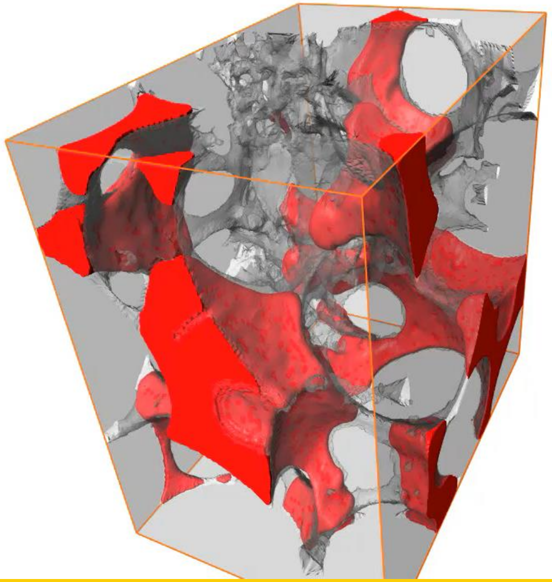
Mobility of Disconnected Fluid Phases

From Ganglion Dynamics to Intermittency and Gas Dynamics

2020 International Symposium of the
Society of Core Analysts
- Online -



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Reserves: Our use of the term "reserves" in this presentation means SEC proved oil and gas reserves.

Resources: Our use of the term "resources" in this presentation includes quantities of oil and gas not yet classified as SEC proved oil and gas reserves. Resources are consistent with the Society of Petroleum Engineers 2P and 2C definitions.

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Presentation on Sept 24

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Outline

- Critical Gas Saturation and Gas Mobility (SCA 2019-021)
  - gas mobility below percolation threshold
  - possible mechanisms
- General case: mobility of non-wetting phase without (permanent) connectivity
  - the relative permeability concept – traditionally: only connected phases are mobile
  - observations by beamline based μCT: mobility without permanent connectivity
  - snap-off during drainage
  - intermittency (showing examples from Imperial College)
  - ganglion dynamics and impact on fluid topology / connectivity
  - discontinuous displacement events and energy dissipation

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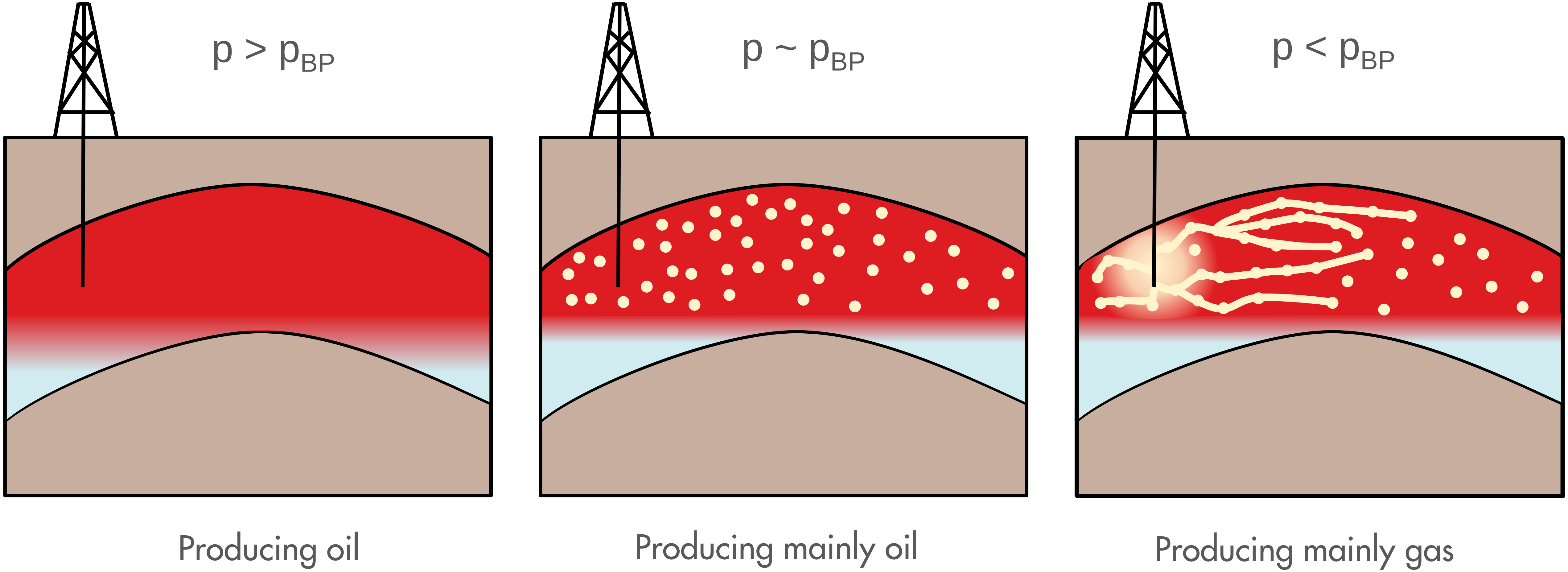
SCA 2019-021: Critical Gas Saturation and Gas Mobility



At which gas saturation does the gas become mobile ?

Relative permeability?

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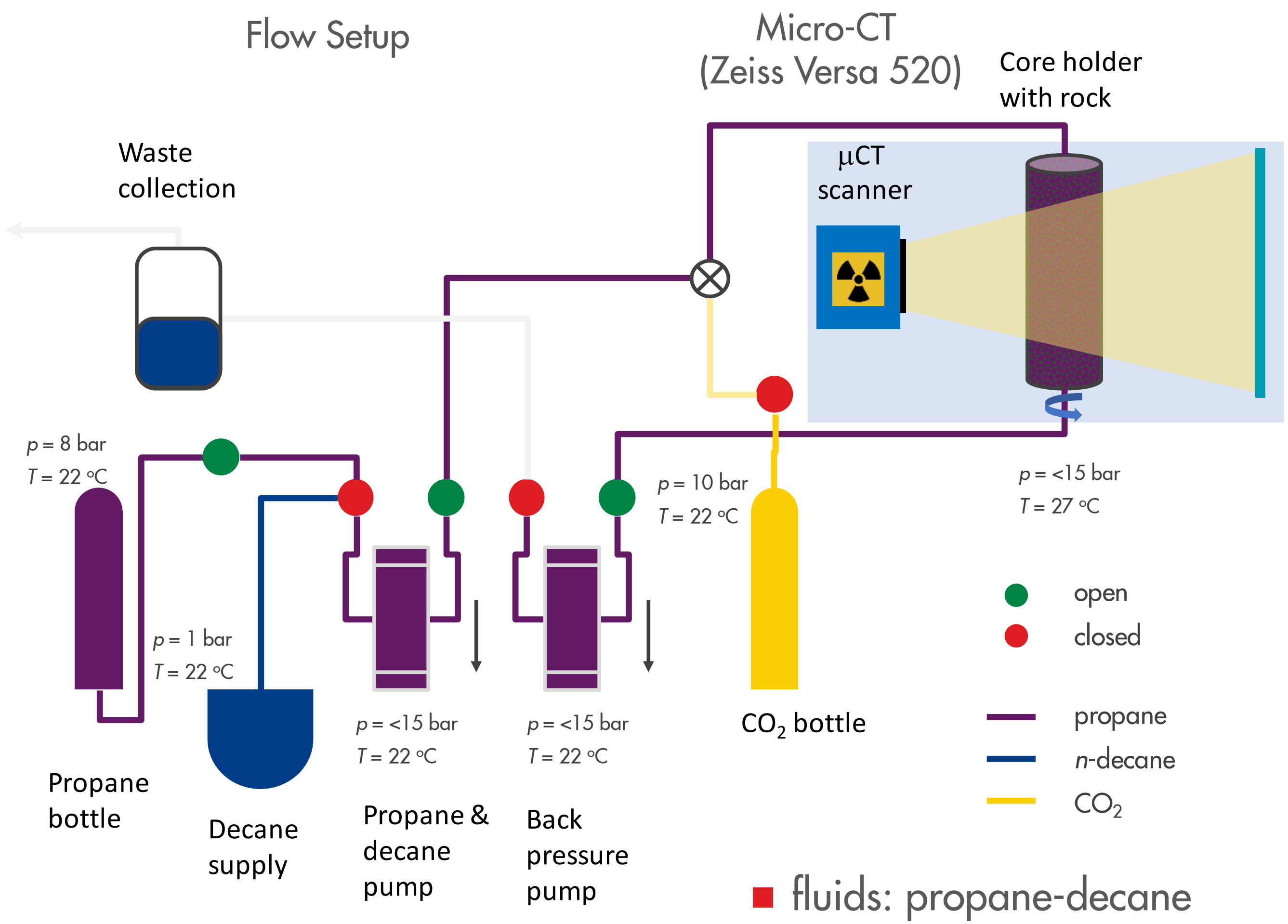
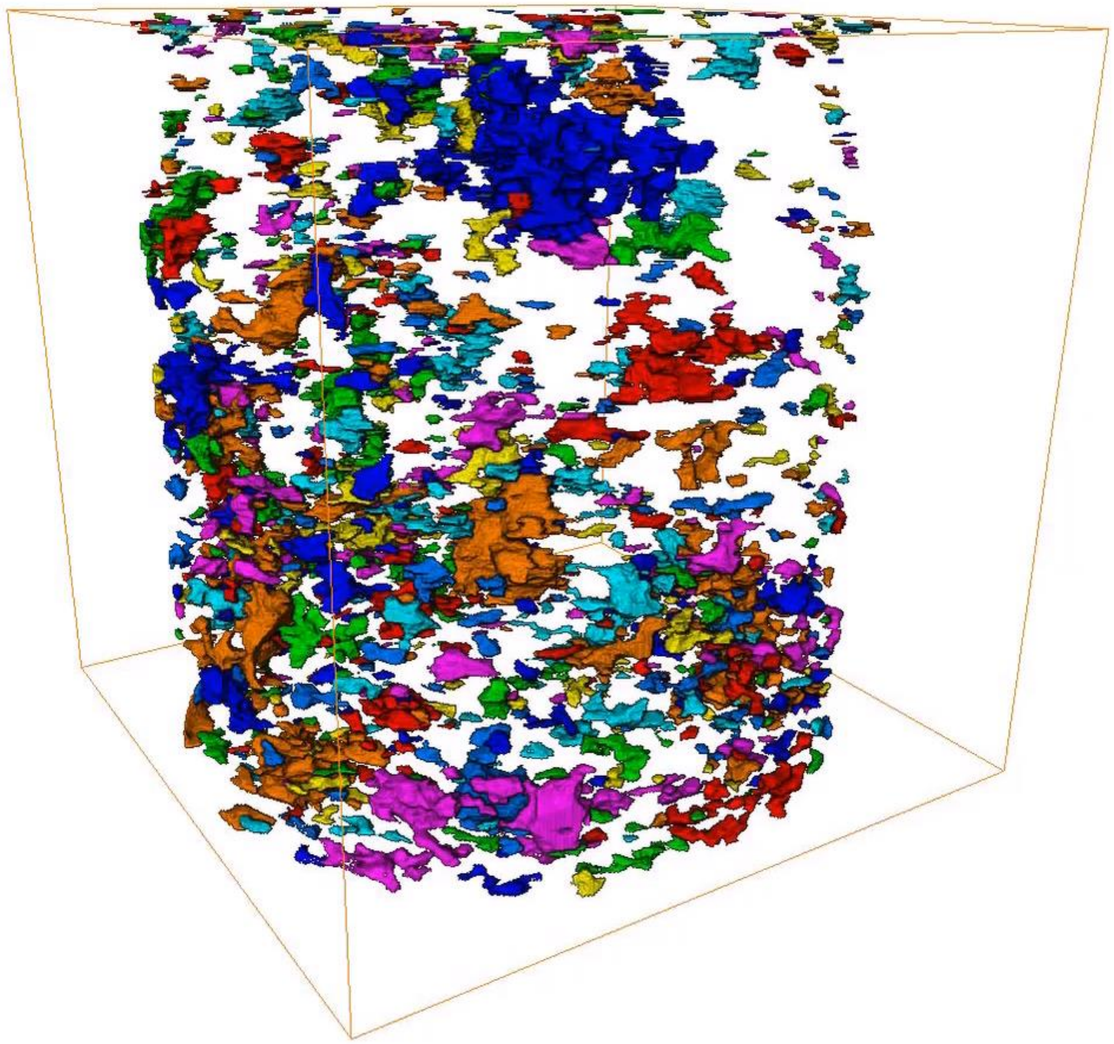
Micro-CT Pressure Depletion & Flow Experiments



- fluids: propane-decane
- Rock: Bentheimer



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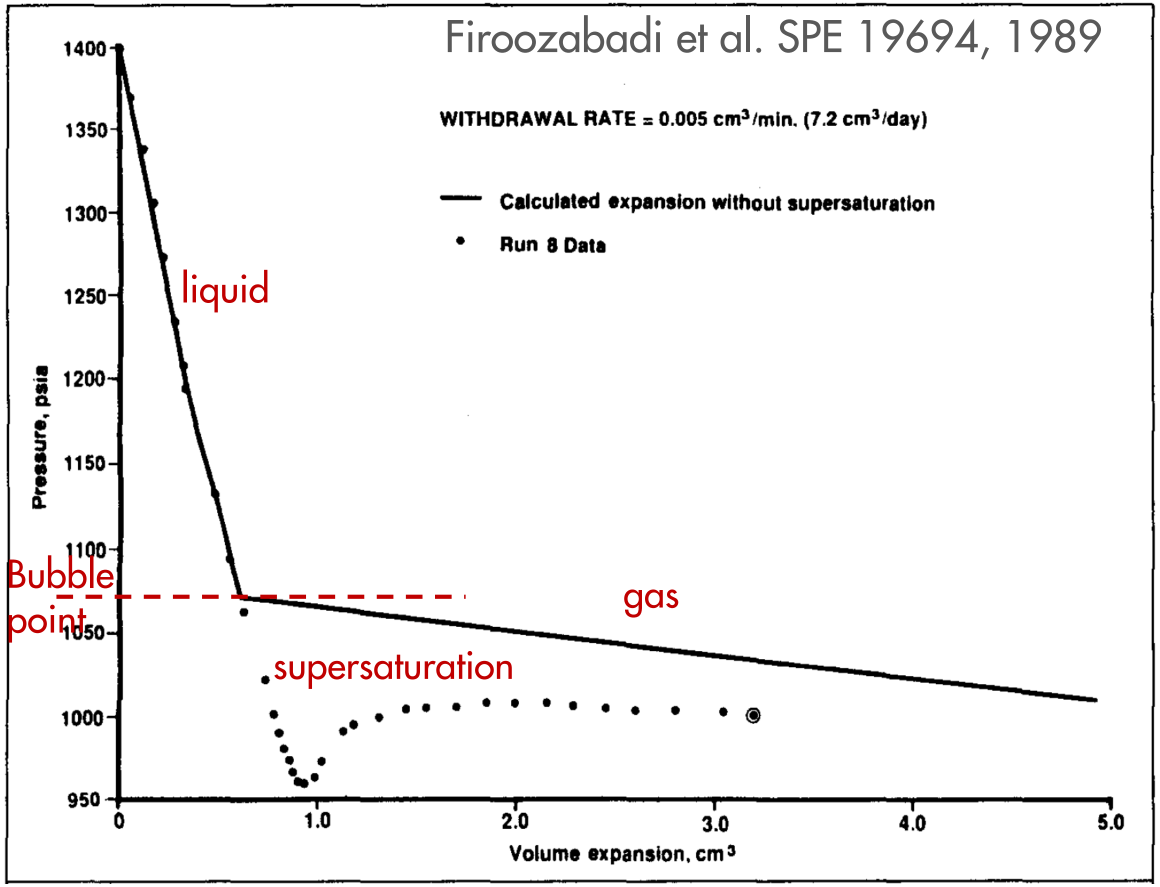
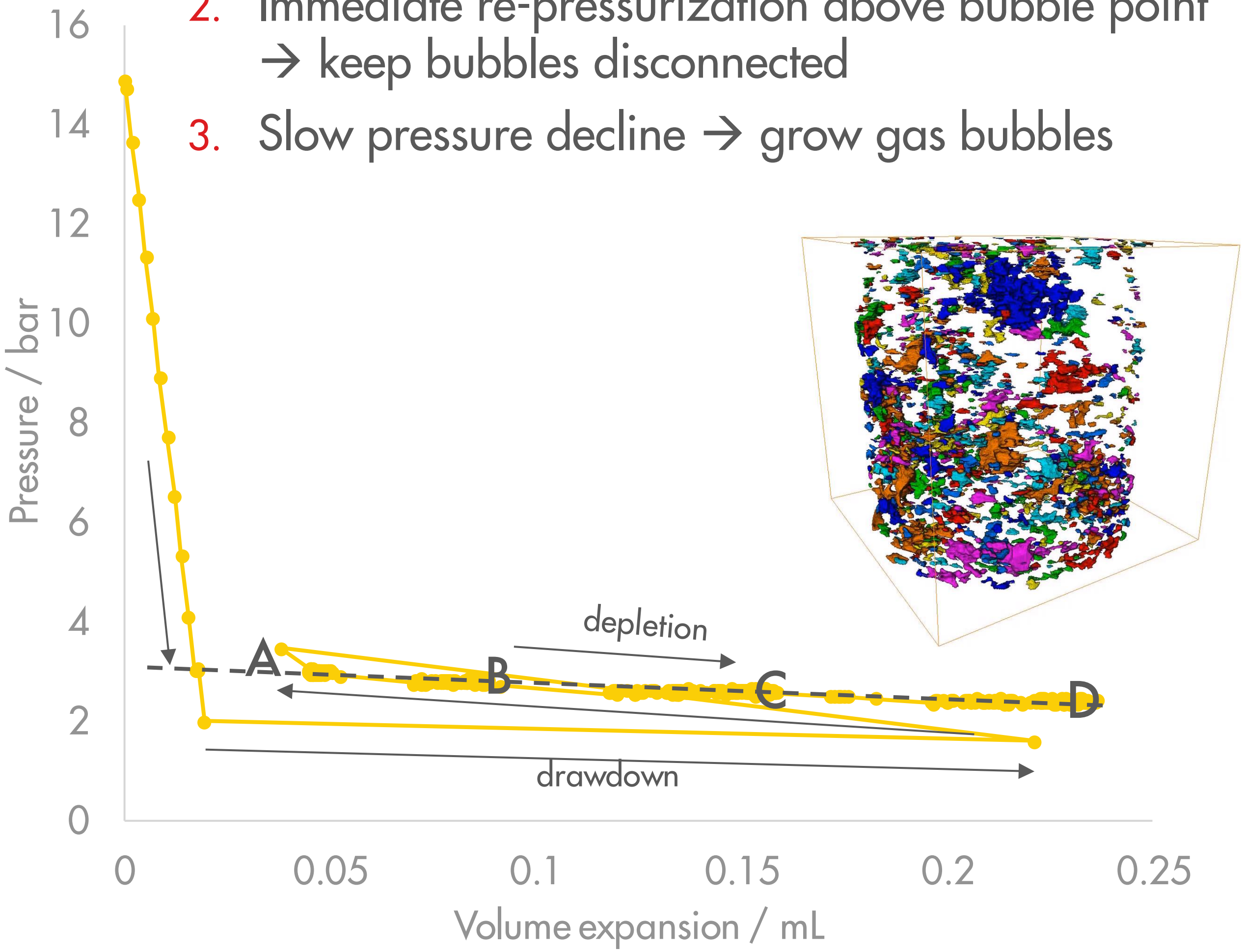
Pressure Depletion Experiments: Gas Nucleation and Connection

Observation of bubble point in porous medium depressed

supersaturation → nucleation → gas bubbles



1. Rapid pressure drawdown into super-saturation → nucleate gas bubbles
2. Immediate re-pressurization above bubble point → keep bubbles disconnected
3. Slow pressure decline → grow gas bubbles



