MANCHESTER 1824

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Pore-Scale Analysis of Dynamics of Two-Phase Flow in Porous Media

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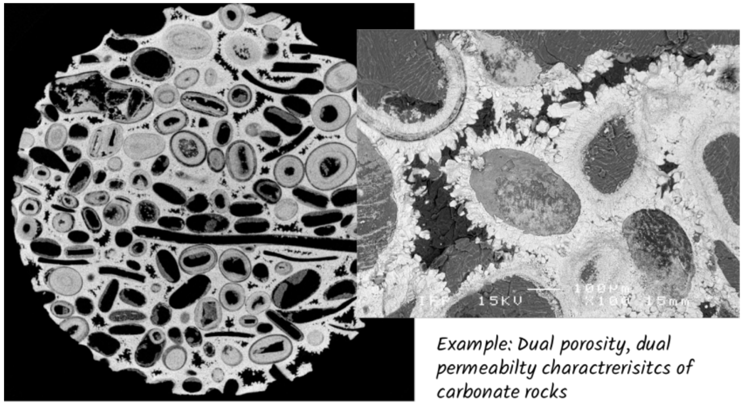
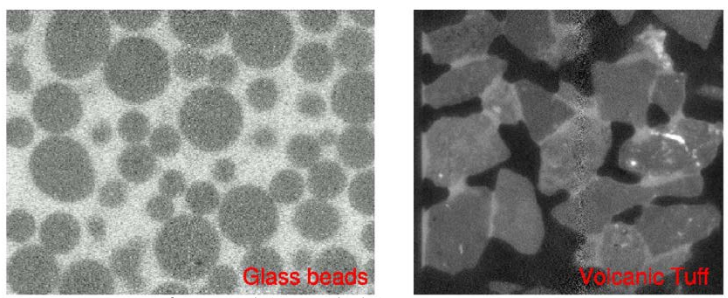
Mike Celia (Princeton University)

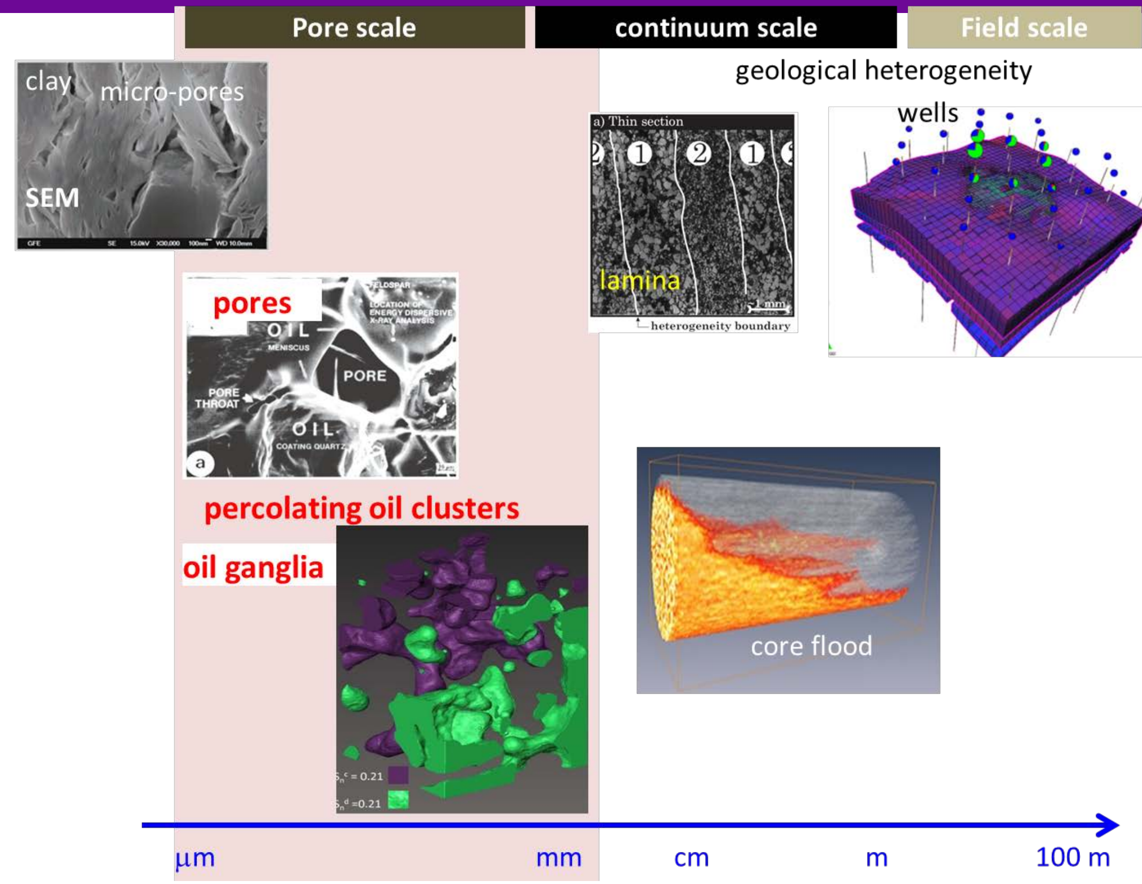
Filling the gaps across scales; pore-scale imaging & modelling



Example: Dual porosity, dual permeabilty charactrerisitcs of carbonate rocks
courtesy of Dr. O. Vizika, IFP, France



courtesy of D. Wildenschild, Oregon State University, USA



courtesy of Shell R&D

- Scale of practical interest (>m up to km)
- Scale of phenomena (<mm down to micrometer)
- Representative Elementary Volume (REV) ?

Micro-scale imaging and modelling infrastructures at the University of Manchester

Diamond Light Source (DLS) synchrotron i 13 facility

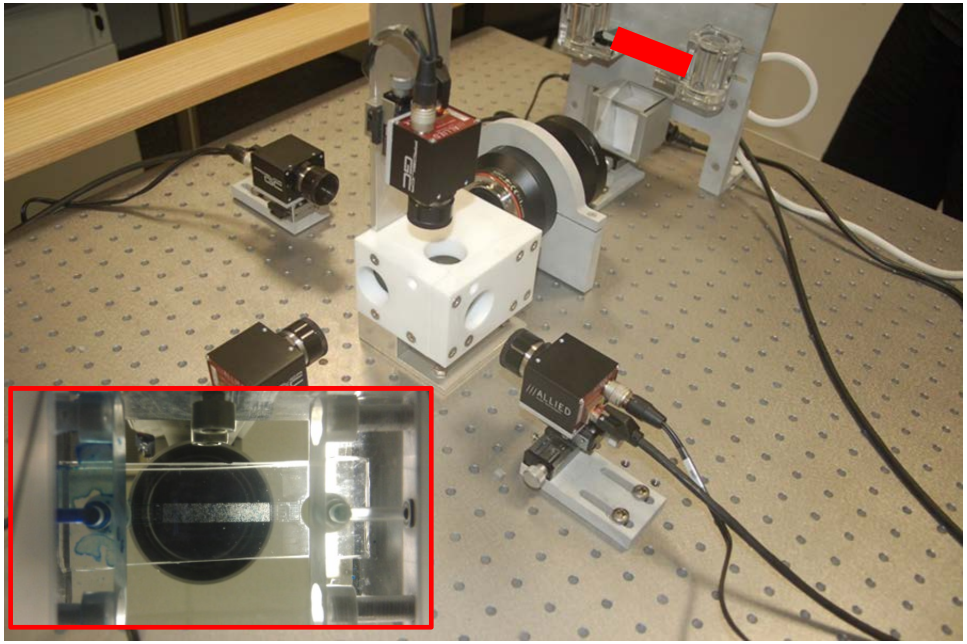
DLS is the UK's national synchrotron facility supporting academic and industrial research. A total of 18 beam lines are operational with funding from The University of Manchester supporting access for academic research. The spatial resolution for this technique is in the micron range. it will be possible to switch the instrument to full-field microscopy with 50nm spatial resolution.

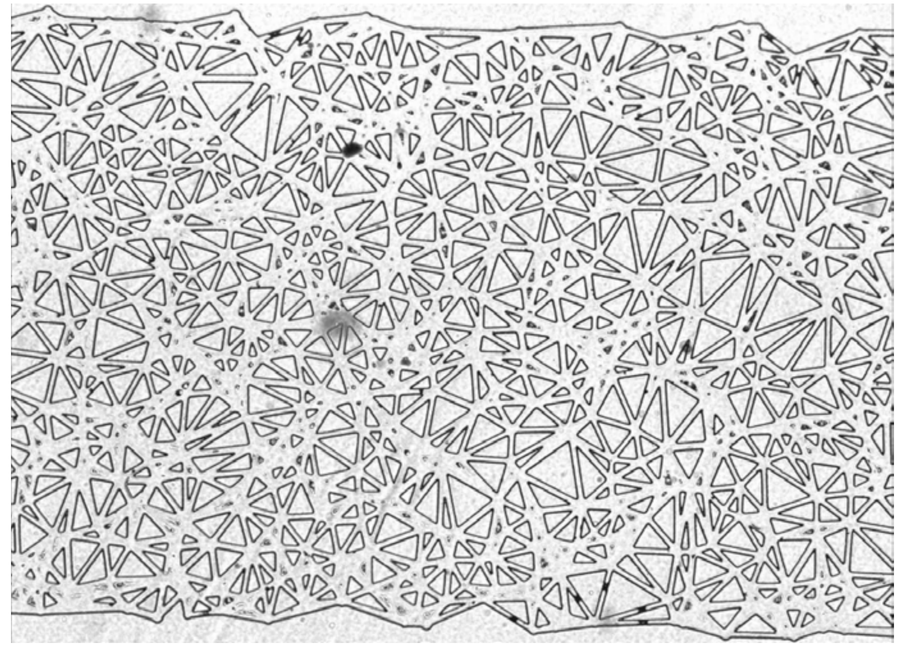
X-radia MicroCT/NanoCT

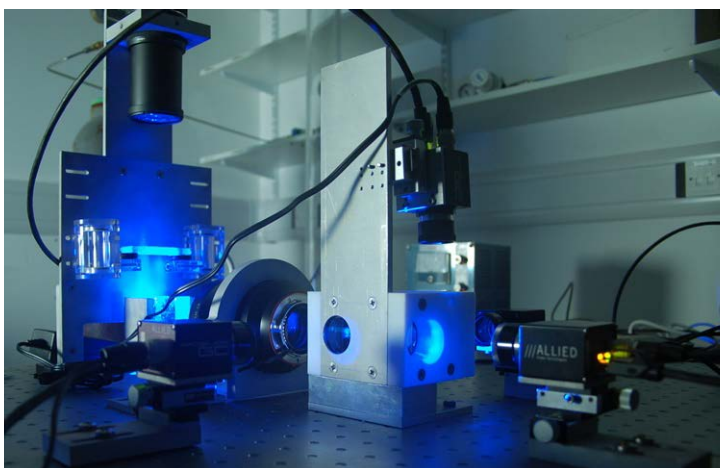
Resolution: 5-120 microns
Maximum field of view: ~170 mm
Sample sizes: 5mm - 170mm, max load 15 kg
Energy range: 225 kV
Typical scan time: 30-120 mins

Resolution: 150 nm or 50 nm
Maximum field of view: 65 microns or 15 microns
Maximum sample size: 0.5 kg
Maximum Energy: 8 kV

