Flow in porous materials: a of tale X-rays, minimal surfaces and wettability

Martin Blunt, Branko Bijeljic, Sam Krevor, Qingyang (Lewis) Lin,
Matthew Andrew, Hu Dong, Ying Gao, Yihuai Zhang, Ali Raeini,
Sajjad Foroughi, Kamaljit Singh, Catherine Spurin, Alessio Scanziani,
Amer Al-Hammadi, Ahmed Alratrout and Abdulla Alhosani

Department of Earth Science and Engineering
Imperial College London

An introduction to Imperial College London

Research-led university in the heart of London specialising in science, engineering, medicine and business

- Top 10 university globally
- Largest research income in UK
- Largest number of science, engineering and medical students
- Honours
    - 14 Nobel prizes
    - 57 Fellows of Royal Society
    - 91 Fellows of the Royal Academy of Engineering
    - 71 Fellows of Academy of Medical Science

Our mission statement

Imperial College London’s mission is to achieve enduring excellence in research and education in science, engineering, medicine and business for the benefit of society.

Our people

Students

17,568 in total (2018-2019)

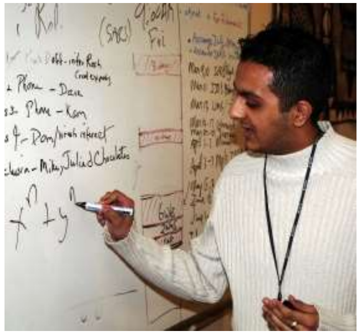
- 10,054 – undergraduate
- 3,864 – taught postgraduate
- 3,650 – research postgraduate
- Students from 130+ countries

Staff

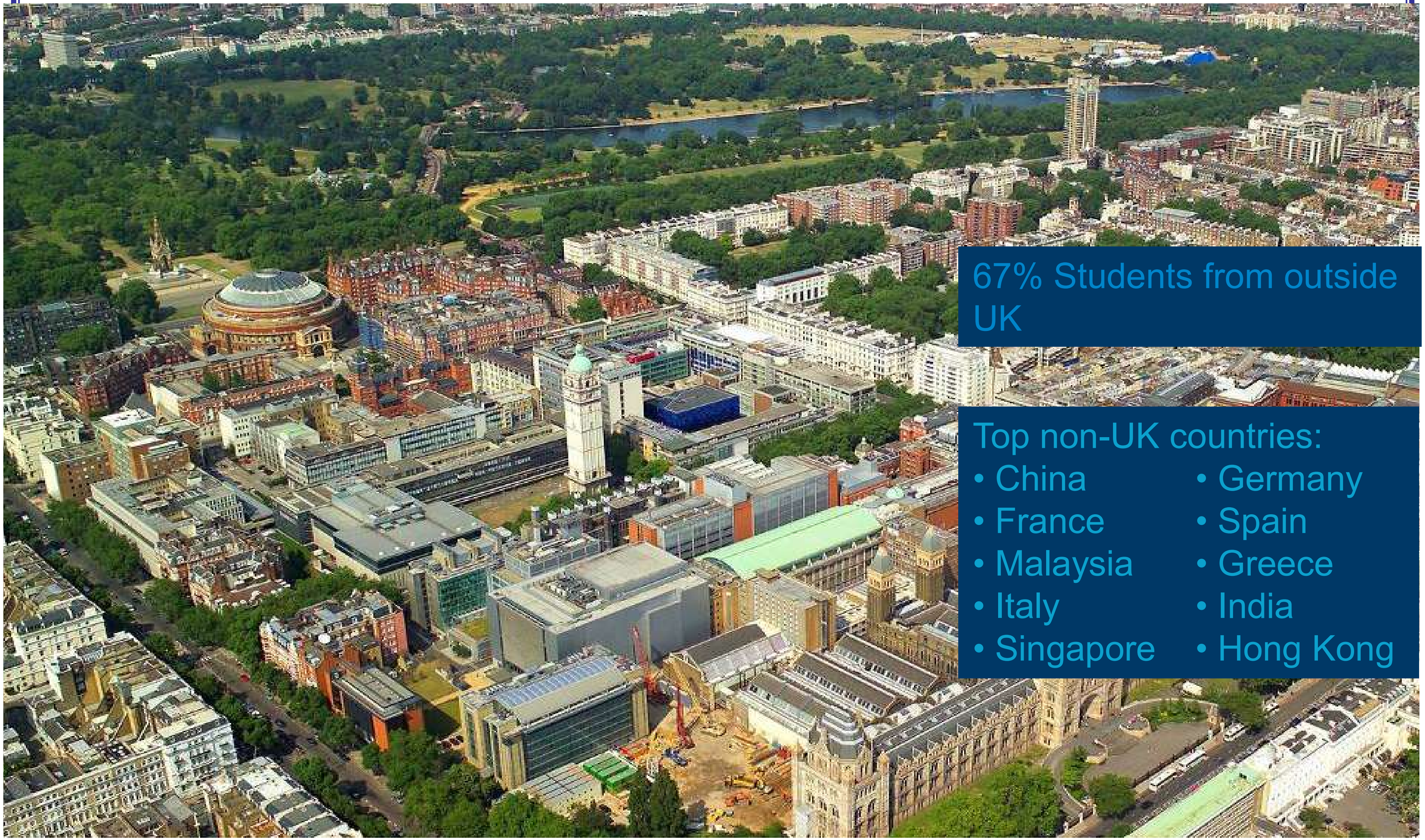
- 4,000 academic and research staff
- 4,000 support staff

Alumni

Over 190,000 alumni



Our students



67% Students from outside UK

Top non-UK countries:

- China
- France
- Malaysia
- Italy
- Singapore
- Germany
- Spain
- Greece
- India
- Hong Kong

Department of Earth Science & Engineering

Staff & Students

Staff
45 academic
80 research staff
30 support staff

Students
300 – undergraduate
200 – taught postgraduate
150 – research postgraduate

Total
Around 800 individuals

Undergraduate Teaching

Undergraduate courses:

- Geology
- Geophysics
- Planetary Science

Graduate with either BSc or MSci degrees

Top ranked in the Guardian and 2nd in THES and Complete University Guide

Postgraduate Teaching

Postgraduate taught courses:

• **Petroleum Engineering**
• **Petroleum Geoscience**
Approximately 80 students
Large international group

• **Mineral and Energy Finance**
with Business School
30 students

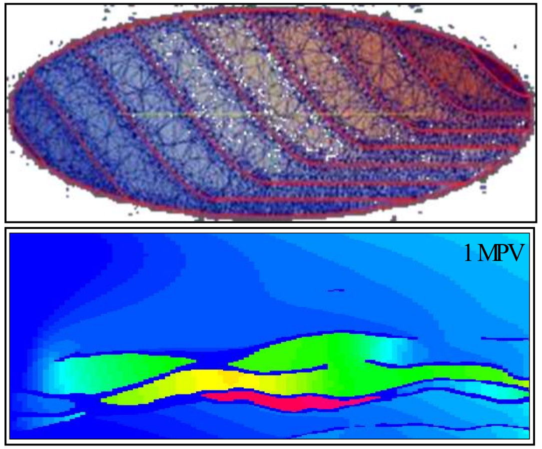
• **Applied Computational Science & Engineering**
120 students

Research Sections

Earth & Planets: E&P (17 staff)

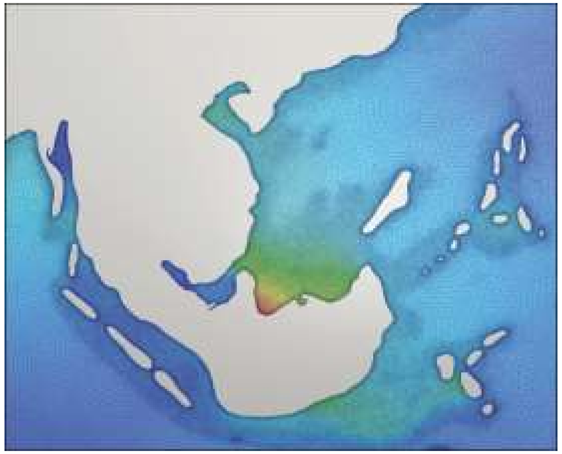
Tidal environments & facies analysis

Natural Resources Geoscience and Engineering NRGE (17 staff)



Modelling tidal/heterolithic reservoirs (tidal cross-bedding & heterolithic facies)

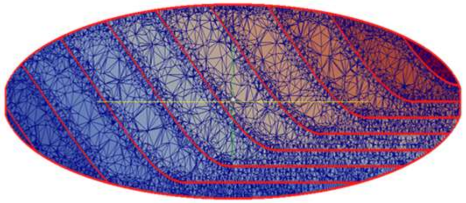
Computational Geoscience and Engineering (15 staff)

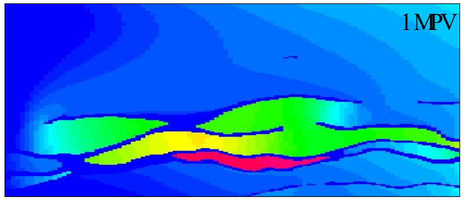


IC Ocean Modelling (reconstruction of paleo-tides in South China Sea)

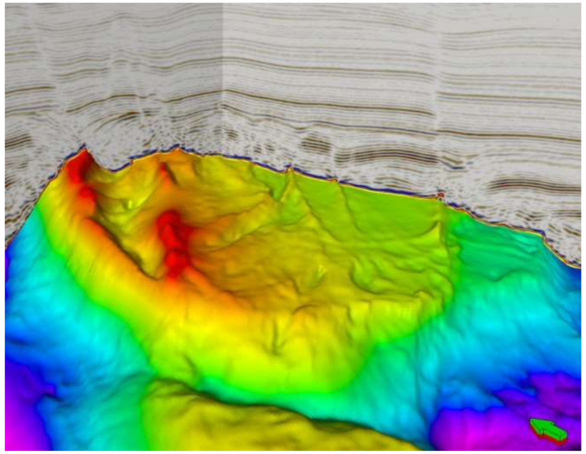
- Three research sections
- Multi-disciplinary research
- Fundamental science provides the insight to solve applied problems
- Engineering solutions provide the technology to solve problems and, simultaneously, improve understanding in fundamental science

Natural Resources Geoscience & Engineering

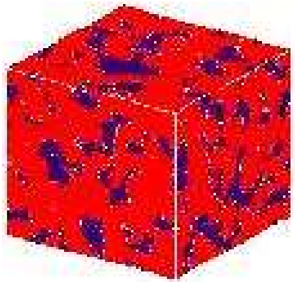


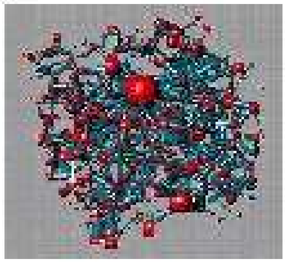


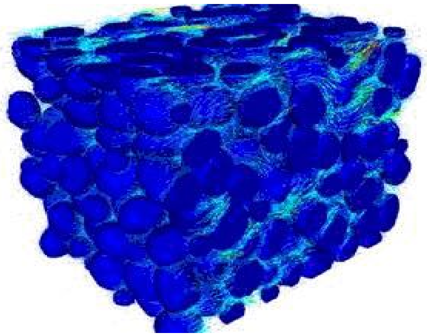
Reservoir Characterization & Modelling



Basins Research
& Geodynamics







Pore Scale Modelling

Rock Mechanics & Fractured Reservoirs   Granular Systems

Reservoir Geophysics-FWI   Well Test Analysis

Carbon Storage   Carbonate Research

Petroleum Research Applications:

