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Design of subsurface CO_2 storage

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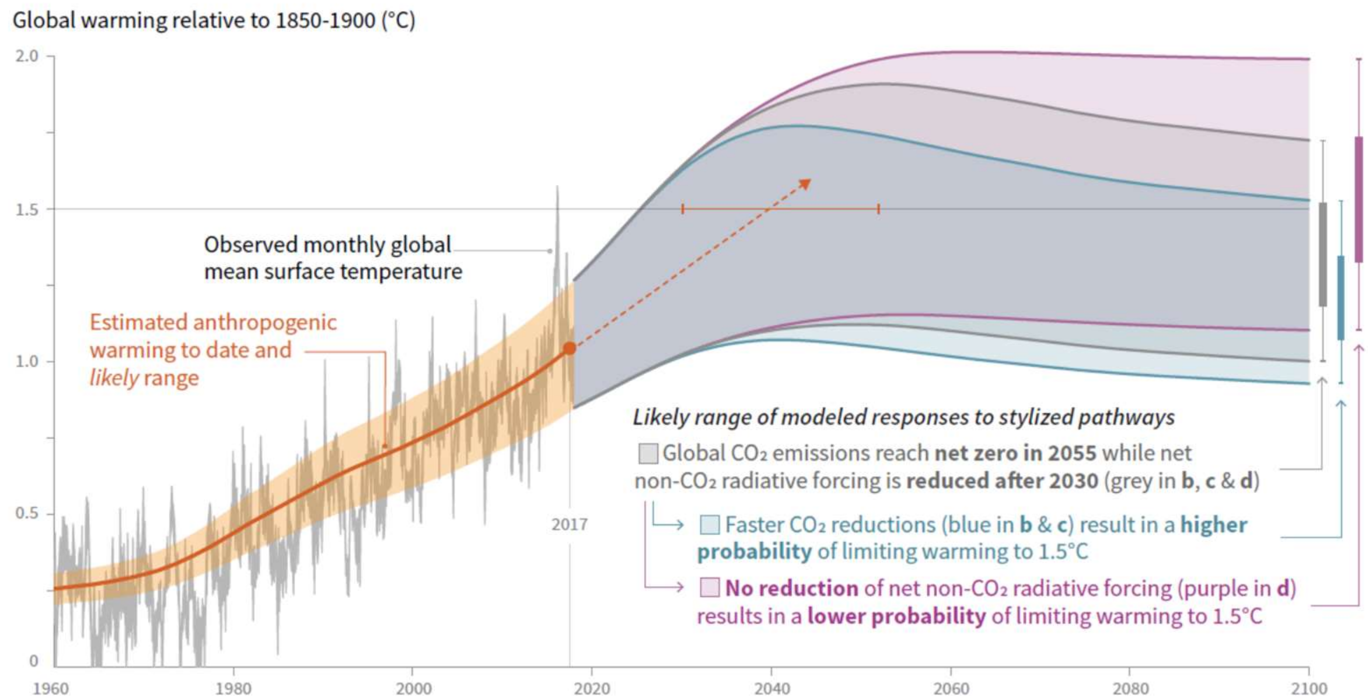
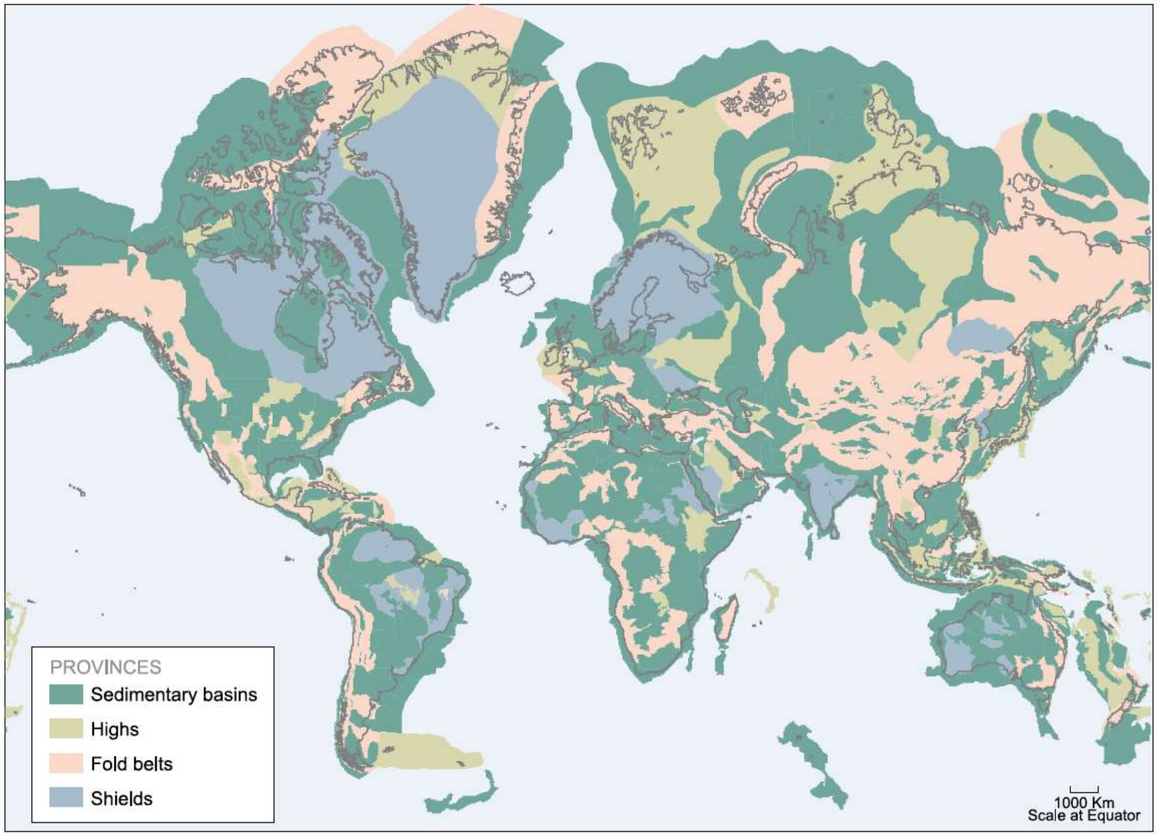
What to do with the CO_2?