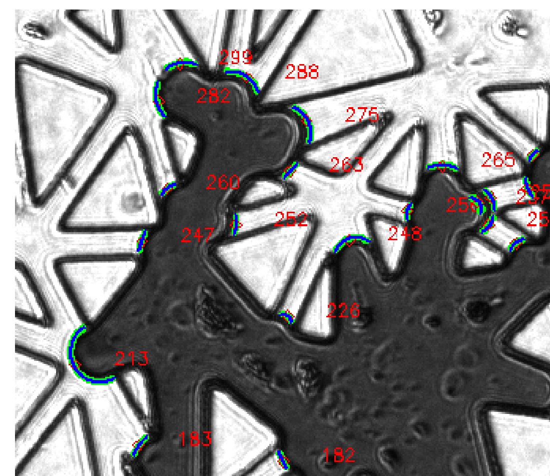
Two-phase flow micromodels lab (Reservoir on Chip)







- *Karadimitriou, N.K., Joekar-Niasar, V., et al (2012), Lab on a Chip.*
- *Karadimitriou, N., Musterd, M., Kleingeld, P., Kreutzer, M., Hassanizadeh, M., Joekar-Niasar, V. (2012), Water Resources Research*



Multi-Process pore-scale modelling

Fundamentals of Porous Media:

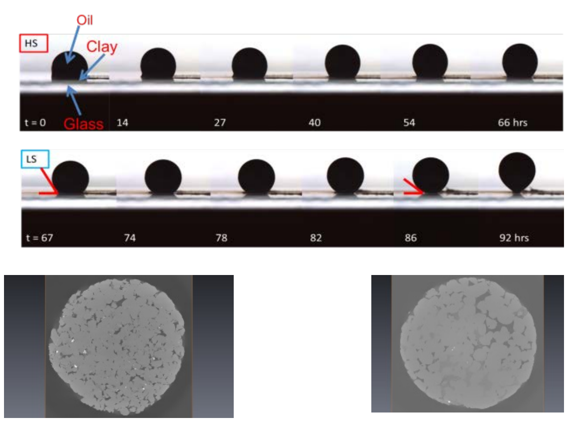
I) Pore-scale two-phase flow simulator; drainage, imbibition, capillary pressure, relperm simulator [WRR (2013), 4244 – 4256. WRR (2010), W06526., Journal of Fluid Mechanics (2010)655:38-71, Vadose Zone Journal (2012), 11(3); TiPM (2008) 74:201-219, TiPM (2012) 94:465-486].

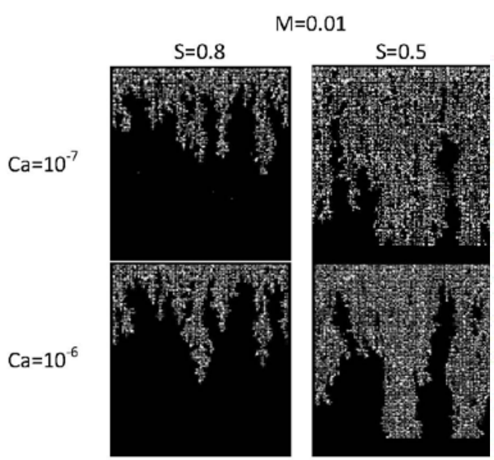
II) Solute transport module [Comp Geo (2014), 1-23]

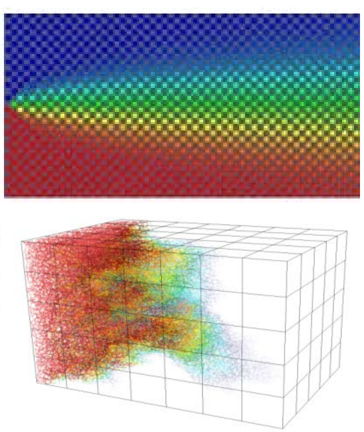
III) Electro-kinetic flow module and wettability alteration [Comp Geo (2013), 497-513, SPE Journal (2015)20 (01), 8-20].

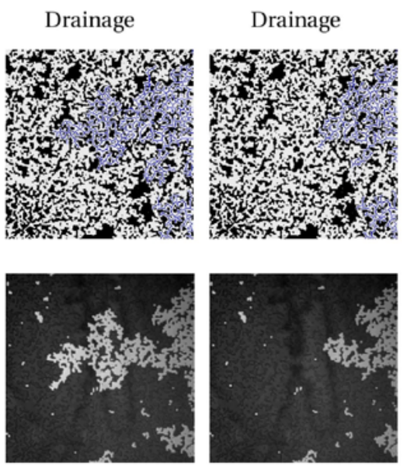
IV) Particle tracking

PetEng Applications: LowSal®, Fine migration control, EOR







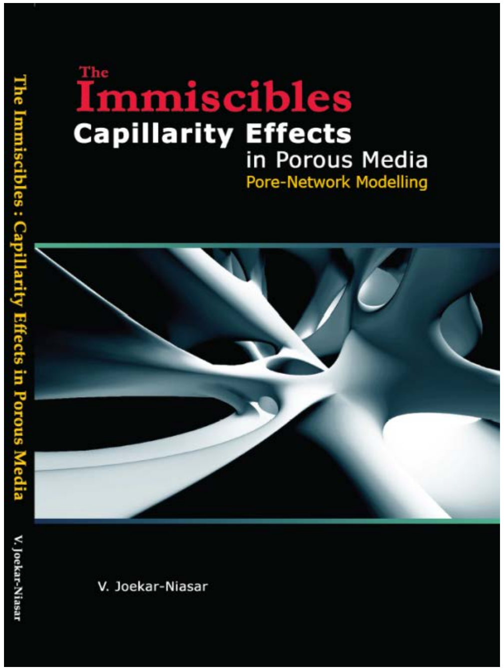


Today

Dynamics of two-phase flow

Understanding the fundamentals of constitutive equations of Darcy's extended equations.

- ❖ Understanding physics of two-phase flow in porous media
- ❖ Providing physically-based simulation support for theoretical studies
- ❖ Improving predictive capability and characteristic curves of porous media (e.g. relative permeability, capillary pressure-saturation)



The immiscibles: Capillarity effects in porous media - pore-network modelling,
ISBN: 978-90-5744-179-0

Motivation: Standard Two-Phase Flow Darcy's Law

q^{α}:flow rate for phase α
S^{α}:saturation of phase α
μ^{α}:viscosity of phase α
n: porosity
K: absolute permeability
P^{α}: pressure of phase α
P^{c}: capillary pressure
$k^{r\alpha}$: relative permeability of phase α

$$\frac{\partial\left(nS^{\alpha}\right)}{\partial t}+\nabla\bullet\mathbf{q}^{\alpha}=0$$

$$\mathbf{q}^{\alpha}=-\frac{k^{r\alpha}}{\mu^{\alpha}}\mathbf{K}\bullet\left(\nabla P^{\alpha}-\rho^{\alpha}\mathbf{g}\right)$$

$$P^{n}-P^{w}=f\left(S^{w}\right)=P^{c}$$

$$k^{r\alpha}=k^{r\alpha}\left(S^{w}\right)$$

Motivation: Extended theories of two-phase flow

$$n\frac{\partial S^\alpha}{\partial t} + \nabla \cdot \mathbf{q}^\alpha = \mathbf{0}$$

$$\mathbf{q}^\alpha = -\mathbf{K}^\alpha \cdot (\nabla p^\alpha - \rho^\alpha \mathbf{g} - \Psi^{\alpha a}\nabla a^{nw} - \Psi^{\alpha S}\nabla S^\alpha)$$

$$\frac{\partial a^{nw}}{\partial t} + \nabla \cdot (a^{nw}\mathbf{w}^{nw}) = E^{nw}(a^{nw}, S^w)$$

$$\mathbf{w}^{nw} = -\mathbf{K}^{nw}(\nabla a^{nw}\gamma^{nw} - \Psi^{wS}\nabla S^w)$$

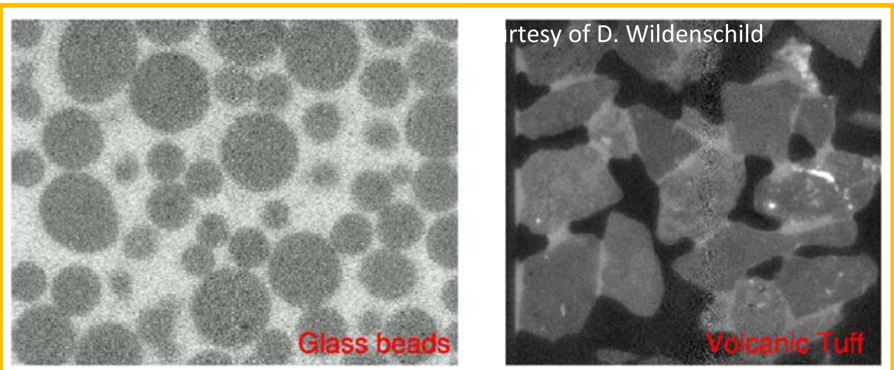
$$p^n - p^w = p^c - \tau\frac{\partial S^w}{\partial t}$$

