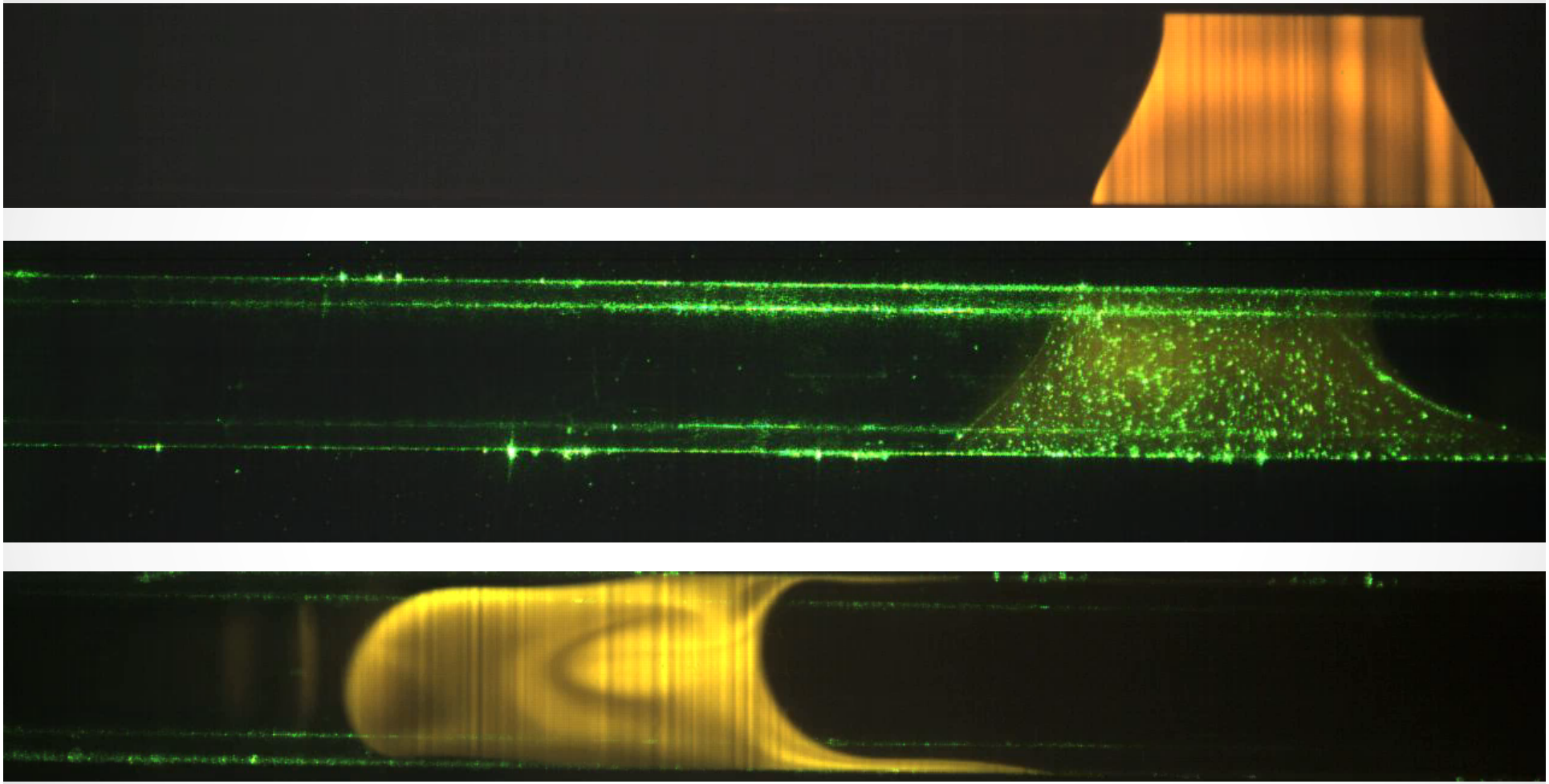


- 孔隙尺度雙相流觀測/強化石油開採

水文與海洋科學研究所
Institute of Hydrological and Oceanic Sciences

孔隙介質雙相流 : 孔隙尺度的觀測與應用
Two-fluids flow in porous media : pore-scale flow visualization and applications

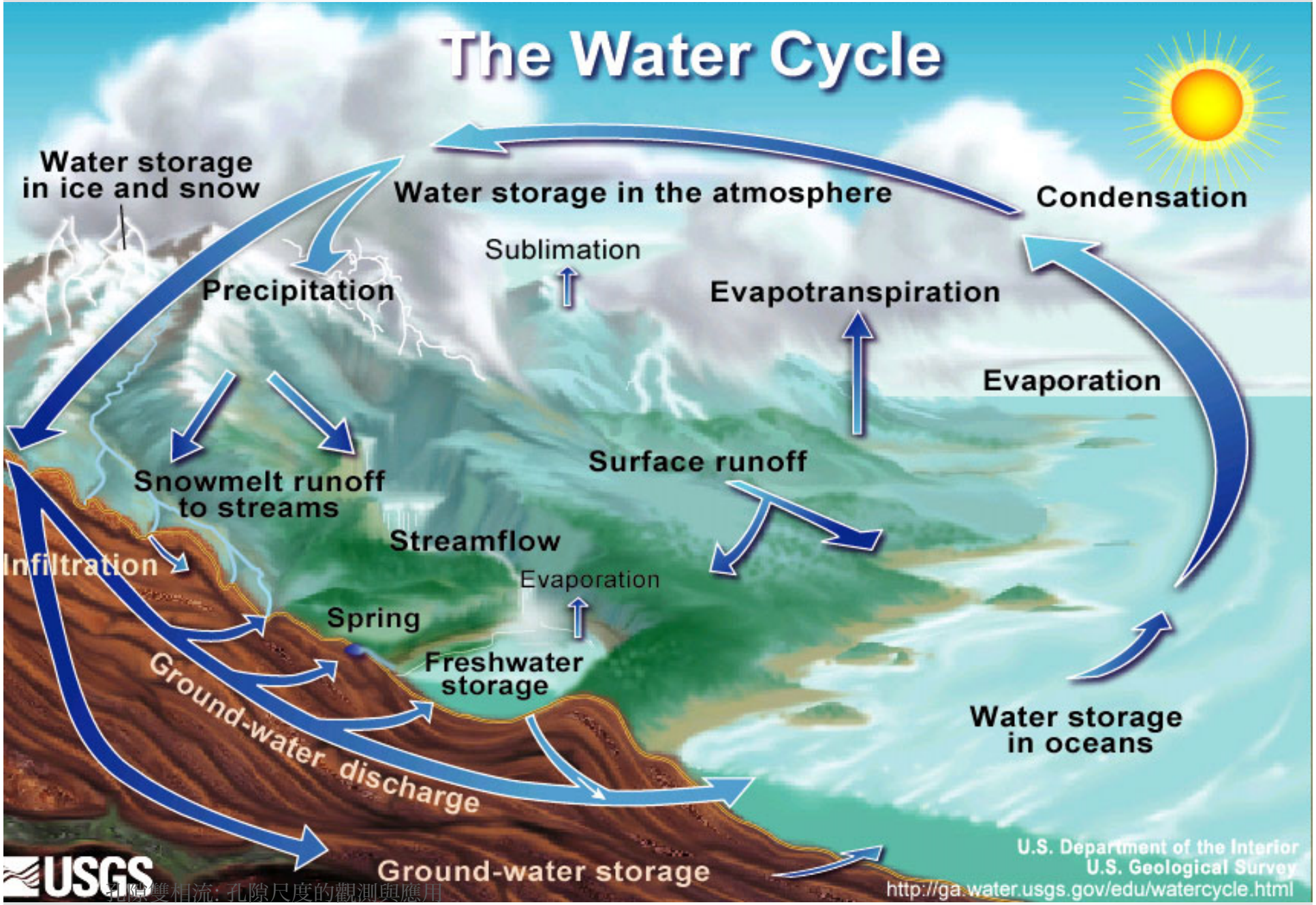
國立中央大學水文與海洋科學研究所
許少瑜

2013 05/24

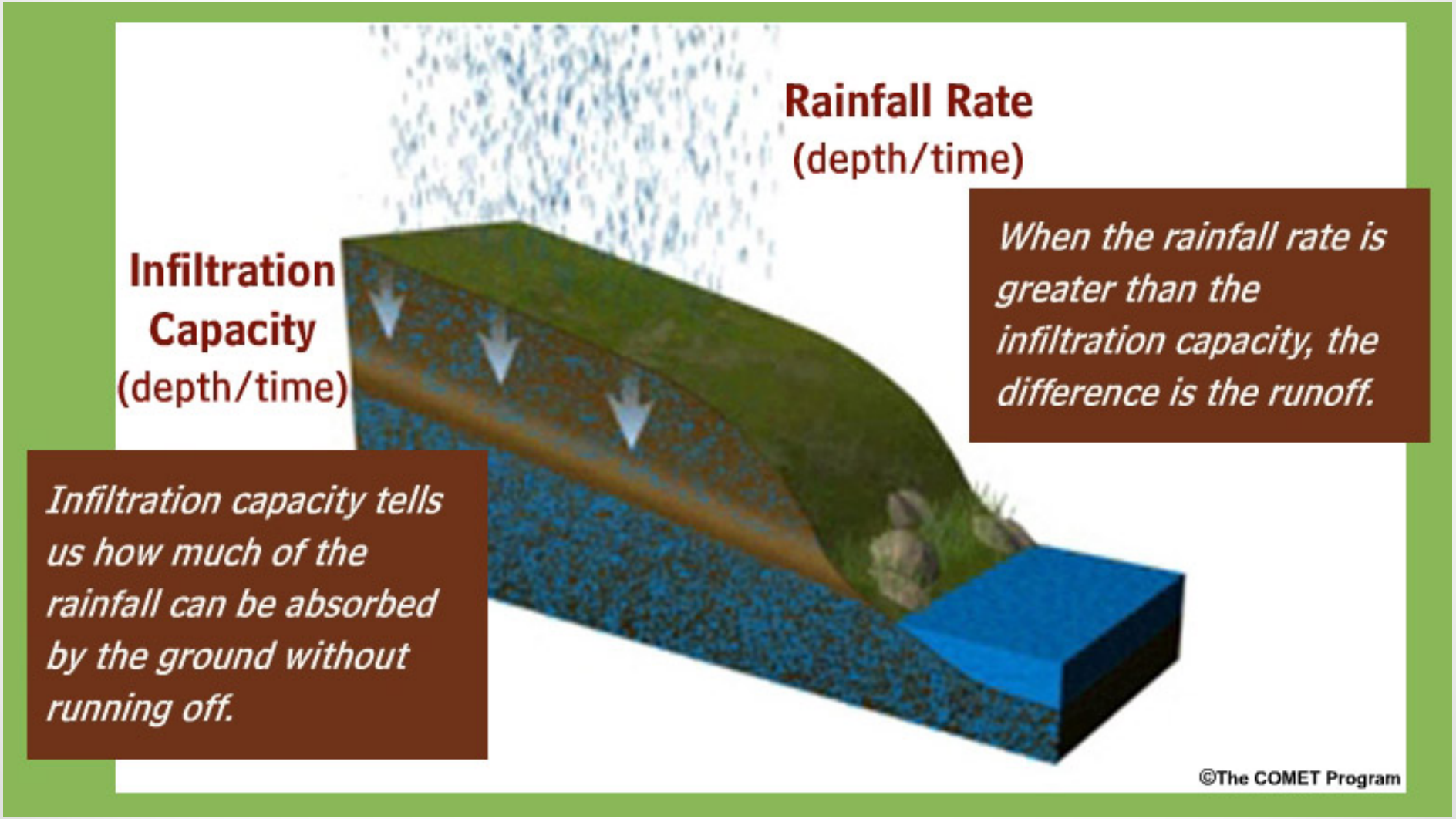
應用地質研究所
Graduate Institute of Applied Geology

地球科學學系暨
地球物理研究所

水文與海洋科學研究所
Institute of Hydrological and Oceanic Sciences


The Water Cycle
Water storage in ice and snow
Water storage in the atmosphere
Condensation
Sublimation
Precipitation
Evapotranspiration
Evaporation
Surface runoff
Snowmelt runoff to streams
Streamflow
Infiltration
Evaporation
Spring
Freshwater storage
Ground-water discharge
Water storage in oceans
Ground-water storage
USGS
U.S. Department of the Interior
U.S. Geological Survey
http://ga.water.usgs.gov/edu/watercycle.html

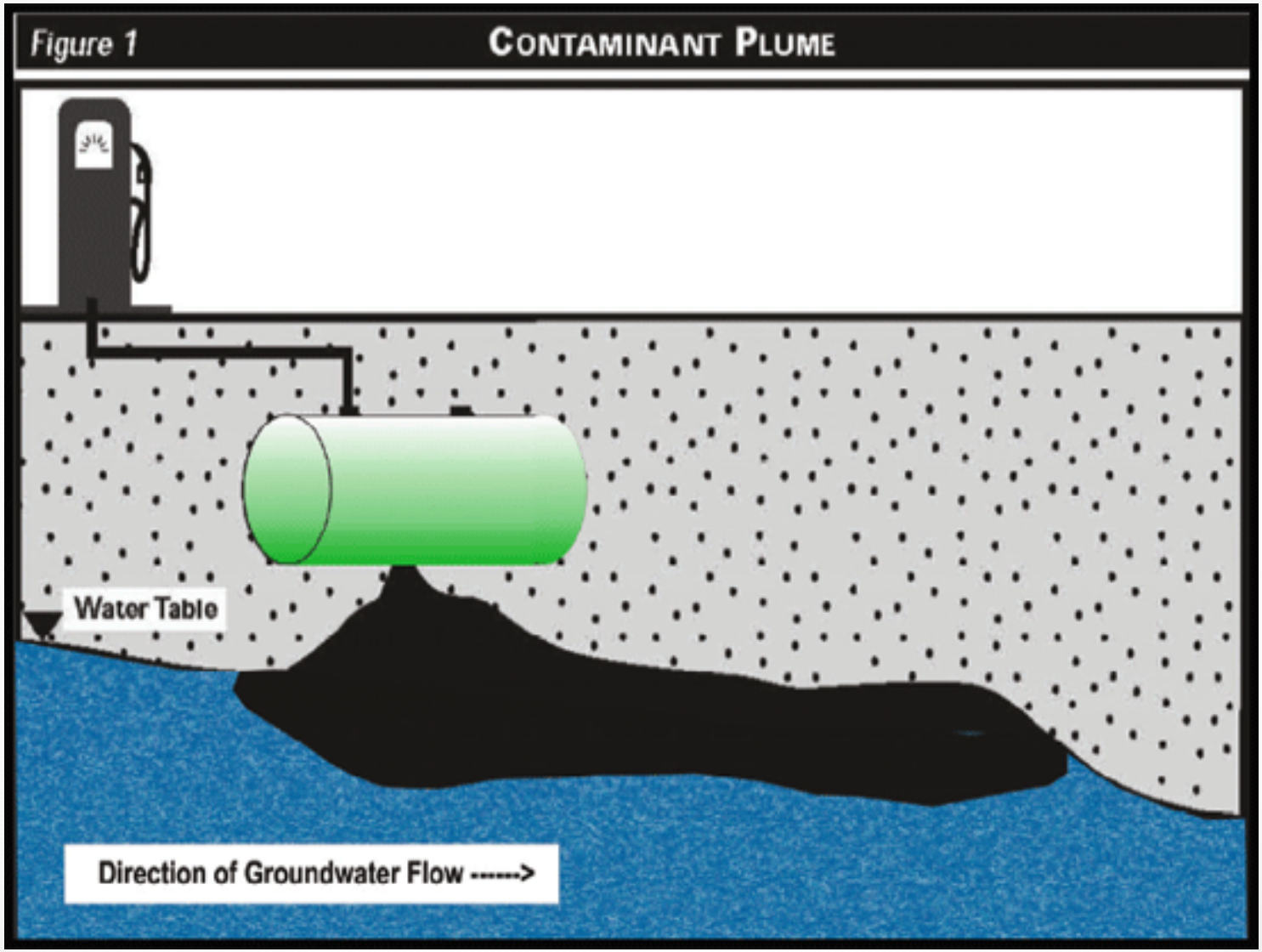
Infiltration



Preferential flow in during infiltration

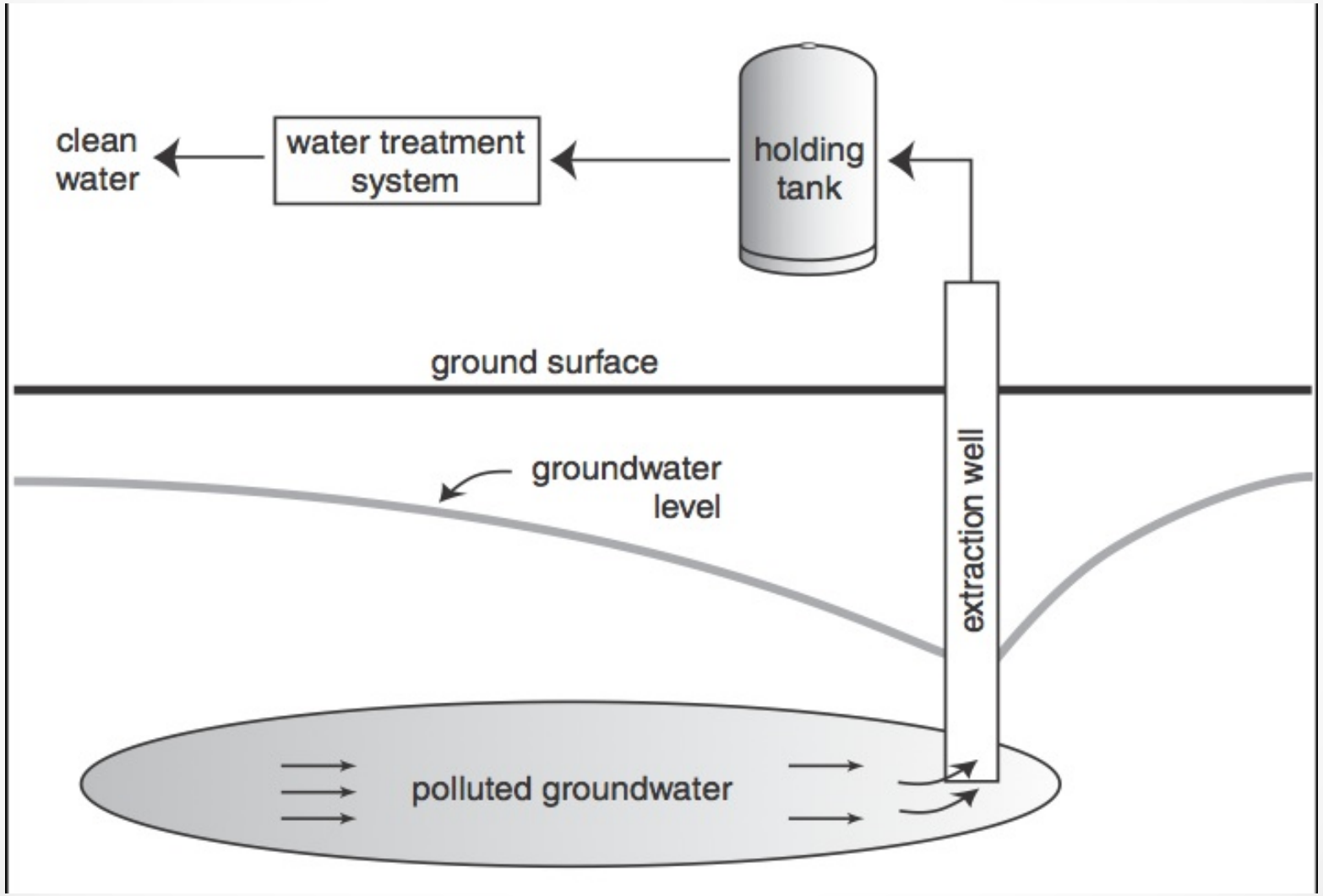
Cornell (BEE)

Groundwater contamination



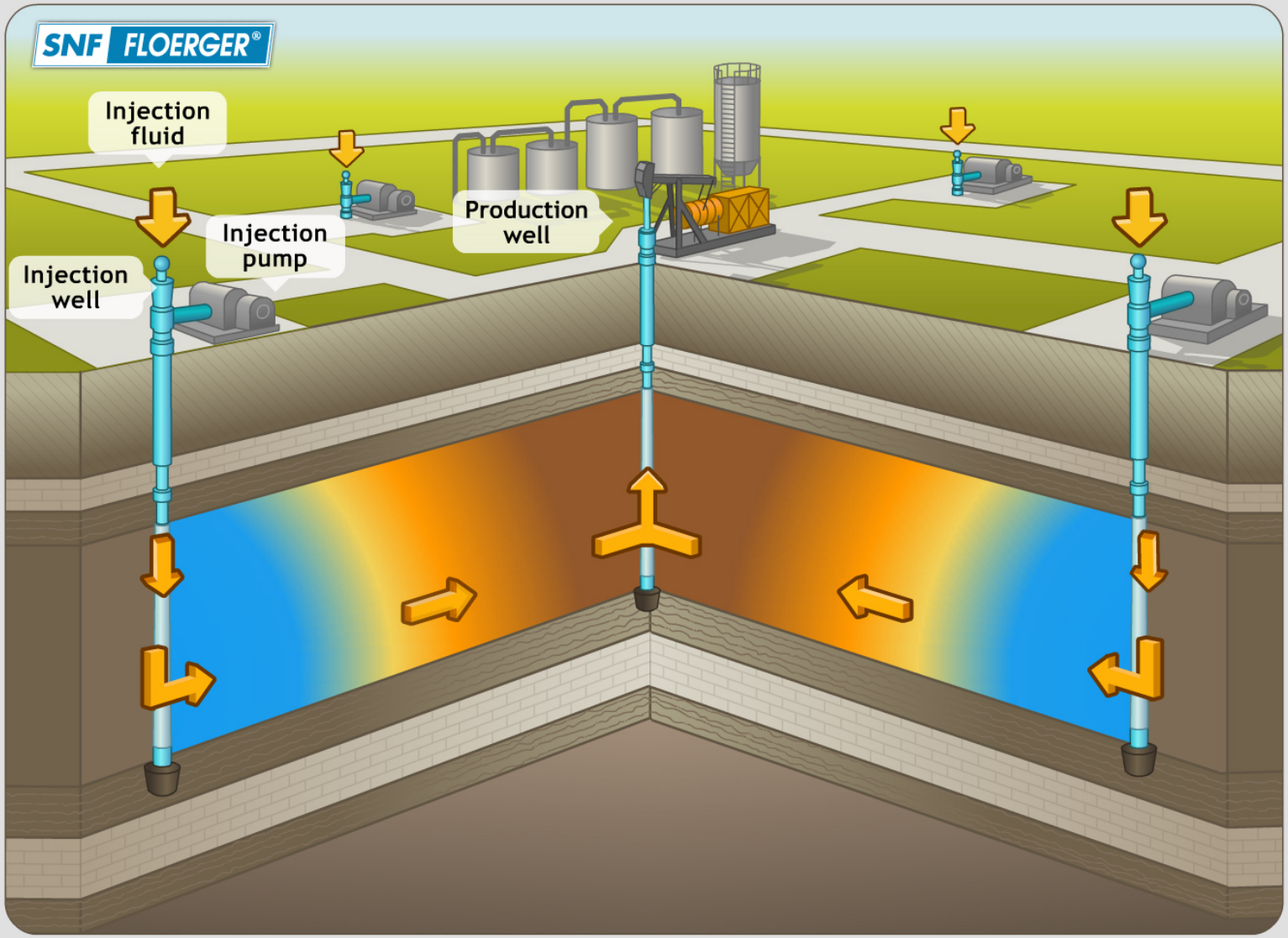
(http://www.wrd.org/engineering/groundwater-contamination.php)

Groundwater remediation



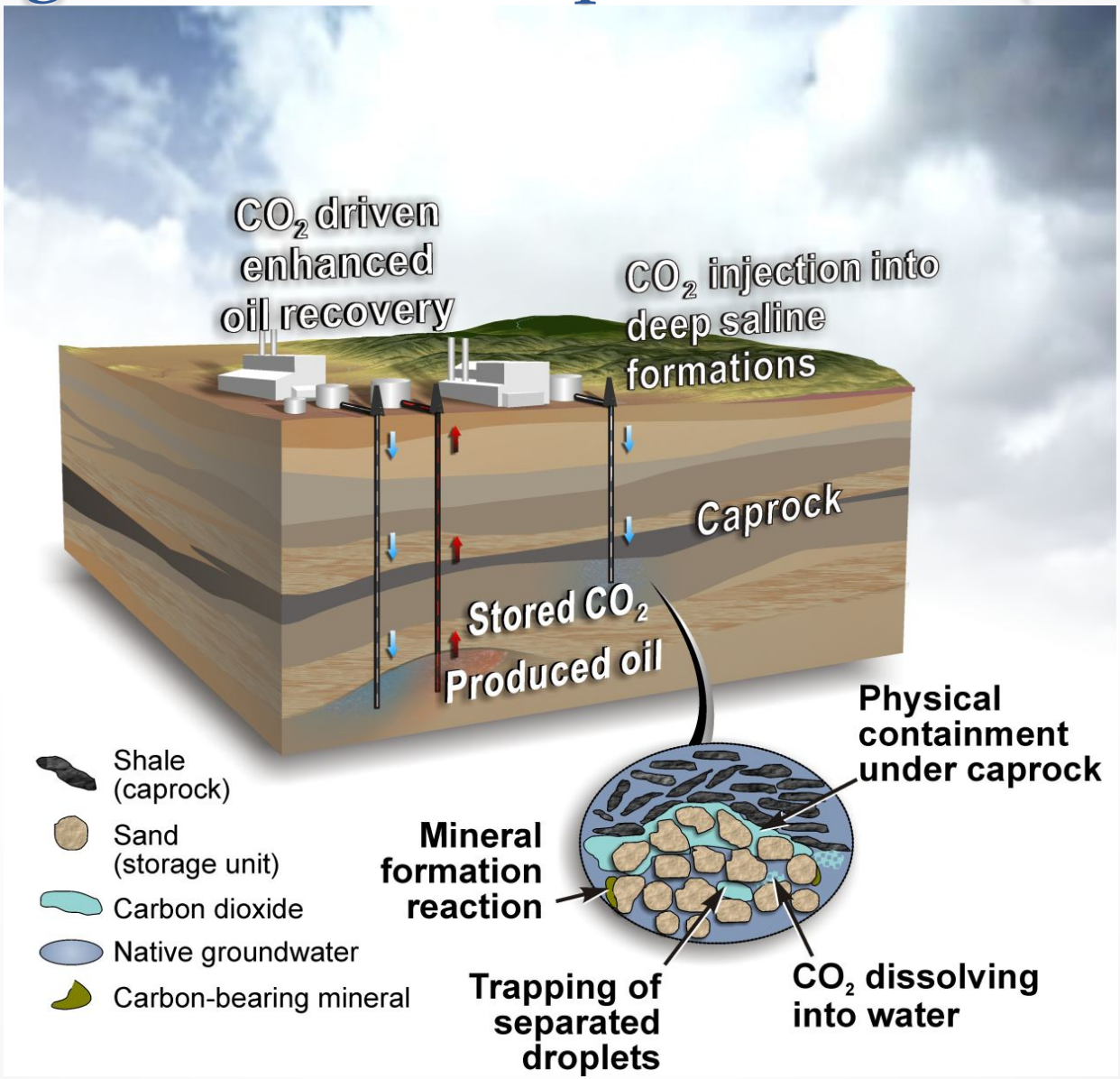
http://remediation.voices.wooster.edu/

(Enhanced) Oil Recovery (EOR)