- *Basin & play analysis*
- *Reservoir Geophysics-FWI*
- *Reservoir characterisation & modelling*
- *'Next generation' reservoir simulation models*
- *IOR/EOR applications in conventional HCs*
- *Carbon capture & storage*

Strategic Aims of Petroleum MSc courses

Develop multi-skilled geoscientists and engineers for the modern petroleum industry

Integrate the core disciplines of geology & petroleum engineering to provide:

- Specialist skills in core subjects
- Competence in allied subjects

Reflect present-day industry structure, workflows and methodologies

Provide students with a framework for pursuing future professional careers

Provide the international petroleum industry with technically competent, well-trained and motivated graduate recruits

Petroleum Geoscience MSc:
52 Students, 15 Countries

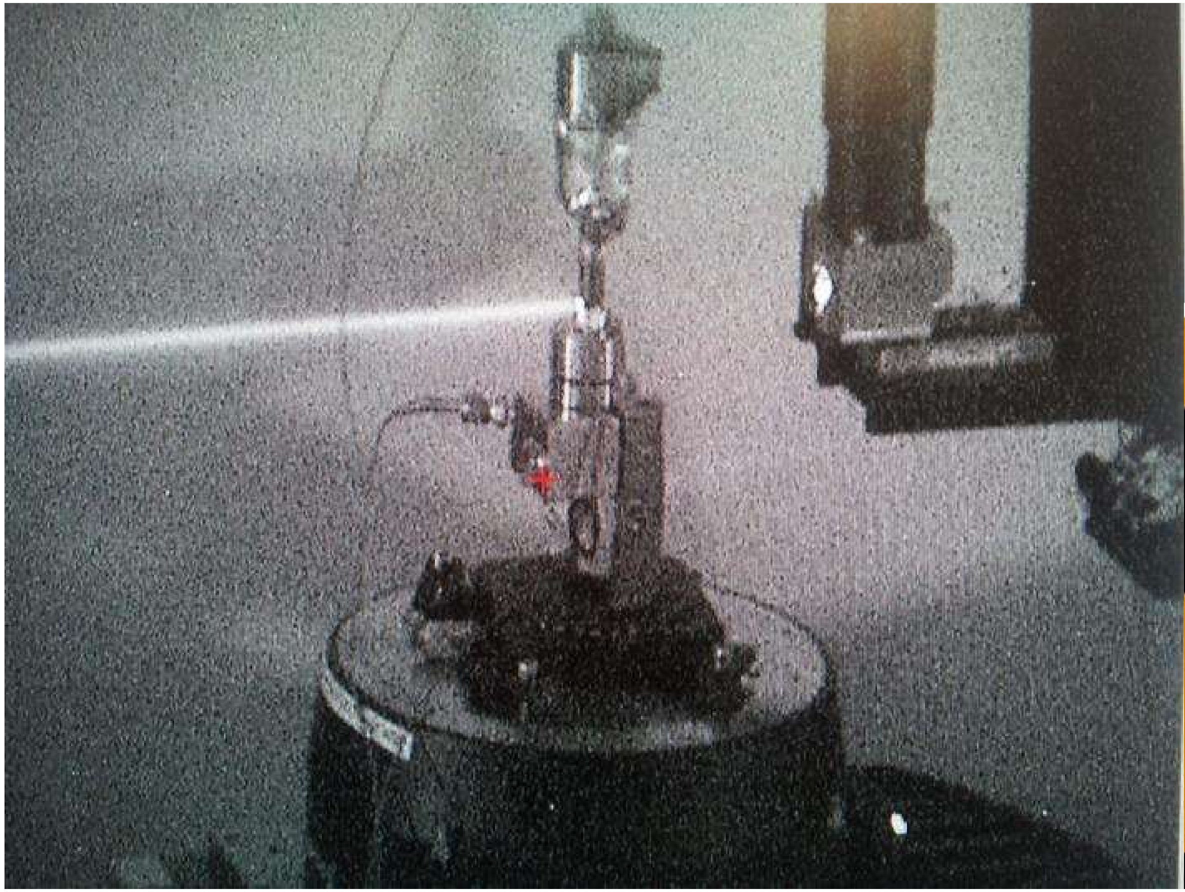
Argentina, China, Colombia, Cyprus, France, Greece, India, Indonesia, Kazakhstan, Malaysia, Nigeria, Russia, Saudi Arabia, Spain, UK

MSc Petroleum Geoscience students (2017-18), Wessex Basin, October 2017

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.

Dynamic Tomography at Synchrotron Sources

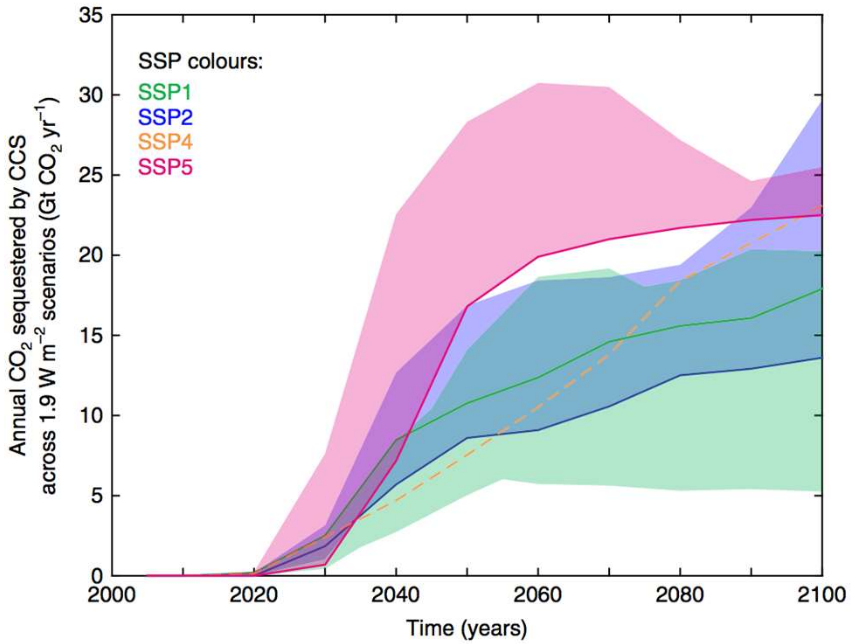


Down to 1 s time resolution.

The need for CO_2 storage

- Climate change mitigation: CO_2 storage underground
- Groundwater use and protection
- Geothermal energy
- Oil & gas production
- Shale oil and gas

Carbon capture and storage alone will create an industry the size of the current oil & gas industry, if not larger!



Rogelj et al, *Nature Climate Change*, 2018

Net Zero by 2050
Our ambition is to be a net zero company by 2050 or sooner. And to help the world get to net zero. This will mean tackling around 415 million tonnes of emissions – 55 million from our operations and 360 million tonnes from the carbon content of our upstream oil and gas production. Importantly these are absolute reductions, to net zero, which is what the world needs most of all. We are also aiming to cut the carbon intensity of the products we sell by 50% by 2050 or sooner

“The world’s carbon budget is finite and running out fast; we need a rapid transition to net zero”

Bernard Looney, chief executive officer
13th February 2020

Imperial College London

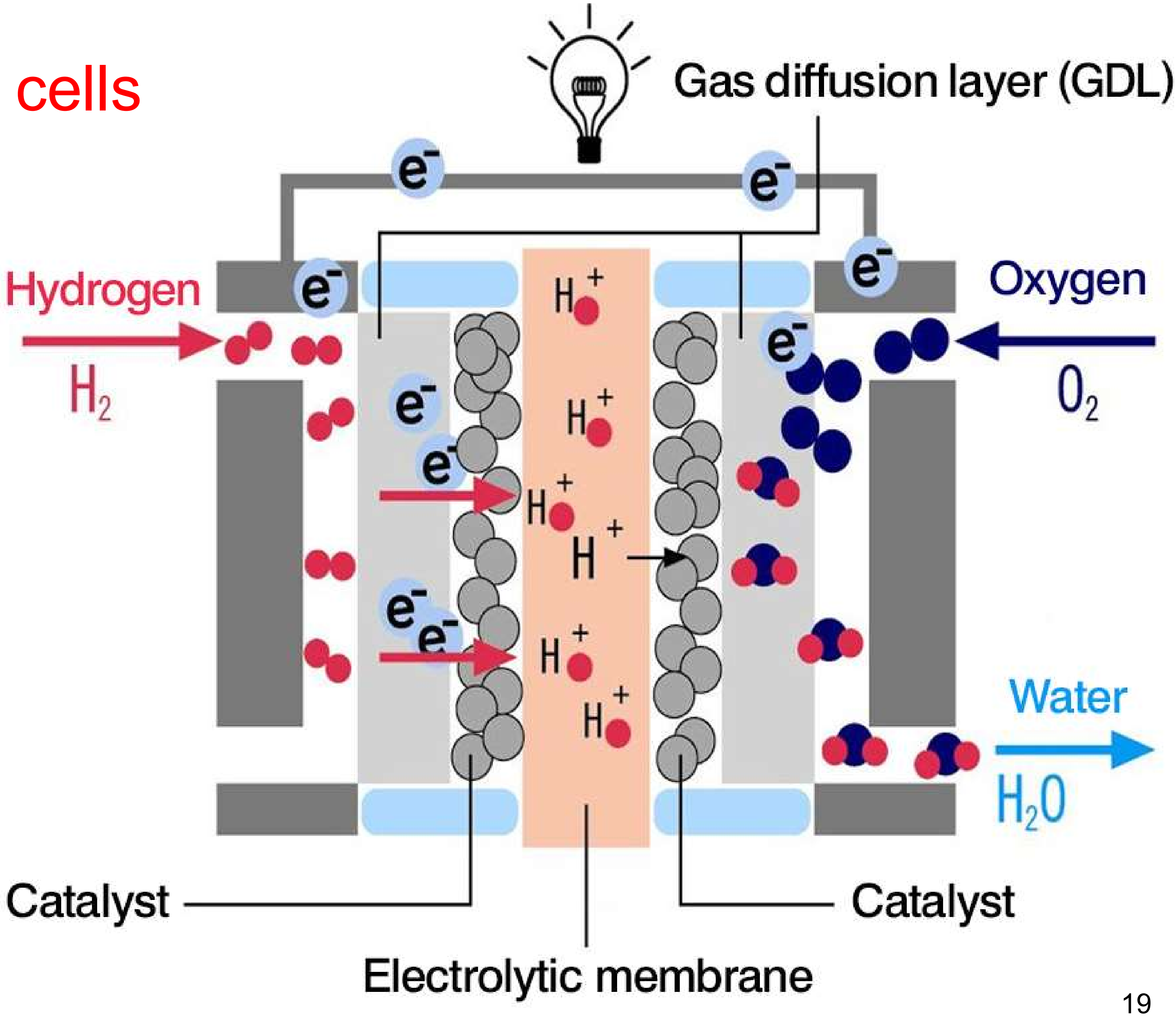
https://www.theguardian.com/education/2018/nov/22/its-like-tobacco-funding-health-research-should-universities-take-money-from-fossil-fuel

'It's like tobacco funding health research': should universities take money from fossil fuel?

