Peering into the pore space: X-rays, fluid flow and oil recovery

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Questions

1. Why do we see a wide range of contact angle inside rocks?
2. Why are rougher surfaces more water-wet?
3. Why is mixed-wettability best for oil recovery?
4. Why is the drainage (drying) capillary pressure twice that of imbibition (wetting)?
5. What is the correct constitutive model of capillary pressure based on spontaneous imbibition behaviour?

Pore-scale modelling and imaging

Multi-scale imaging – particularly ability to image the pore space of rock and fluids at 10 nm to micron resolution.

Public-domain availability of good-quality software for scientific computing – changes the way we develop computational models. Use of a variety of innovative CFD (computational fluid dynamics methods).

Combine imaging, experiments and modelling to provide a more robust and better characterization of rocks over multiple scales.

Motivation. Complex carbonates, unconventional oil and gas, improved oil recovery, water resources, CO_2 storage.

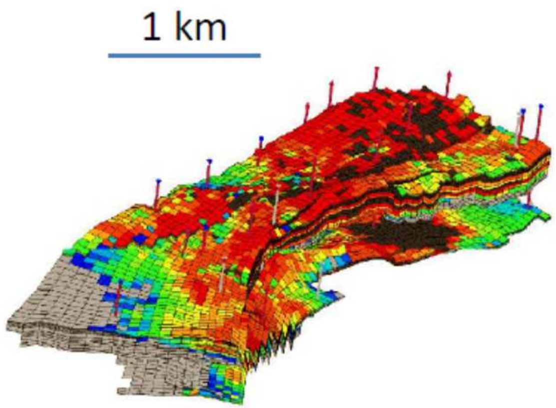
How much oil do we recover, *V*?

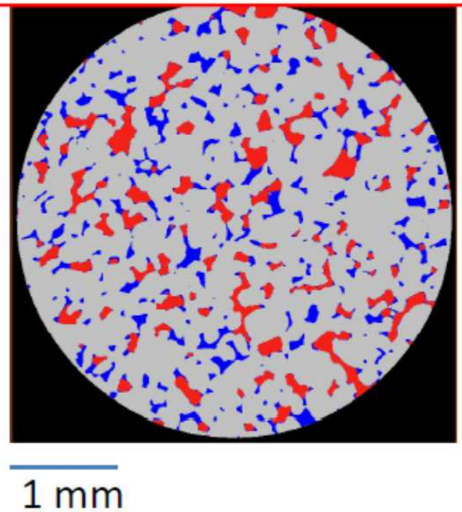
$$V = V_r \times E_s \times E_d$$

The rock volume, determined from seismic, well logs and well test analysis.

The sweep efficiency, governed by large-scale reservoir geology and well placement.

The local displacement efficiency – how much oil is recovered locally. *Our target* – how to understand and design the most efficient displacement: determined using core floods combined with pore-scale imaging and modelling.





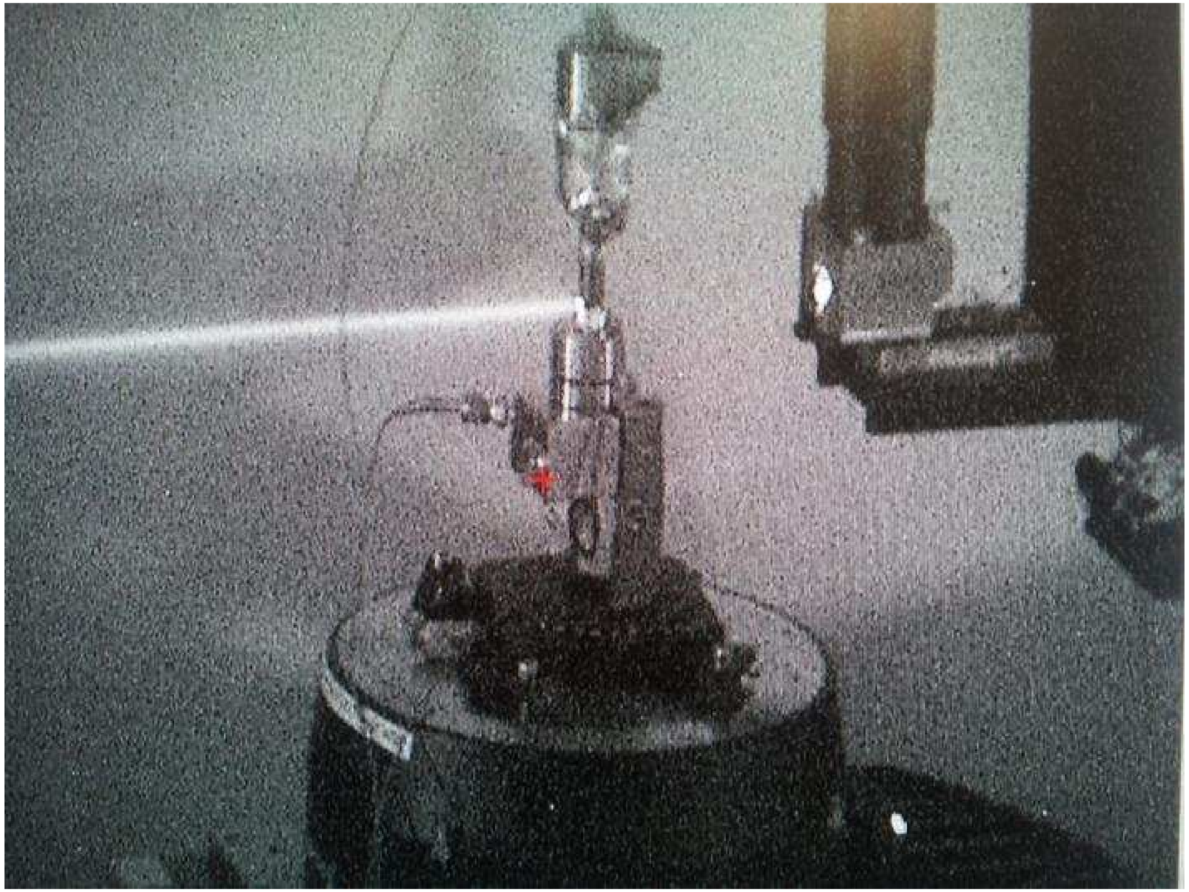
How much CO_2 do we store?

Imperial College multi-scale imaging lab

Start with the fundamentals – understand processes experimentally at the pore scale. Micron-to-metre imaging with *in situ* displacement at reservoir conditions.

Micro-CT – Flow loop

Dynamic Tomography at Synchrotron Sources



45 s time resolution.

Synchrotron Experimental Team:

Matthew Andrew

Hannah Menke

Cat Reynolds

Kamal Singh

Branko Bijeljic

Martin Blunt

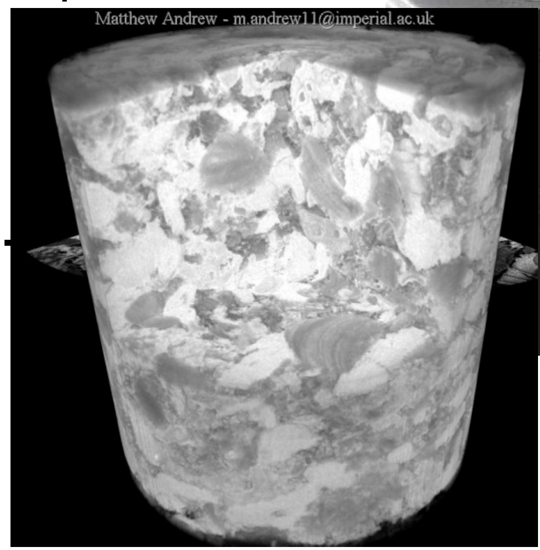
Imaging and computing

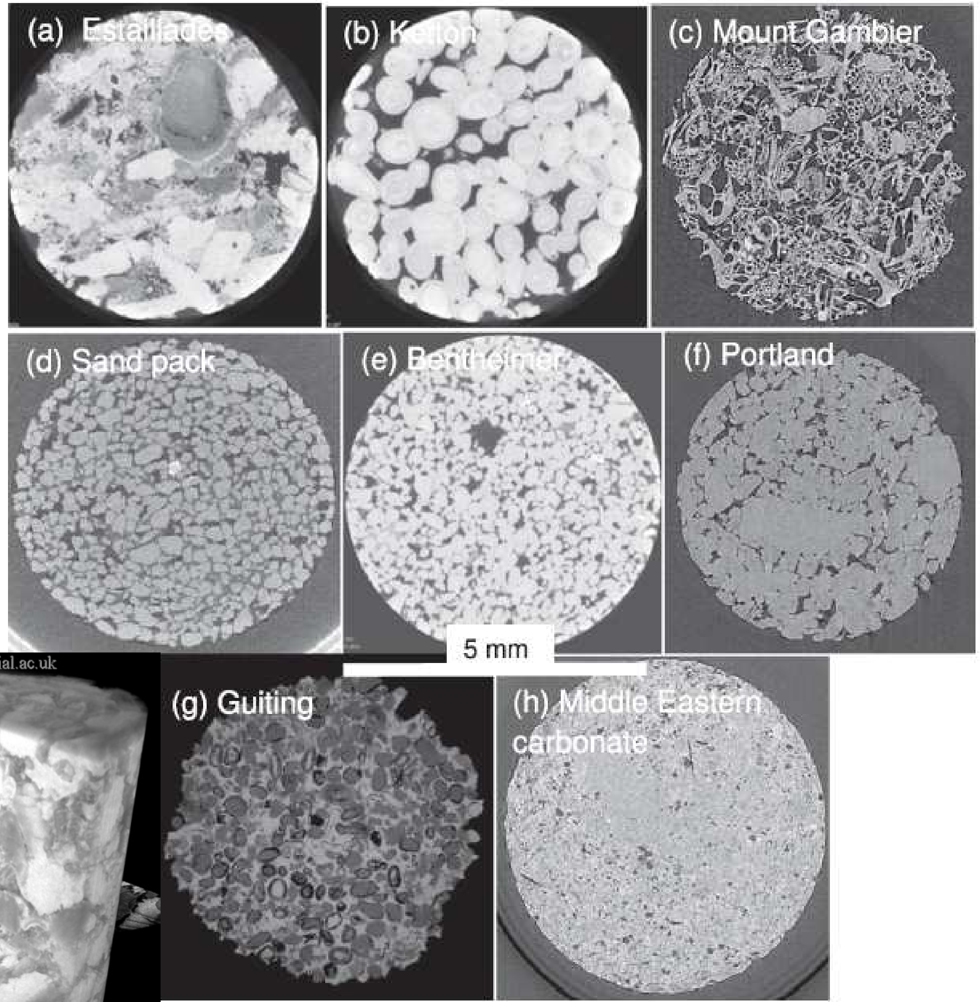
Bench-top **micro-CT** scanners are convenient, no time limitations and modern systems have optics.