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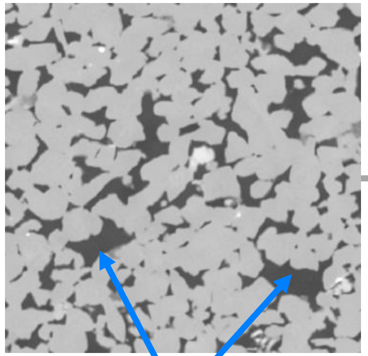
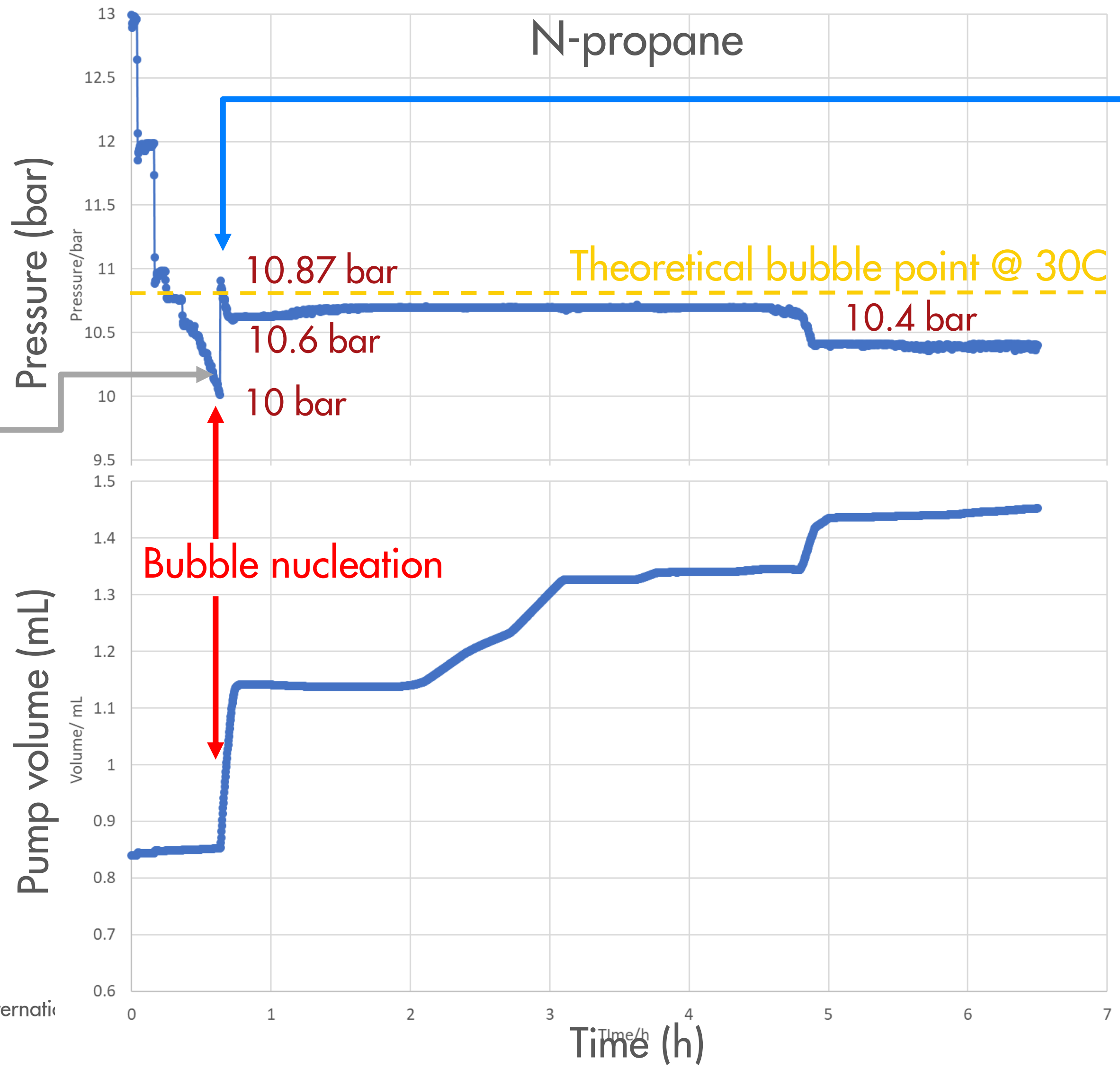
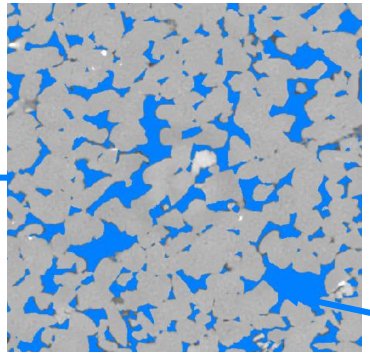
Bubble Point Depression also for Single-Components







- At bubble point: no nucleation (same as propane-decane mixture)
- Observation of bubble point depleted
- Gas coming out of solution, displacing all liquid from pores

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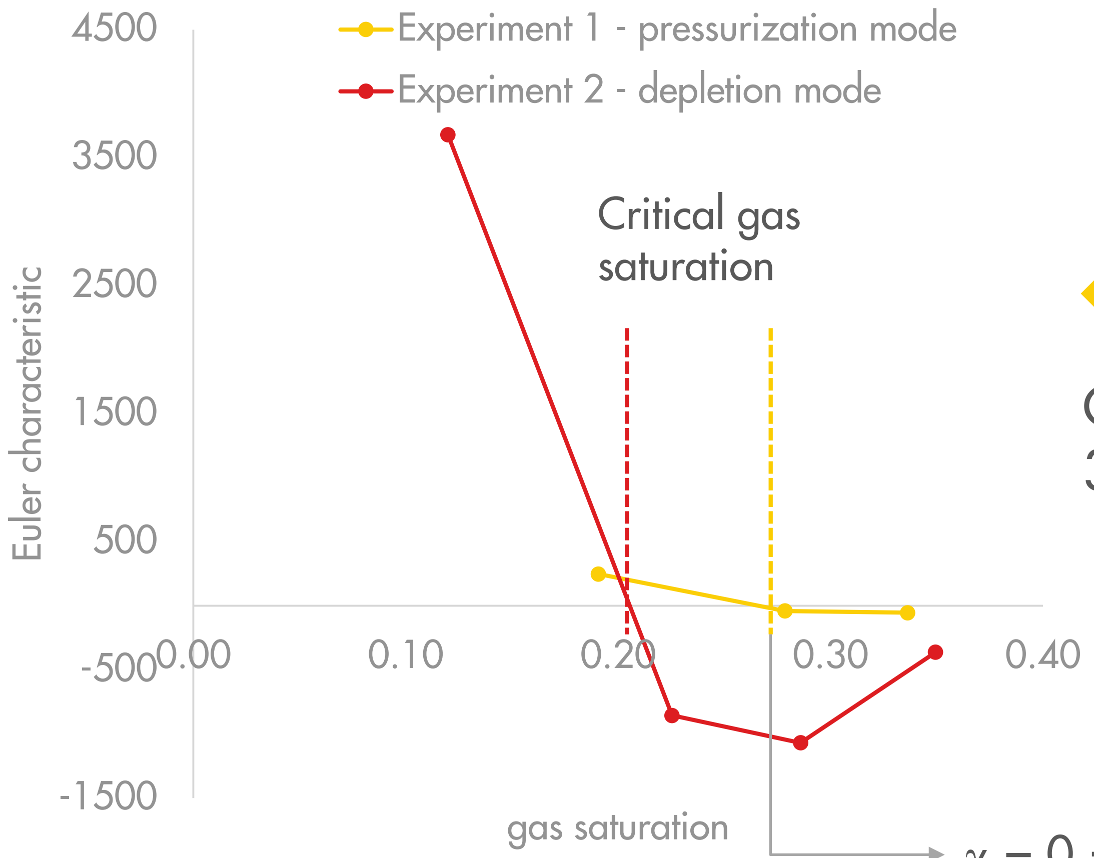
Depletion: Gas Connectivity Consistent with 3D Percolation Threshold

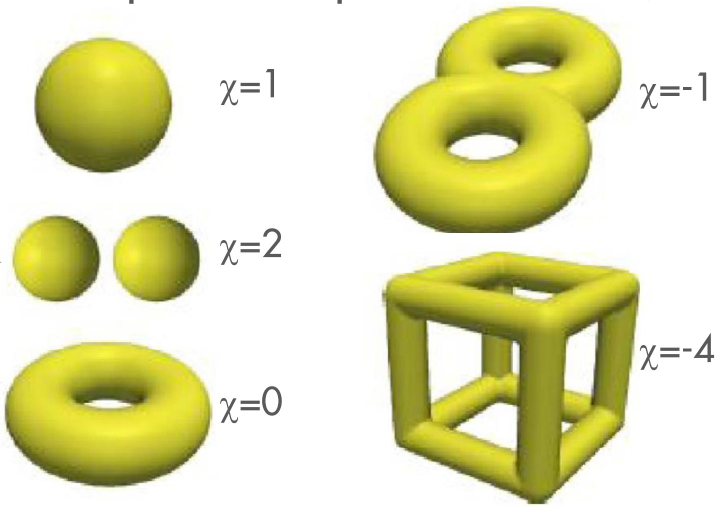


Consistent with 3D percolation thresholds

Structure	Coordination number	percolation threshold
Simple cubic lattice	6	0.30-0.31
bcc lattice	8	0.24-0.25
fcc lattice	12	0.19-0.20
Sphere pack	6	0.31

Euler Characteristic χ = Objects – Loops (+ Inclusions)

χ = 0 → percolation threshold



Herring, AWR 2013

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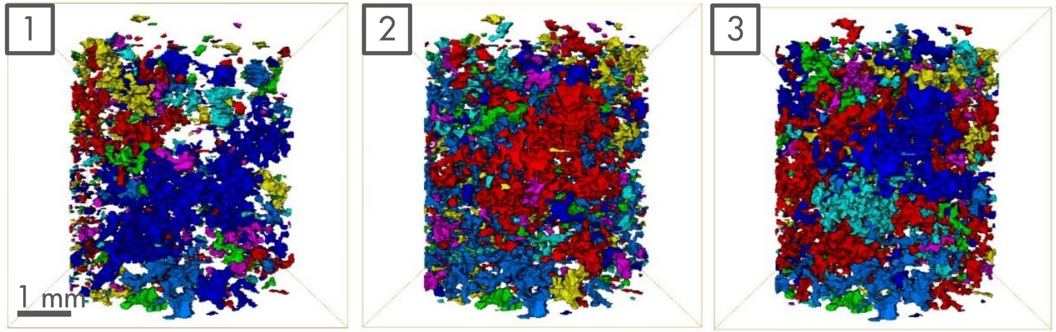
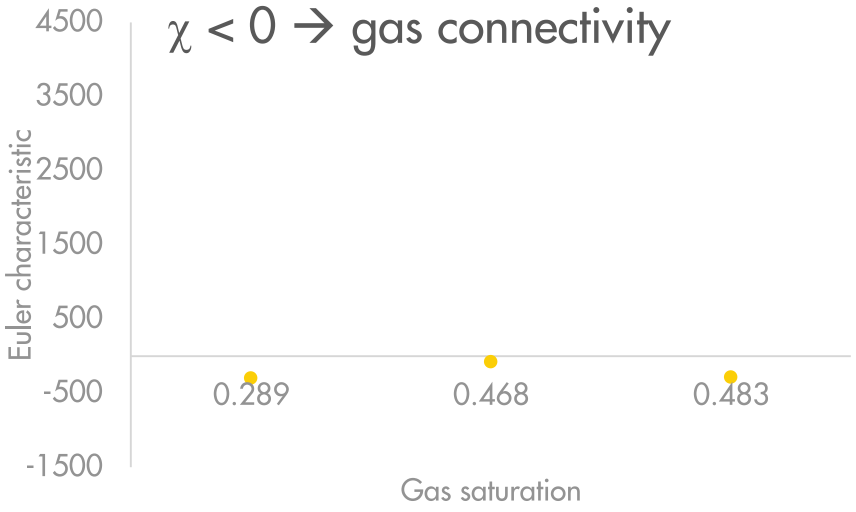
Injection of Gas Near Bubble Point

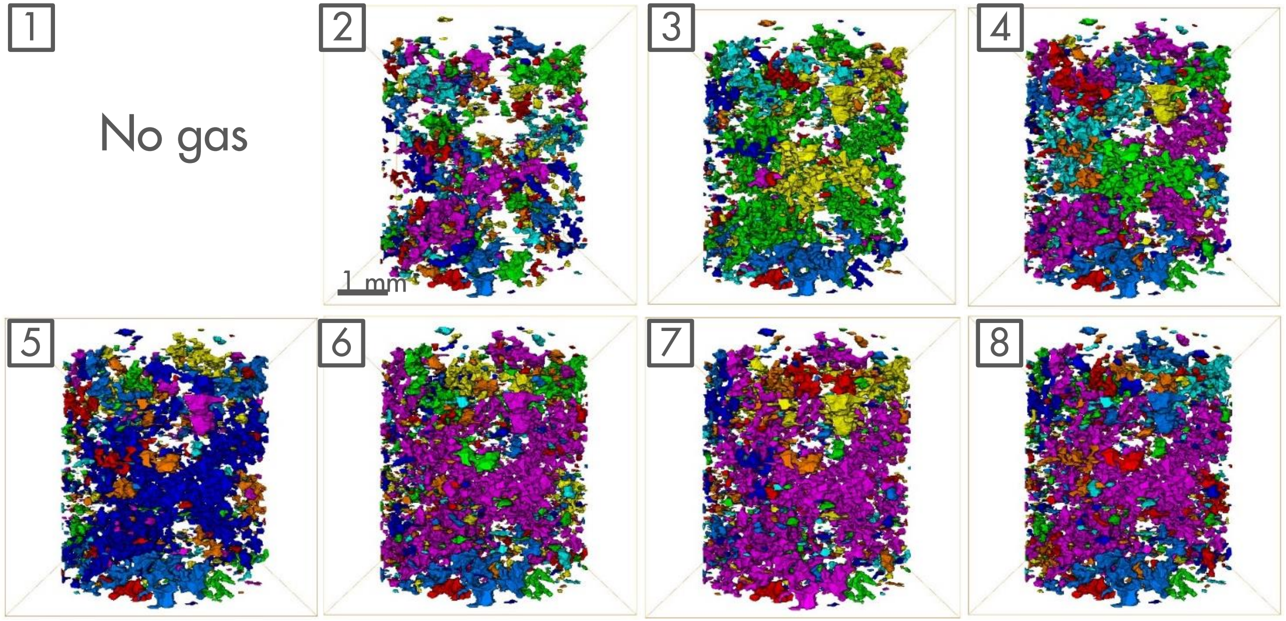
High flow rate (72 mm/h)
Ca~1.8 10^{-6}, Pe~1



$\chi < 0 \rightarrow$ gas connectivity

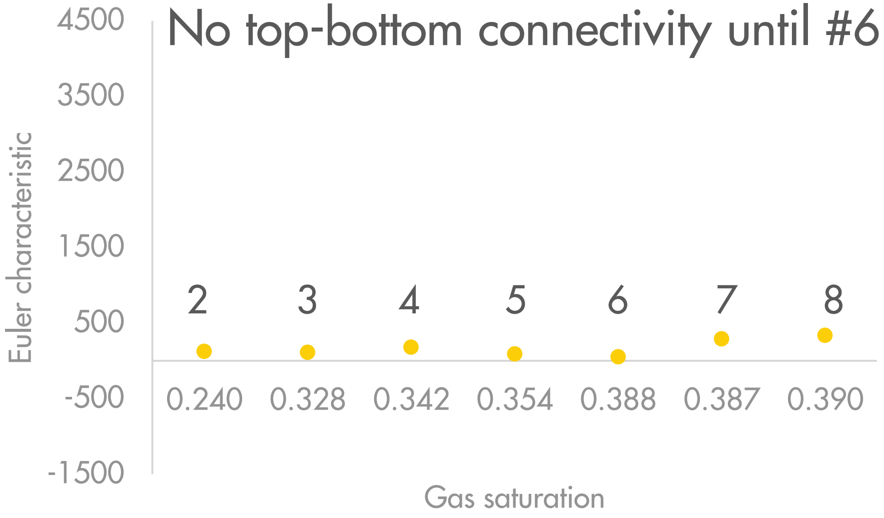


Low flow rate (2.4 mm/h)
Ca~6 10^{-8}, Pe<<1



$\chi > 0 \rightarrow$ no 3D gas connectivity

No top-bottom connectivity until #6



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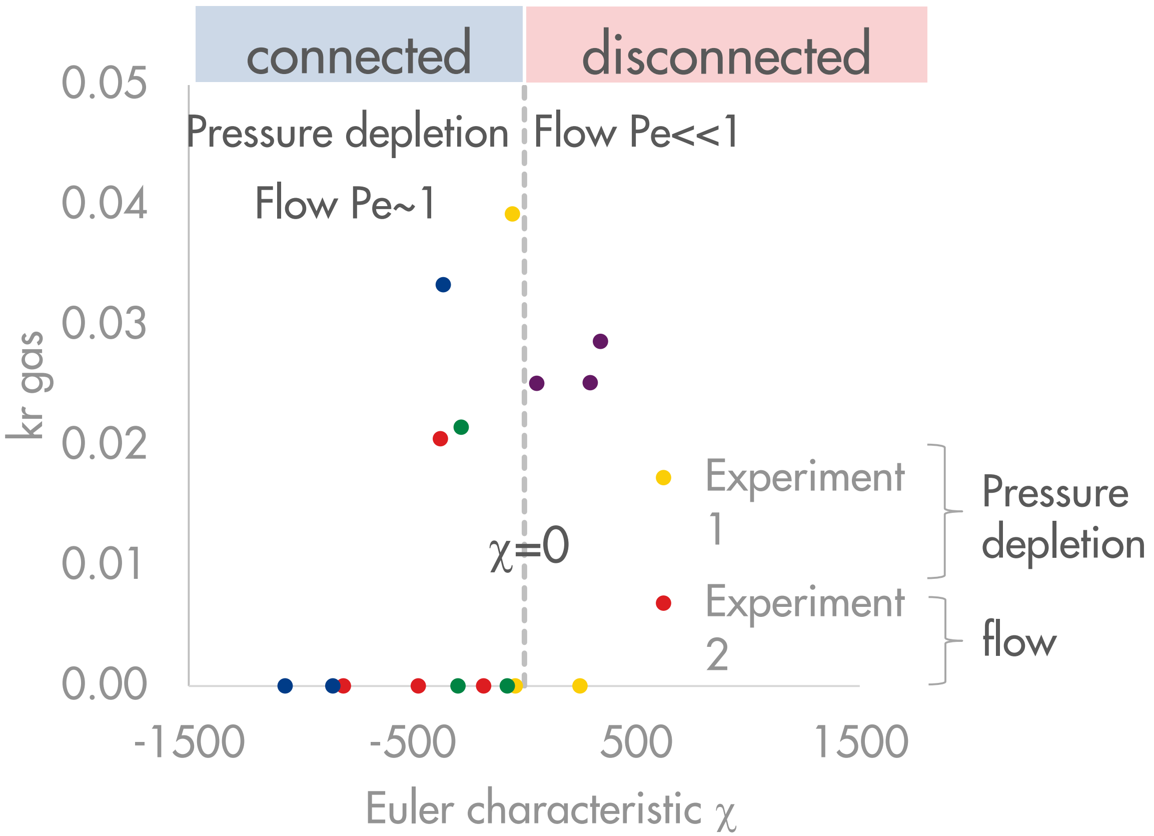
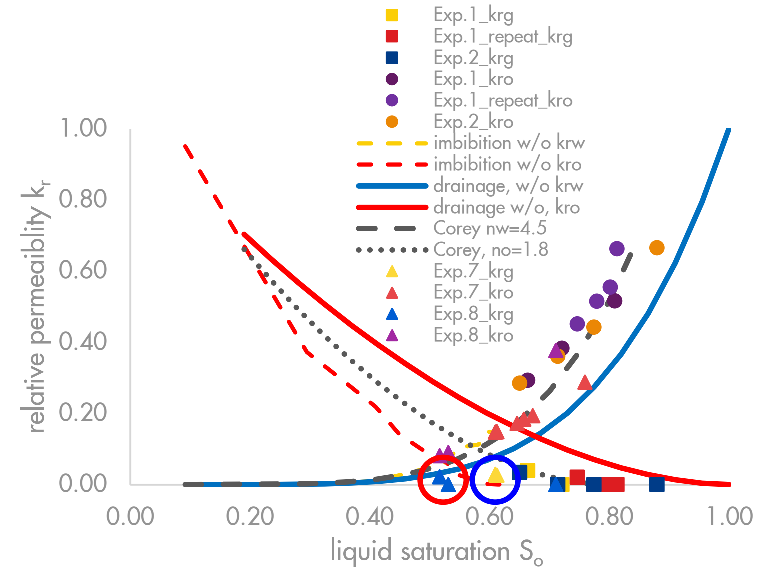
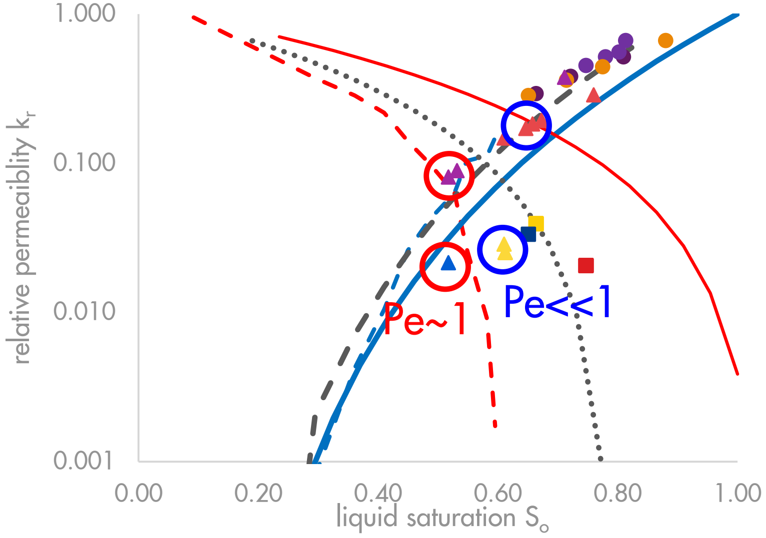
Gas Mobility Below Percolation Threshold







- Gas relative permeability from flow experiments different than depletion experiments
- slow flow experiments have systematically different connectivity than fast flow experiments

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Also: injection kr different than pressure-depletion

→ relative permeability process-dependent !