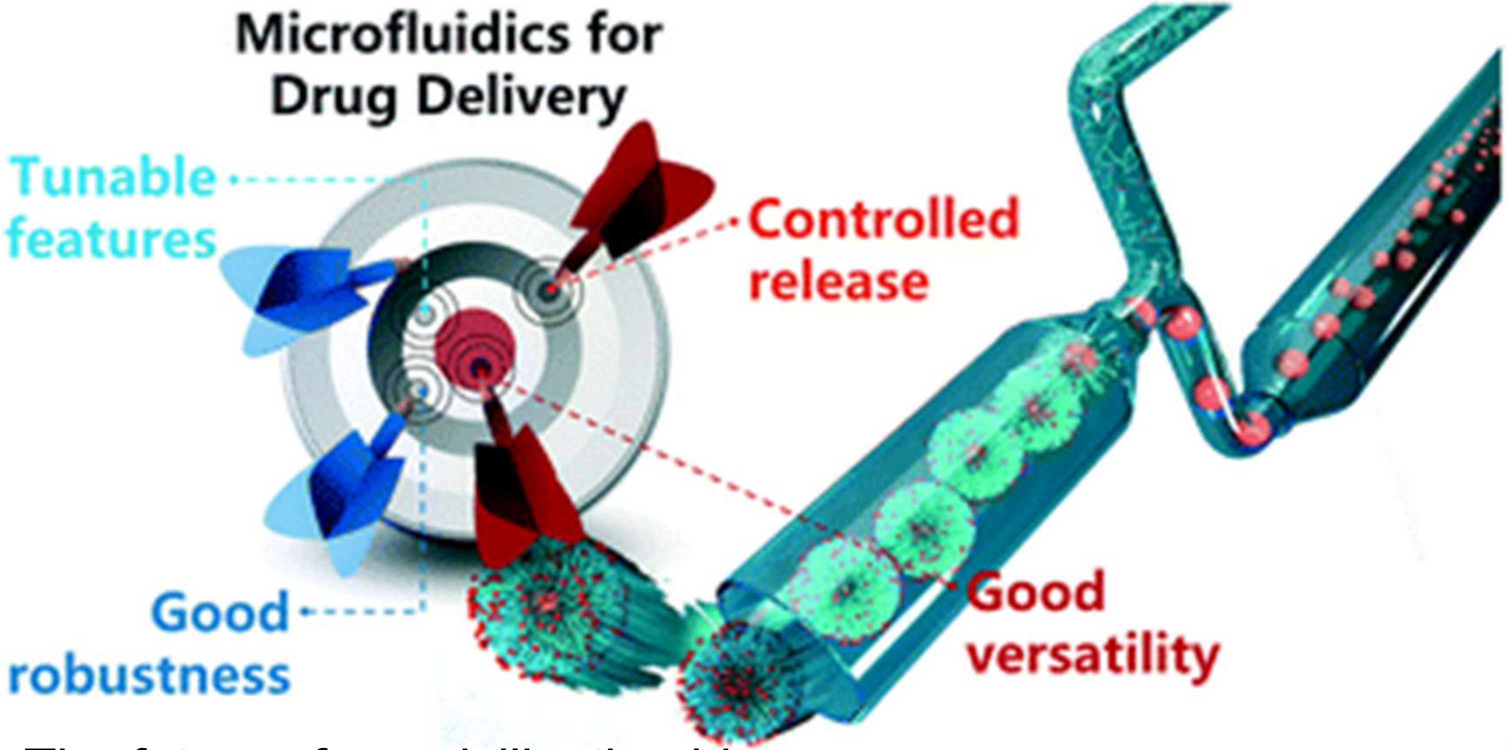
Fossil fuel companies have infiltrated universities for years.

Are students and academics increasingly turning against them?

Fuel cells



Gas diffusion layer (GDL)
Hydrogen
H_2
Oxygen
O_2
Water
H_2O
Catalyst
Catalyst
Electrolytic membrane



The future of our civilization hinges on engineering the subsurface: hydrocarbon recovery and carbon dioxide storage. Plus lots of other applications from food preparation, drug delivery to electrochemical devices.

To do this we need to understand multiphase flow, starting at the pore scale.

Trapping, flow and dynamics

There are two things we need to design:

1 **Trapping.** One phase is surrounded by the other in the wider pore spaces and cannot flow. CO_2 storage, surgical masks.

2 **Flow.** Both phases can flow over a wide saturation range with little trapping or retention of either phase. Fuel cells, oil recovery.

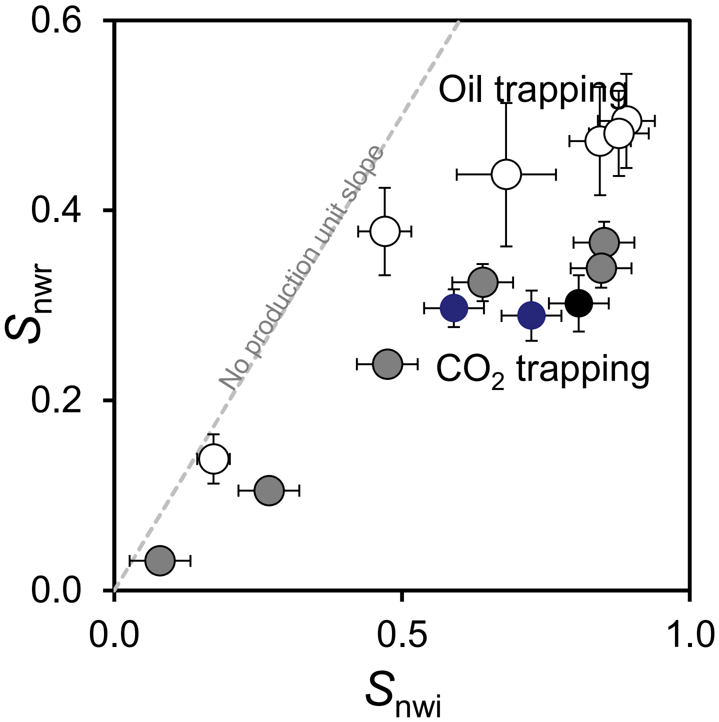
Controlled by pore structure and ***wettability*** – the local distribution of contact angle.

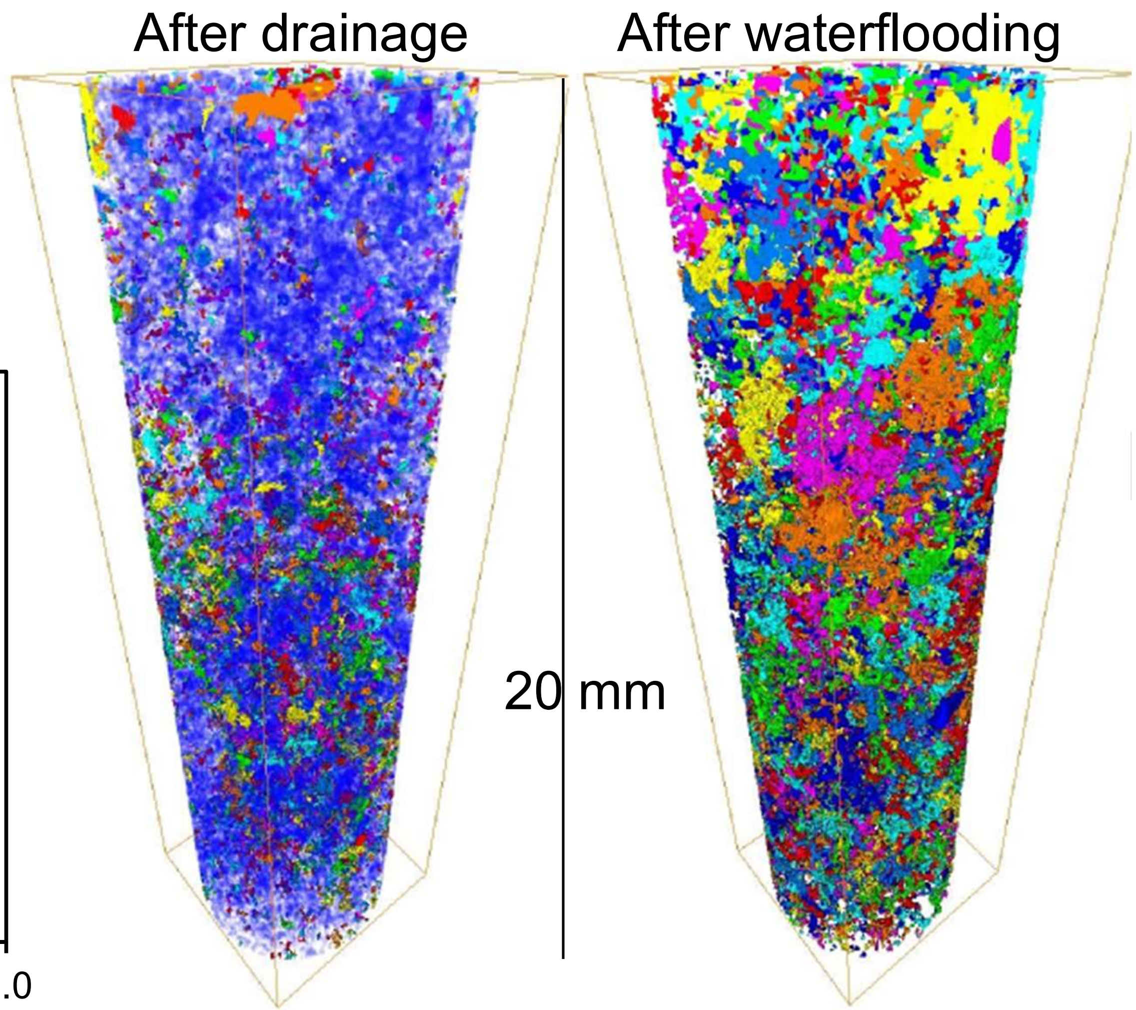
Finally, even at low flow rates see the emergence of ***non-linear dynamics***.

Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

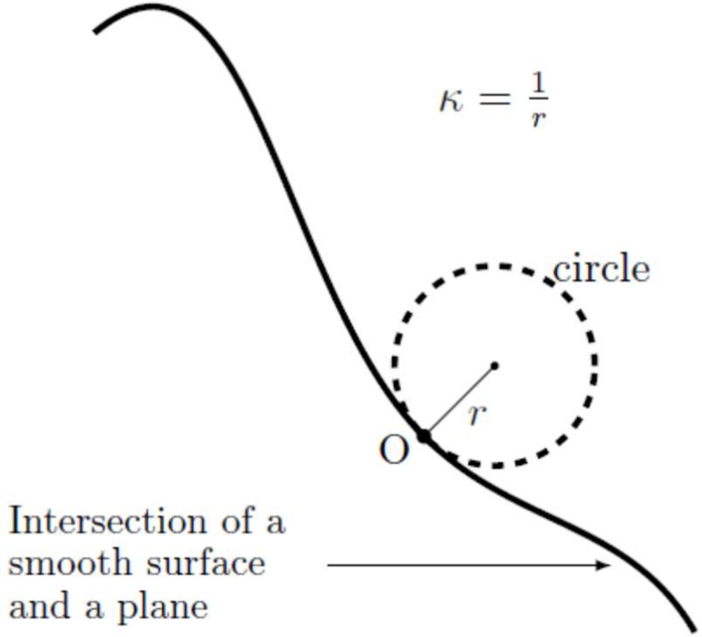
Results in sandstones (Doddington, Bentheimer and Berea).





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

Curvature



Consider the fluid-fluid interfaces.

In three dimensions have two principal radii of curvature, r_1 and r_2, in orthogonal directions: $\kappa_1 = 1/r_1$ and $\kappa_2 = 1/r_2$. Can have different sign.