Synchrotron sources. Bright, mono-chromatic and fast.

Computationally, not interested in GPU, parallel, but better algorithms.

Availability of excellent public-domain solvers: algebraic multigrid, OpenFoam Navier-Stokes solver. Fluid mechanics: unstructured adaptive grids.





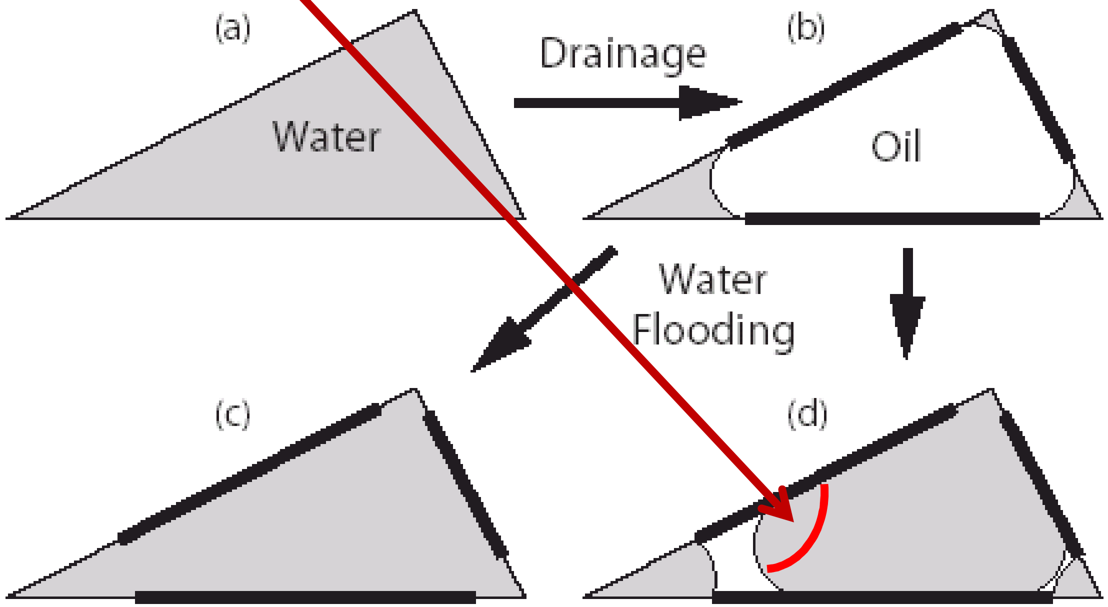
Blunt *et al., Adv. Water Res.* 2013

Waterflooding and wettability

Complex displacement sequences, shown here for a single idealized pore. What are the contact angles? Can now measure them *in situ*.

Altered wettability surfaces after primary drainage: mixed-wettability.

Relative permeability is governed by the interplay of displacement, structure and wettability, which can vary across the field



Basic equations

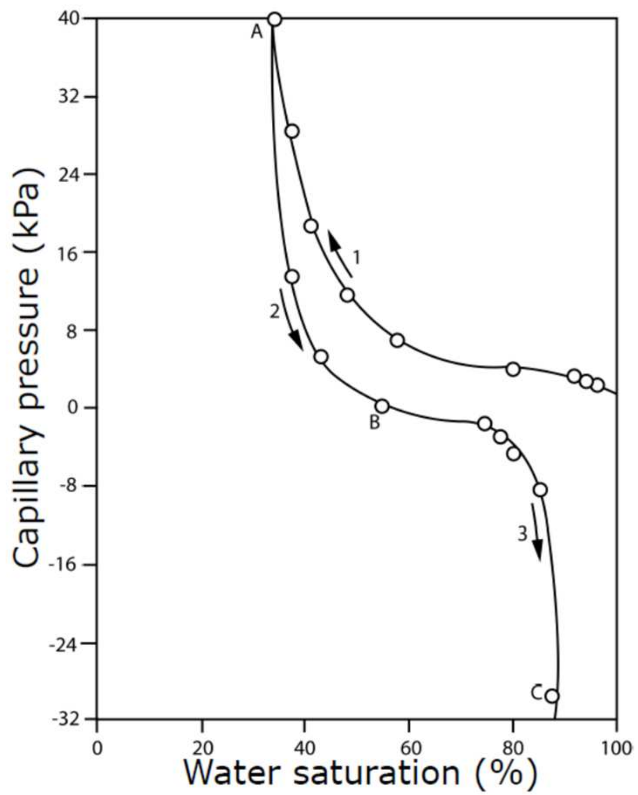
Three main differences with hydrology:

(1) Need to consider fluid flow of two (or three) fluid phases.

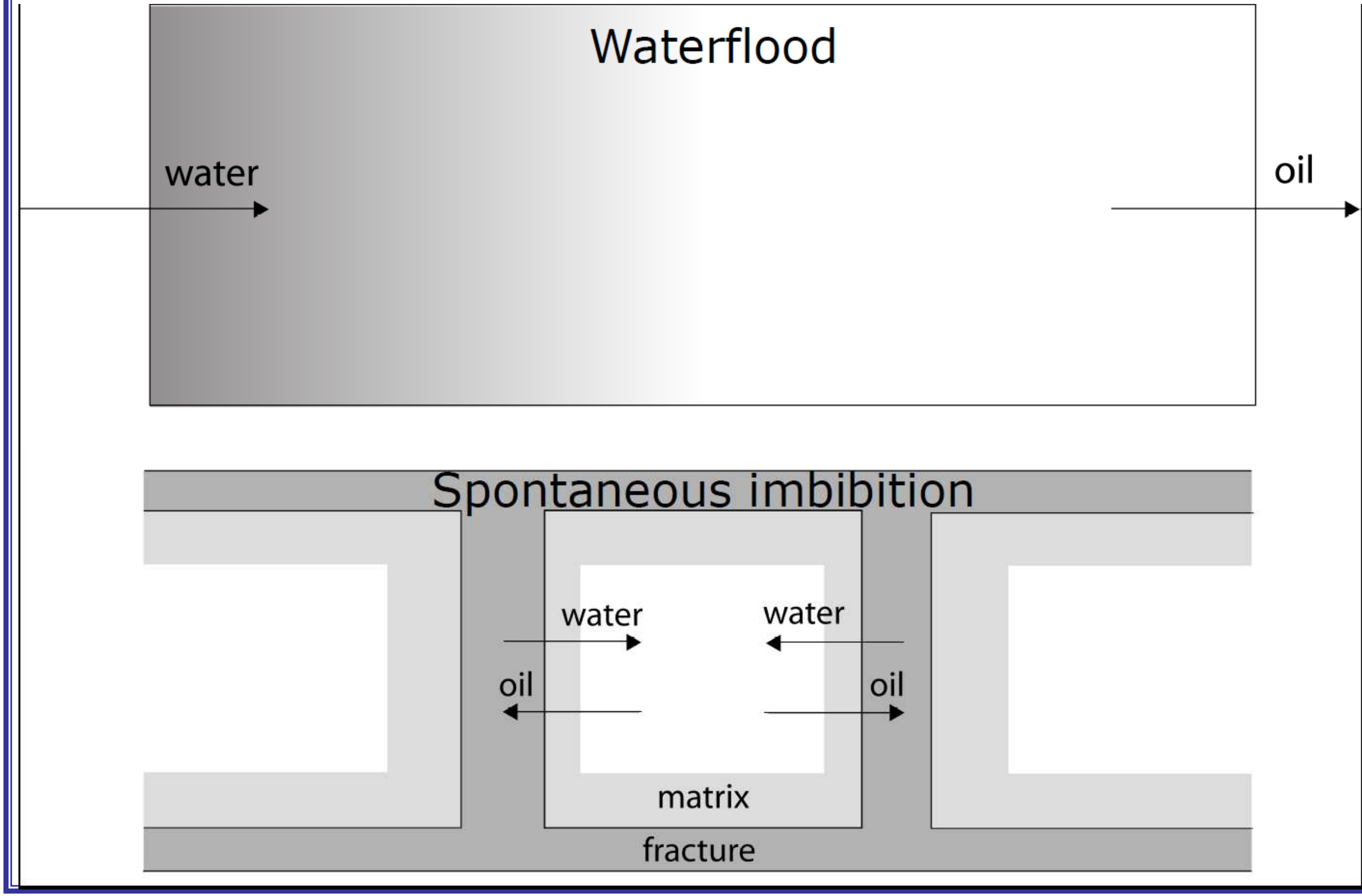
$$q_p = -\frac{Kk_{rp}}{\mu_p} \nabla P_p$$

(2) Capillary pressure is not always positive (and I am not sure it is always positive in real soils either……): $P_c = P_o - P_w$

(3) Interested in recovery, so always write the equations in terms of (water) saturation: $k_{rp}(S_w)$, $P_c(S_w)$