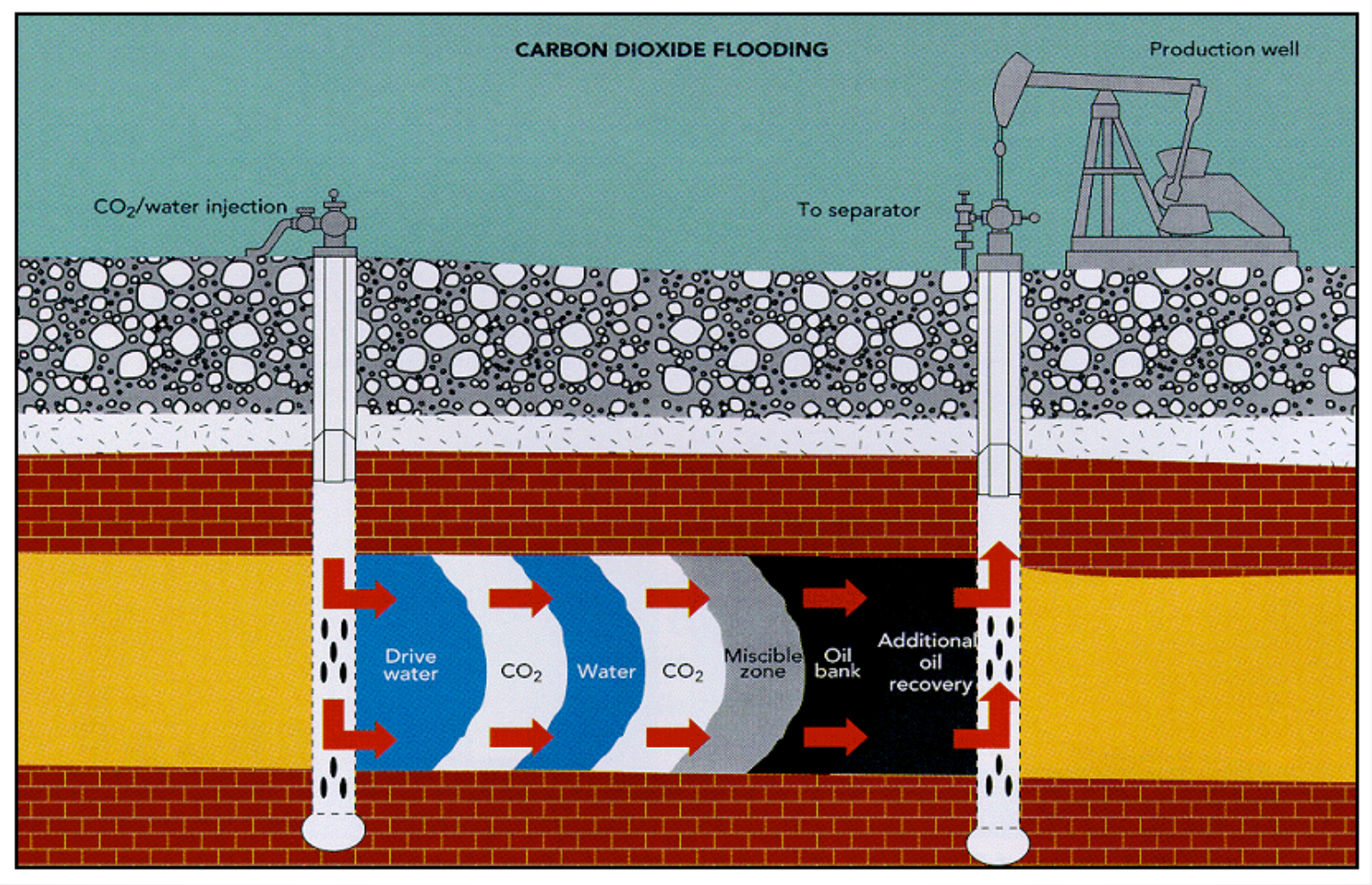
http://www.snf-oil.com/

Geologic Carbon Sequestration (GCS)



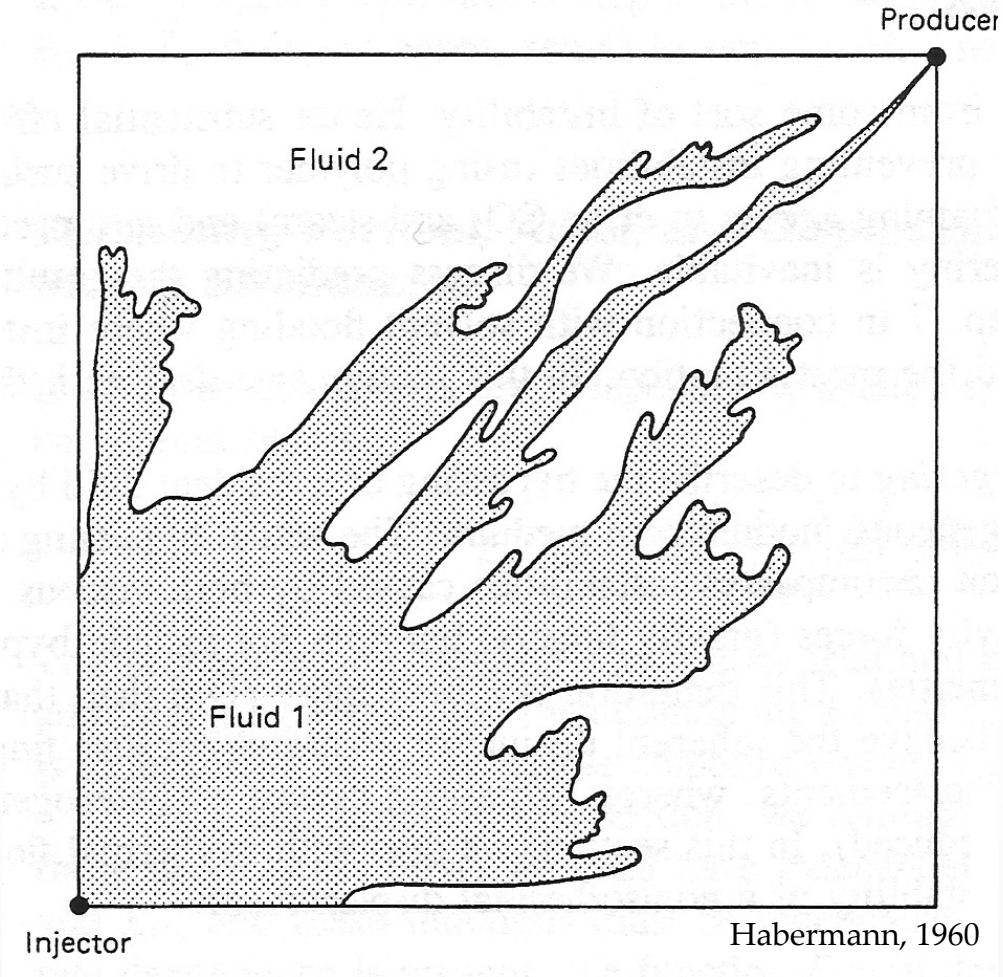
http://dbsa.sks.com/

EOR X GCS

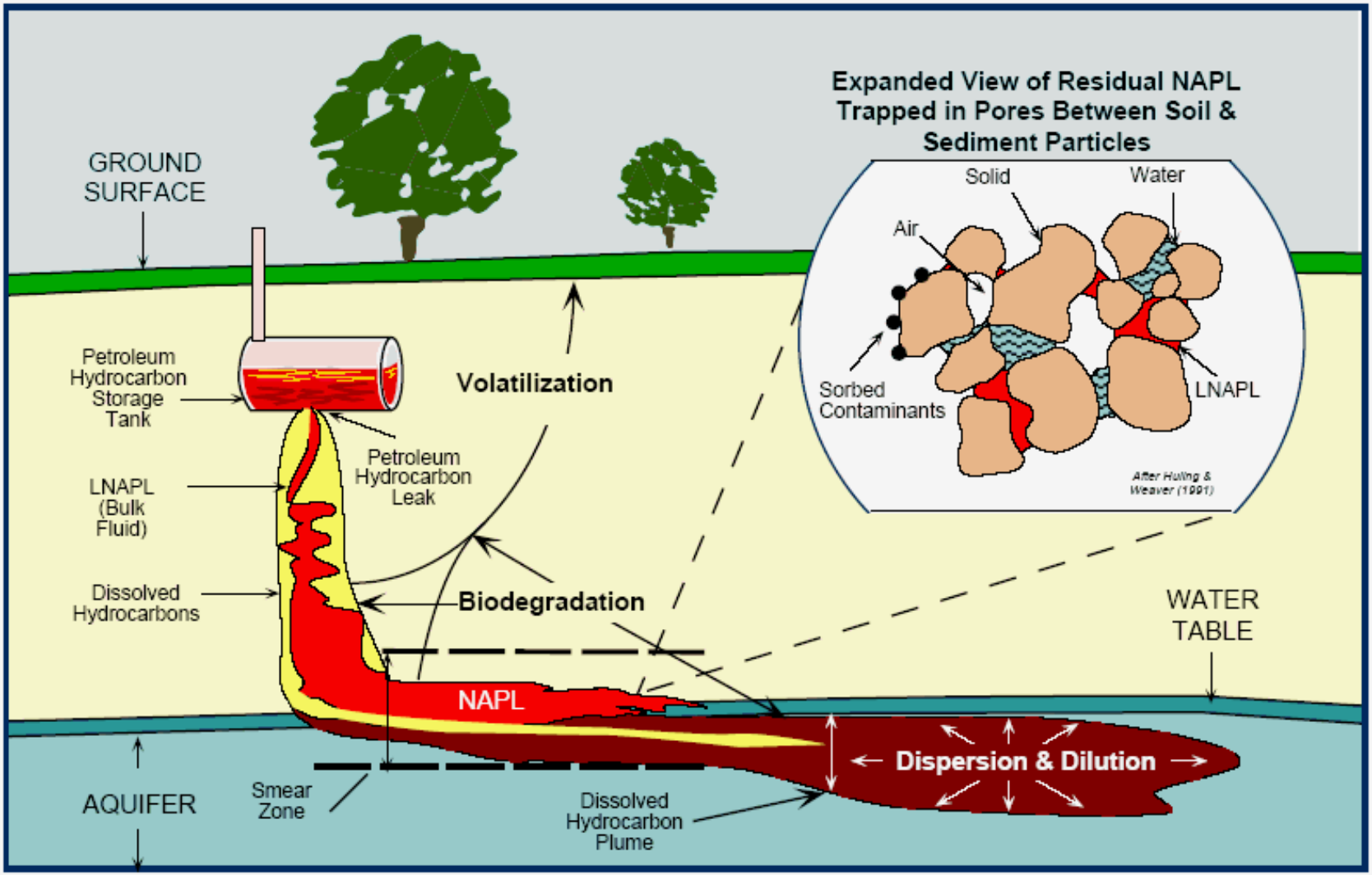


Univ. of Kansas

Viscous Fingering flow

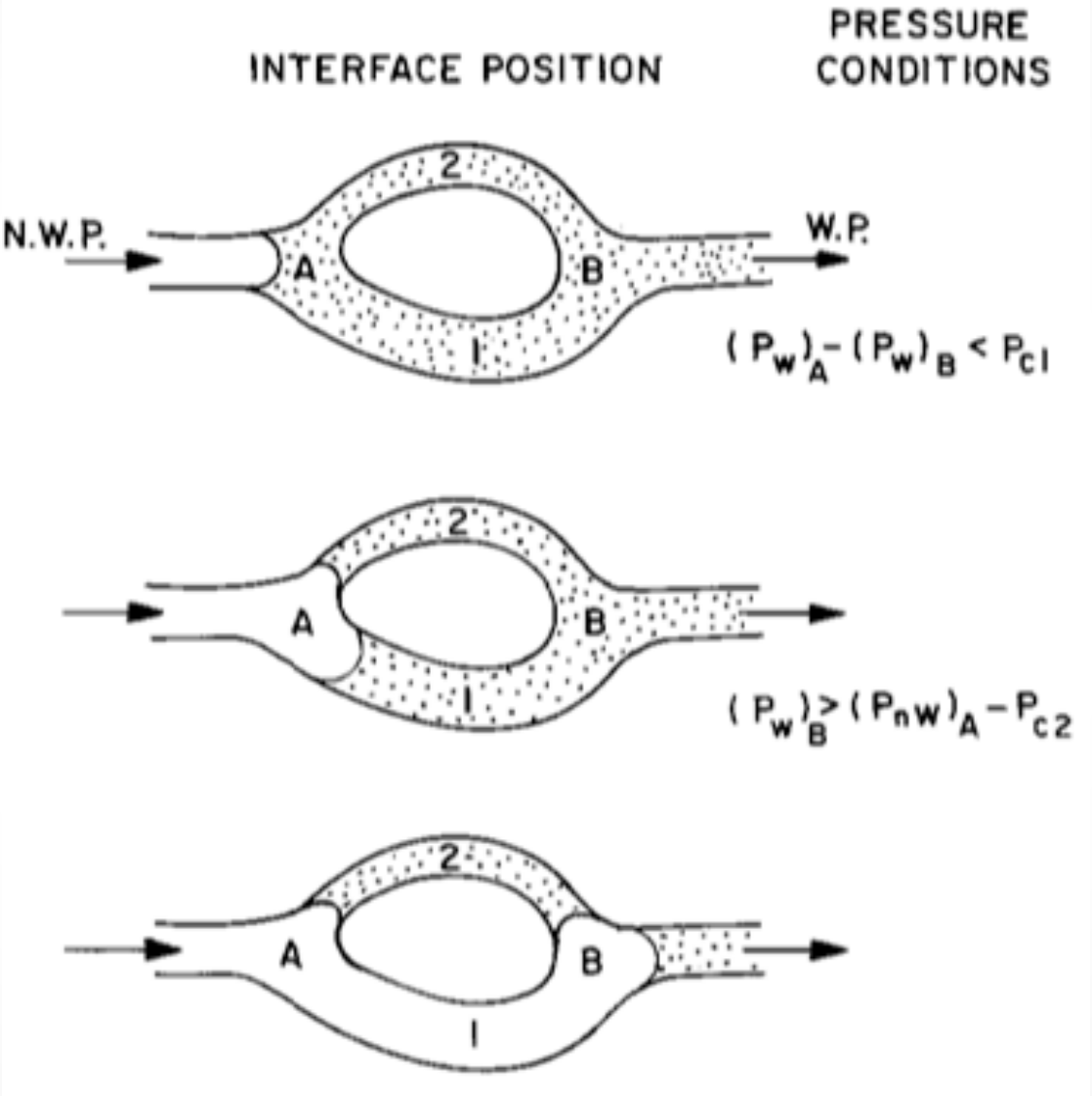


Residual NAPL Blob



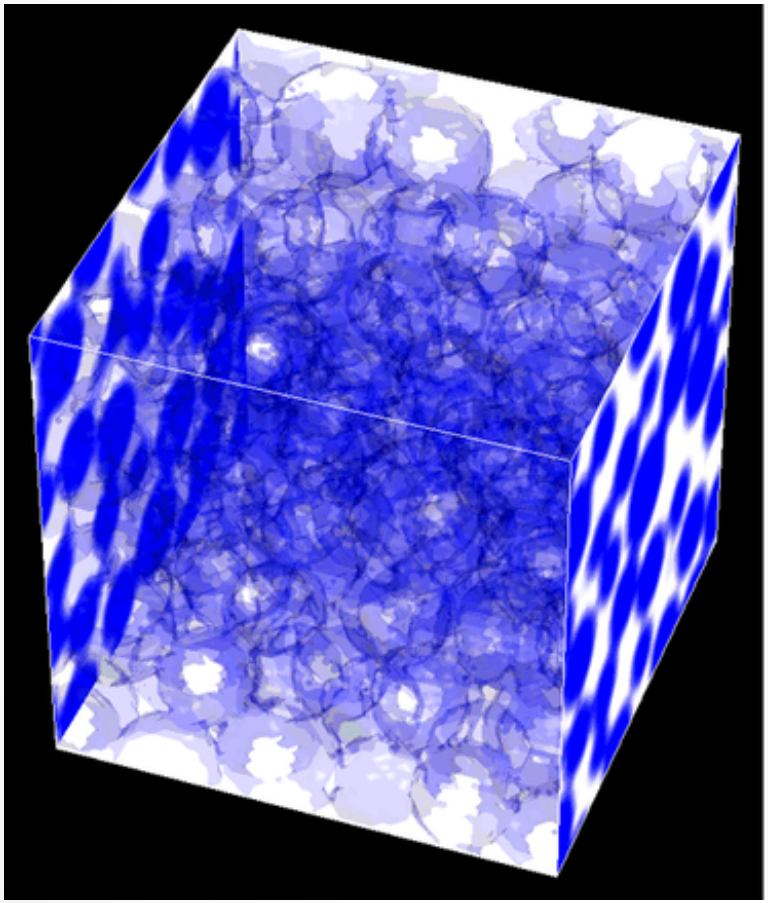
NAPL: non-aqueous phase liquid (Texas A&M Univ.)

Residual NAPL blob



(Dullien)

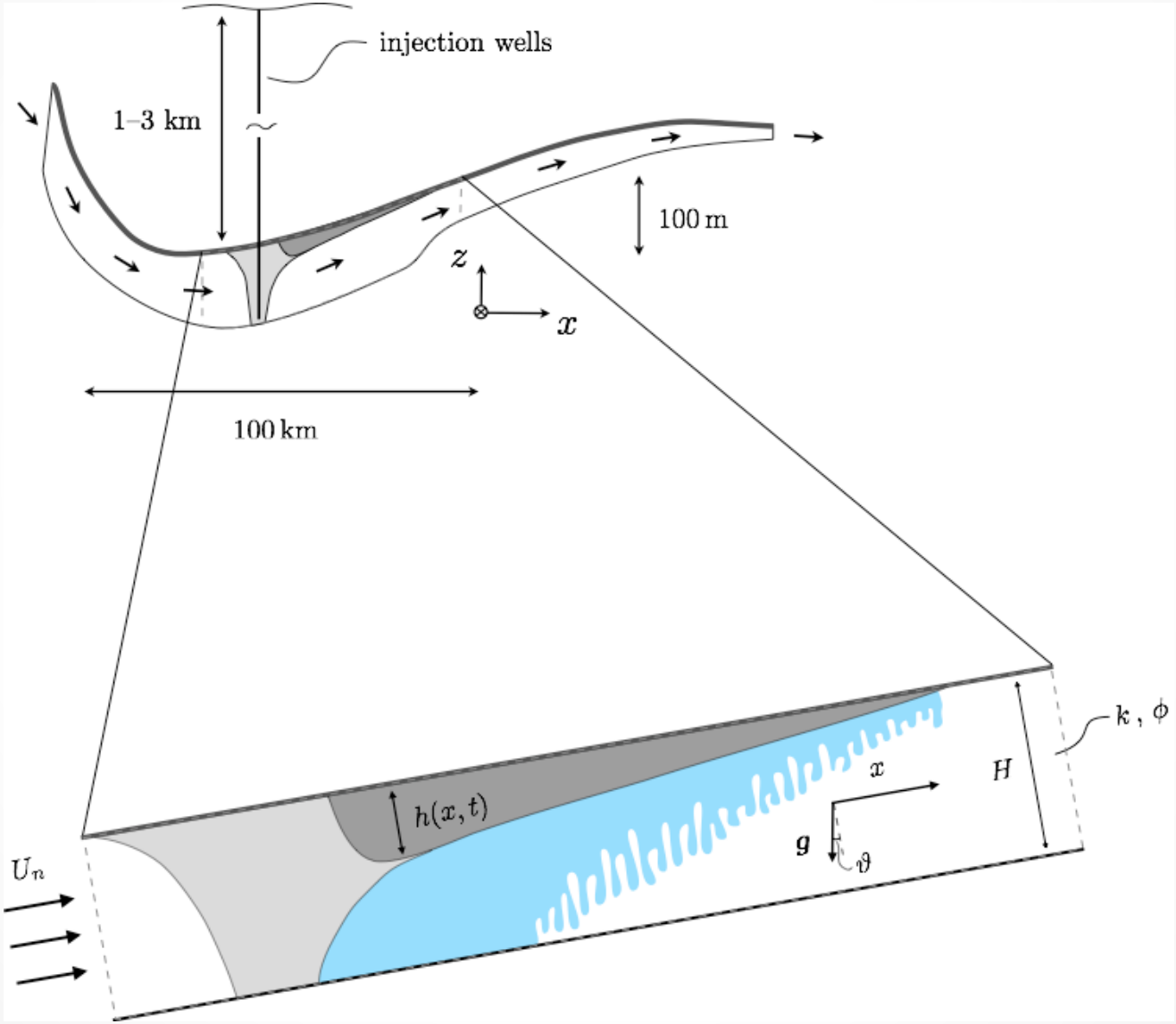
NAPL trapping



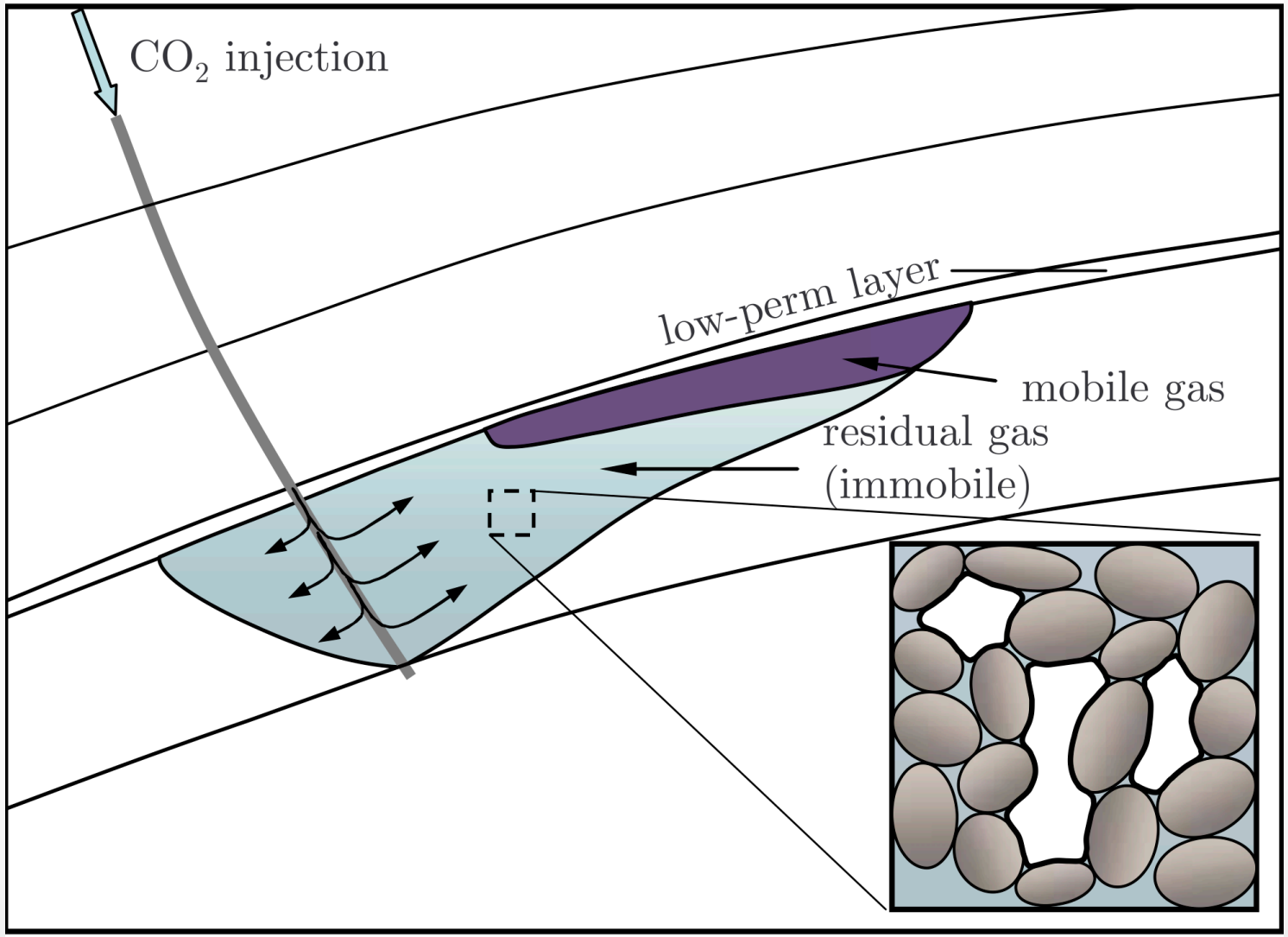
Mixing from fingering flow

JRG

Mixing from fingering flow (GCS)

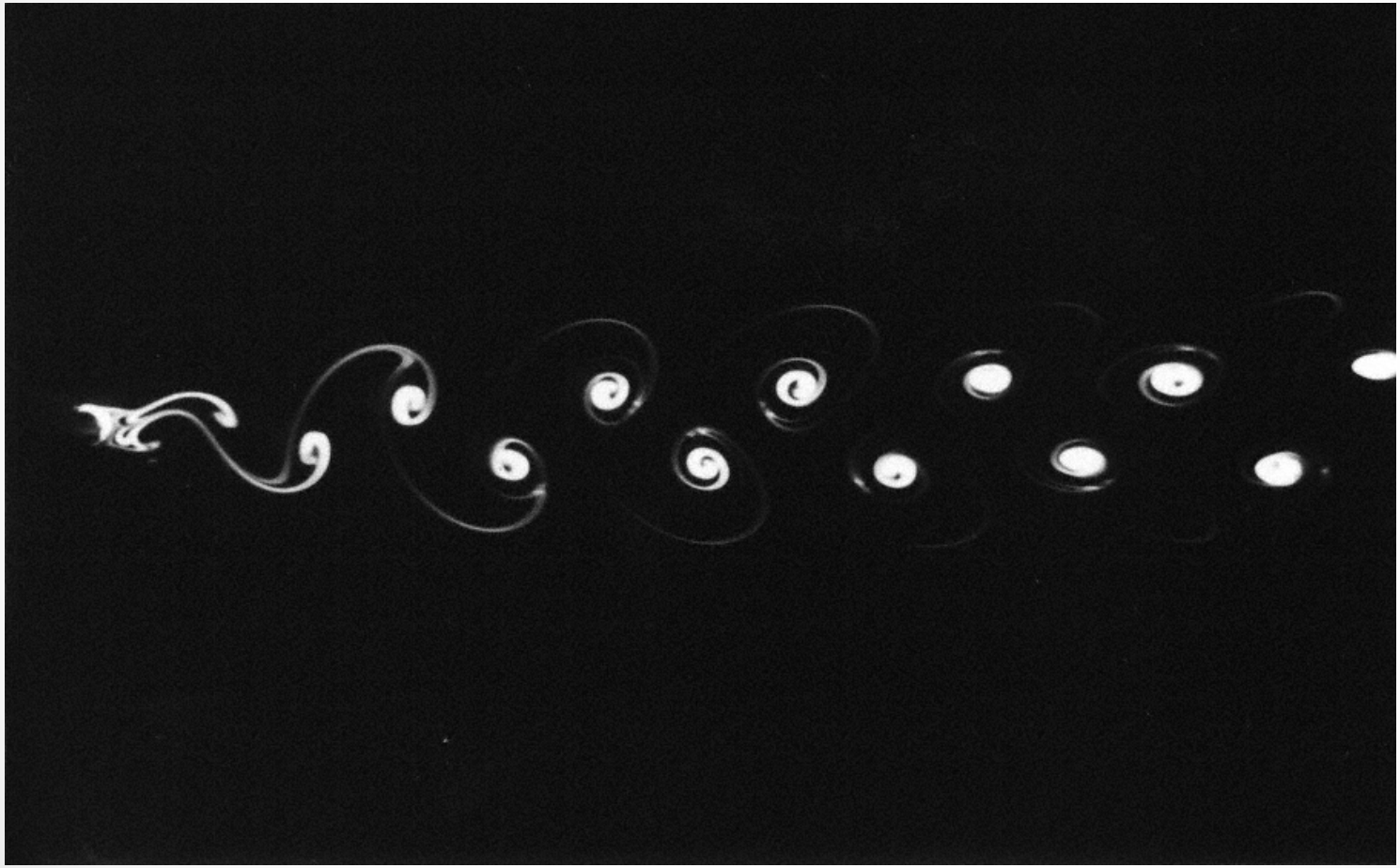


Capillary trapping (GCS)



Juanes et al., 2006

Flow visualization



von Karman vortex, Taneda (RE=105)