Ying Gao, Jesse Dietderich, Omer Alpak

Gas Mobility Below Percolation Threshold: Possible Mechanism

Peclet number $Pe = \frac{L \cdot v}{D}$

High flow rate: Pe ~ 1

→ more convective transport

Low flow rate: $Pe=4 \cdot 10^{-2}$

→ diffusive transport

Phase-field + PVT modelling

of phase transition methane-decane

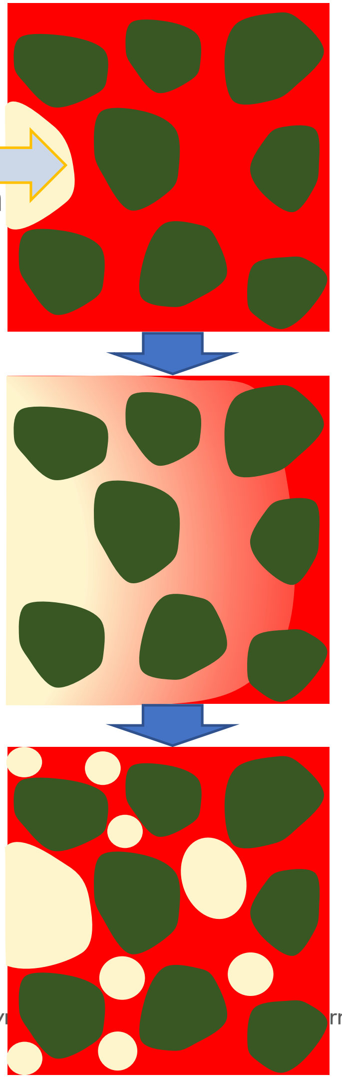
+ **diffusive** mass exchange

RICE

Courtesy of

Beatrice Riviere

Gas injection

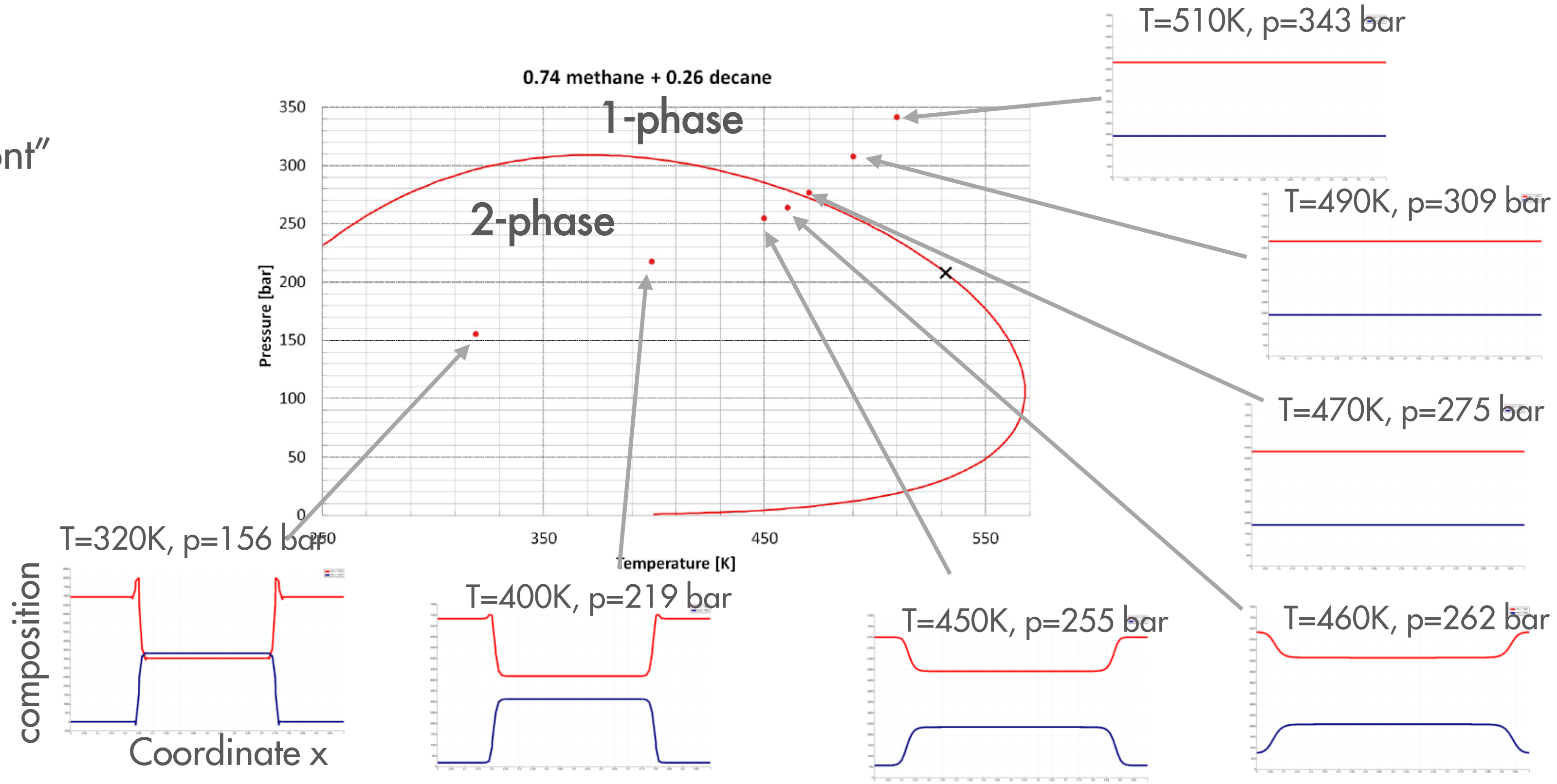


gas can diffuse
ahead of convective "front"

bubble point decreases
below set pressure

Phase separation
into liquid and gas

gas center
liquid
pore throats



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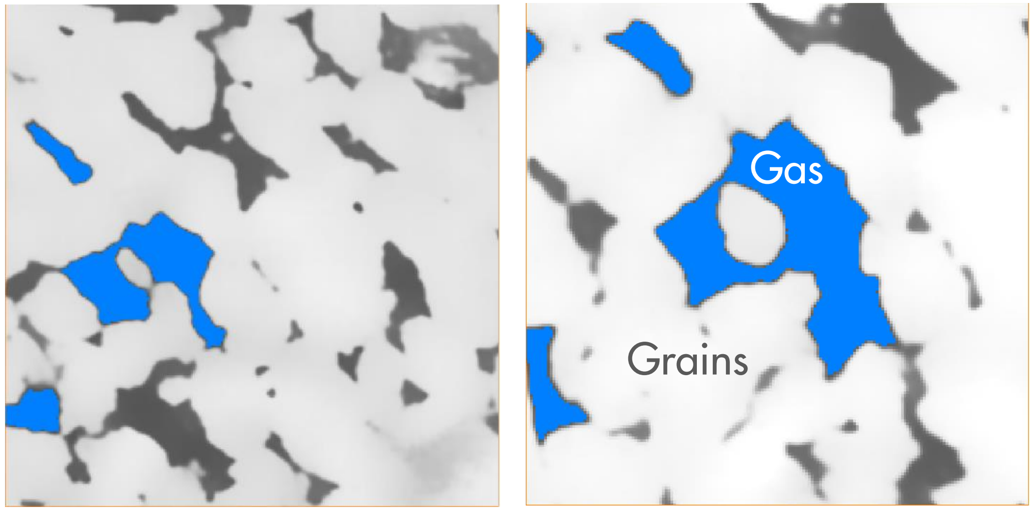
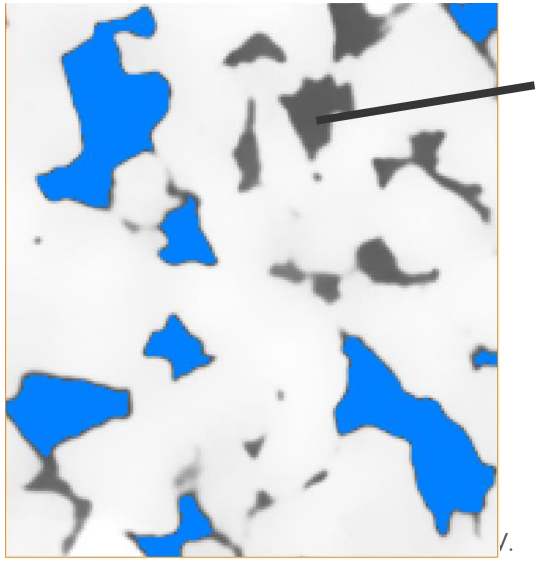
Evidence: Pore Level Occupancy – Different than w/o Displacements

Propane-decane pressure depletion experiment

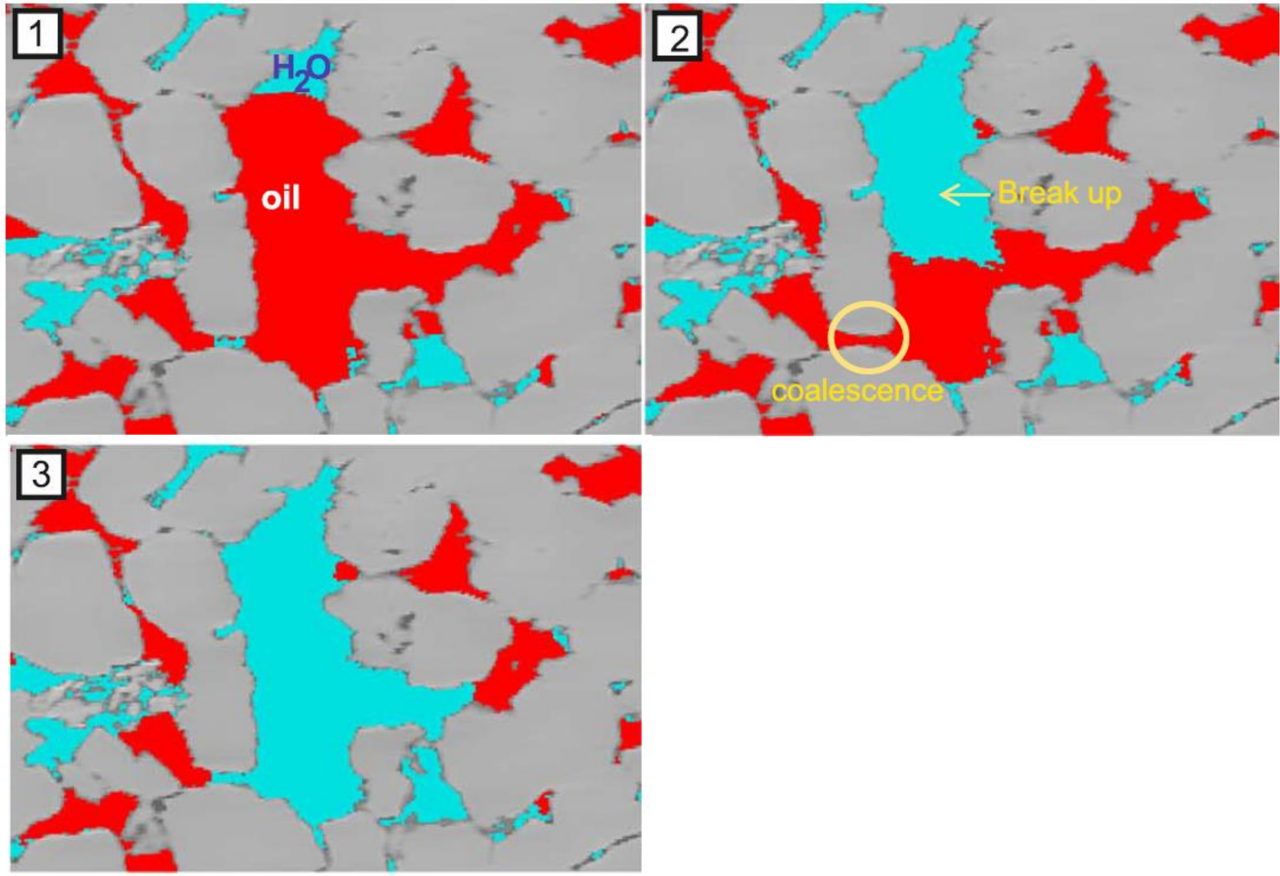




Liquid

Observation:
Pores bodies filled with either 100% gas or 100% liquid

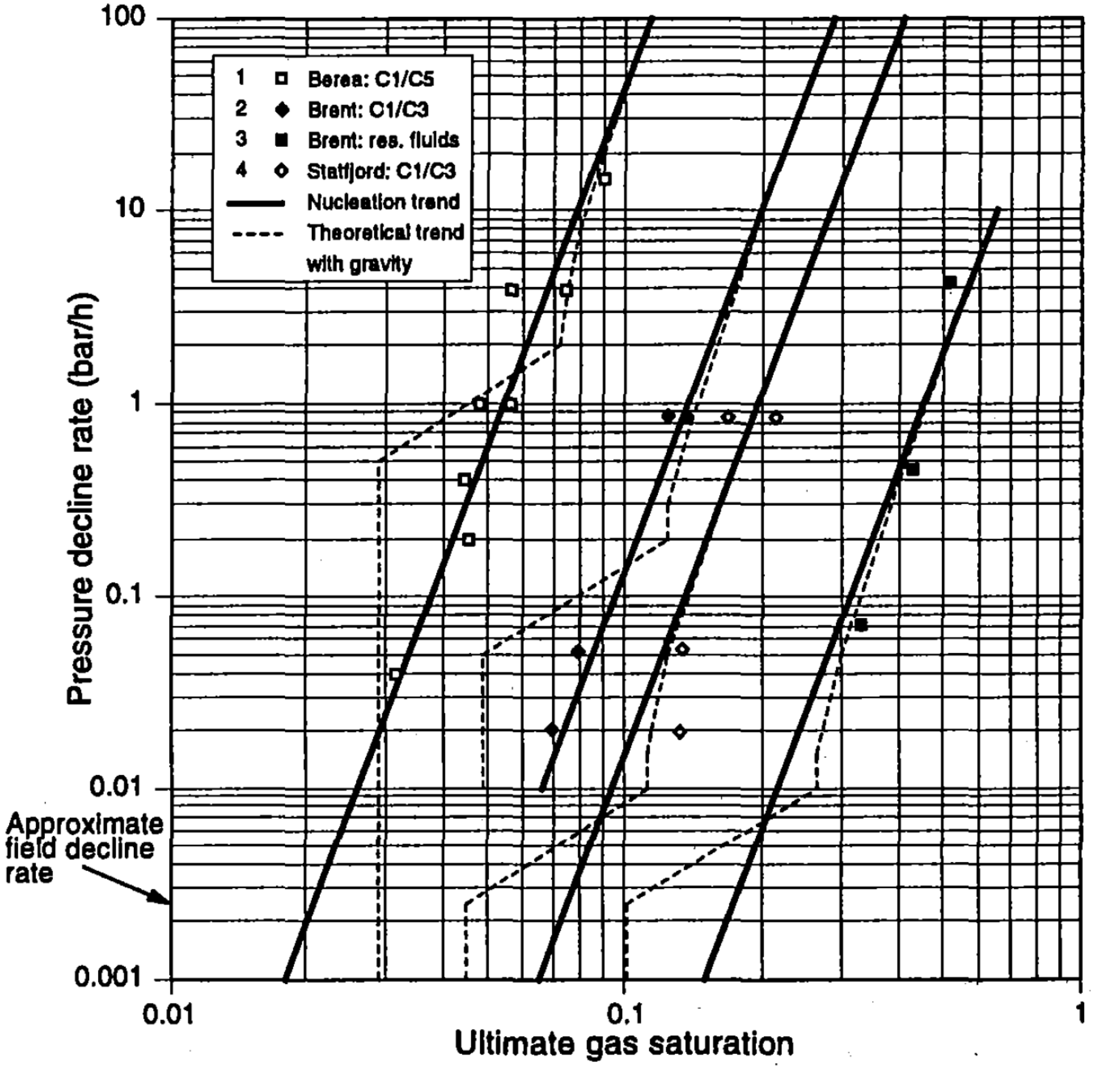
Water-oil imbibition experiment in Gildehauser sandstone



Oil and water co-exist in pore space to a larger extent

Relevance of (anti-) ripening ? (Ke Xu et al. PRL 2017, GRL 2019)

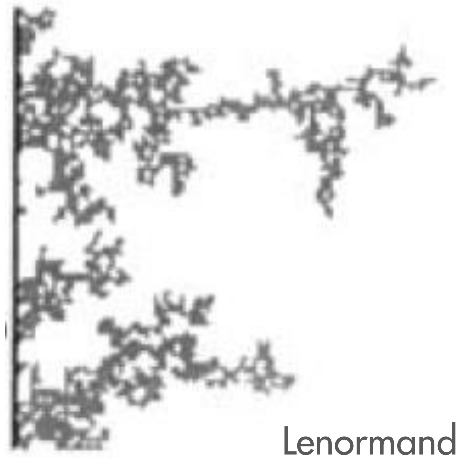
Gas Mobility Below Percolation Threshold Consistent with Literature!



Scherpenisse et al. 1994

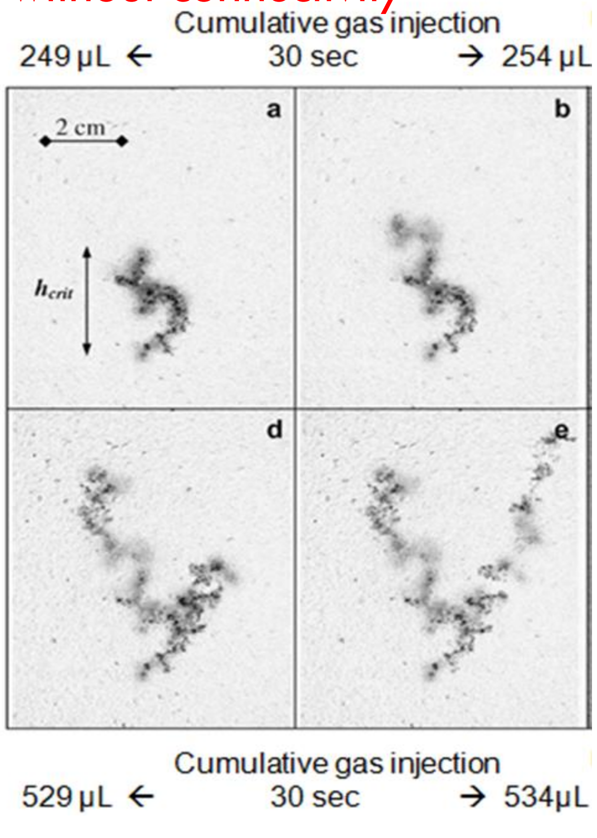
- Literature: 3% < S_g^{crit} < 50 % - in field studies often 5-10%
- Depends on - rock, fluid (near-critical ?), depletion rate.

Unstable displacement at pore scale



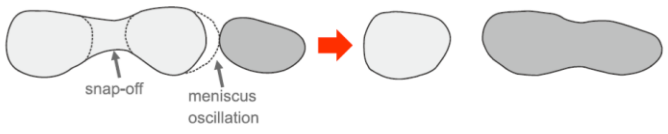
Lenormand, 1998.

Gas clusters can be mobile without connectivity



Ji 1993, Plummer 1997, Mumford 2008

Ganglion dynamics



Rücker et al. GRL 2015

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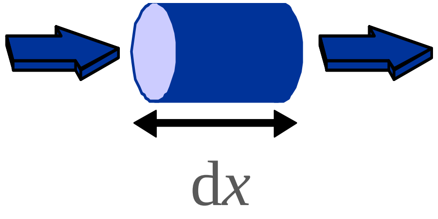
2-Phase Darcy Implicitly Assumes Connected Pathway Flow

Single-Phase

water



$$v_{Darcy} = -\frac{K}{\mu}\frac{dp}{dx}$$

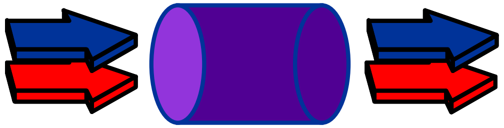
Darcy's law

μ viscosity
P pressure
K (K_{abs}) absolute permeability

Viscous law (similar to pipe flow) can be derived from upscaling Stokes flow at pore scale by homogenization

Two-Phase

water, oil

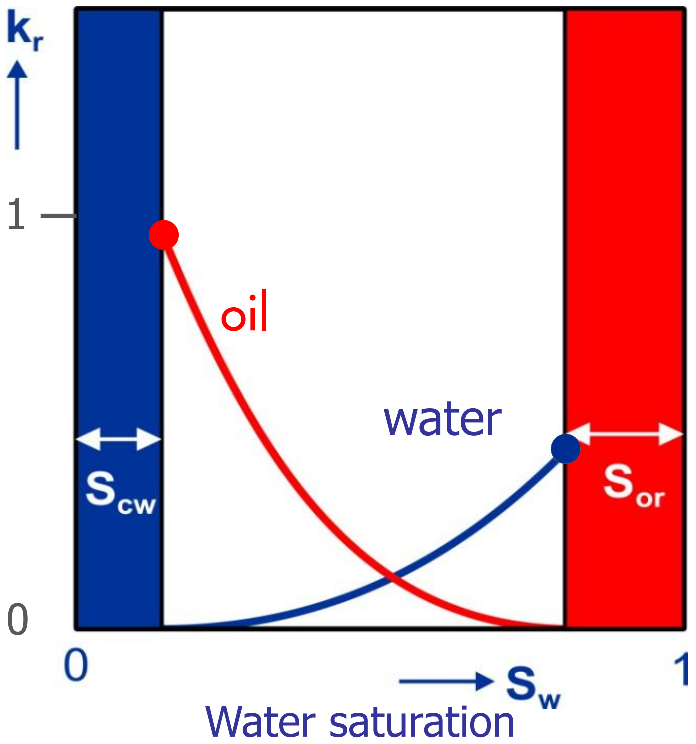


i=w,o

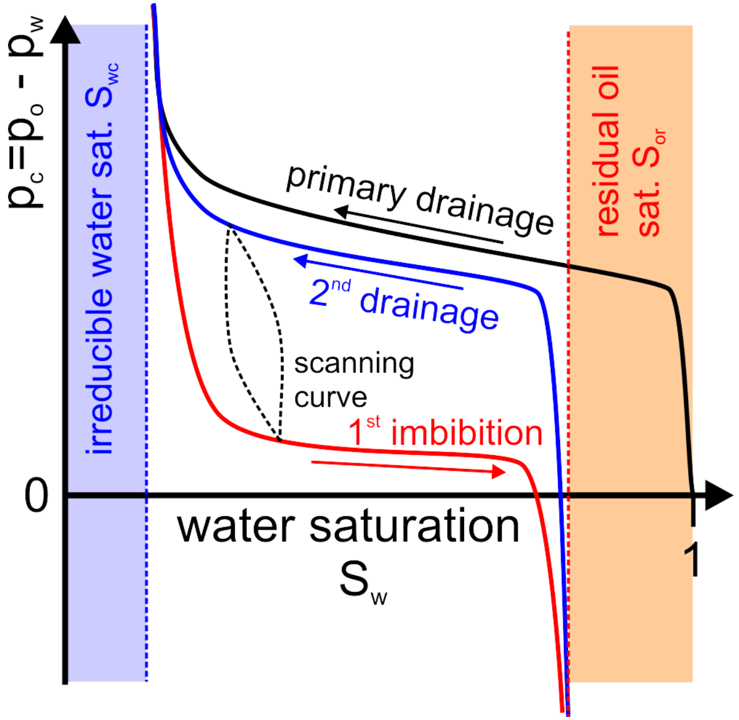
$$v_i = -k_{r,i}\frac{K}{\mu_i}\frac{dp_i}{dx}$$