Oil recovery and the trillion barrel question



The trillion barrel question

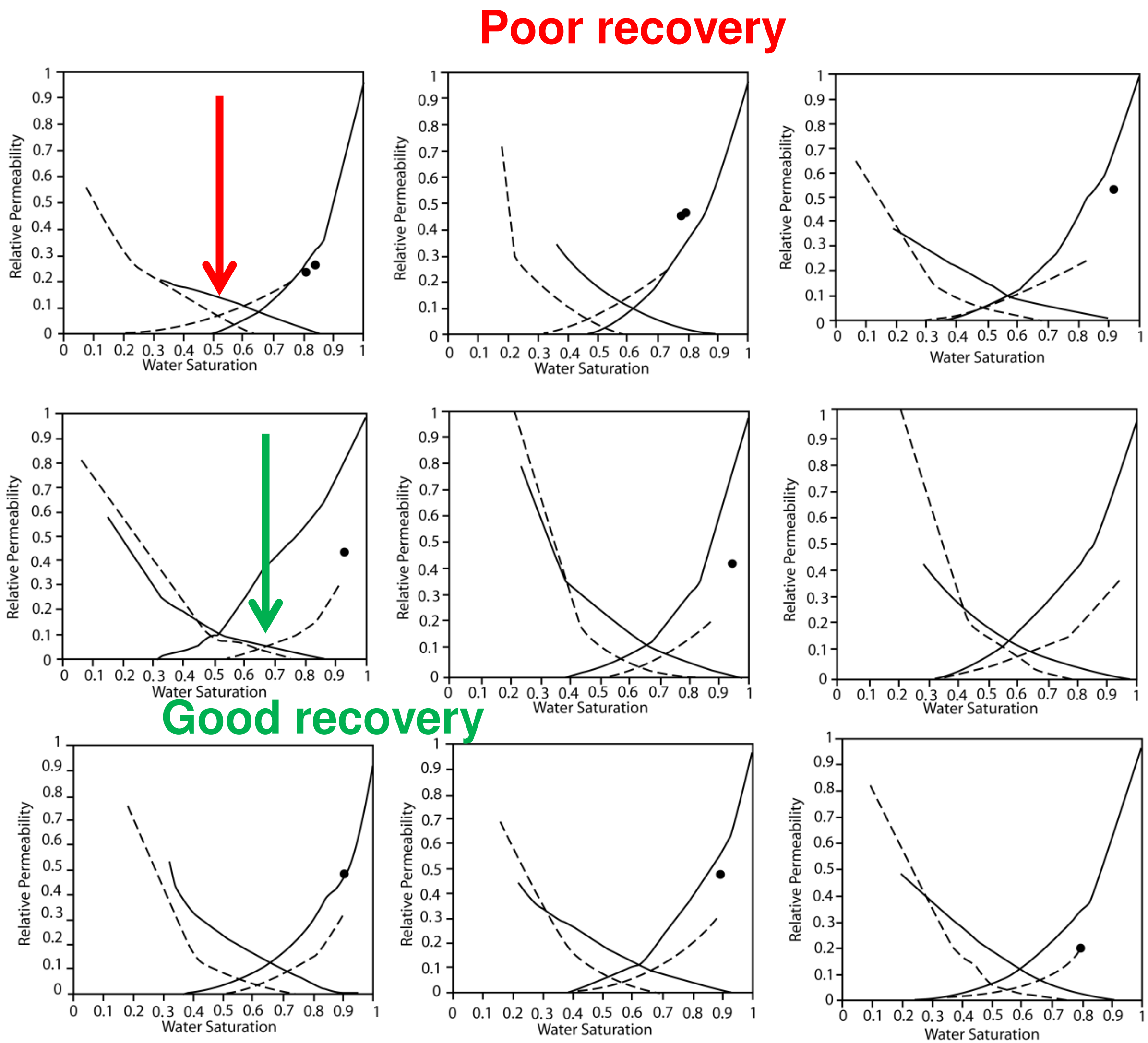
Measured relative permeability on mixed-wet reservoir carbonates from Abu Dhabi; Dernaika *et al.* SPEREE, (2013).

Difference of 10-15% in local displacement efficiency.

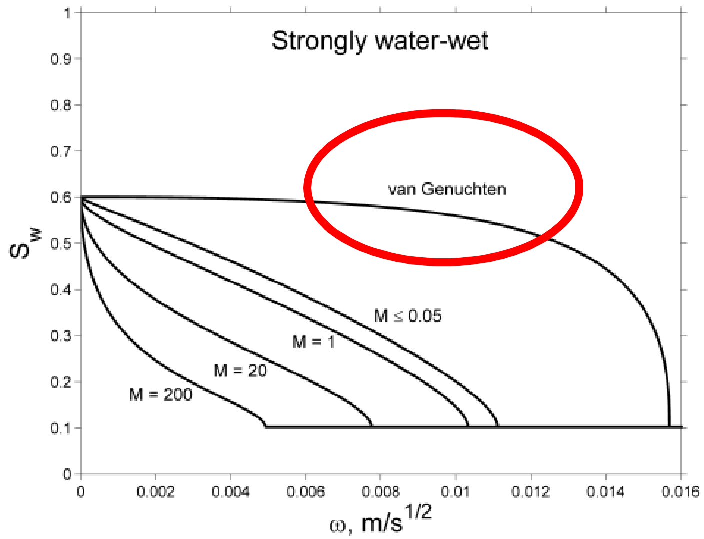
Why?

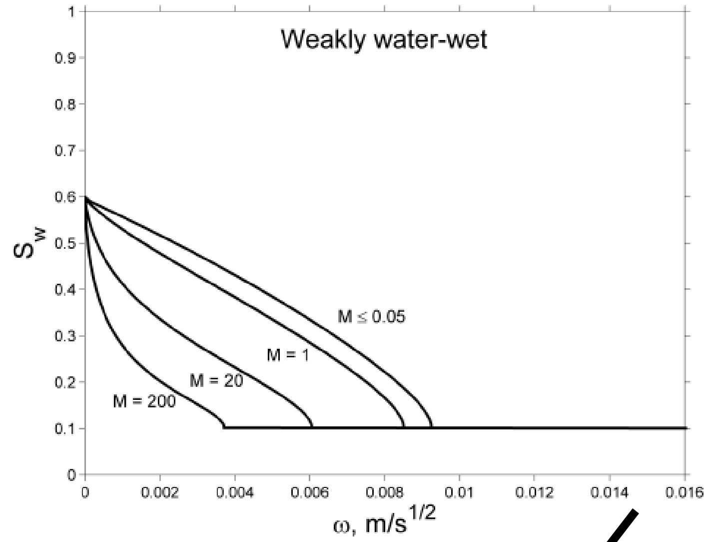
Can we design this?

And then there are unconventionals….



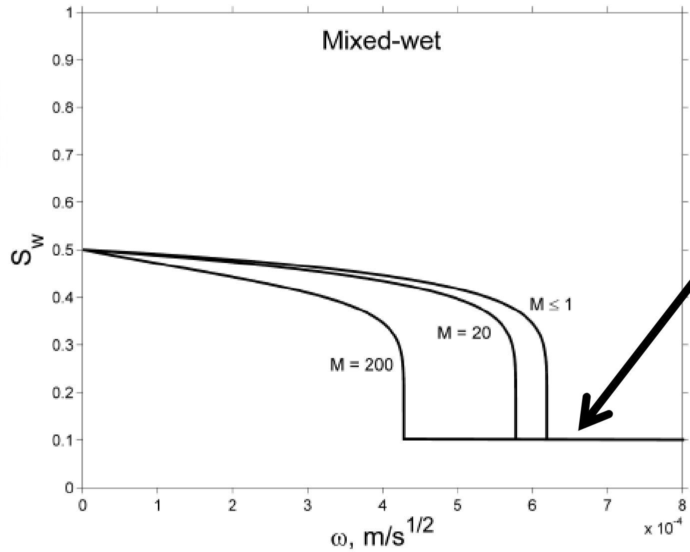
Imbibition recovery





$$\phi \frac{\partial S_w}{\partial t} = \frac{\partial}{\partial x}\left(D(S_w)\frac{\partial S_w}{\partial x}\right)$$

