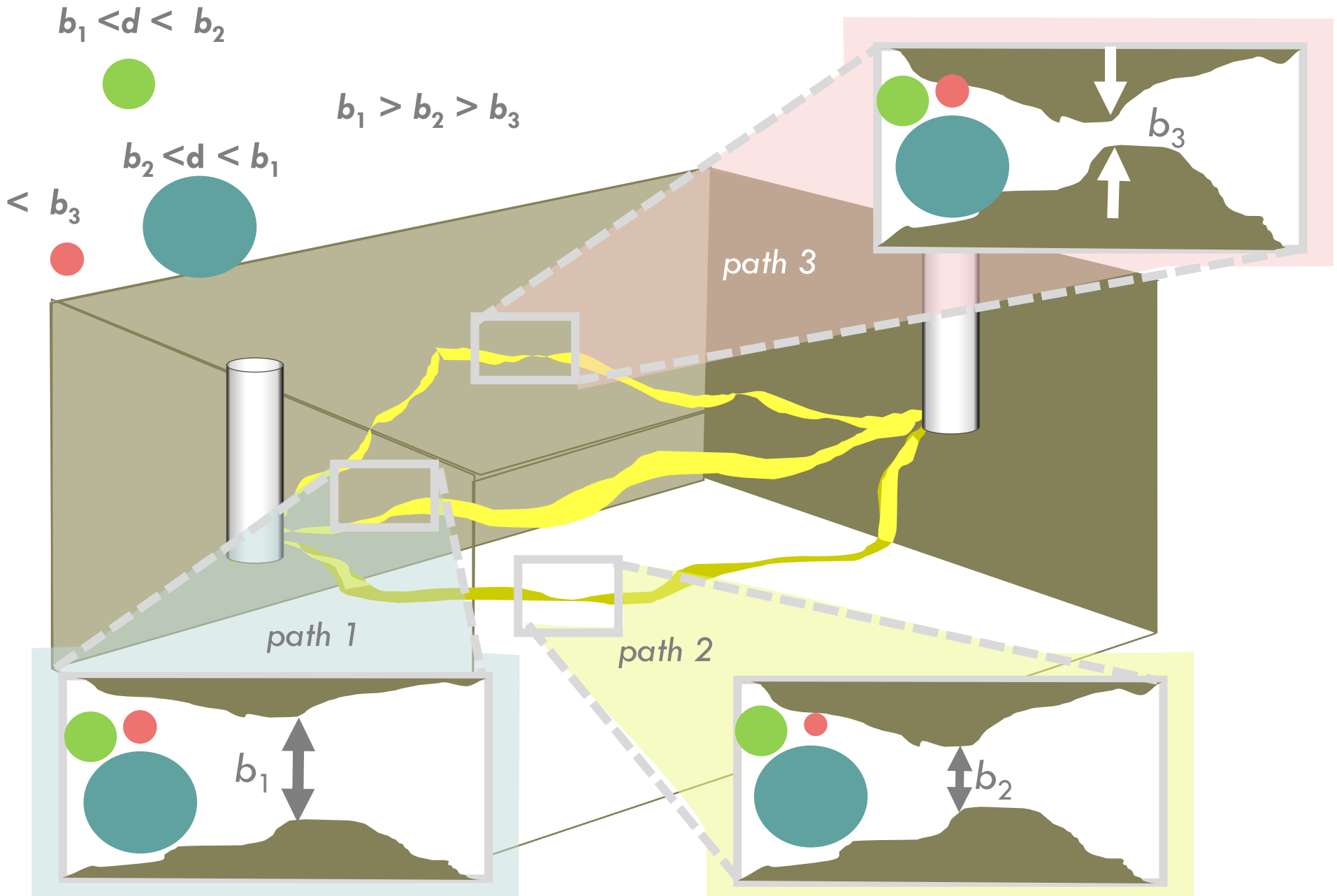


Fracture aperture

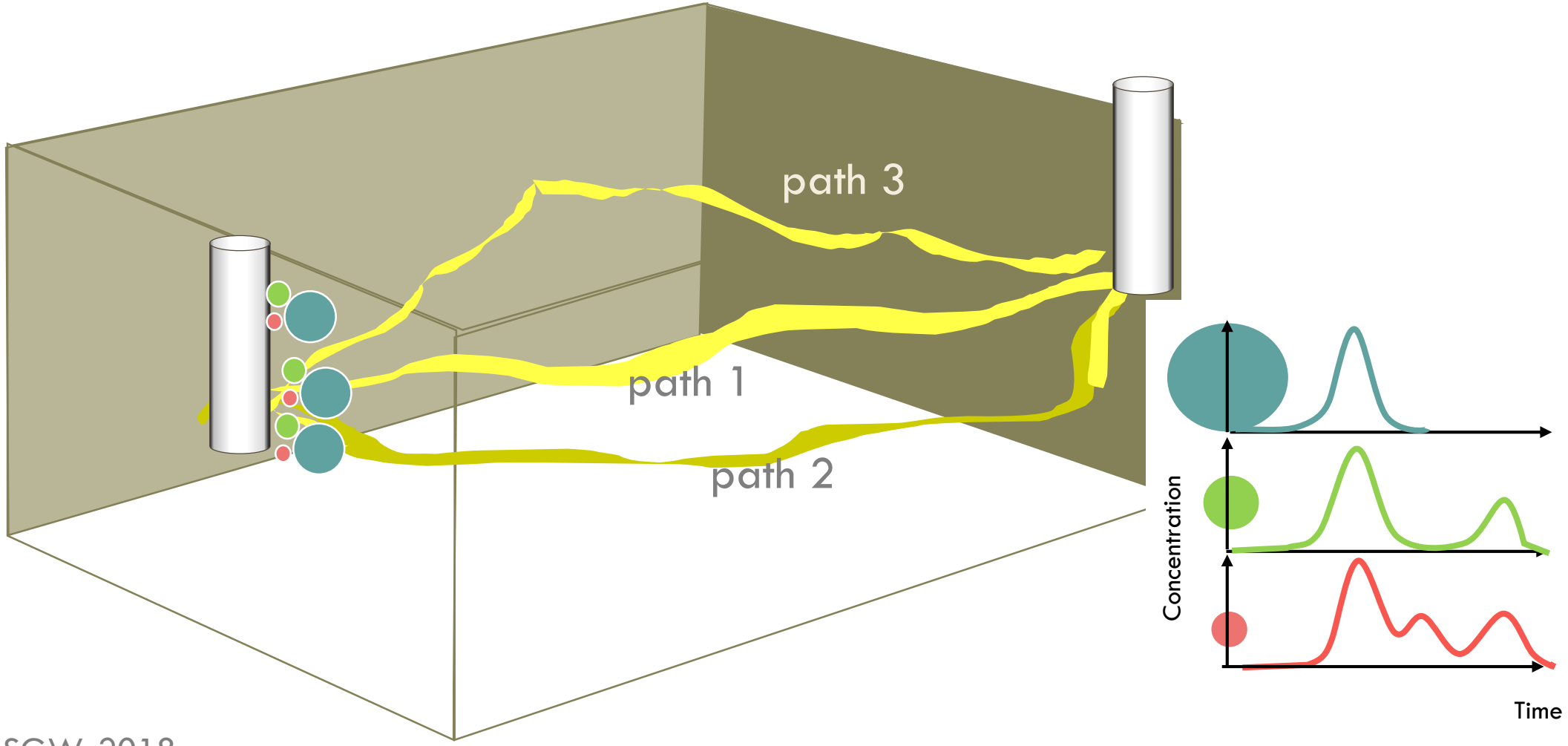
$$b_1 > b_2 > b_3$$

Suzuki et al., Proc. SGW, 2018

PROPOSED METHOD



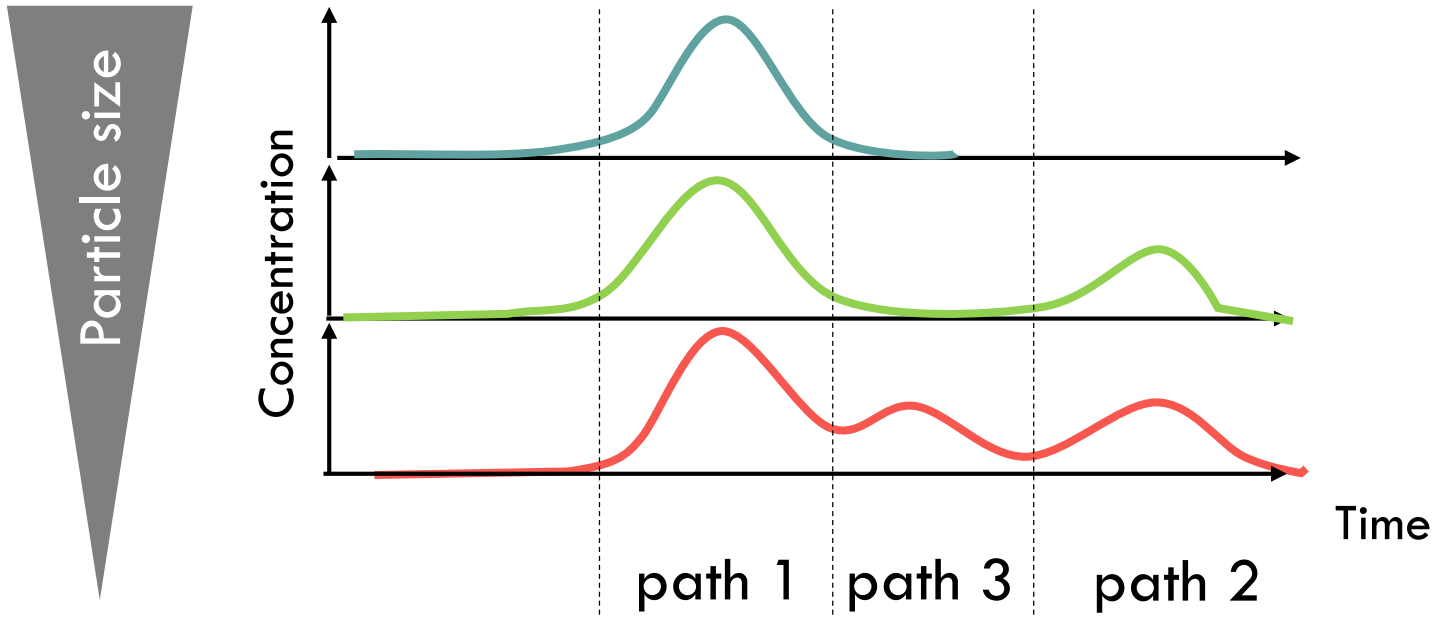
Estimation method for critical aperture



Suzuki et al., Proc. SGW, 2018

PROPOSED METHOD

Estimation method for critical aperture



Particle size [nm]	$< b_1$	$< b_3$	$< b_2$
Critical aperture [nm]			
Permeability [m^2]	$k_i = b_i^2 / 12$		
Flow rate [m/s]	$q_i = -k_i // \mu \nabla P$		
Travel time [sec]	t_i		
Path length [m]	$L_i = q_i / t_i$		

Suzuki et al., Proc. SGW, 2018

QUESTION

1) How do structure and flow interact each others?

