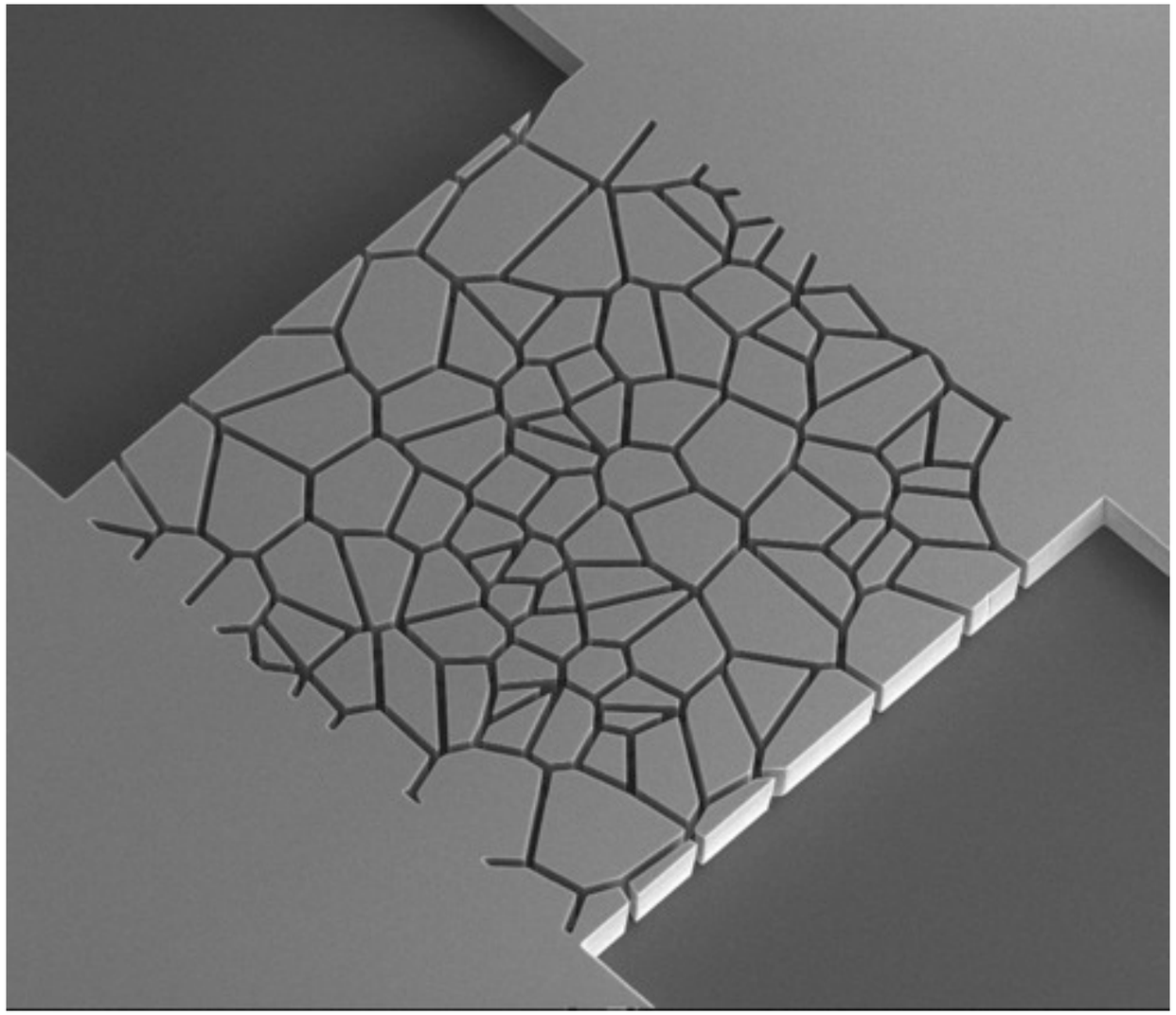
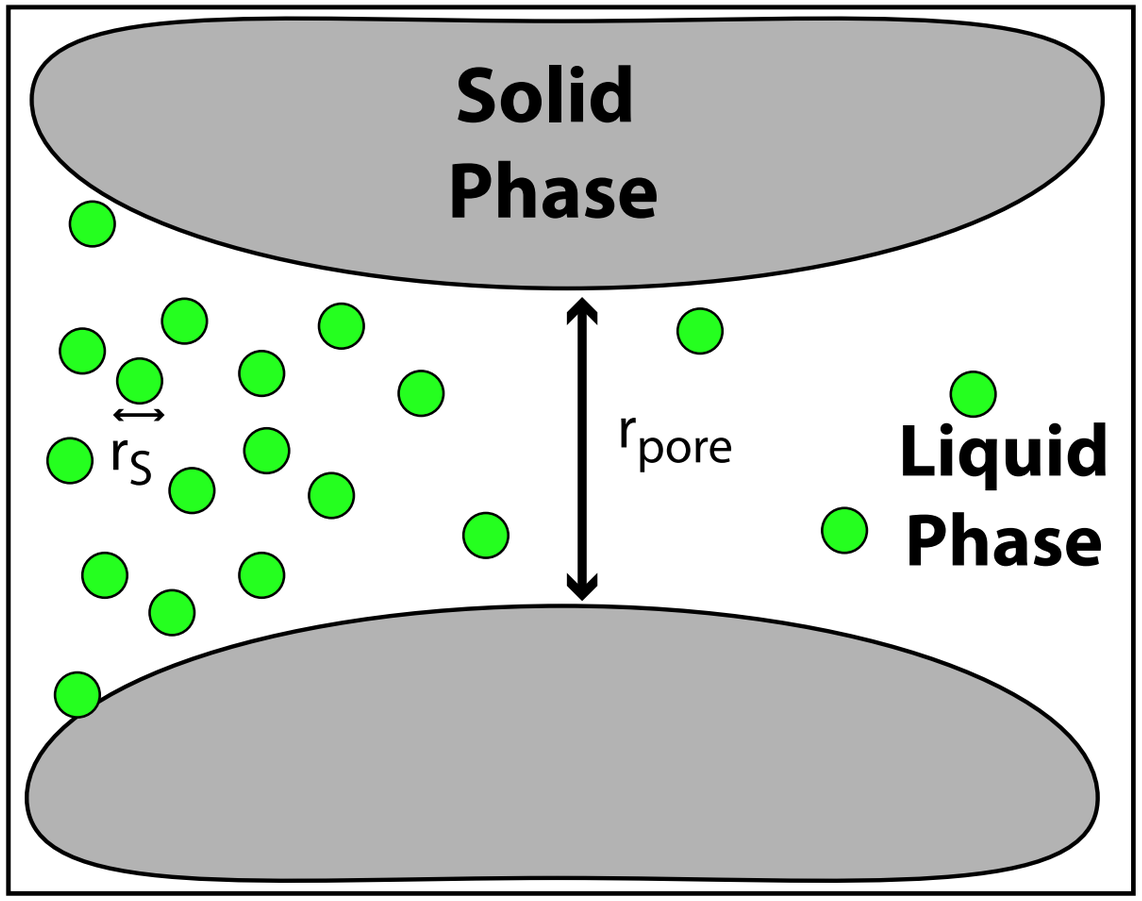
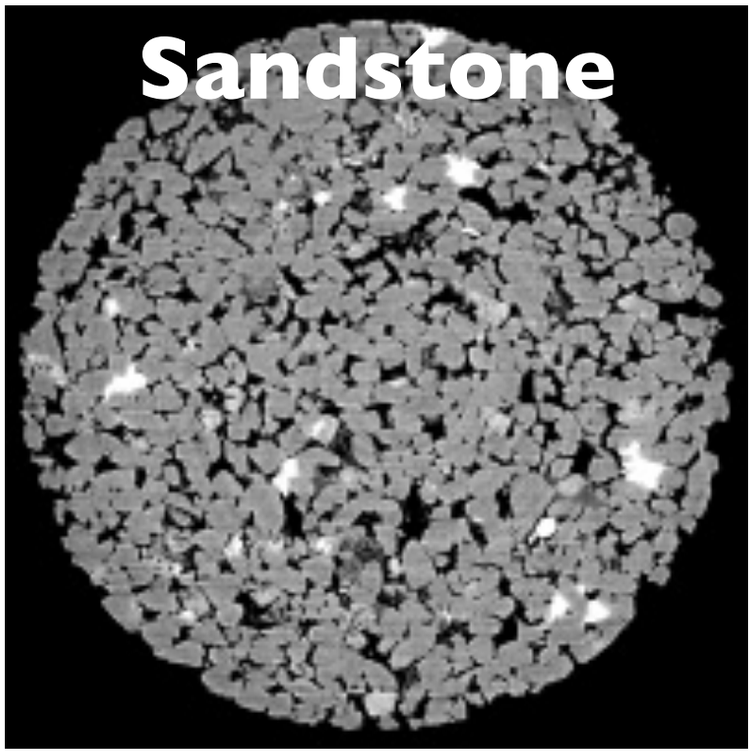
Micro- and nanoscale porous media analogs for studying multiphase flow

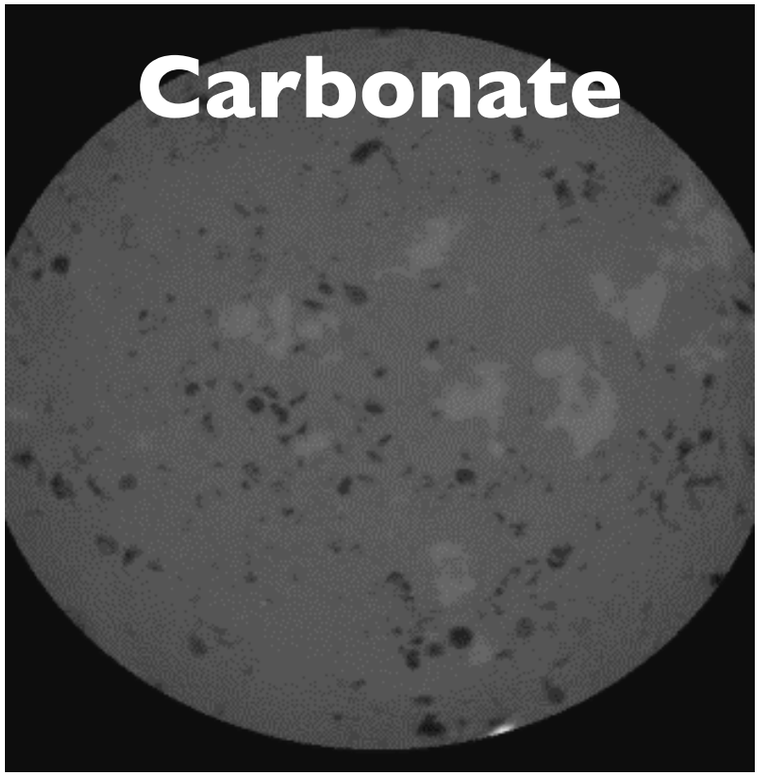


Keith B. Neeves
Boettcher Investigator
Chemical & Biological Engineering
Colorado School of Mines