IPCC Special report 2018 – limiting warming to 1.5 °C: up to 1,000Gt of CCS.



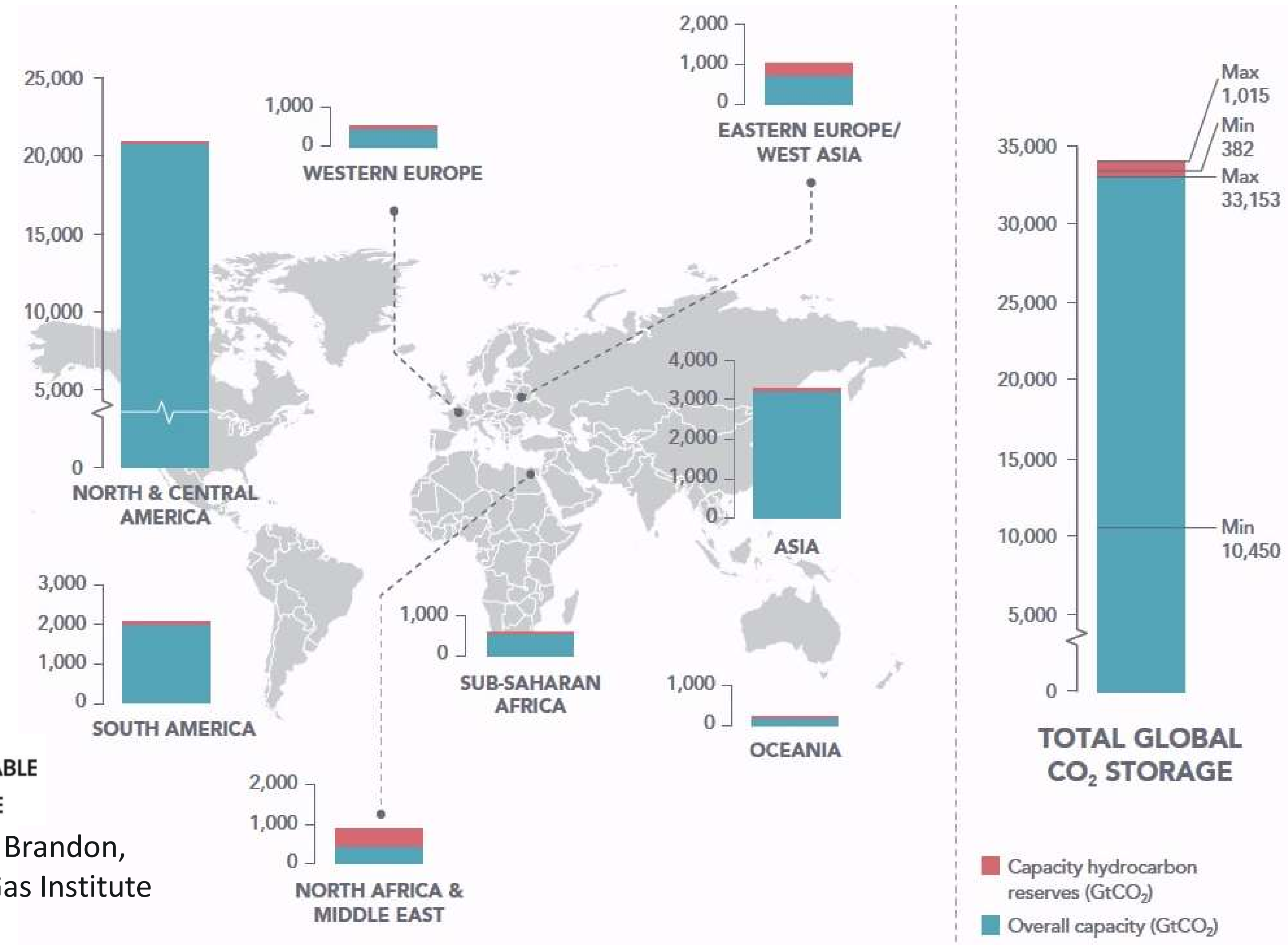
Global distribution of sedimentary basins



IPCC (2005) Special Report on Carbon Capture and Storage

Vast capacity for CO_2 storage globally