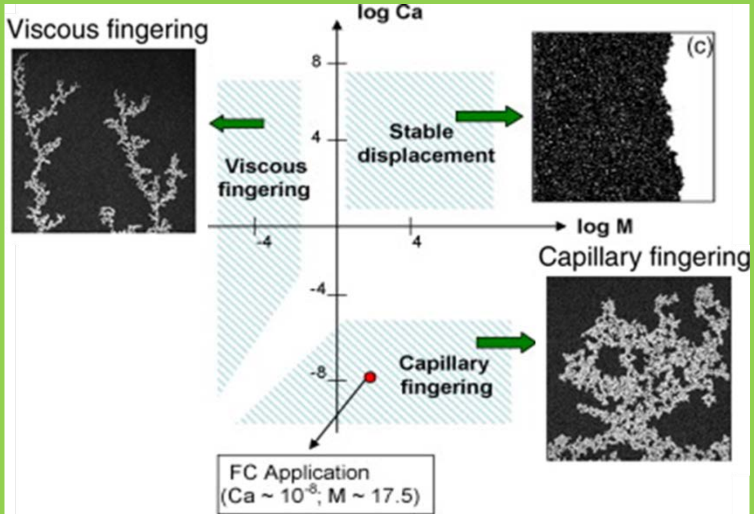
$$f(p^c, S^w, a^{nw}) = 0$$

Hassanizadeh and Gray, WRR, 1993,1998

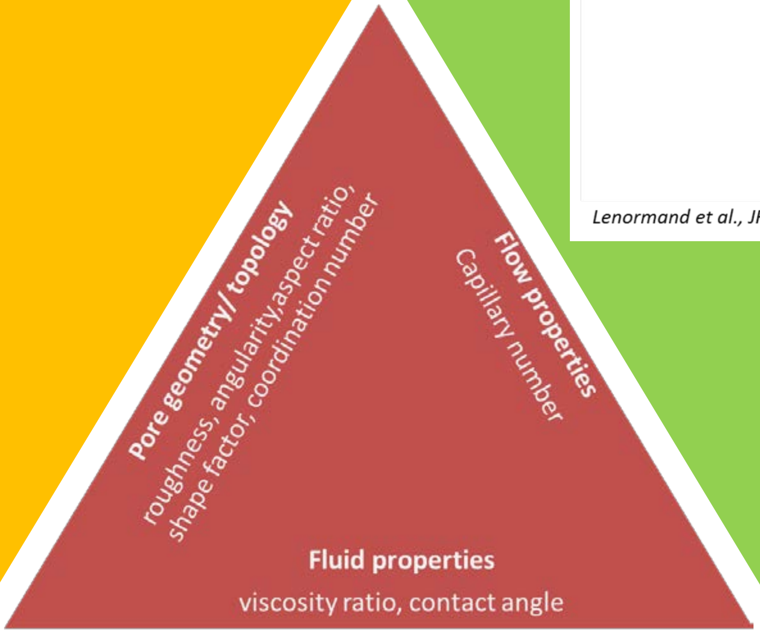
Pore-network modelling

Major advantages of pore-scale modelling

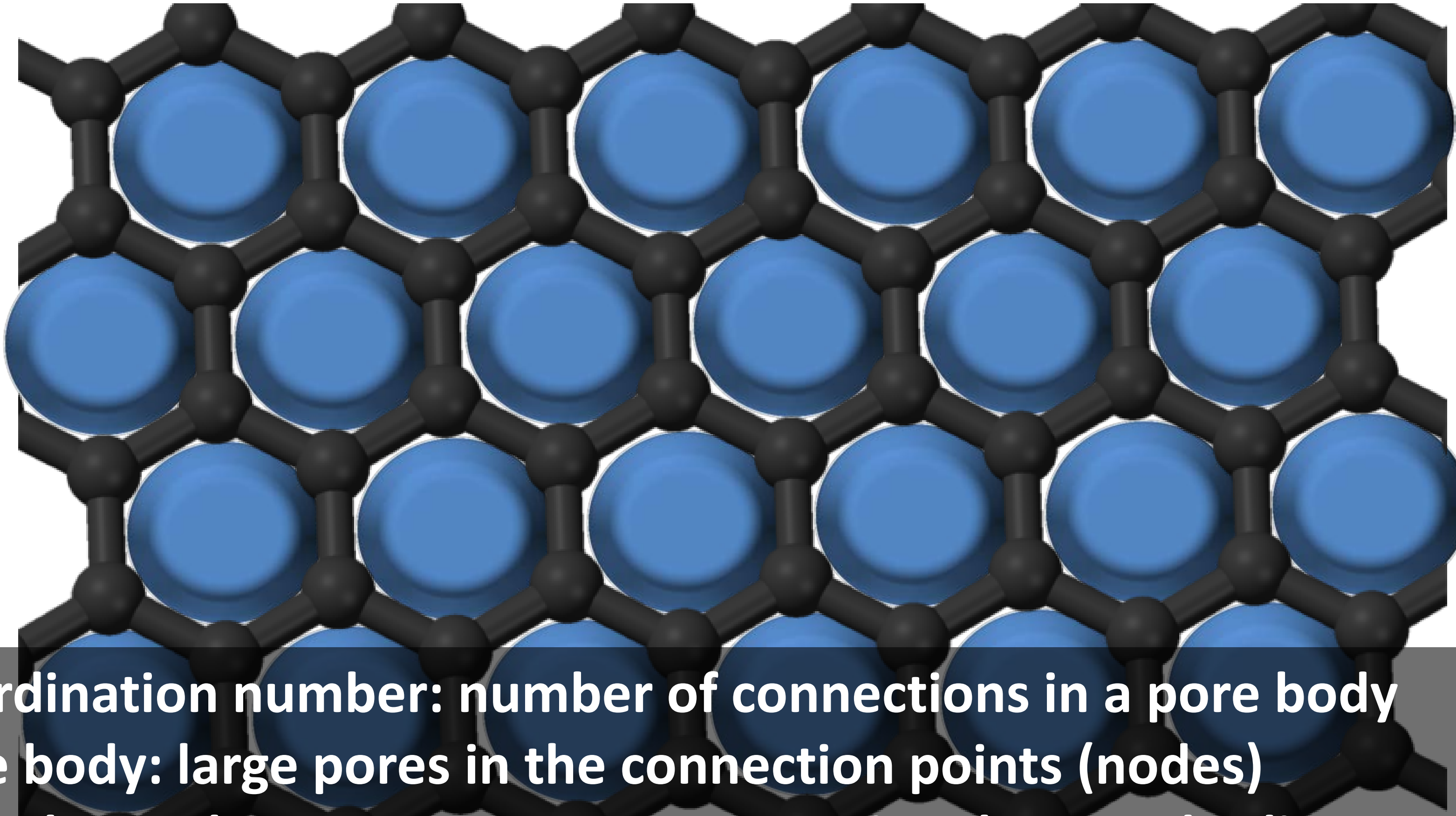




Lenormand et al., JFM (1988), Sinha & Wang, Electrochimica Acta (2007)



Conceptual model : definitions

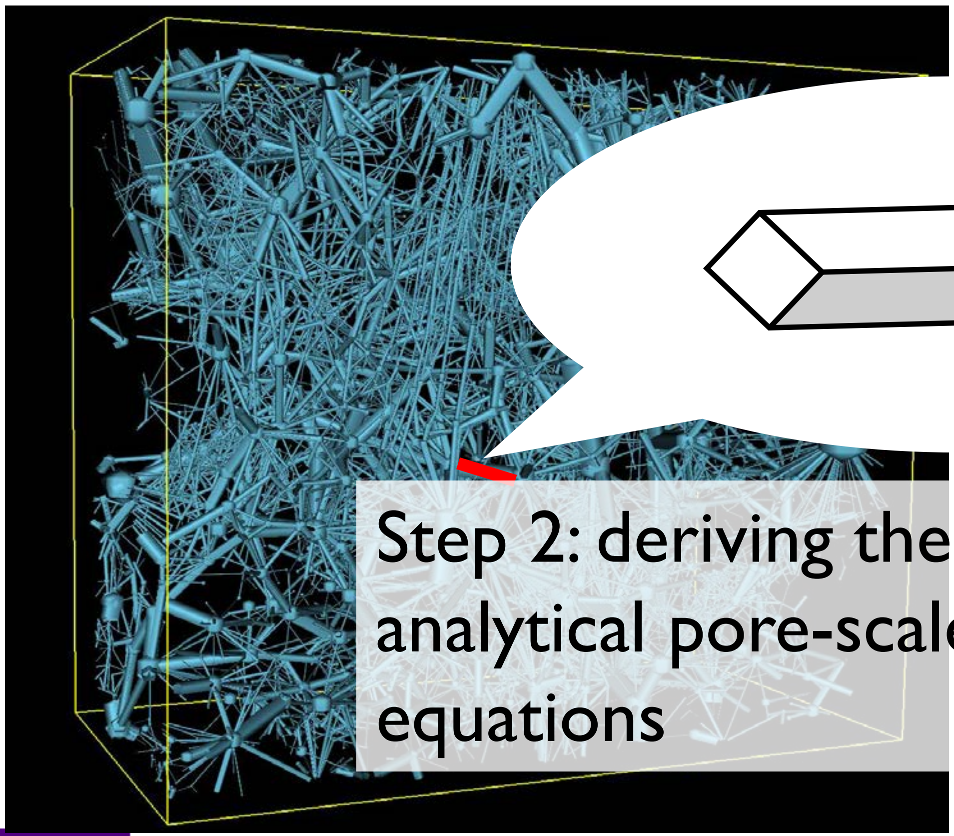


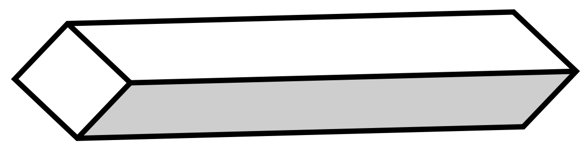
Coordination number: number of connections in a pore body
Pore body: large pores in the connection points (nodes)
Pore throat: long narrow pores connecting the pore bodies

Pore-network modelling

Step 1: defining the geometries and the network

Step 3: solving a system of equations in a network of inter-connected capillaries





Step 2: deriving the analytical pore-scale equations

Quasti-static vs. dynamic PNMs

- Computationally expensive.
- Pressure field is solved.
- Network and fluids properties are important.
- Not been used as extensively as quasi-static ones; P^c-S^w, k^r-S^w,S^w-a^{nw}, mobilization of disconnected phase, dynamic pressure field
- Weak tractability due to nonlinearities at pore scale

- Computationally very cheap.
- No pressure field is solved.
- Pore-scale geometry and topology are only important.
- Used extensively, for two-phase and three-phase flow; P^c-S^w, k^r-S^w, S^w-a^{nw}, reactive transport, etc.
- …. as a predictive tool

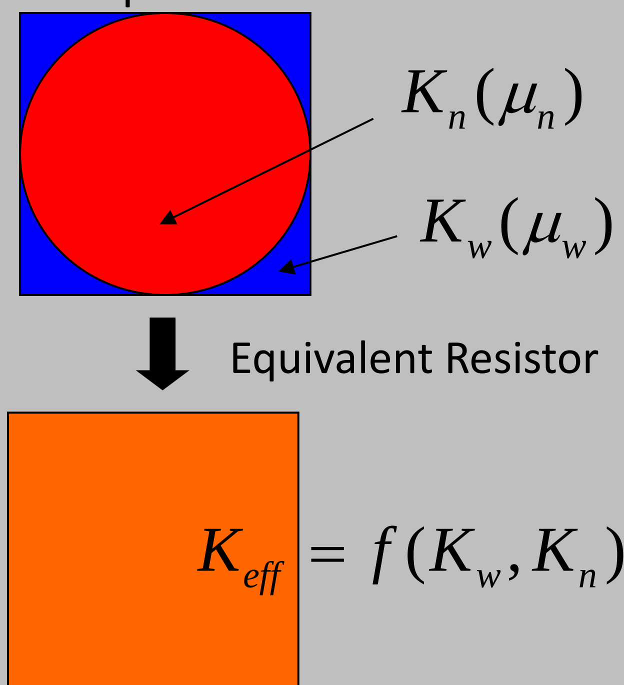
Dynamic pore-network modeling

Previous DPNMs

One-pressure solver

Simplified physics

Inconsistency in fluid configuration versus quasi-static models

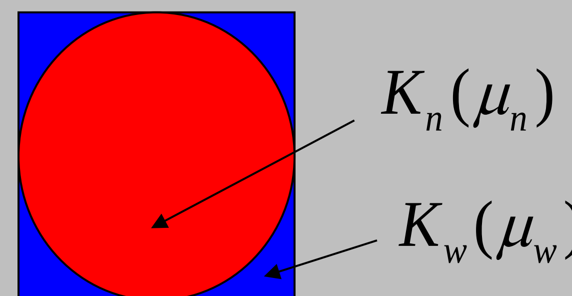


Previous DPNMs

One-pressure solver

Detailed physics

Computationally more expensive.