Microfabrication approach will help to understand.

2) How to quantify fracture patterns?

Persistent homology will help.

3) Can we estimate structure or flow from the other data?

Particle tracers will estimate critical fracture aperture.

Design of Structure and Flow in the Earth Lab

application

fundamental

3D printing fractures

TOPIC 1

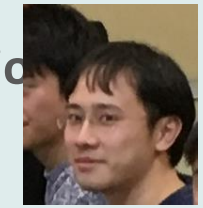
Topological fracture characterization

Miyazawa (M1)

TOPIC 2

Fractional derivative mass/heat transfer equation

Aperture estimatio by particle tracers



Cui(M1)

TOPIC 3

Supercritical fluid fracturing simulation

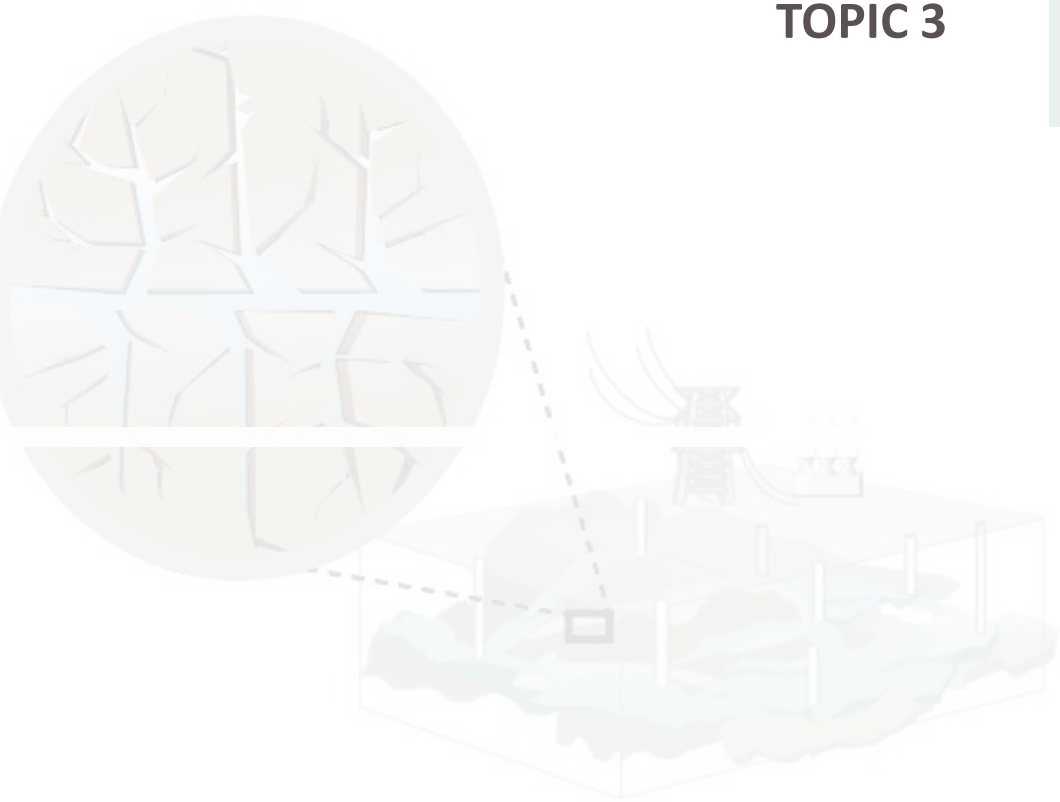
Liu (D1)

Microfluidics for salt precipitation due to CO2 injection

Huong (M2)

Surface area estimation by trace thermal breakthrou

Machine learning for permeability distribution estimation



My Ph.D.

Design of Structure and Flow in the Earth Lab

application

fundamental

3D printing fractures

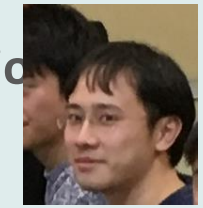
Topological fracture characterization

Miyazawa (M1)

