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Flow in Porous Media in the Energy Transition

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What is flow in porous media?

- Porous media are solid objects with holes.
- Water, air, oil, etc flow through the holes.
- Rainfall on soil, filling a babies’ nappy, soaking up a spill with a cloth, water uptake in plants, as well as gas exchange in your lungs and blood flow are all examples of flow in porous media.
- Also sedimentary rock underground is usually porous (has holes) and permeable (allows flow). This rock contains water (salty water at depth), but also oil and gas, and could store carbon dioxide, hydrogen or heat.

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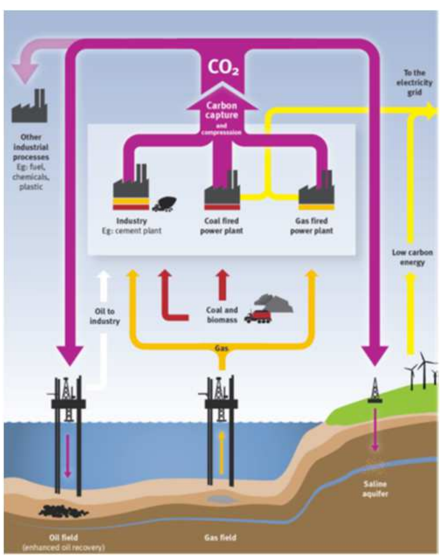
Carbon capture and storage



- Collect carbon dioxide where it is produced and inject into porous rock deep underground.
- Potential for hydrogen storage: hydrogen is produced from natural gas or renewable energy.
- Thermal energy storage – injection and withdrawal of hot/cold water.
- Opposite of oil and gas production.

Many of the societal challenges for the 21st century involve flow in porous media

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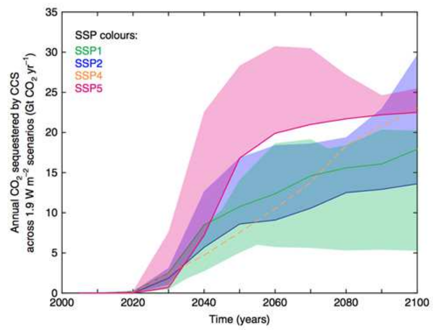
- Climate change mitigation: CO_2 storage underground
- Groundwater use and protection
- Geothermal energy
- Hydrogen storage
- Oil & gas production

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

How do we manage the subsurface?



Rogelj et al, *Nature Climate Change*, 2018

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Imperial College multi-scale imaging lab

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

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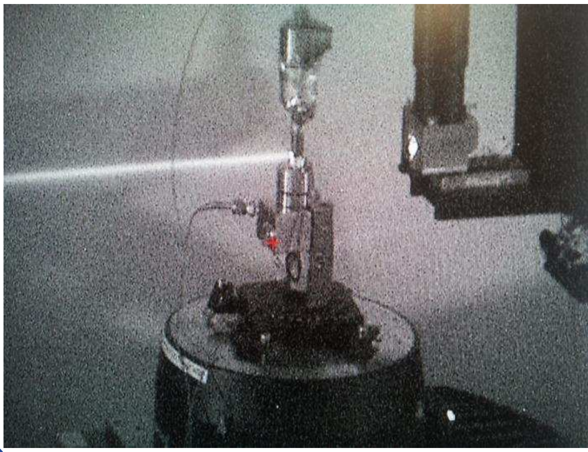
Dynamic Tomography at Synchrotron Sources

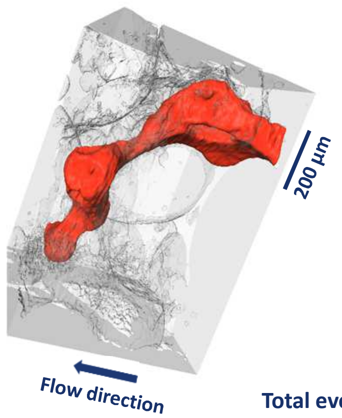


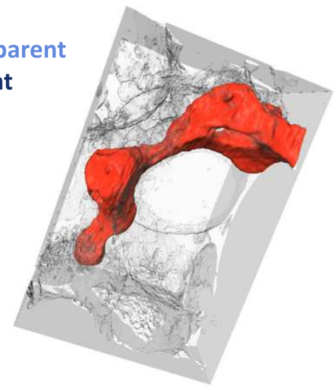
Down to 1 s time resolution.