(Total) curvature $\kappa = (\kappa_1 + \kappa_2)$:

Young-Laplace – capillary pressure, $P_c = \sigma\kappa$

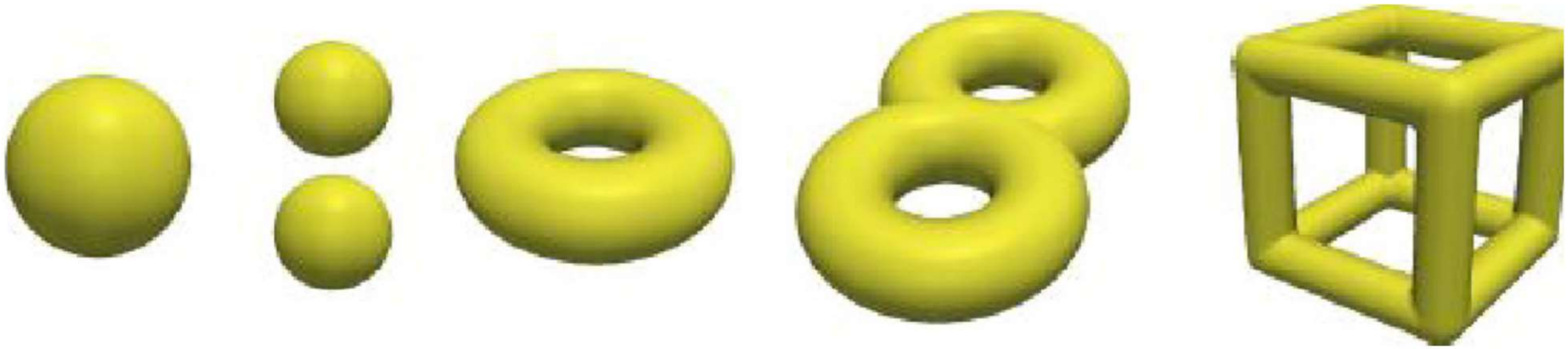
Gaussian curvature is defined as $G = \kappa_1 \times \kappa_2$.

Gauss-Bonnet theorem

$$\int G dS = 4\pi\chi\,,$$

where χ is the Euler characteristic (objects – loops + holes).

A large negative value implies an object with good connectivity (many loops in the structure) while a positive values – ball shaped interfaces – implies poor connectivity.



(1,0,0) $\chi = 1$ (2,0,0) $\chi = 2$ (1,1,0) $\chi = 0$ (1,2,0) $\chi = -1$ (1,5,0) $\chi = -4$

Trapping and flow, apples and pears

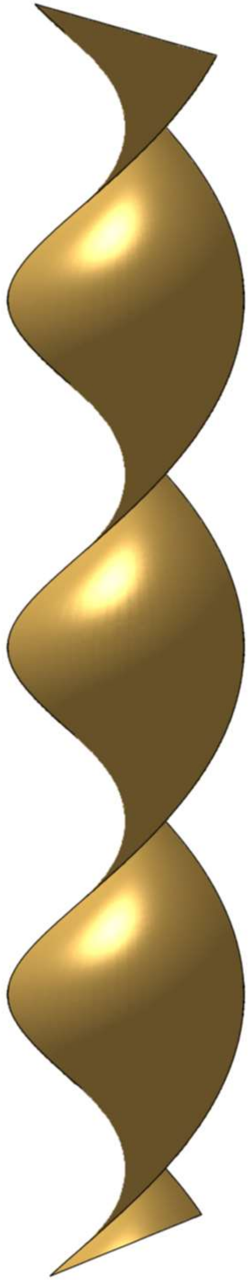
So for trapping, want one phase to be wetting (contact angles below 90^o) – the non-wetting phase is trapped. Ball-shaped fluid-fluid interfaces: two approximately equal radii of curvature r_1 and r_2. $G = 1/r_1 r_2 > 0$. Trapped phases.

So what's the opposite? Two approximately ***equal and opposite*** curvatures: $r_1 = - r_2$. Surely this is ideal for flow/recovery?

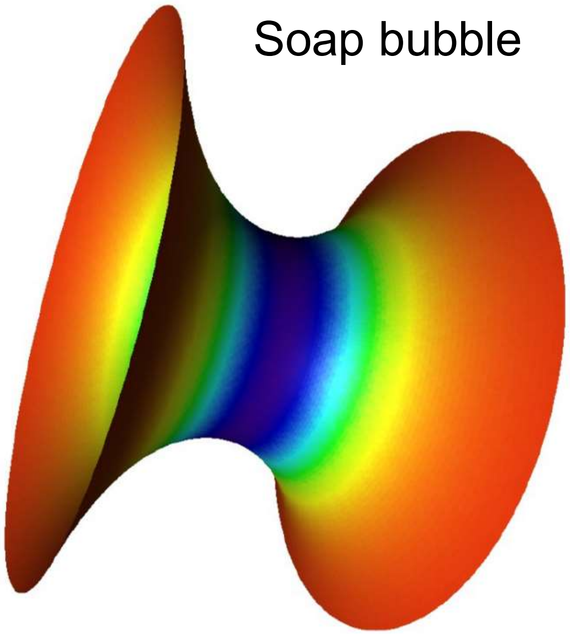
Apples and pears!

Minimal surfaces

Helicoid: $\tan z = x/y$



Soap bubble



Minimal surfaces (a catenoid, left, and a helicoid, right) have a negative Gaussian curvature – the product of the two curvatures but a zero mean curvature. $G < 0$, $\kappa = 0$.

This implies that the fluid phases are well connected.

Minimal surfaces are found in equilibrium when the three-phase contact lines are pinned.

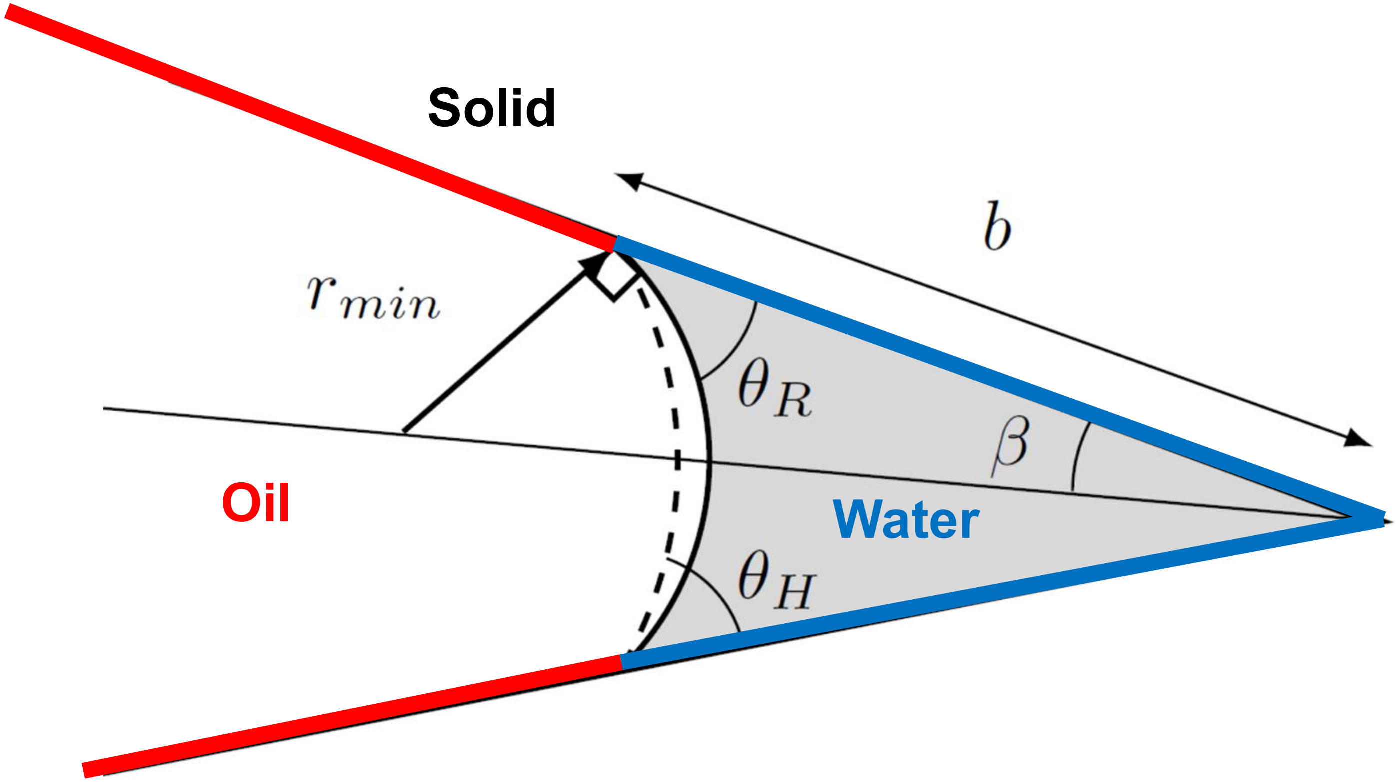
How can we engineer this in porous materials?

Catenoid: $\frac{1}{a^2}\cosh^2 az = x^2 + y^2$

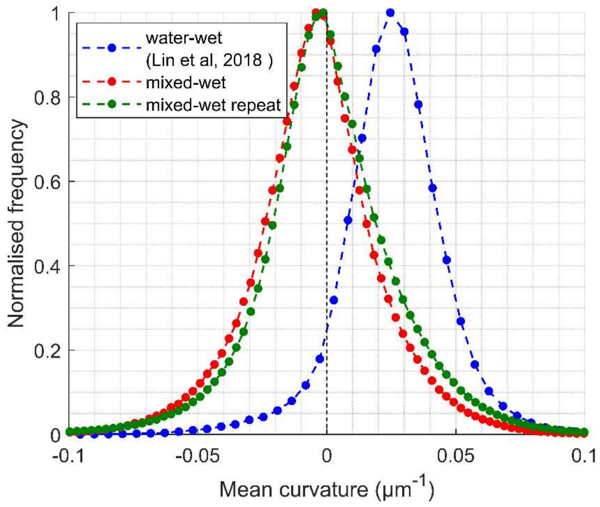
The mixed-wet state

Have a wide range of contact angle – it varies from place to place. Contacts are pinned, as shown.

Rocks in contact with crude oil, soils with organic material, mixture of hydrophilic and hydrophobic fibres.



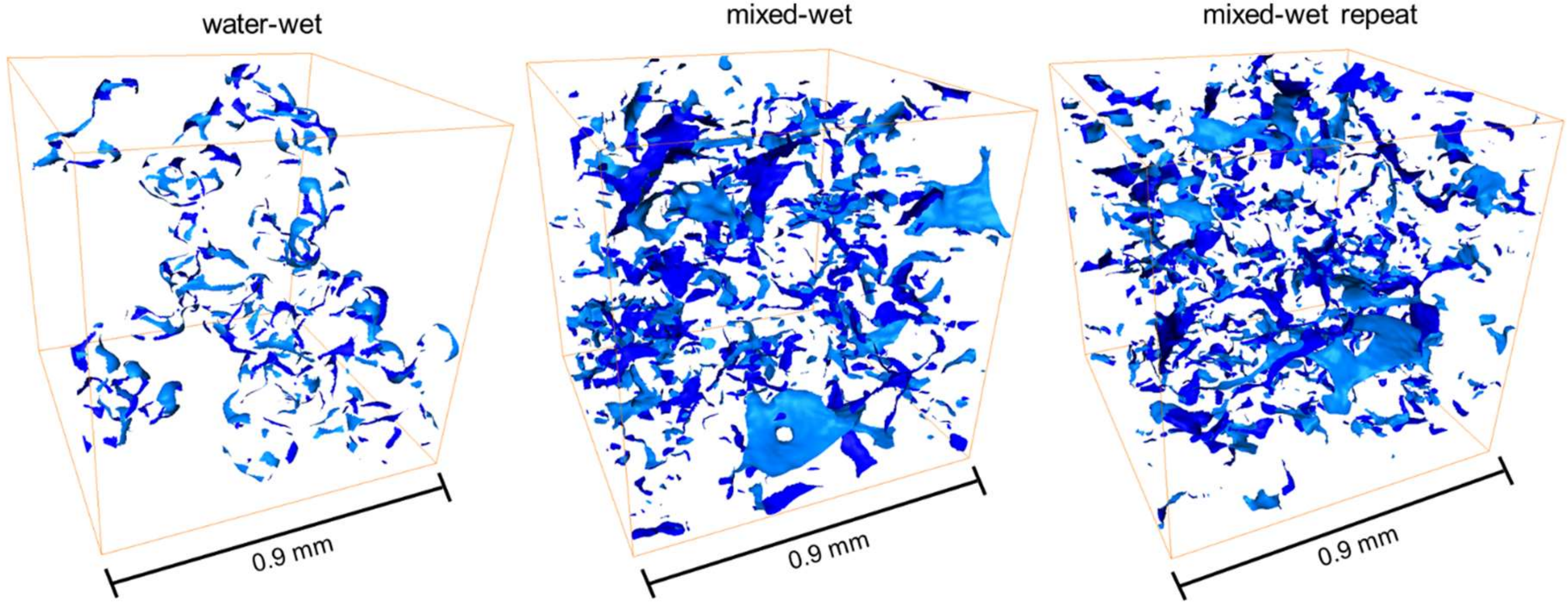
Minimal surfaces – small curvature



The interfacial curvature is much lower – near zero – in the mixed-wet case. But the interfaces are not flat, but have curvature in two equal and opposite directions.