Phenomenological extension of Darcy's law
Richards, Leverett,
R. Wyckoff and H. Botset
M. Muskat and M. Meres,

relative permeability $k_{r,i} = k_{r,i}(S_w)$



Capillary pressure $p_c = p_o - p_w$



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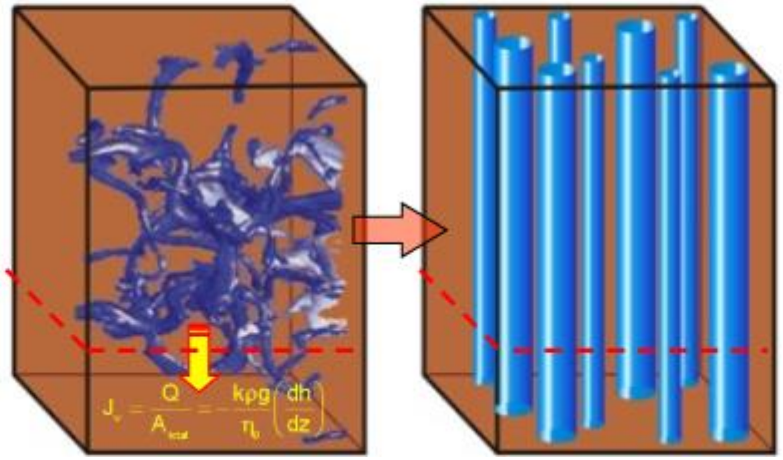
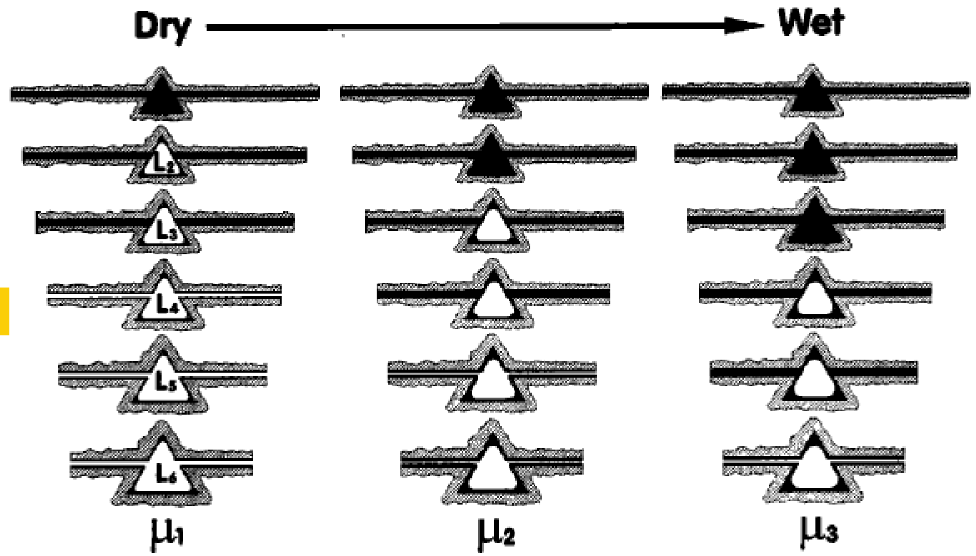
Assumption: Connected Pathway Flow – Brooks-Corey Model

- Building on Burdine equations – Capillary Tubes



Implicit assumption:
connected pathway flow
in parallel capillaries

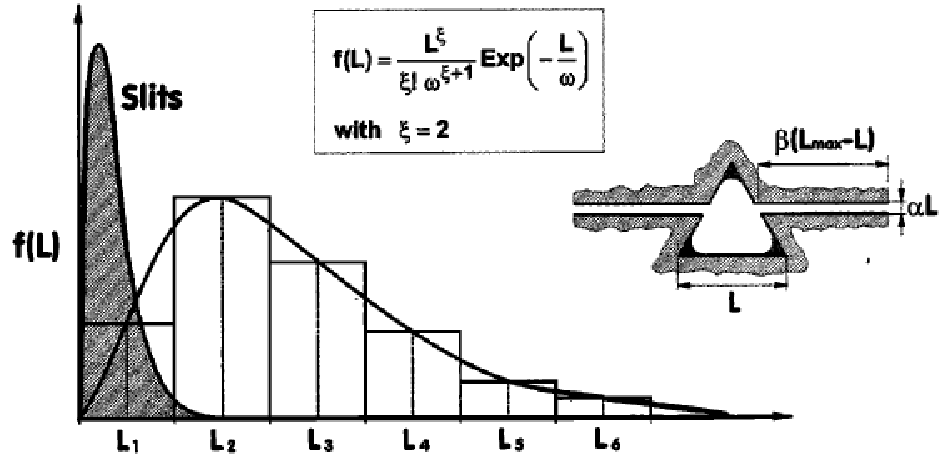


- Capillary pressure and relative permeability

$$p_c = p_{c,t}\left(\frac{1 - S_{o,r}}{S_o - S_{o,r}}\right)^{1/\lambda}$$

λ related to pore size distribution

$$k_{r,w} = \left(\frac{S_w - S_{w,c}}{1 - S_{w,c}}\right)^{\frac{2+3\lambda}{\lambda}} \qquad k_{r,o} = k_r^o\left(\frac{1 - S_{o,r} - S_w}{1 - S_{o,r} - S_{w,c}}\right)^2\left(1 - \left(\frac{S_w - S_{w,c}}{1 - S_{w,c}}\right)^{\frac{2+\lambda}{\lambda}}\right)$$



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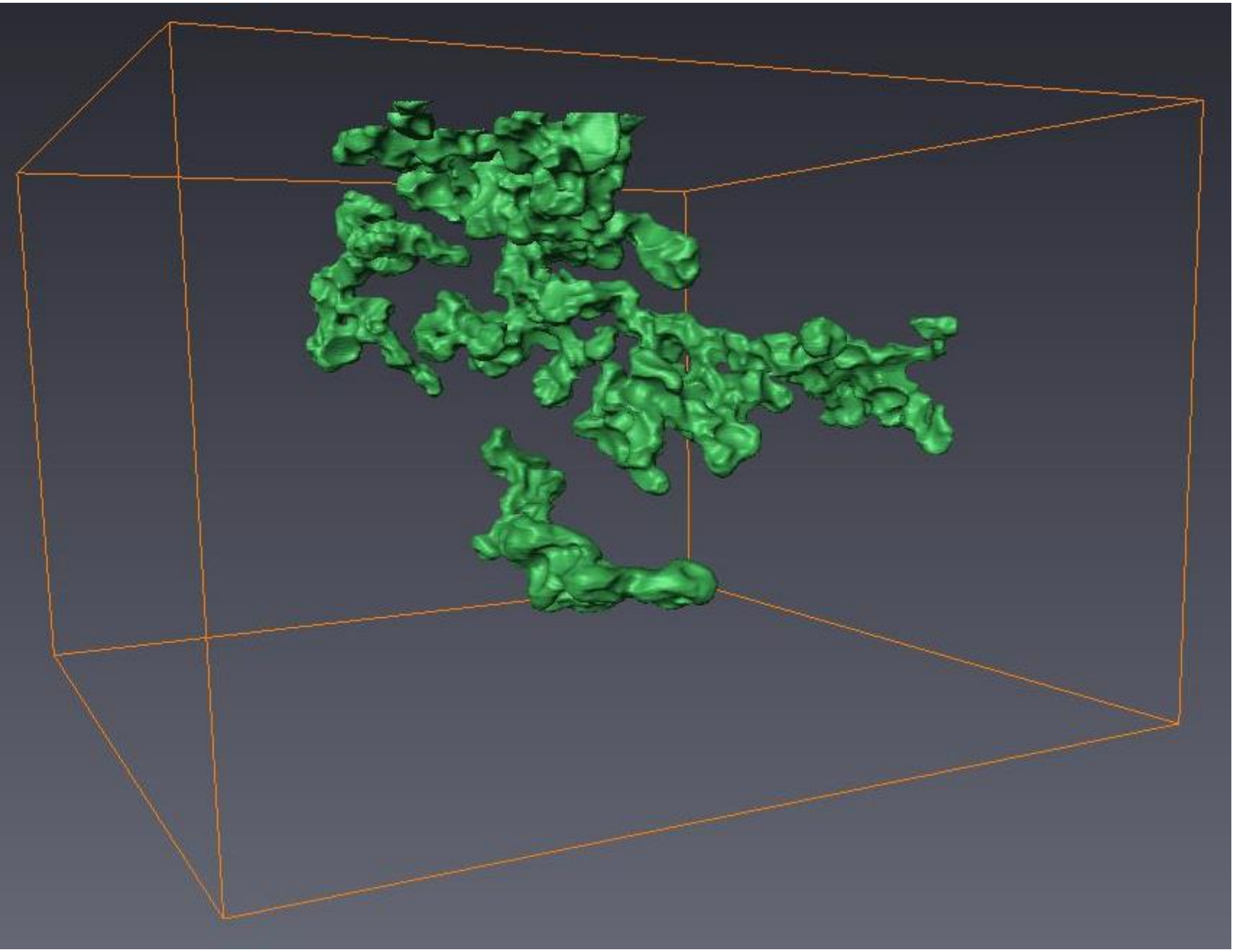
M. Tuller & D. Or, WRR 2001

Water-wet - Intermittent Connectivity: Snap-Off During Drainage



sintered glass (Robuglas), Δt~42 s, continuous scanning

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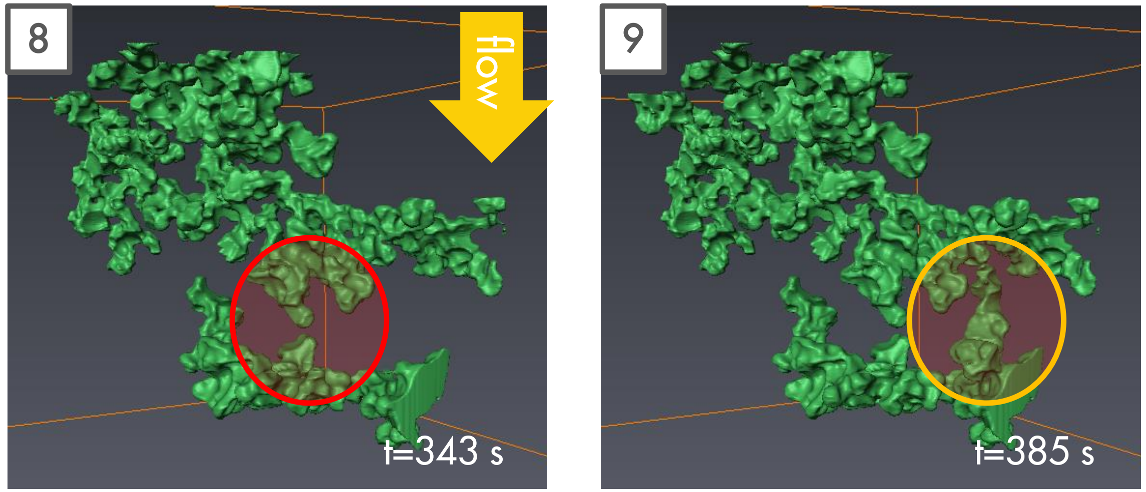
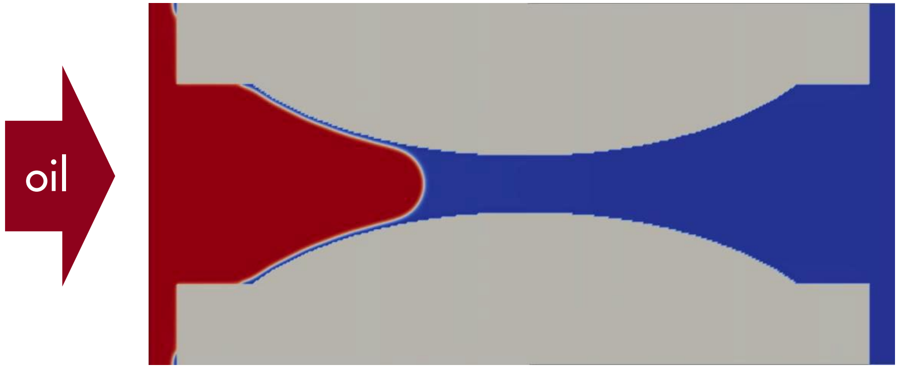
SCA2013-011



- Until frame #8 no permanent connectivity
- snap-off in pore throat: free-energy LBM simulation



- Only *intermittent* connectivity

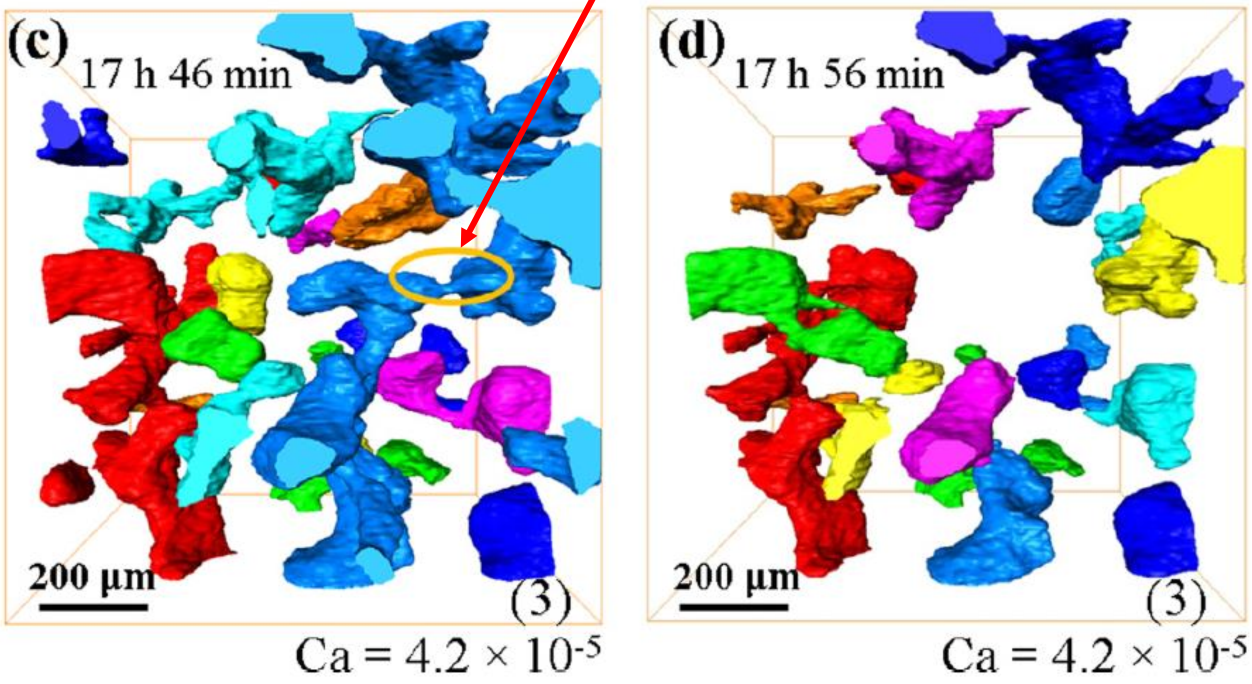
Roof,1970
Armstrong et al. 2016
Alpak et al. 2019

Ying Gao (Imperial College)

Imperial College London

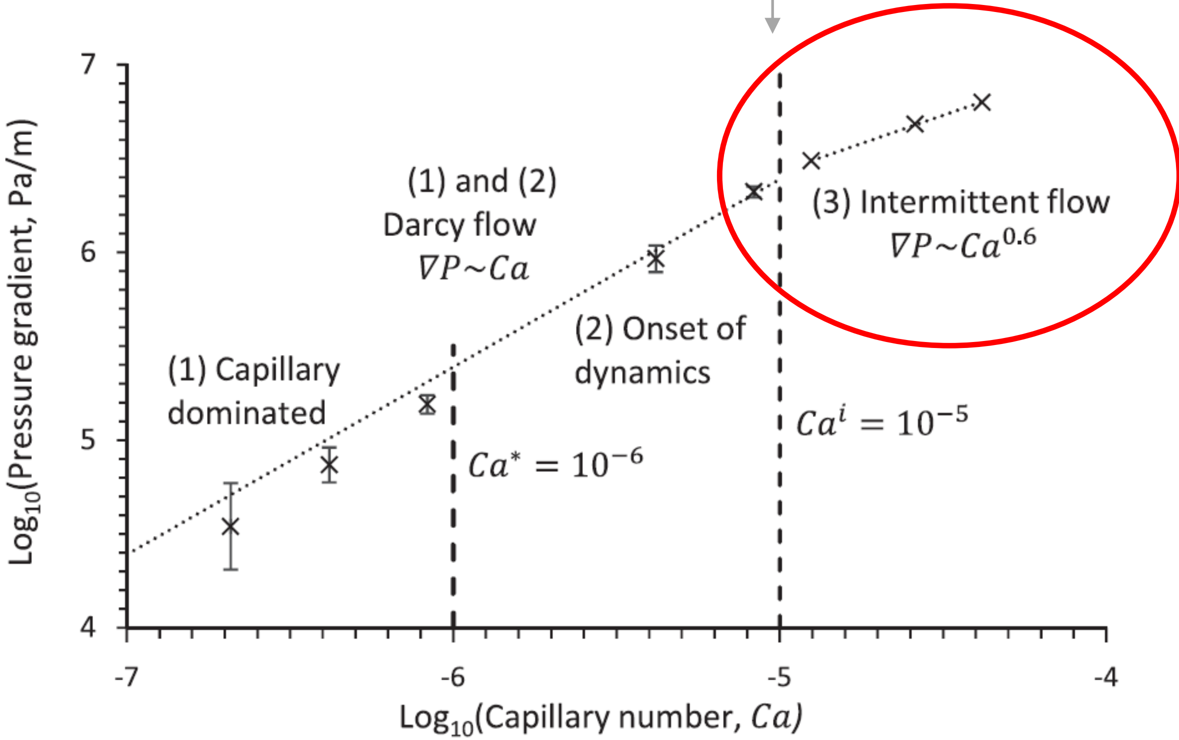
Intermittency at "High" Capillary Numbers

Connection-disconnection at pore scale



→ Armstrong et al. GRL, 2014

$Ca^{cluster} \sim 1$



→ Intermittency can lead to non-Darcy flow

Y. Gao et al. Phys. Rev. Fluids 2020

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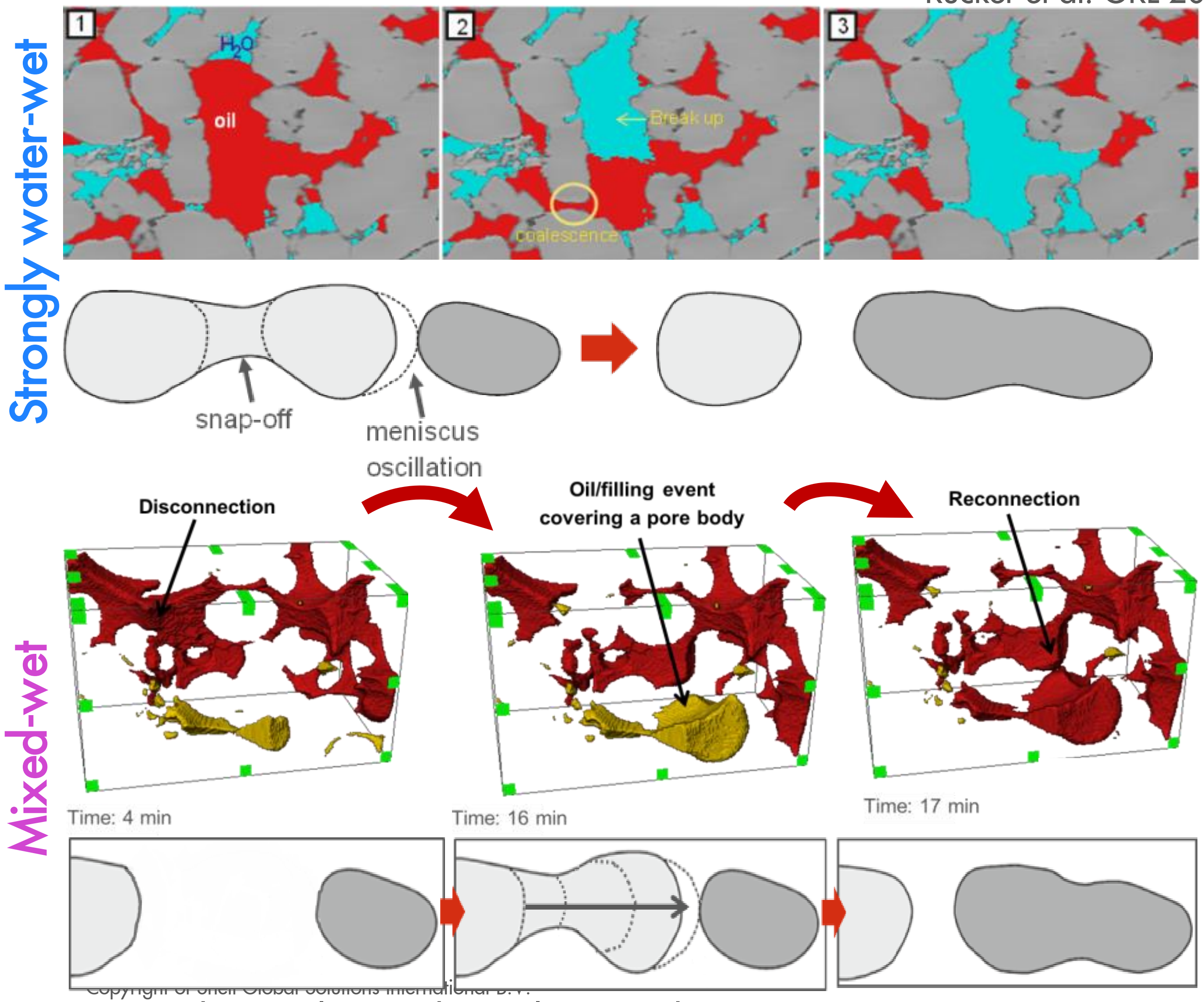
Maja Rücker