Measurement of contact angle

Ganglion trapping event

Oil – Red
Rock – Semi-transparent
Brine – Transparent





Δt = 38 s
Total event time = 24 min 4 s

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

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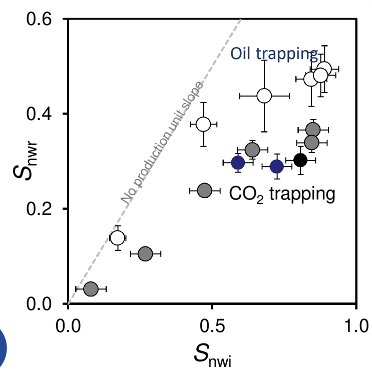
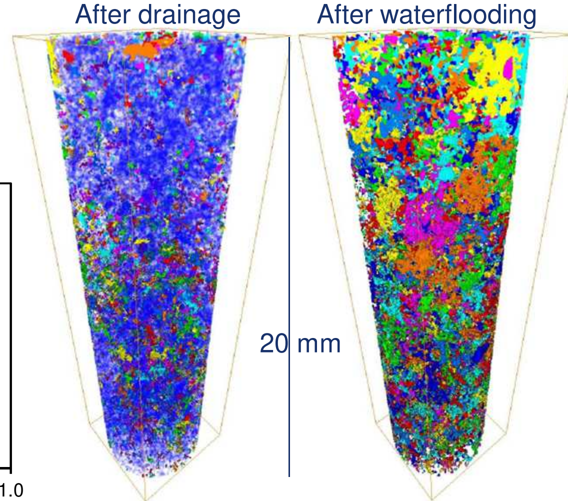
Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

Results in sandstones (Doddington, Bentheimer and Berea).

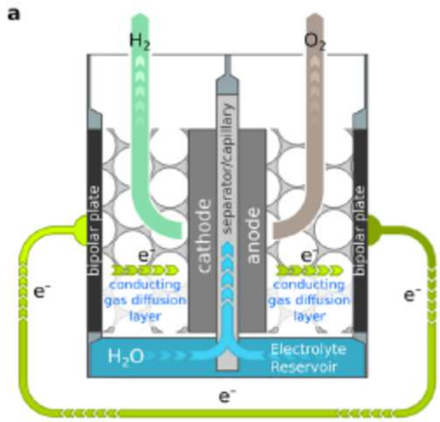


After drainage After waterflooding

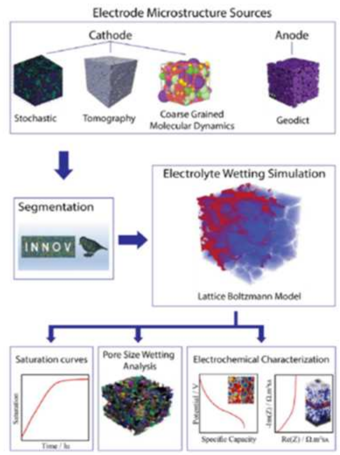


Pentland *et al., Geophysical Research Letters* (2011)
Andrew *et al., IJGGC*, (2014)

Electrolysis, and wetting a Li-ion battery

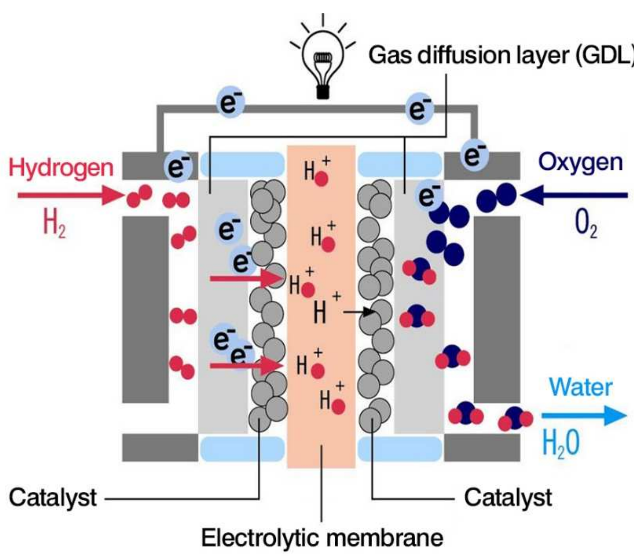


Hodges *et al. Nature Communications* (2022)