$$D(S_w) = -K\frac{\lambda_w \lambda_o}{\lambda_t}\frac{dP_c}{dS_w}.$$

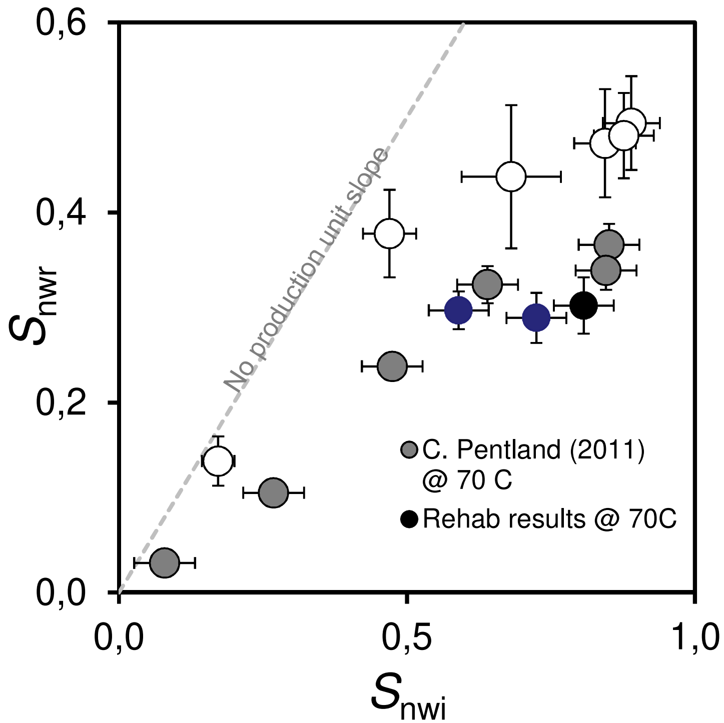


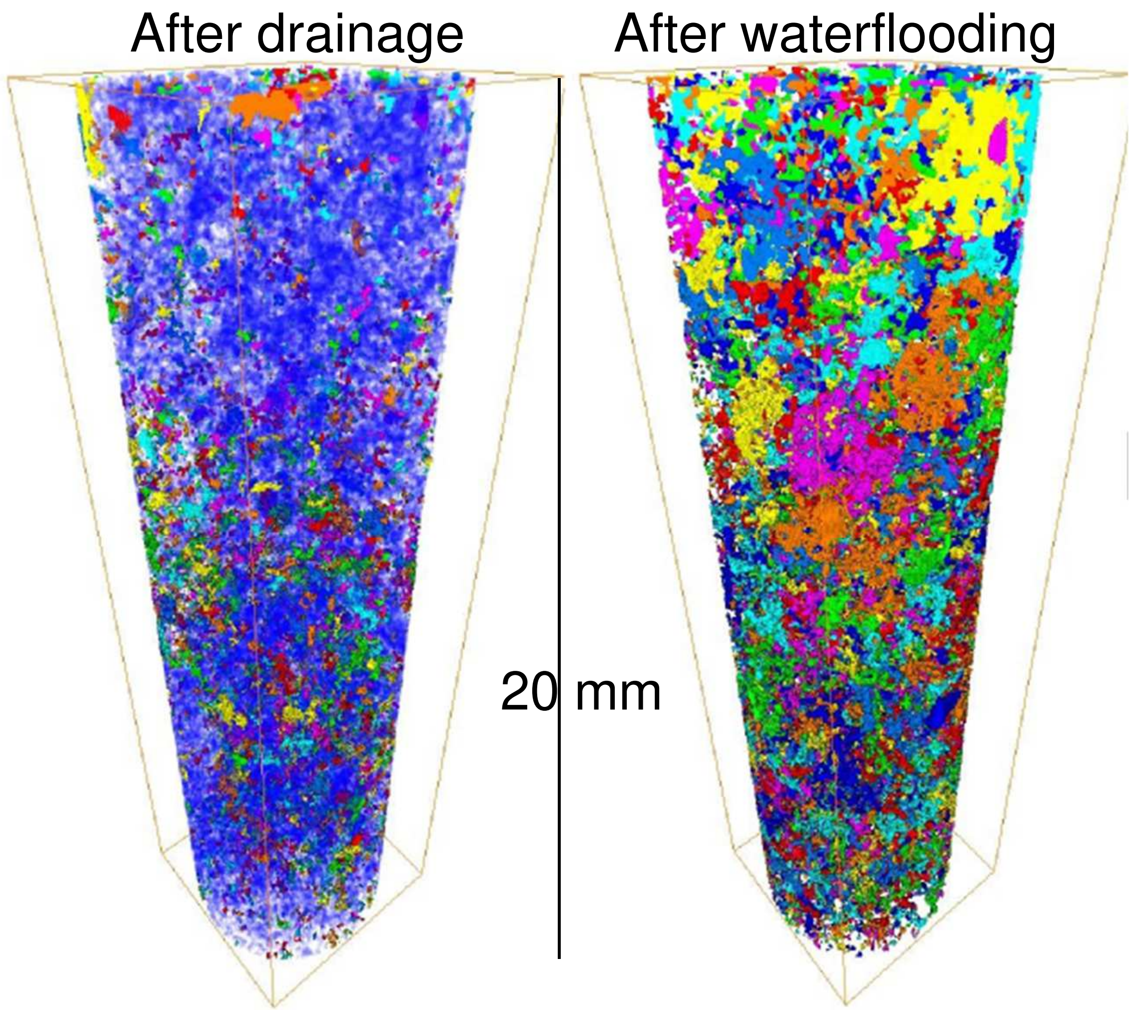
20 times slower

Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

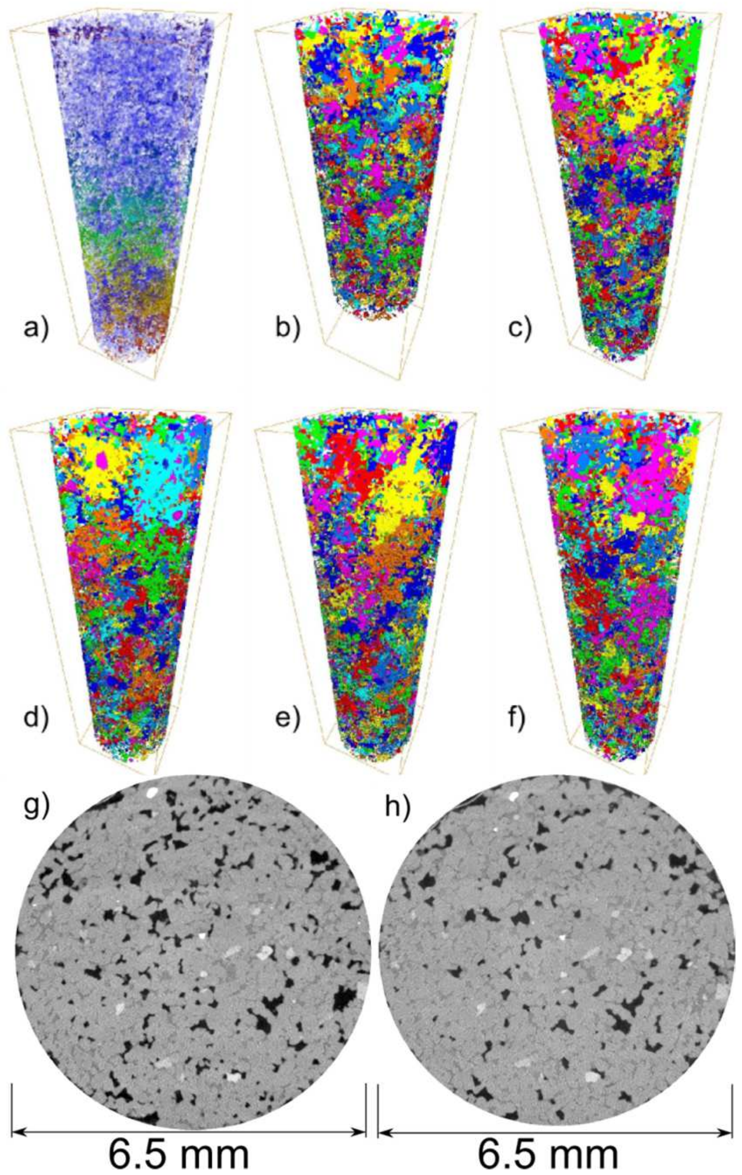
Results in sandstones (Doddington, Bentheimer and Berea).