We gain:

Co-current and counter-current flow

Piston-like movement vs. snap-off

Interface dynamics &

Ganglia dynamics

Quasi-static vs. Dynamic PNMs

Q

$$p_i^n - p_i^w = f(\kappa_i) = f(s_i^w)$$

$$s_i^w + s_i^n = 1$$

appended to the local rules:

$$K_{ij}^{\alpha} = K_{ij}^{\alpha}(\kappa_{ij}, \mu_{ij}^{\alpha})$$

$$p_{e_{ij}}^c = f(r_{ij})$$

$$p_{s_{ij}}^c = f(r_{ij})$$

D

$$V_i \frac{\Delta s_i^{\alpha}}{\Delta t} = -\sum_{j=1}^{N_i} Q_{ij}^{\alpha}, \alpha = w, n$$

$$Q_{ij}^{\alpha} = K_{ij}^{\alpha}(p_i^{\alpha} - p_j^{\alpha})$$

$$p_i^n - p_i^w = f(\kappa_i) = f(s_i^w)$$

$$s_i^w + s_i^n = 1$$

appended to the local rules:

$$K_{ij}^{\alpha} = K_{ij}^{\alpha}(\kappa_{ij}, \mu_{ij}^{\alpha})$$

$$p_{e_{ij}}^c = f(r_{ij})$$

$$p_{s_{ij}}^c = f(r_{ij})$$

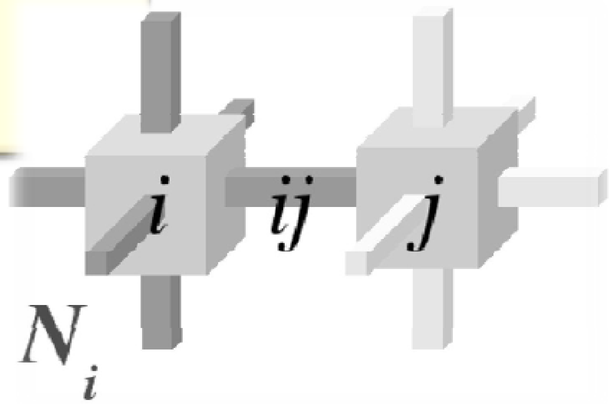
Governing equations

$$V_i \frac{\Delta S_i^\alpha}{\Delta t} = -\sum_{j=1}^{N_i} Q_{ij}^\alpha, \quad \alpha = w, n$$

$$Q_{ij}^\alpha = K_{ij}^\alpha (P_i^\alpha - P_j^\alpha) \quad K_{ij}^\alpha = K_{ij}^\alpha(\kappa_{ij}, \mu_{ij}^\alpha)$$

$$P_i^n - P_i^w = f(\kappa_i) = f(S_i^w)$$

$$S_i^w + S_i^n = 1$$



Governing equations:pressure field

Introducing $\bar{P}_i = S_i^w P_i^w + S_i^n P_i^n$

We can write:

$$\sum_{j=1}^{N_i} [(K_{ij}^w + K_{ij}^n)(\bar{P}_i - \bar{P}_j) + (K_{ij}^n S_i^w - K_{ij}^w (1 - S_i^w)) P_i^c + (K_{ij}^w (1 - S_j^w) - K_{ij}^n S_j^w) P_j^c] = 0$$

Joekar-Niasar, JFM, 2010

Governing equations: saturation update

we can write saturation update in a semi-implicit way; as the summation of an advective term and a diffusive term:

$$V_i \frac{(S_i^w)^{k+1} - (S_i^w)^k}{\Delta t} -$$
$$\sum_{j=1}^{N_i} \left(\frac{K_{ij}^n}{K_{ij}^{tot}} Q_{ij}^{tot} + \frac{K_{ij}^w K_{ij}^n}{K_{ij}^{tot}} \frac{\partial P_{ij}^c}{\partial S_{ij}^w} \left((S_i^w)^{k+1} - (S_j^w)^{k+1} \right) \right) = 0$$

Joekar-Niasar, JFM, 2010

Local rules

$$P_i^c = 2\sigma^{nw}\kappa_i$$

Local P^c_i –S^w_i curve for a pore body: drainage

$$\kappa_i = \begin{cases} \left(\frac{1}{r_{ij}} - \frac{1}{R_i}\right)\left(\frac{S_i^w - S_i^{dr}}{1 - S_i^{dr}}\right)^{3.5} + \frac{1}{R_i} & S_i^w \geq S_i^{dr} \\ \frac{1}{R_i}\left(\frac{S_i^w}{S_i^{dr}}\right)^a, a = \frac{1}{2.98 S_i^{dr} - 3.85} & S_i^{min} < S_i^w < S_i^{dr} \end{cases}$$

Local P^c_i –S^w_i curve for a pore body: imbibition

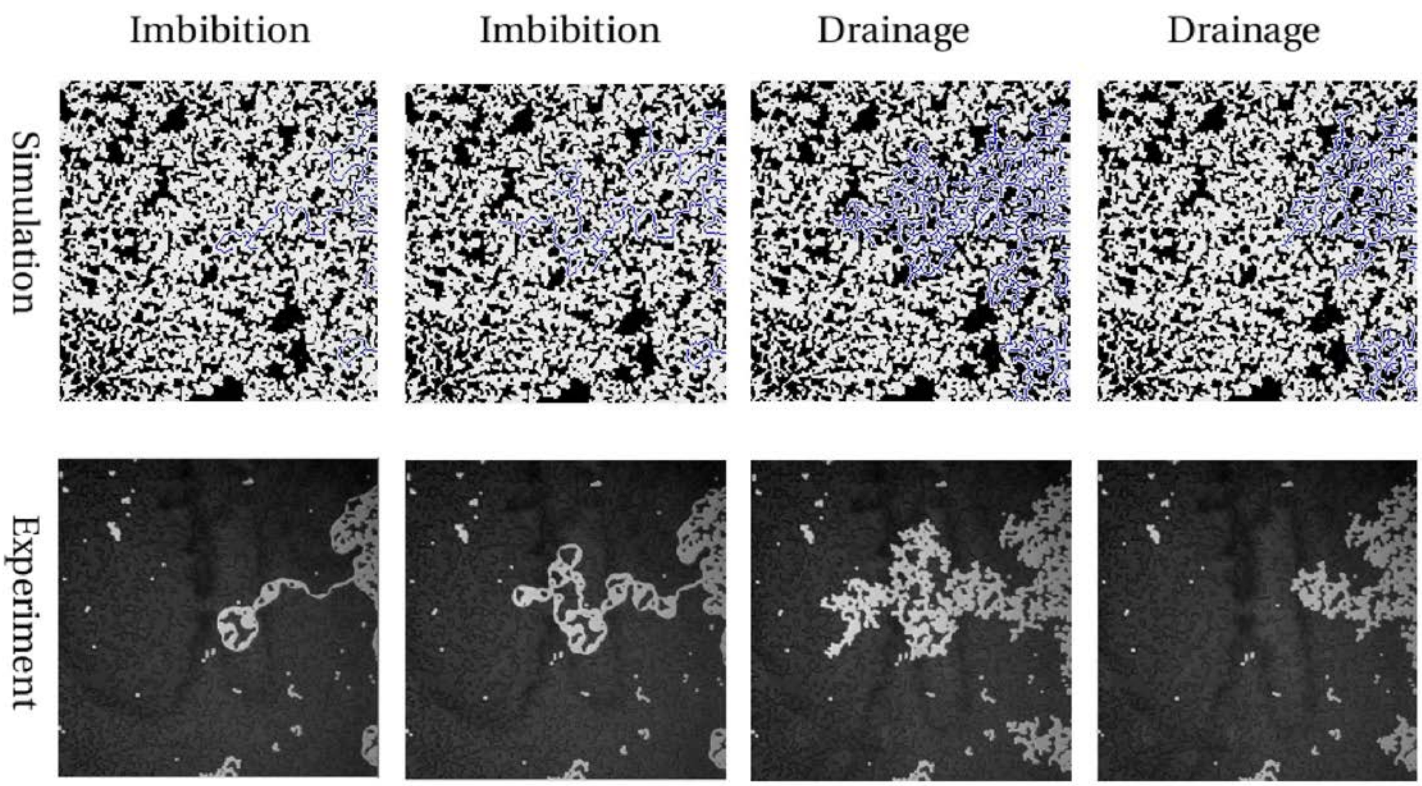
$$\kappa_i = \begin{cases} \left(\frac{1}{r_{ij}} - \frac{1}{R_i}\left(\frac{S_i^{imb}}{S_i^{dr}}\right)^a\right)\left(\frac{S_i^w - S_i^{imb}}{1 - S_i^{imb}}\right)^{3.5} + \frac{1}{R_i}\left(\frac{S_i^{imb}}{S_i^{dr}}\right)^a & S_i^w \geq S_i^{imb} \\ \frac{1}{R_i}\left(\frac{S_i^w}{S_i^{dr}}\right)^a, a = \frac{1}{2.98 S_i^{dr} - 3.85} & S_i^{min} < S_i^w < S_i^{imb} \end{cases}$$

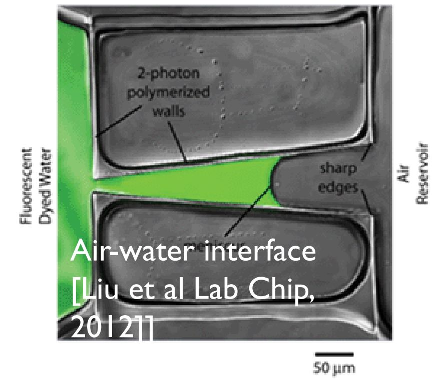
Features of the new formulation

- Fully consistency between quasi-static and dynamic model
- Numerically stable under a very wide range of capillary number and viscosity ratio
- Major pore-scale mechanisms included:
  - Pinston-like invasion
  - Snap-off
  - Trapping
  - Capillary interface dynamics
  - Mobilization of the disconnected phase

Joekar Niasar et al,JFM (2010)

Equilibrium: micromodels simulations vs. experiments

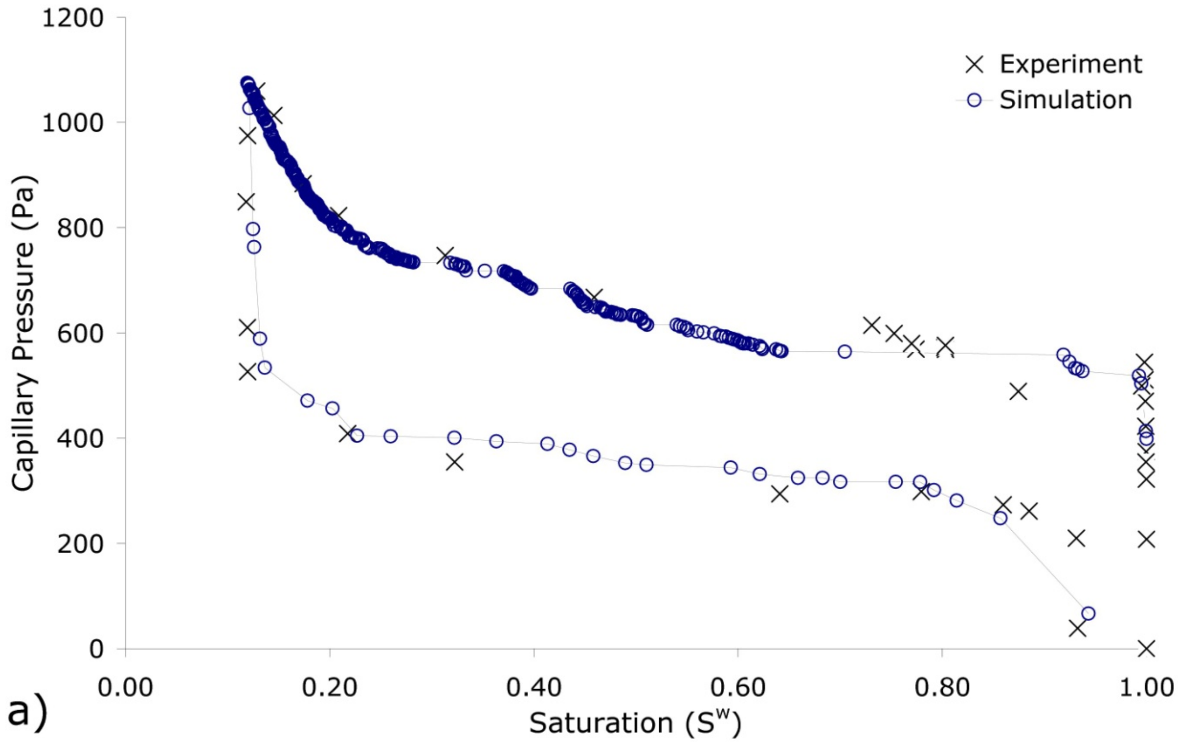


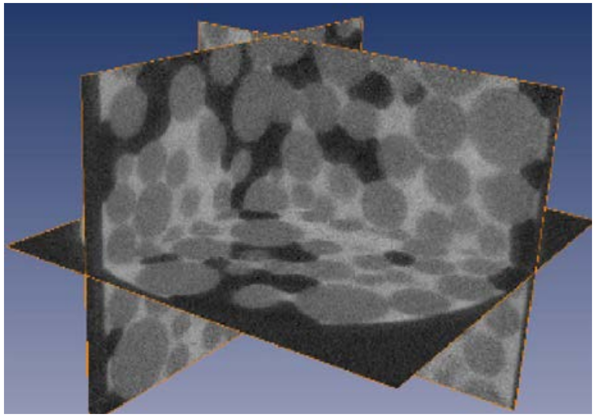


Air-water interface [Liu et al Lab Chip, 2012]]