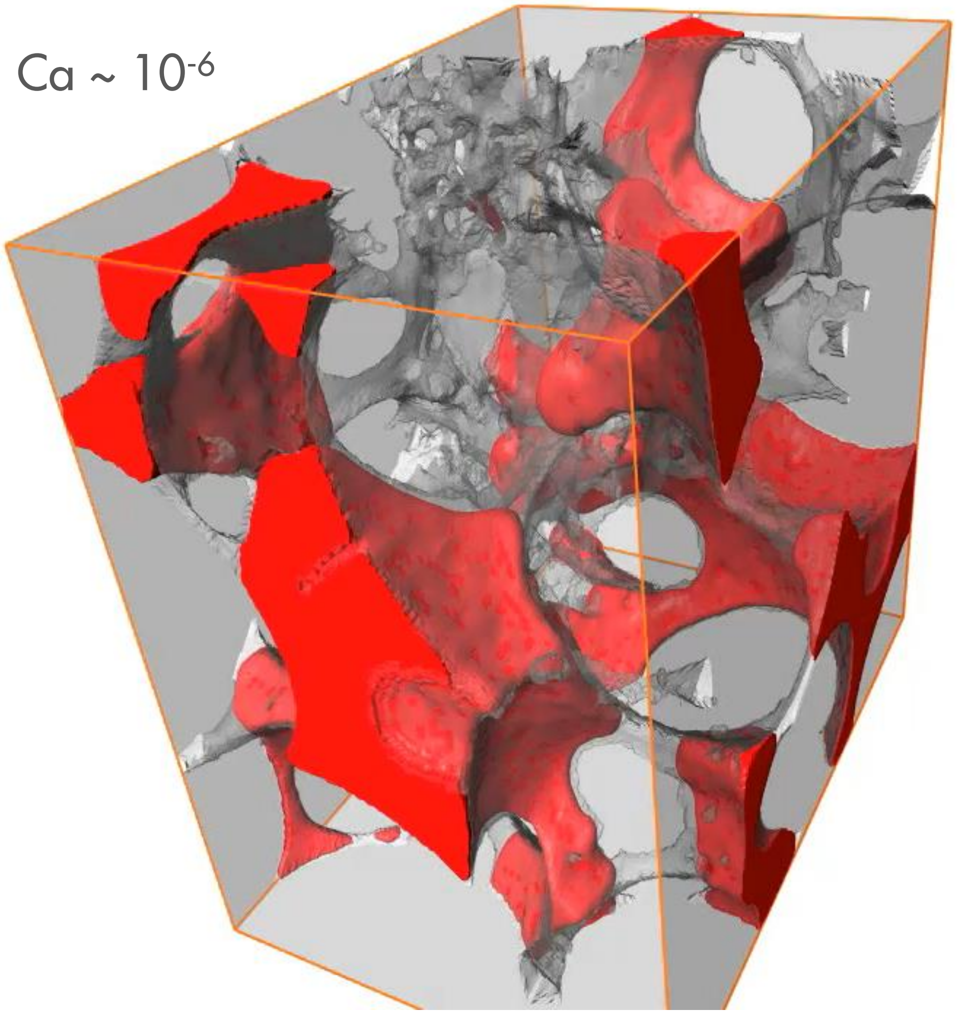
Snap-off + Coalescence = Ganglion Dynamics

Rücker et al. GRL 20

Disconnected phases can be mobile!



Ca ~ 10^{-6}

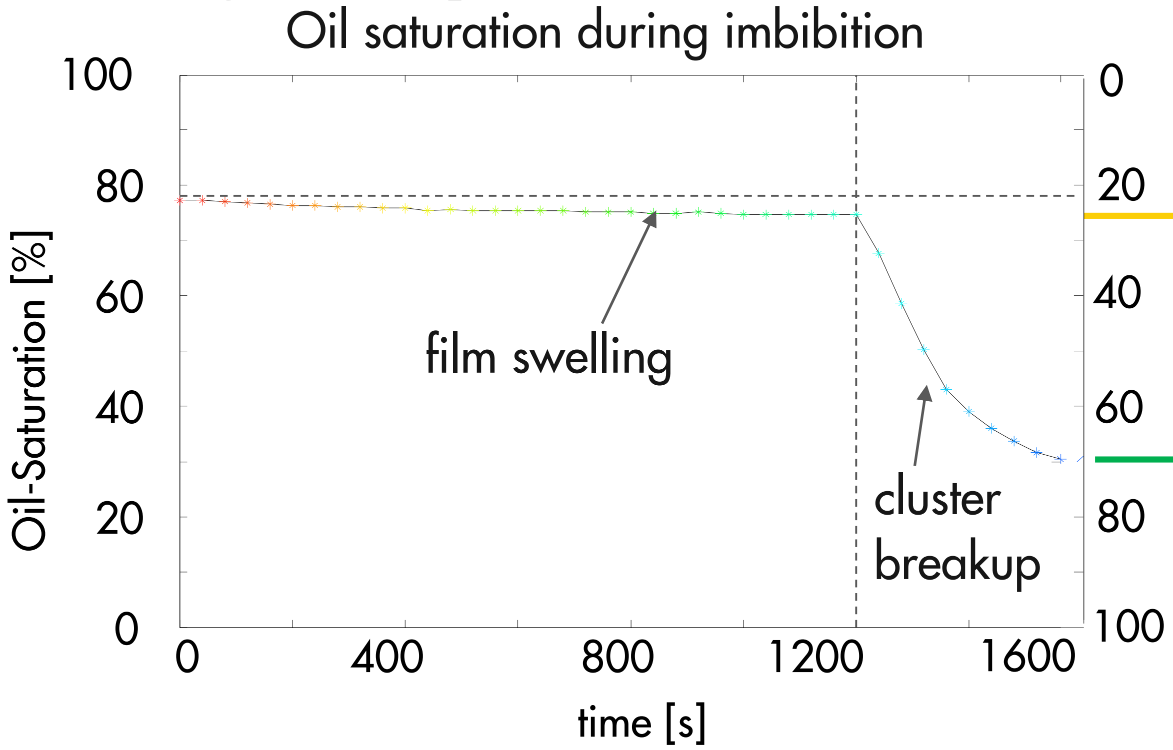


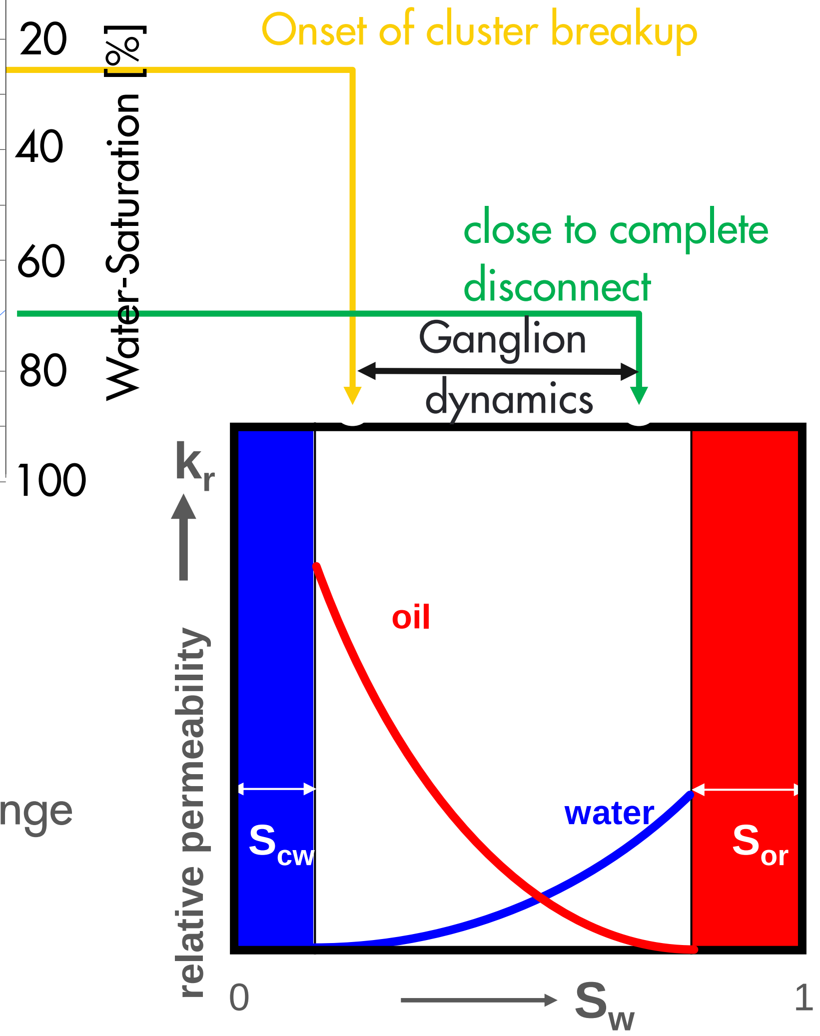
Rücker et al. Geophysical Research Letters 46(6), 3225-3234, 2019.

Wettability → presentation Sam Krevor

Ganglion Dynamics Occurs Over Wide Saturation Range

SCA2014-022





Co-existence
of
connected pathway flow
and
ganglion dynamics

- Onset of cluster breakup at relatively oil saturation
- Oil clusters remain mobile over large saturation range
- S_{or} reached when no further coalescence possible

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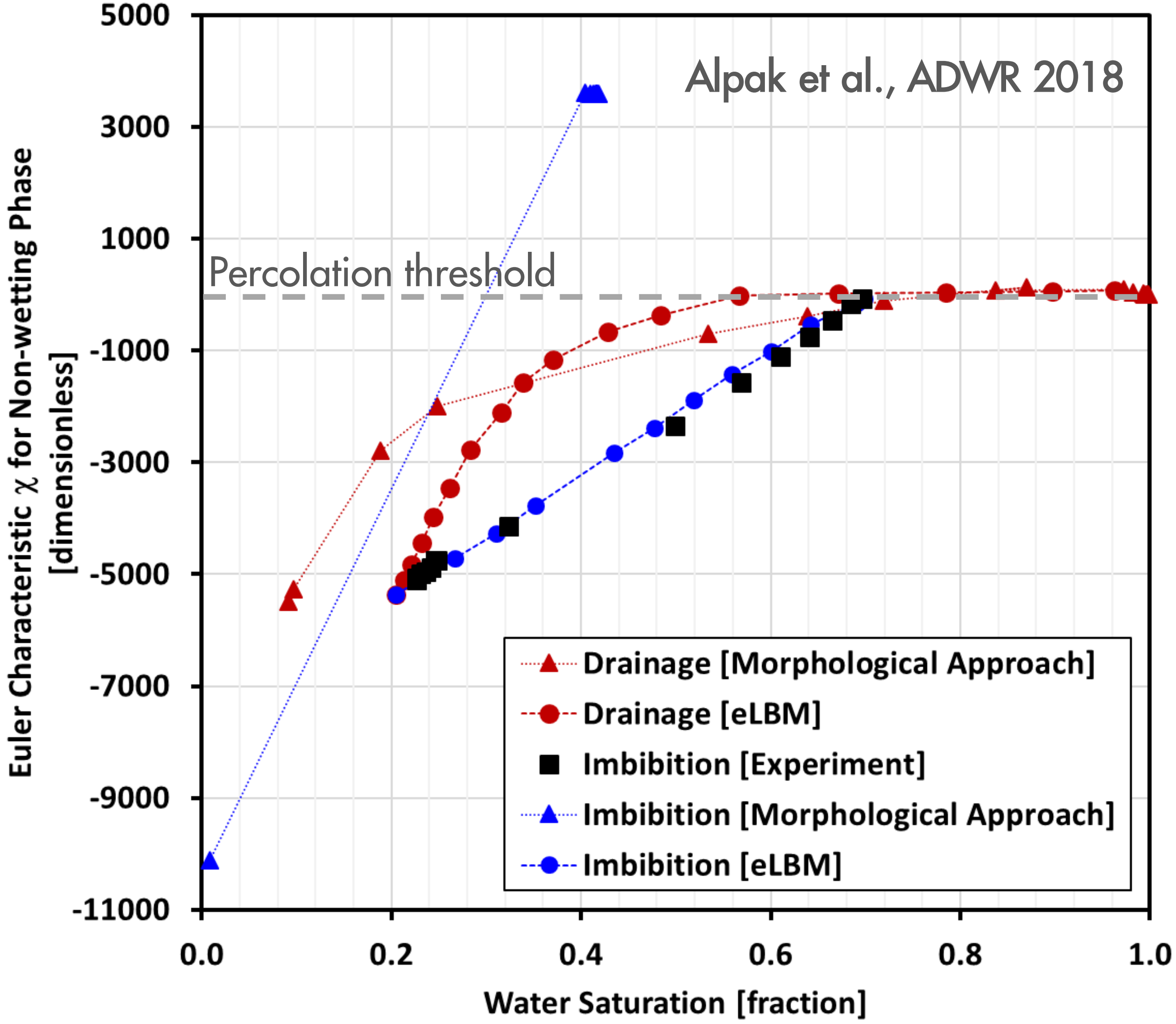
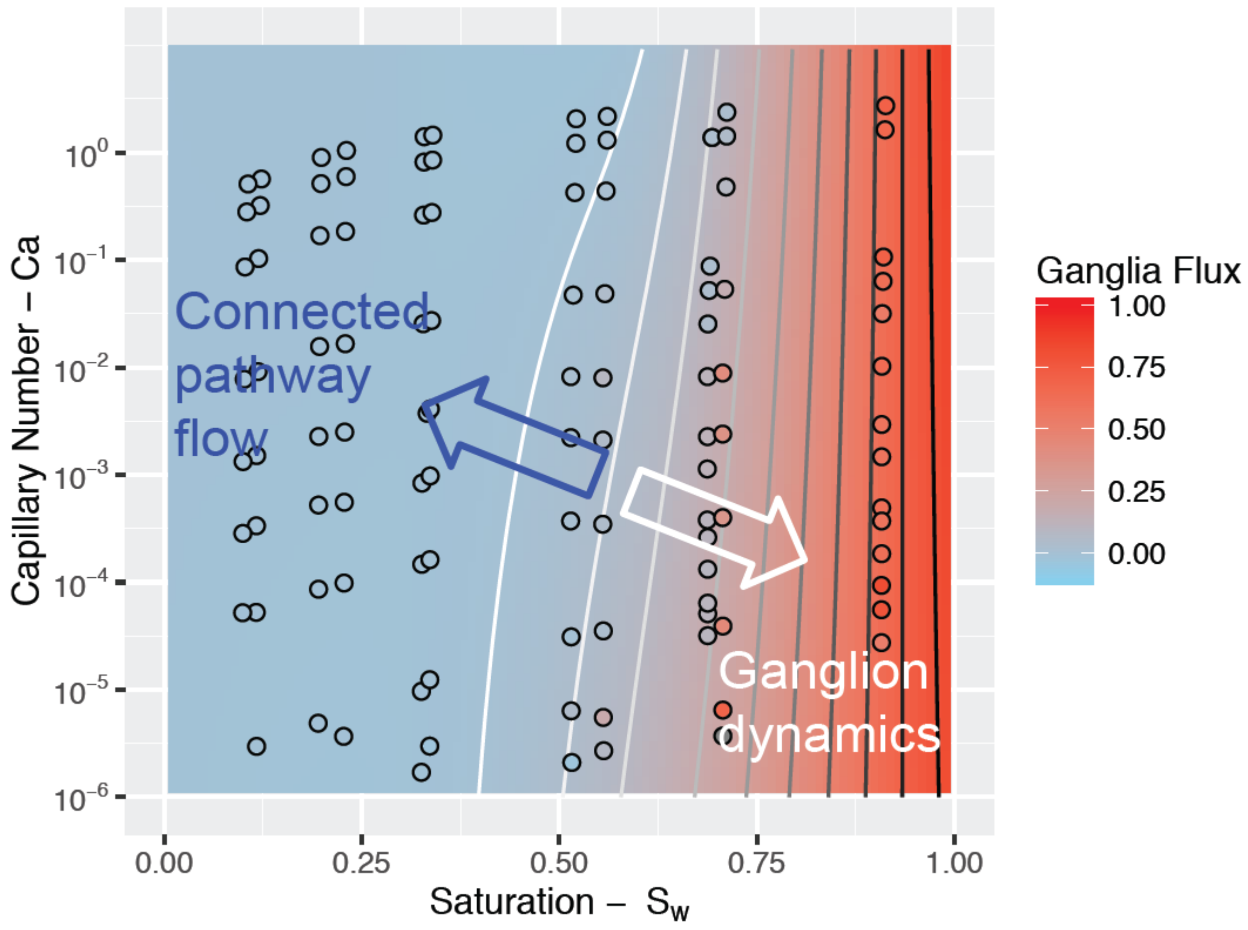
Ganglion Dynamics Impacts Connectivity

Free-Energy LBM correctly predicts connectivity !



Most flux through connected pathway, except for close to endpoint saturation

McClure et al, PRE, 2016



But: ganglion dynamics changes connected path

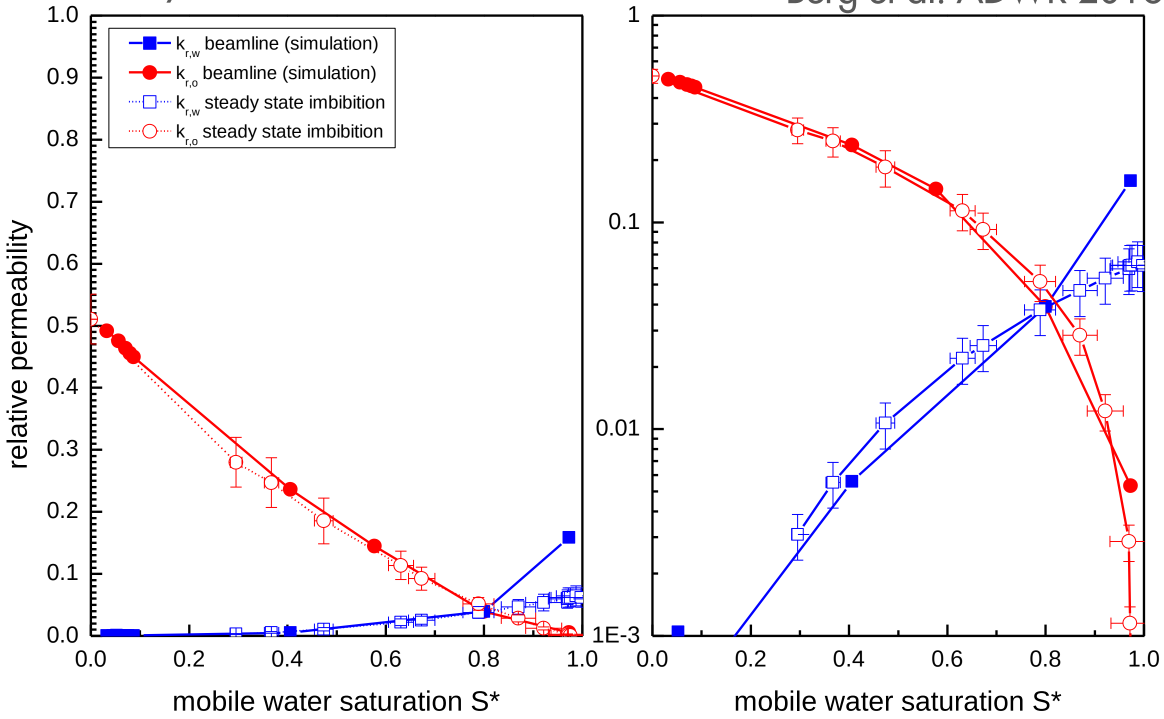
Mixed-Wet: Ganglion Dynamics Contributes To Flux