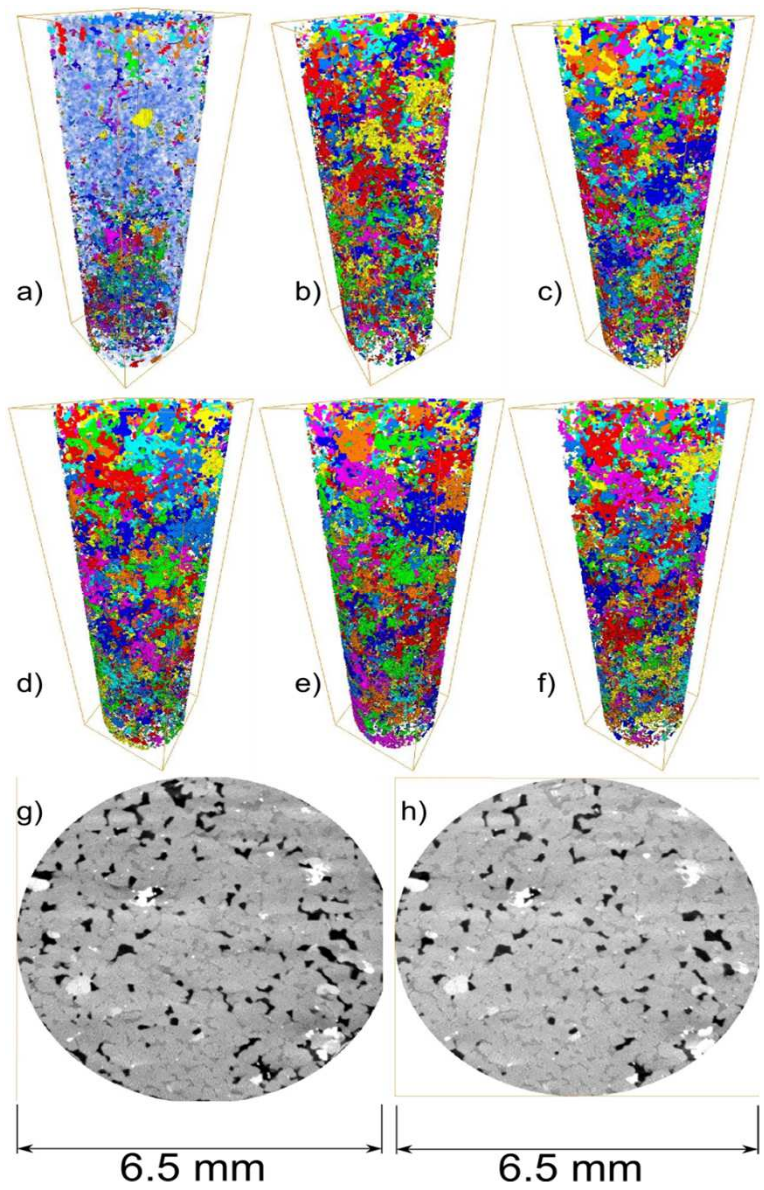




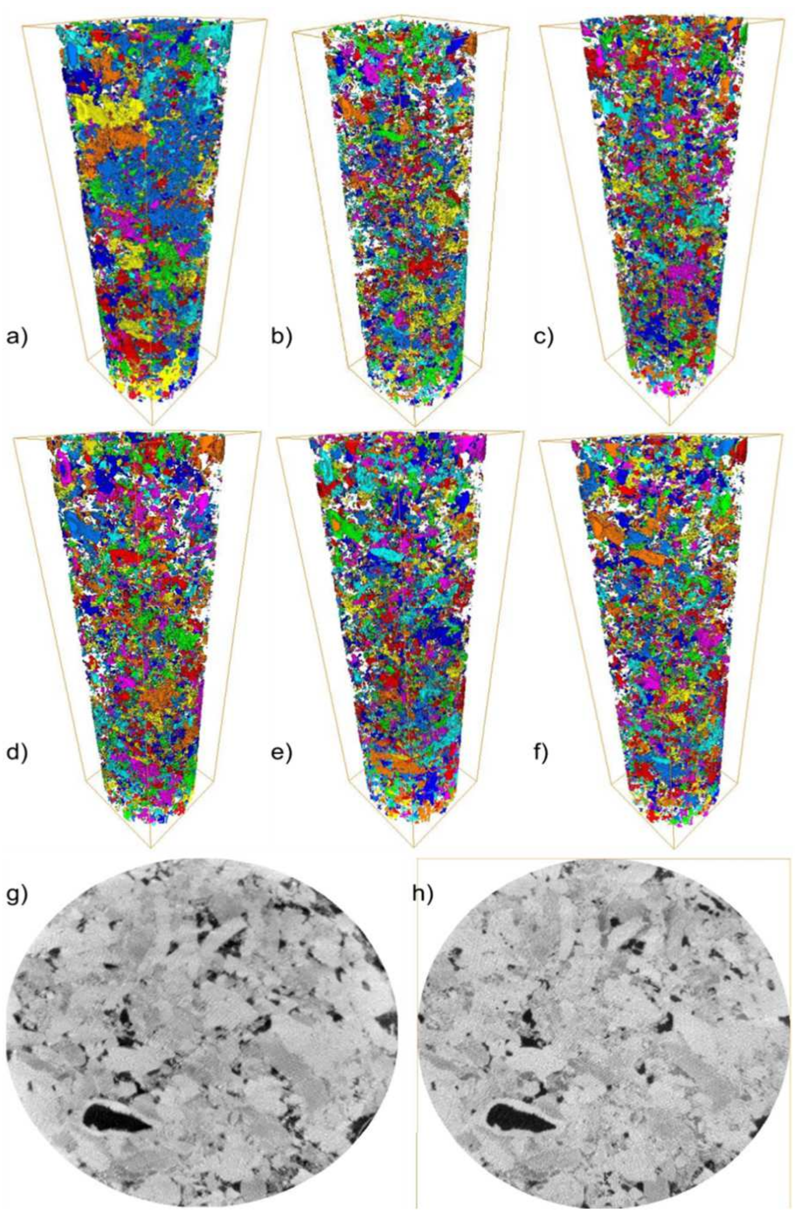
Pentland *et al., Geophysical Research Letters (*2011)
Andrew *et al., IJGGC*, (2014)

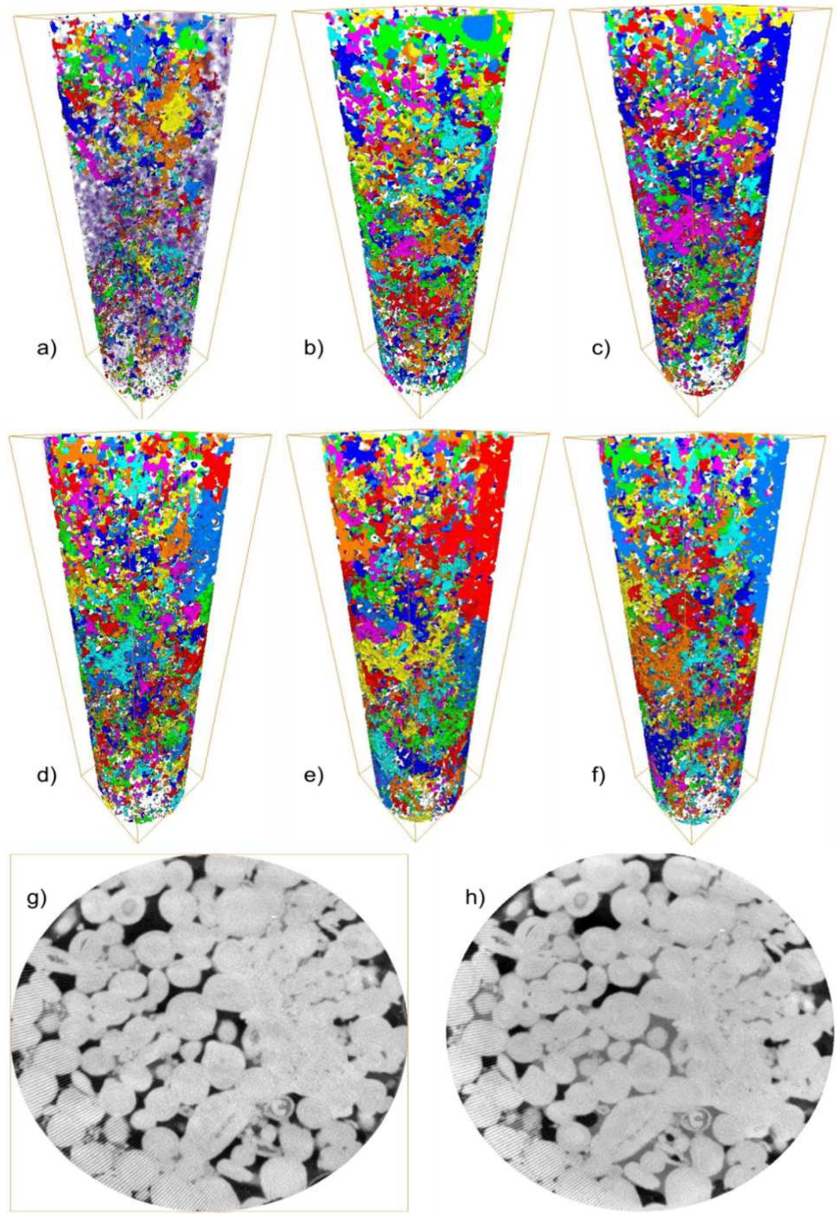
Can study many systems – Bentheimer and Doddington