Fractional derivatives in mass/heat transfer equation

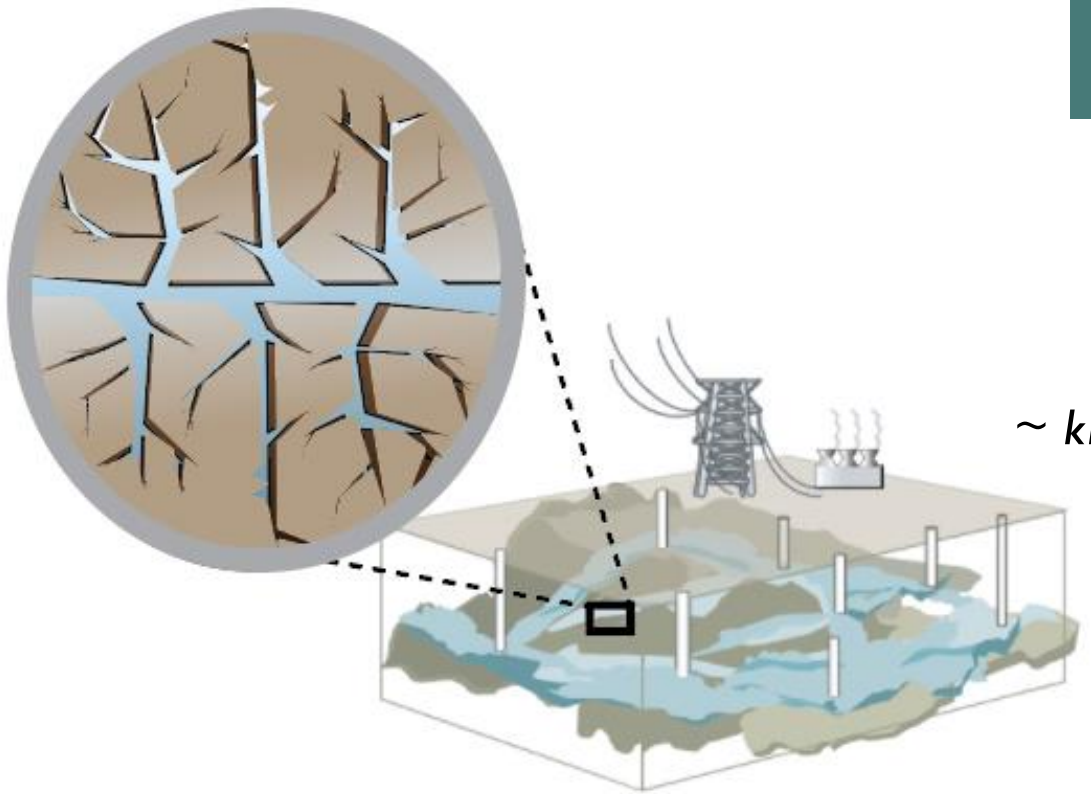
My Ph.D.

Aperture estimatio by particle tracers



Cui(M1)

~ μm

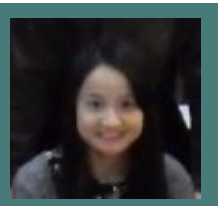


~ km

Supercritical fluid fracturing simulation

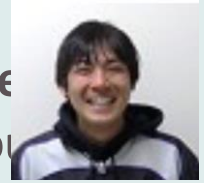
Liu (D1)

Microfluidics for salt precipitation due to CO2 injection



Huong (M2)

Surface area estimation by trace thermal breakthrou



Yamaguchi (B4)

Machine learning for permeability distribution estimation

Design of Structure and Flow in the Earth Lab

fundamental

Topological fracture characterization

3D printing fractures

Fractional derivatives in mass/heat transfer equation

My Ph.D.