Flow visualization

von Karman vortex (Tristan da Cunha island), NASA, 2010

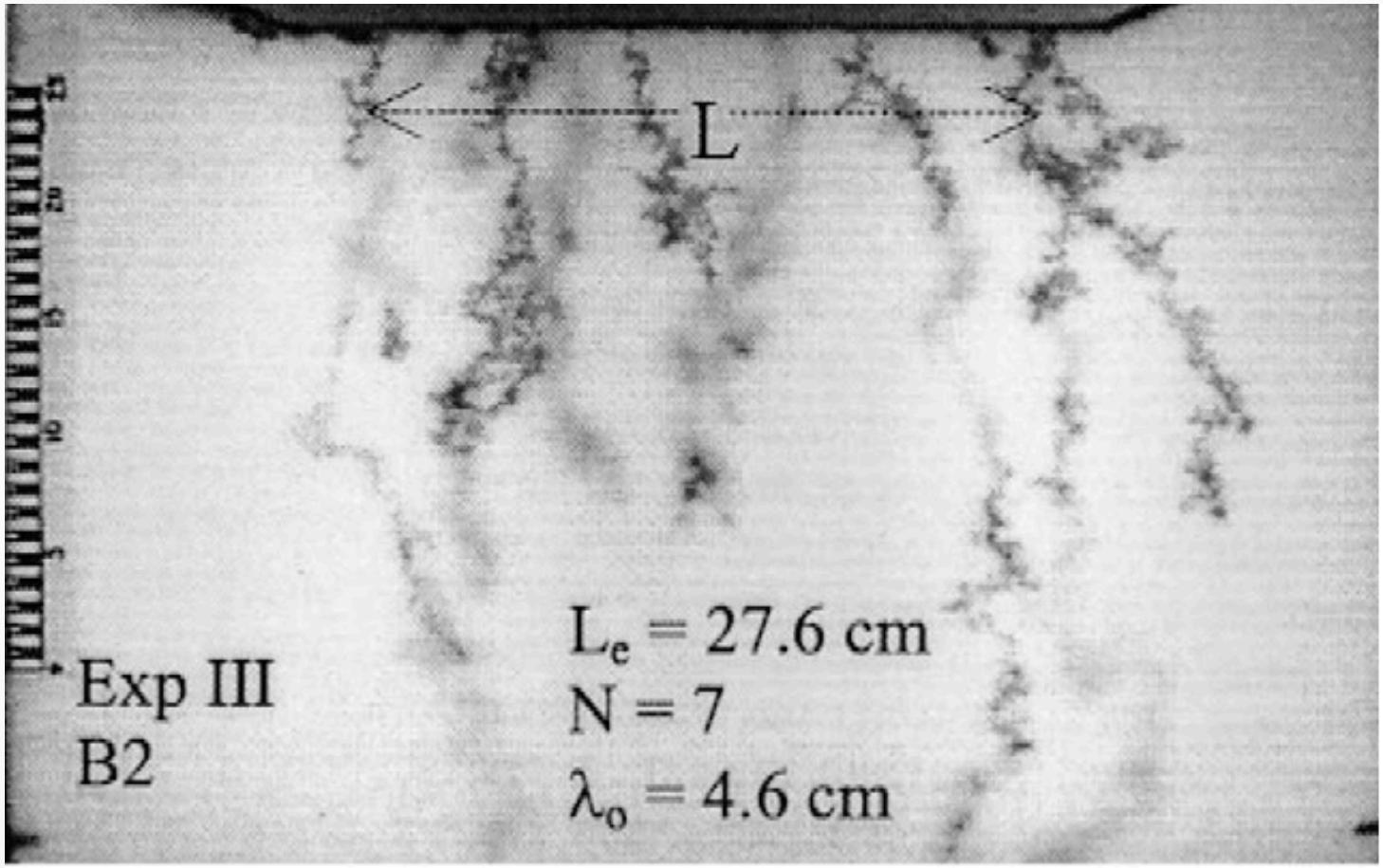
Outline

- 2D flow visualization
  - 2D Sand box
  - 2D monolayer glass beads (Hele-shaw cell)
  - Micromodel
- 3D flow visualization
  - Micro X-ray computed tomography
  - Refractive index matching (RIM)
  - Planar laser-induced fluorescence (PLIF) and RIM
- Applications
  - Fingering flow
  - Residual NAPL

2D sand box (Darcy scale)

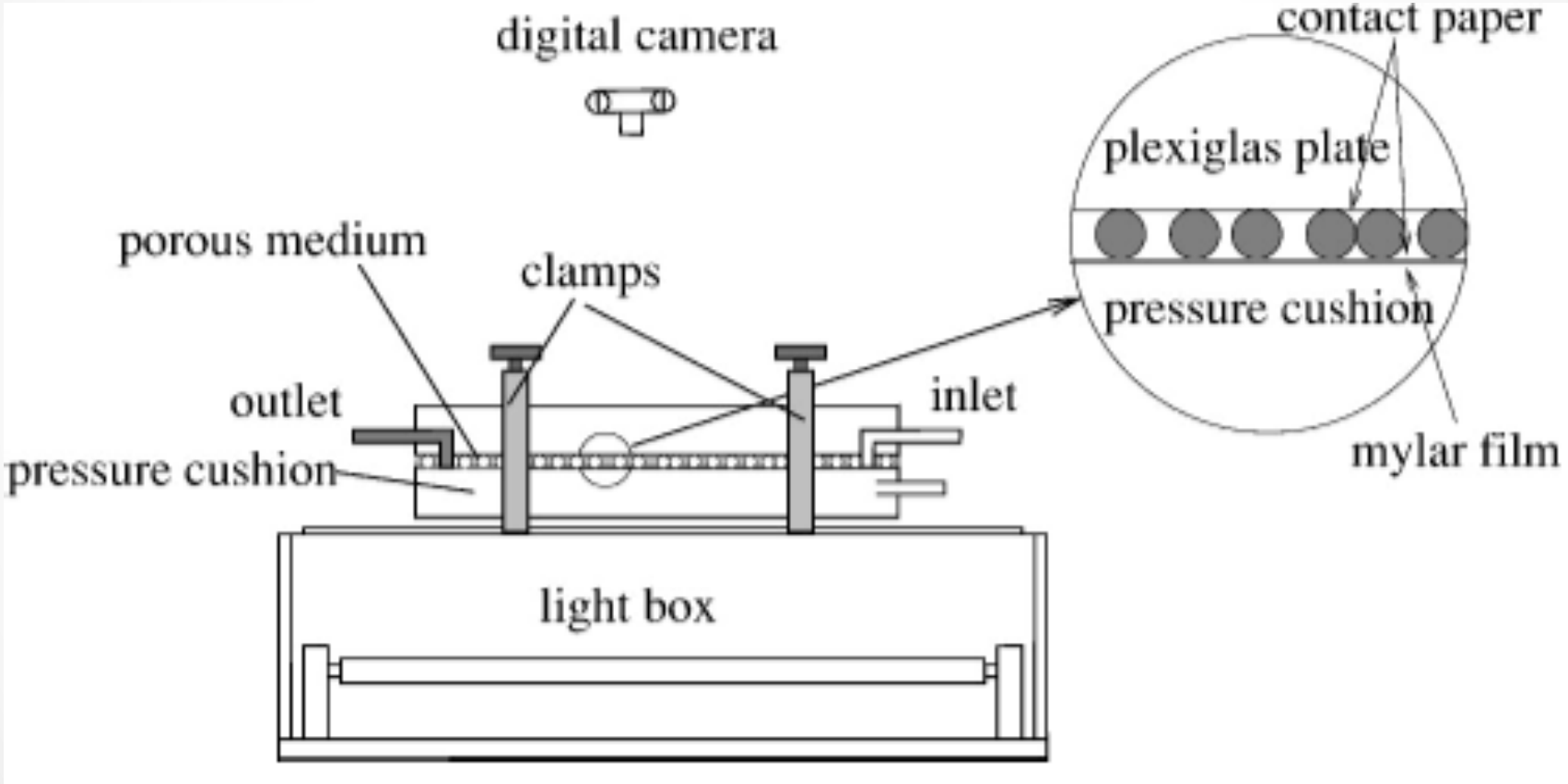
地下水模擬與分析實驗室, NCU

2D glass-bead box (fingering)



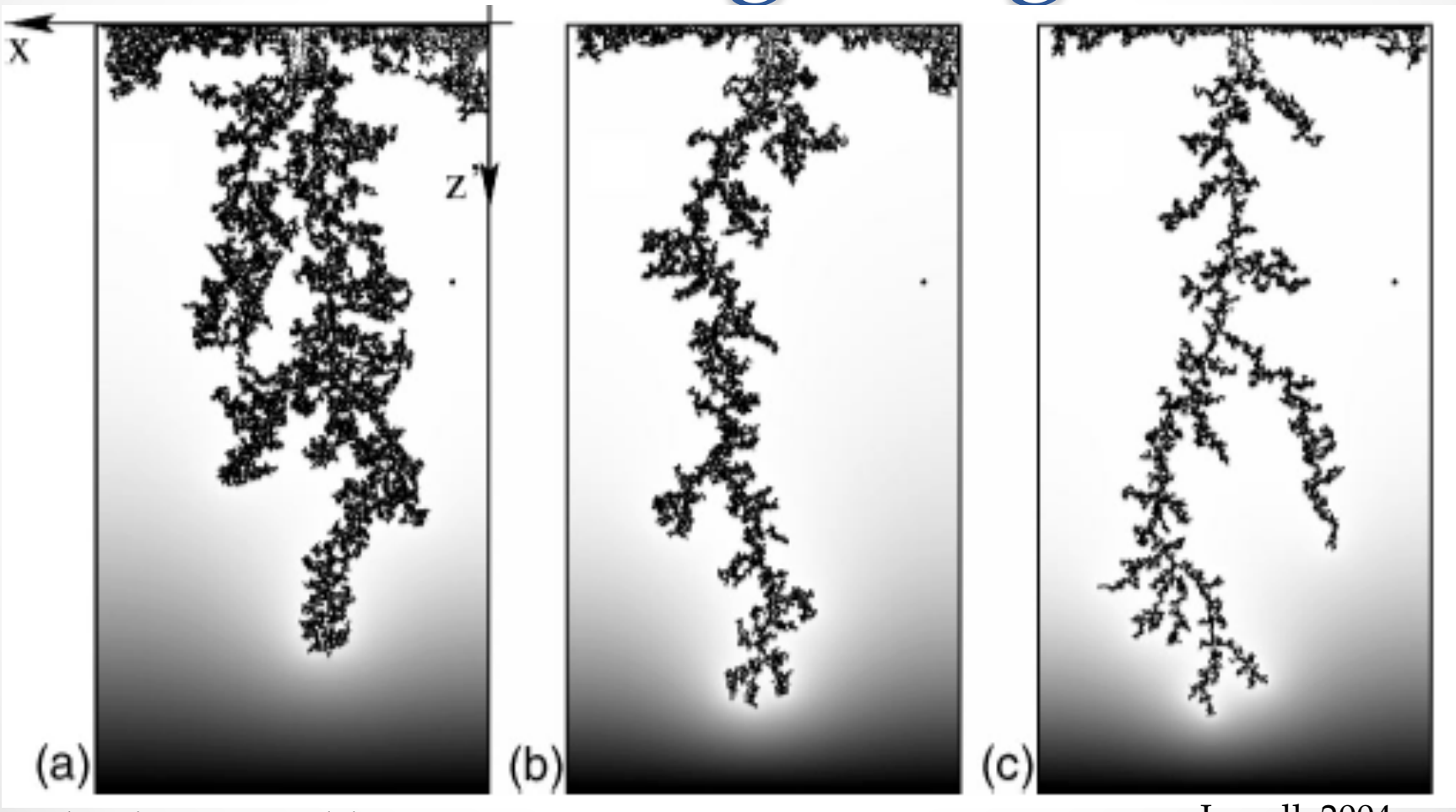
Smith, 2001

2D Hele-Shaw cell



Løvoll, 2004

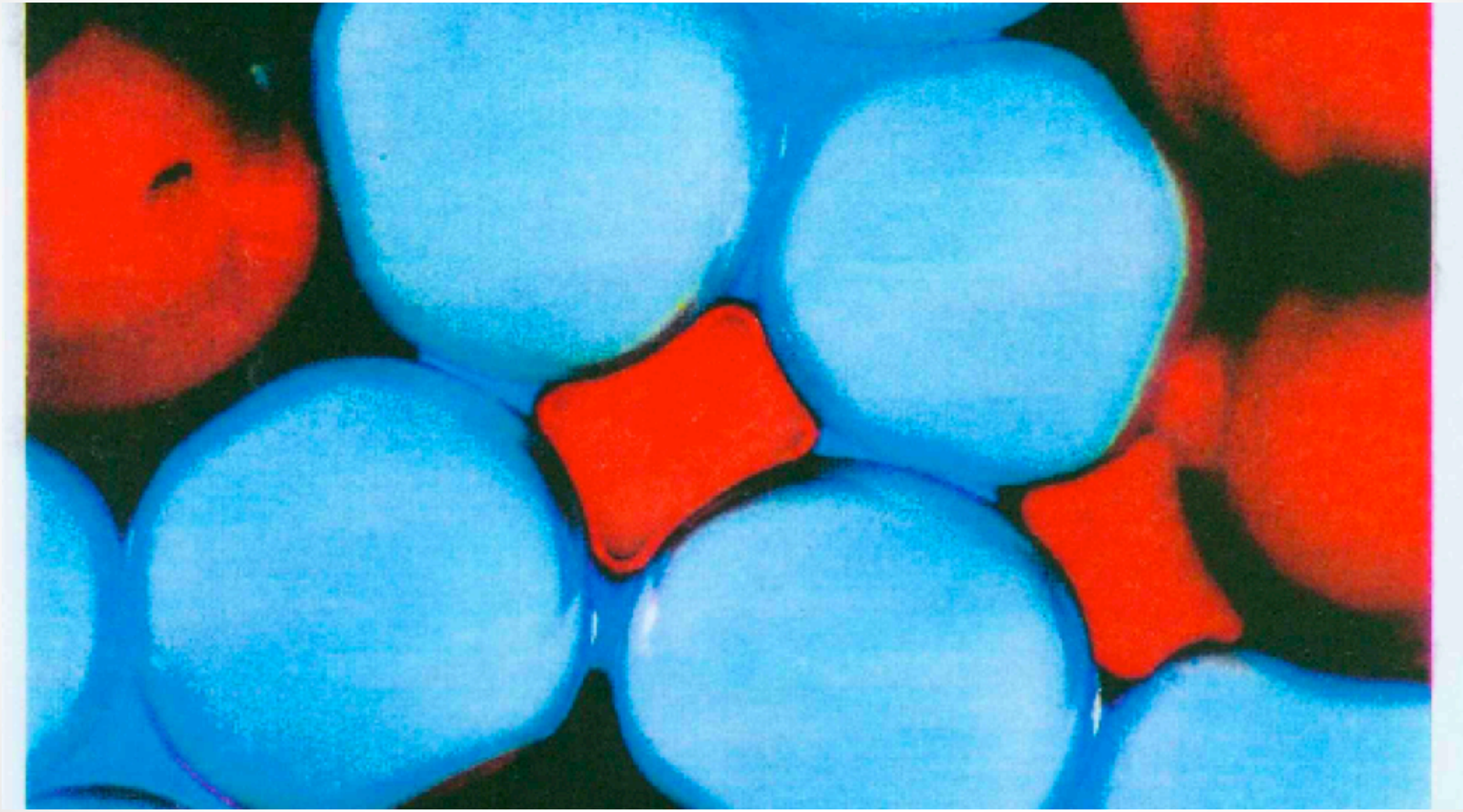
2D fingering



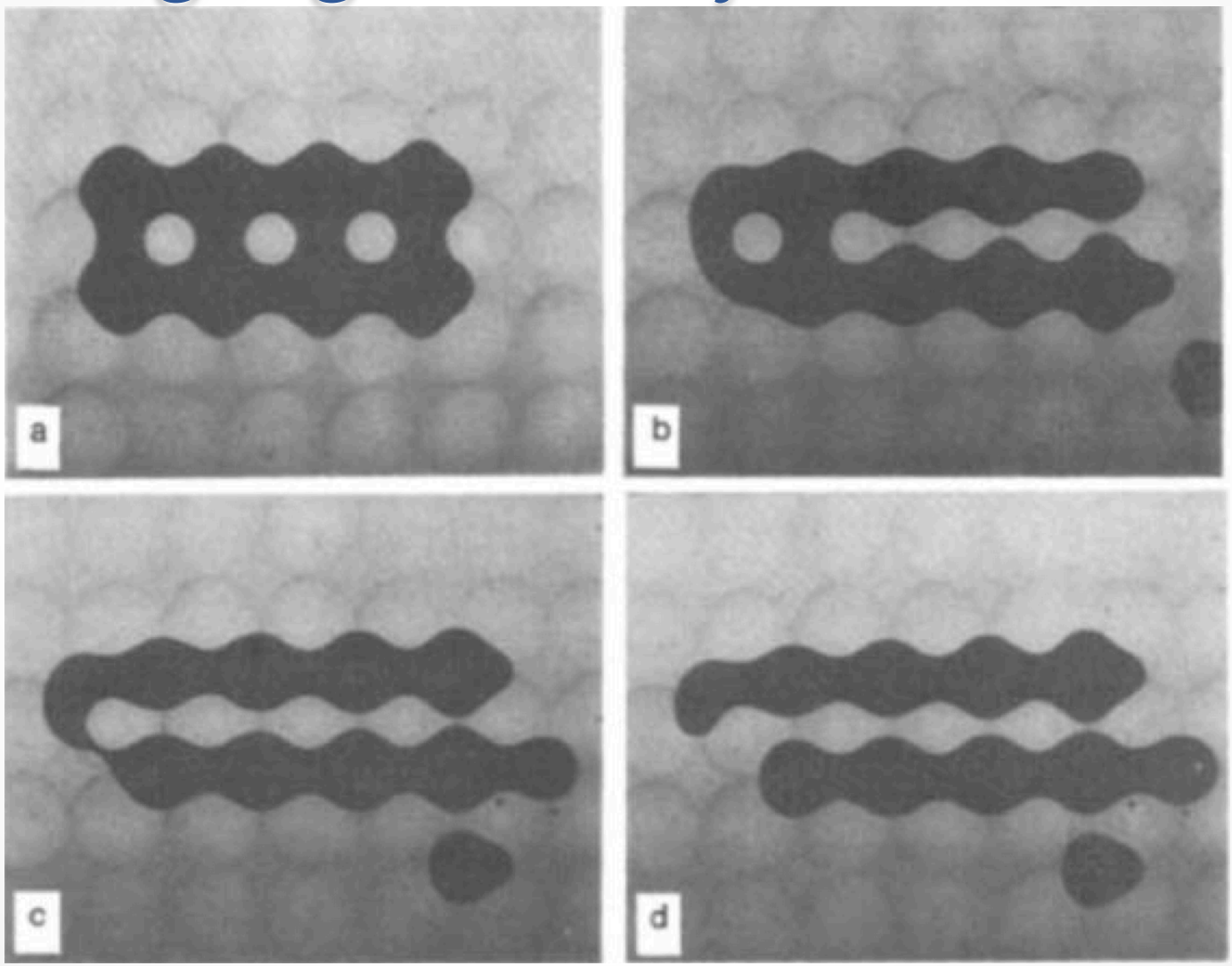
1(depth)x215(width) mm

Løvoll, 2004

Residual NAPL blob



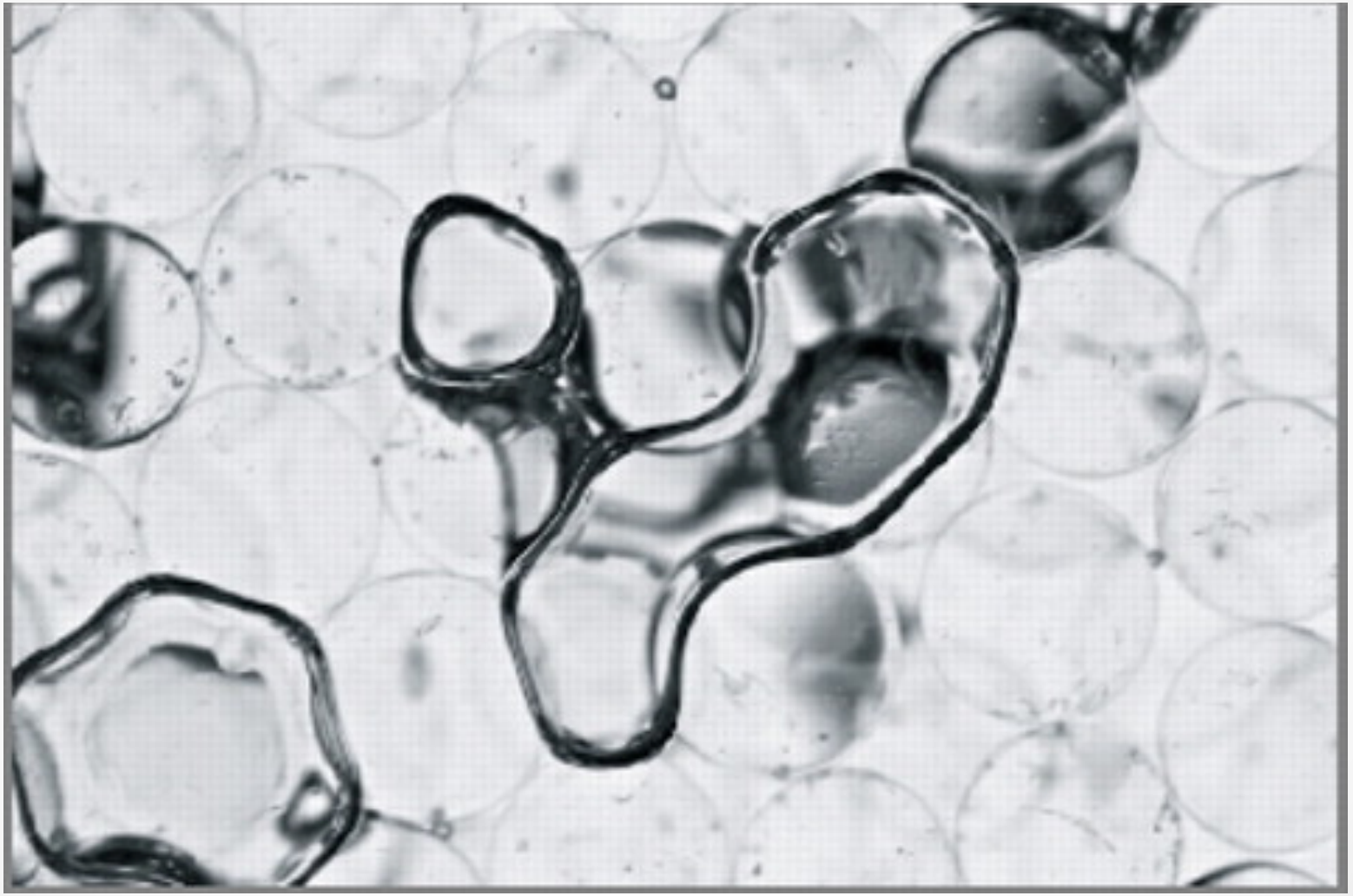
An oil ganglion in dynamic motion



3-mm–diameter glass beads

Hinkley, 1981

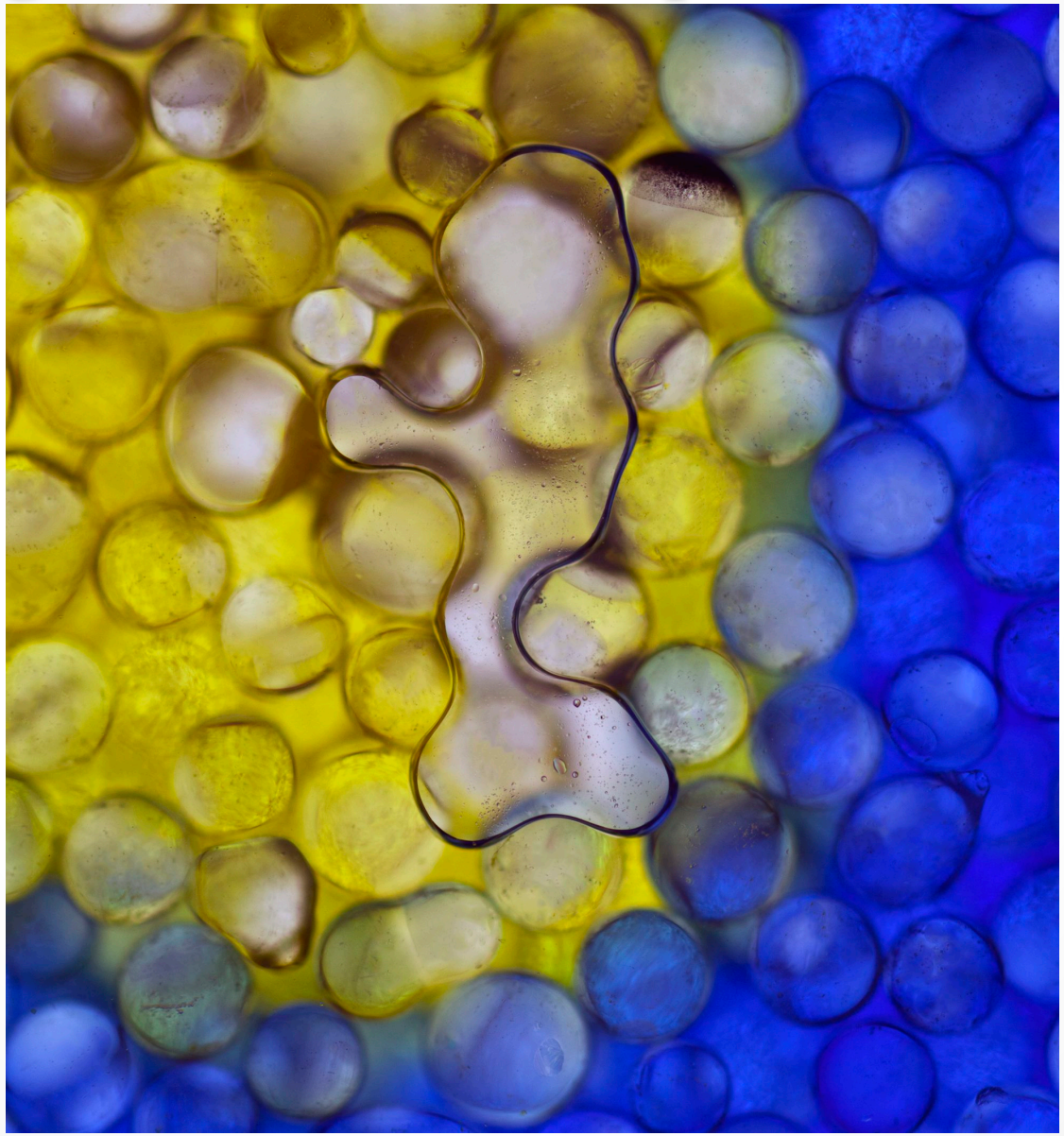
Residual CO_2 gas bubble



0.5-mm–diameter glass beads

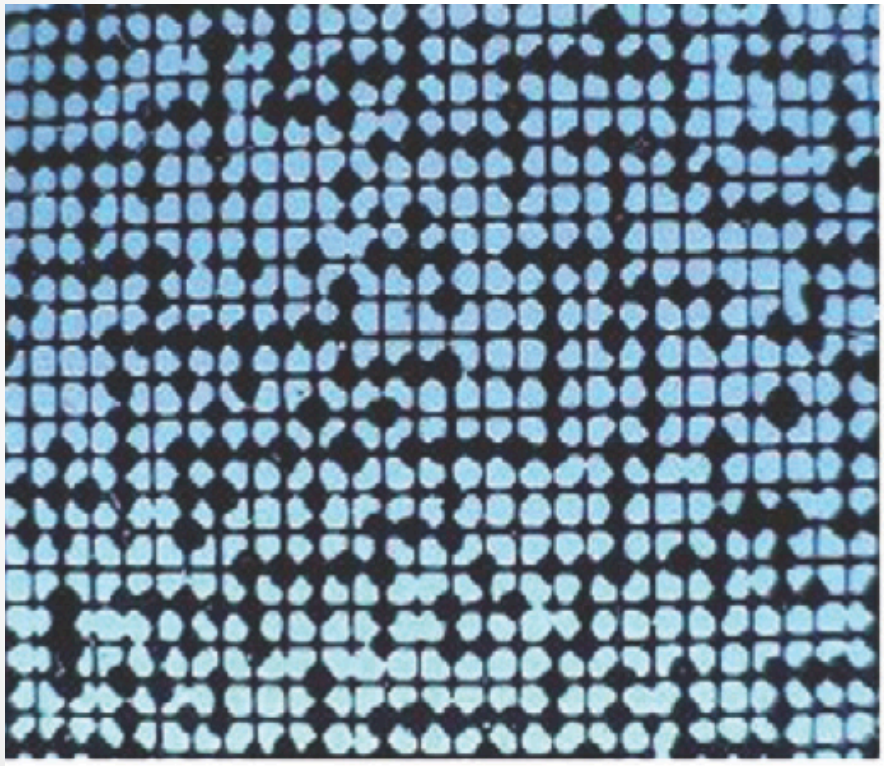
Szulczewski et al., 2012

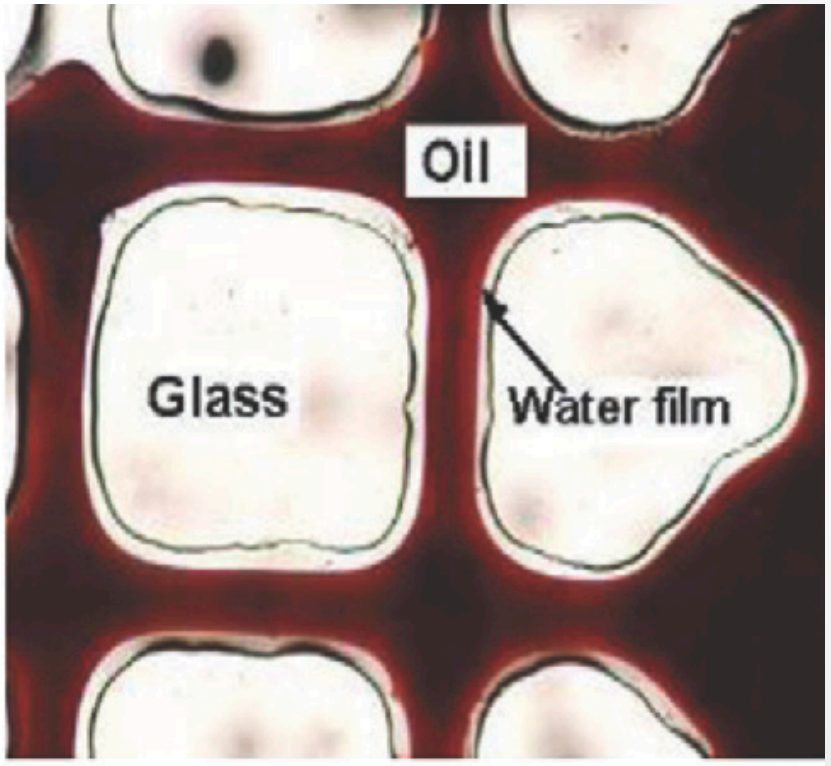
CO_2 gas bubble with pH indicator



Michael L. Szulczewski. 2012 (PNAS cover image)