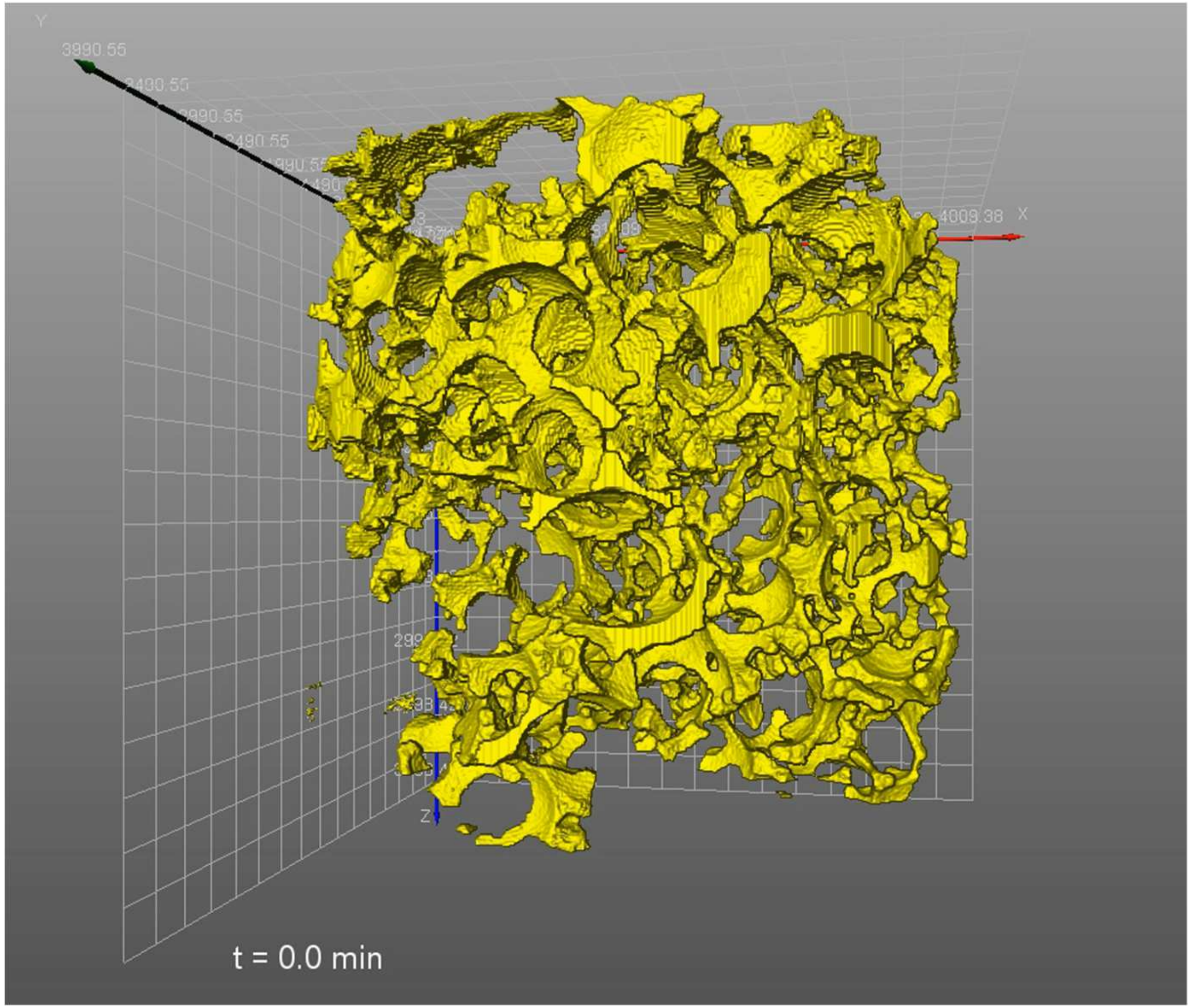


Can study many systems – Estaillades and Ketton





Imaging waterflooding



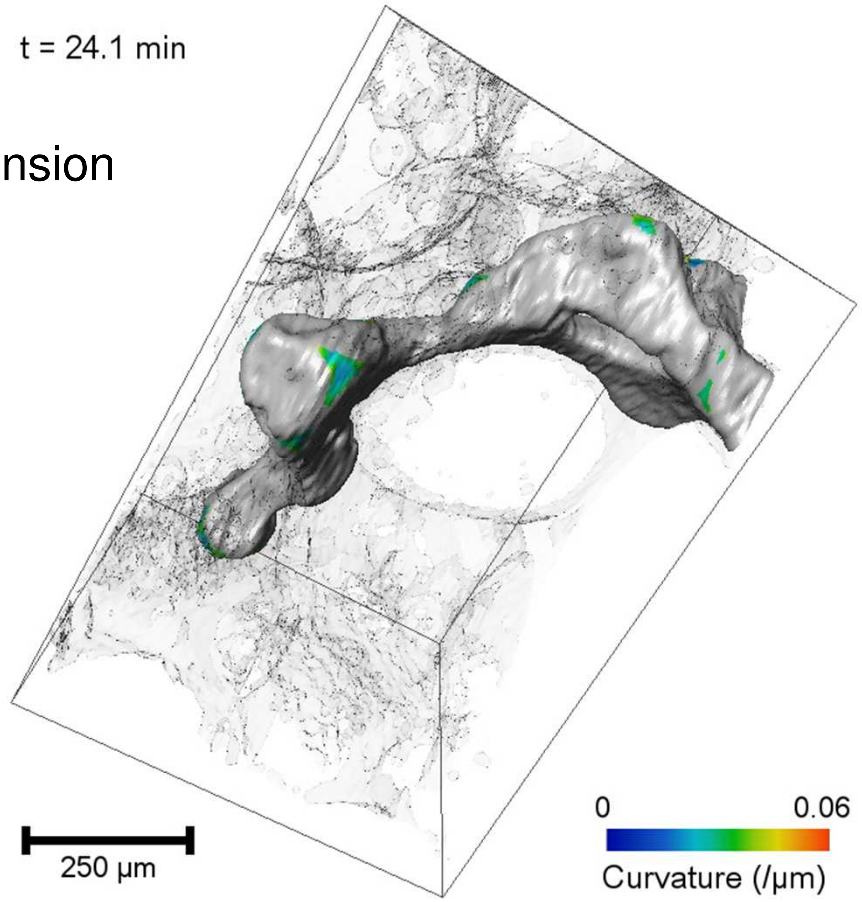
Singh *et al.*, *Scientific Reports* (2017)

Curvature mapping and trapping

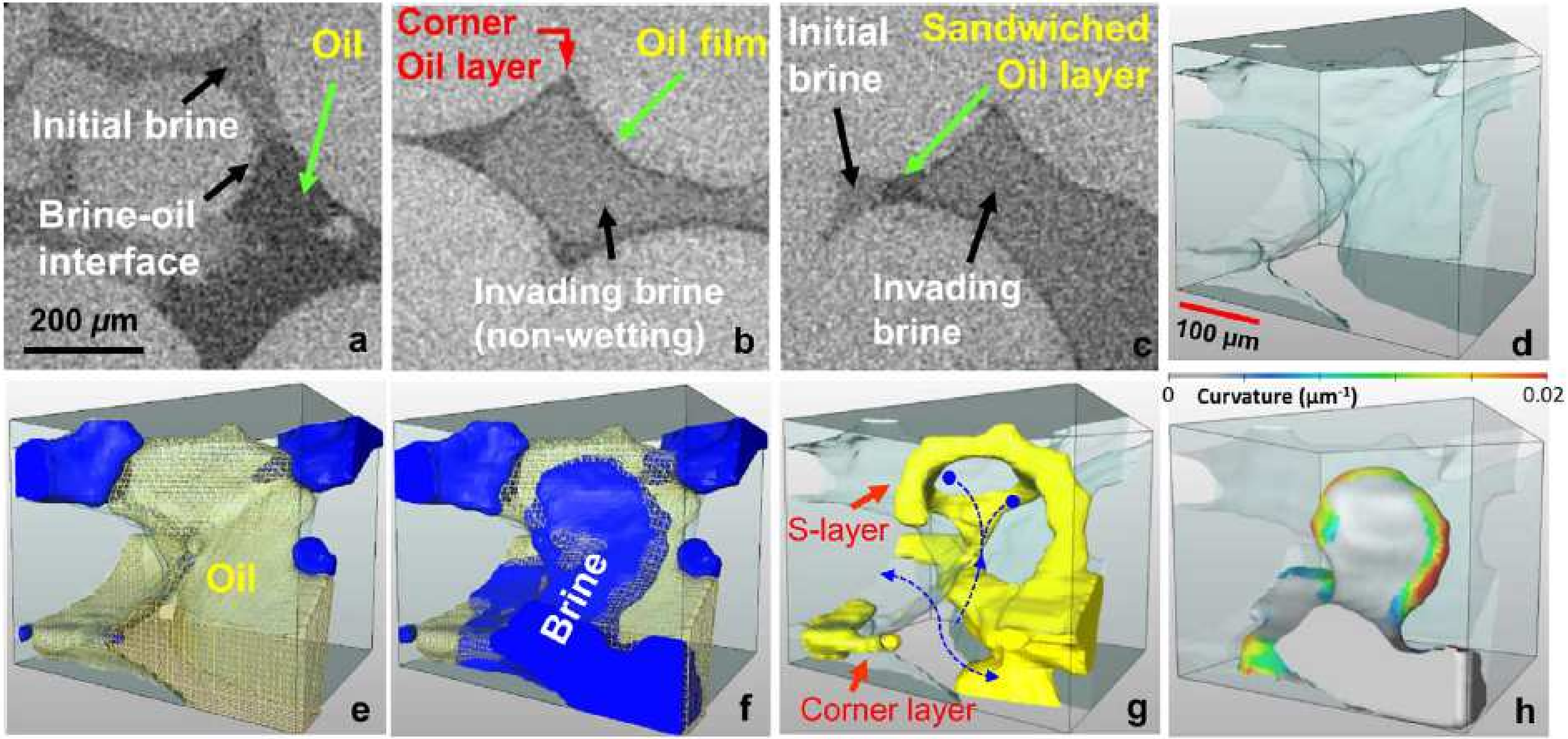
Young-Laplace equation

Capillary pressure, P_c and curvature κ. σ is interfacial tension

$$P_c = \sigma\left(\frac{1}{r_1}+\frac{1}{r_1}\right) = \sigma\kappa$$



Images in mixed-wet media



Pinned water layers – low water relative permeability at low saturation.

Oil layers – low residual oil saturation.

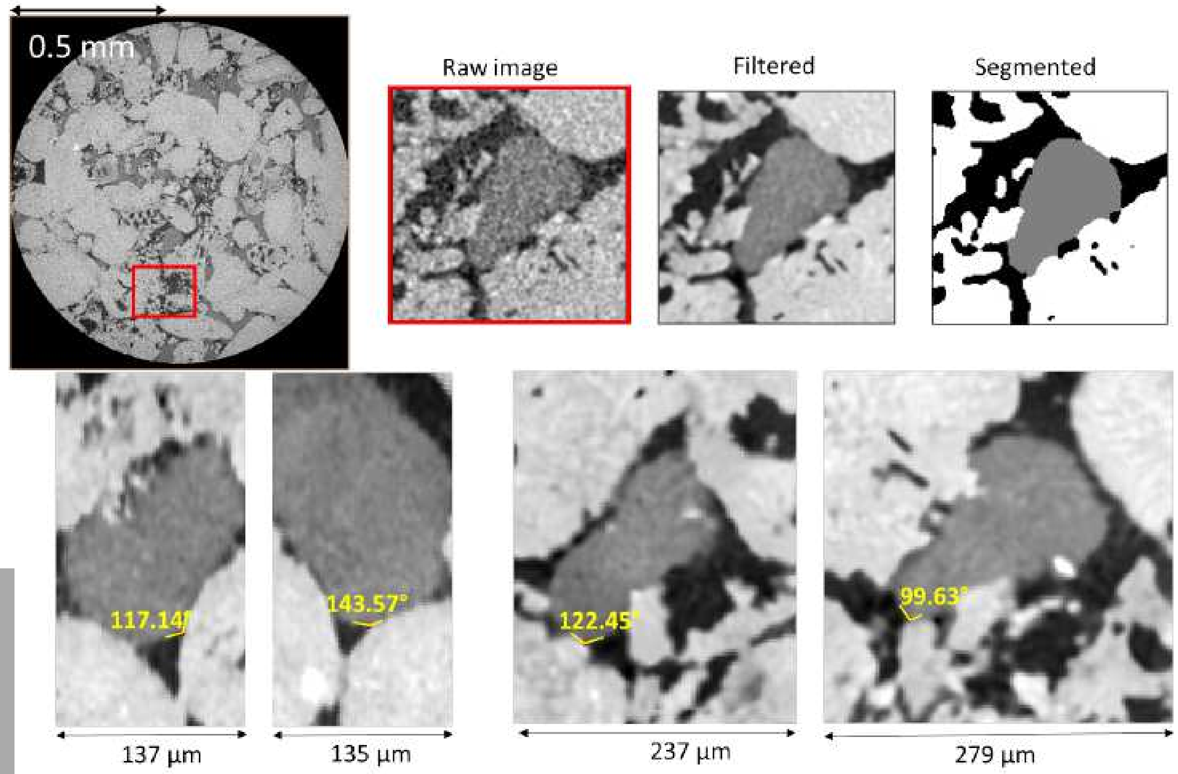
Singh *et al.*, *WRR* (2016)

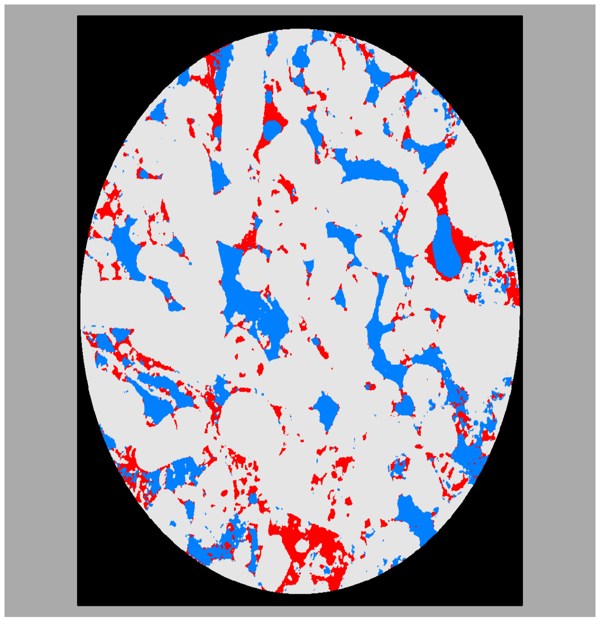
Measurement of contact angle

In situ measurements on reservoir samples

Measurements of contact angle on a reservoir samples from Abu Dhabi, aged in crude oil after waterflooding at reservoir conditions.