-Joekar-Niasar, V., Hassanizadeh, S. M. (2011), International Journal of Multiphase Flow
-Joekar-Niasar, V., Hassanizadeh, S.M. (2011), WRR
-Joekar-Niasar, V., Hassanizadeh, S.M. (2012), Transport in Porous Media

Equilibrium: glassbeads simulations vs. experiments

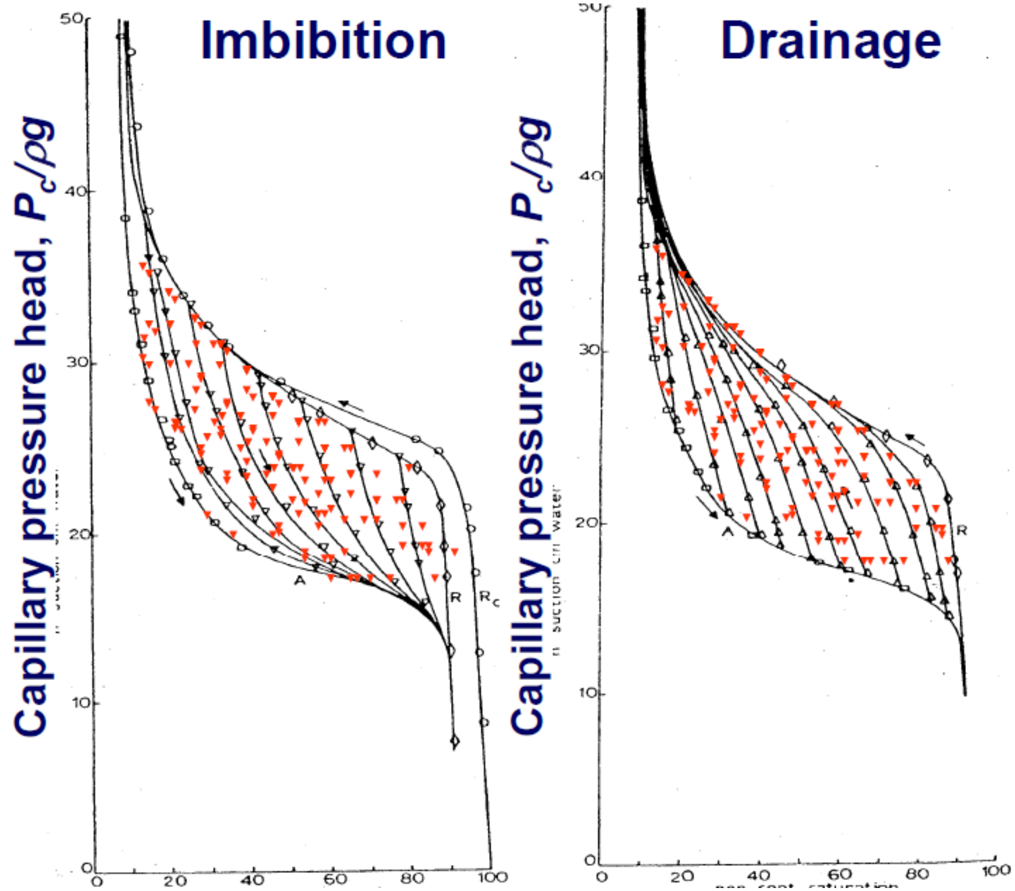




An irregular unstrucutred network with hyperbolic polygonal cross sections.

Joekar-Niasar et al, WRR, 2010

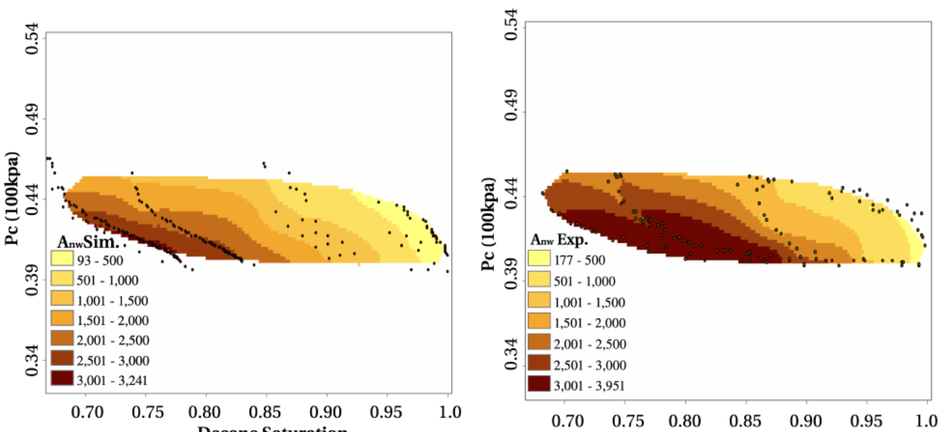
On hysteresis of P^c-S function



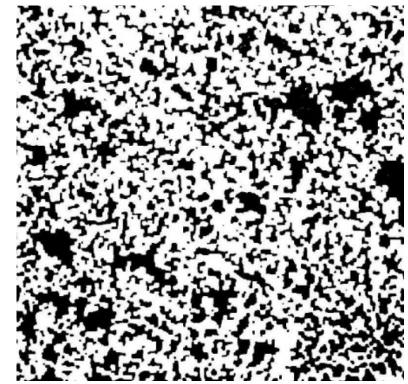
Capillary pressure-saturation data points measured in laboratory (Morrow and Harris, 1965)

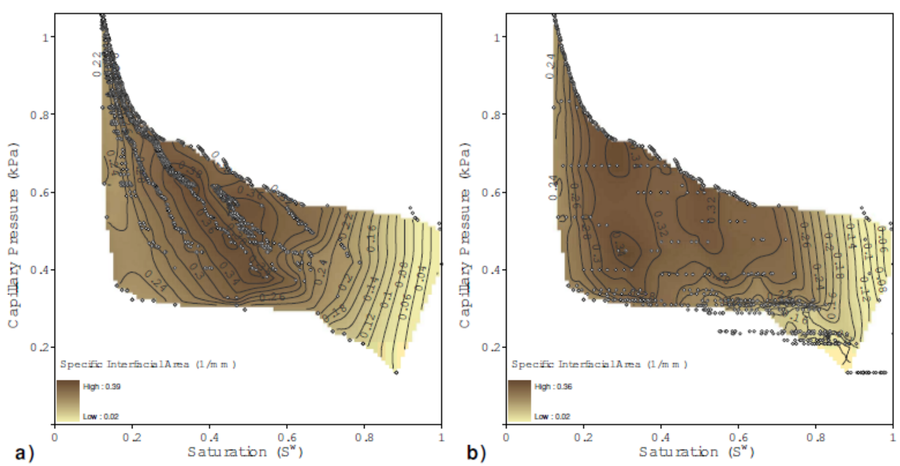
On hysteresis of P^c-S function

$$f(p^c, S^w, a^{nw}) = 0$$

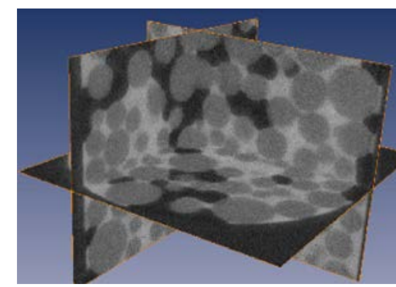


a) b)



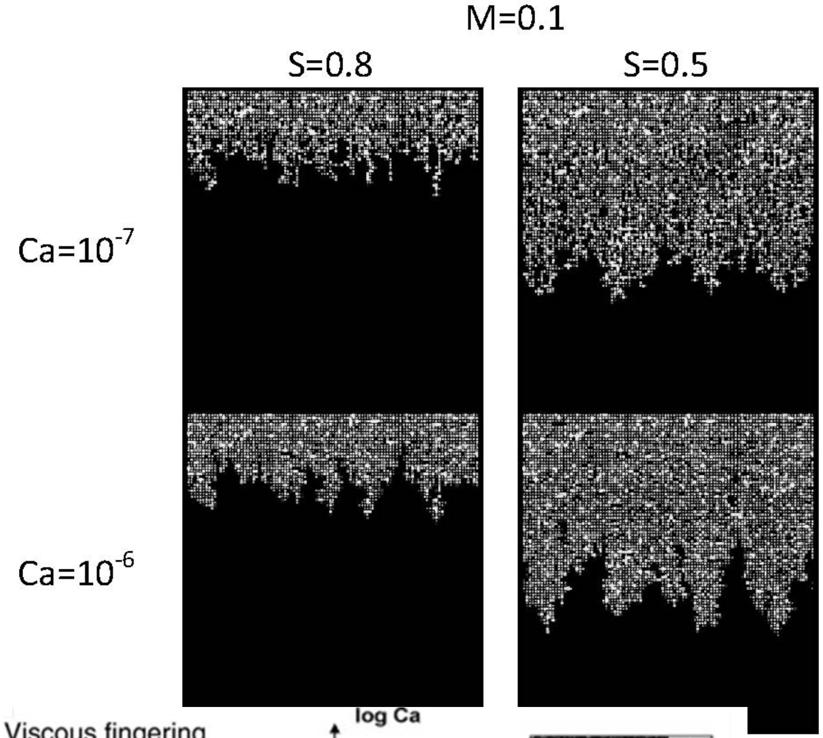


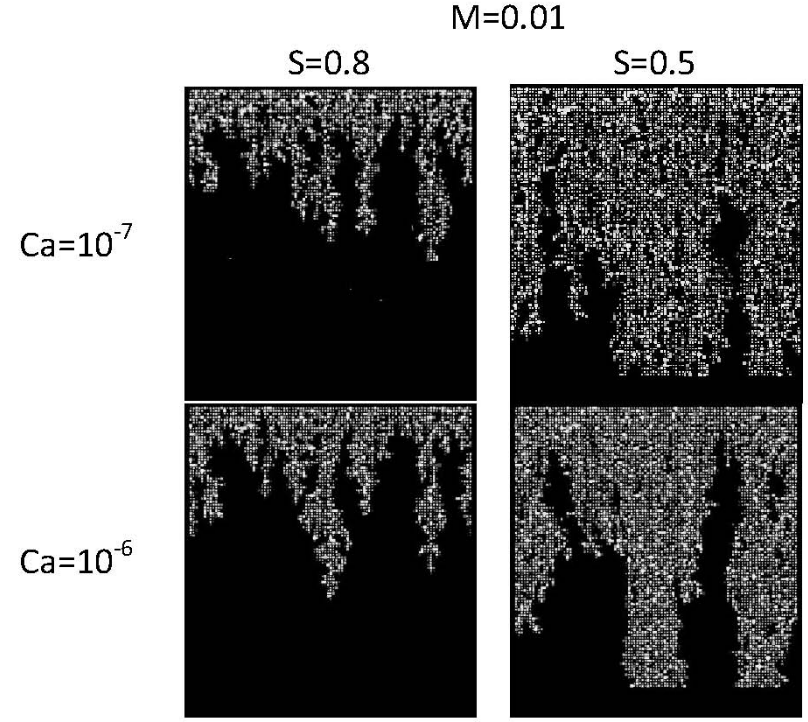
a) b)