Physical meaning of fractional derivatives

$0 < \gamma < 1$

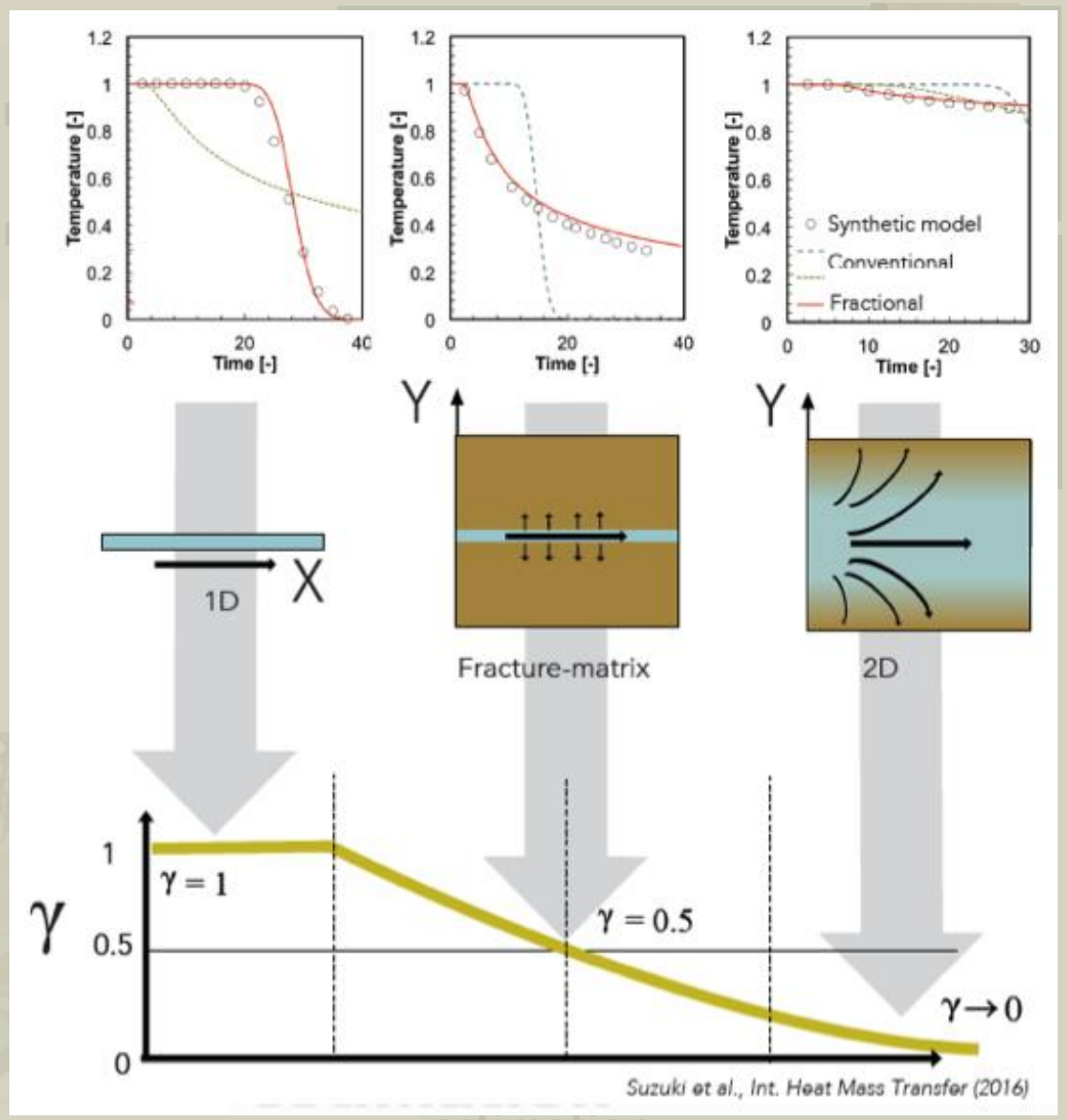
Fractional mass transport model

$$\frac{\partial c}{\partial t} + b\frac{\partial^{\gamma} c}{\partial t^{\gamma}} = -v\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2}$$

Fractional heat transfer model

$$\frac{\partial T}{\partial t} + b\frac{\partial^{\gamma} T}{\partial t^{\gamma}} = -\frac{\phi \varrho C_p v}{\varrho_T C_{pT}}\frac{\partial T}{\partial x}$$

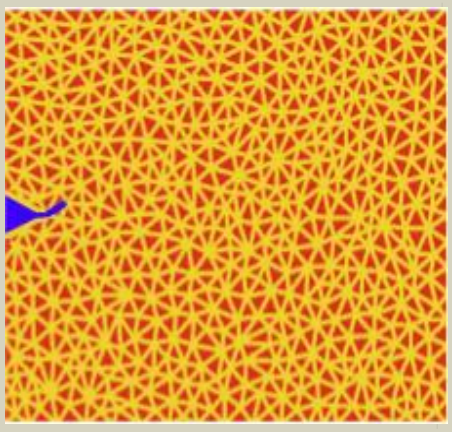
c: concentration
t: time
x: distance
v: velocity
D: diffusion
b: retardation parameter
T: temperature
ϕ: porosity
ϱ: density
C_p: heat capacity



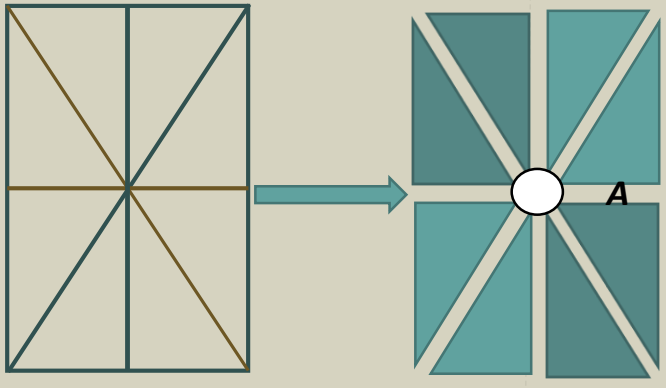
Design of Structure and Flow in the Earth Lab

Supercritical fluid fracturing simulation

Liu (D1)