Shodiev et al.
Energy Storage Materials 38 (2021) 80–92

Fuel Cells



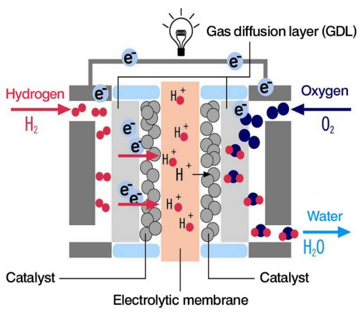
Trapping and flow

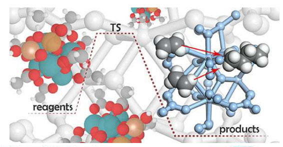
There are two things we can design:

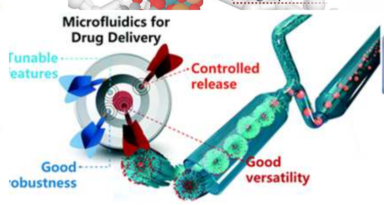
1 **Trapping.** One phase is surrounded by the other in the wider pore spaces and cannot flow. CO_2 storage, surgical masks.

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

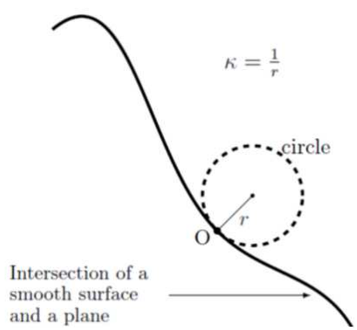
Controlled by pore structure and ***wettability*** – the local distribution of contact angle.







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 $G = \kappa_1 \times \kappa_2$.

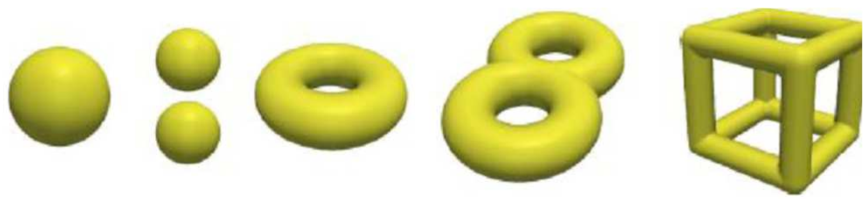
Complete characterization of properties: saturation, areas, curvature and Gaussian curvature.

Gauss-Bonnet theorem

$$\int GdS = 4\pi\chi\,,$$

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) $\chi = -4$

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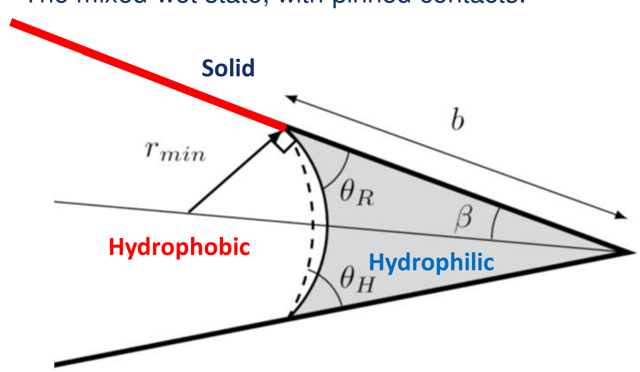
Trapping and flow, apples and pears

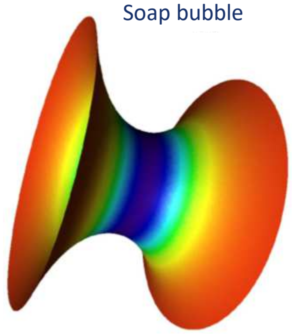
For trapping, want one phase to be wetting (contact angles below 90°) – the non-wetting phase is trapped. Ball-shaped fluid-fluid interfaces: two approximately equal radii of curvature r_1 and r_2. $G = 1/r_1 r_2 > 0$. Trapped phases.