First generation of projects underpinned by up to 350 Gt capacity in oil and gas reservoirs

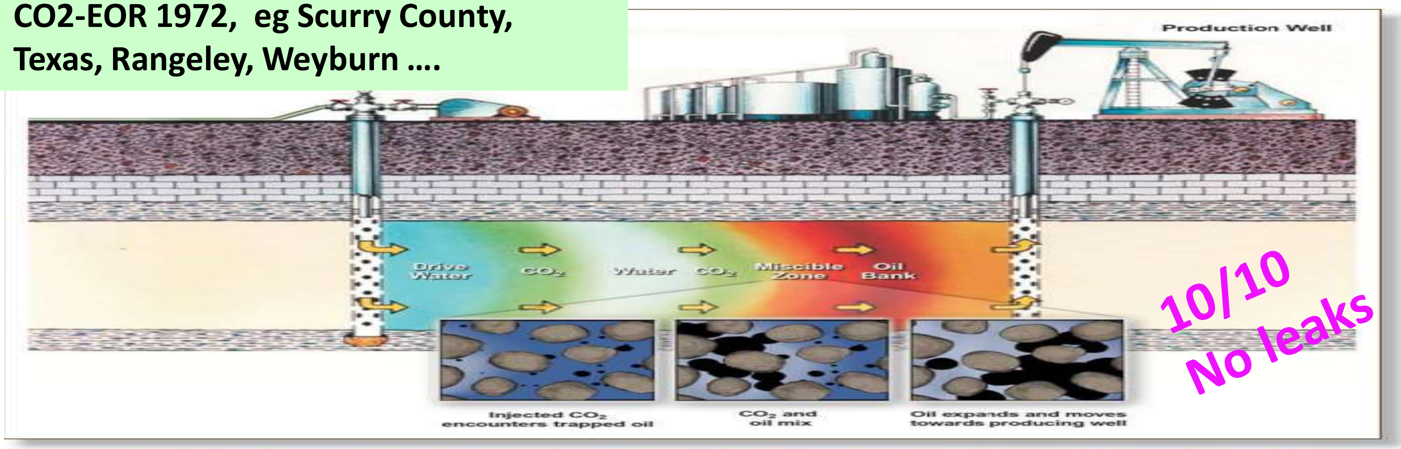


Imperial College London | SUSTAINABLE GAS INSTITUTE

Budinis, Krevor, Mac Dowell, Brandon, Hawkes (2016) Sustainable Gas Institute White Paper