Porous media transport-from geo to bio







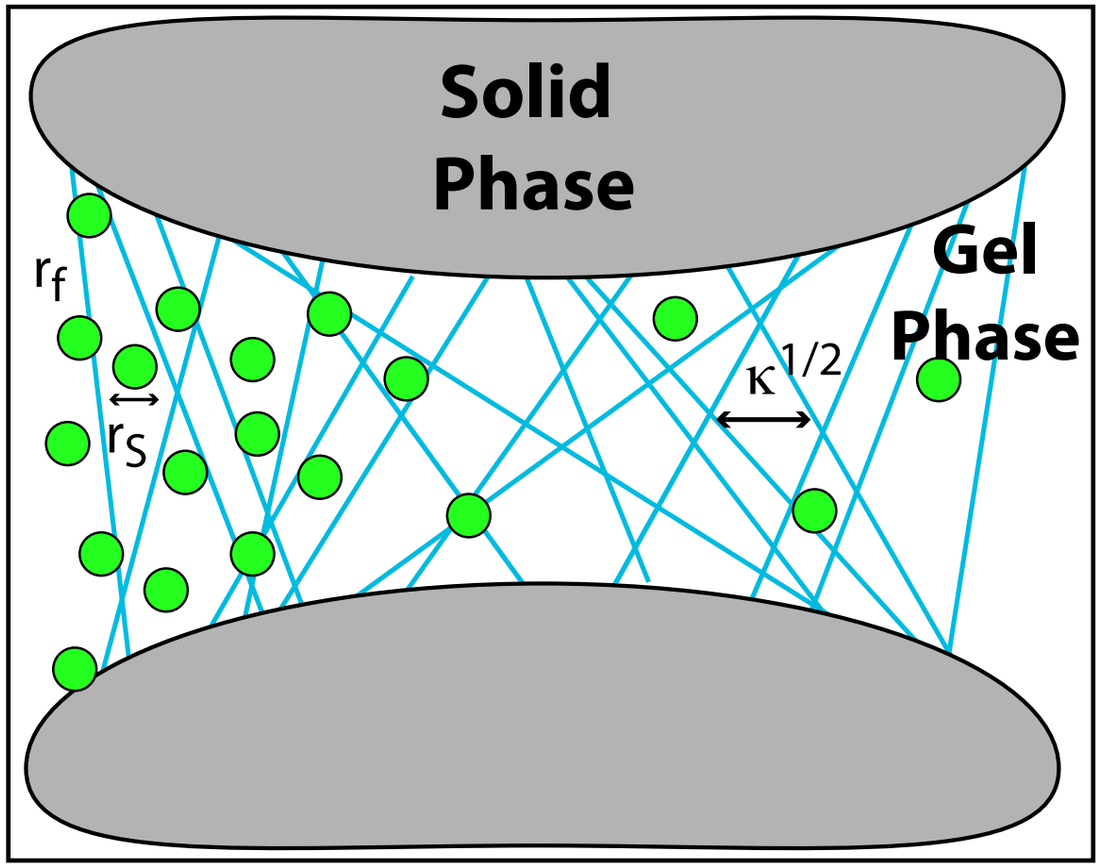
Applications

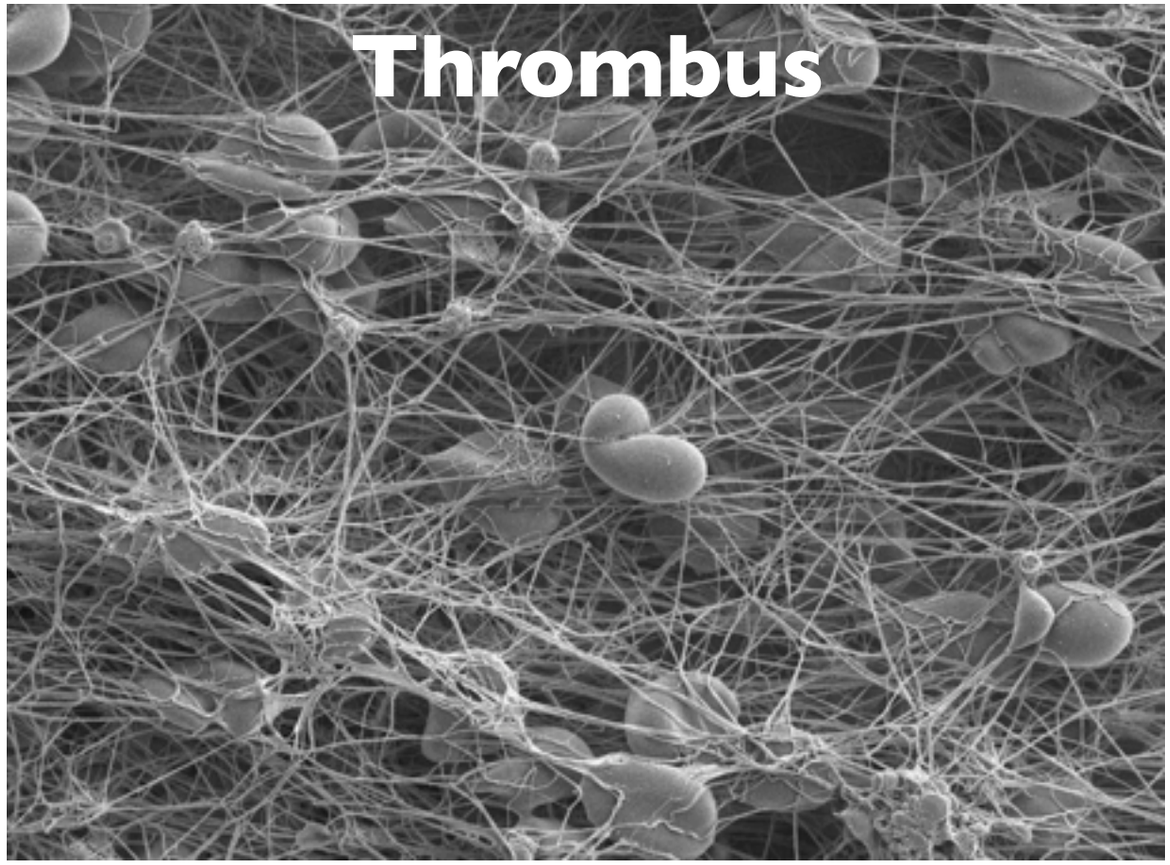
Oil and gas recovery
Groundwater flow
Reactive transport

Length Scales

L_{field} = 100 m-1 km
r_{pore} = 10 nm-100 um
(typically two length scales)

Porous media transport-from geo to bio





Applications

Drug delivery

Tissue engineering

Physiology and pathology

Length Scales

L_{tissue} = ~1 cm

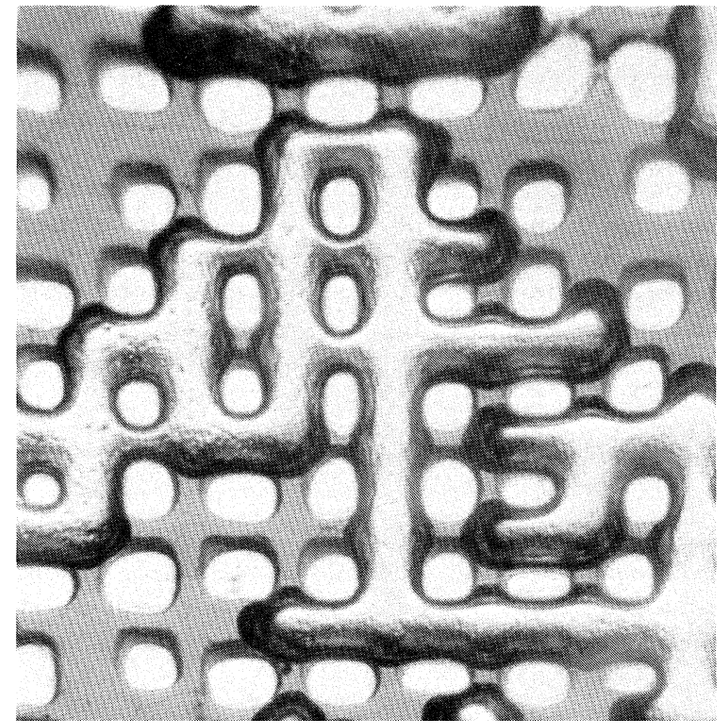
r_{pore} = 10 nm-100 um

r_{fiber} = 10-100 nm

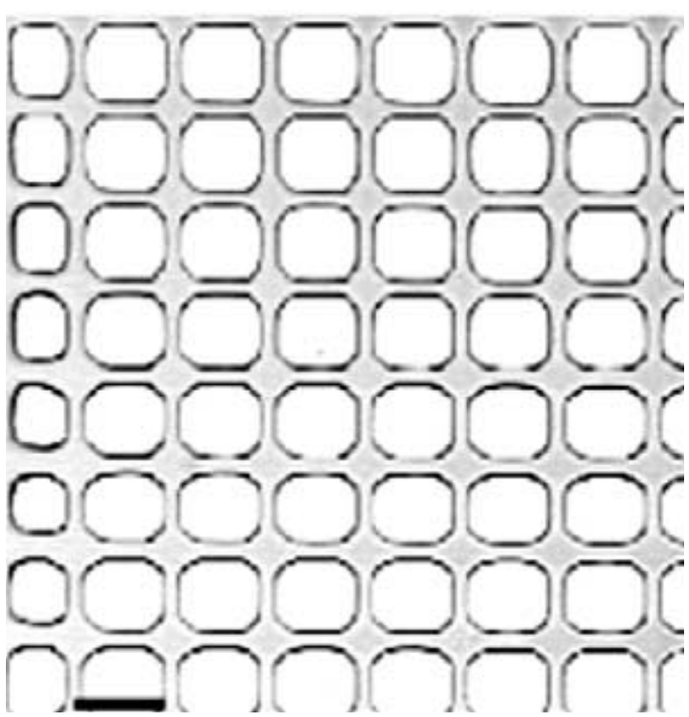
Inherently two length scales

Porous media analogs

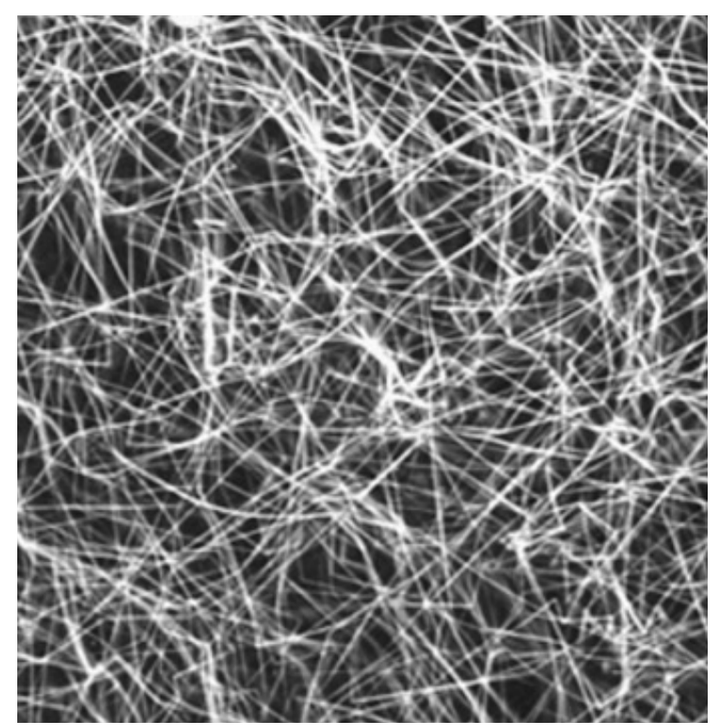
Homsy, *Ann Rev Fluid Mech* (1987)



Lenormand & Zarcone, *PRL*(1985)



Auset & Keller, *Water Resource Res* (2004)



Neeves et al., *Biophys J* (2010)