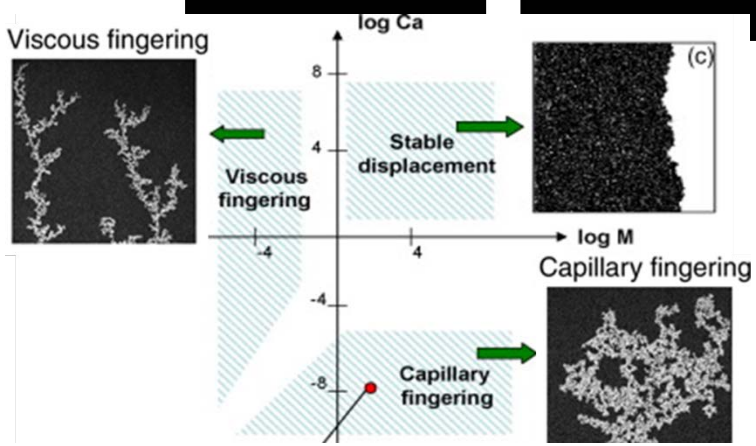


Reeves and Celia1996,Held and Celia 2001, Joekar-Niasar et al, TiPM, 2008, WRR,2009, 2010

Non-equilibrium: flow regime





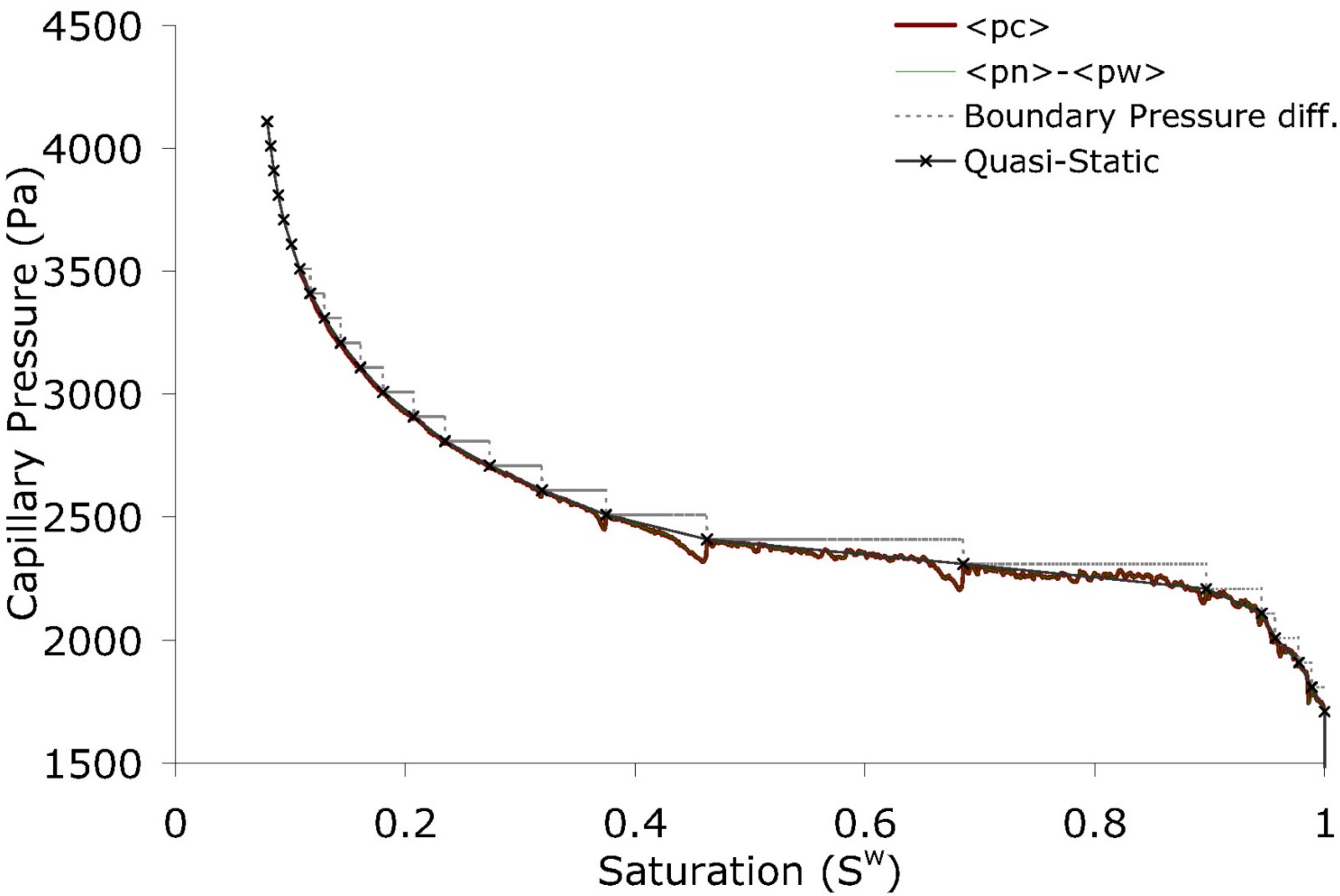


-*Joekar-Niasar, V., Hassanizadeh, S. M. (2011), International Journal of Multiphase Flow, 37: 198-214.*

-*Joekar-Niasar, V., Hassanizadeh, S.M. (2011), Water Resources Research, 47, W05513.*

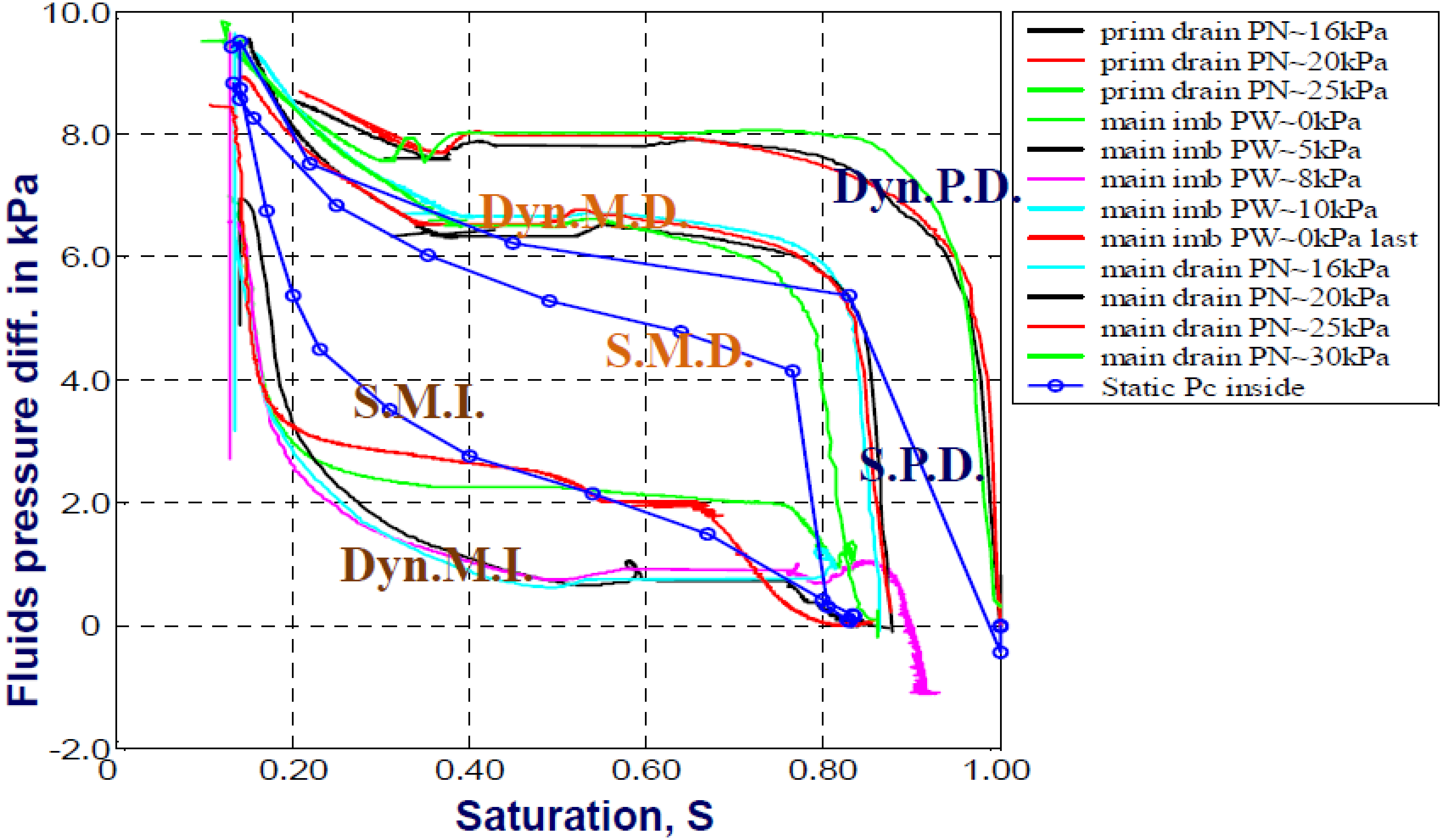
-*Joekar-Niasar, V., Hassanizadeh, S.M. (2012), Transport in Porous Media, doi: 10.1007/s11242-012-9958-3.*

Close-to-equilibrium phase pressure difference vs. capillary pressure



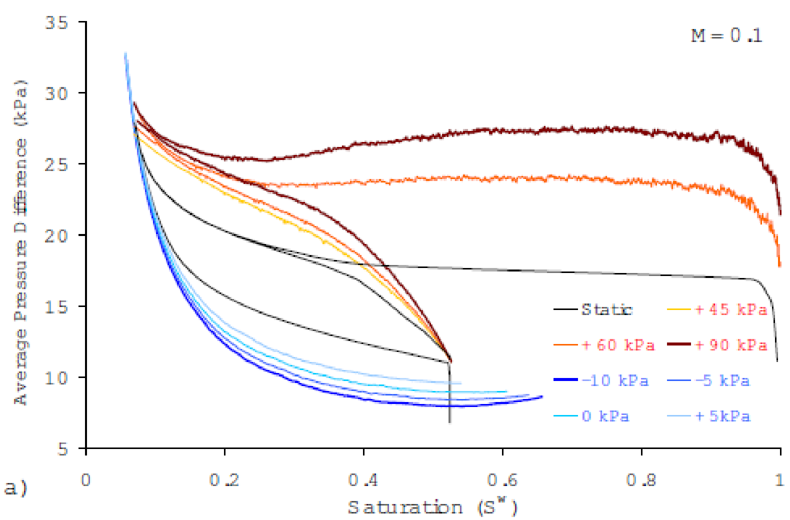
Joekar-Niasar, Hassanizadeh, Dahle, JFM, 2010