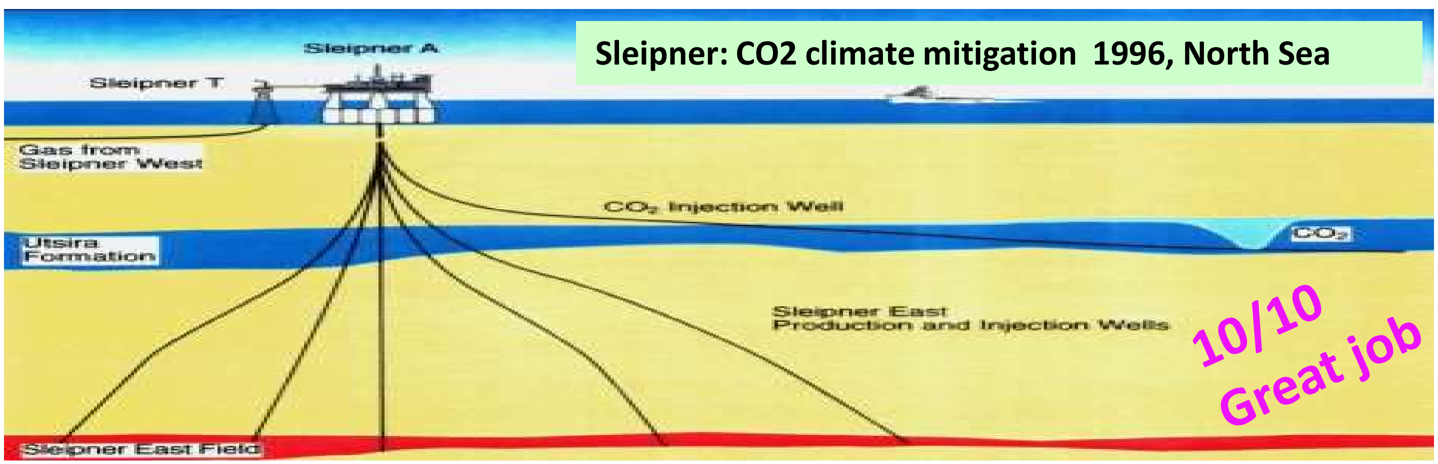
CCS exists: decades of injection & monitoring

CO2-EOR 1972, eg Scurry County, Texas, Rangeley, Weyburn ….