Next generation porous media analogs

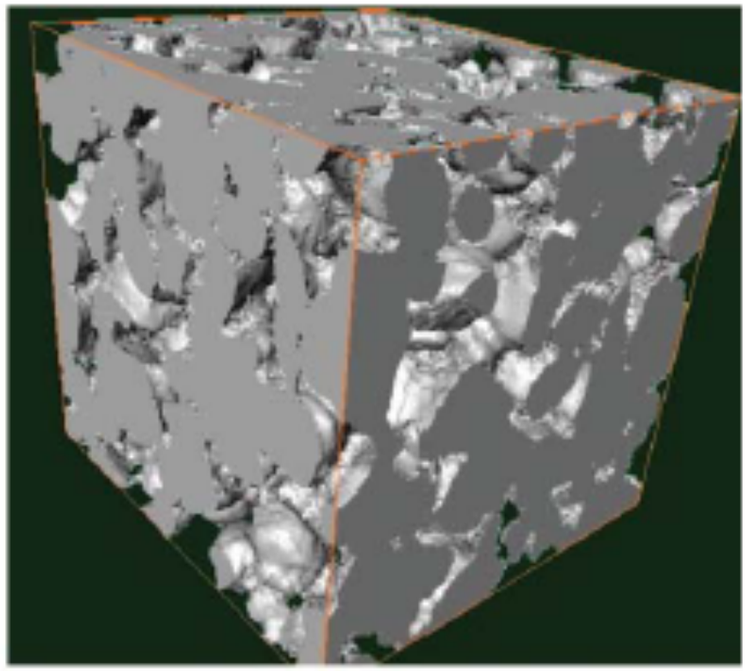
Real geometry reconstructed from imaging

-Realistic

-Limited resolution

-No control over geometry

-Empirical correlations



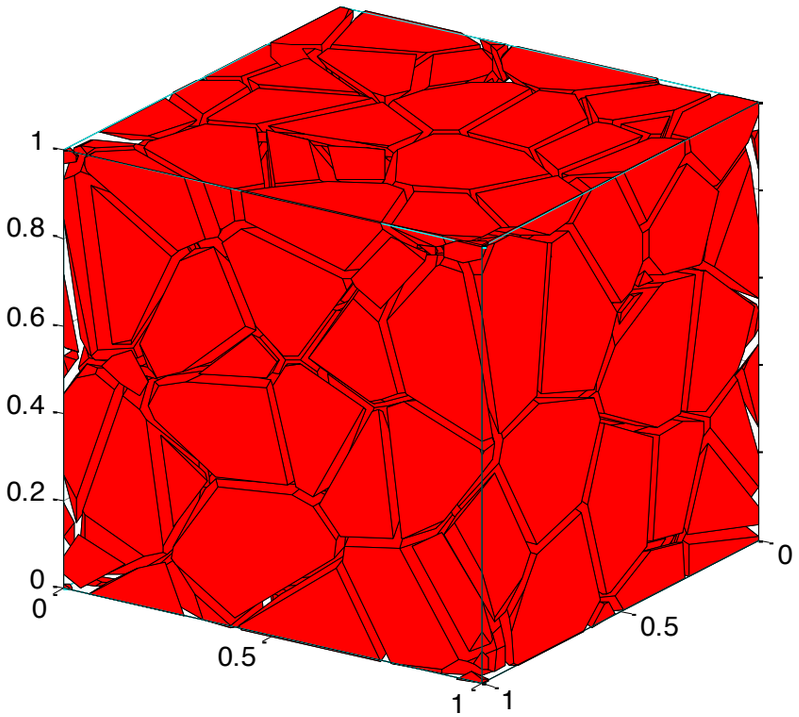
Modeled stochastic geometry

-Not real

-Precise control over geometry

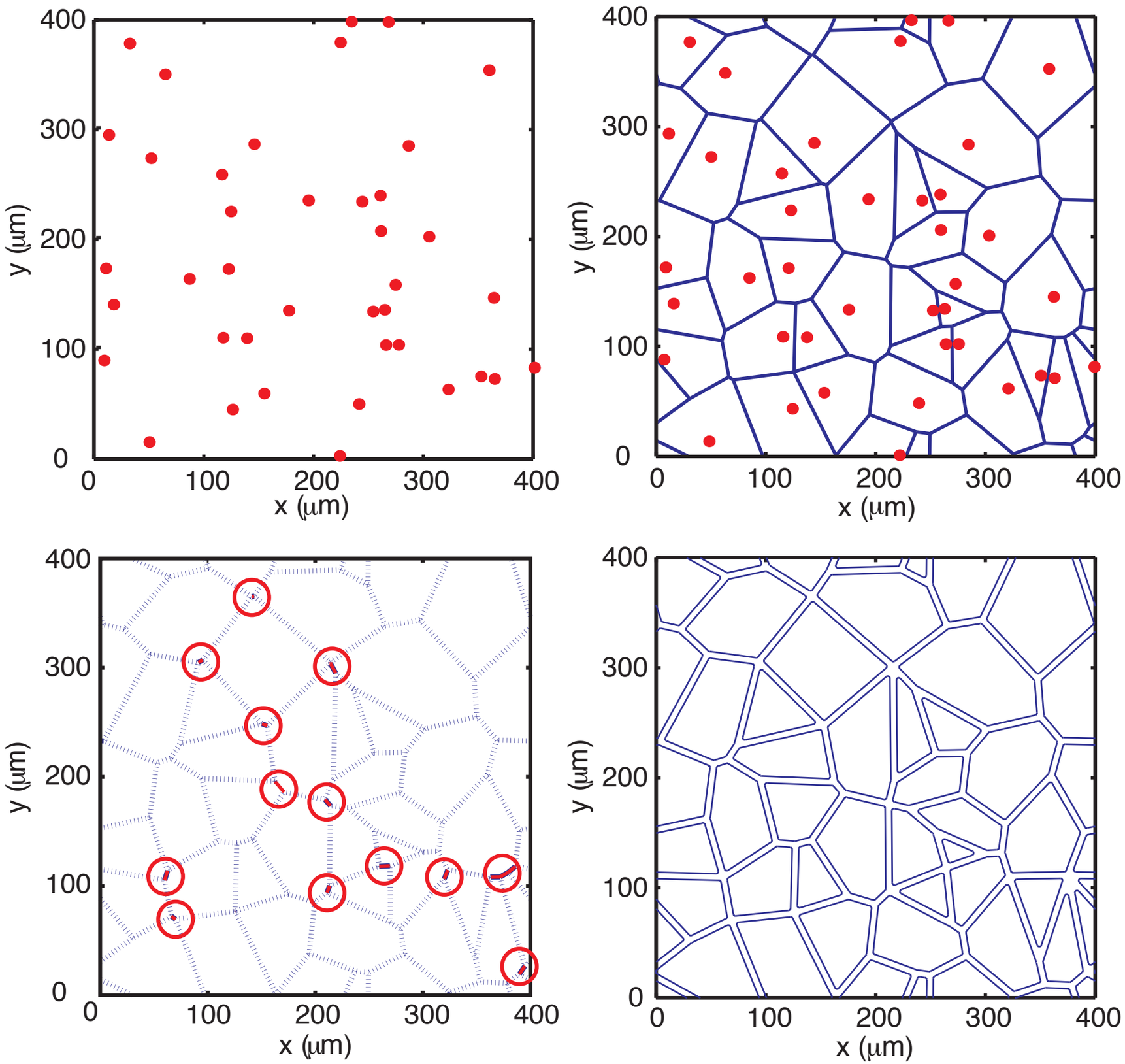
-Many samples with the same statistics can be generated

-Derive fundamental porosity-permeability relations



In collaboration with X.Yin (CSM)