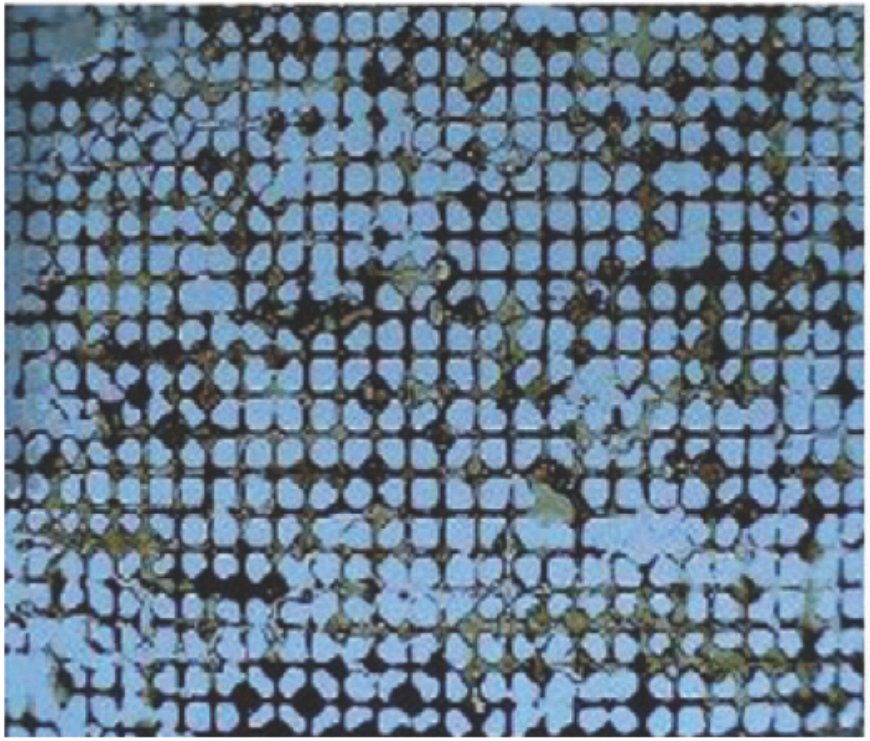
Micromodel – oil/water

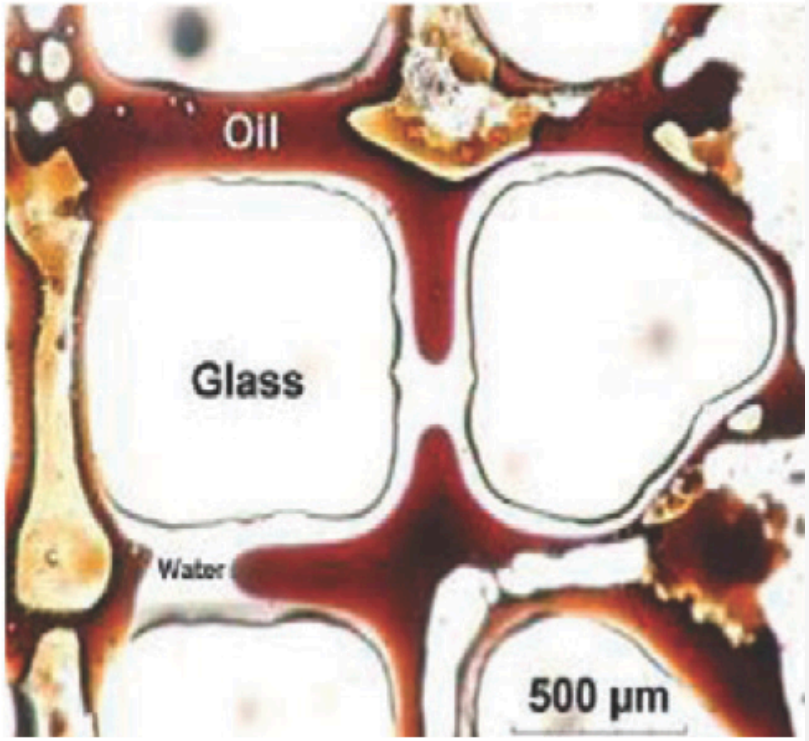




Dong et al., 2007

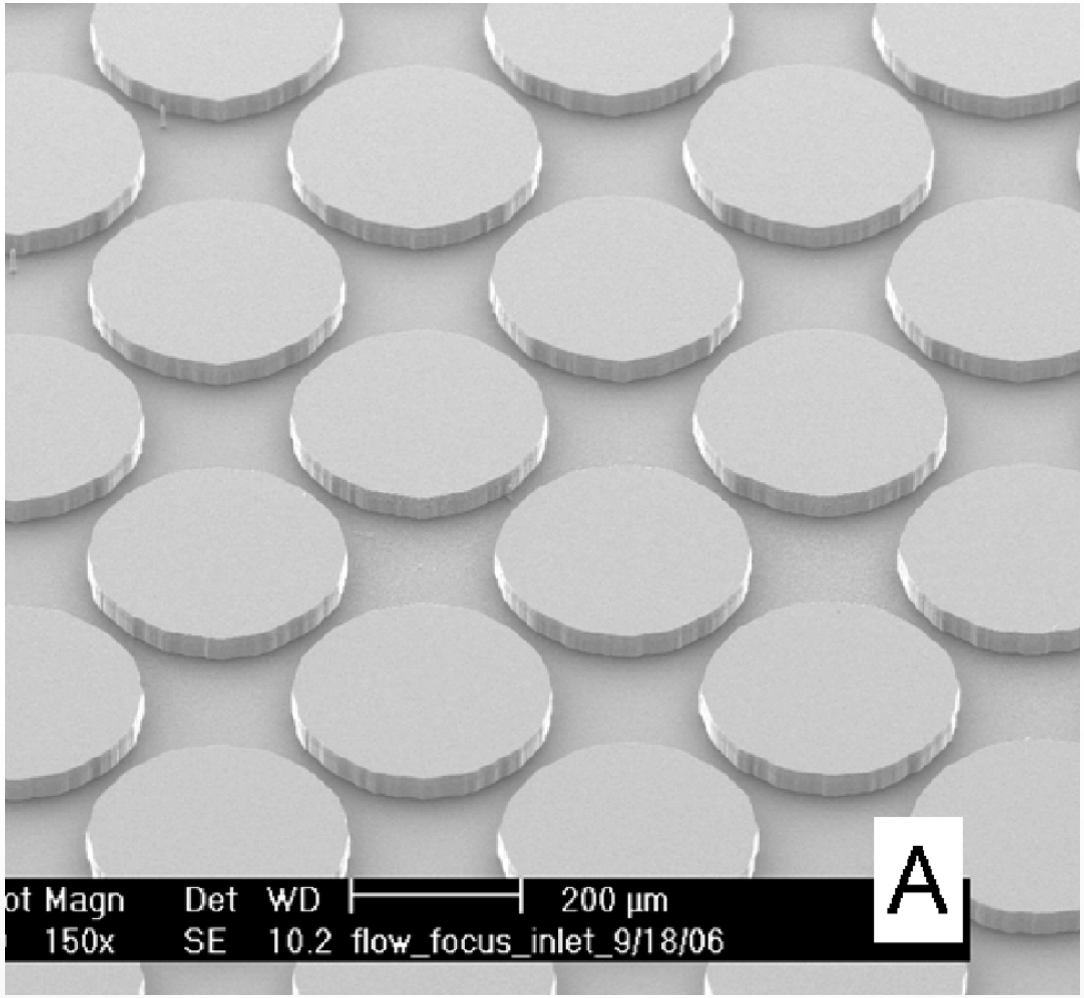
Micromodel – alkaline injection





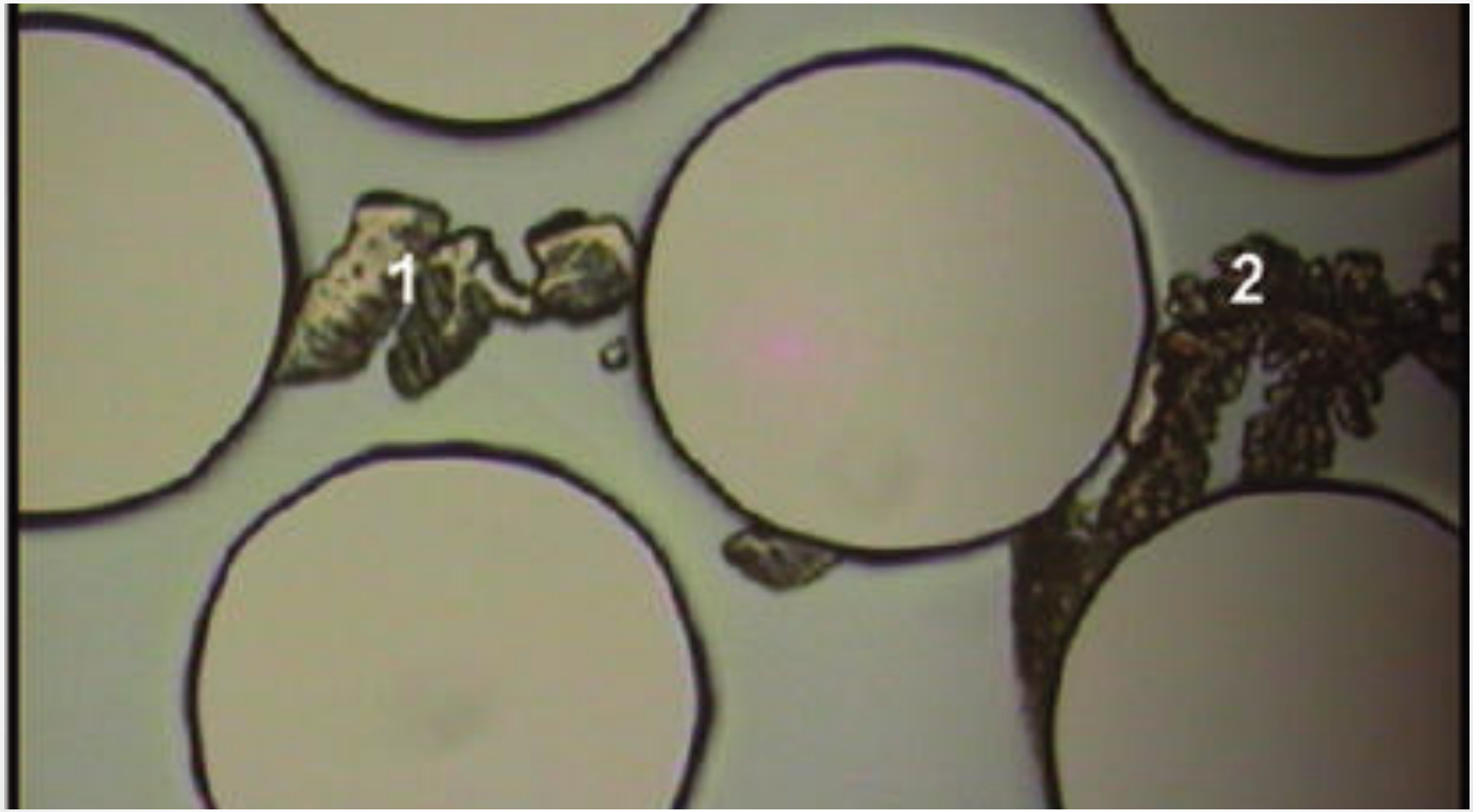
Dong et al., 2007

Micromodel – silicon wafer



Willingham et al, 2008

$CaCO_3$ precipitation

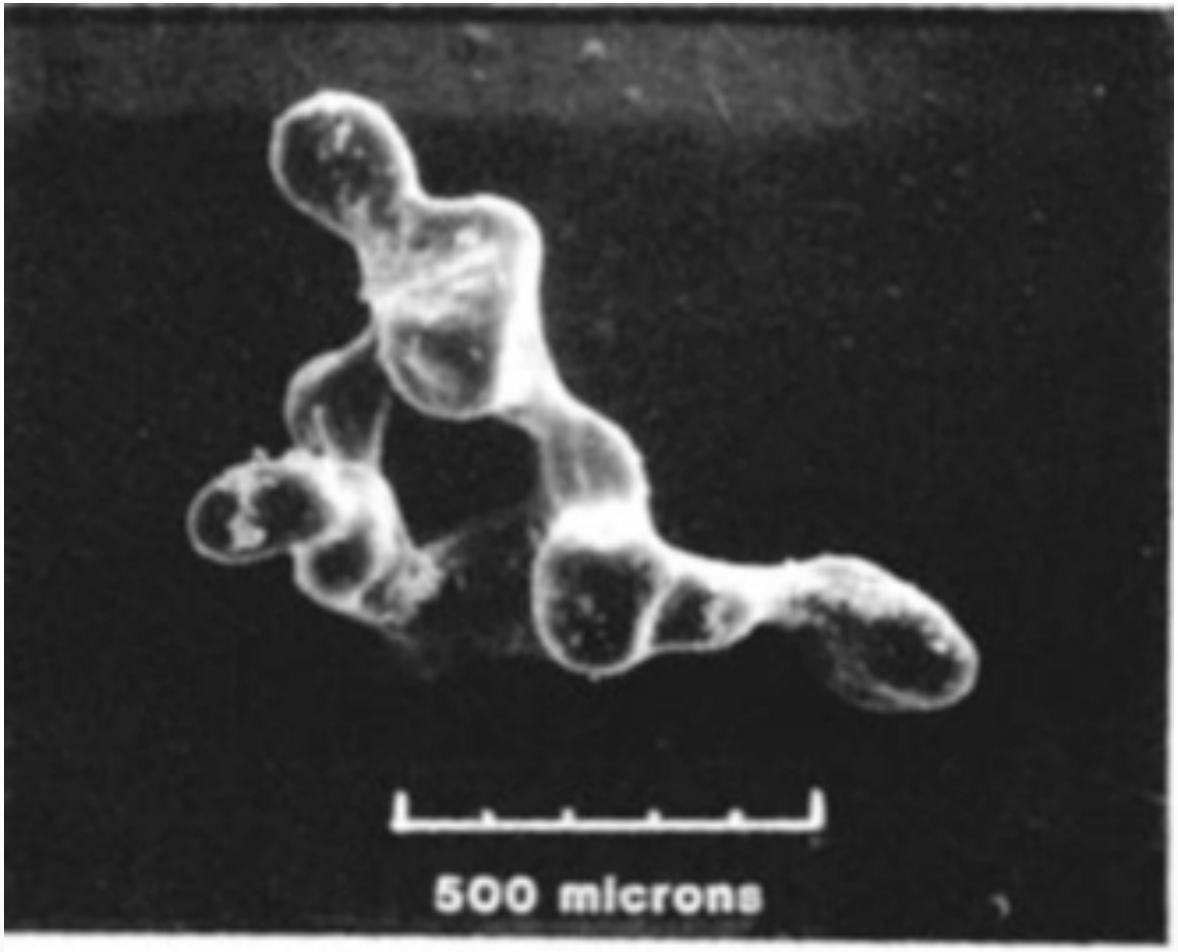


Zhang et al, 2010

3D flow visualization

- Micro X-ray computed tomography
- Refractive index matching (RIM) + Planar laser-induced fluorescence (PLIF)
- Confocal microscopy
- Digital Holography

Organic Liquid Polymerization



Conrad, 1992

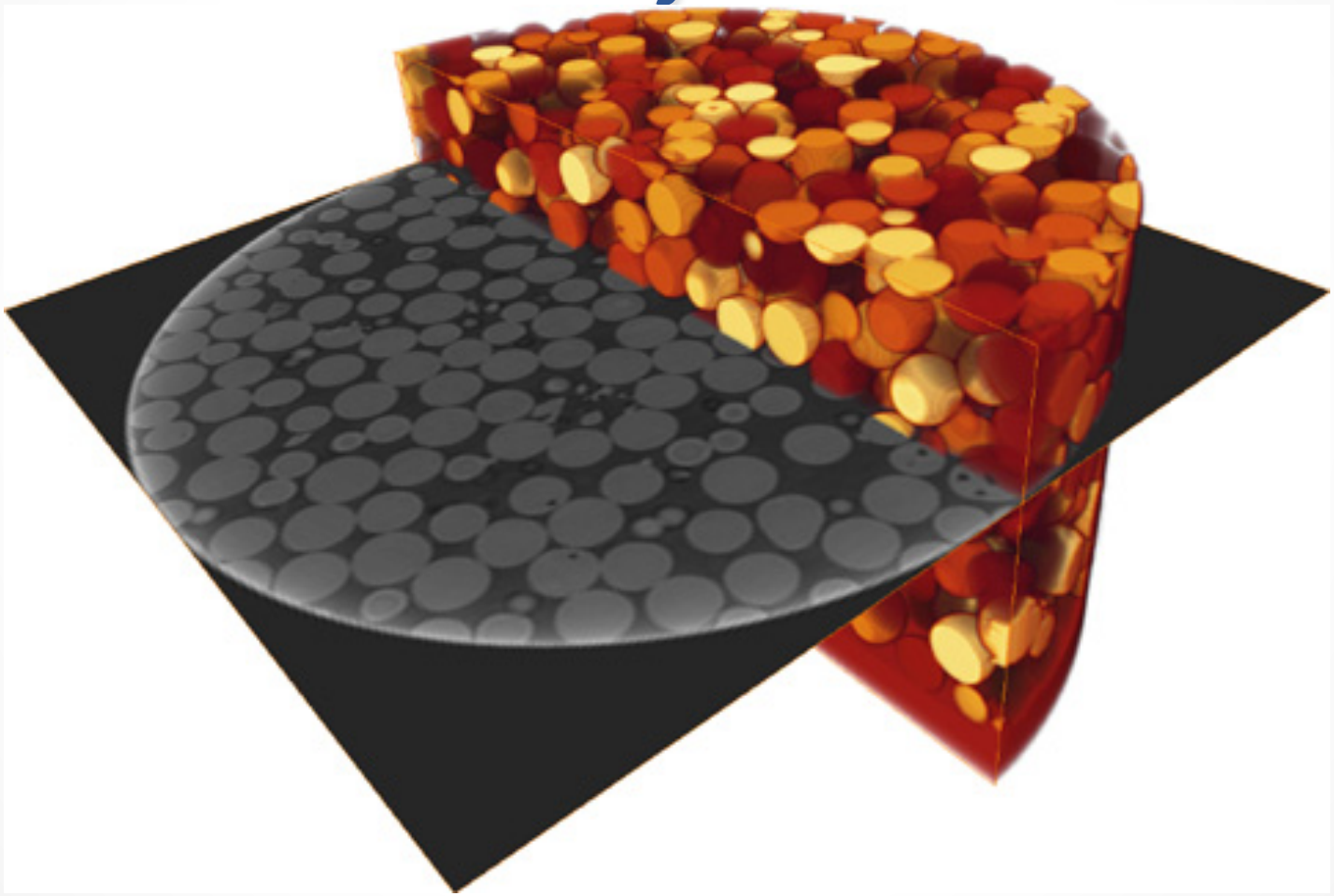
Styrene monomer

X-ray CT

MH21, Japan

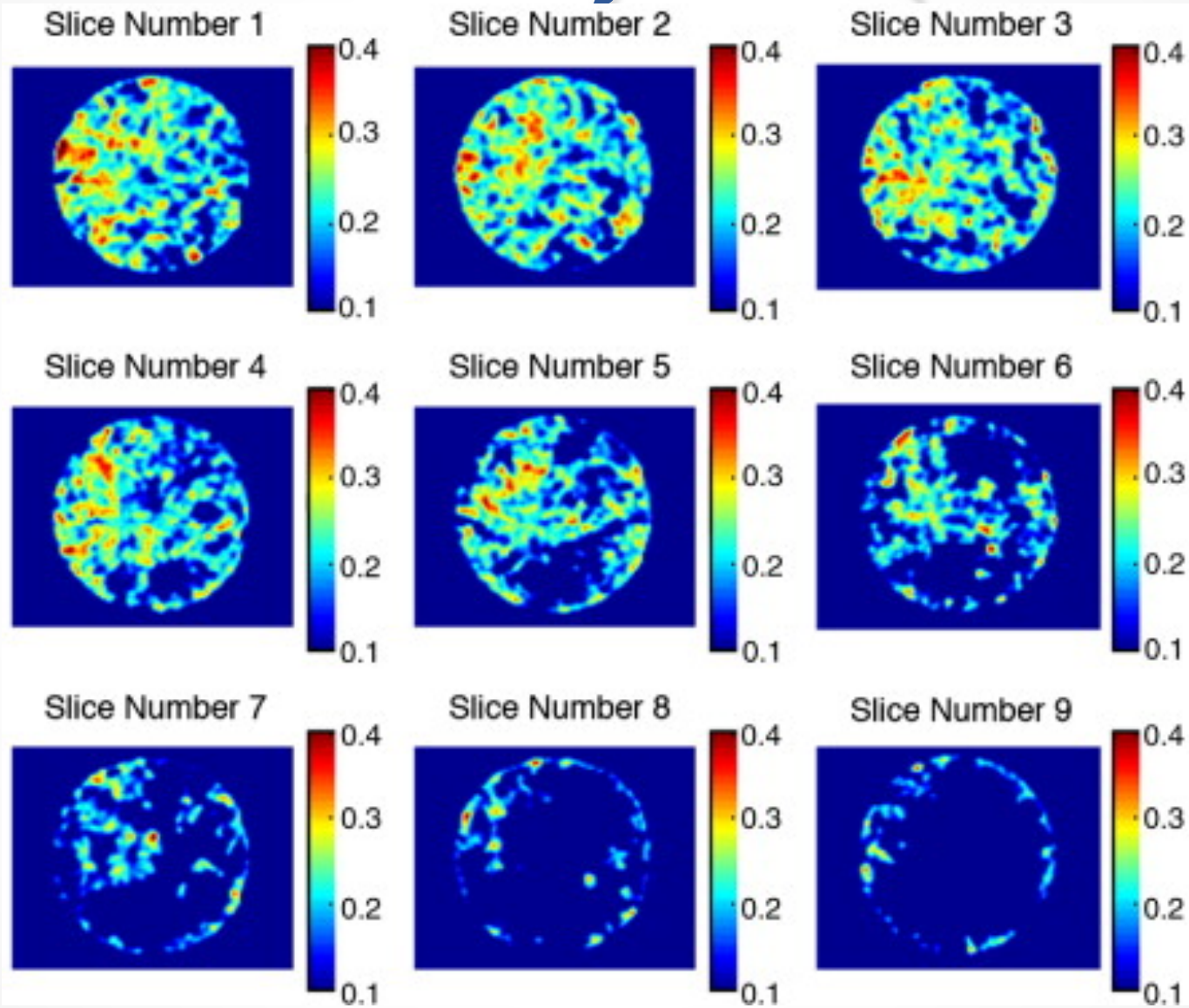
CT: computed tomography

X-ray CT



http://www.cuijpers-imaging.nl/3d-imaging.html

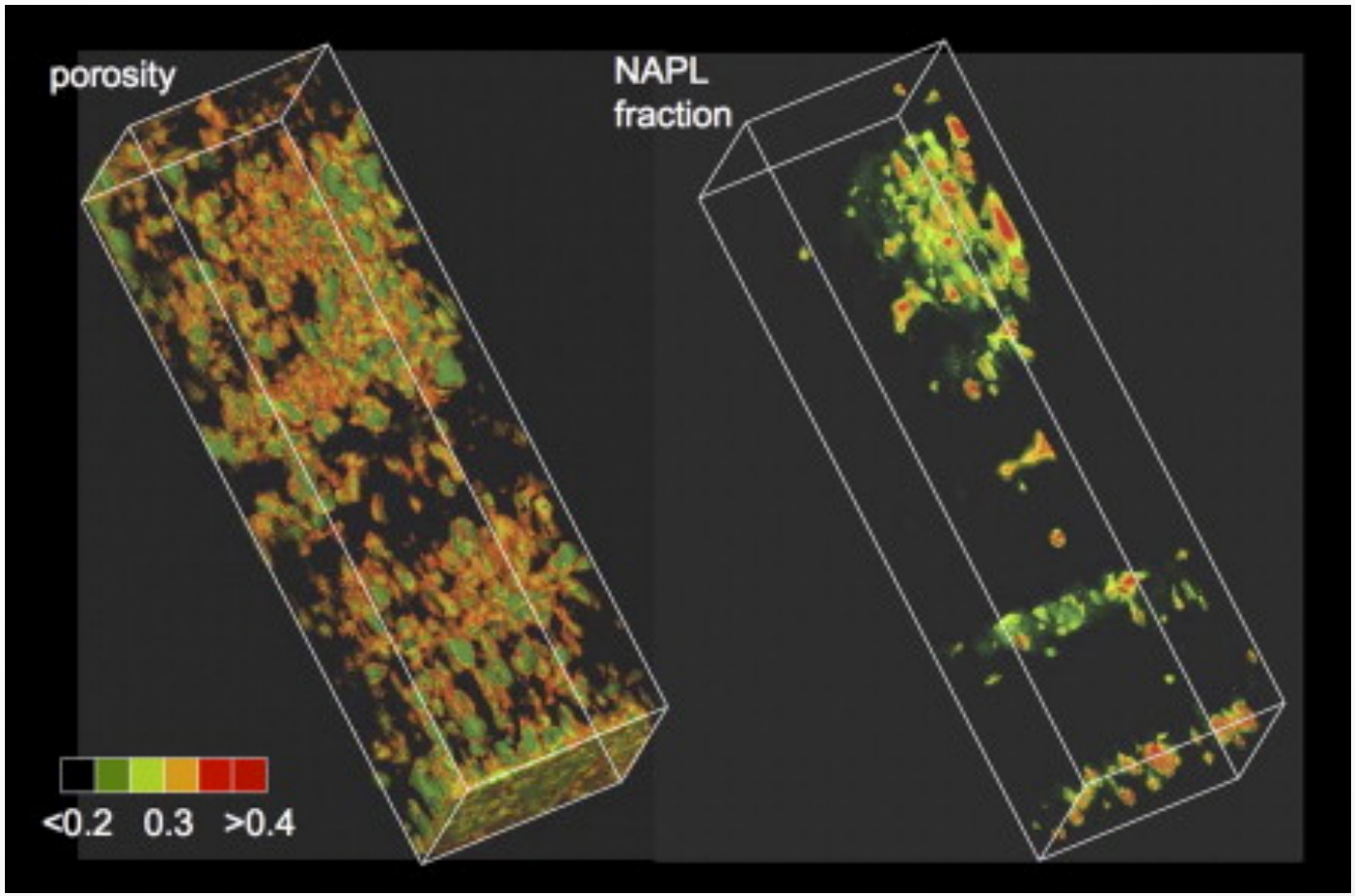
Medical X-ray CT (NAPL)



Res. : 0.35 mm

Goldstein et al., 2007

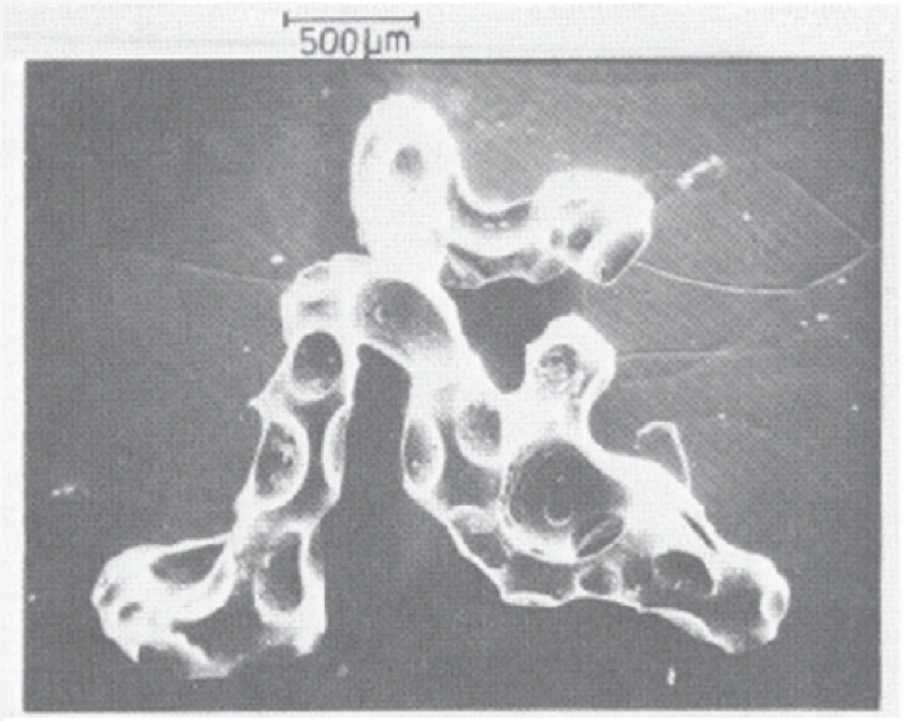
Medical X-ray CT (NAPL)