Water-wet: mainly connected pathway flow

Connected pathway kr computed from micro-CT fluid pathways

= steady-state kr

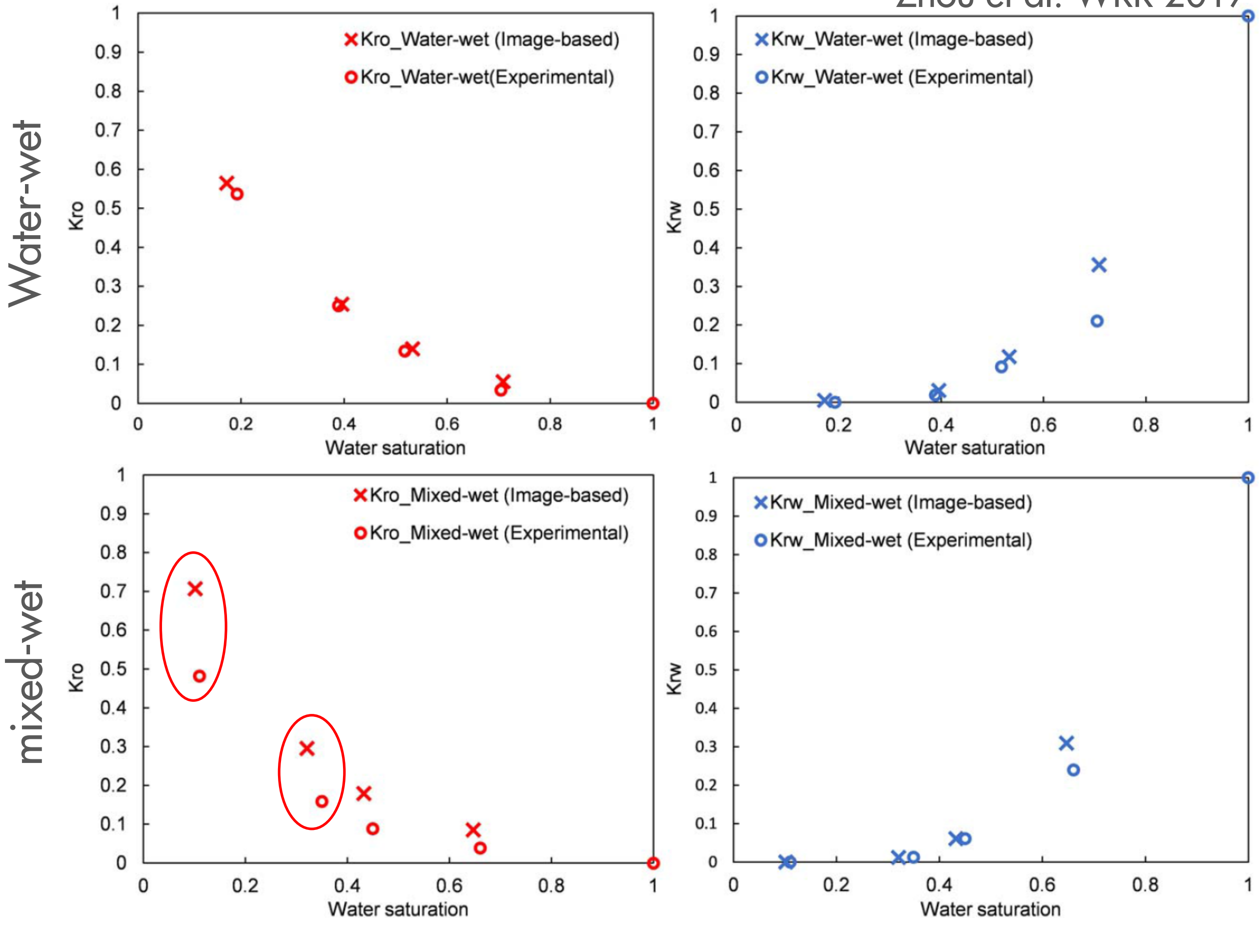
Berg et al. ADWR 2016



$$S^* = \frac{S_w - S_{w,c}}{1 - S_{w,c} - S_{o,r}}$$

Mixed-wet: ganglion dynamics contributes to flux

Zhou et al. WRR 2017



For non-water wet situations the connected pathway relative permeability over-estimates the true relative permeability

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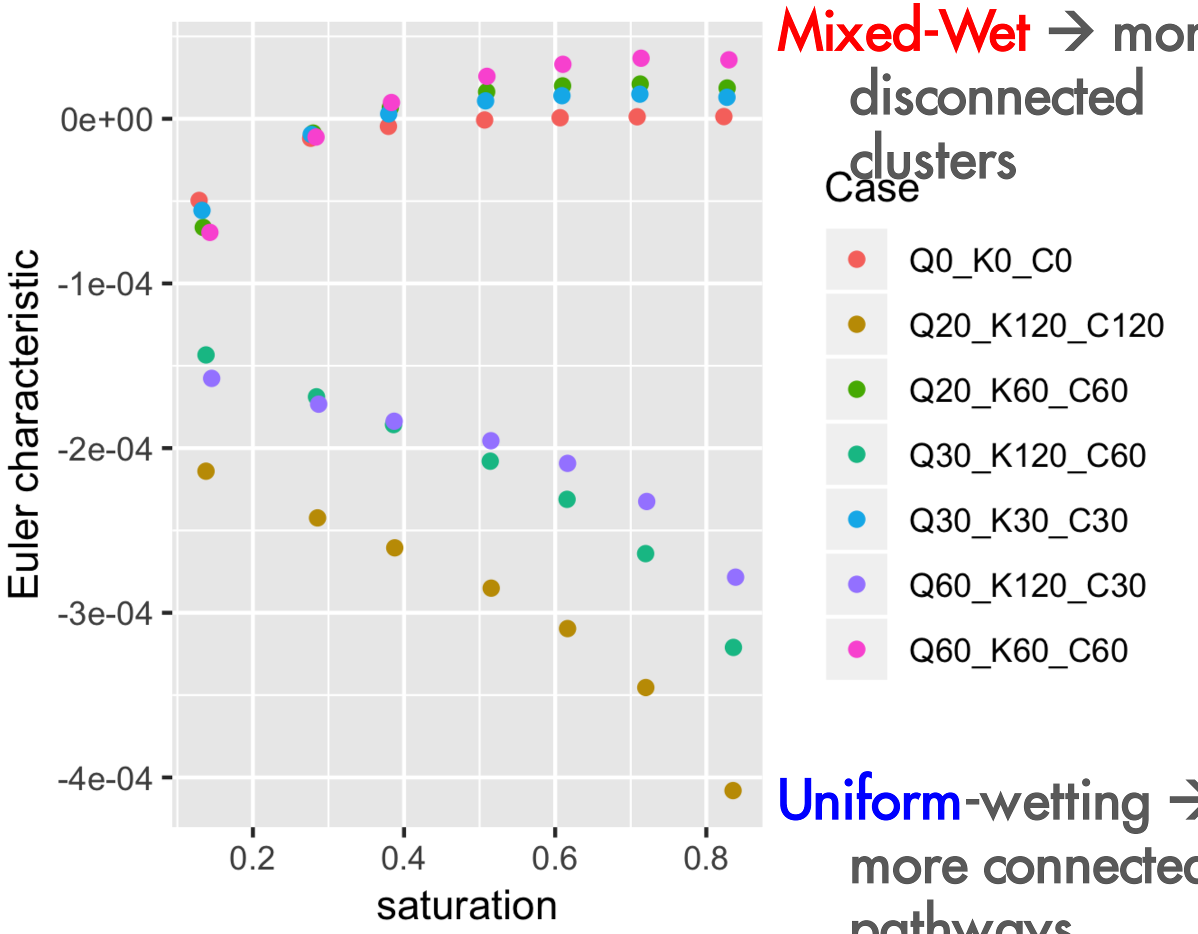
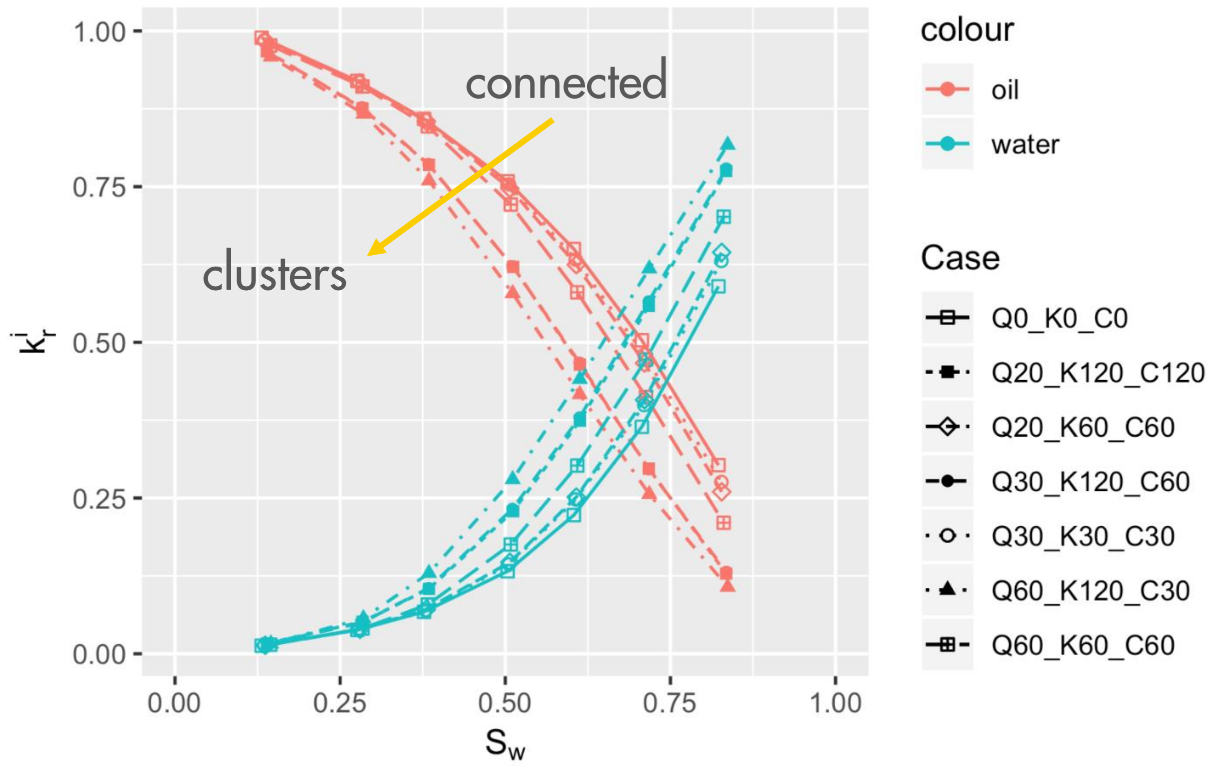
Ryan T. Armstrong, James McClure

LBM Simulation: Mixed-Wettability Causes Disconnected Clusters



Mixed-Wet → more disconnected clusters

Uniform-wetting → more connected pathways



Strong dependency on 3D wettability distribution!

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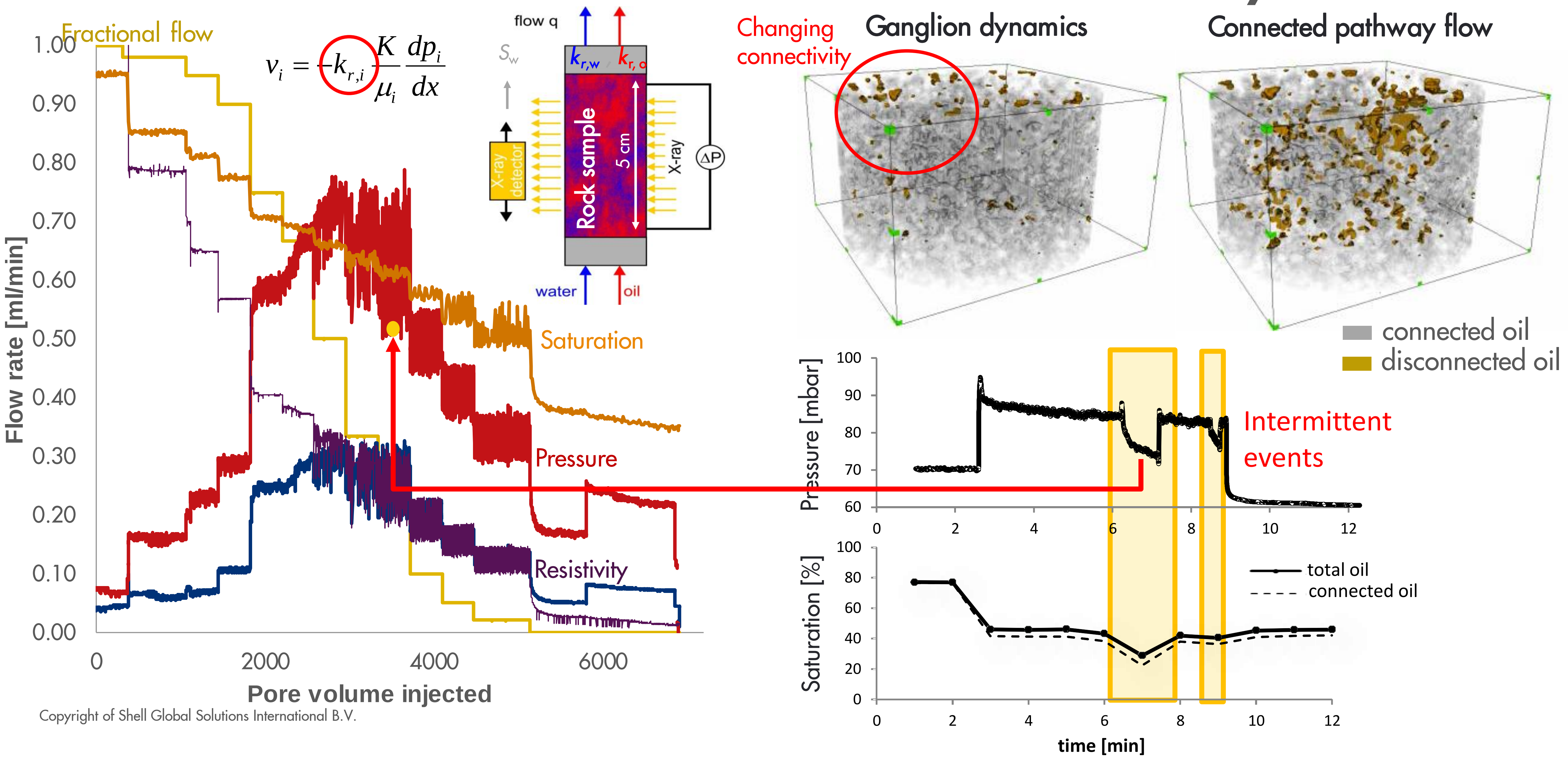
Non-thermal Fluctuations in SCAL: Intermittent Connectivity



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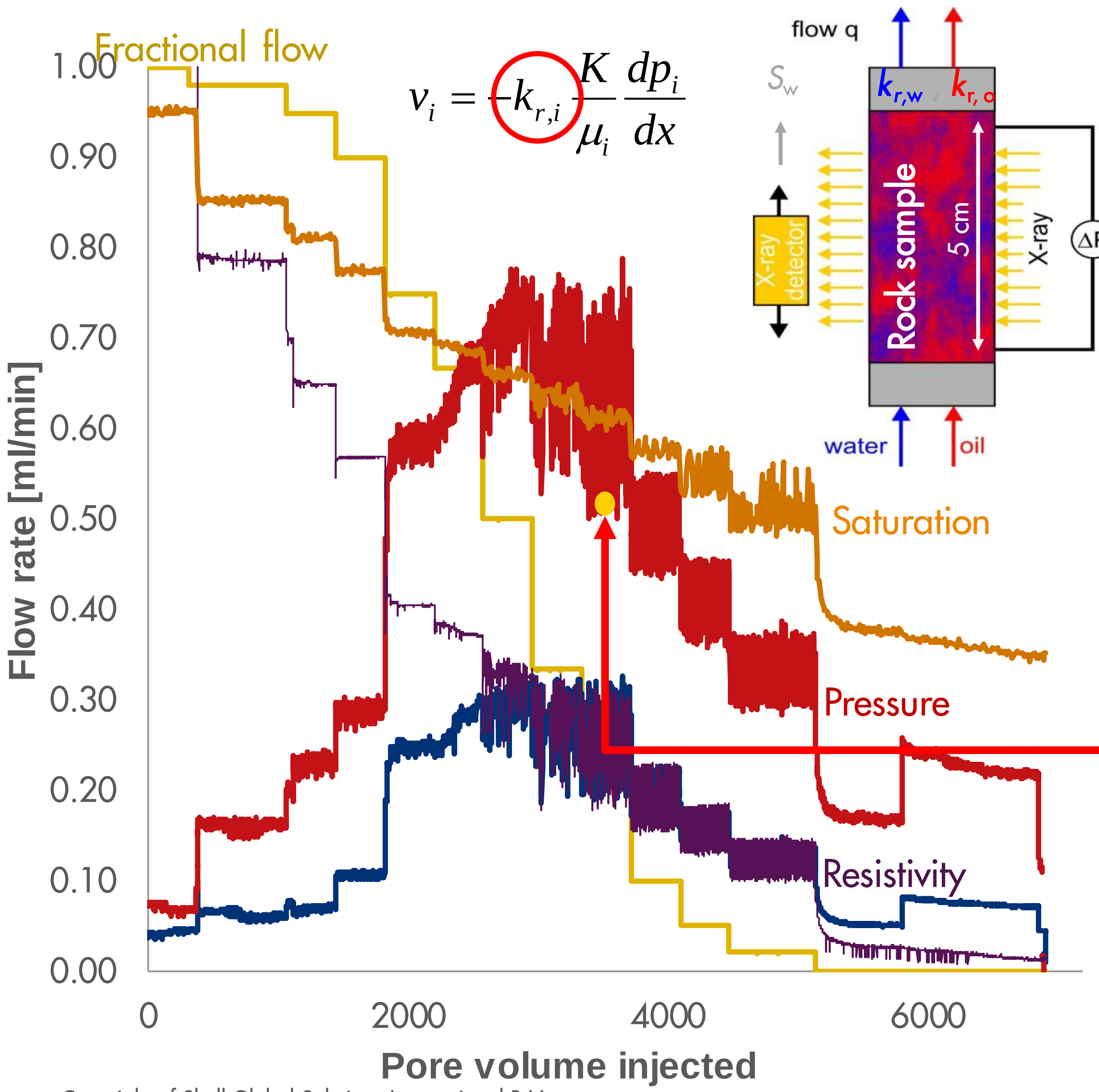
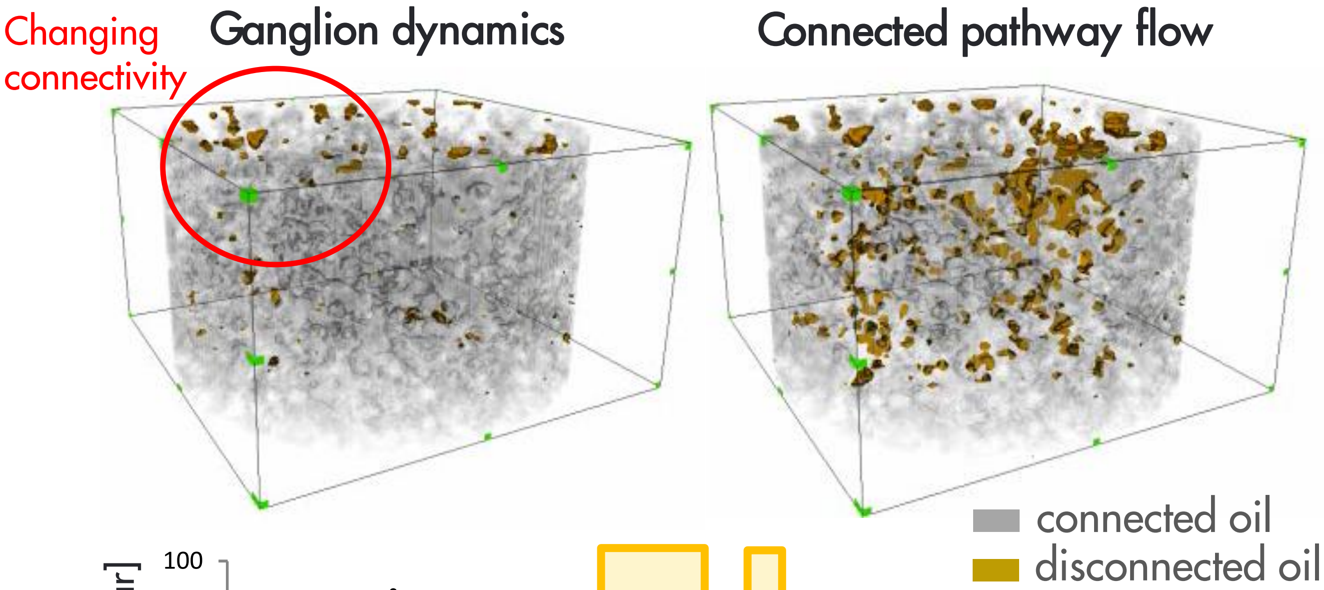
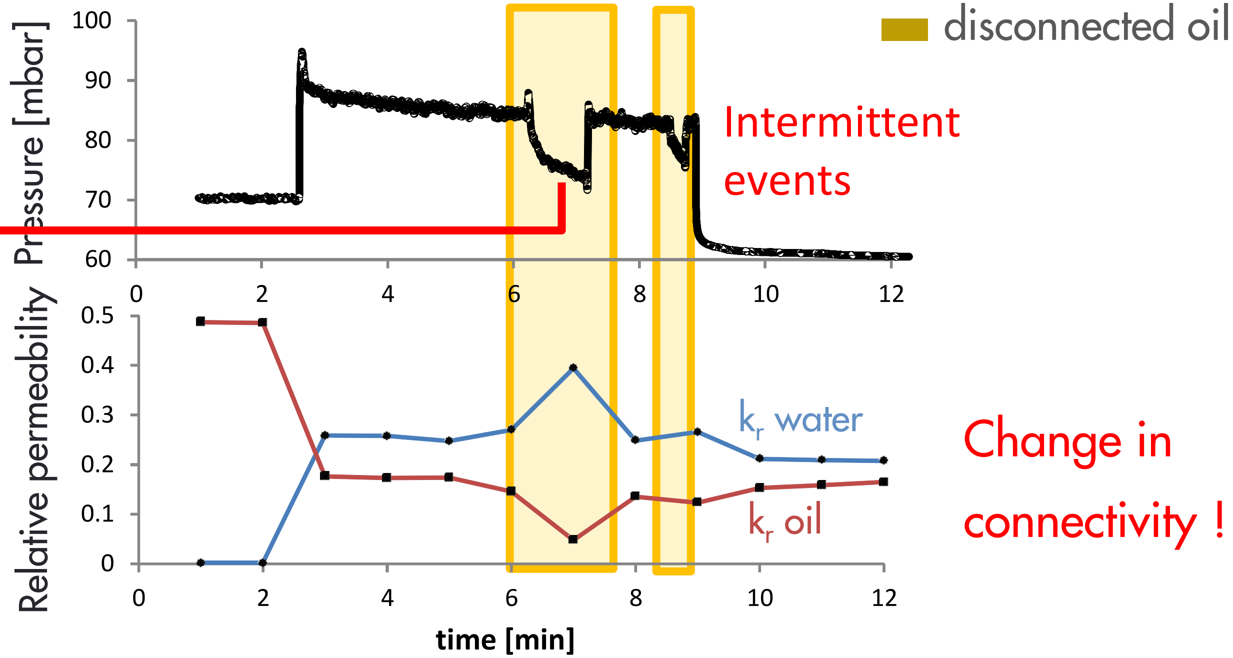
Non-thermal Fluctuations in SCAL: Intermittent Connectivity