10/10
No leaks

Sleipner: CO2 climate mitigation 1996, North Sea



10/10
Great job

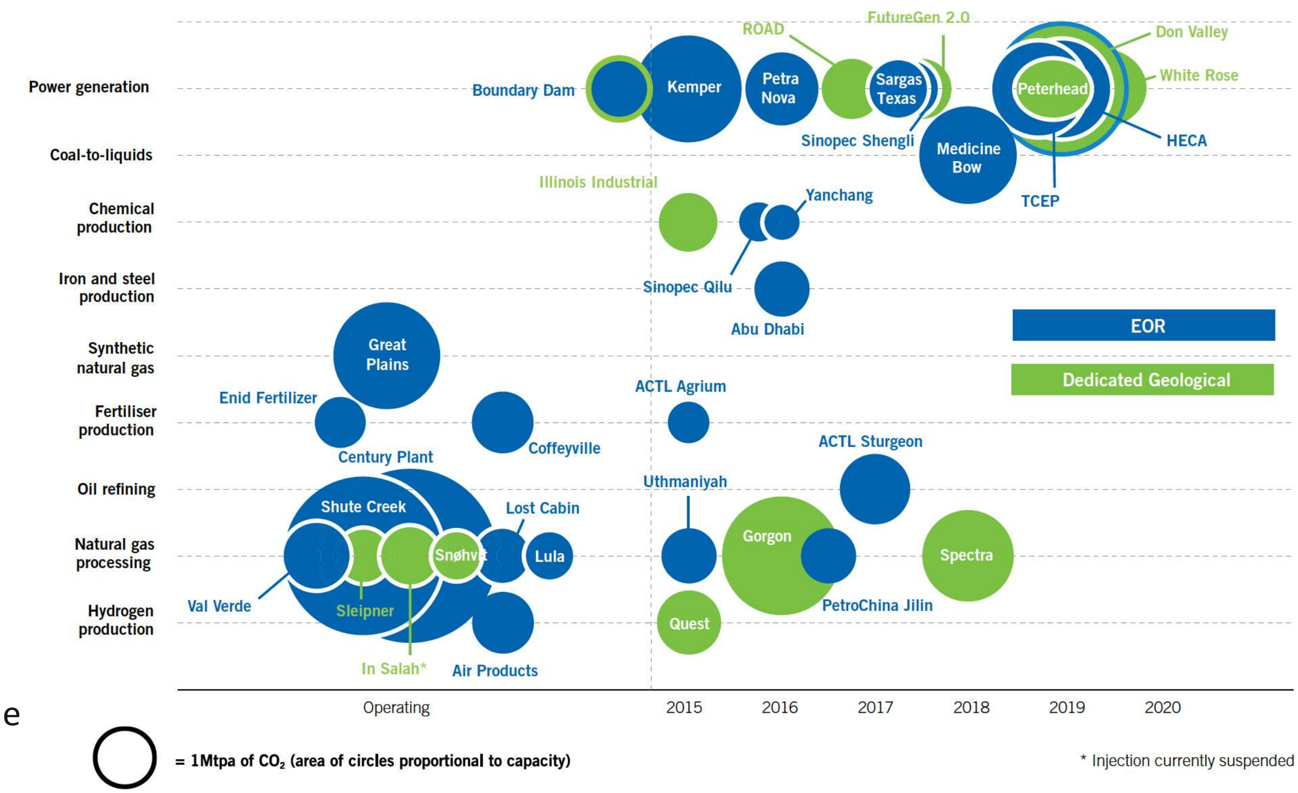
Where is CO_2 storage happening?