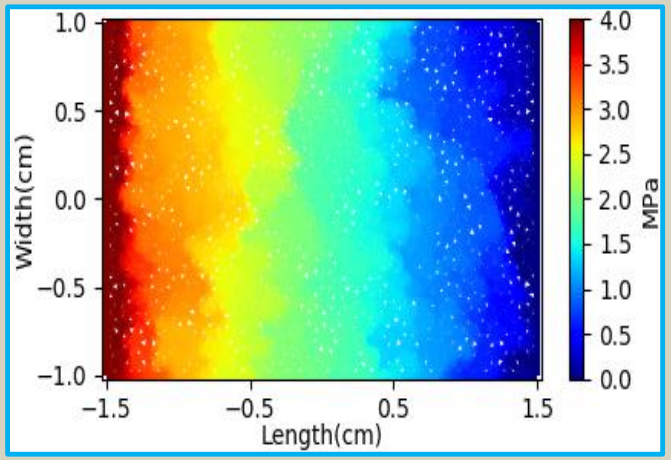


Pore network model

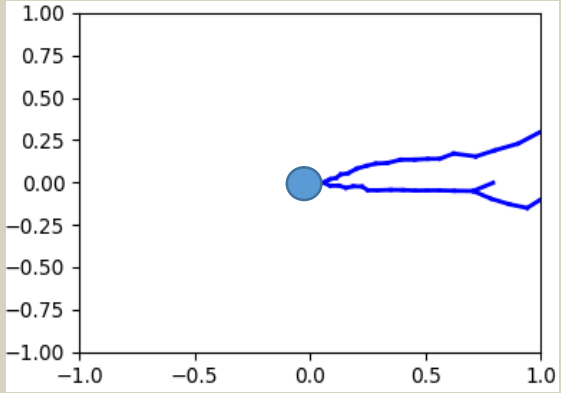


Double nodes

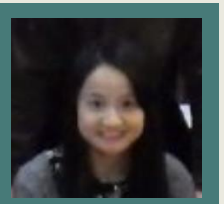
Two phase flow



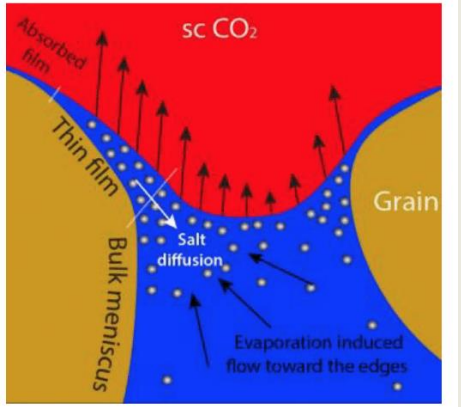
Fracture propagation



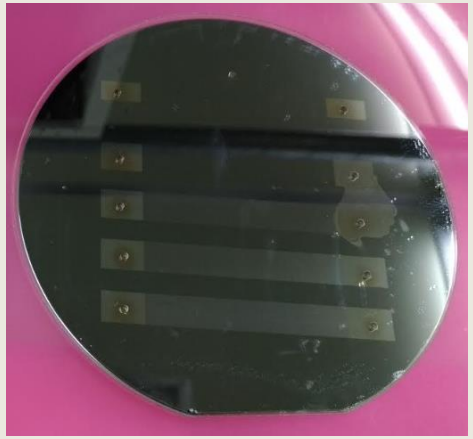
Microfluidics for salt precipitation due to CO2 injection



Huong (M2)

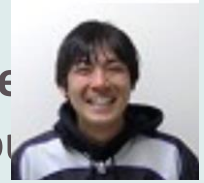


[4] Miri.R, Hellenvang.H *Salt precipitation during CO2 strrage-A review. 2015.*

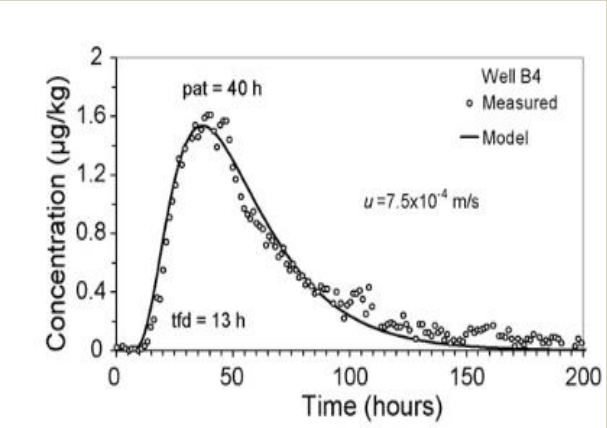


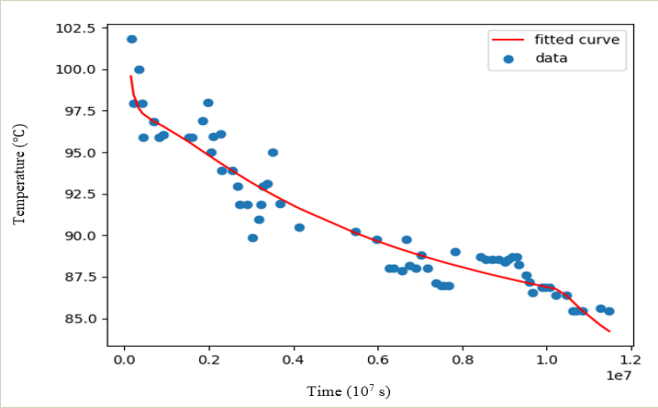
Design of Structure and Flow in the Earth Lab

Surface area estimation by trace thermal breakthrou

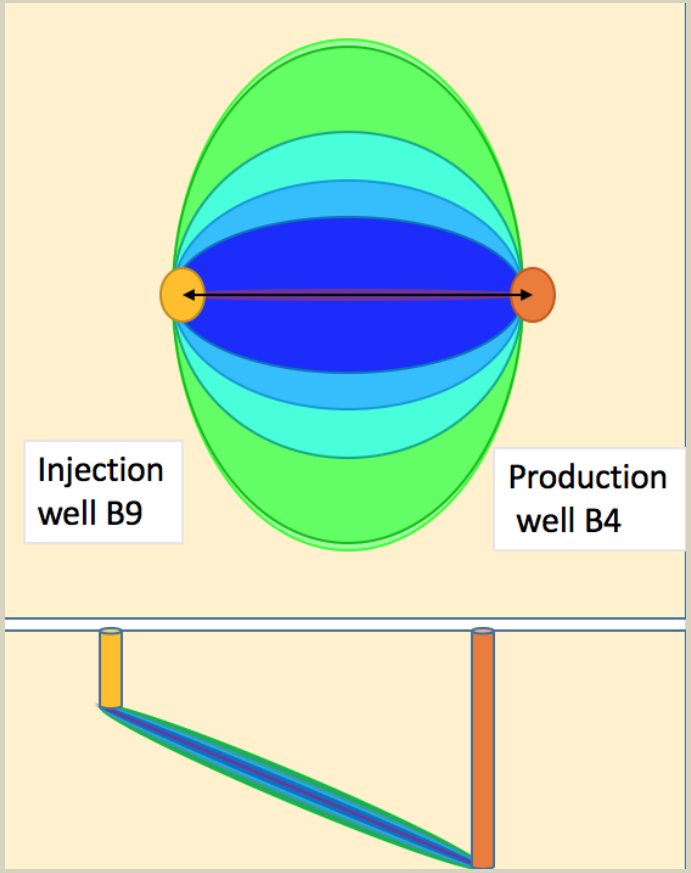


Yamaguchi (B4)