So what's the opposite? Two approximately ***equal and opposite*** curvatures: $r_1 = - r_2$. The mixed-wet state, with pinned contacts.



Minimal surfaces

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.

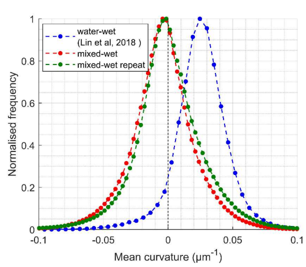
Minimal surfaces are found in equilibrium when the three-phase contact lines are pinned.

How can we engineer this in porous materials?

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

Helicoid: $\tan z = x/y$

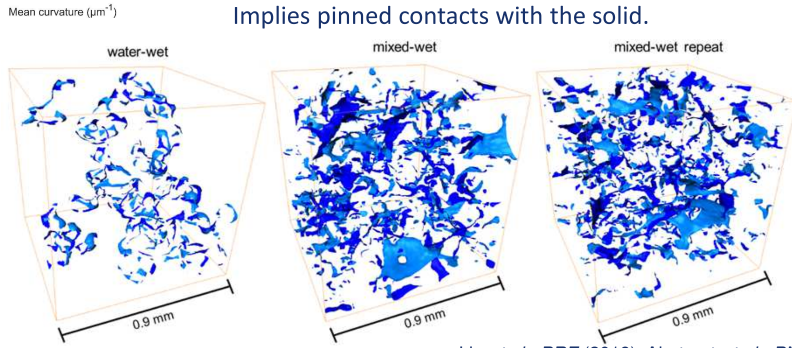
Minimal surfaces – small curvature



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)

Steady-state flow in a carbonate reservoir

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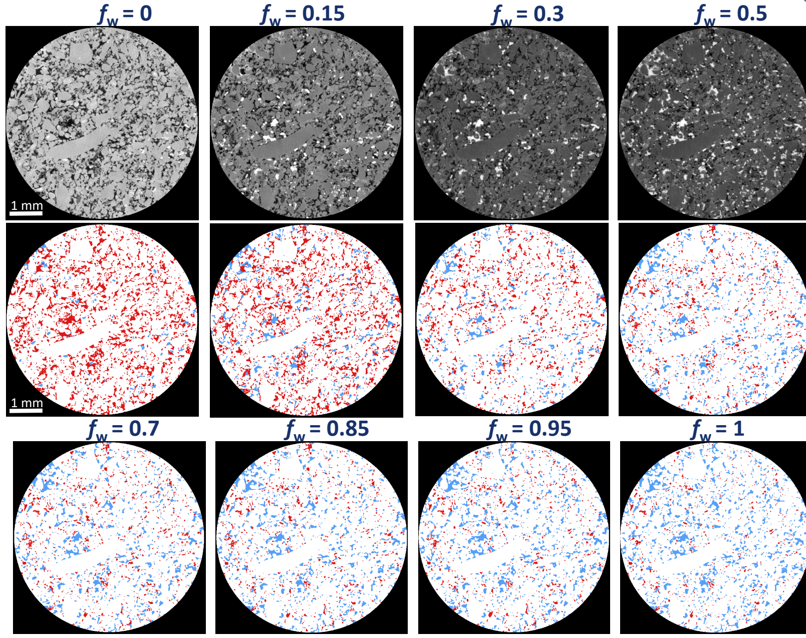
Raw

Oil
Brine
Rock

Segmented

Oil
Brine
Rock

$f_w = 0$ | $f_w = 0.15$ | $f_w = 0.3$ | $f_w = 0.5$



$f_w = 0.7$ | $f_w = 0.85$ | $f_w = 0.95$ | $f_w = 1$

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Brine phase configuration

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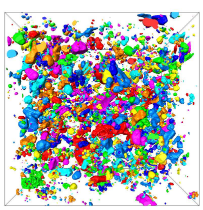
$f_w = 0.15$

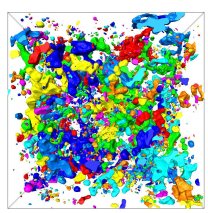
Water flows slowly close to the surface



2 mm

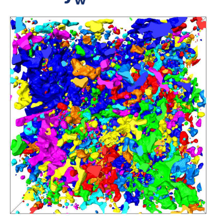
$f_w = 0.30$

Water blobs enlarge.