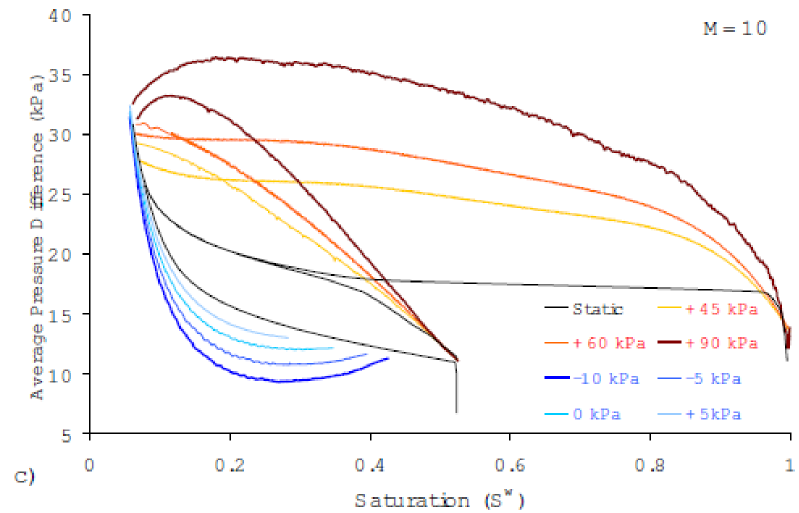
Non-equilibrium phase pressure versus capillary pressure (PCE-Water column experiments)

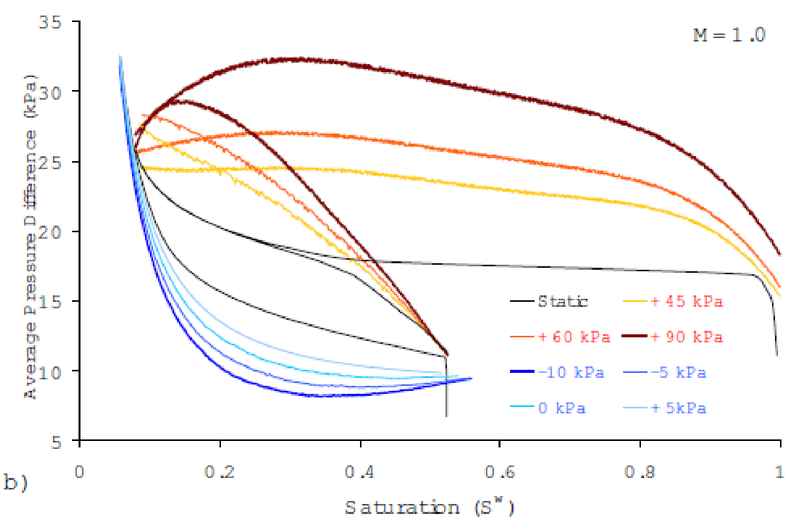


Hassanizadeh, Oung, Mohanty, 2004

Non-equilibrium phase pressure versus capillary pressure





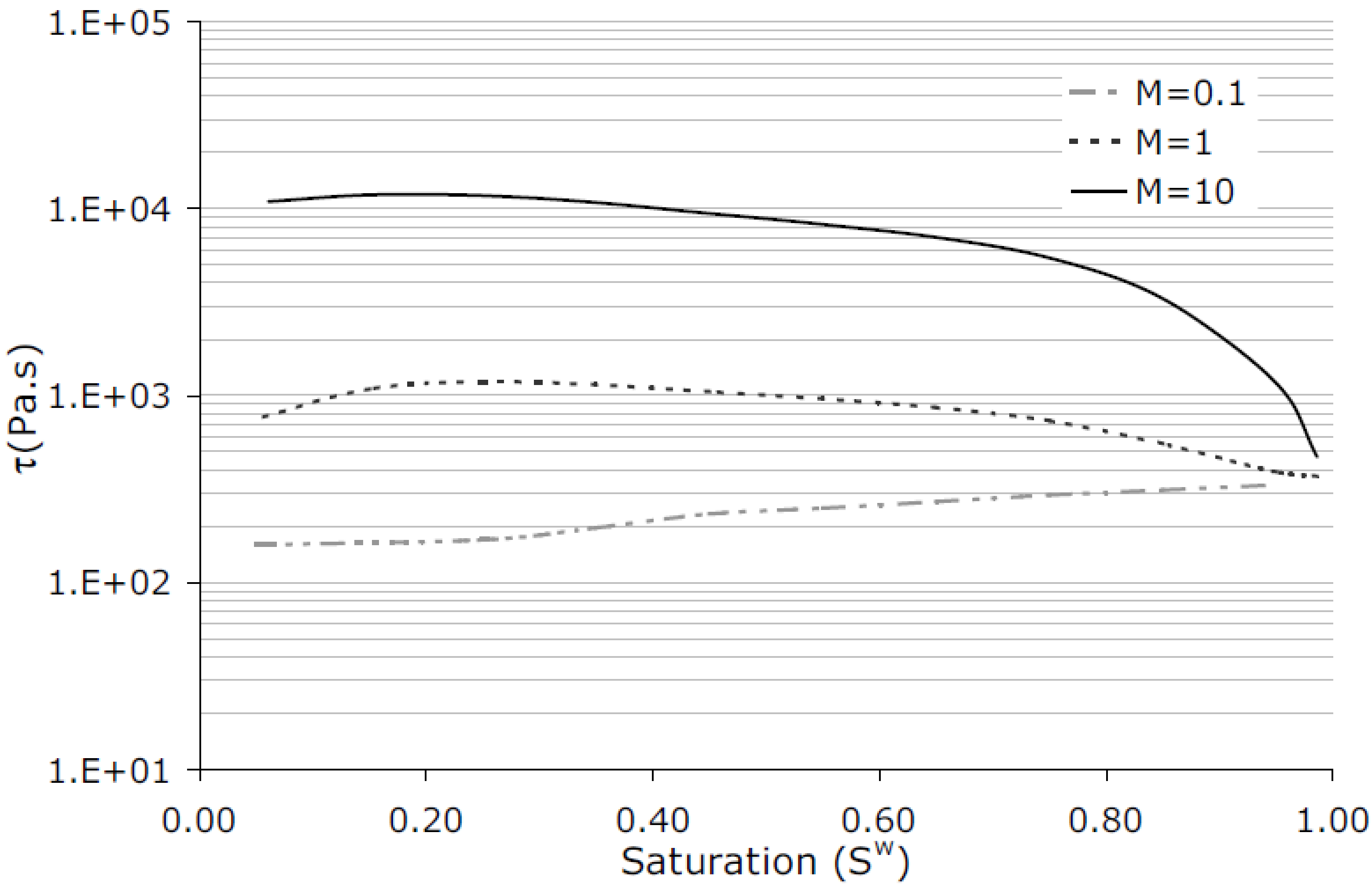


$$M = \mu^n / \mu^w, \mu^n = 0.001 Pa.s$$

$$P^n - P^w = P^c - \tau \frac{dS^w}{dt}$$

Joekar-Niasar, Hassanizadeh, Dahle, JFM, 2010

Dynamic effect on capillary pressure



Joekar-Niasar, Hassanizadeh, Dahle, JFM, 2010

Discussion

Flexibilities

Physically-based approach to integrate the pore-scale information.

Pore space definition is not resolution-dependent.

Application to many static and dynamic multi processes.

Compared to other pore-scale simulators, computationally cheaper.

Post-processing straight forward. Capability to provide up-scaled information.

Challenges and limitations:

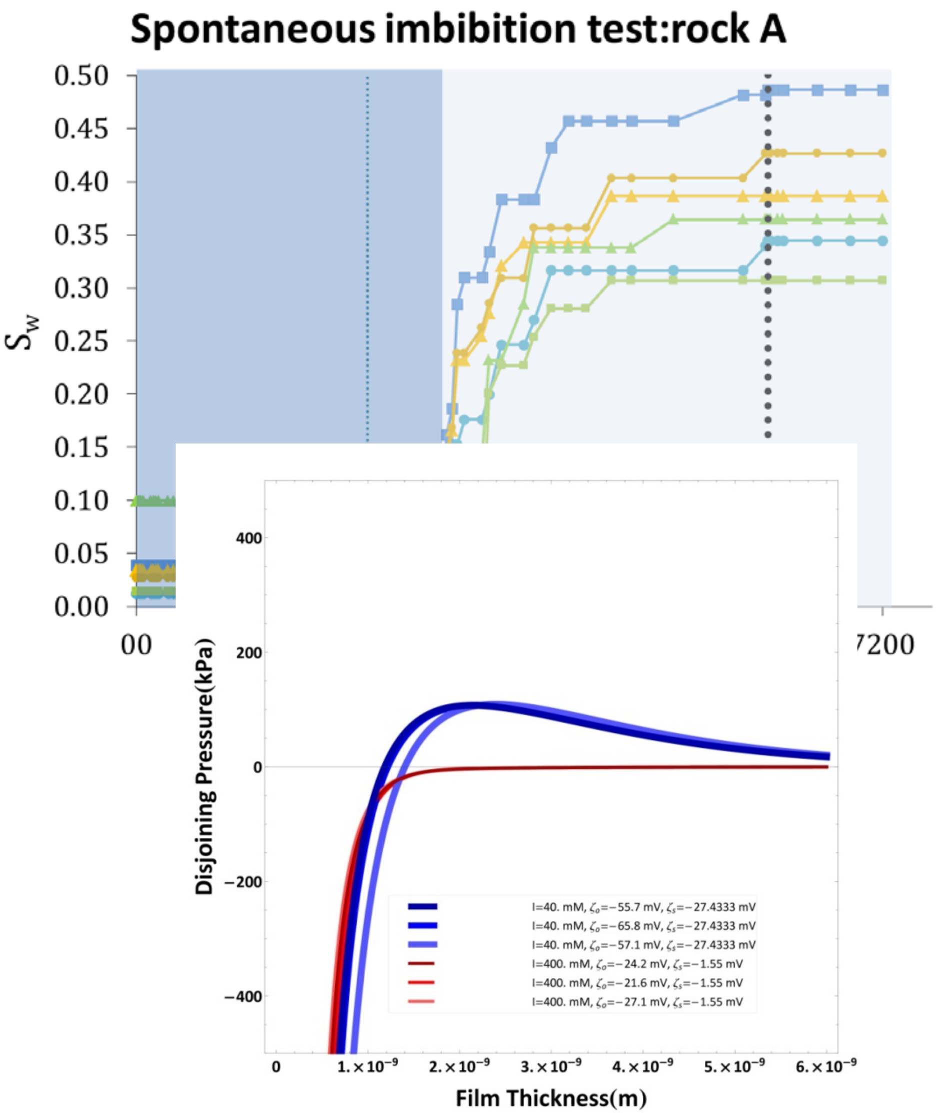
- **Pre-processing**:Idealization of void space topology and geometry is an inevitable non-unique solution. It is not always straight forward!.
- **Processing: a)** No detail information within a discrete pore (e.g. pressure field in a pore). **b)** local rules are important and need to be supported by high resolution single-pore CFD.