Use automated methods to extract a contact angle distribution.





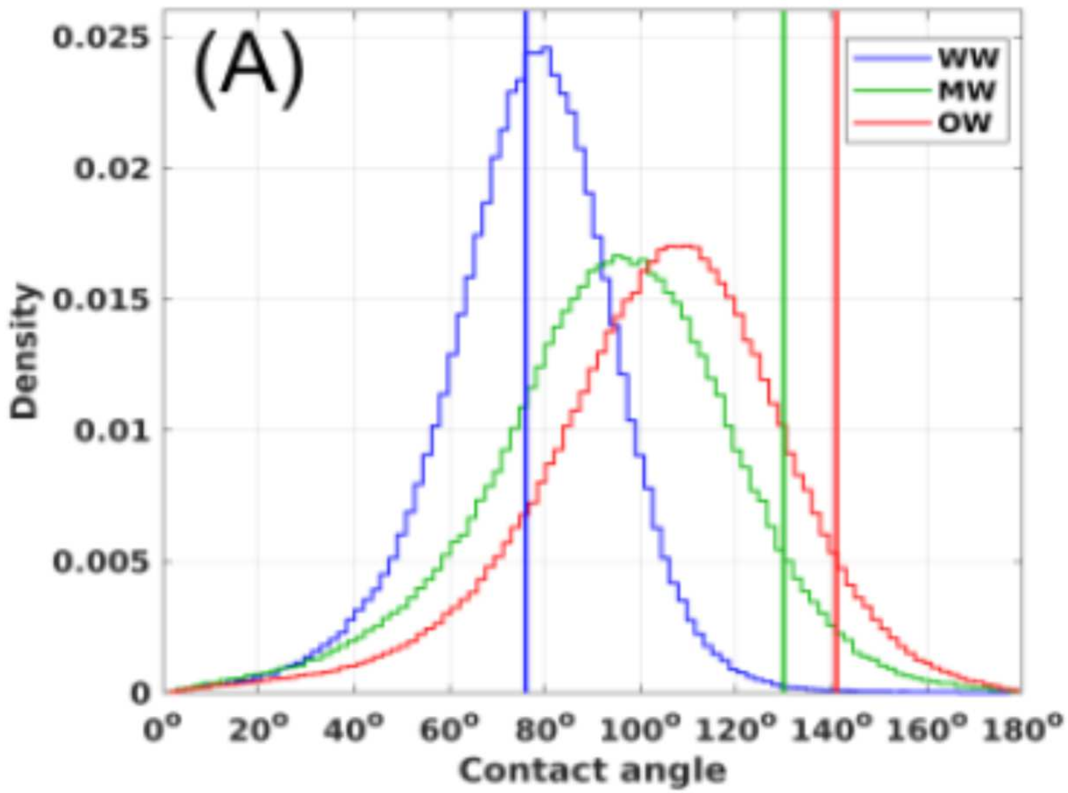
http://www.digitalrocksportal.org/projects/151

http://www.github.com/AhmedAlratrout.

Al Hammadi *et al.*, *Scientific Reports* (2017)

In situ measurements on reservoir samples

Wide distribution of contact angle – different distributions for different crude oils and ageing conditions. Average lower than measured on a flat surface (vertical lines).

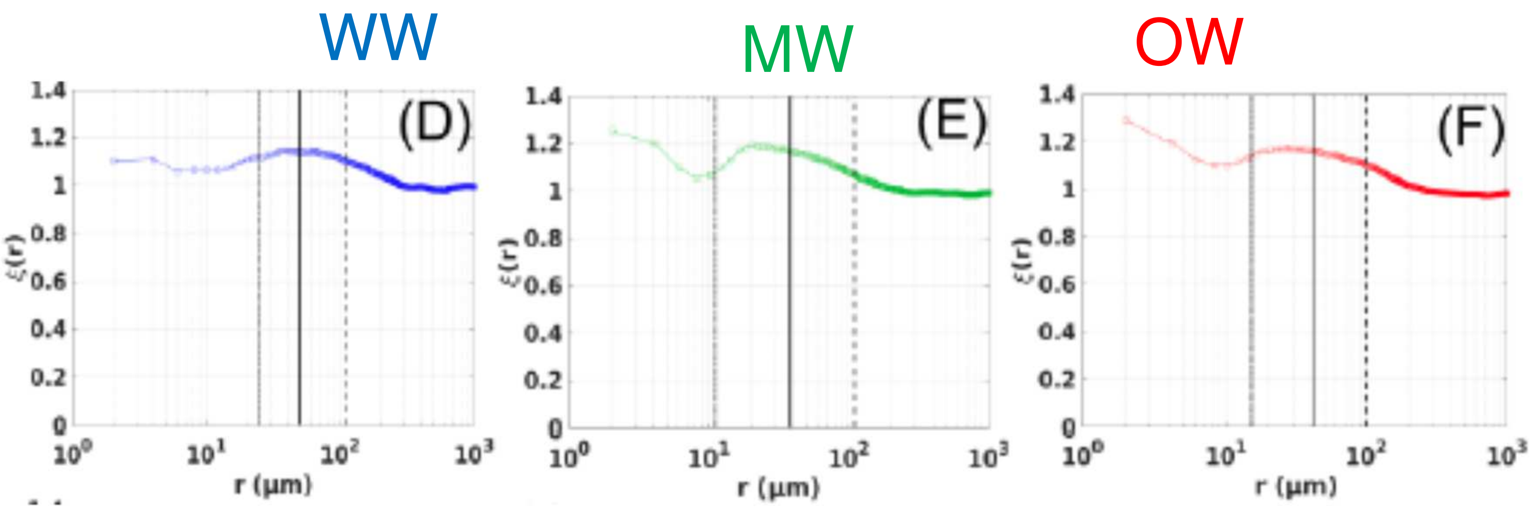


Alratrout *et al.*, *Advances in Water Resources* (2017)

Spatial correlations

Correlation between contact angle and surface roughness as a function of distance between the measurements.

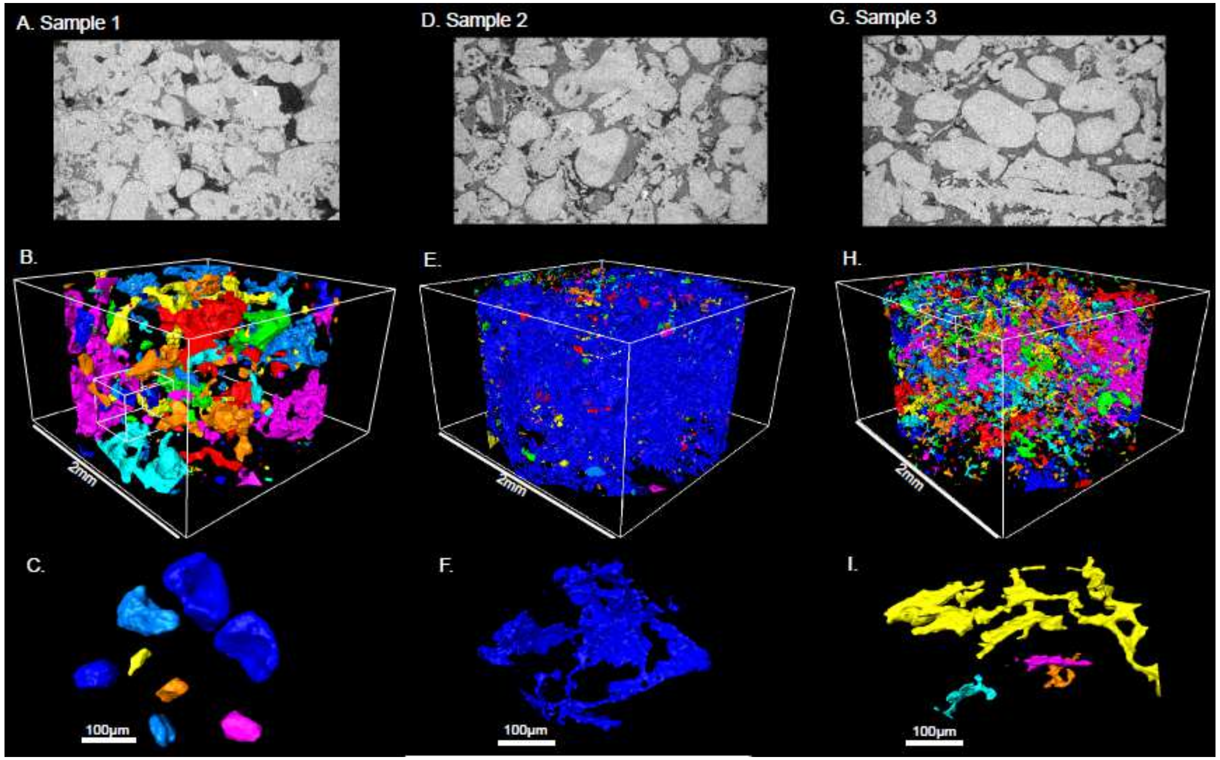
Anti-correlated over a pore size >1: rougher surfaces are (slightly) more water-wet.