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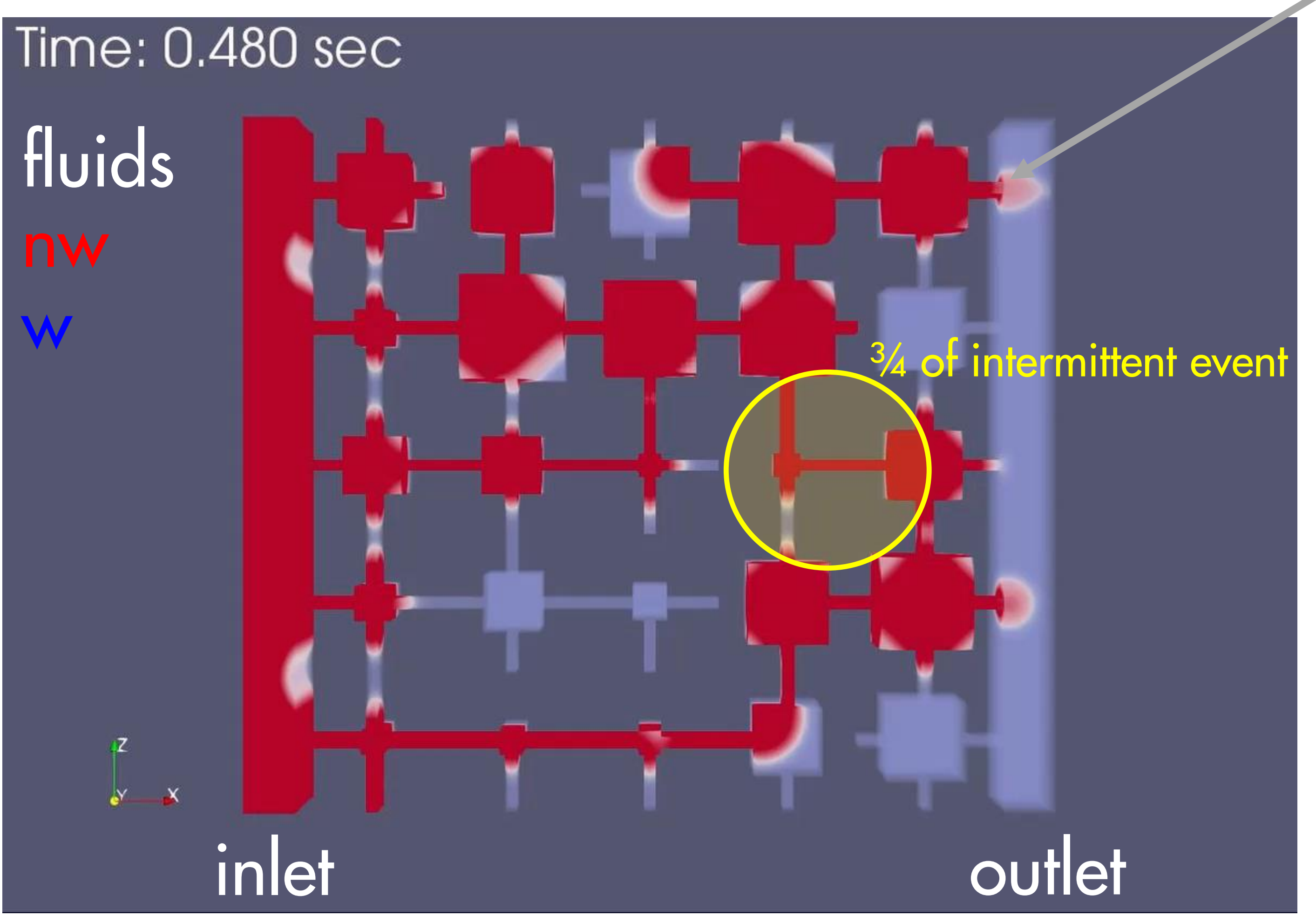
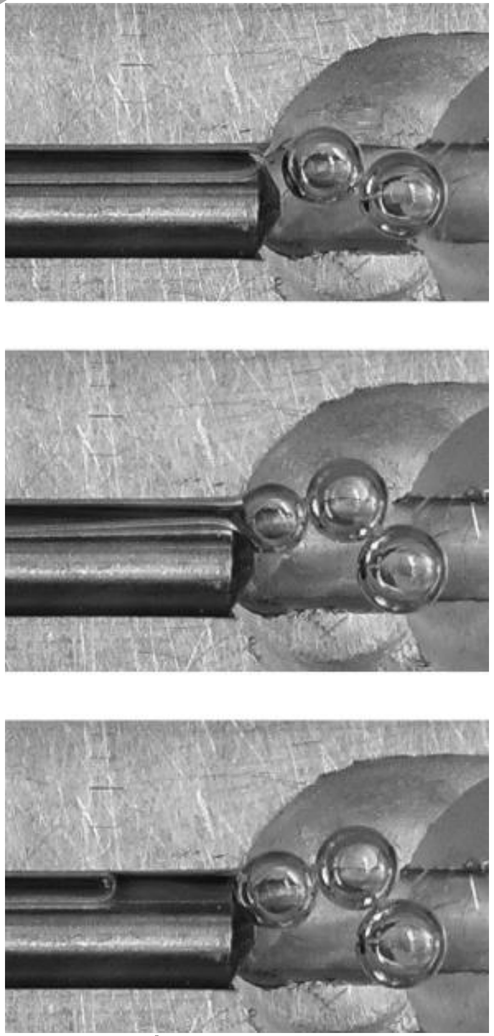
Intermittency Mediated by Drainage Snap-Off ?

Imperial College London

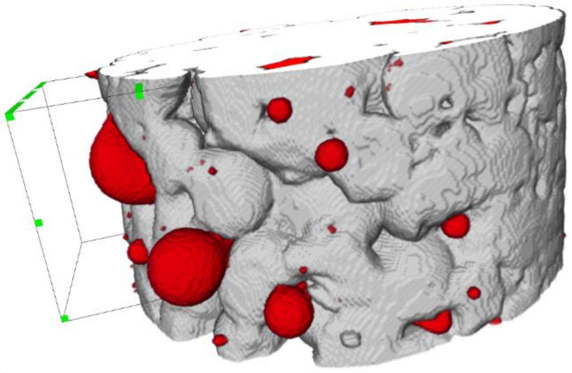
LBM Simulation – Takashi Akai, Catherine Spurin

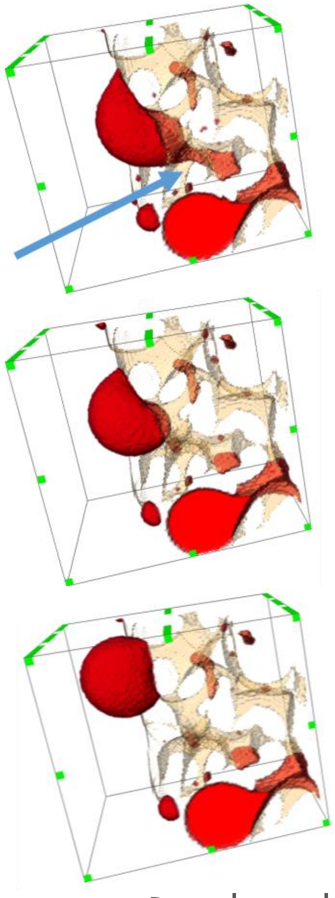


Bubble snap-off



Unsal, Mason, Morrow, Ruth, Langmuir 2009





Bartels et al. SCA2017-00

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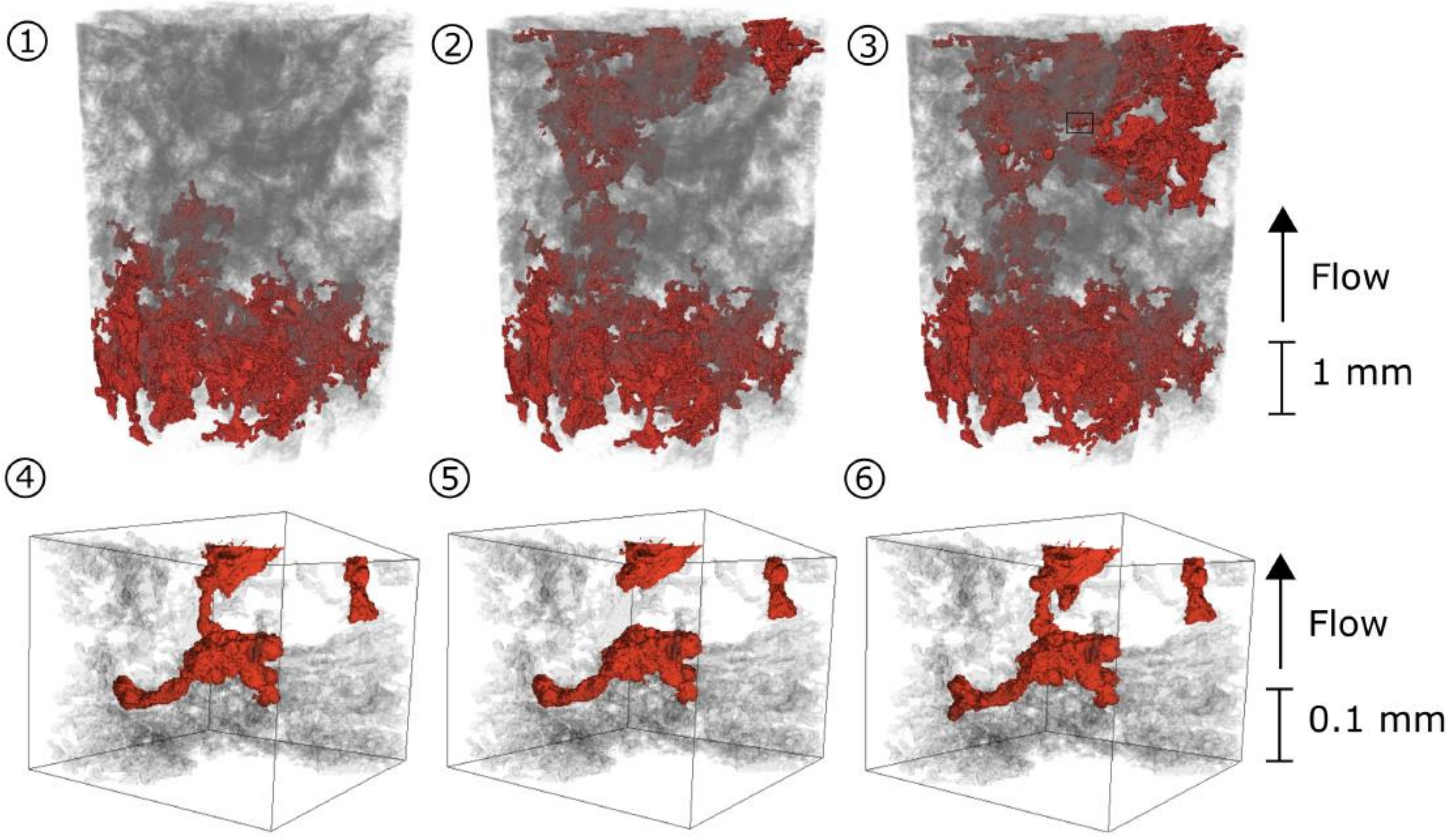
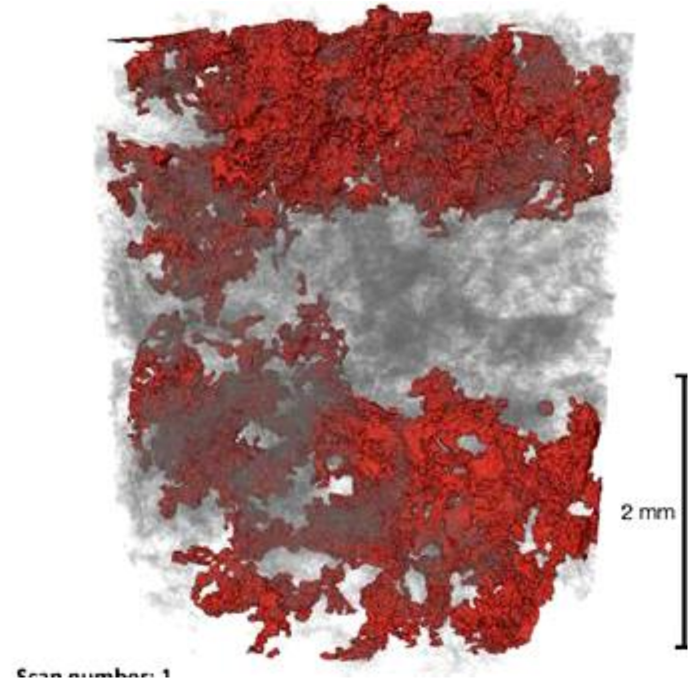
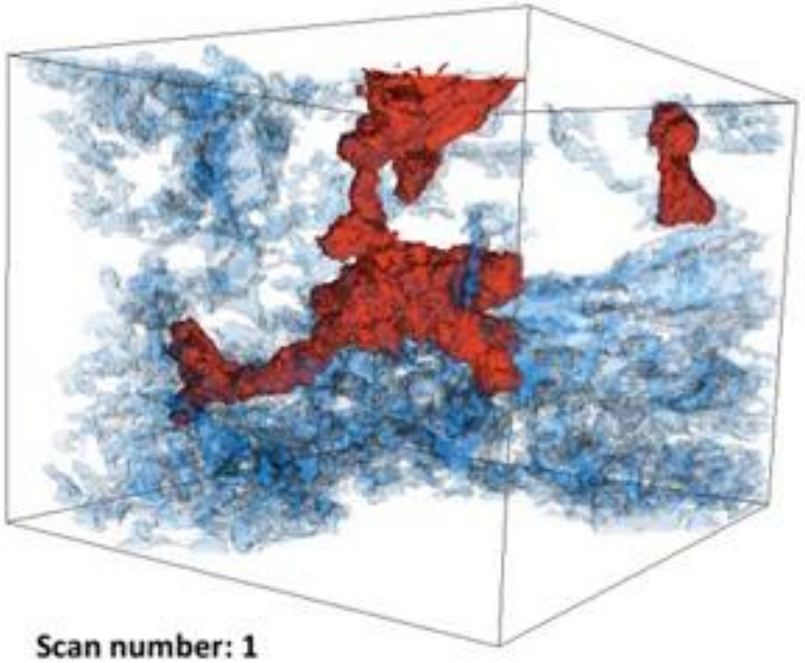
Catherine Spurin

N_2 Injection into Brine - Intermittency

N_2 – brine co-injection (fractional flow $f_w = 0.85$ at capillary number $Ca = 1.6 \cdot 10^{-7}$)







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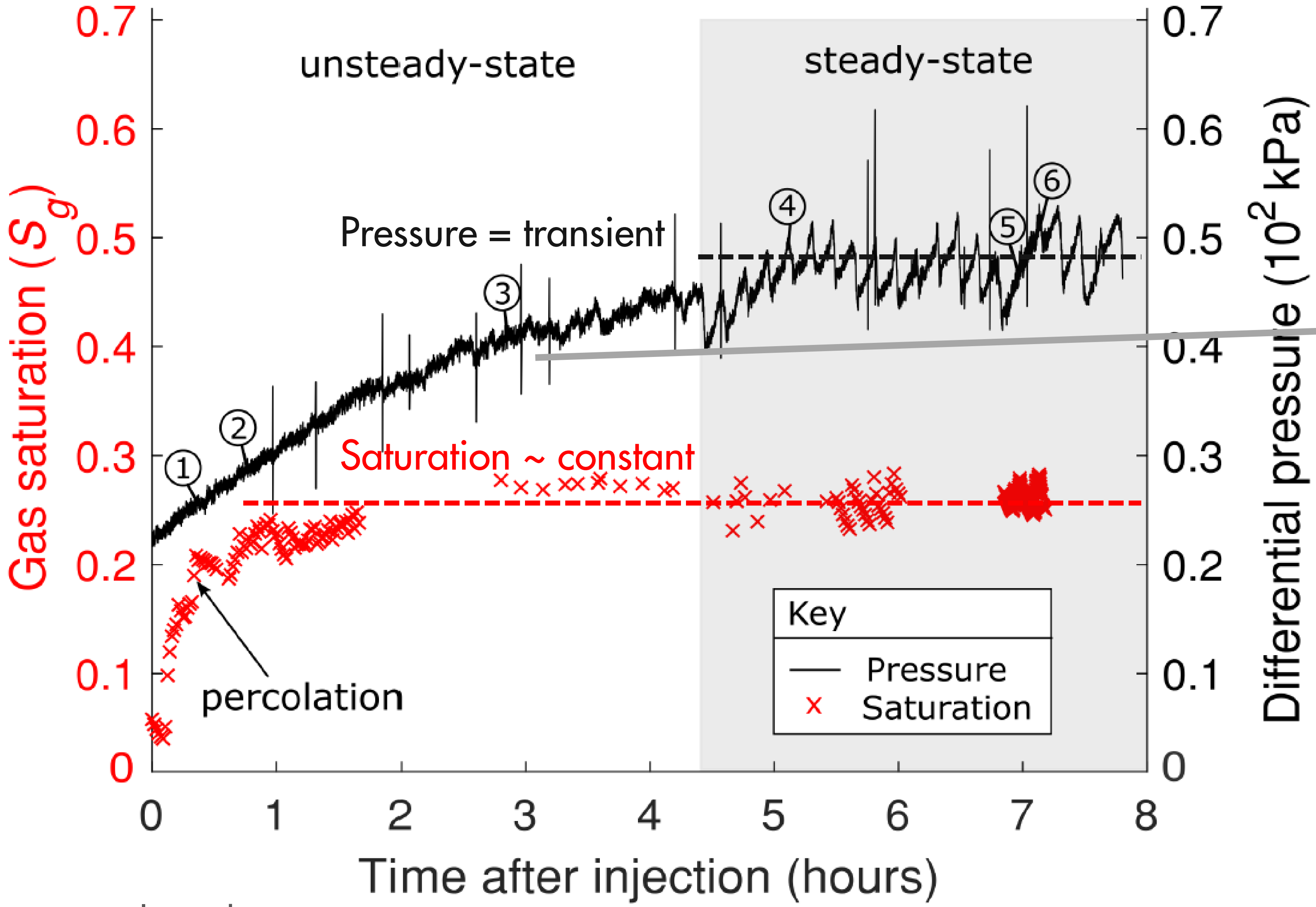
- Under review -