Zero curvature interfaces that minimize their surface area (energy) are minimal surfaces.

Implies pinned contacts with the solid.



Lin *et al., PRE* (2019); Alratrout *et al.*, *PNAS* (2018)

And then….?

Quantify flow properties in rocks: is this really good for recovery?

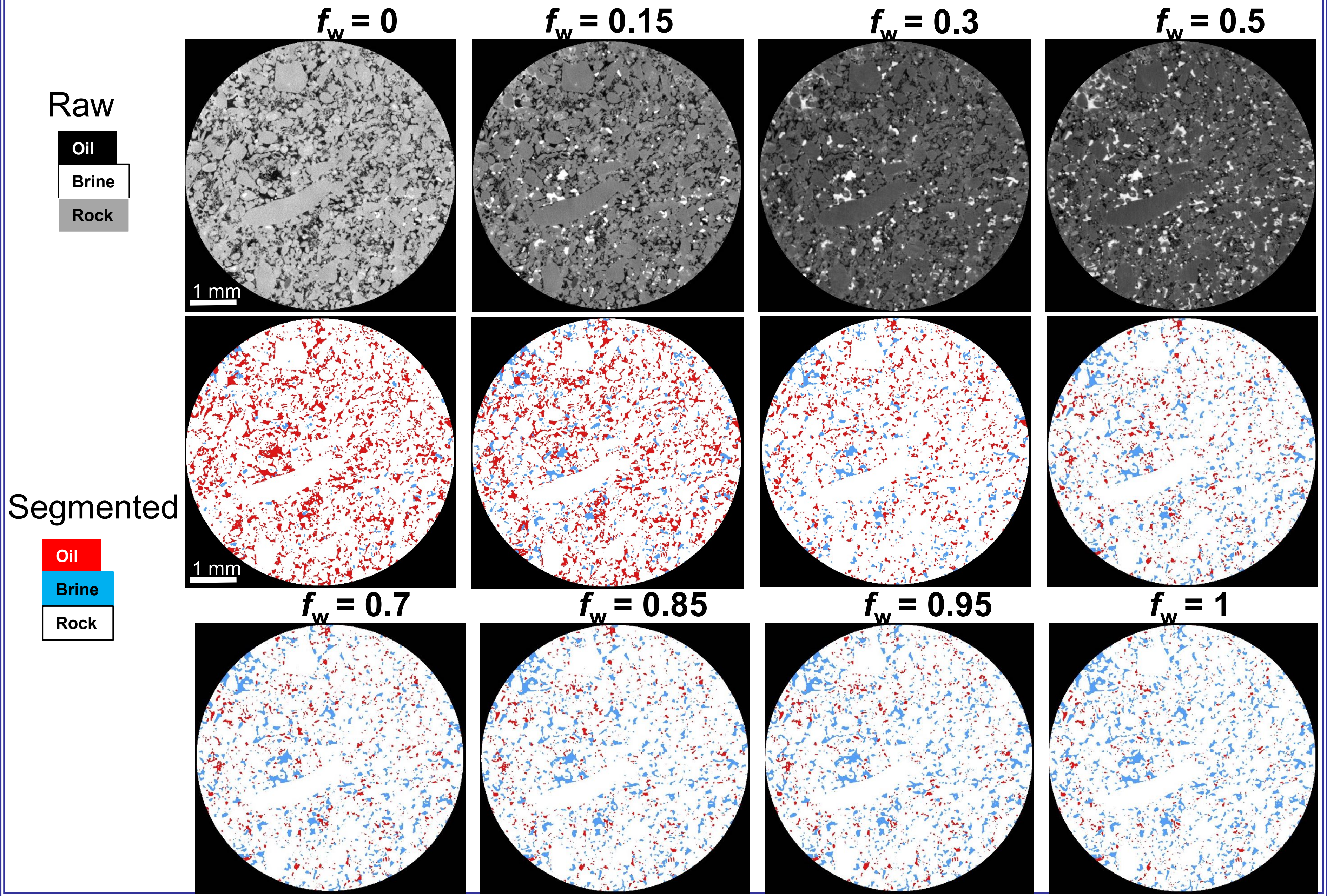
Measure wettability in different ways – displacement and topology.

Three fluid phases.

Dynamic effects.

And – finally – back to masks and fuel cells.

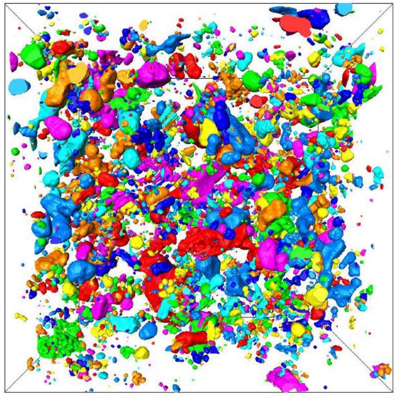
Steady-state flow in a reservoir sample



Brine phase

$f_w = 0.15$

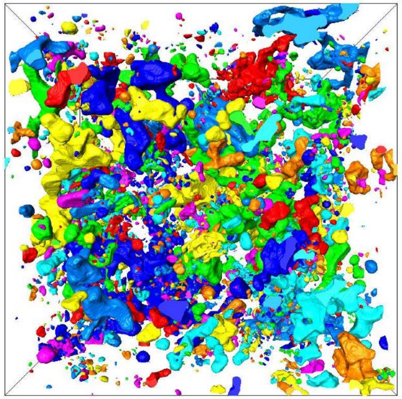
Water flows slowly close to the surface



2 mm

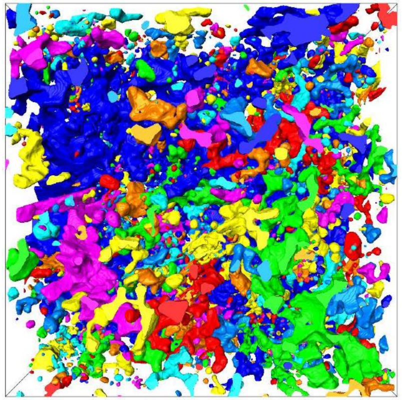
$f_w = 0.30$

Water blobs enlarge.

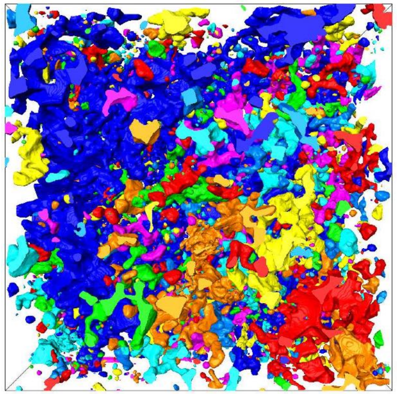


$f_w = 0.50$

Water starts to connect

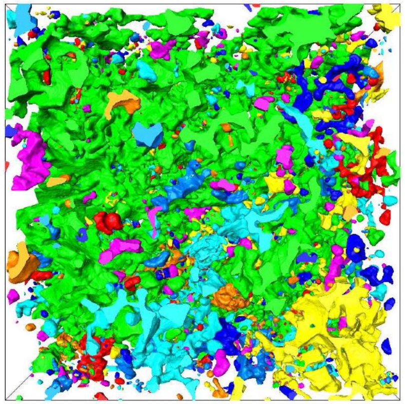


Better water connec-tivity



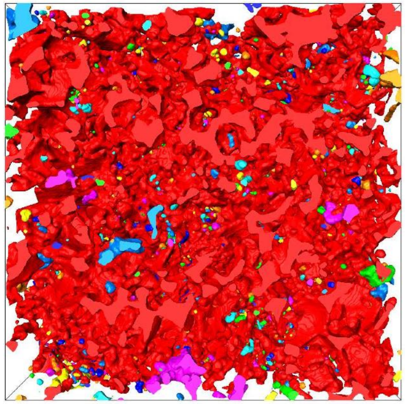
$f_w = 0.70$

Now water fills the big pores and flows



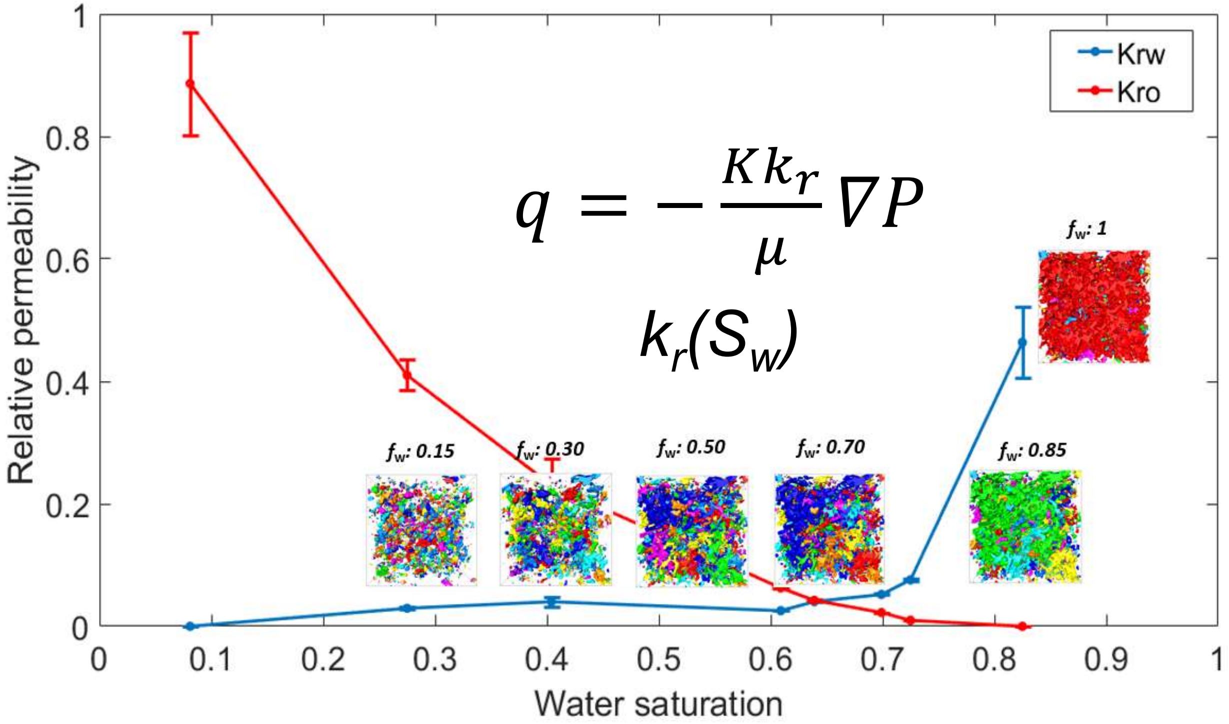
$f_w = 0.85$

Water fills most of the pore space



$f_w = 1$

Favourable oil recovery



$$q = -\frac{K k_r}{\mu} \nabla P$$

$$k_r(S_w)$$

Brine saturation increases by water layer swelling.