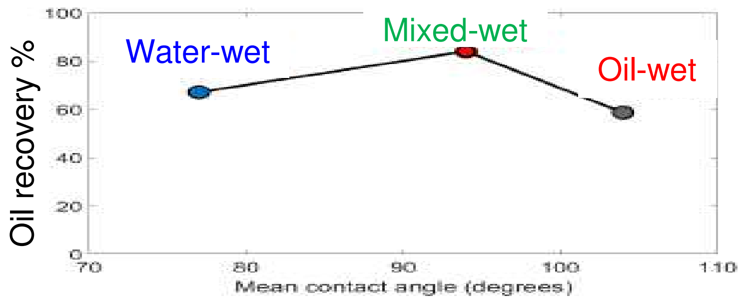


$$\xi(r) = \frac{\sum_{j=1}^{N_y} \sum_{i=1}^{N_x} I_{ij} (\tilde{x}_i - \tilde{y}_j)^2}{2 \sum_{j=1}^{N_y} \sum_{i=1}^{N_x} I_{ij}}$$

Relationship to recovery

WW OW MW

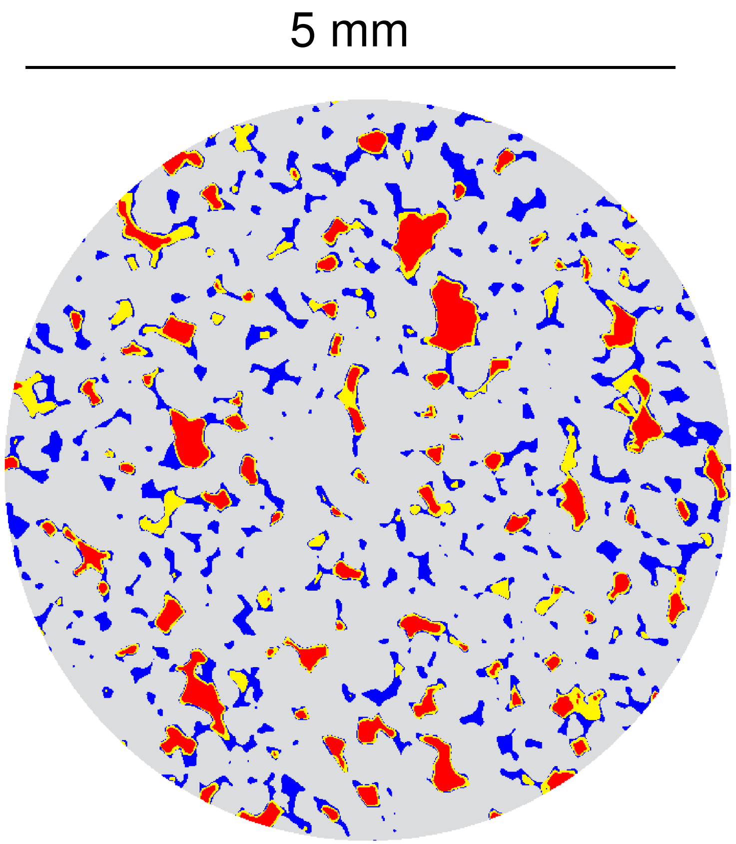




Future work in 2005

- Characterization of mixed-wet media
  - Miniaturisation of steady-state experiments in conjunction with micro-CT will allow for pore-scale visualisation

Steady-state experiments



Quantification of intermittency in two-phase flow.

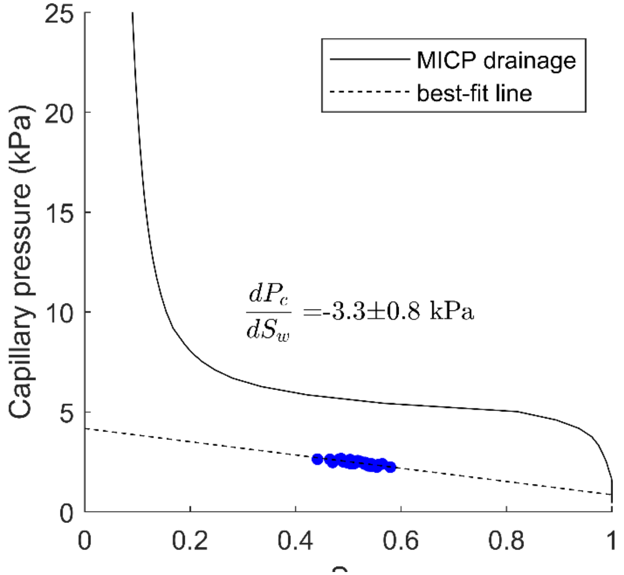
Images taken during steady-state flow in imbibition.

Red = oil
Water = blue

Yellow = oscillation between oil and water during the hour-long time-scale of the scan.

Gao *et al.*, *WRR* (2017)

Micro-CT core analysis

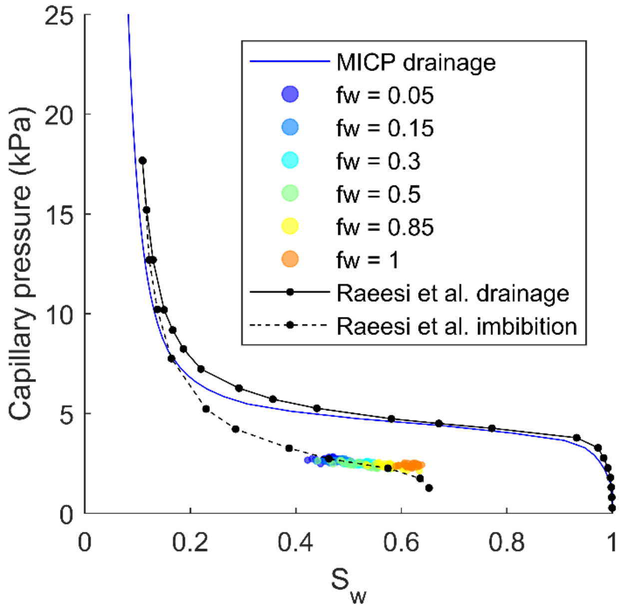


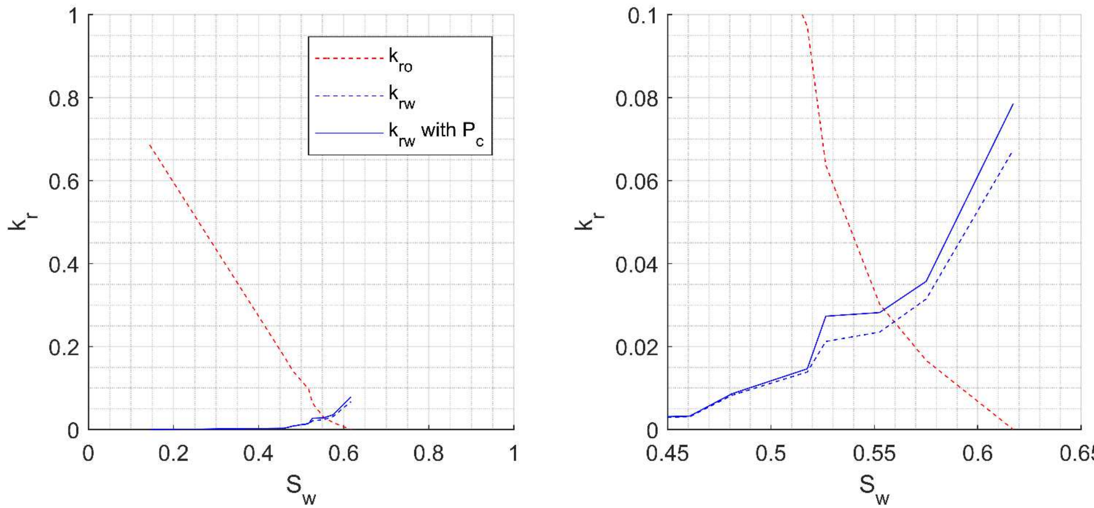
Simultaneous measurement of relative permeability and capillary pressure from steady-state flow experiments.

Capillary pressure is found from measuring the local oil/water interfacial curvature in pore-space images.

Can also account for the capillary end effect.

Generate validated pore-scale models.





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Acknowledgements

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Imperial College London

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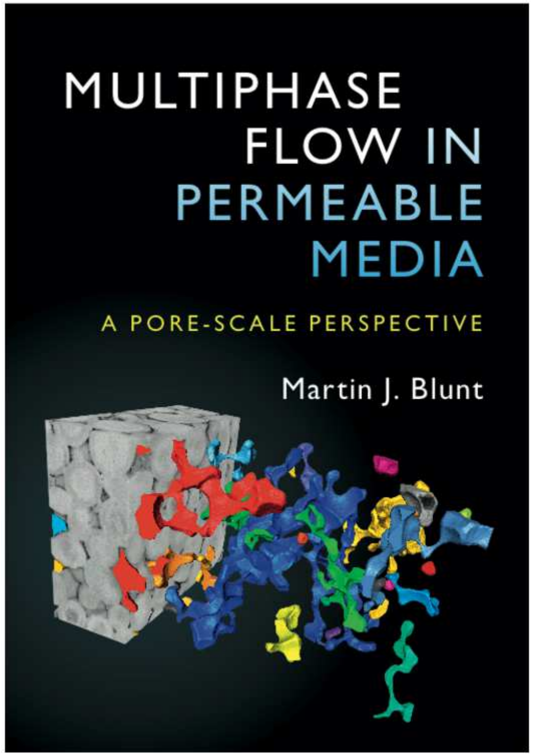
Qatar Petroleum



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