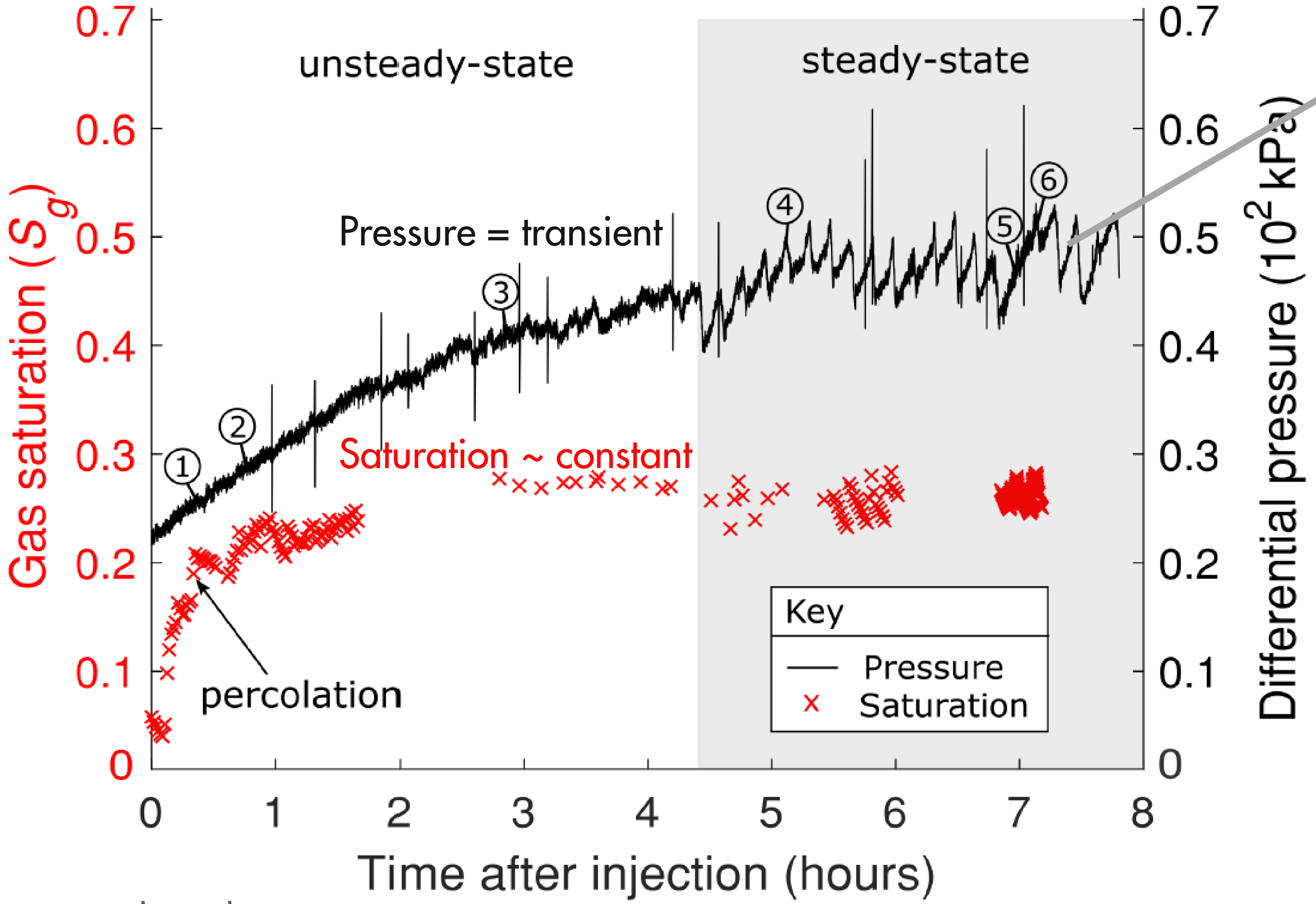
N_2 Injection into Brine – Non-equilibrium Effects



- Several hours before "steady-state" is reached
- "steady-state" = intermittent fluctuations
  → fully developed flow
- Unsteady-state
  saturation constant, close to steady-state
  pressure drop = transient
  → relative permeability smaller than "steady-state"

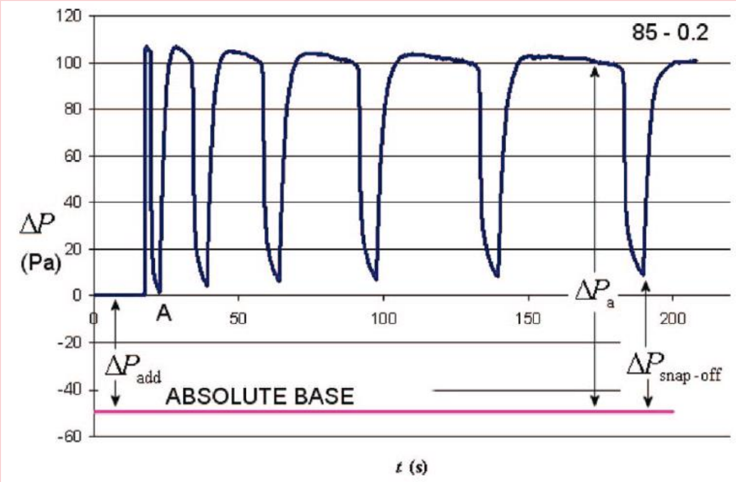
Spurin et al., under review

N_2 Injection into Brine – Intermittency



Spurin et al., under review

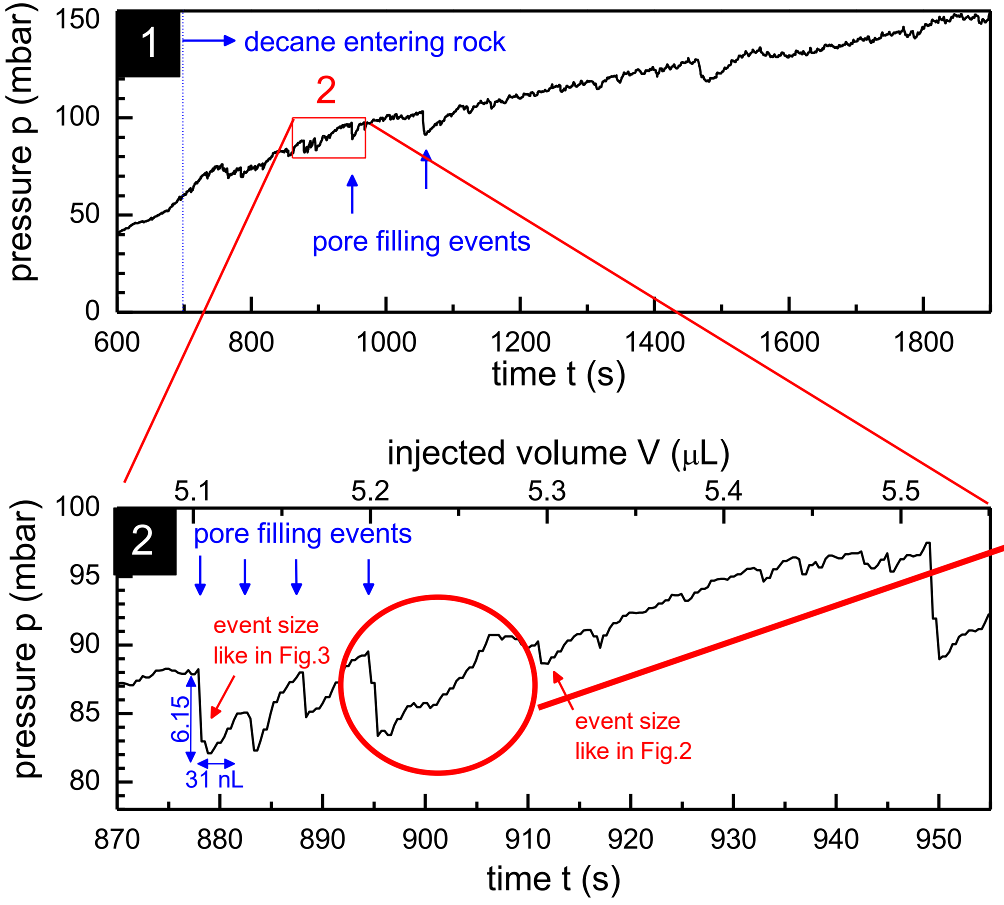
- "steady-state" = intermittent fluctuations → fully developed flow
- Pressure drop: regular oscillations, similar to bubble snap-off

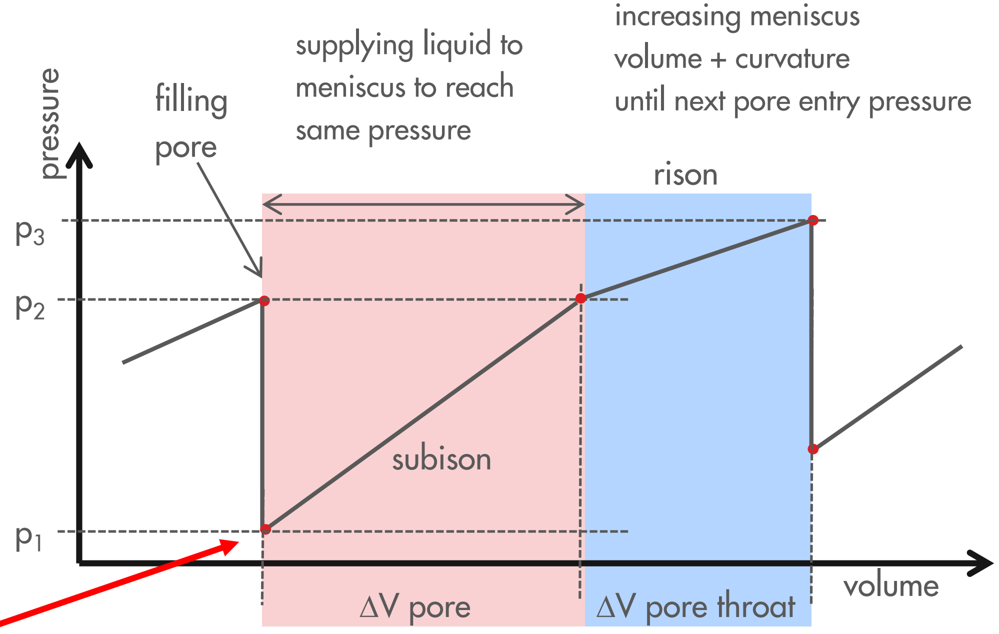


Unsal, Mason, Morrow, Ruth, Langmuir 2009

Discontinuous Events and Energy Dissipation

Drainage experiment (PNAS 2013)





risons (reversible)

$$W_{rison} = \sum \frac{p_2 + p_3}{2} \Delta V_{porethroat} = 2.99 \cdot 10^{-5}\, J$$

subisons (irreversible)

$$W_{subison} = \sum \frac{p_1 + p_2}{2} \Delta V_{pore} = 5.26 \cdot 10^{-5}\, J$$

$$\frac{W_{Subisons}}{W_{tot}} = 0.64$$

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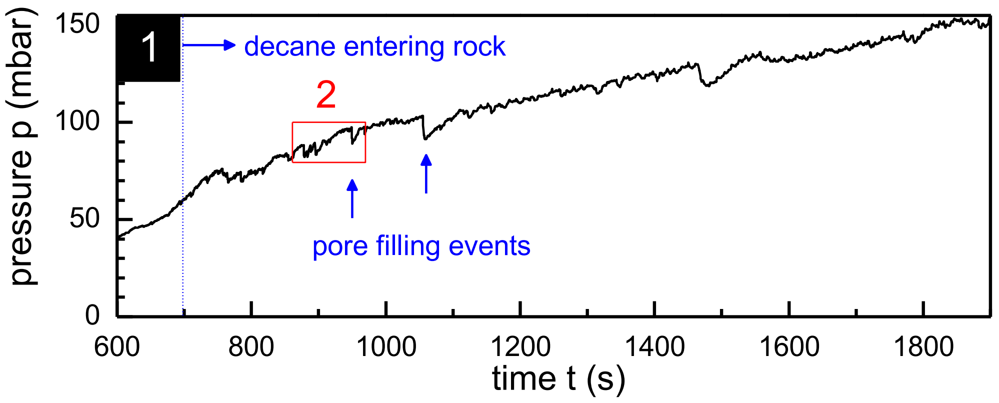
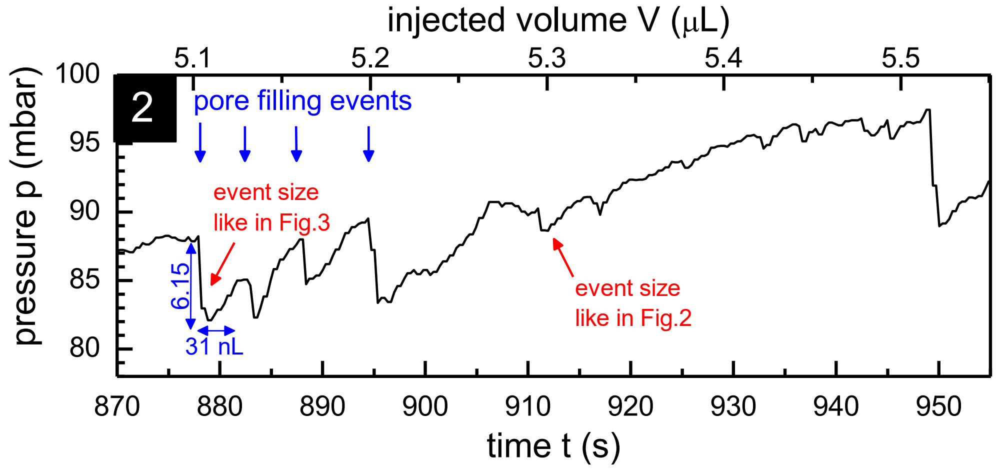
Discontinuous Events and Energy Dissipation

Drainage experiment (PNAS 2013)





Hypothetical connected pathway flow without discontinuous events

$$W_{visc} = \int_0^{\Delta V} p_\alpha dV_\alpha \qquad p_\alpha = \frac{Q_\alpha}{A}\frac{\mu_\alpha}{k_{r,\alpha}K}L \quad \text{2-phase Darcy}$$

$$W_{visc} = \int_0^{\Delta V/Q} \frac{Q_\alpha}{A}\frac{\mu_\alpha}{k_{r,\alpha}K} L Q_\alpha dt = \frac{Q_\alpha}{A}\frac{\mu_\alpha}{k_{r,\alpha}K} L\Delta V = 4.4\cdot 10^{-7}\,J$$

Actual dissipation (risons & subisons)

$$W_{tot} = W_{rison} + W_{subison} = 8.25\cdot 10^{-5}\,J$$

ratio $$\frac{W_{visc}}{W_{tot}} = \frac{4.4\cdot 10^{-7}\,J}{8.25\cdot 10^{-5}\,J} = 0.0053$$

Connected pathway flow underestimates dissipation by factor 200

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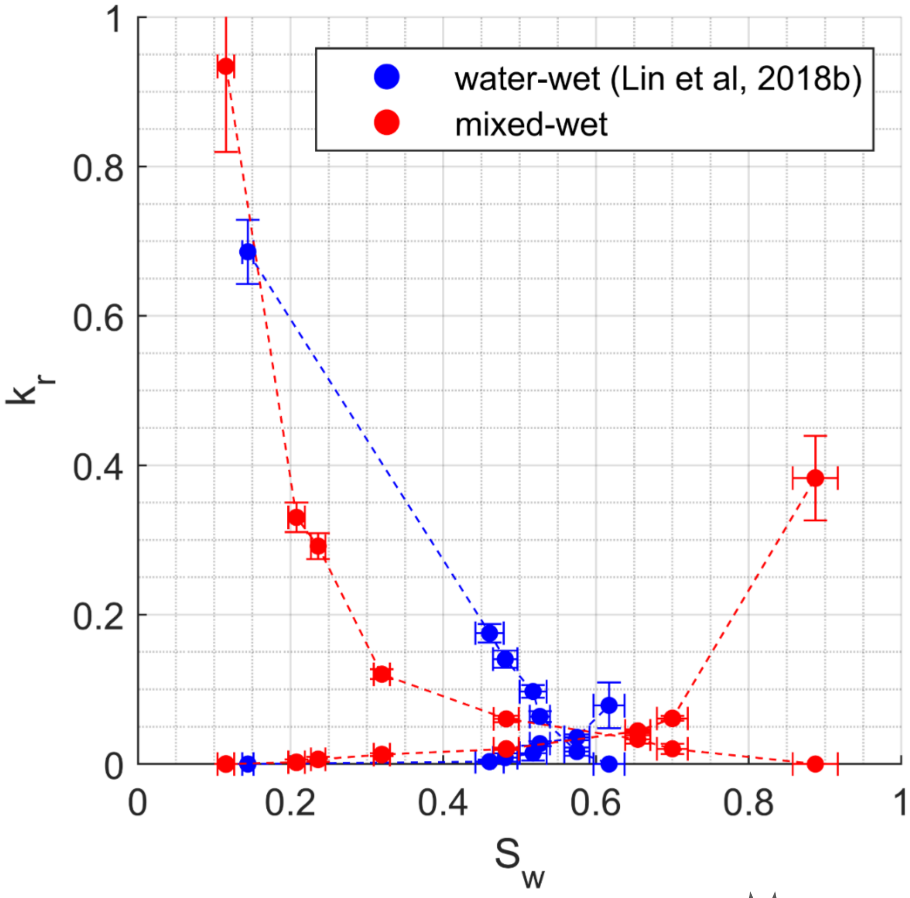
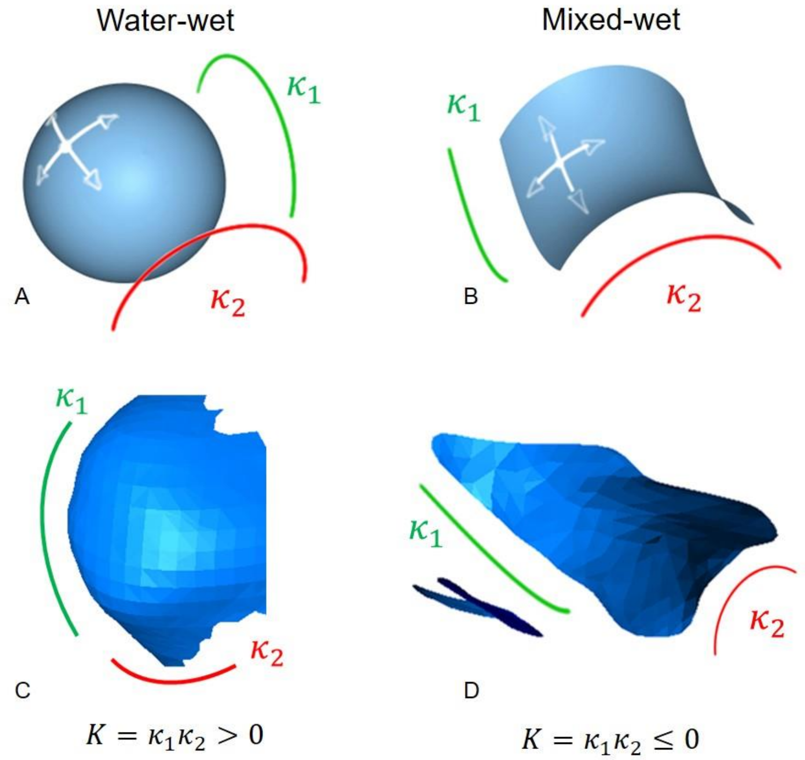
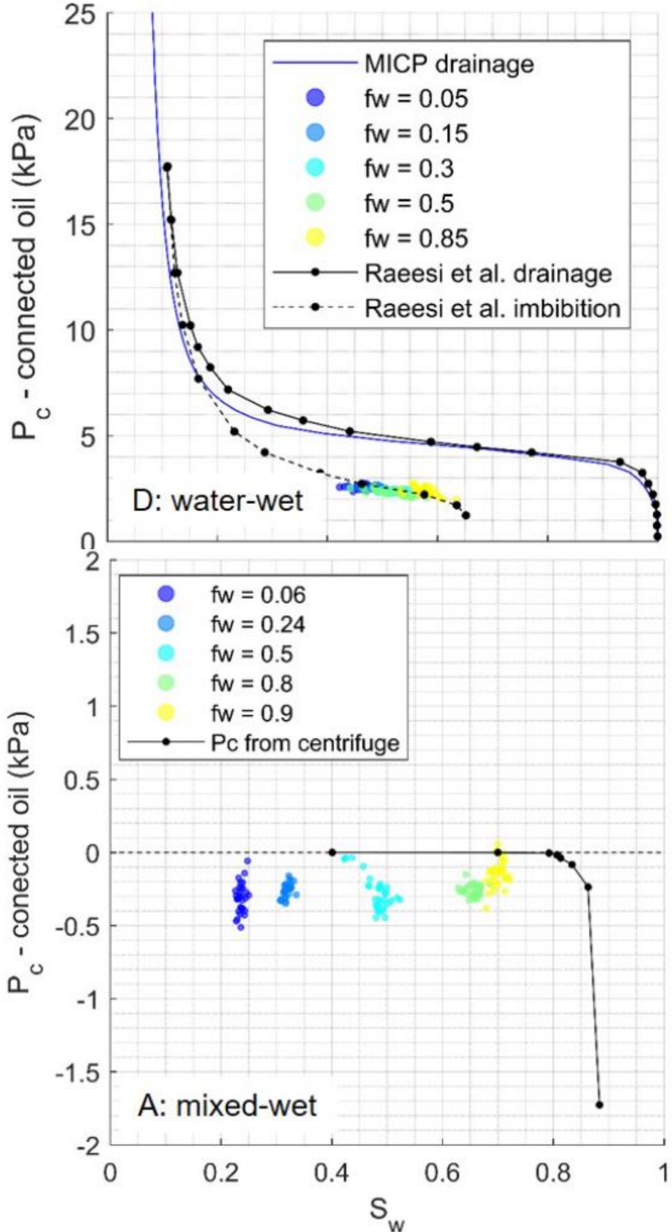
Imperial College London

Discontinuous Events and Energy Dissipation→ Bi-continuous Interfaces



Lin et al. *Phys. Rev. E, 2019*





- Mean curvature ~ 0
- Gaussian curvature < 0
  → bi-continuous interfaces with high connectivity
  → avoid dissipative discontinuous displacements ?

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Summary & Conclusions

- **Mobility of gas**
  - literature: gas mobility significantly below percolation threshold
  - in depletion experiments (quasi-static): connectivity ~ percolation threshold of 3D lattice
  - injection: at low rate mobility without permanent connectivity
  - relative permeability process dependent (depletion vs. flow)
  - possible mechanism: diffusion dominated transport (Pe<<1) + PVT ?
- **2-Phase flow in porous media: nw-phase mobility without connectivity**
  - many cases already documented in literature: snap-off during drainage, ganglion dynamics
  - in mixed-wet rock: more ganglion dynamics, contribution to flux
  - intermittent flow: **Fast synchrotron based μCT flow experiments**
  - **energy dissipation**: 2-phase Darcy = mass + momentum balance, but not energy balance
  - universal principle governing pore scale fluid distribution: minimization of dissipation ?

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Questions and Answers

Q&A

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