Geometry algorithm



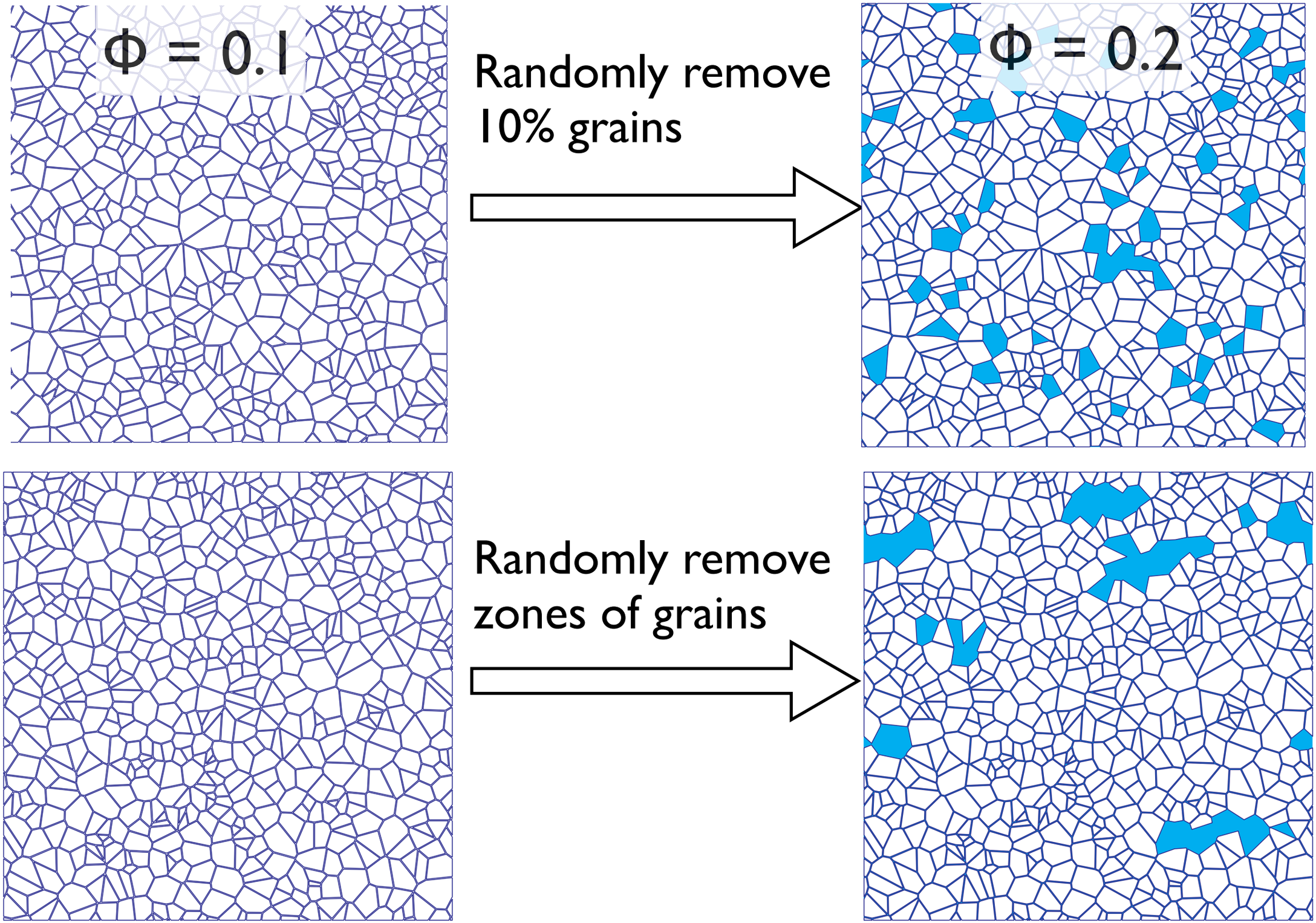
A. Poisson points

B. Voronoi tessellation (coord. number = 3)

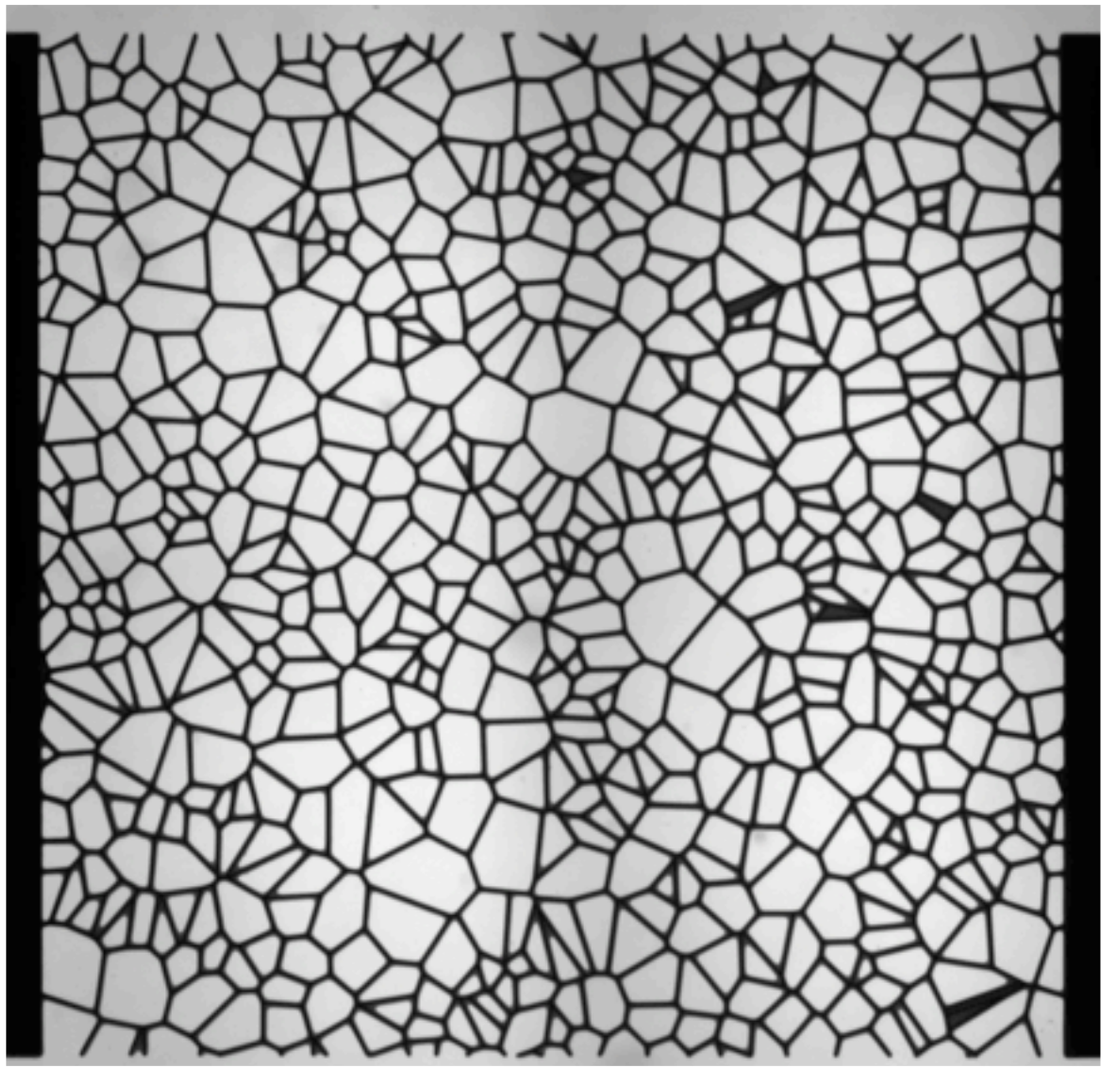
C. Perturbation in coordination number

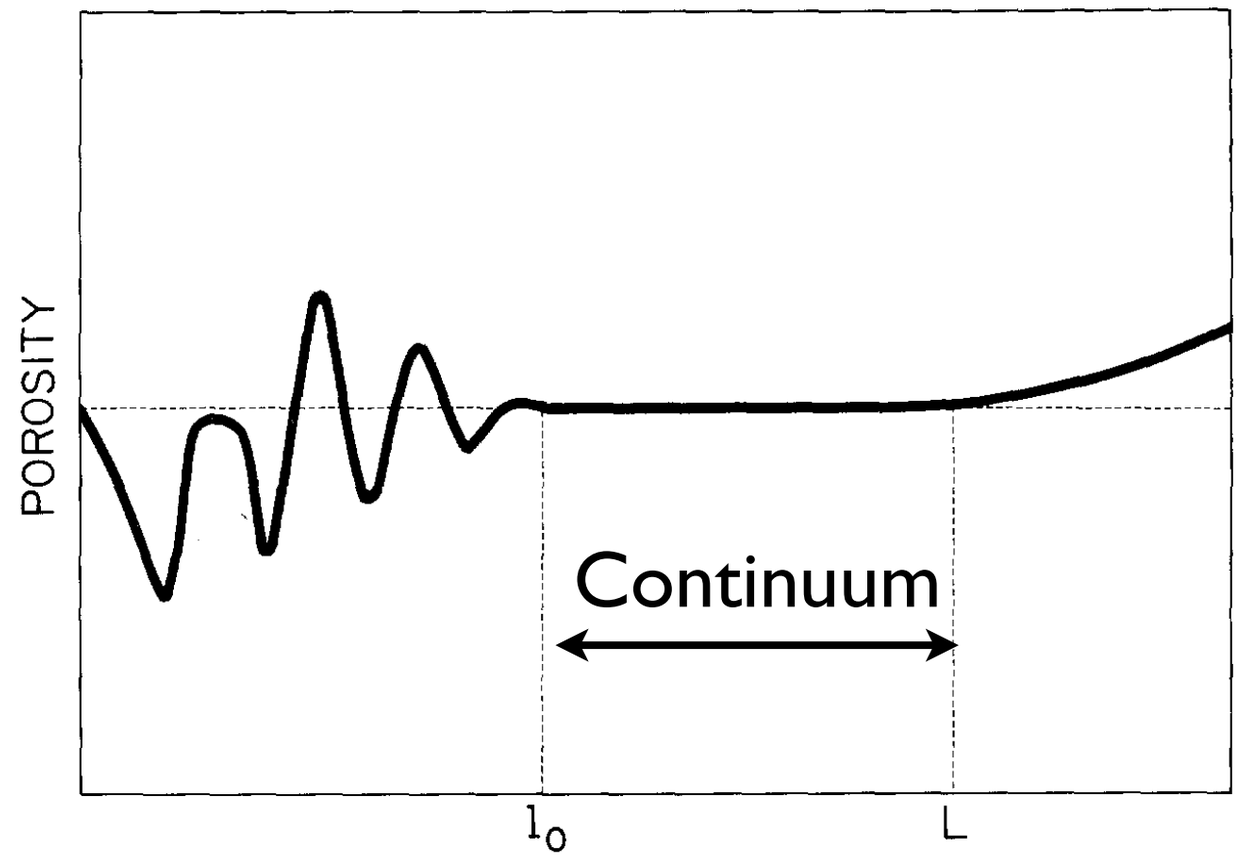
D. Edges given a finite width

Introducing a second length scale



Device specifications



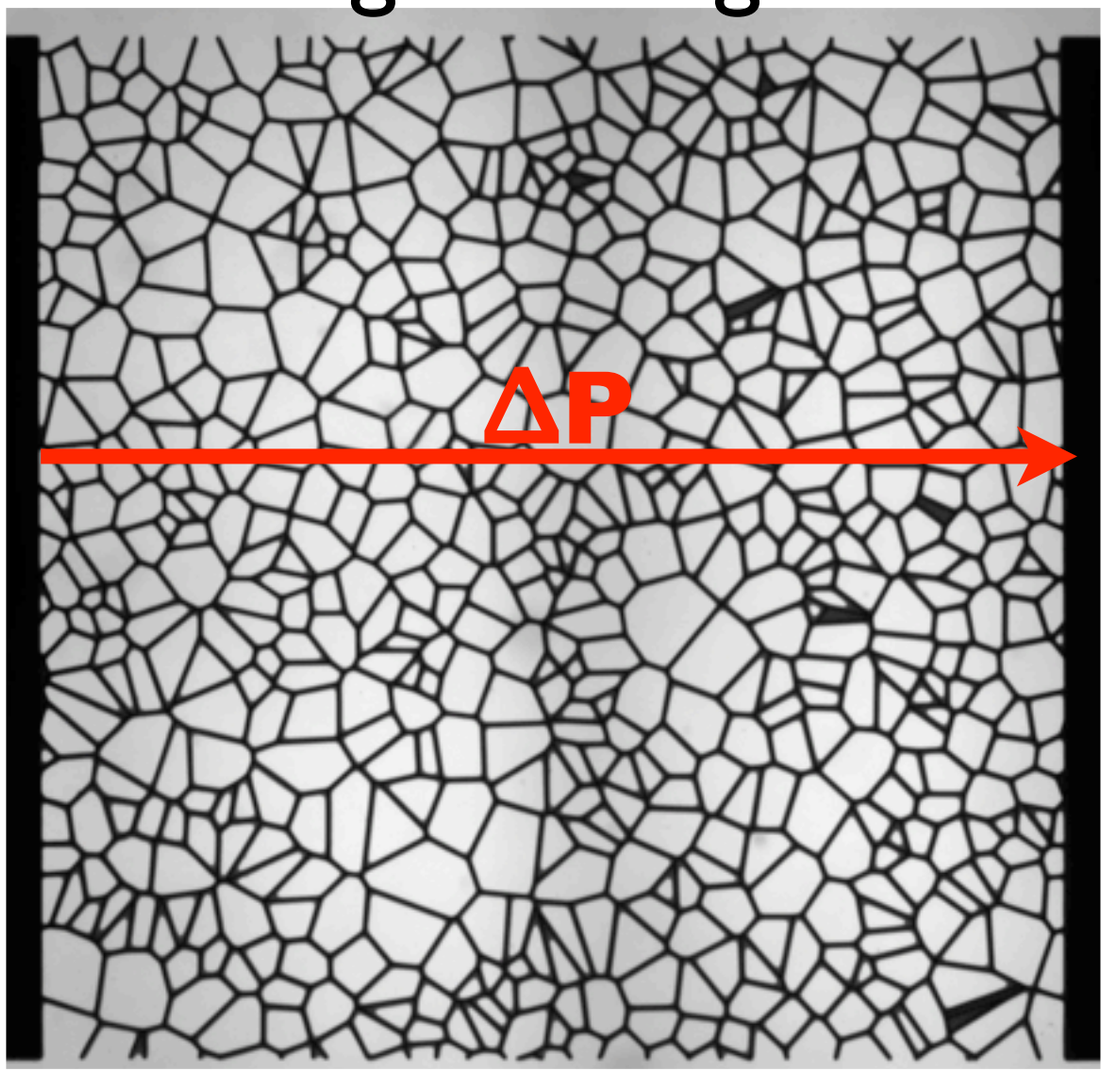


~600 grains
5 mm x 5 mm (3 X l_o)
Pores: w=10 μm, h=50 μm
Ø = 0.1 (Porosity)