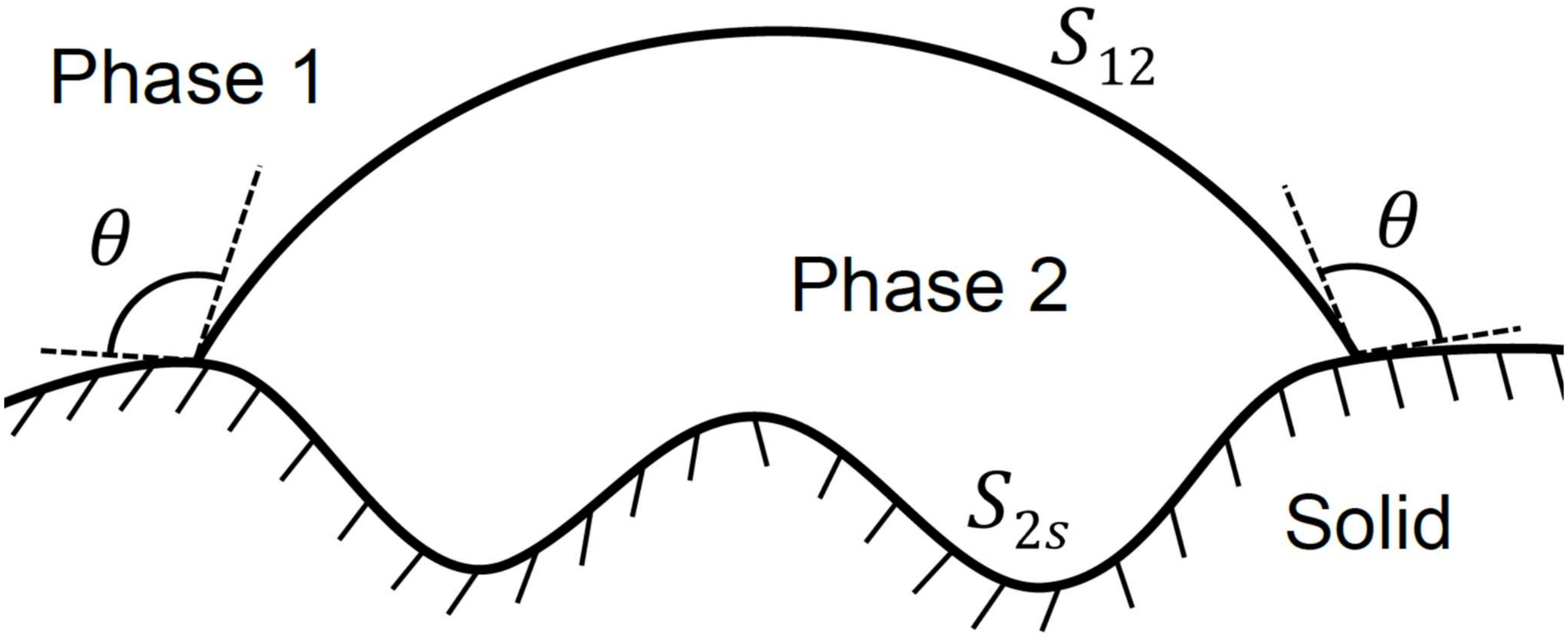
So, brine bulges into the oil. As the saturation of brine increase these patches of brine expand but are still disconnected

This allows oil to drain to low oil saturation by flow through connected oil layers.

Alhammadi *et al., Fuel* (2020)

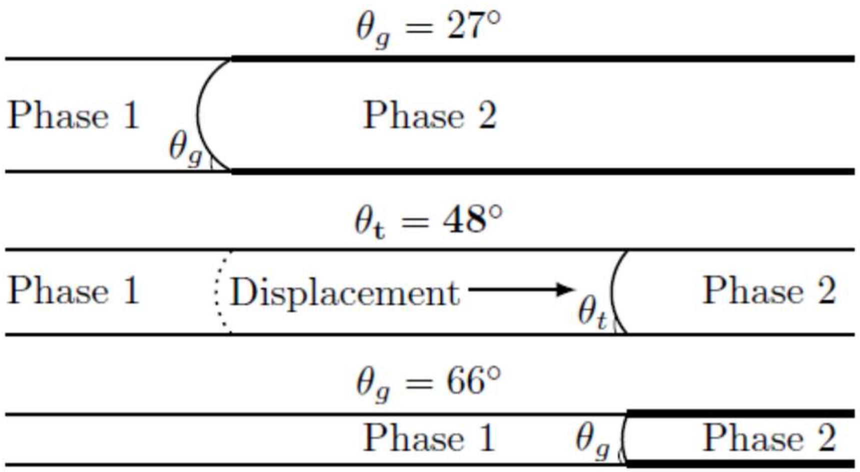
Topology and contact angle

Apply the Gauss-Bonnet theorem. There is a deficit curvature representing the kink at the contact line – can relate this to contact angle.



Sun *et al., JCIS* (2019, 2020), *GRL* (2020); Blunt *et al., JCIS* (2020)

Energy balance for displacement



$$\sigma \cos\theta_t = \sigma_{2s} - \sigma_{1s},$$

$$\Delta E = (\Delta A_{12} - \Delta A_{1s}\cos\theta_t)\sigma.$$

Work done – change in Helmholtz free energy (Morrow, 1970):

$$\Delta F = 0 = \Delta E + P_c \Delta V_1 = \Delta E + P_c V \phi \Delta S_1, \qquad P_c = \sigma\kappa = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right),$$

Final equation – in terms of areas per unit volume, *a=A/V*:

$$\Delta a_{1s}\cos\theta_t = \kappa\phi\Delta S_1 + \Delta a_{12}$$

Can measure all these terms on pore-space images.

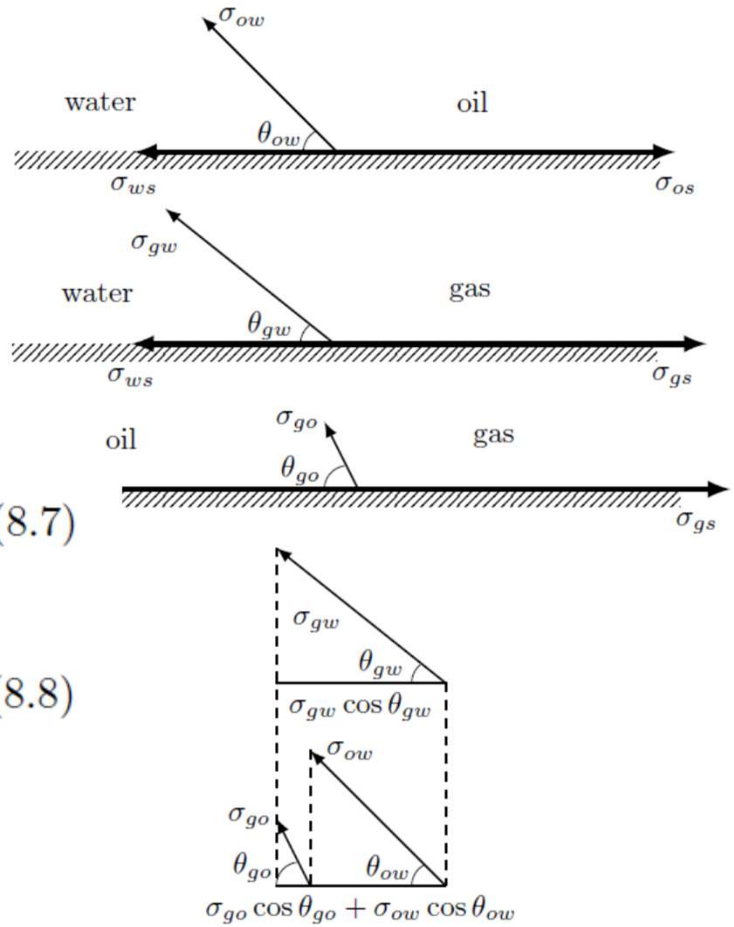
Three-phase flow: Young equations

Bartell-Osterhof relation

+
$$\sigma_{os} = \sigma_{ws} + \sigma_{ow} \cos\theta_{ow}, \tag{8.4}$$

$$\sigma_{gs} = \sigma_{ws} + \sigma_{gw} \cos\theta_{gw}, \tag{8.5}$$

-
$$\sigma_{gs} = \sigma_{os} + \sigma_{go} \cos\theta_{go}. \tag{8.6}$$



1
$$\sigma_{ws} + \sigma_{gw} \cos\theta_{gw} = \sigma_{os} + \sigma_{go} \cos\theta_{go}, \tag{8.7}$$

2
$$\sigma_{gw} \cos\theta_{gw} = \sigma_{ow} \cos\theta_{ow} + \sigma_{go} \cos\theta_{go}. \tag{8.8}$$

Why ducks (and surgeons in masks) don't get wet

Water-wet and oil-wet media: spreading, so $\theta_{go} = 0$

$$\sigma_{gw} \cos\theta_{gw} = \sigma_{ow} \cos\theta_{ow} + \sigma_{go} \cos\theta_{go}. \quad (8.8)$$

Water-wet: $\cos\theta_{ow} = 1$

$$\cos\theta_{gw} = (\sigma_{ow} + \sigma_{go})/\sigma_{gw} = 1, \text{ as } C_s = \sigma_{gw} - \sigma_{ow} - \sigma_{go} = 0$$

Oil-wet: $\cos\theta_{ow} = -1$

$$\cos\theta_{gw} = (-\sigma_{ow} + \sigma_{go})/\sigma_{gw} < 0, \text{ as } \sigma_{ow} > \sigma_{go}$$

An oil-wet (or made of oil) surface is hydrophobic: repels water – gas is wetting to water.