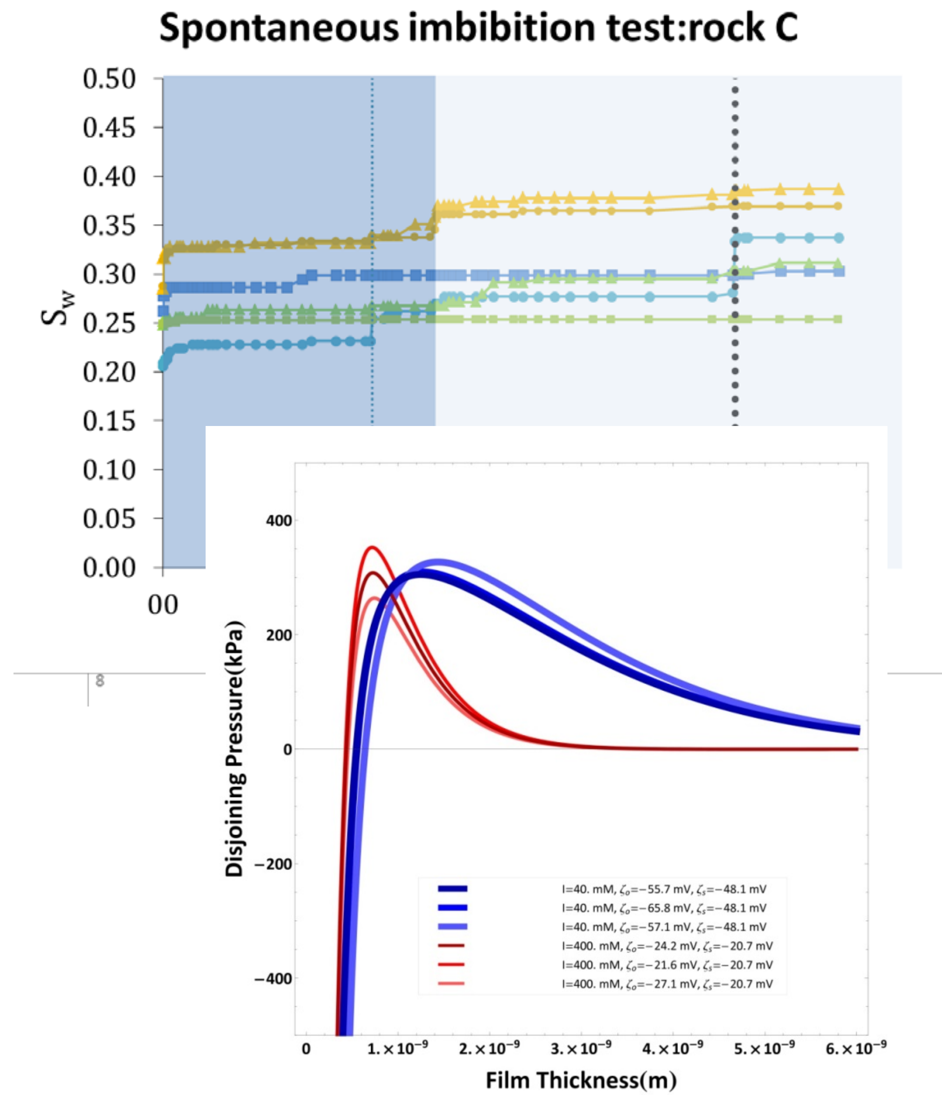
Discussion

- Compared to other pore-scale modelling techniques, pore-network modelling can still provide more flexibility in tractability and decoupling of processes. There is a huge potential in further development of hybrid pore-scale models.
- Pore-scale modelling provides valuable insights into physics of porous media phenomena, such as multiphase flow, mixing.
- Multi-process pore-scale modelling is an important tool for EOR applications..
- Investment in "benchmarking" of various pore-scale models is yet to be done.

Thanks for your attention!

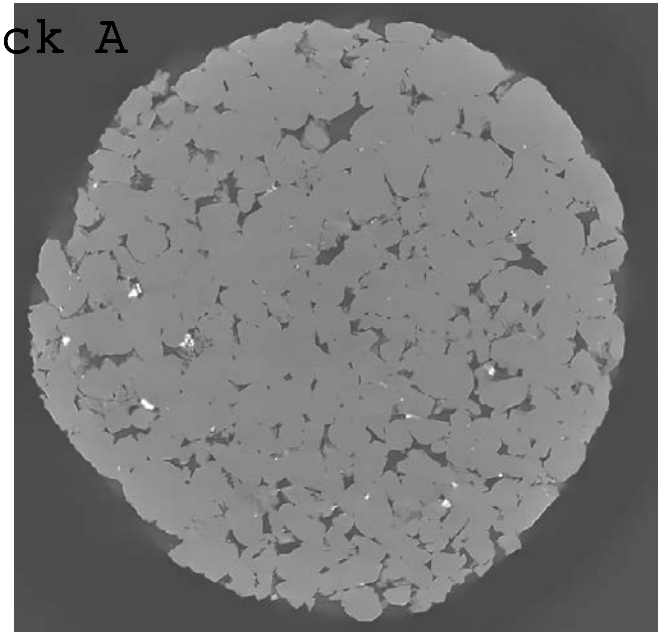
Low salinity effect; wettability alteration





Network modelling of fractional flow for LoSal®

Rock A



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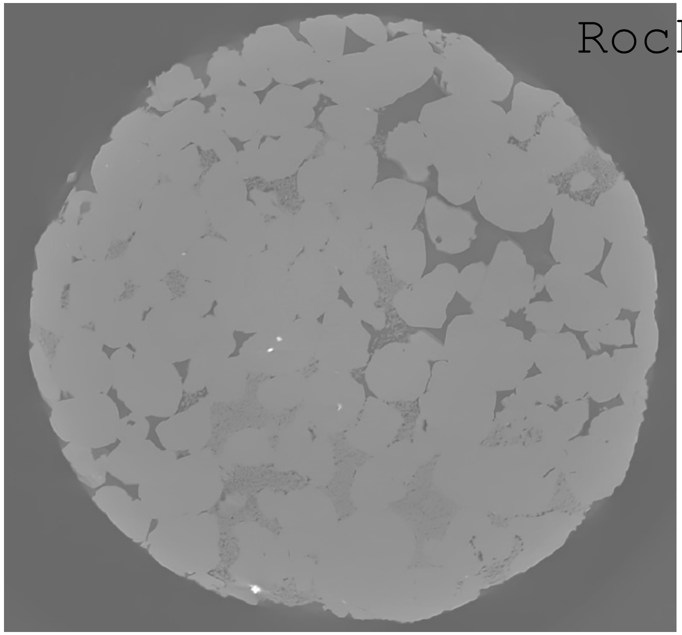

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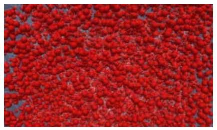
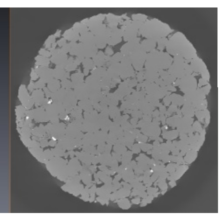
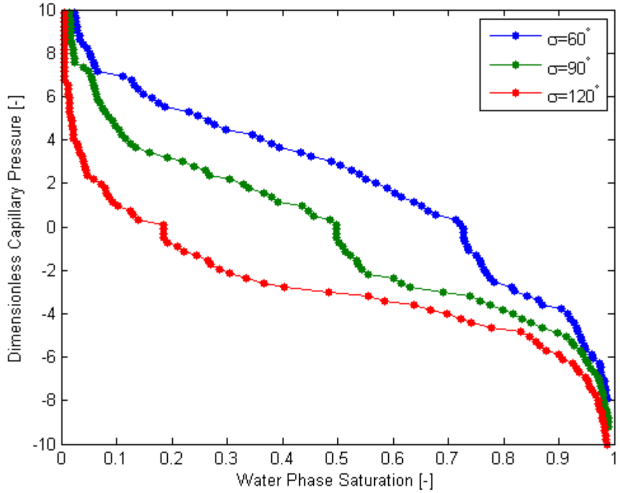
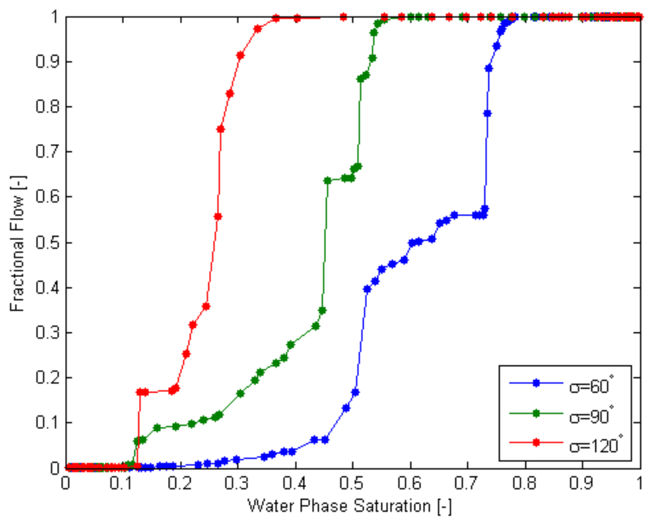
Network modelling of fractional flow for LoSal®

Rock A









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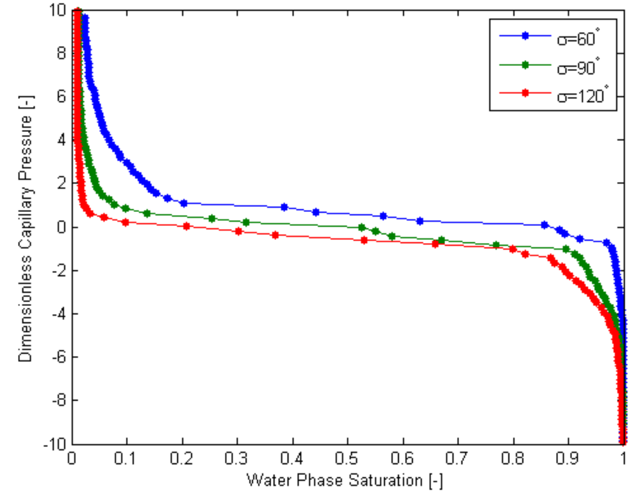

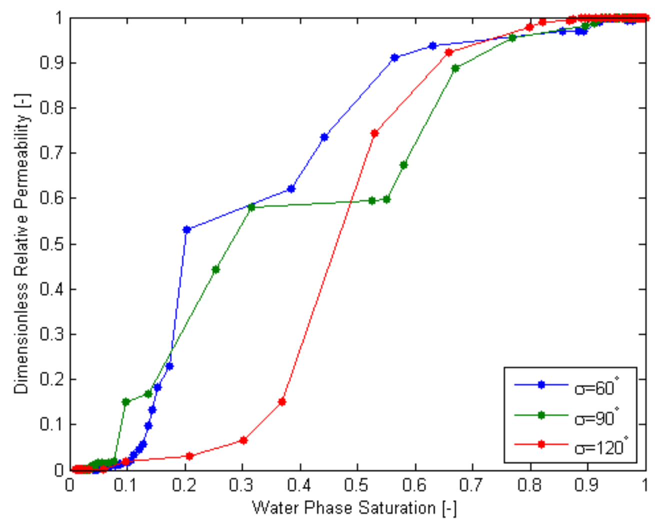

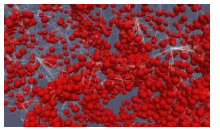

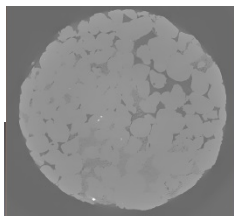

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