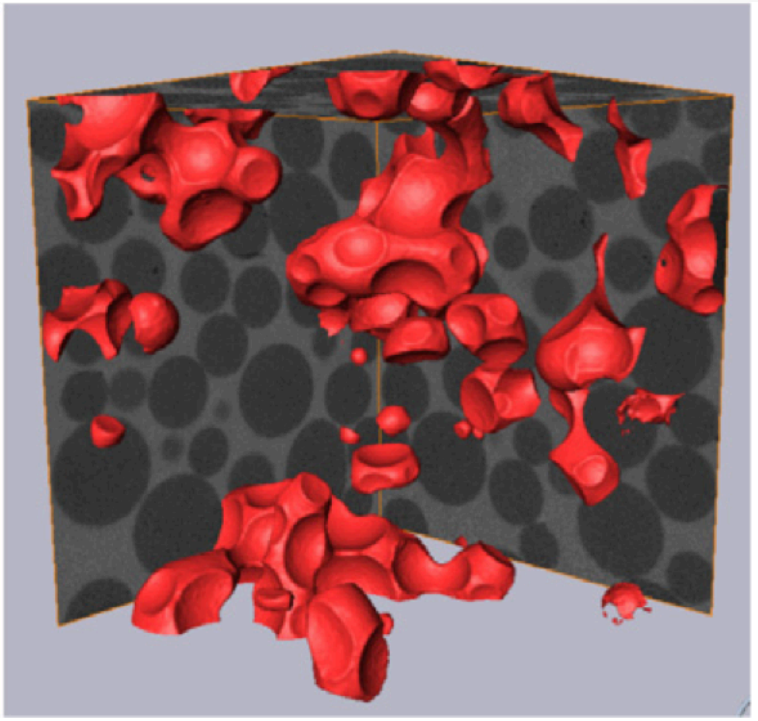
Goldstein et al., 2007

Res. : 0.35 mm

Micro X-ray CT

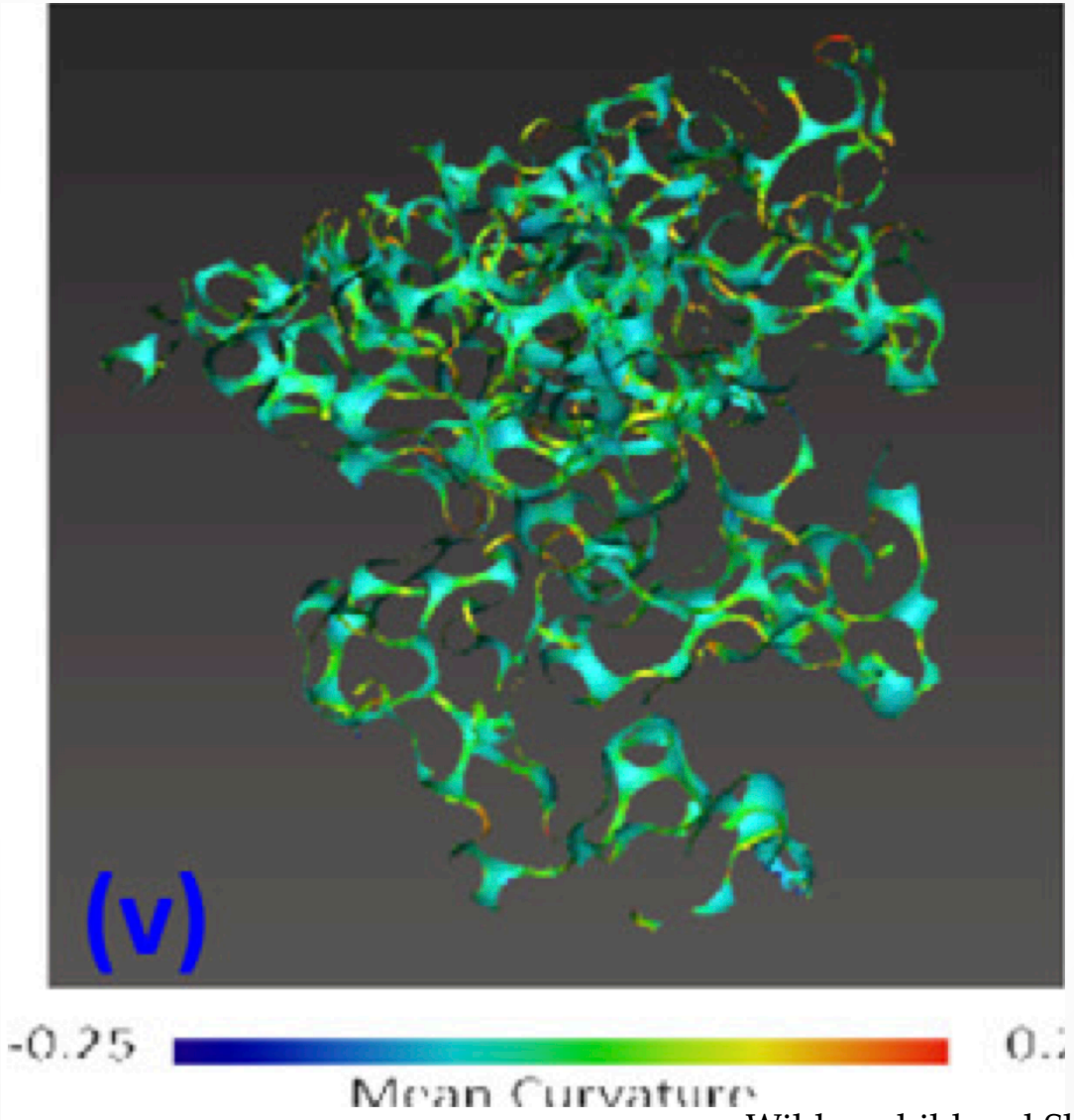


Res. : 10 microns



Wildenschild and Sheppard, 2012

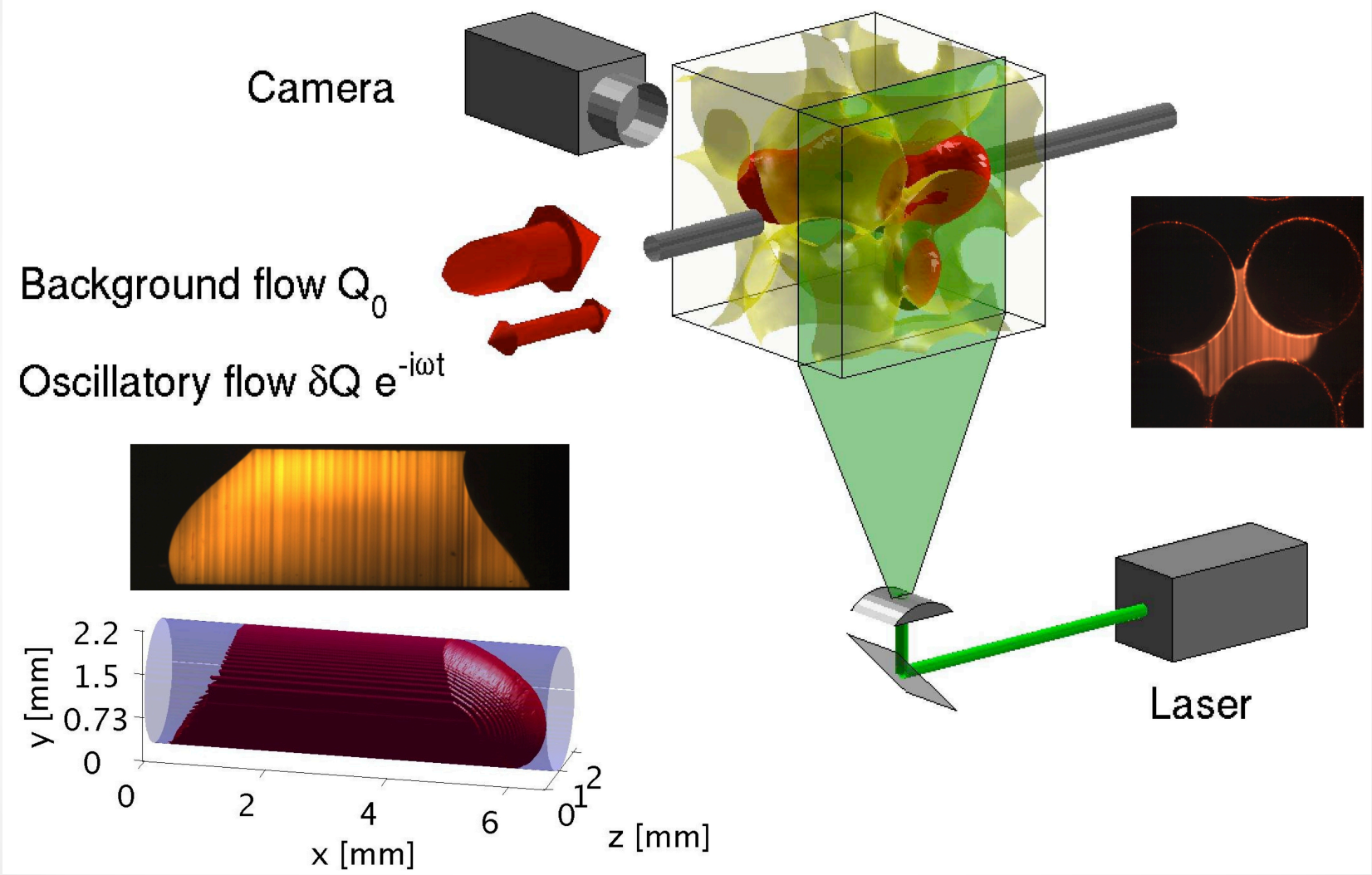
Micro X-ray CT



Wildenschild and Sheppard, 2012

Res. : 10 microns

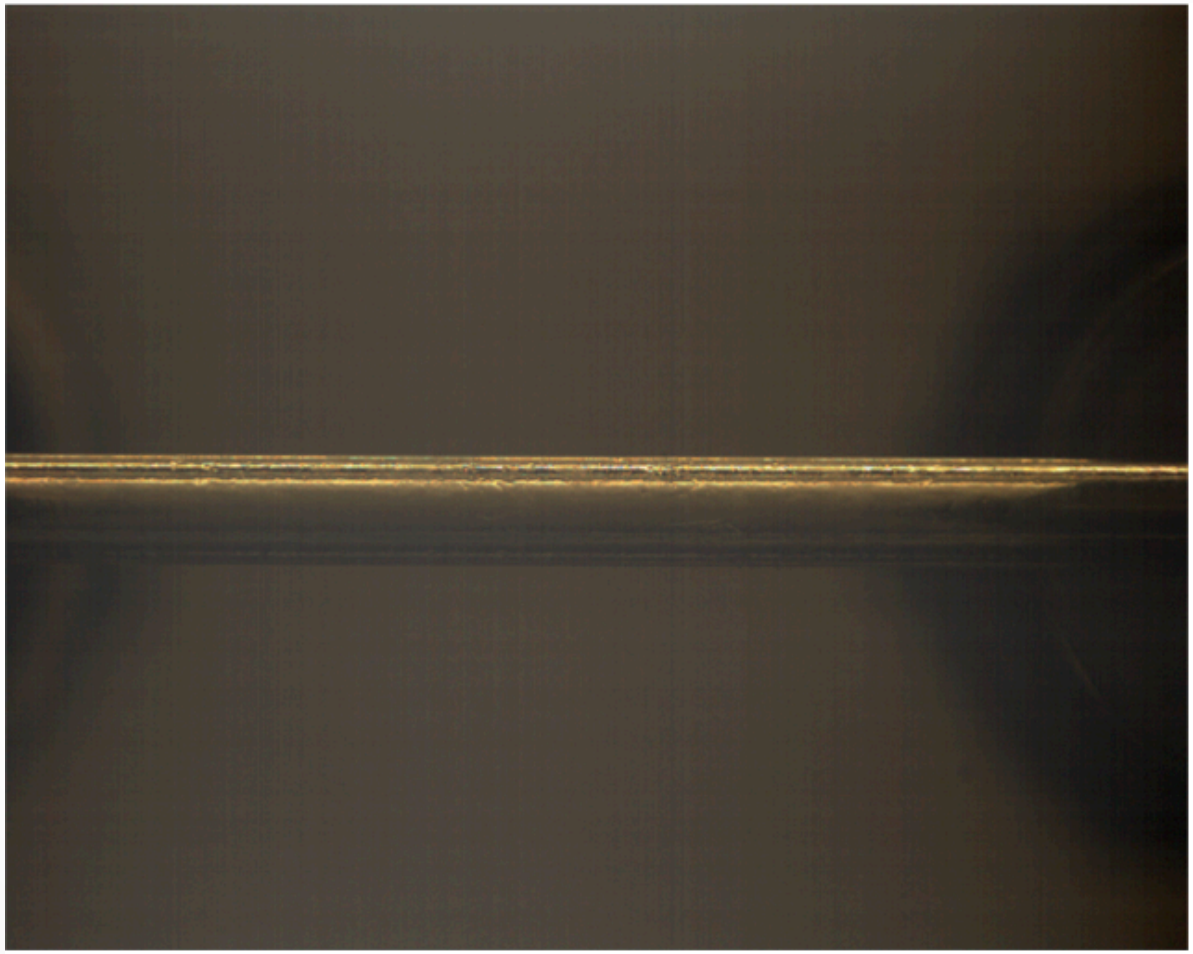
PLIF and RIM



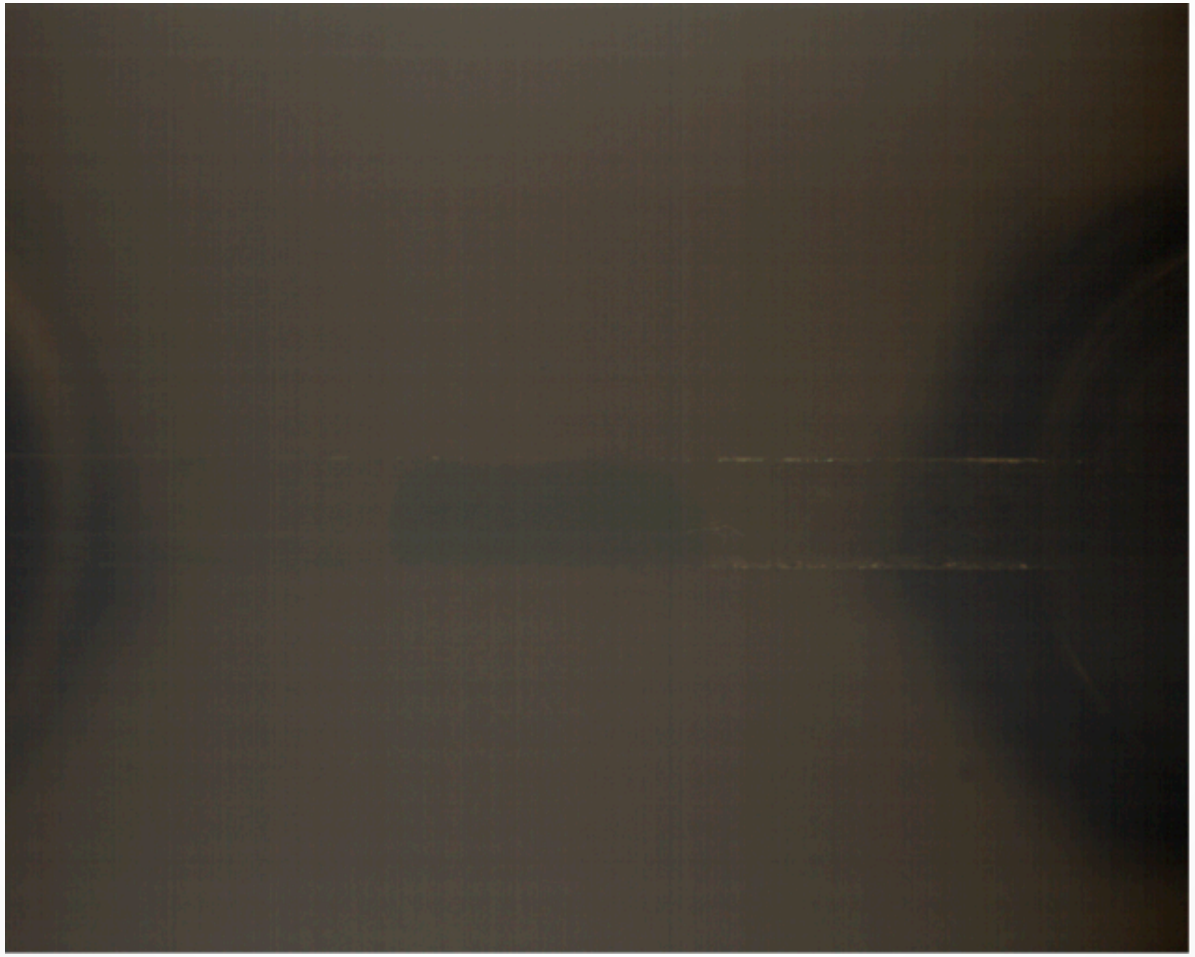
PLIF: planar laser-induced fluorescence
RIM: refractive index matching

Hsu et al, 2012

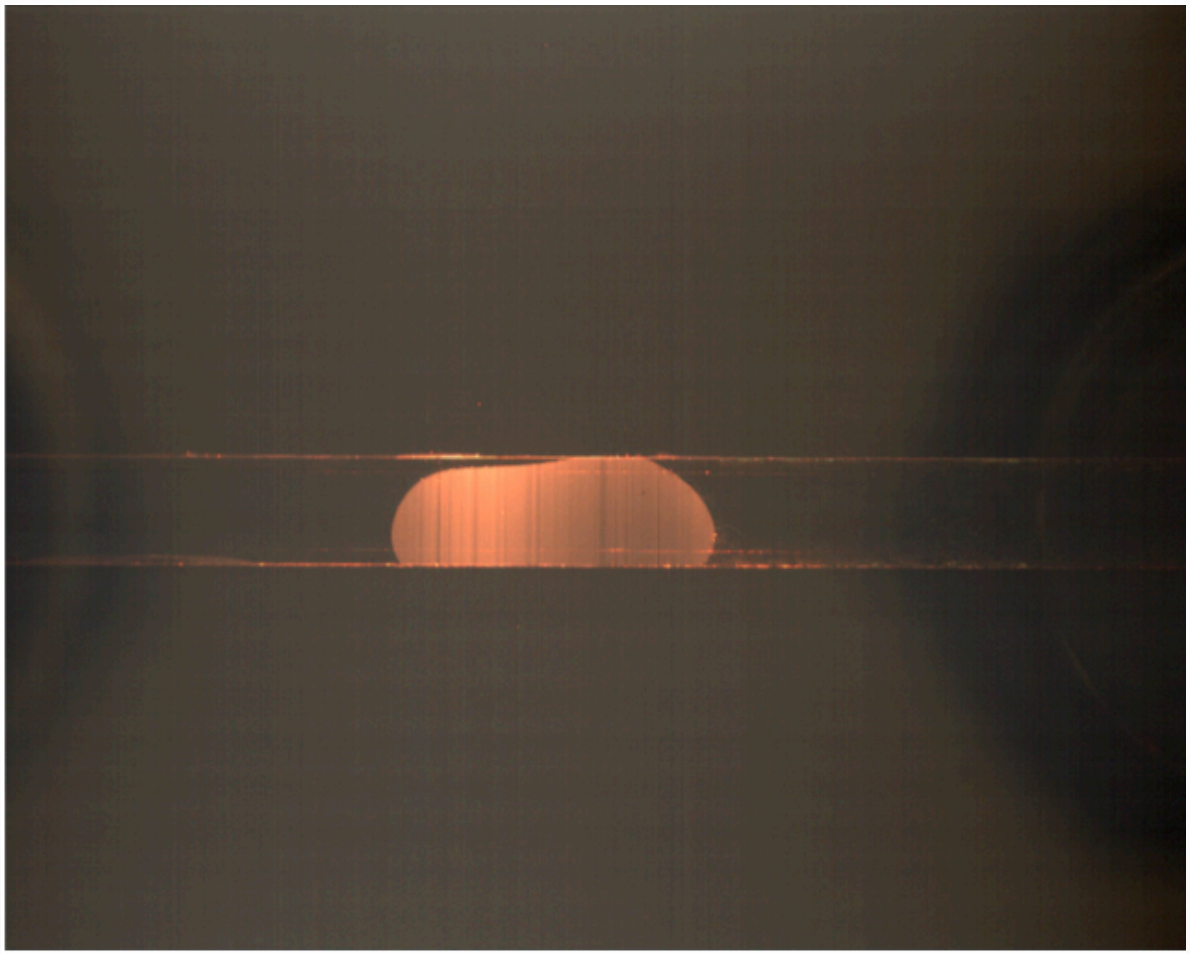
PLIF and RIM



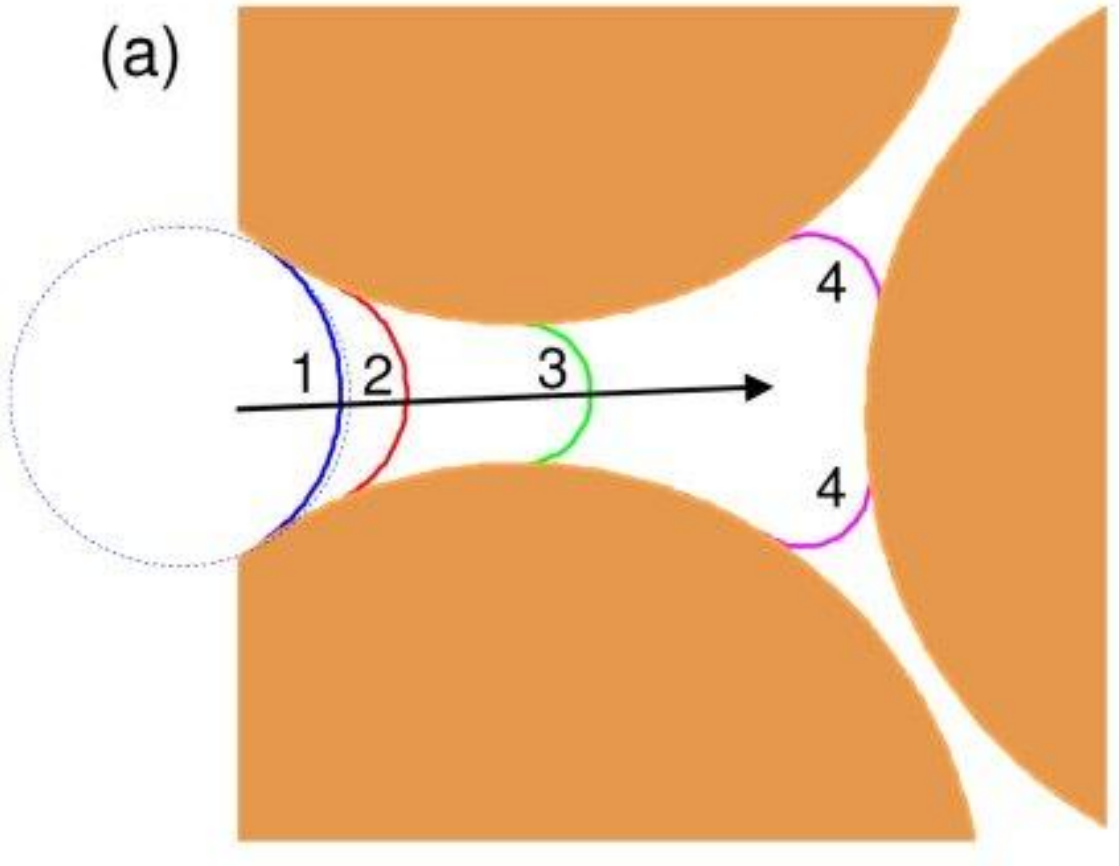
PLIF and RIM



PLIF and RIM

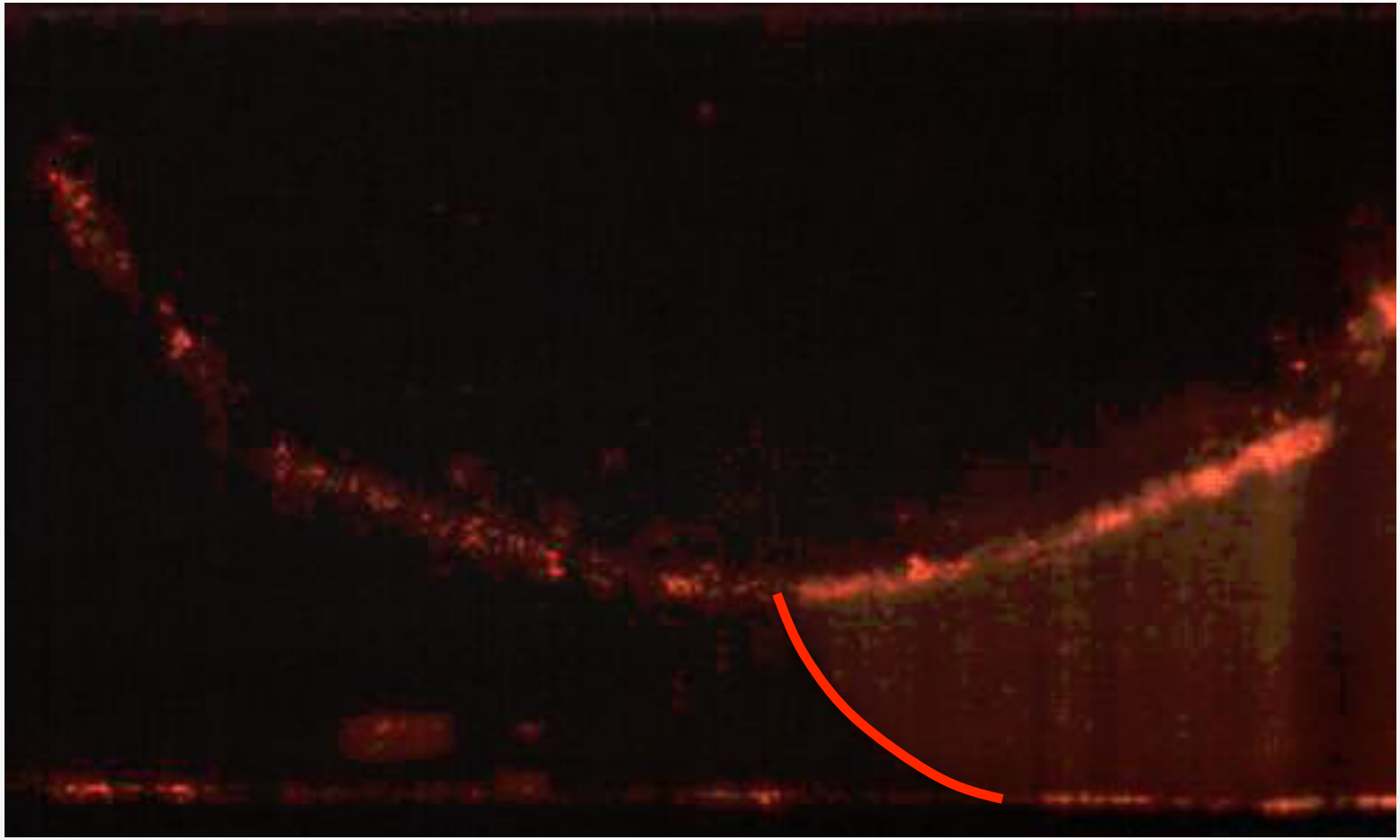


Haines Jump

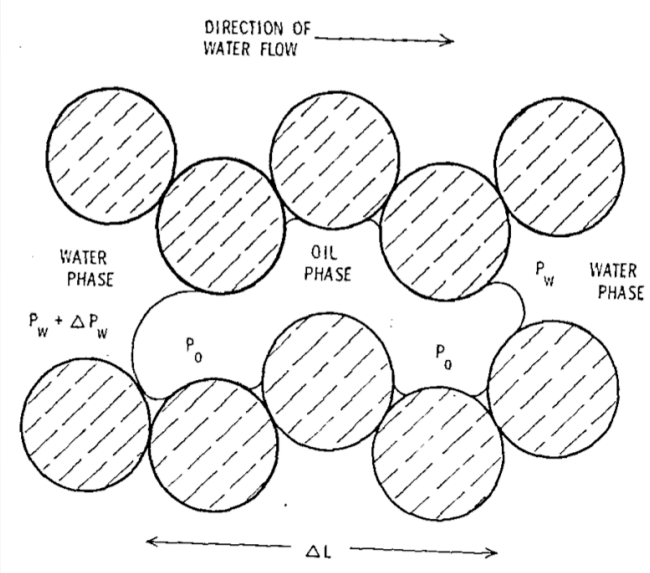


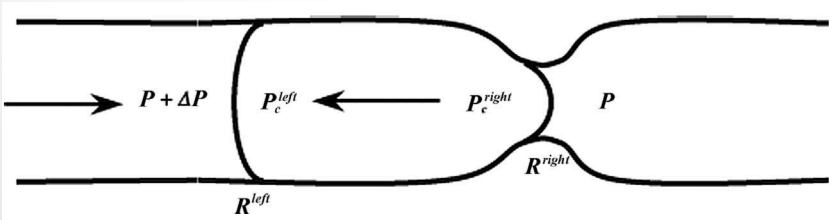
Motealleh et al., 2010

Haines Jump



NAPL blob mobilization





Li et al., 2005

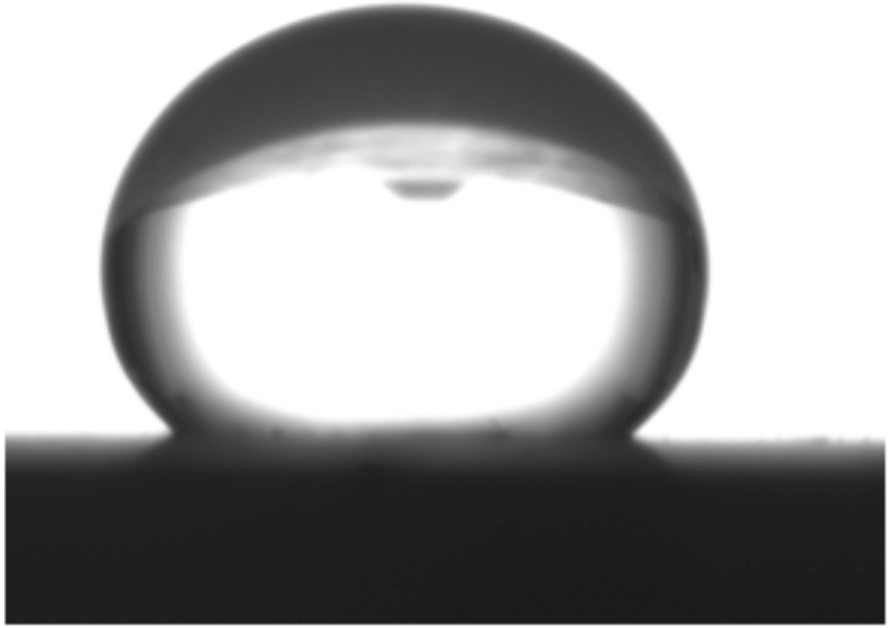
$$\left(\frac{\Delta P_w}{\Delta L}\right)_{crit} = -\frac{[P_c(dr) - P_c(im)]}{L_{blob}}$$