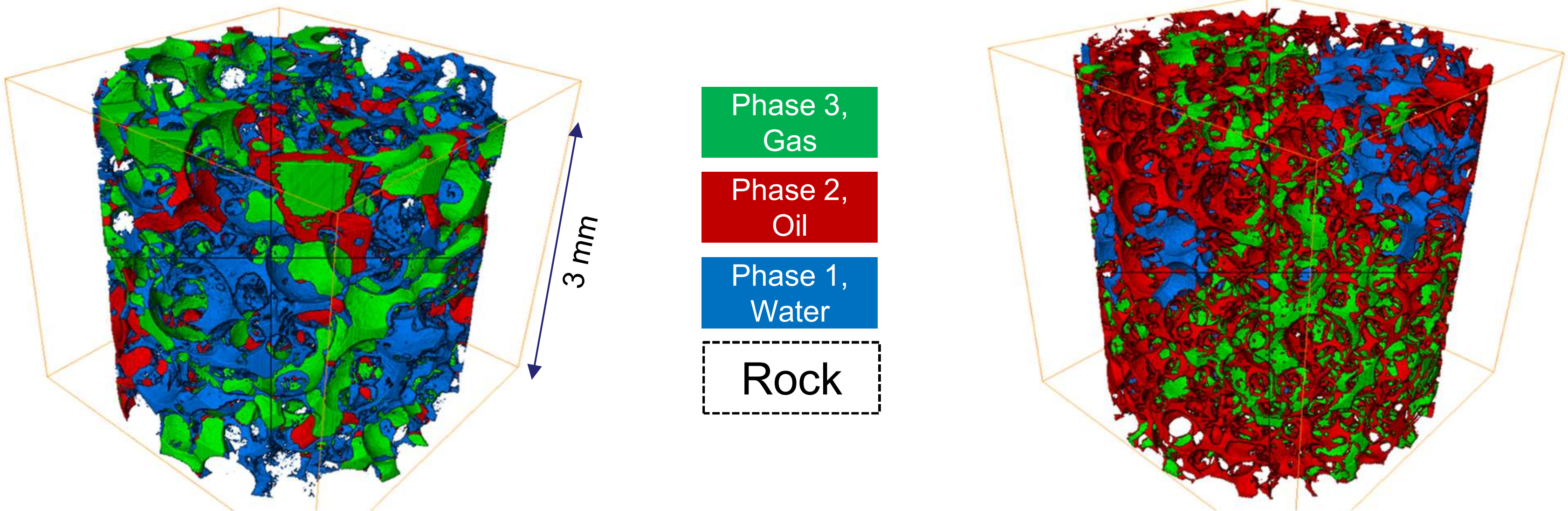
Energy balance: three-phase flow

Energy balance on pore-scale images is used to find contact angles, θ, in three-phase flow:

$$(\Delta a_{1s}\cos\theta_{12} - \Delta a_{12} - \phi\kappa_{12}\Delta S_1)\sigma_{12} = (\Delta a_{3s}\cos\theta_{23} + \Delta a_{23} - \phi\kappa_{23}\Delta S_3)\sigma_{23} + \Delta a_{13}\,\sigma_{13}$$

Δ is the difference in specific interfacial areas *a*, and saturations *S*. σ is interfacial tension, κ total curvature, and ϕ porosity. 1, 2, 3 and *s* label the three fluid phases and the solid respectively.

Water-wet | Altered-wettability



$\theta_{12} = 48^o, \theta_{13} = 44^o, \theta_{23} = 0^o$

Water is wetting, oil is intermediate-wet and gas is non-wetting

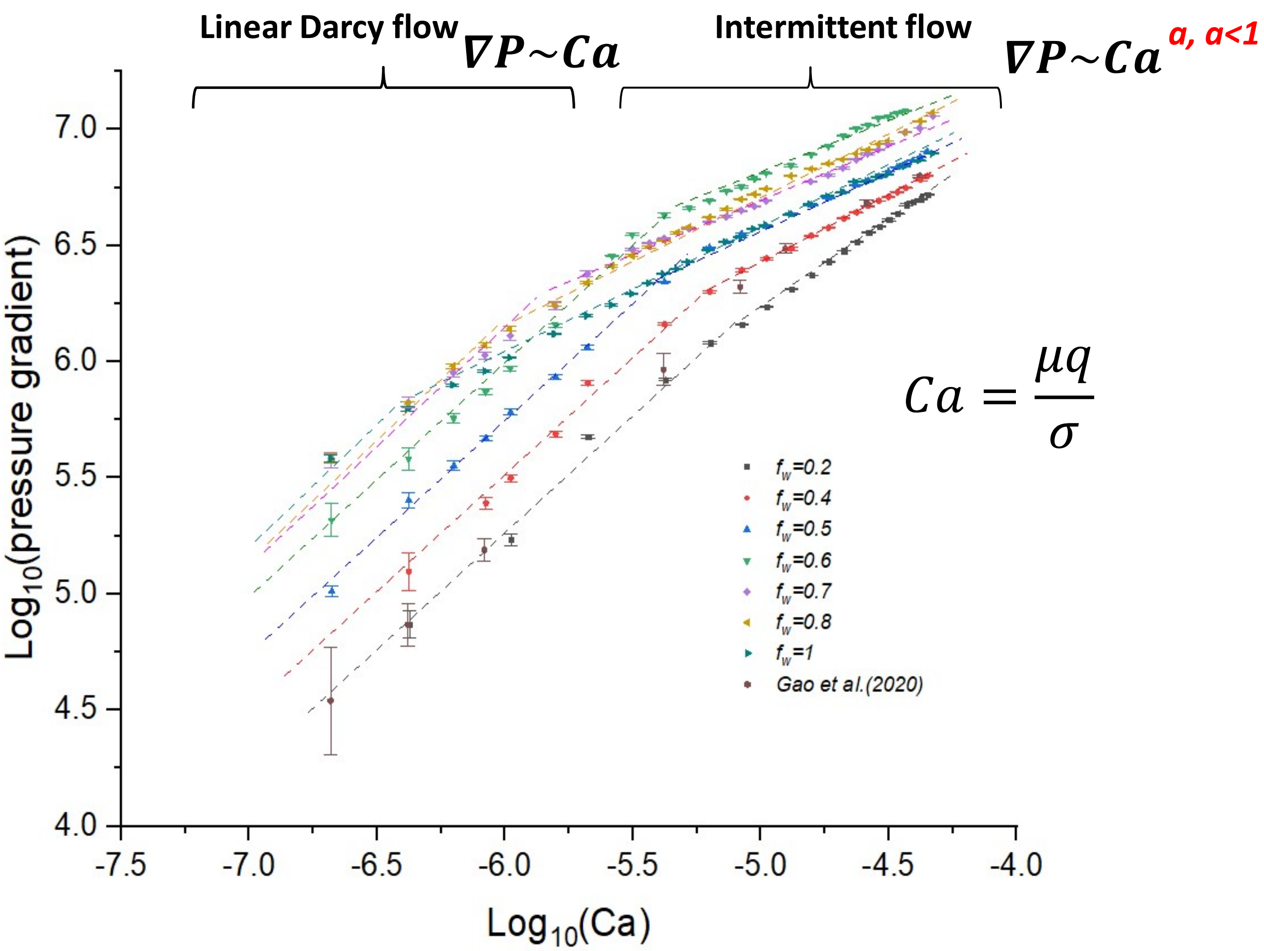
$\theta_{12} = 134^o, \theta_{13} = 119^o, \theta_{23} = 66^o$

Oil is wetting, gas is intermediate-wet and water is non-wetting

Blunt *et. al. JCIS* (2021)

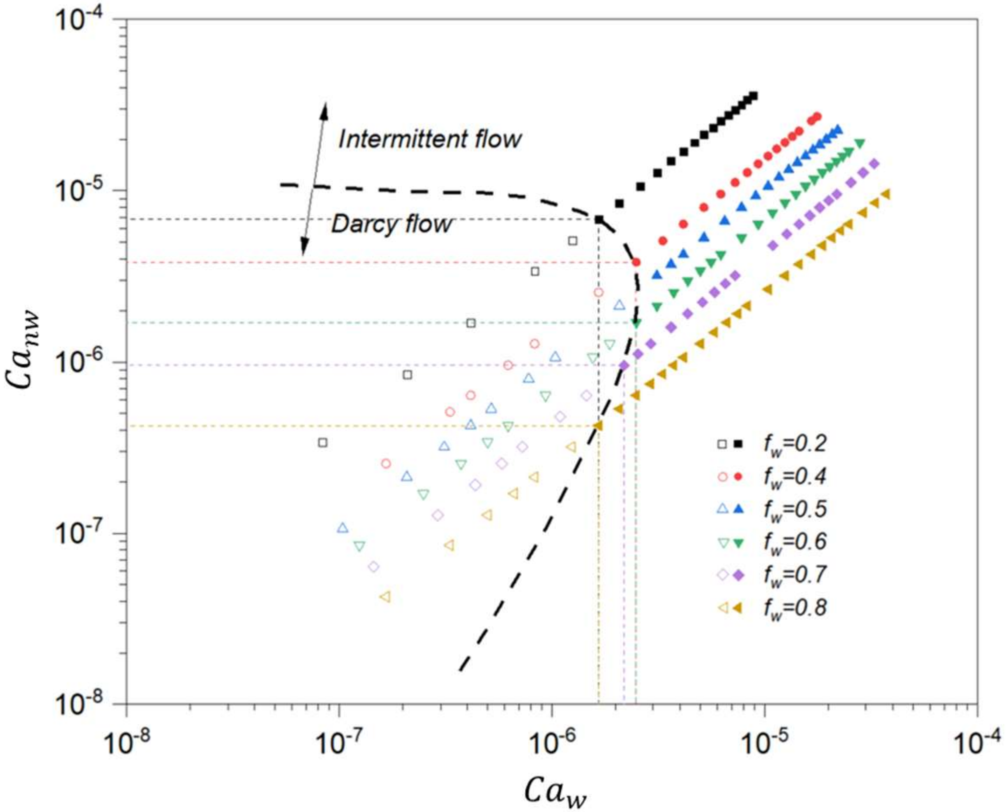
Dynamic effects – non-Darcy flow

Measure pressure drop as a function of flow rate (capillary number): see the emergence of non-linear behaviour. Study different fractional flows in steady state.



$$Ca = \frac{\mu q}{\sigma}$$

Can predict the onset of intermittency



The phase diagram of the transition from Darcy flow (empty symbols) to intermittent flow (filled symbols) as a function of non-wetting phase capillary number Ca_{nw} and wetting phase capillary number Ca_w

Threshold line equation using simple energy balance:

$$Ca_{nw}^i = Y^i(1-f_w)^2$$

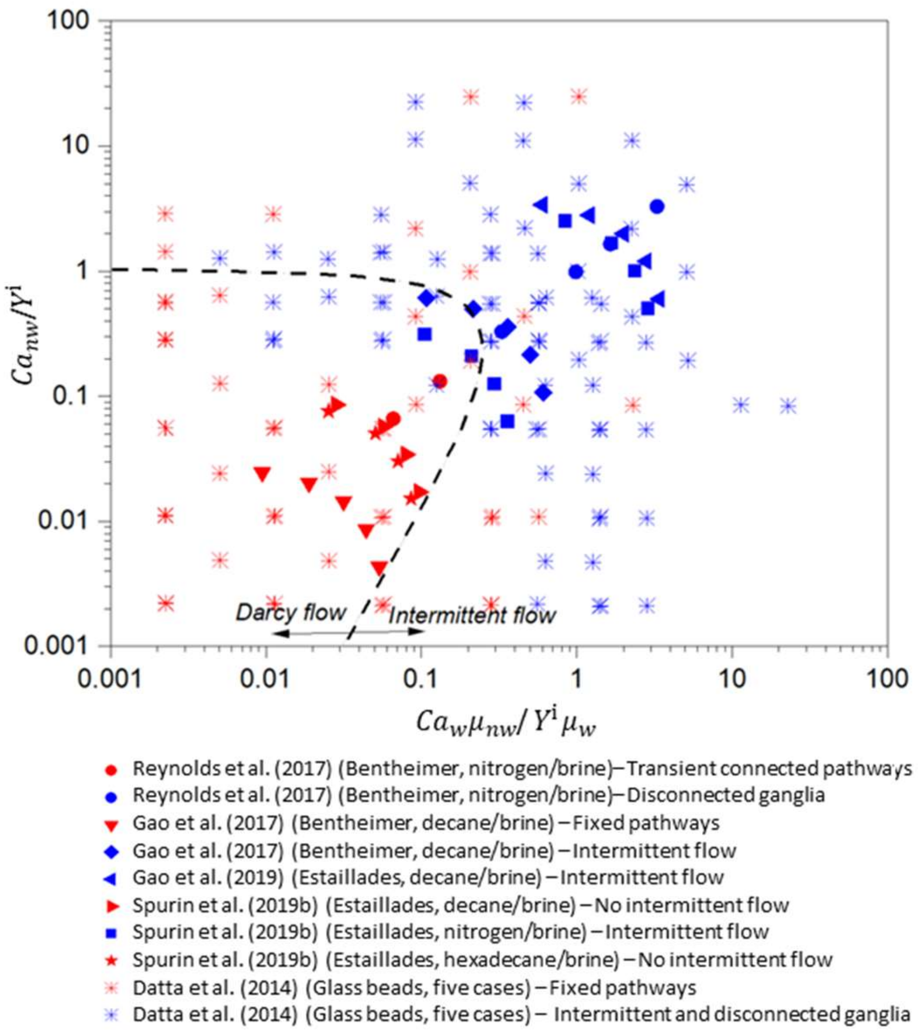
$$Ca_w^i = Y^i f_w(1-f_w)\frac{\mu_w}{\mu_{nw}}$$