Fabrication
Silicon masters by DRIE
Soft lithography PDMS
PDMS-glass bonding

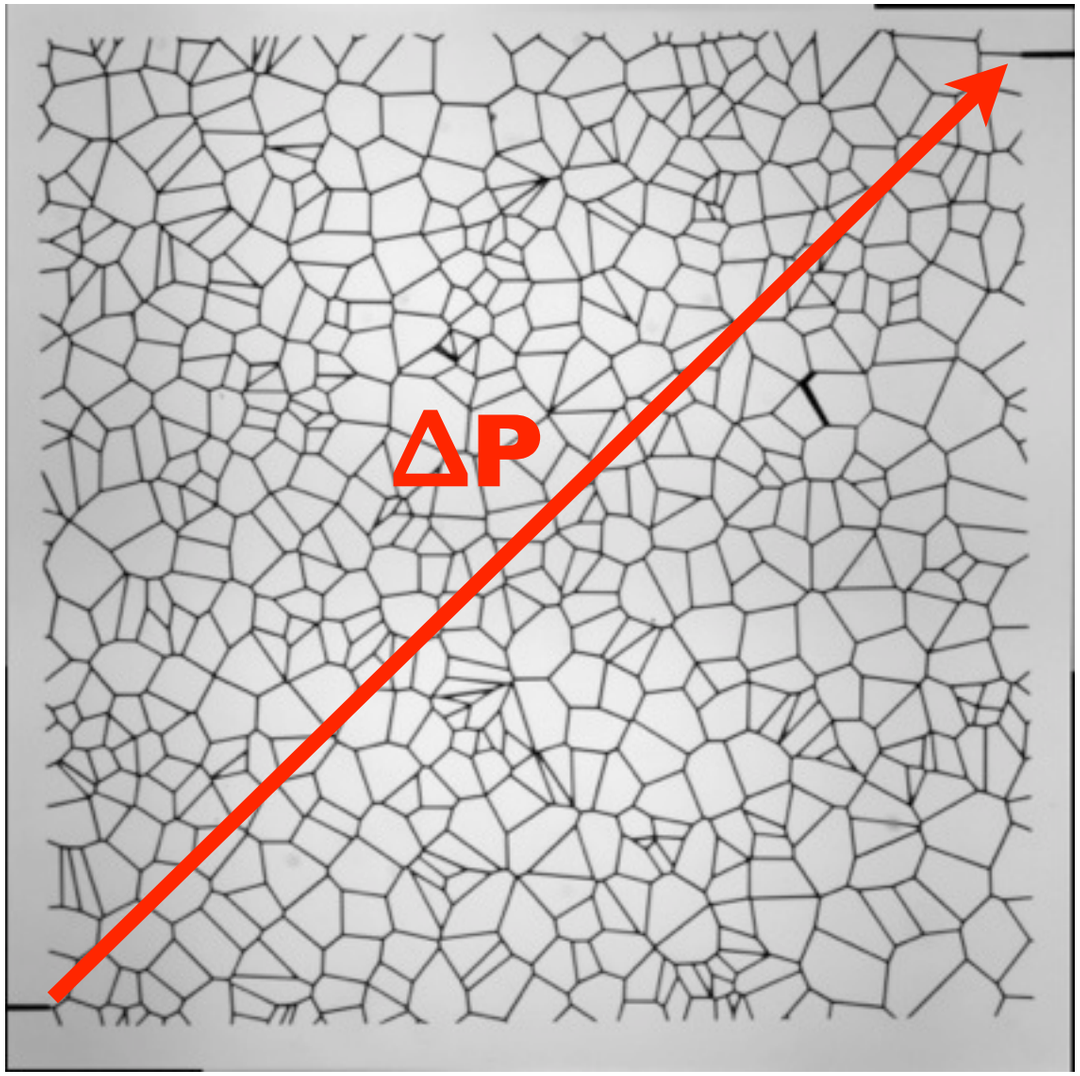
Device specifications

Edge-to-Edge



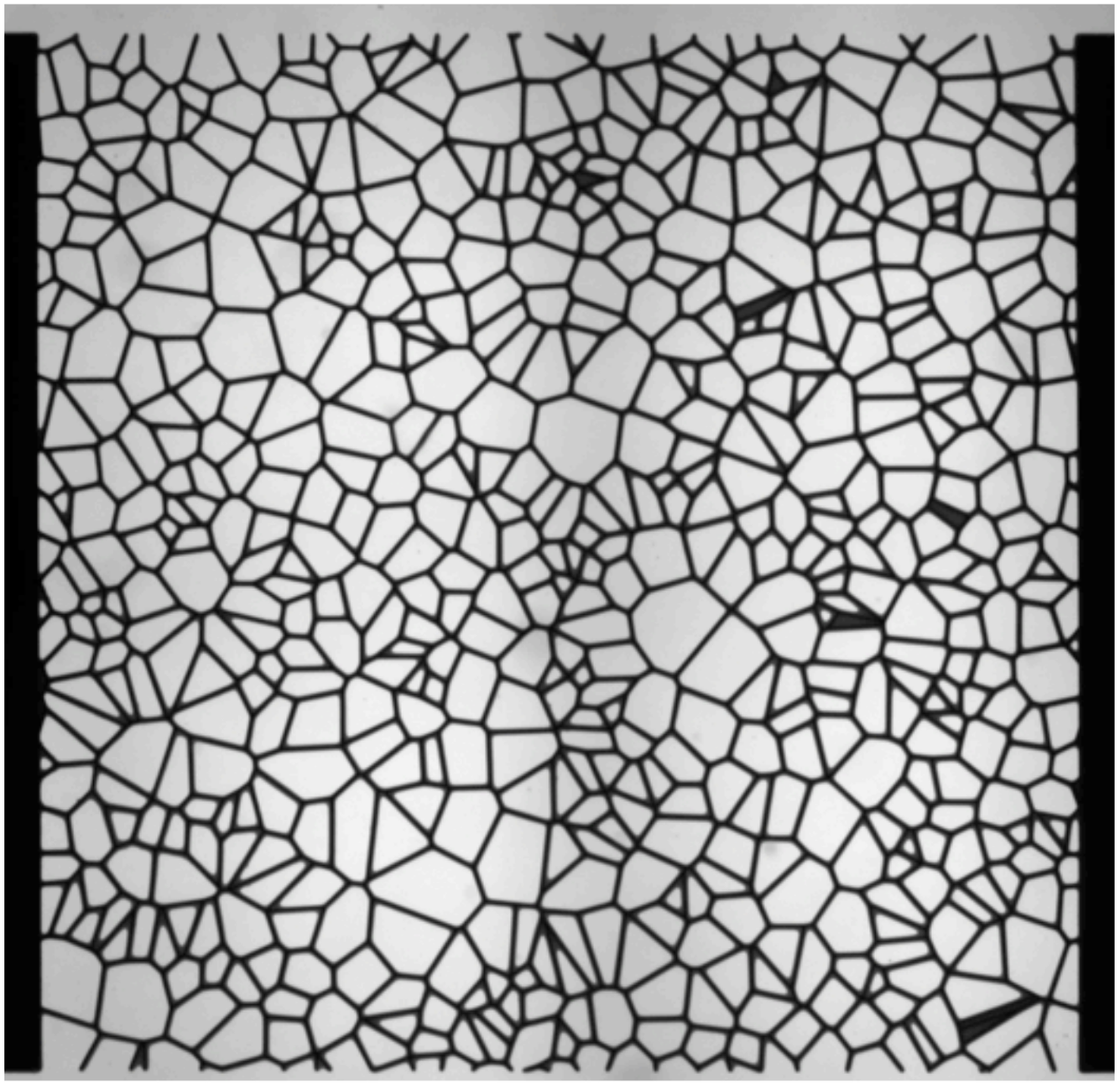
~600 grains
5 mm x 5 mm (3 X l_o)
Pores: w=10 μm, h=50 μm
Ø = 0.1 (Porosity)