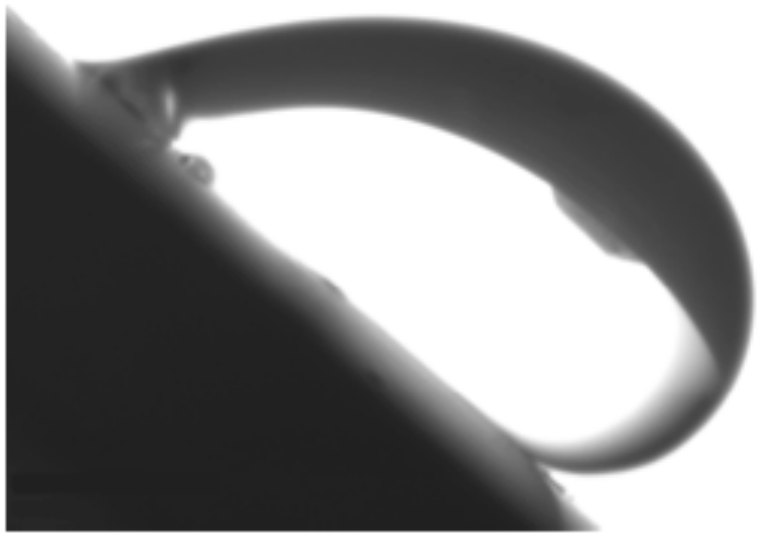
$$P_c(dr/im) = \frac{2\gamma}{R_{dr/im}} \cos(\vartheta_{dr/im})$$

dr/im: drainage/imbibition interfaces
$\vartheta_{dr/im}$: contact angle, $R_{dr/im}$: pore radius
γ: interfacial tension

ϑ constant ? "Contact angle hysteresis"

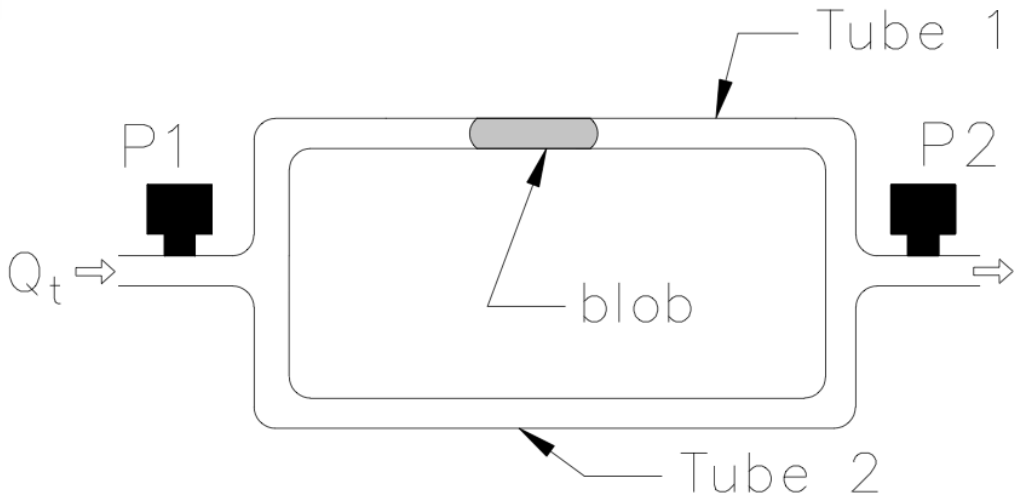
Contact angle hysteresis





(Pierce, Carmona, and Amirfazli, 2006)

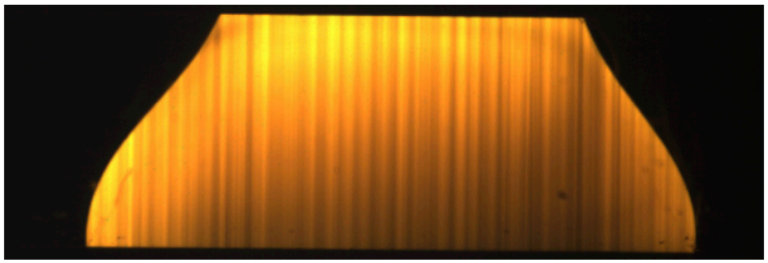
Pore doublet



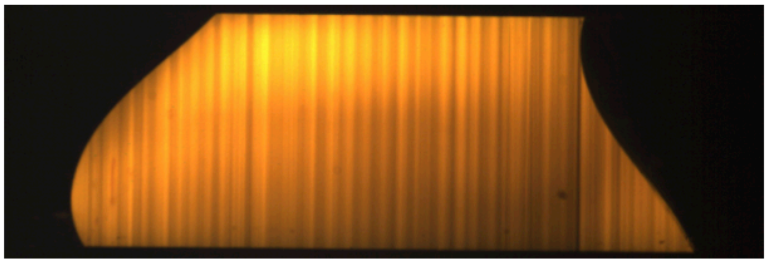
$$\begin{aligned}\Delta p &= -2\gamma\,[H_{dr} - H_{im}] \\ &= \frac{-2\gamma}{r_1}\,[\cos(\vartheta_{dr}) - \cos(\vartheta_{im})]\end{aligned}$$

$r_{1/2}$: the radius of Tube 1 and 2
$H_{dr/im}$: mean curvatures

Pore doublet



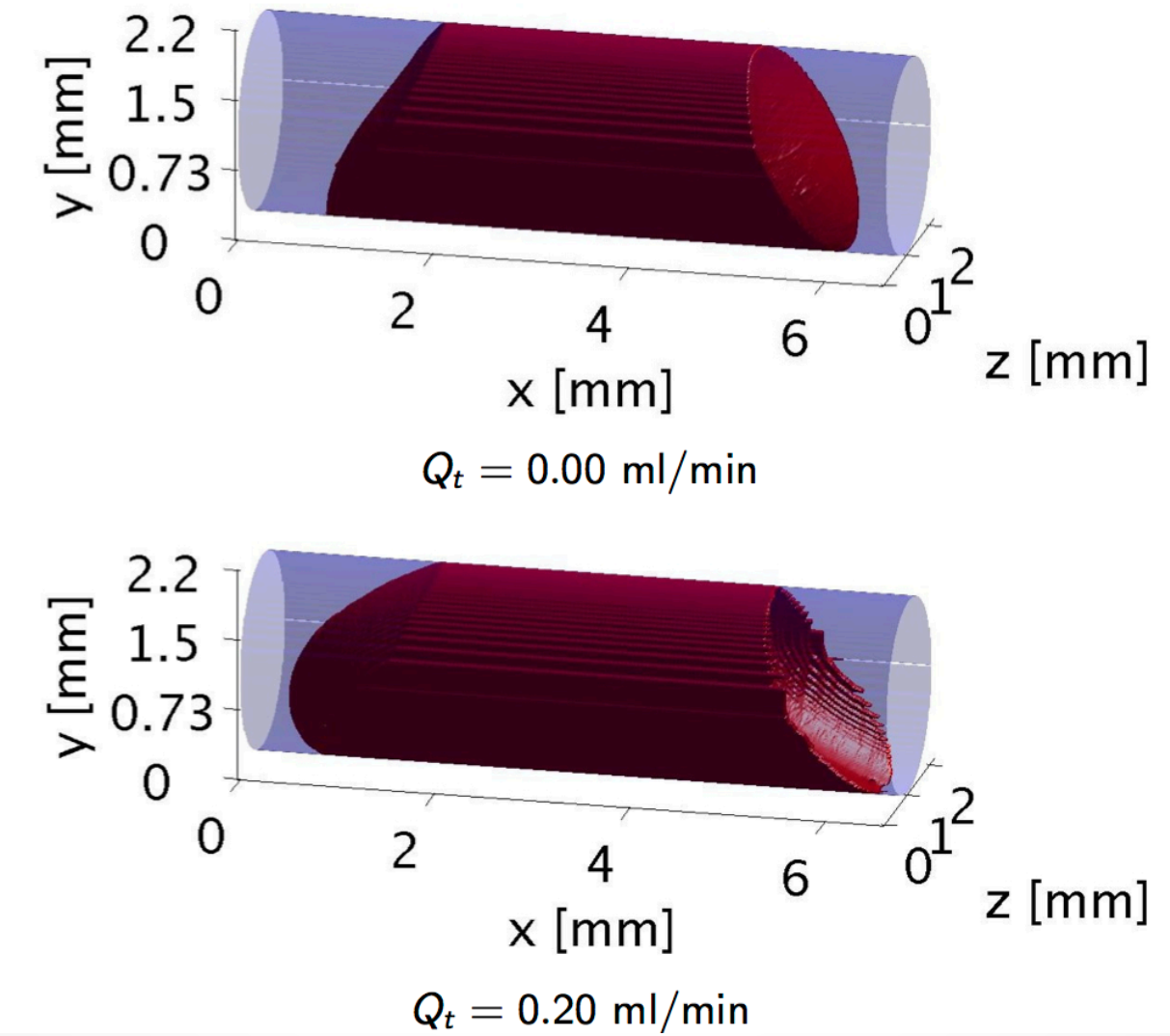
$Q_t = 0.00$ ml/min



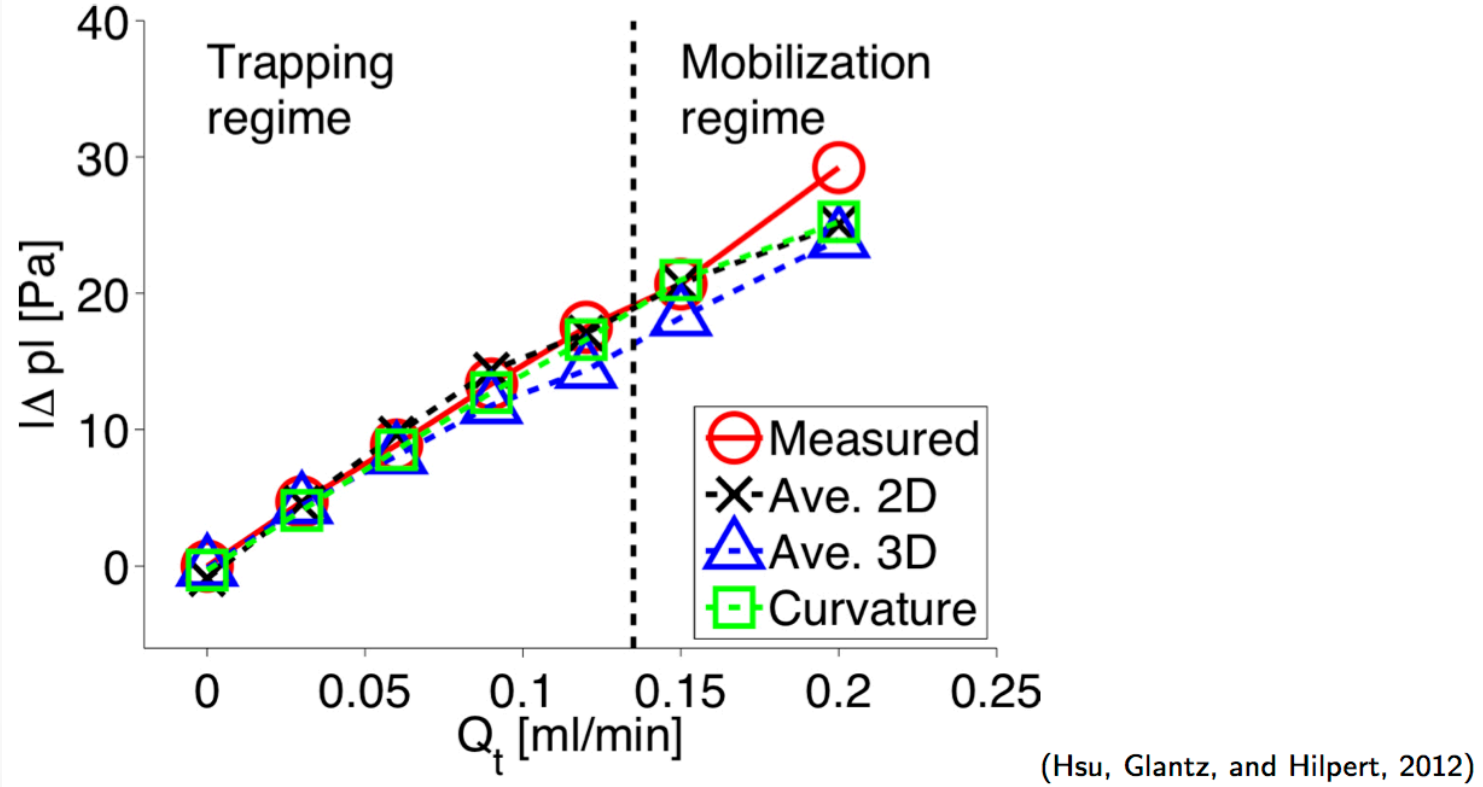
$Q_t = 0.09$ ml/min

$Q_t = 0.20$ ml/min

PLIF tomography



Predicted and measured pressure drops

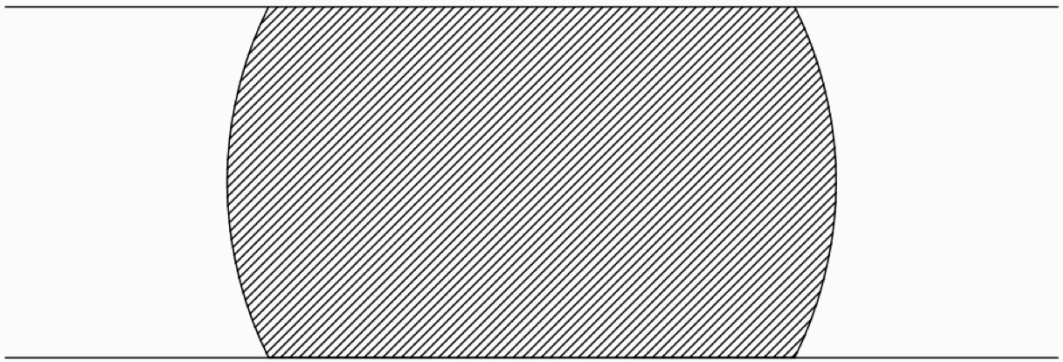


(Hsu, Glantz, and Hilpert, 2012)

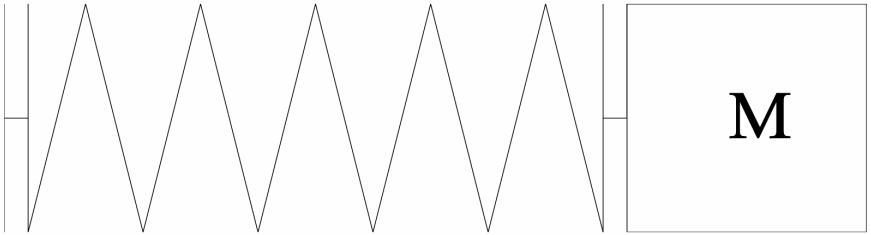
Ave. 2D: $\vartheta_{dr/im} = (\vartheta^{top}_{dr/im} + \vartheta^{bot}_{dr/im})/2$

Ave. 3D: $\vartheta_{dr/im} = \overline{\vartheta_{3D(dr/im)}}$

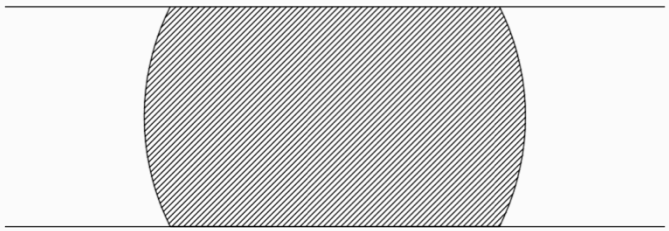
Response of a trapped blob to incident waves



Interfacial resonance



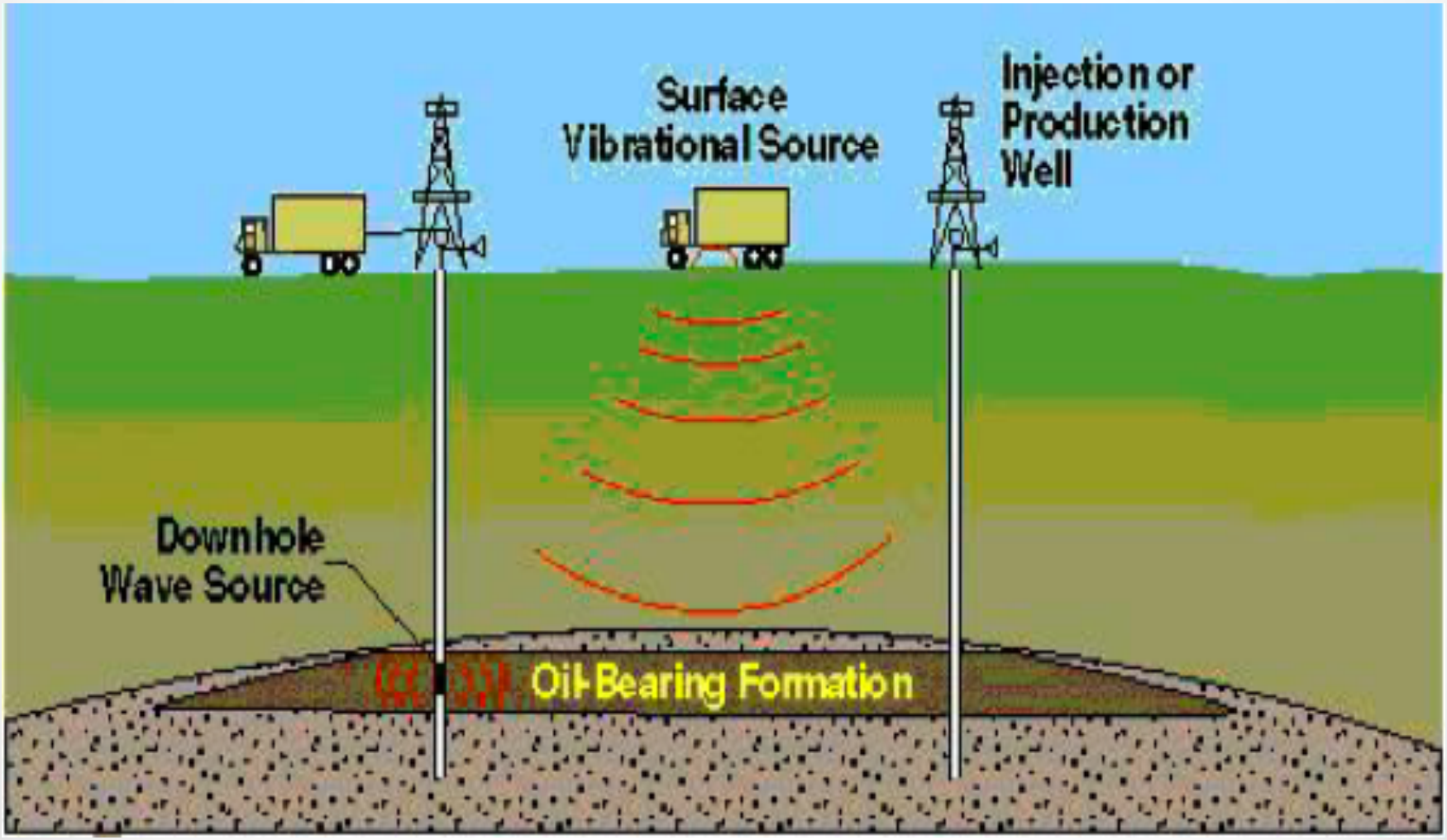
- Harmonic oscillator
- Resonance



Capillary-Induced Resonance

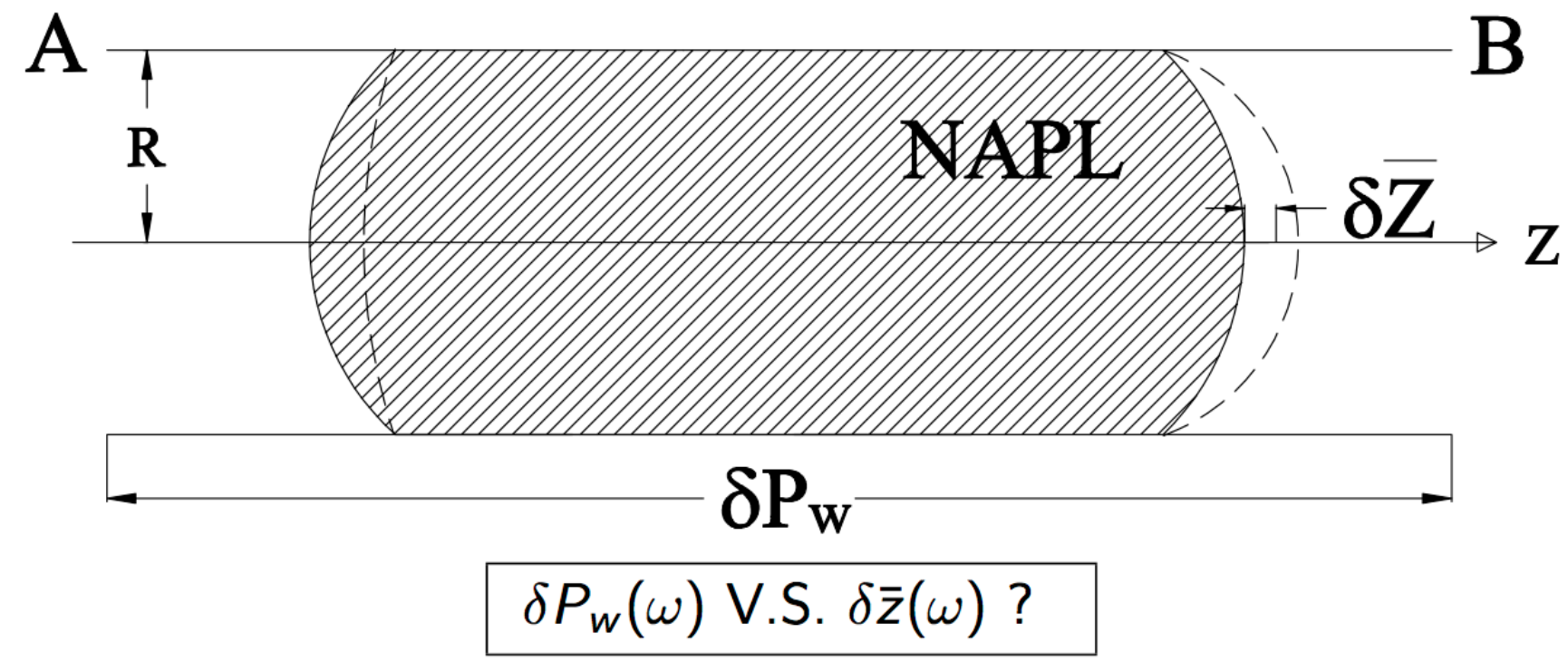
=> large residual NAPL blob oscillations

Enhanced oil recovery (Seismic Stimulation)



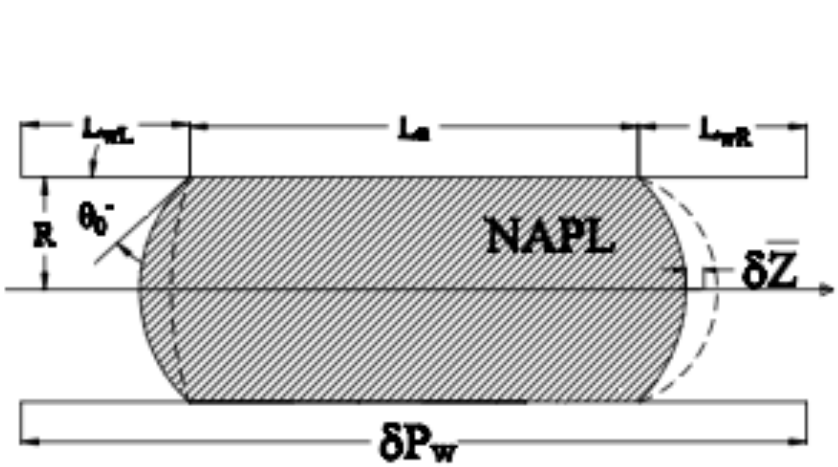
Picture courtesy of Peter Roberts

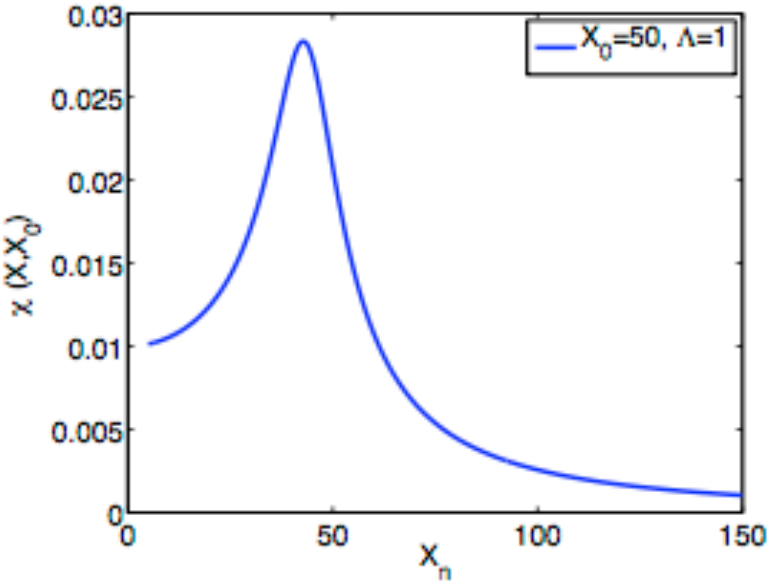
Blob displacement and oscillatory pressure drop



- Navier-Stokes equation
- Young-Laplace equation

Frequency response





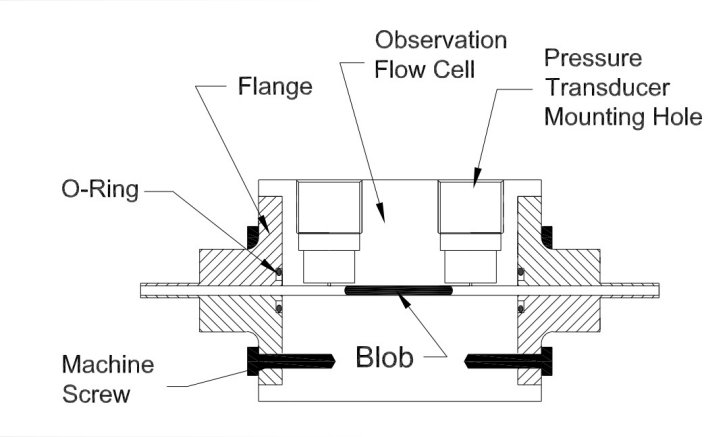
$$\chi(X_n, X_w, X_0) = \frac{\delta\bar{z}(\omega)}{\delta P_w(\omega)}[\rho_n L_n + \rho_w L_w]\omega_{cn}^2$$