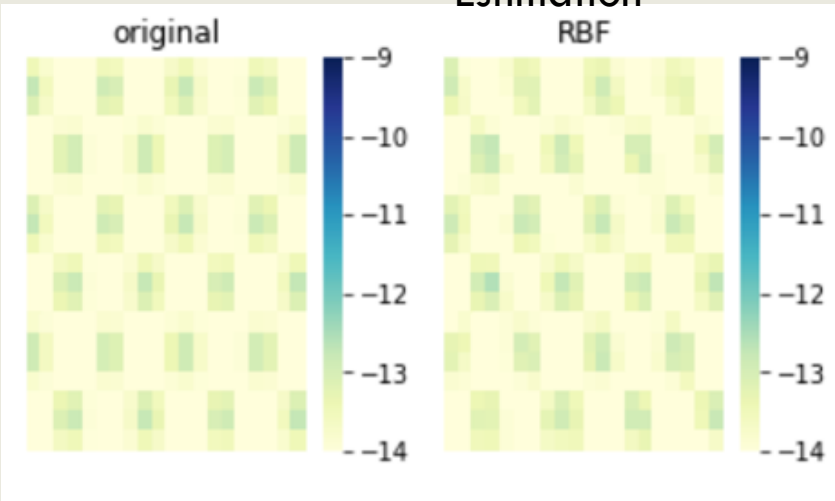


Fracture surface area estimation

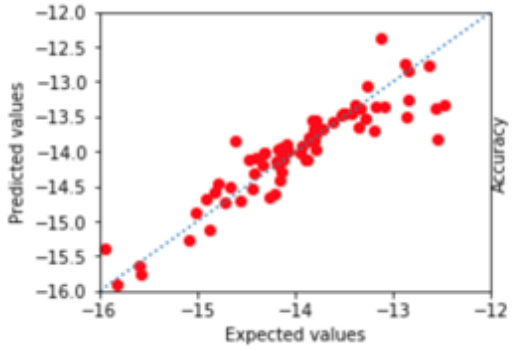


Machine learning for permeability distribution estimation

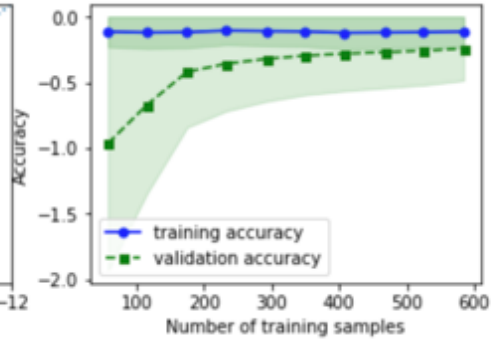
Estimation



Error



Learning curve



Institute of Fluid Science
Tohoku University

IFS

Joint Usage / Research Center
Fluid Science Global Research and Education Hub

Information | Links | Contact | JAPANESE

Outline | Fluid Science Global Research and Education Hub | Collaborative Research Project | Events | Results and Publications