Corner-to-Corner



Fabrication
Silicon masters by DRIE
Soft lithography PDMS
PDMS-glass bonding

Measuring hydraulic permeability



$\Delta P/L$

Darcy's Law

$$v = (k/\mu)\nabla P$$

v = fluid velocity
k = permeability
μ = viscosity
P = pressure

Kozeny Relation

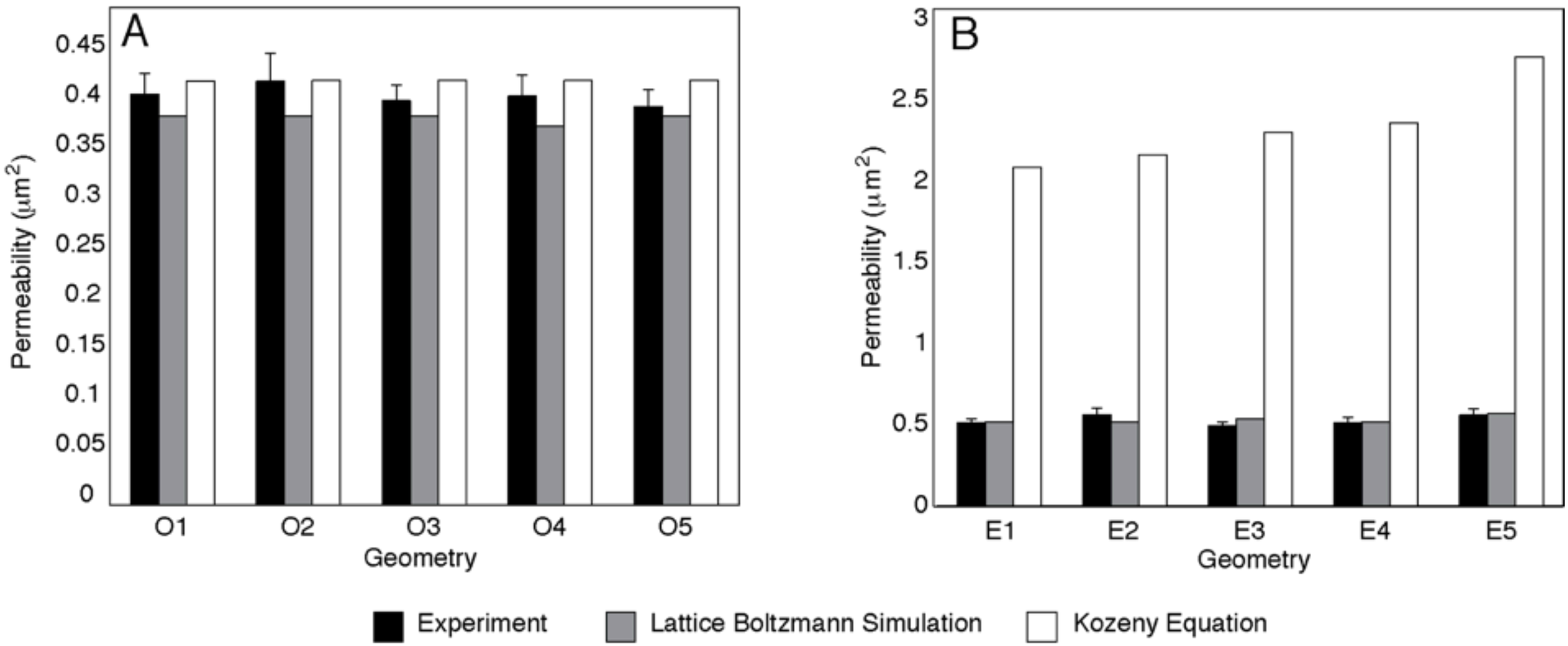
$$k = \phi^3/Cs^2$$

ø = porosity
C = shape factor
s = surface area/pore volume

Hydraulic permeability on stochastic networks

Homogeneous

Heterogeneous



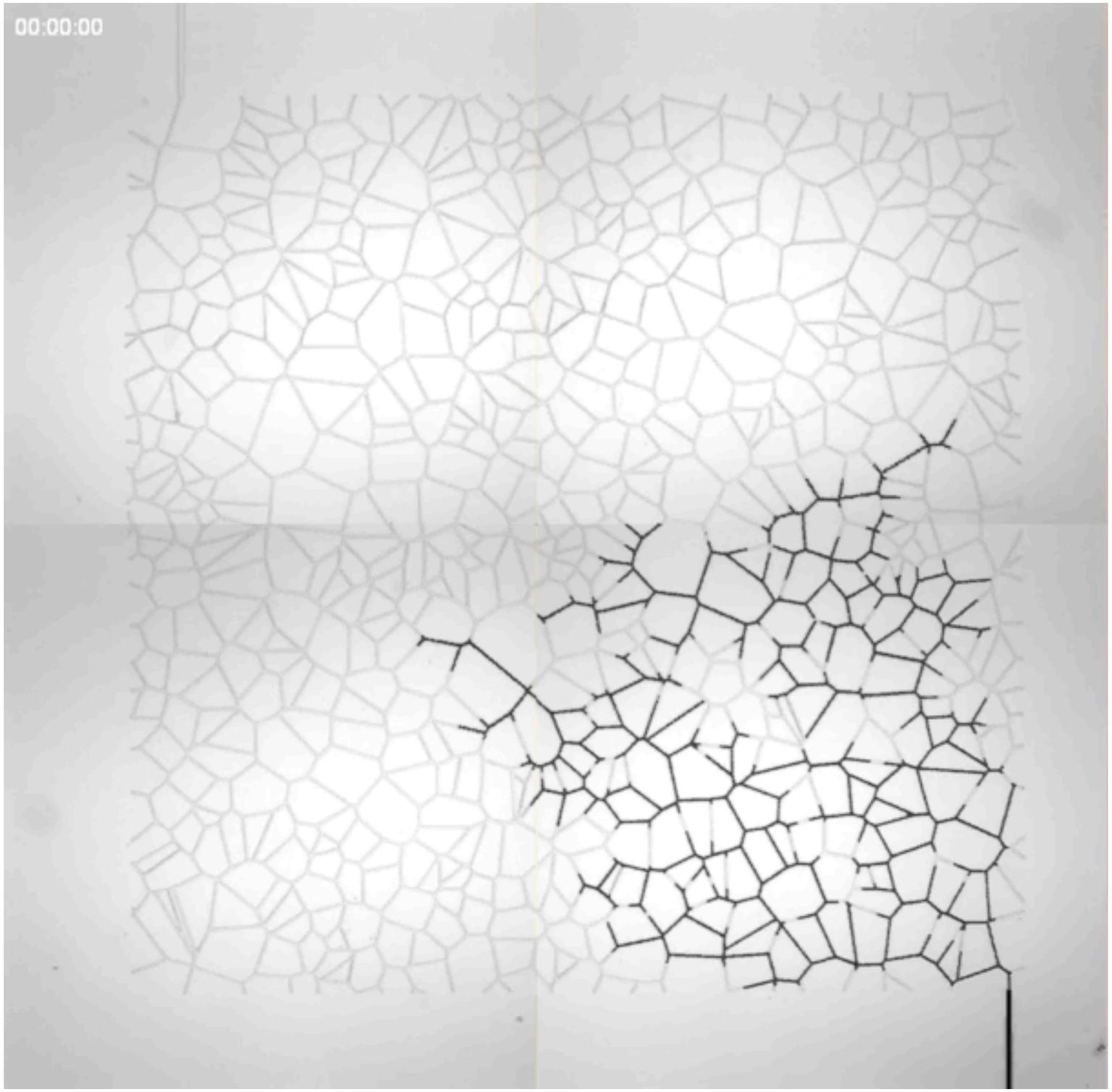
<u>Experimental Conditions</u>

ΔP = 5, 10, 15 psi

μ_{H2O} = 1 cP

Least squares fit to Darcy's Law (n = 5)

Drainage in homogeneous networks



<u>Experimental Conditions</u>

$\Delta P = 5$ psi

$Ca = 10^{-5}$

$M = 100$

Invasion Percolation and Trapping (IPT)

$Ca = v_2\mu_2/\gamma$

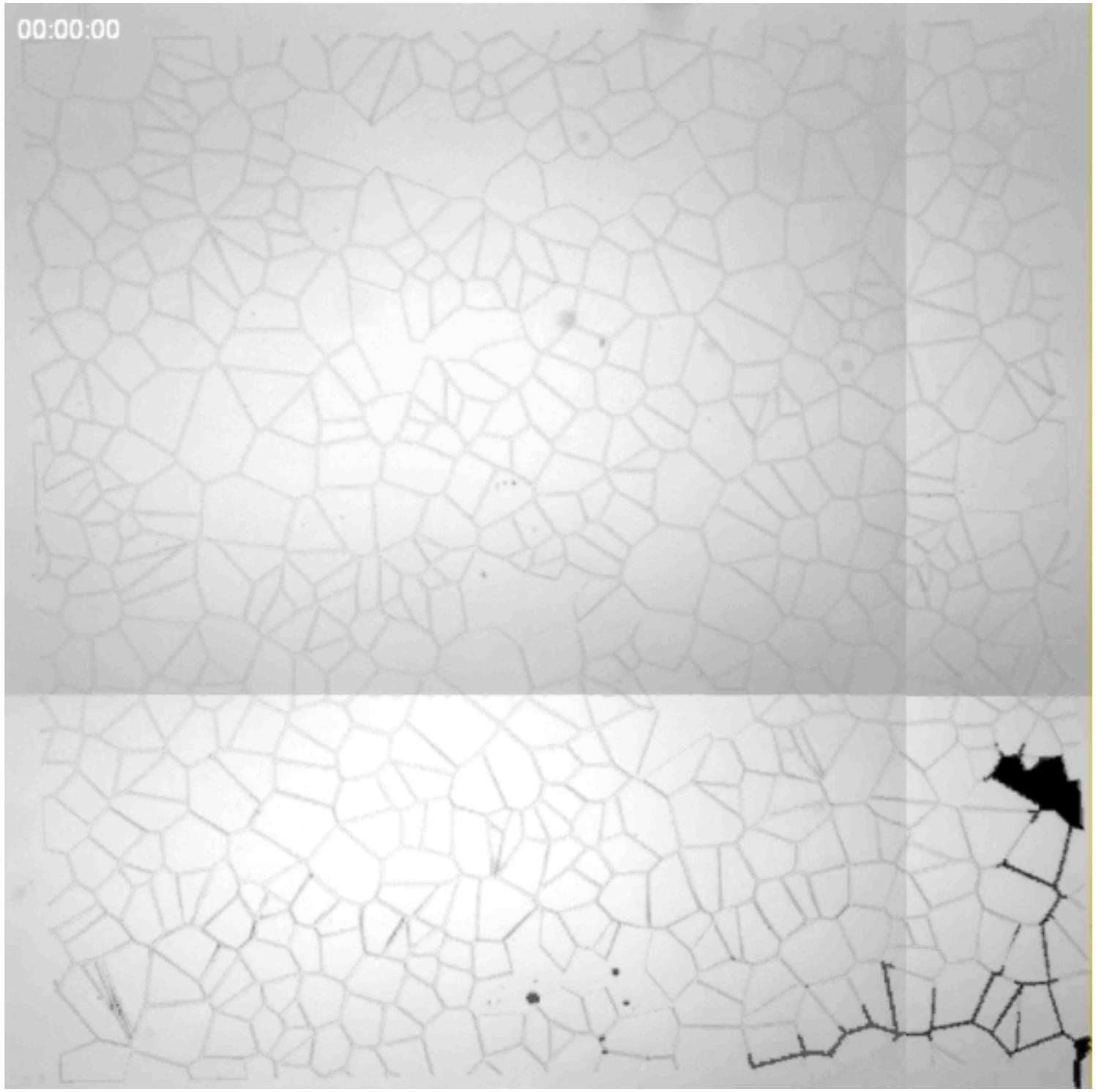
$M = \mu_1/\mu_2$

Phase 1 = Oil

Phase 2 = Water

Drainage: Non-wetting fluid displacing wetting fluid

Drainage in heterogeneous networks



<u>Experimental Conditions</u>

$\Delta P = 5$ psi

$Ca = 10^{-5}$

Viscosity Ratio = 100 (o:w)