$$Y^i = \frac{\mu_{nw}}{\mu_w}\frac{Kr^2}{\phi l^4}$$

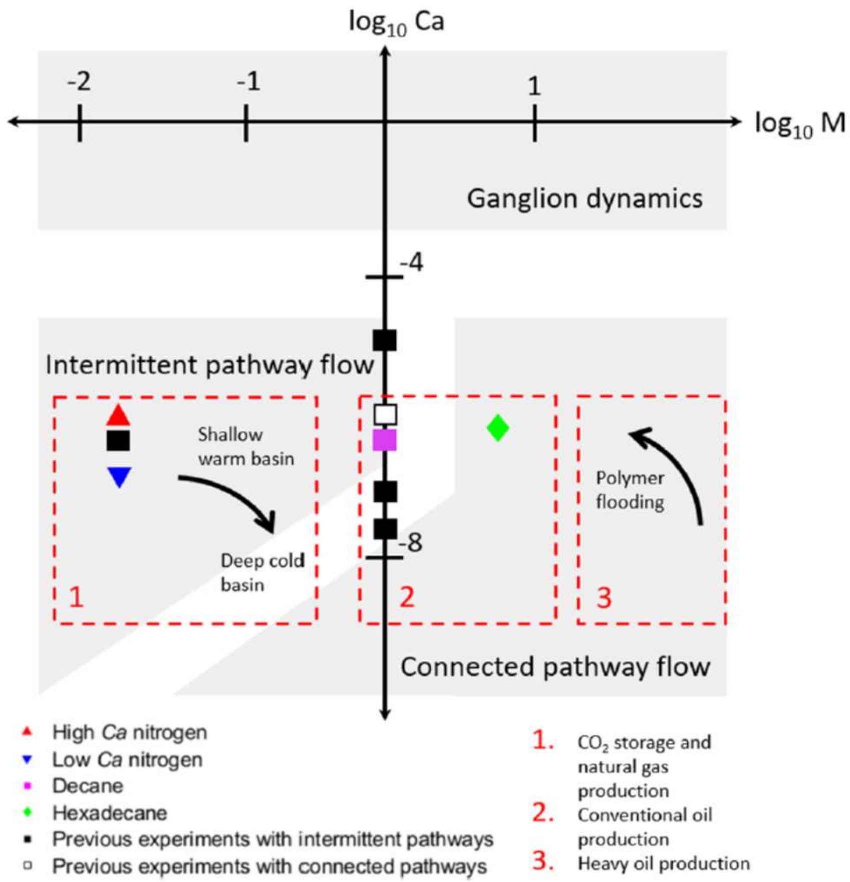
Details can be found:

Zhang, Y., Bijeljic, B., Gao, Y., Lin, Q., & Blunt, M. J. (2020, August 20). Quantification of non-linear multiphase flow in porous media. https://doi.org/10.31223/osf.io/2rxbn

Works on literature data



We apply the theory successfully to literature data.



Spurin et. al. PRE (2019)

Surgical masks and fuel cells

Masks: porous fibrous plastic (oil-wet) layer to repel/trap water.

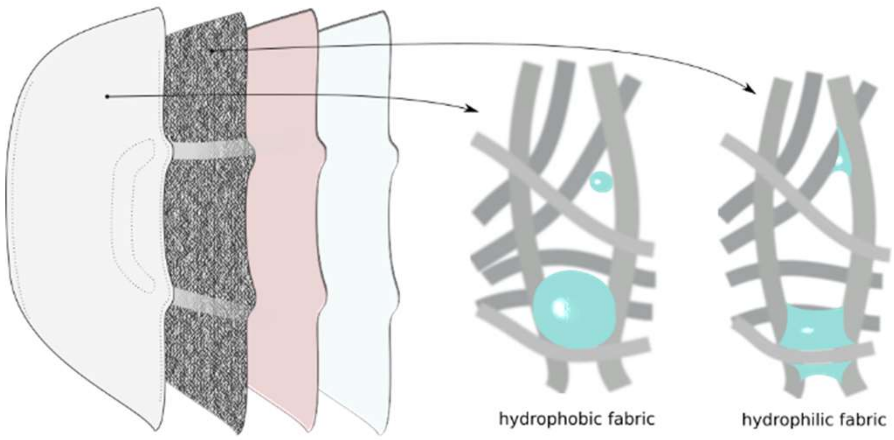
Aerosols are smaller than the pore size, so need to stick to the surface. Have a water-wet (retains water) layer.

So alternating layers of hydrophobic and hydrophilic layers.

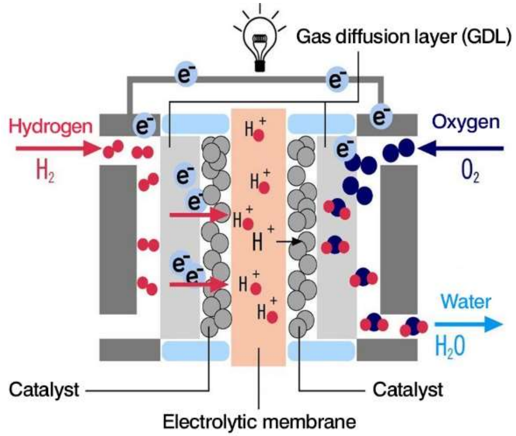
Can we design this more effectively?

Fuel cells: mix of naturally water-wet carbon fibres and Teflon-coated coated fibres (hydrophobic) – mixed-wet.

Again can we design this to maximize flow?

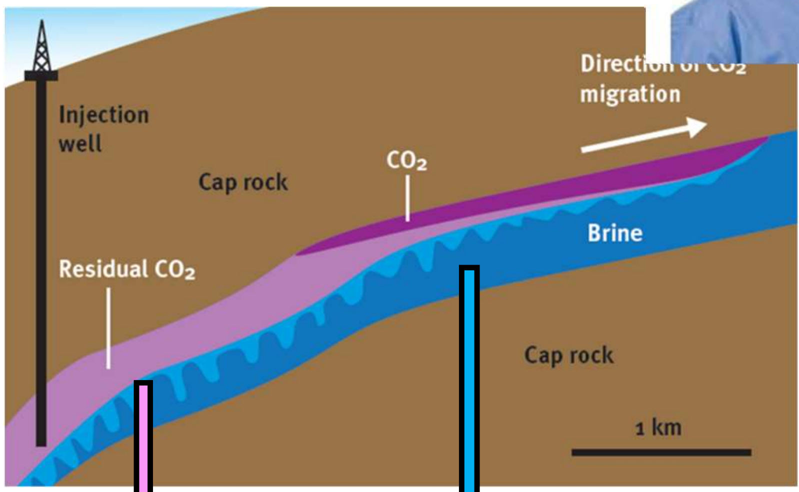


Does it matter?



/html/groundwater.html

Carbon Storage

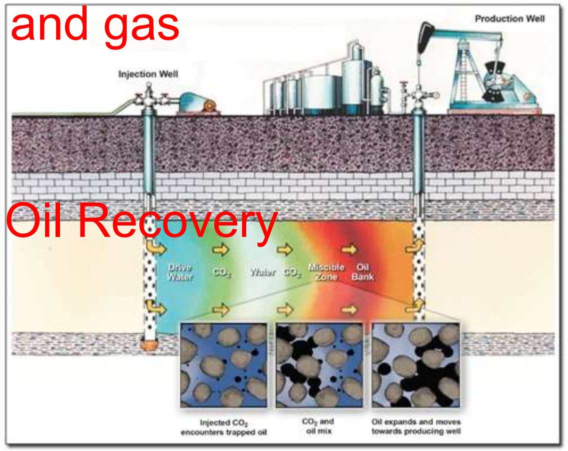


Contaminant Transport

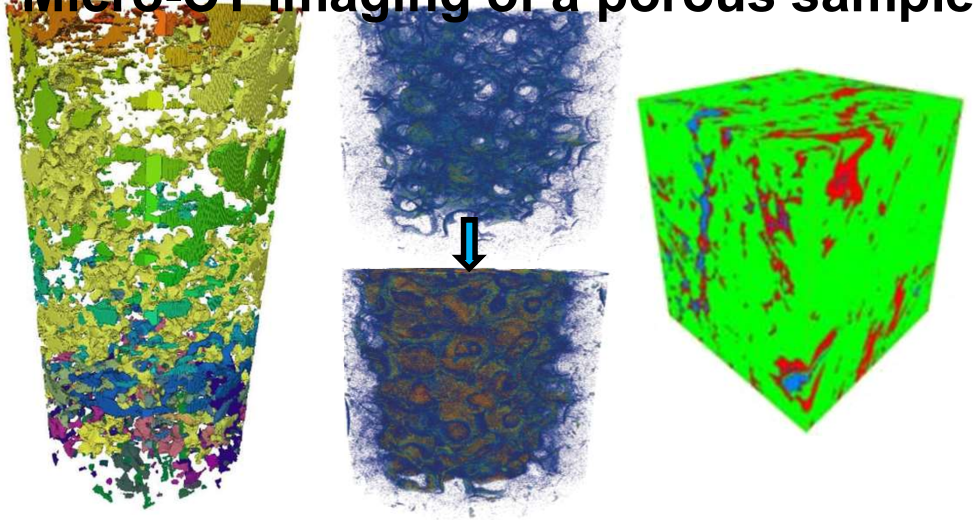
http://energy.gov/

Shale oil and gas

Enhanced Oil Recovery



3D X-ray Micro-CT imaging of a porous sample



Acknowledgements

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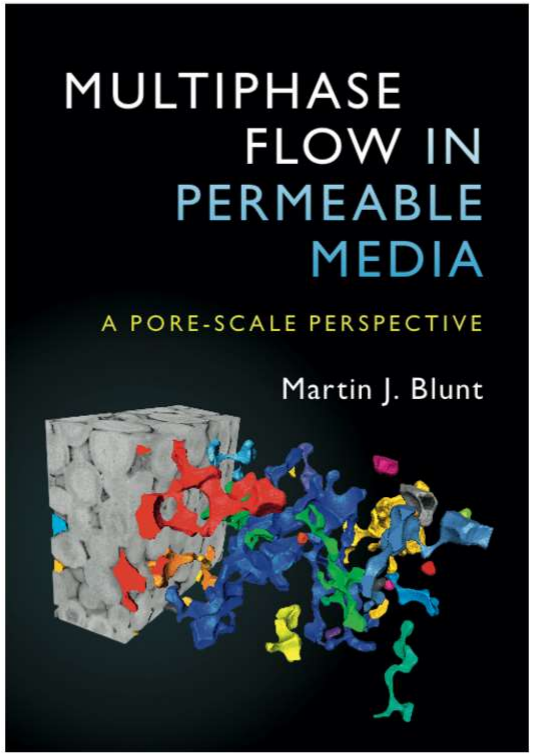

شركة نفط الكويت

Kuwait Oil Company

إحدى شركات مؤسسة البترول الكويتية

A Subsidiary of Kuwait Petroleum Corporation

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