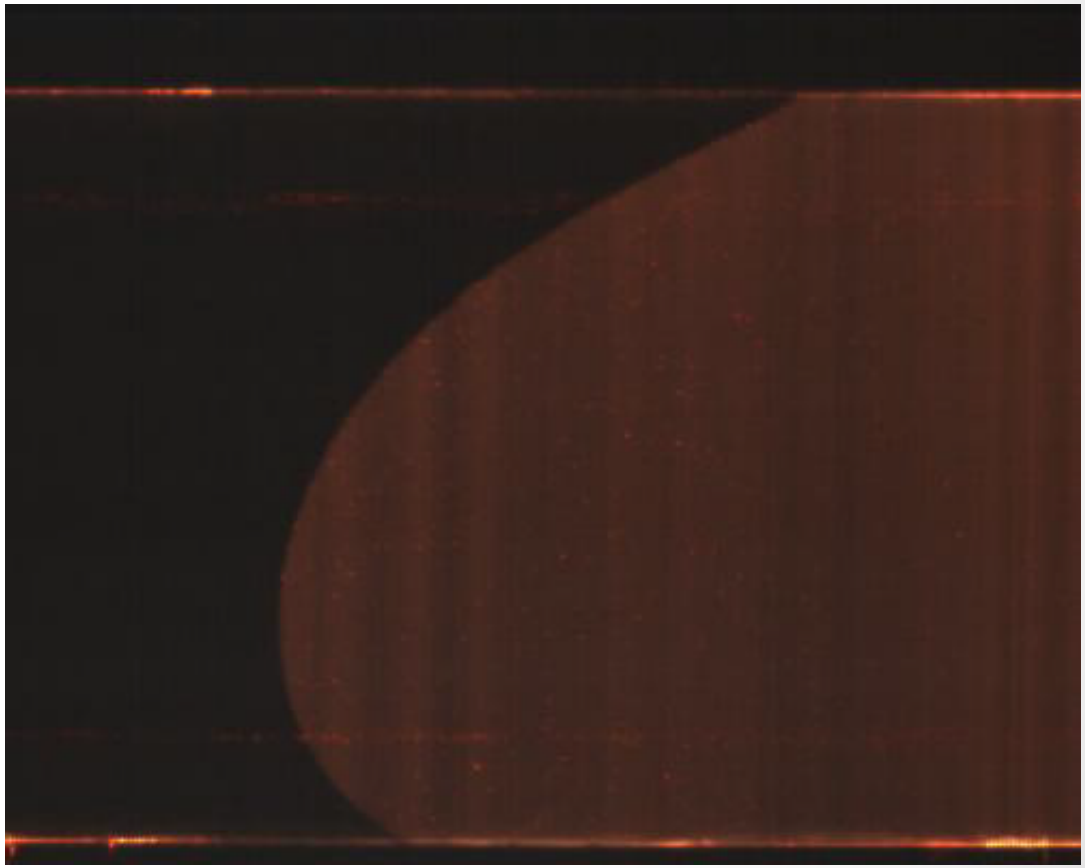
$$= \left\{\left[\frac{1}{(1+\lambda)h(X_w)} + \frac{1}{(1+\lambda^{-1})h(X_n)}\right] X_n^2 - X_0^2\right\}^{-1}$$

where $X_0 = \frac{\omega_0}{\omega_{cn}}$, $X_{w/n} = \frac{\omega}{\omega_{cw/cn}}$, $\omega_{cw/cn} = \frac{\nu_{w/n}}{R^2}$, $\lambda = \frac{\rho_n L_n}{\rho_w L_w}$, $h(X_{w/n}) = -\frac{J_2(\sqrt{iX_{w/n}})}{J_0(\sqrt{iX_{w/n}})}$

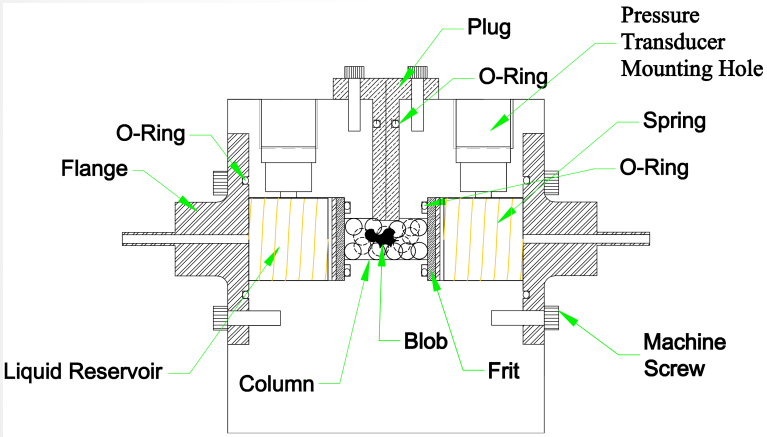
Hsu and Hilpert, 2012 ●

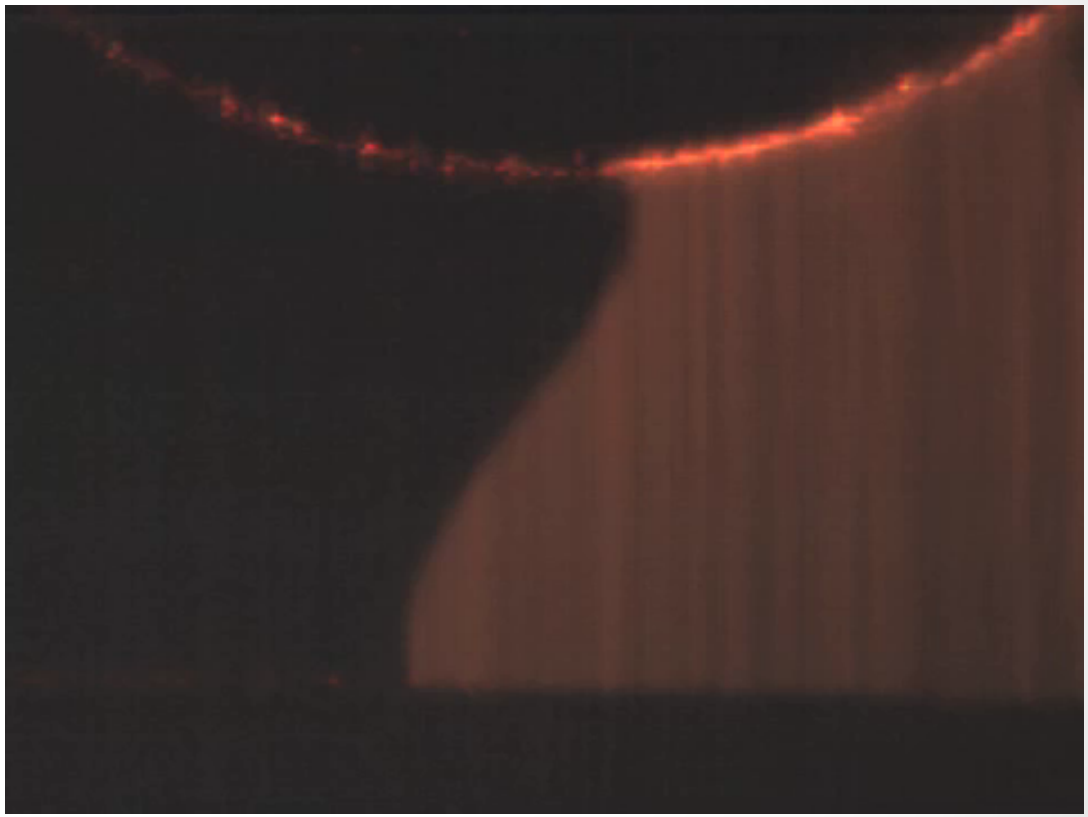
Blob in a capillary tube





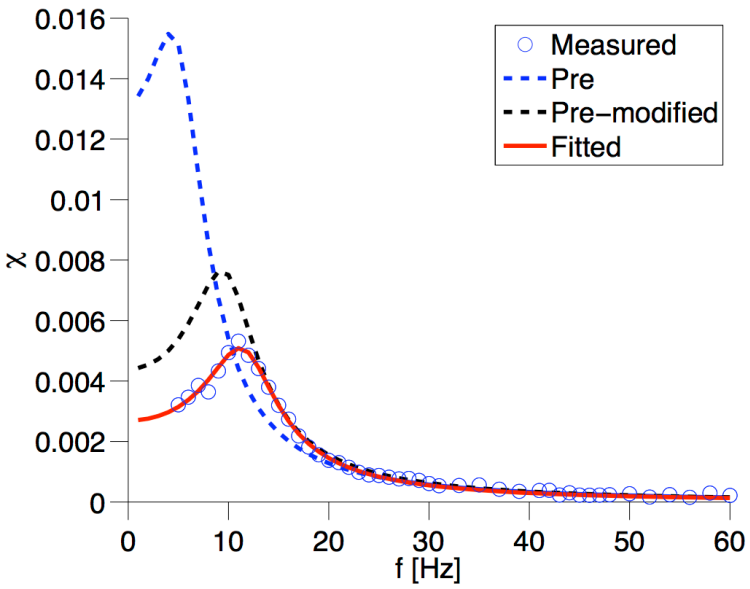
Blob in a sphere packing



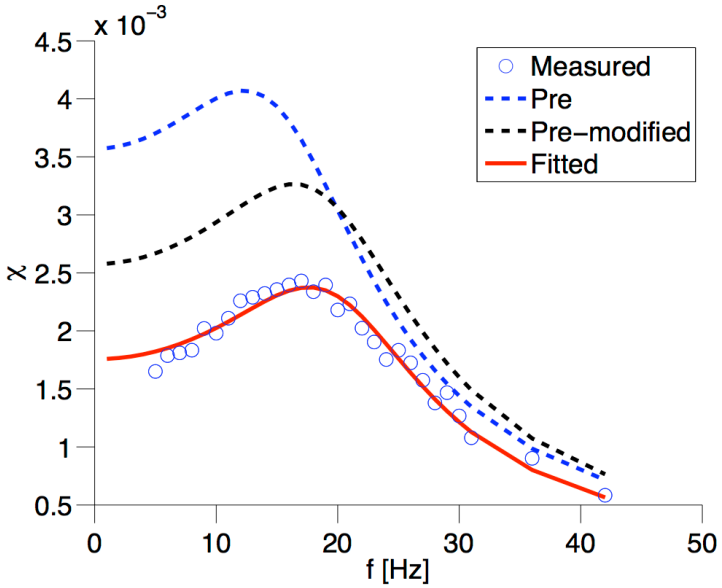


Frequency response

Capillary tube system

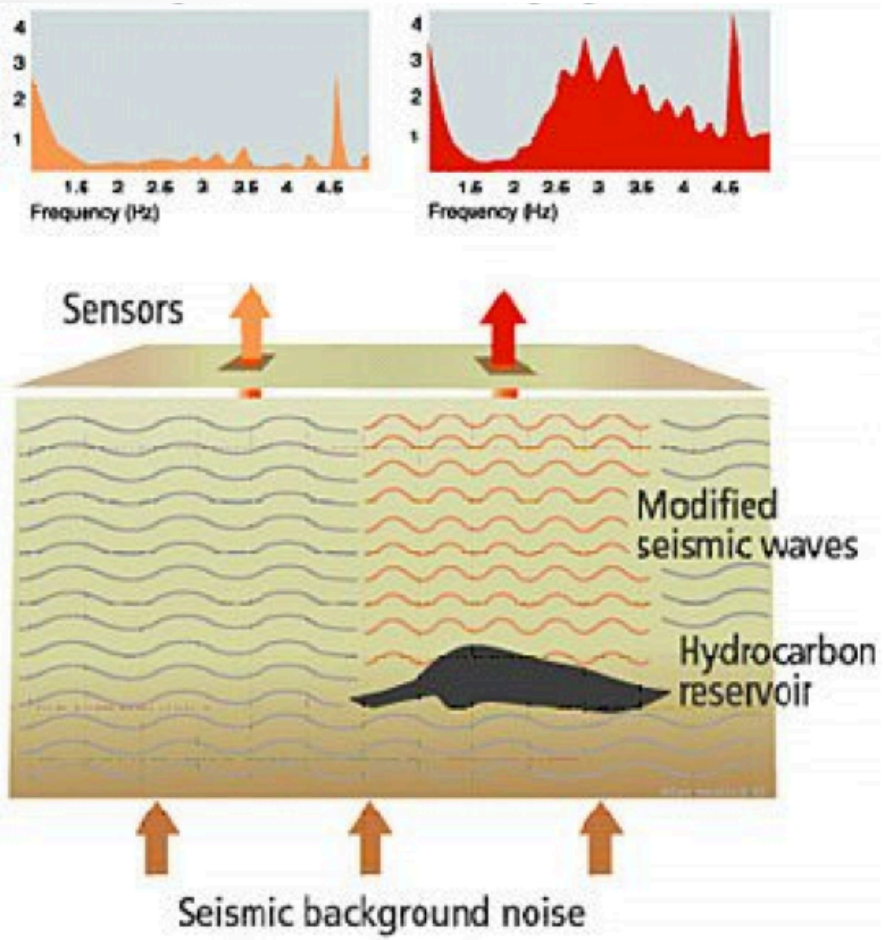


Sphere packing system



(Hsu and Hilpert, 2012)

Hydrocarbon reservoir detection



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Hydrocarbon microtremors interpreted as nonlinear oscillations driven by oceanic background waves

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Spectral modification of seismic waves propagating through solids exhibiting a resonance frequency: a 1-D coupled wave propagation–oscillation model

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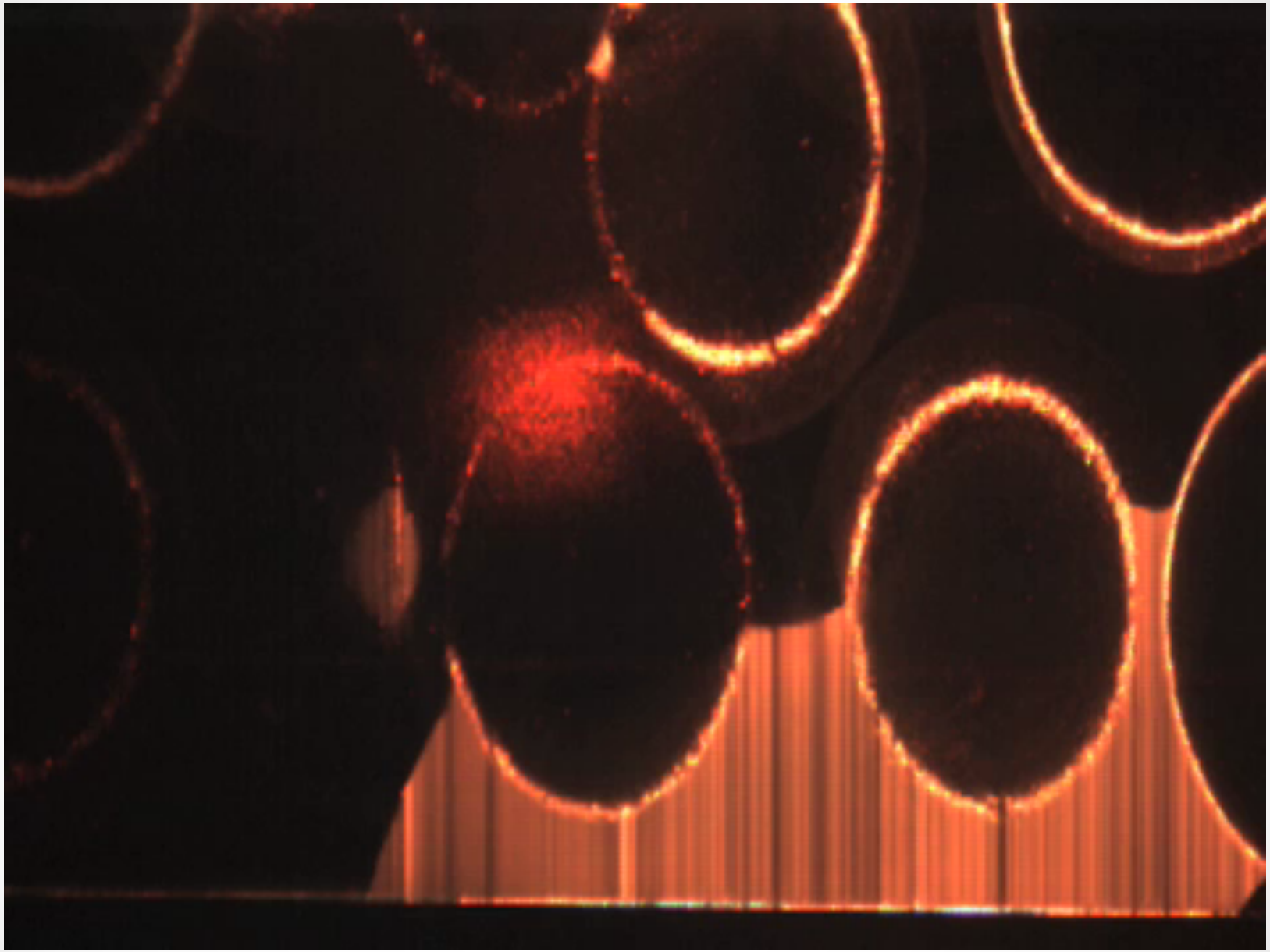
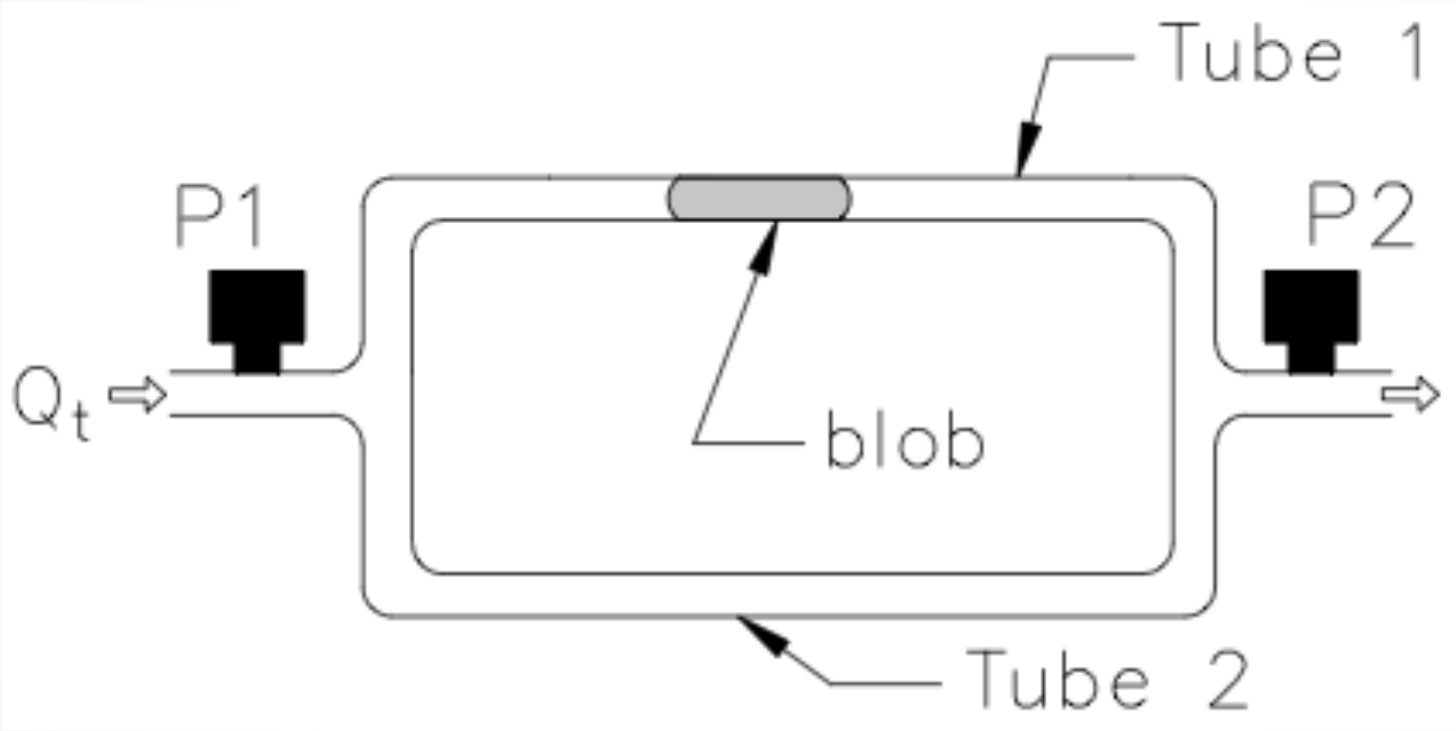
[2] Physics of Geological Processes (PGP), University of Oslo, Norway