Invasion Percolation and Trapping (IPT) to anti-DLA type displacement

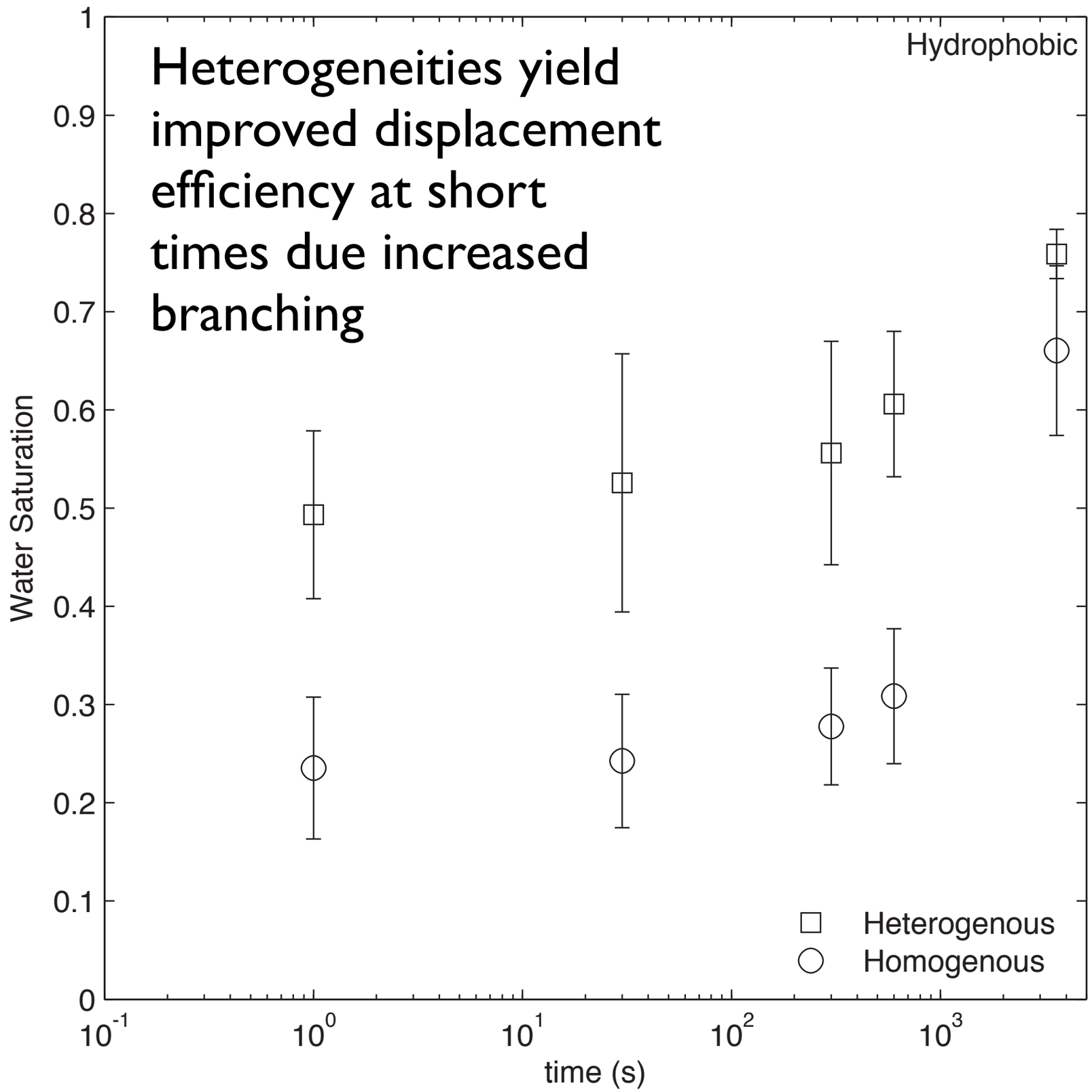
$Ca = v_2\mu_2/\gamma$

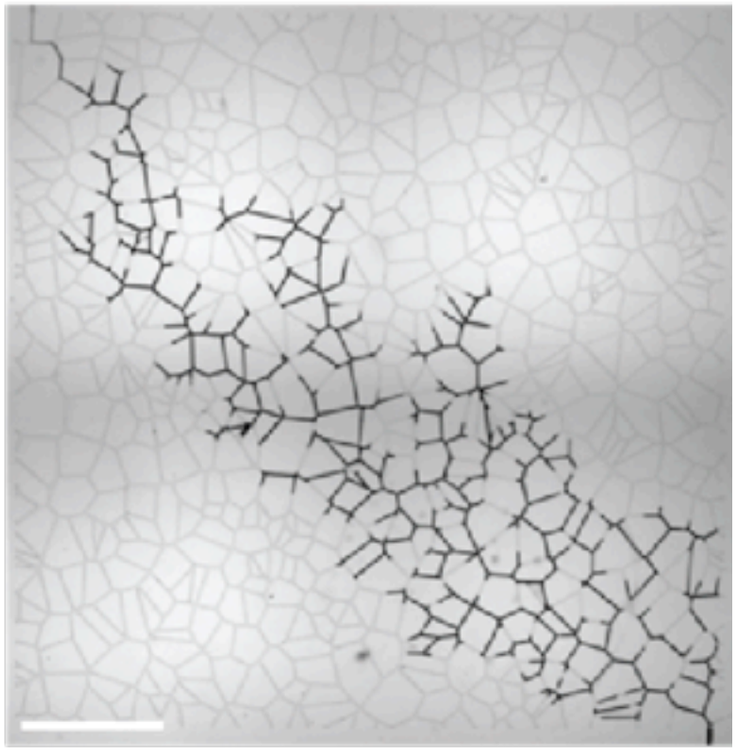
$M = \mu_1/\mu_2$

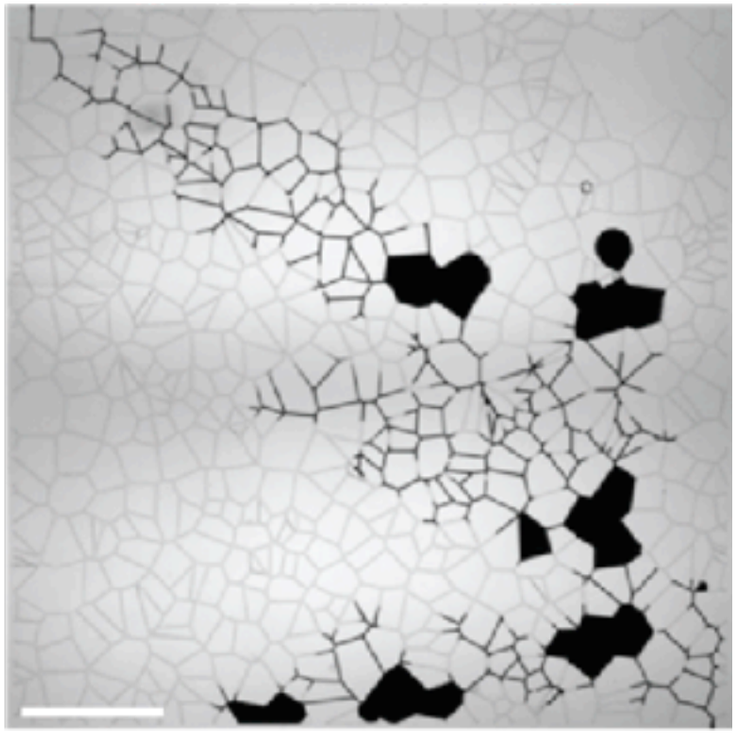
Phase 1 = Oil

Phase 2 = Water

Displacement efficiency in drainage experiments

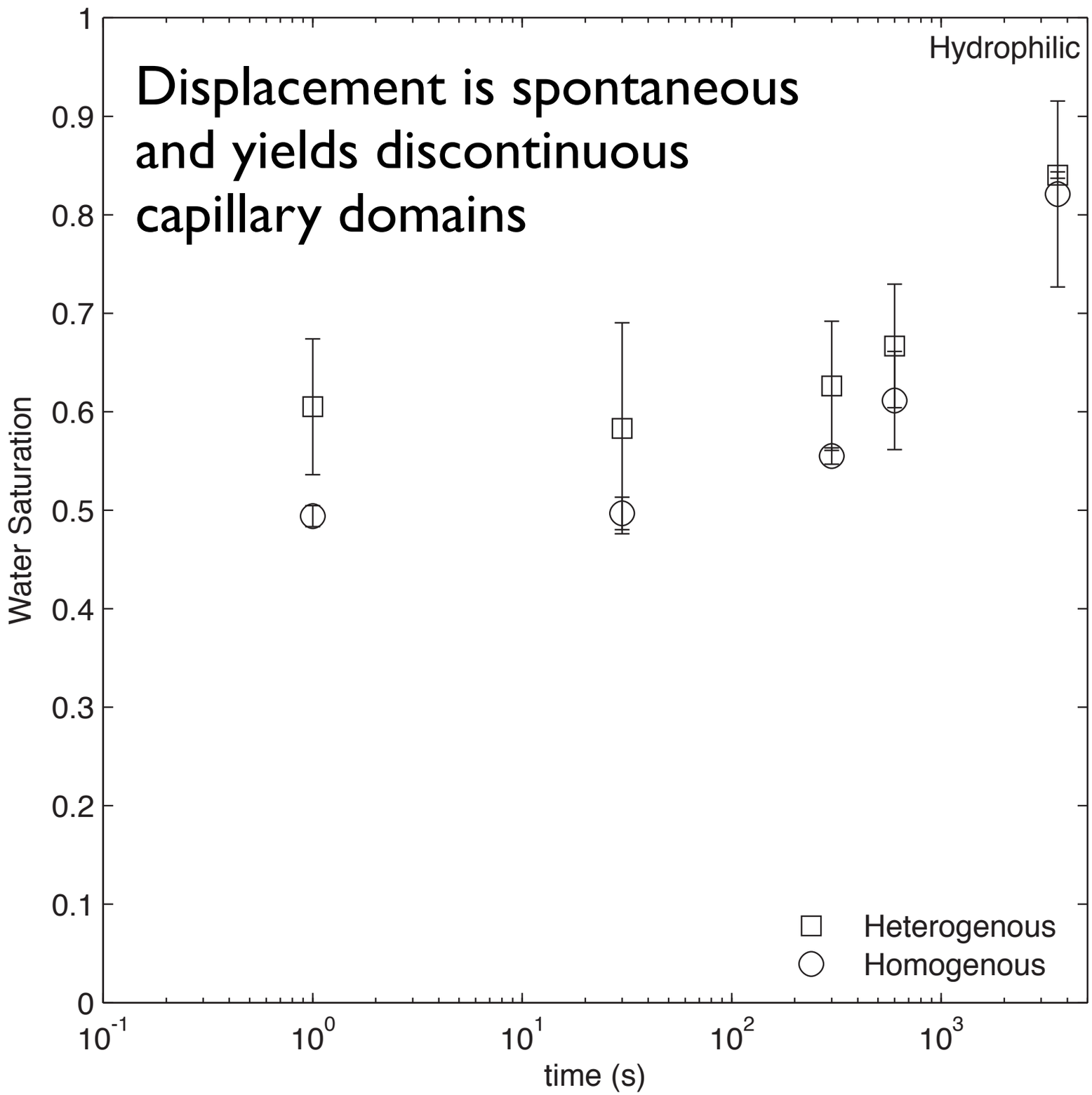


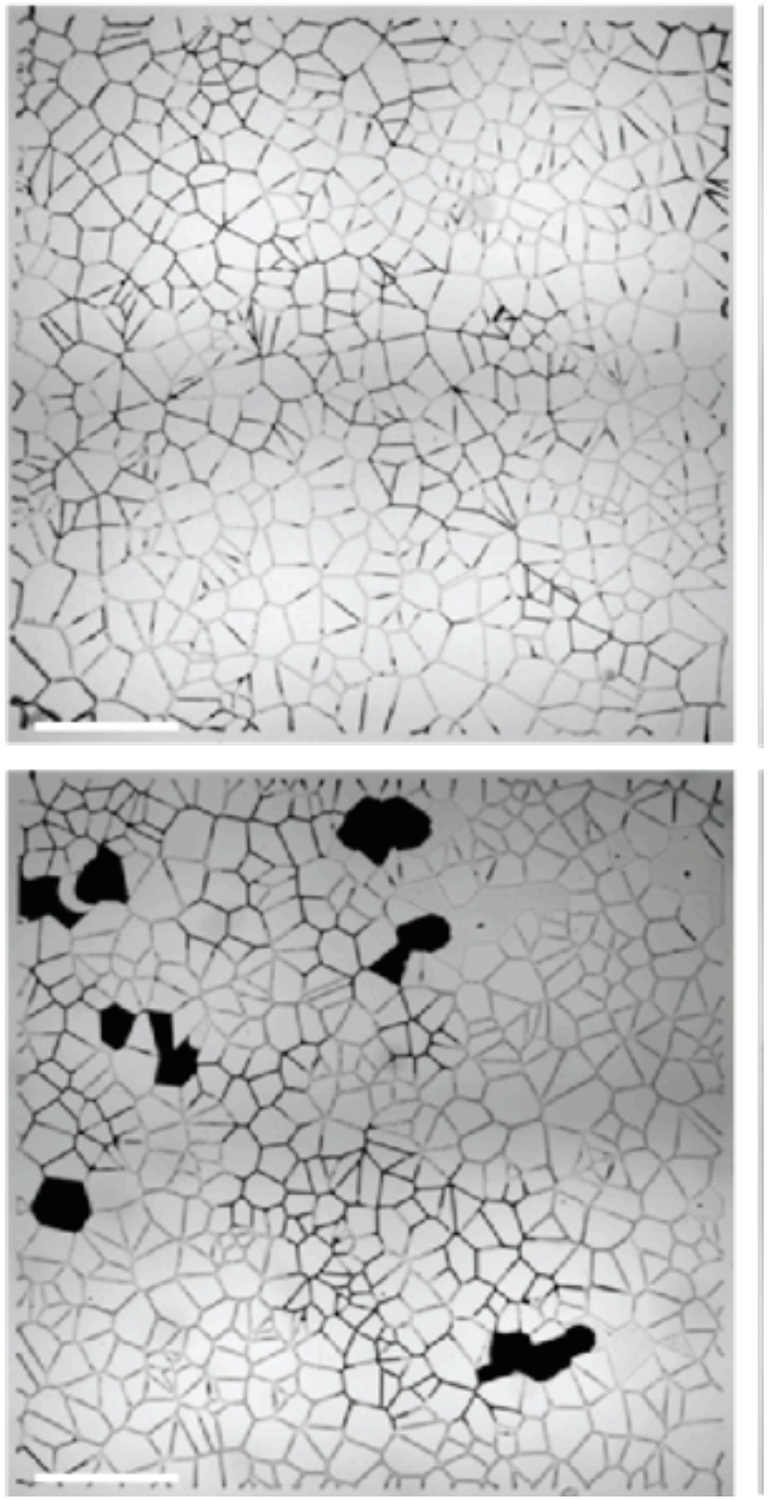




Scale bar = 1 mm

Displacement efficiency in imibition experiments

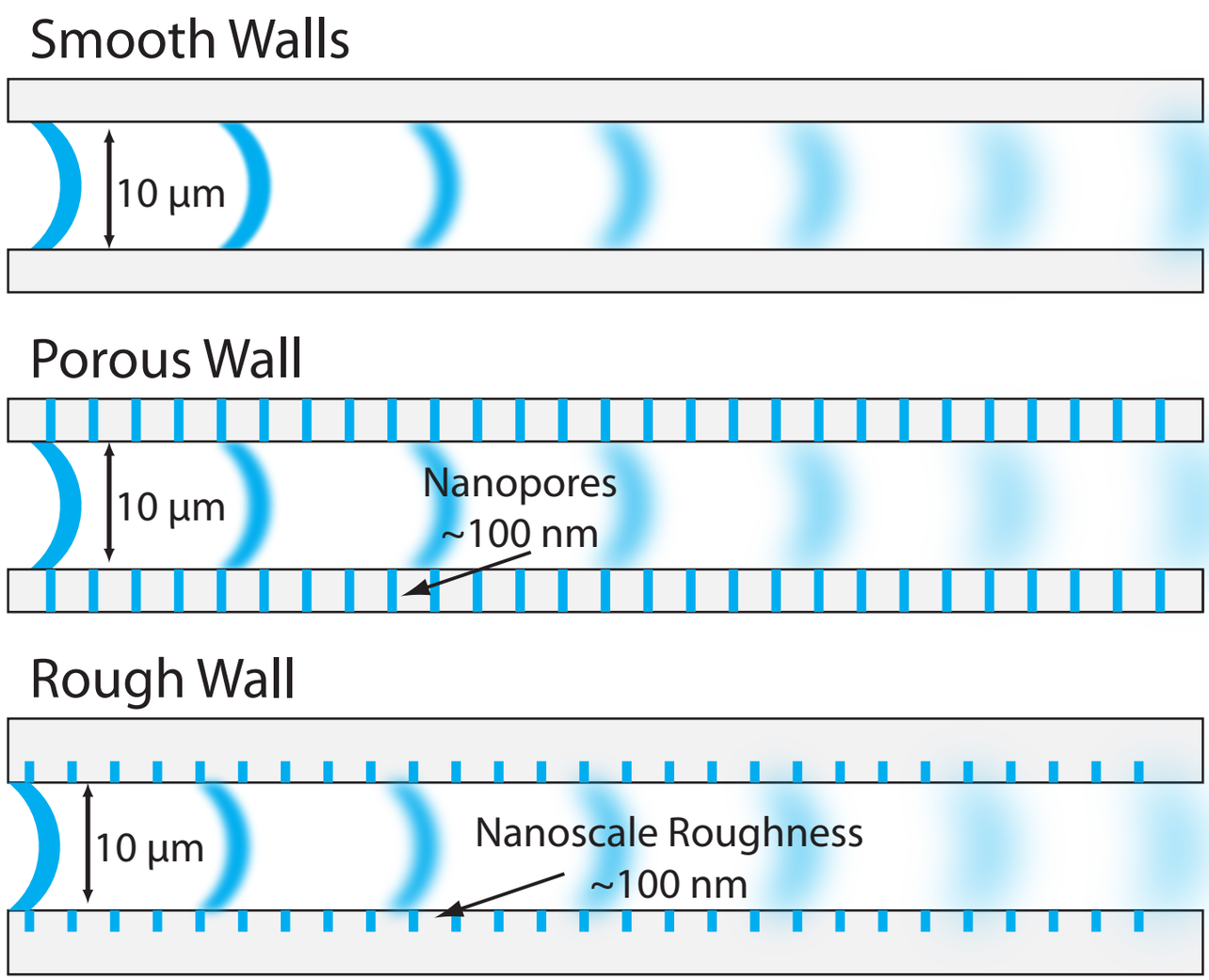


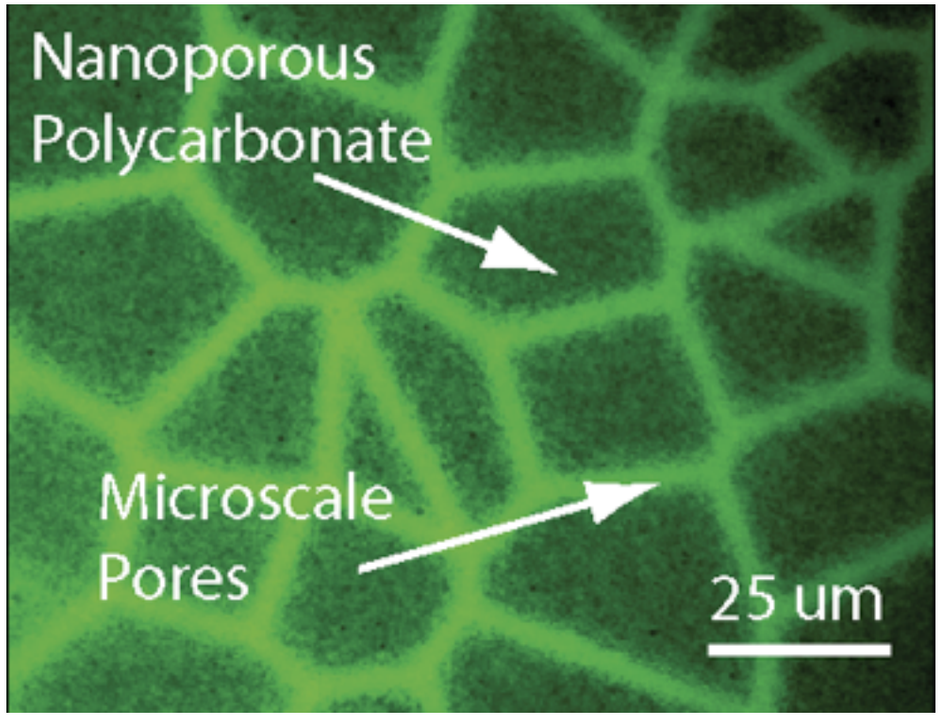


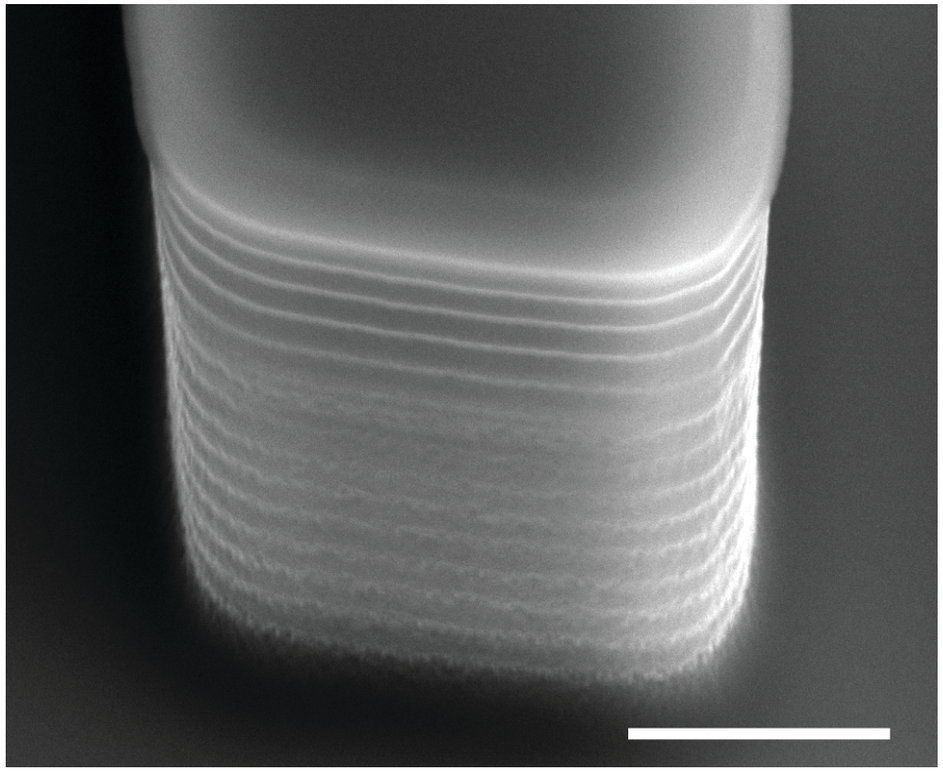
Scale bar = 1 mm