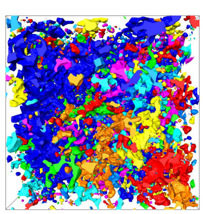


$f_w = 0.50$

Water starts to connect

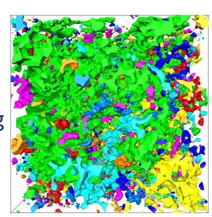


Better water connec-tivity



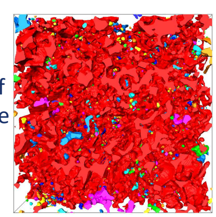
$f_w = 0.70$

Now water fills the big pores and flows



$f_w = 0.85$

Water fills most of the pore space



$f_w = 1$

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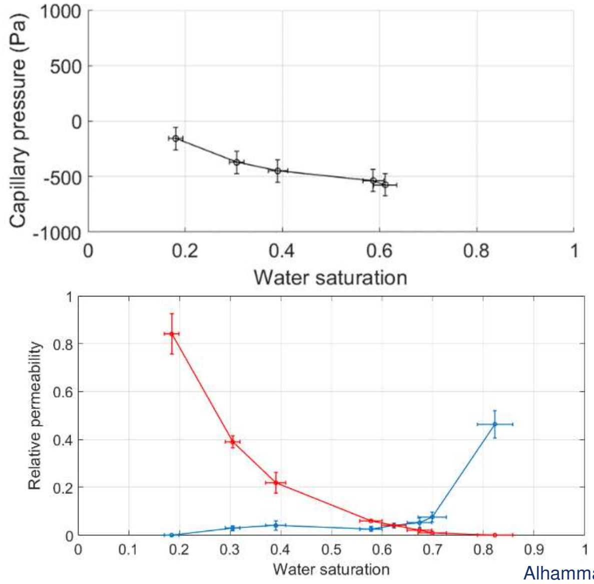
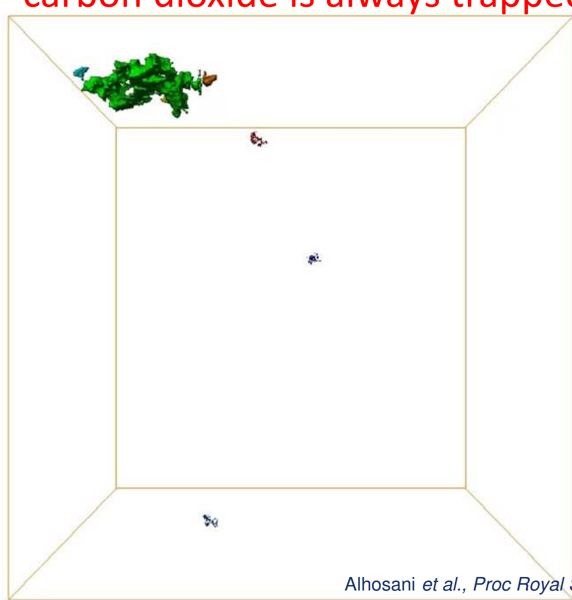
Middle Eastern reservoir sample: capillary pressure and relative permeability



Alhammadi *et al., Fuel* (2020)

Storage in oil fields: carbon dioxide is always trapped



Alhosani *et al., Proc Royal Soc. A* (2020)