- 孔隙雙相流: 孔隙尺度的觀測與應用



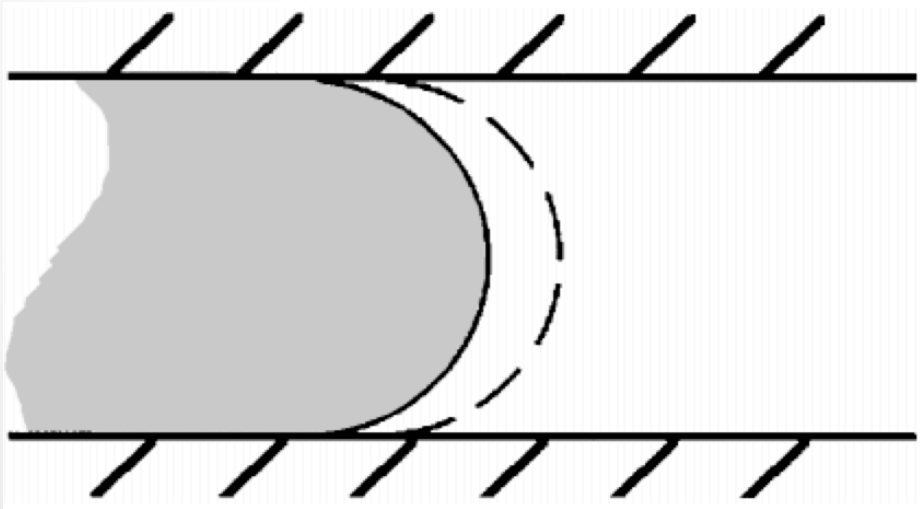
Blob mobilization



Pore doublet

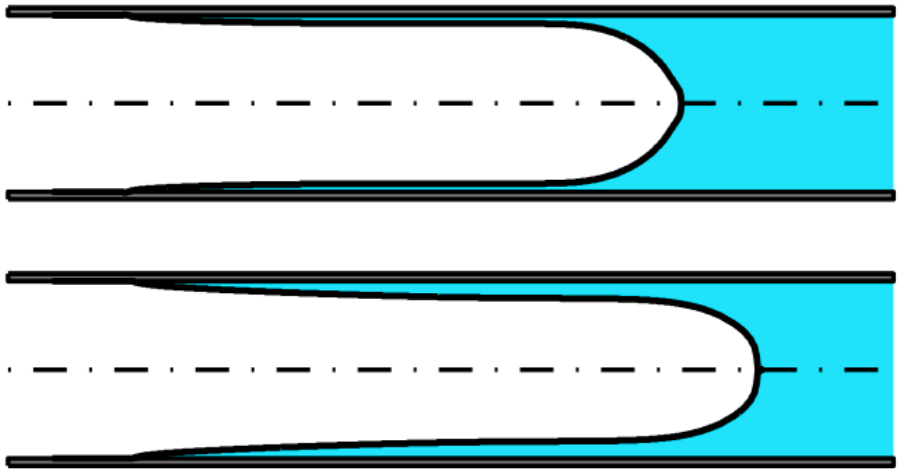
Interfacial movement

Sliding



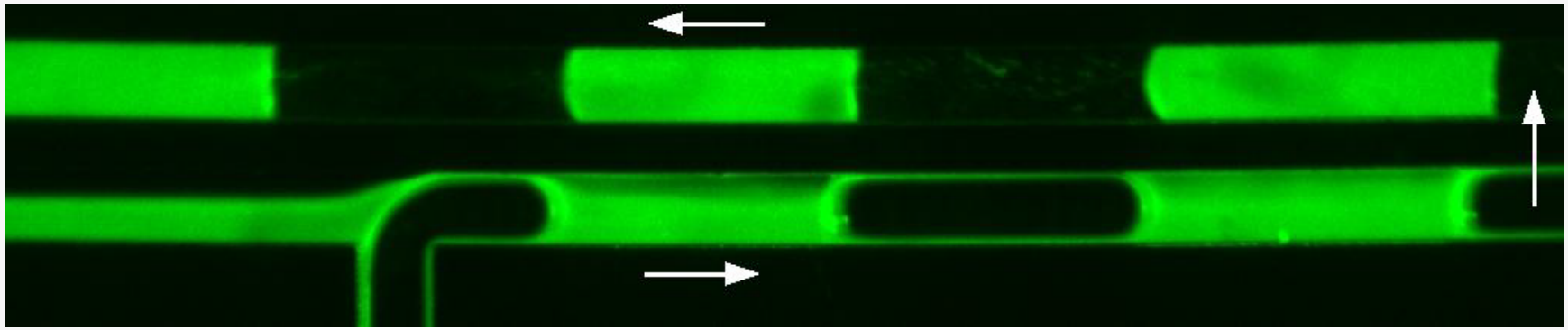
Hilpert, 2000

Fingering

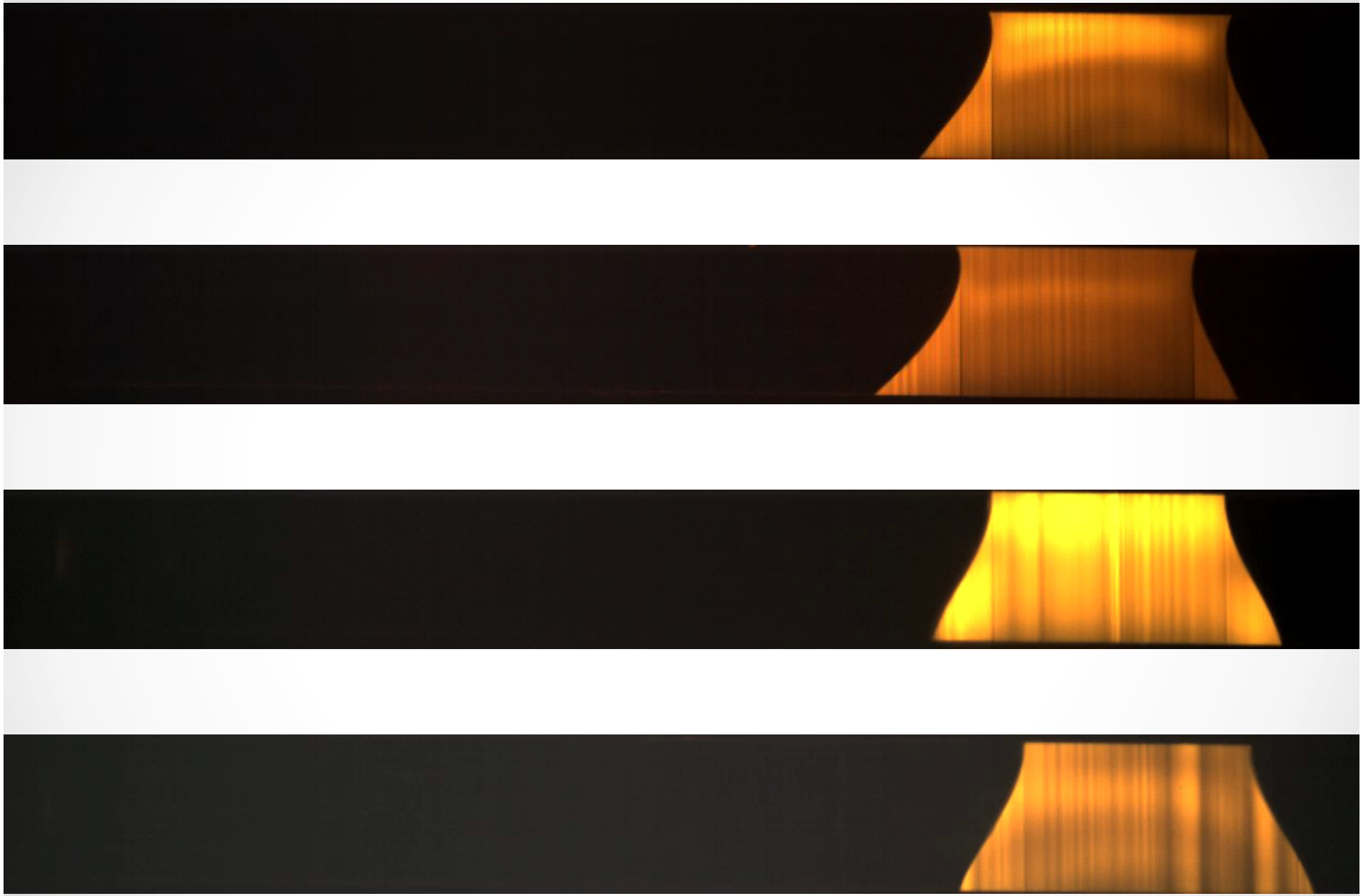


Cueto-Felgueroso and Juanes, 2012

Nonwetting and Partial wetting in microfluidics

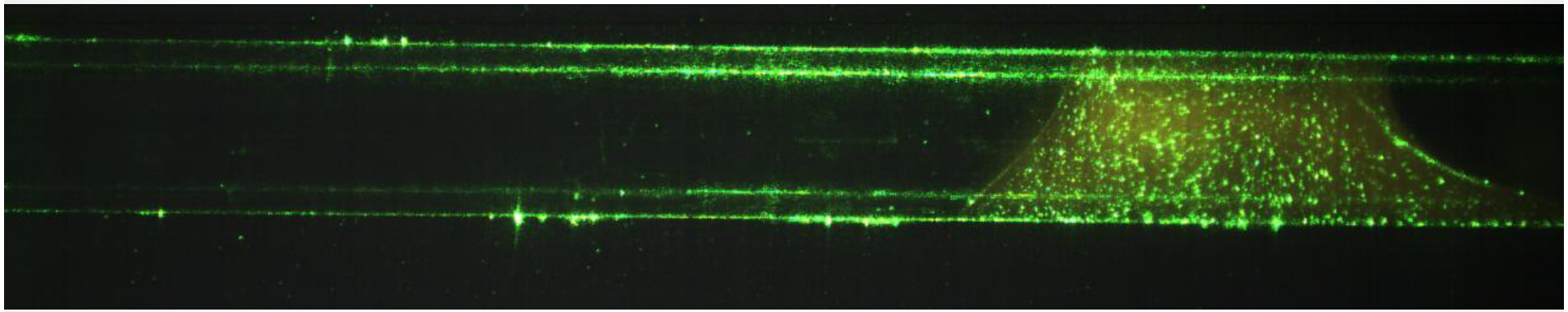


Kazemi and Sinton, 2010



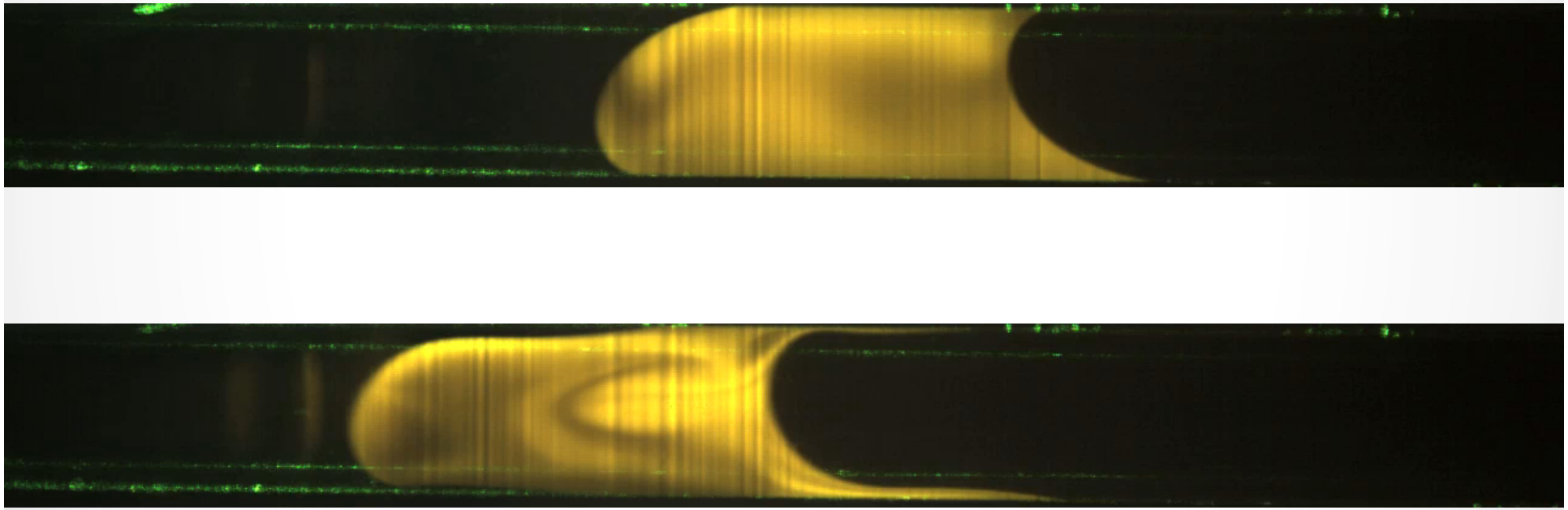
- 孔隙尺度雙相流觀測/強化石油開採

Flow patterns inside mobilized blob (PLIF+PIV)

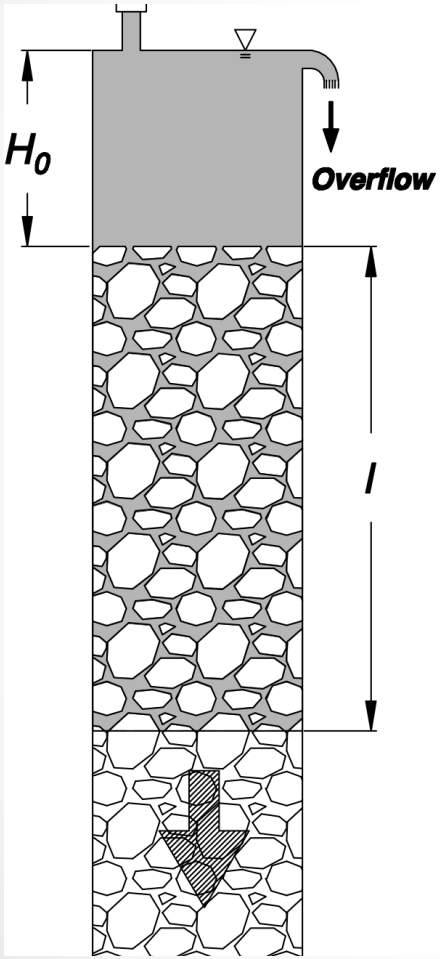


PIV: particle image velocimetry

Blob mobilization with oscillatory flow



Dynamic capillary pressure (Infiltration)



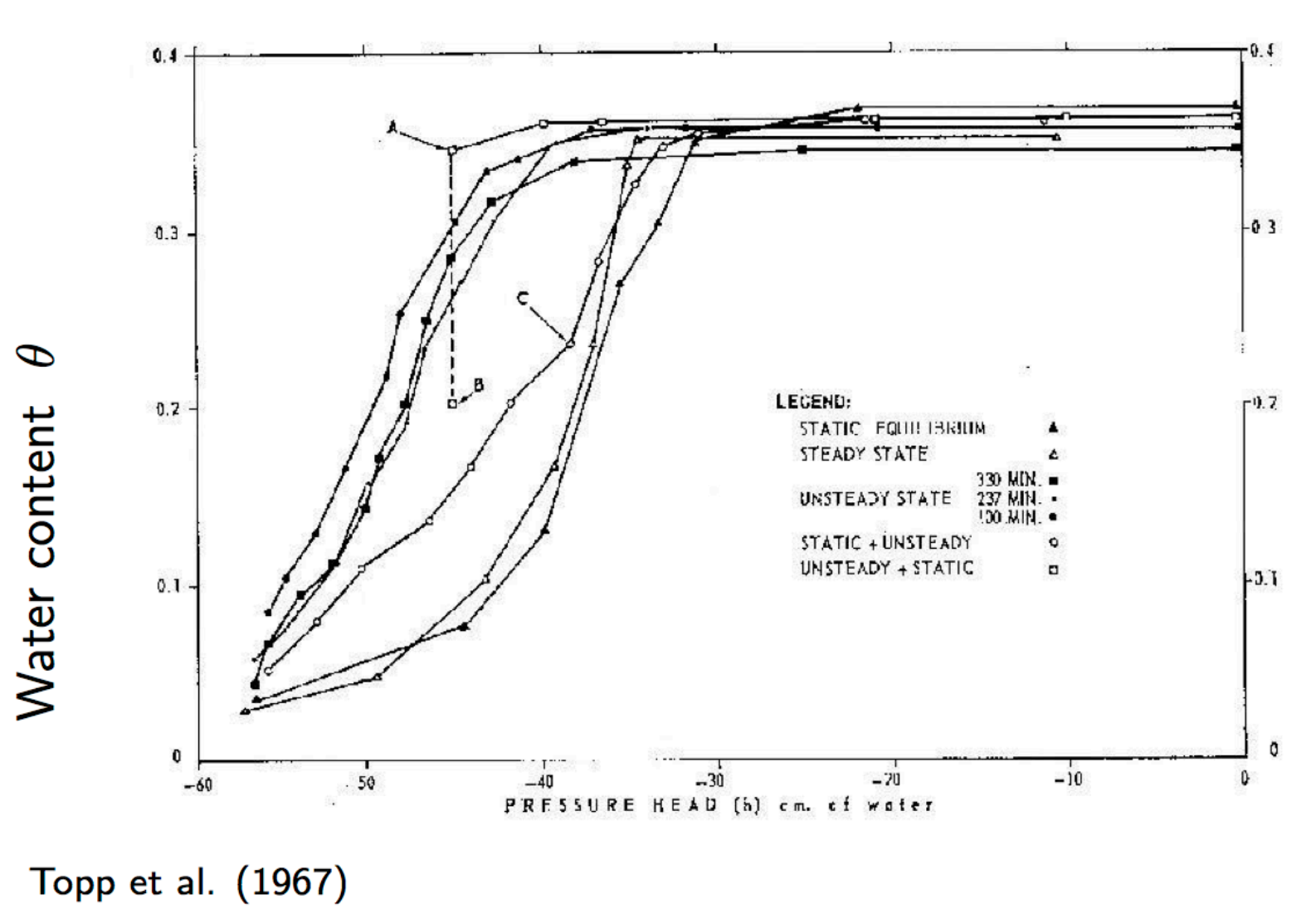
$$q = K\frac{H_0 - h_p(l) + l}{l}$$

where
q: Darcy velocity
K: hydraulic conductivity

$$-h_p(l) = \frac{P_c}{\rho g}$$

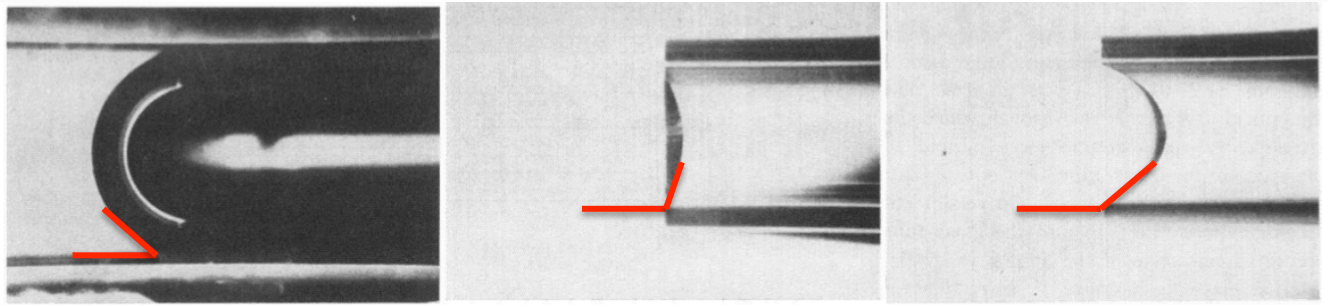
Is capillary pressure P_c dynamic ?

Dynamic capillary pressure



Topp et al. (1967)

Dynamic contact angle



Equilibrium | Low velocity | High velocity

Hoffman (1975)

Dynamic contact angle: $\vartheta = \vartheta(\mathrm{Ca})$

$$\cos\vartheta_{eq} - \cos\vartheta = \alpha \mathrm{Ca}^{\beta}$$

Pore scale: $p_c = \frac{2\gamma}{R}\left(\cos\vartheta_{eq} - \alpha \mathrm{Ca}^{\beta}\right)$

Capillary number: $\mathrm{Ca} = \frac{v\eta}{\gamma}$

(Cox, 1986; Mumley et al., 1986; Joos et al., 1990; Schäffer and Wong, 2000)

Dynamic capillary pressure

Pore scale: $\frac{p_c R}{\gamma} = \cos\vartheta_{eq} - \alpha \mathrm{Ca}^{\beta}$

Darcy scale: $\frac{p_c D}{\gamma} = \underbrace{\mathcal{E}(\varepsilon, \theta_i)\cos\vartheta_{eq}}_{P_{eq}} \underbrace{- \mathcal{E}(\varepsilon, \theta_i)\alpha \mathrm{Ca}^{\beta}}_{P_{neq}}$

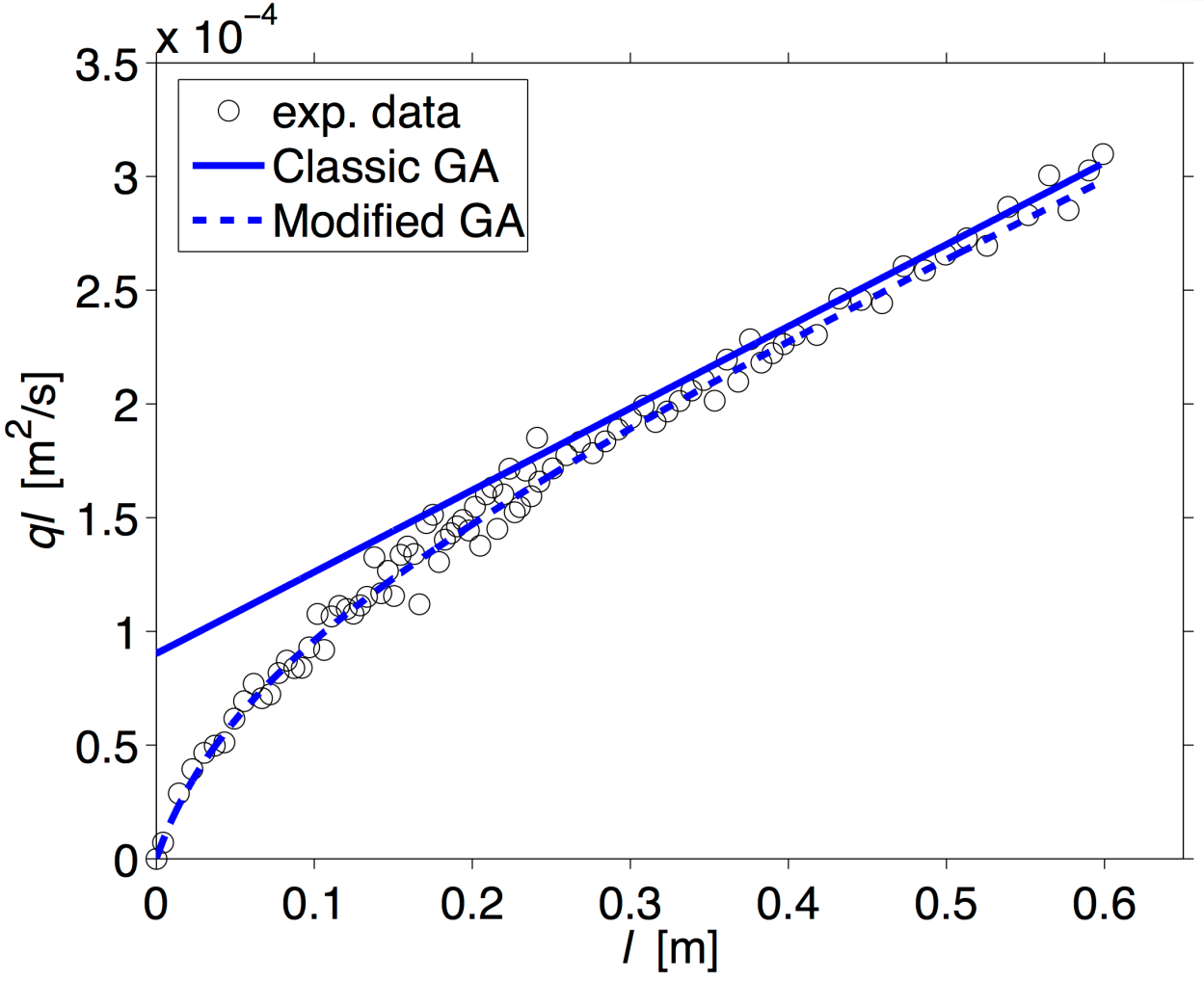
θ_i: initial water content

ε : porosity

Hsu and Hilpert (2010)

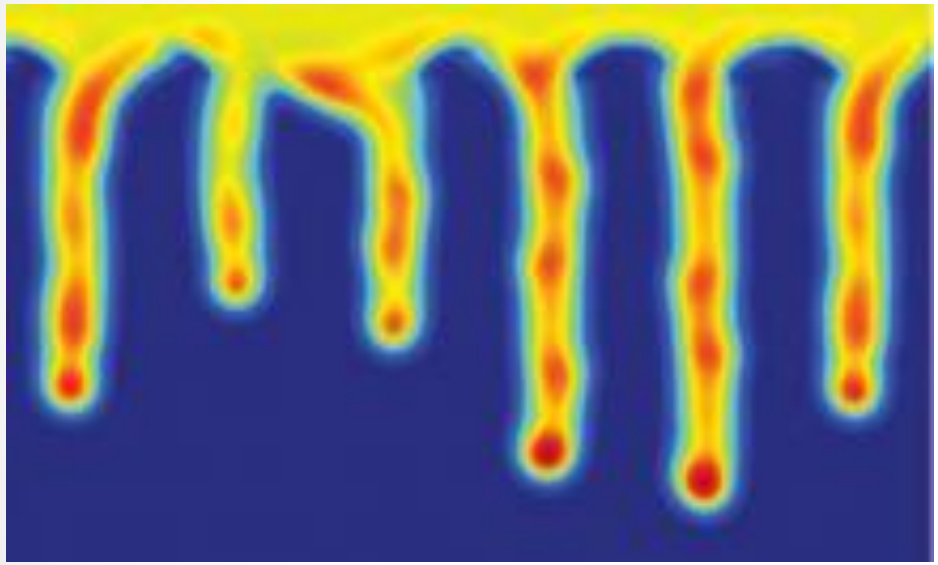
Modified Green Ampt model

$$ql = K(H_0 - h_p(Ca) + l)$$

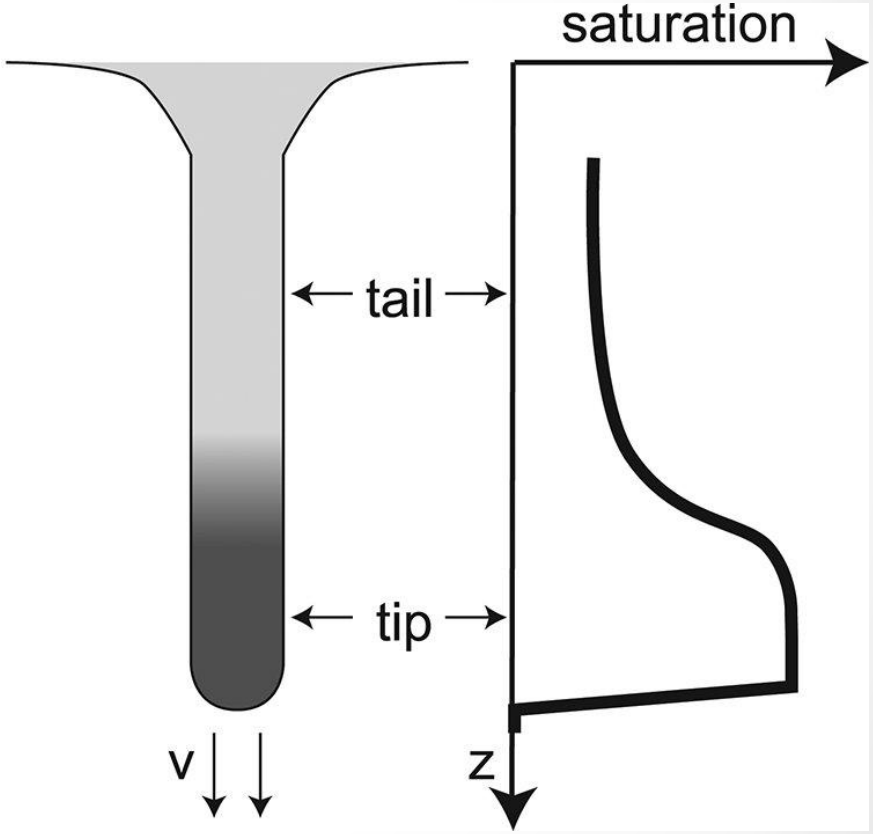


Pellichero et al., 2012

Gravitaty-driven fingers & saturation over shoot

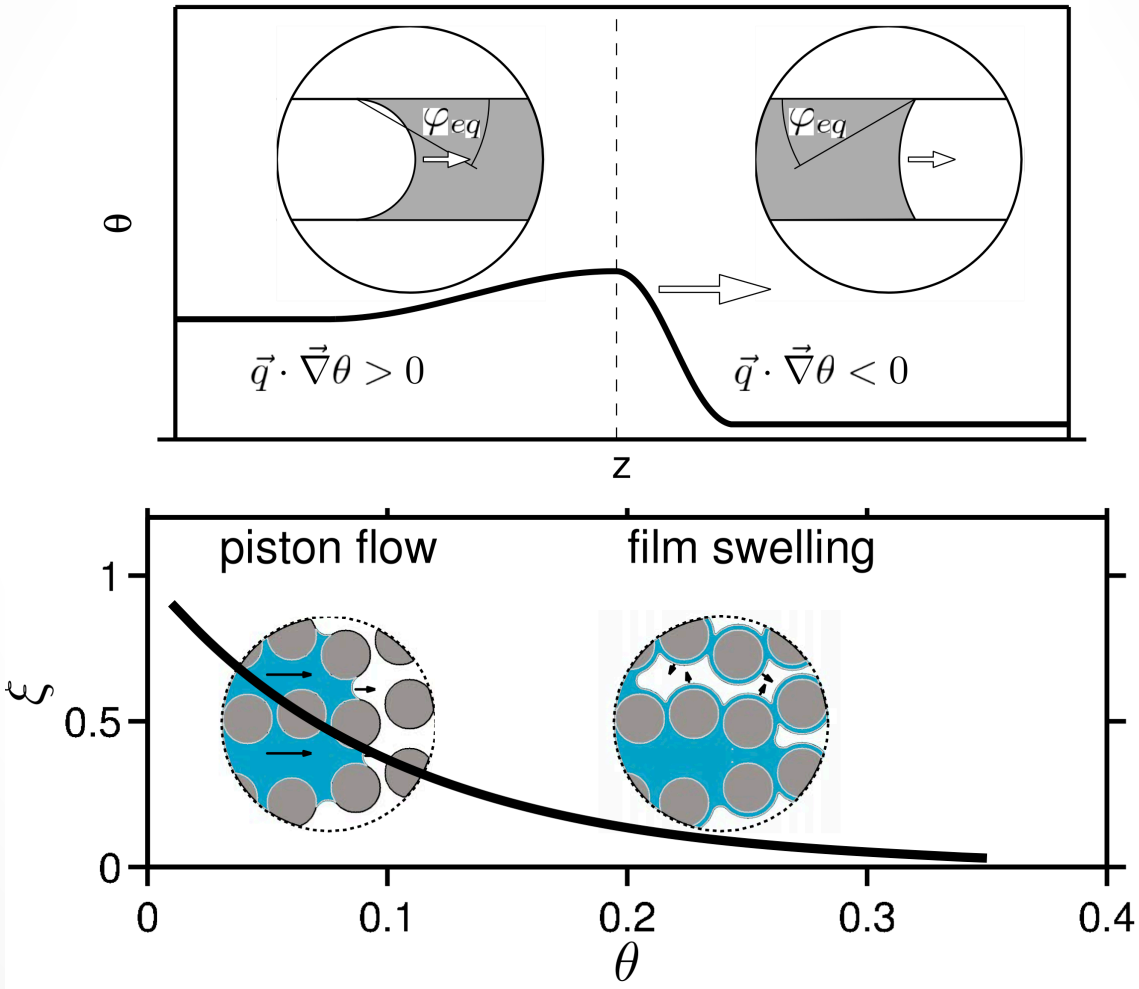


Cueto-Felgueroso



DiCarlo, 2004

Dynamic contact angle & saturation over shoot



Hilpert, 2012

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Isco 500D

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Dr. William P. Ball

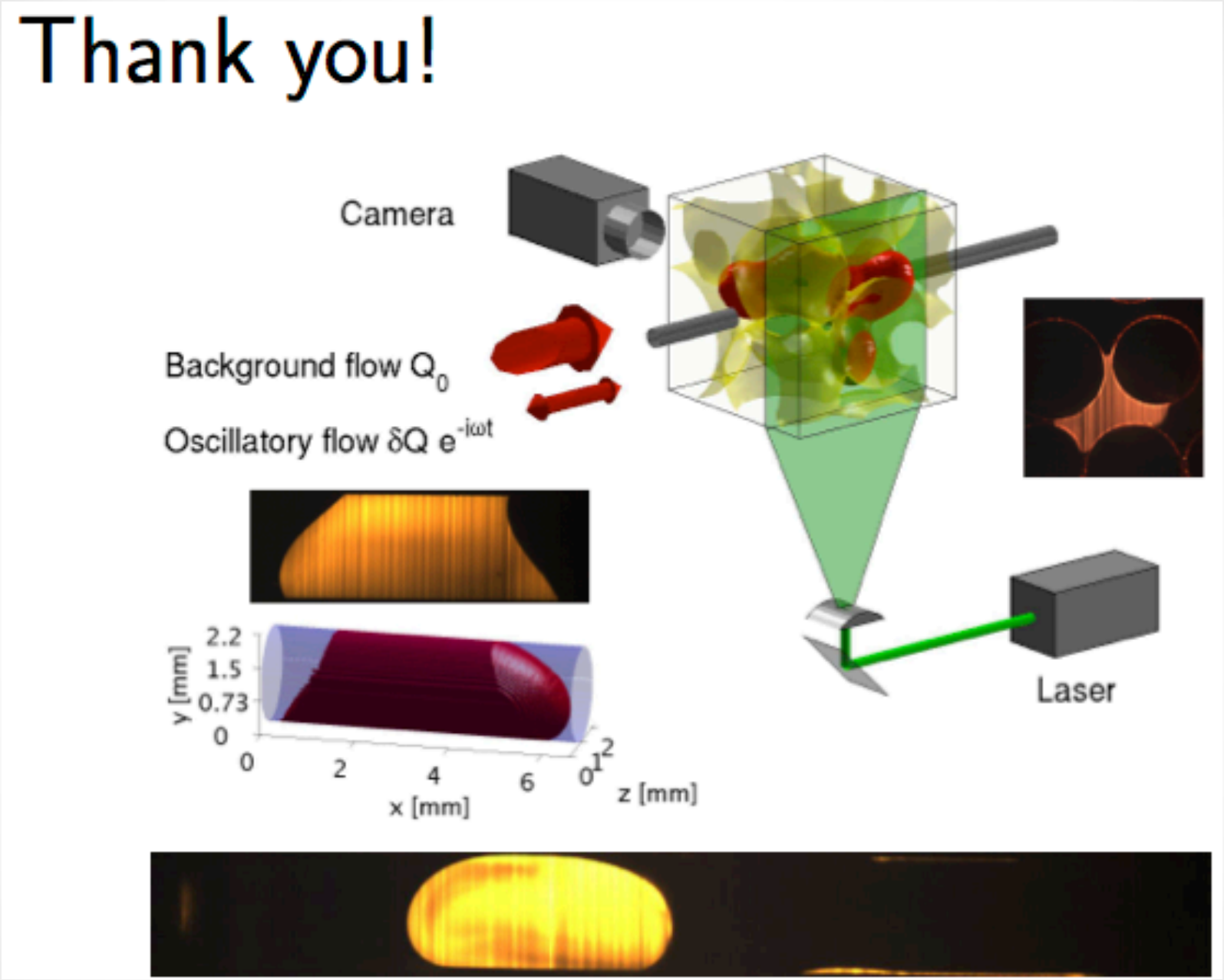
孔隙流概論

Introduction to porous media flow

- **課程目標**:了解水與其他流體在孔隙介質中的**行為機制**，並進一步探討**地下水**資源管理、強化**石油開採與地質碳封存等地質水文問題**。

- **授課內容**：將從日常生活常見的毛細現象出發，探討流體的內聚力與附著力，以及固體對流體的溼潤性。並配合基礎流體力學，解釋單種或多種流體在孔隙介質中的各種物理現象及其相關理論。進一步利用這些觀念來探討地表入滲、地下水資源管理、 強化石油開採與地質探封存等地質水文問題。

Thank you!


Camera
Background flow Q_0
Oscillatory flow $\delta Q\ e^{-i\omega t}$
Laser
y [mm]
2.2
1.5
0.73
0
0
2
4
6
x [mm]
0
1
2
z [mm]