Home > Collaborative Research Project

Collaborative Research Project

Fifteenth International Conference on Flow Dynamics, Sendai, Miyagi

JSPS Postdoctoral Fellowships for Research in Japan

Inviting Excellent Researchers from Other Countries to Japan

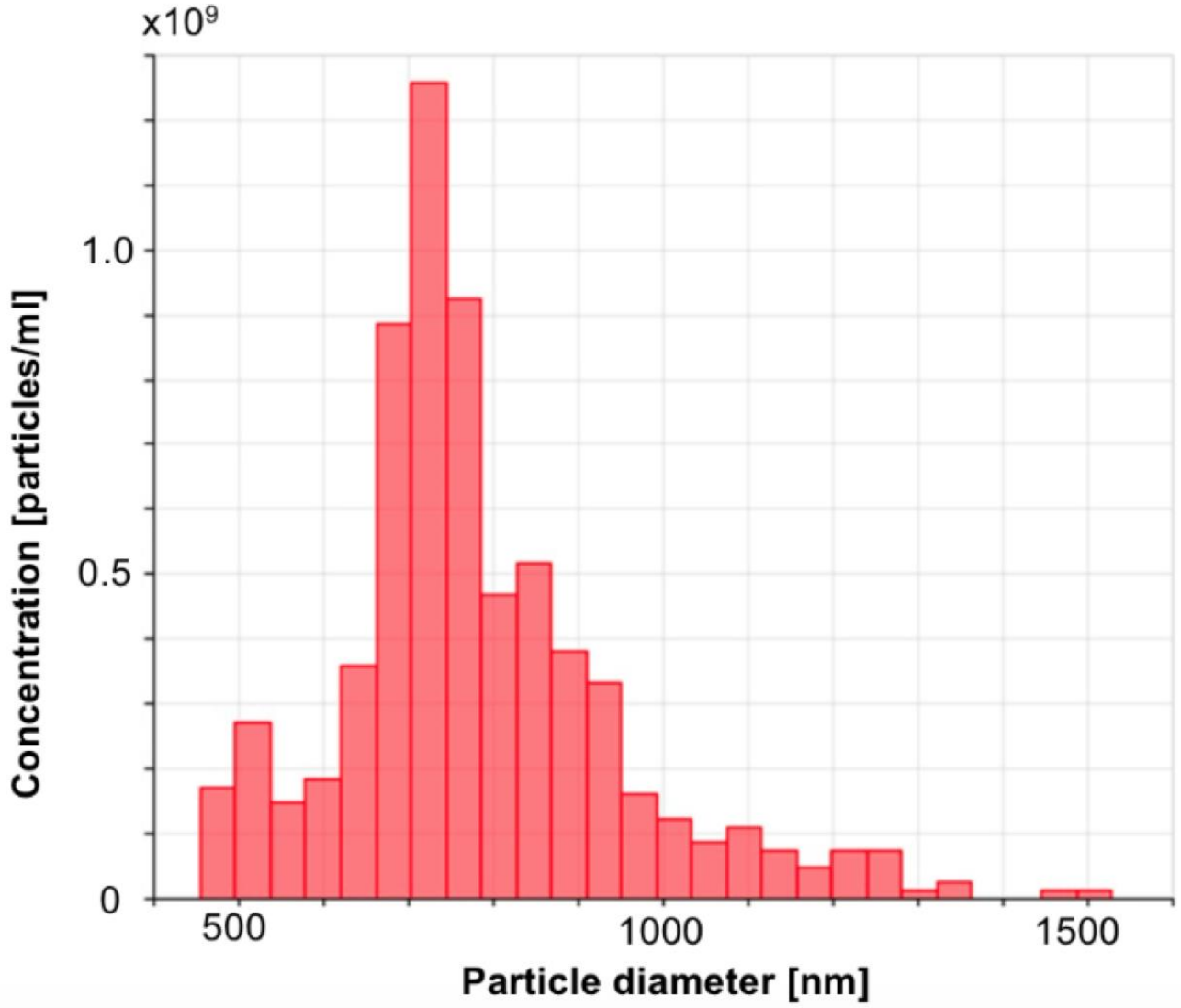
THANK YOU

anna.suzuki@tohoku.ac.jp

EXPERIMENTAL RESULTS

Size distribution measured by qNano

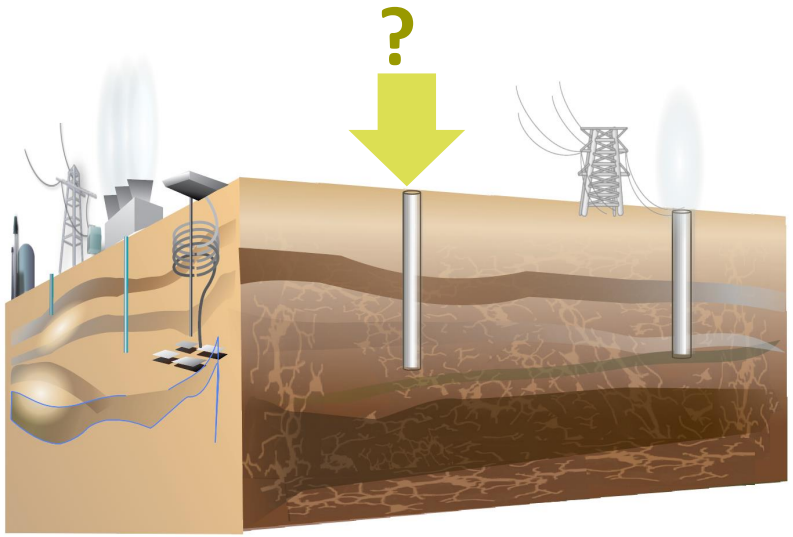
Analyzed sample before injection



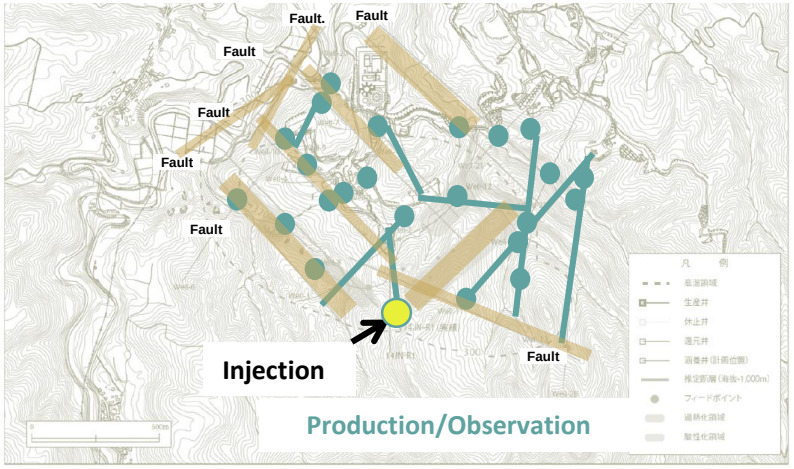
Sustainable design for geothermal systems

Anna Suzuki

Collaboration : Geothermal company

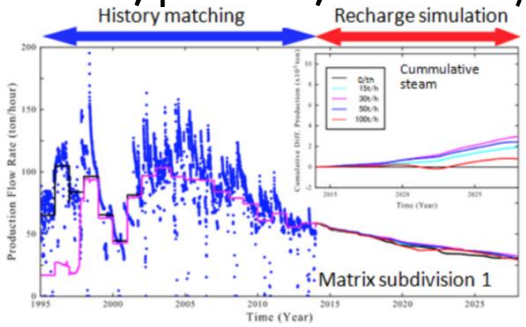


Geothermal field = Fracture network



Sparse data

(temperature, pressure, tracer …)



Network estimation
Future prediction
Sustainable design