Future work: Transport in nanoscale pores

How do nanoscale features effect solute transport?
Do we see the same multiphase phenomena in pores <10 nm?

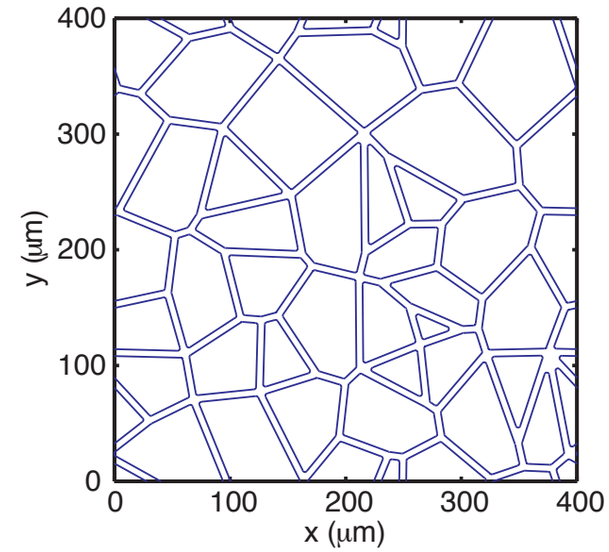




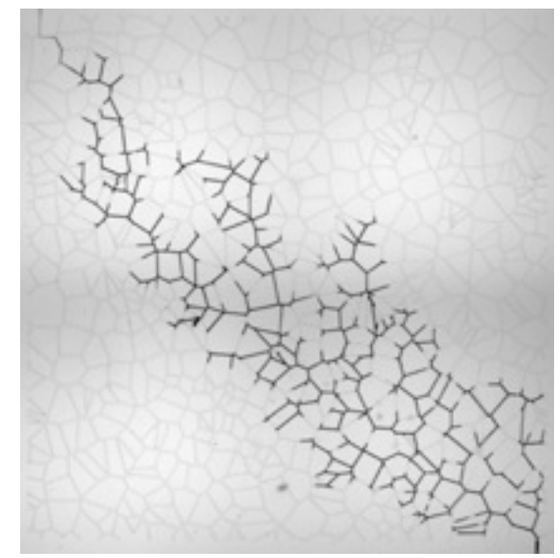


Summary

Novel geometry generation algorithm for stochastic porous media based on Vornoi tessellation



Porosity-permeability correction for heterogeneous media based on conductive porosity



Heterogeneities can alter displacement patterns in drainage, but not imbibition

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Research Partnership to Secure Energy for America

ACS PRF