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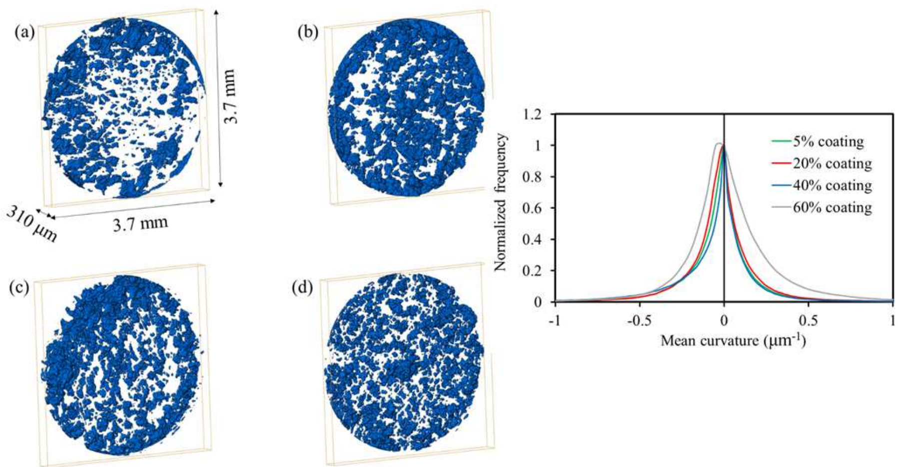
Gas diffusion layers – minimal surfaces allow simultaneous water and gas flow



Shojaei *et al.*, *ACS Applied Energy Materials* (2022)

Surgical masks and fuel cells

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

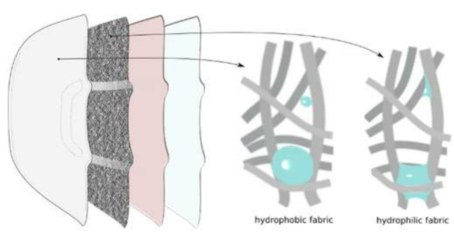
Aerosols are smaller than the pore size, so need to stick to the surface. Have a water-wet, electrically charged layer.

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?

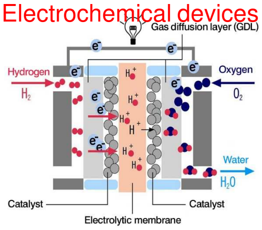


Li-ion batteries: full saturation if strongly wetting to electrolyte with no layer flow.

Electrolysers: mixed-wet or discrete water-wet and hydrophobic sections?

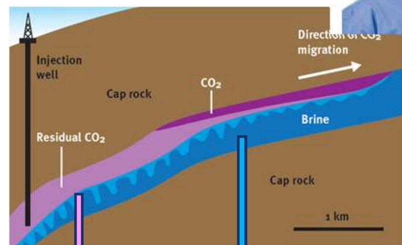
Does it matter?

Electrochemical devices

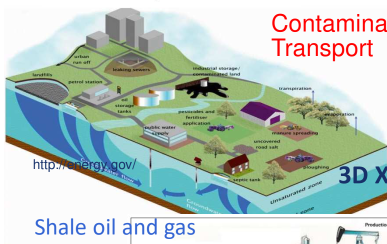


Carbon and Hydrogen Storage

/html/groundwater.html

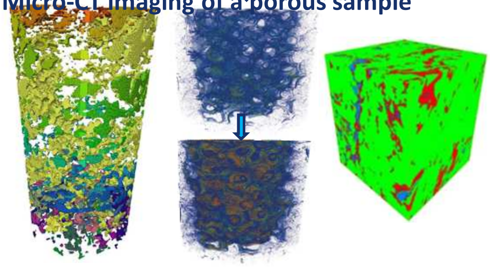


Contaminant Transport



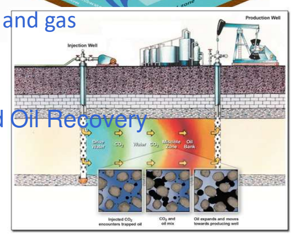
http://energy.gov/

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



Shale oil and gas

Enhanced Oil Recovery



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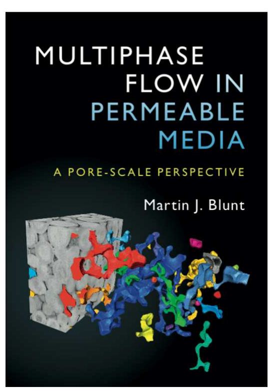

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