Injection into oil reservoirs dominates, 11 of 14 industrial scale projects

Revenue from EOR

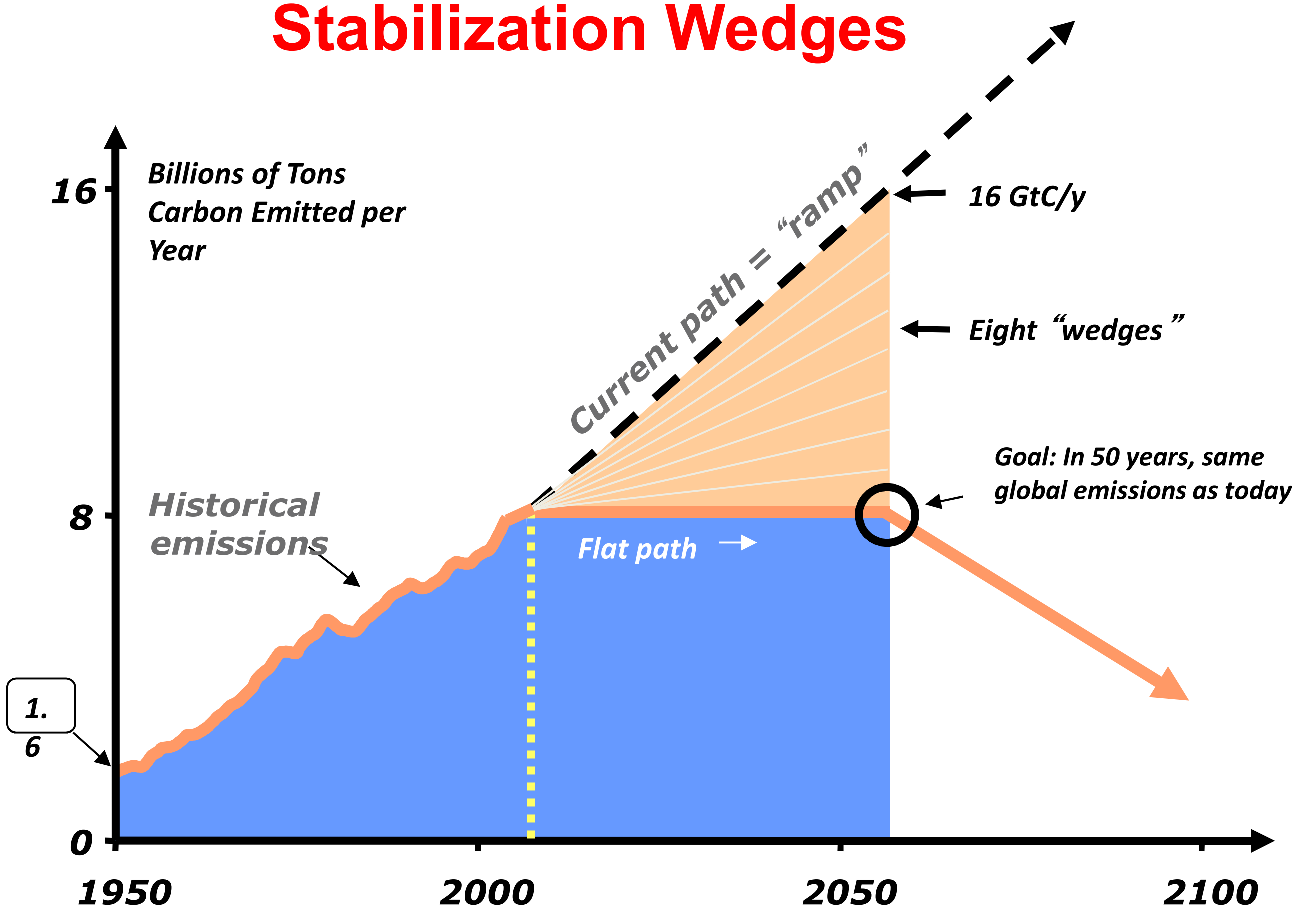
Site characterisation

Infrastructure



Global CCS Institute (2014) The global status of CCS 2014

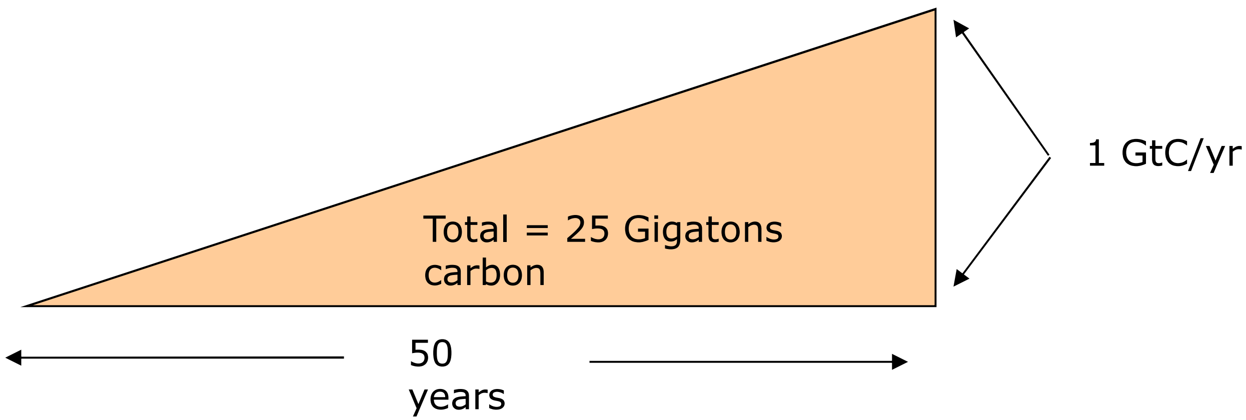
Stabilization Wedges



Carbon Mitigation Initiative, Princeton University - http://cmi.princeton.edu/about/

What is a "Wedge"?

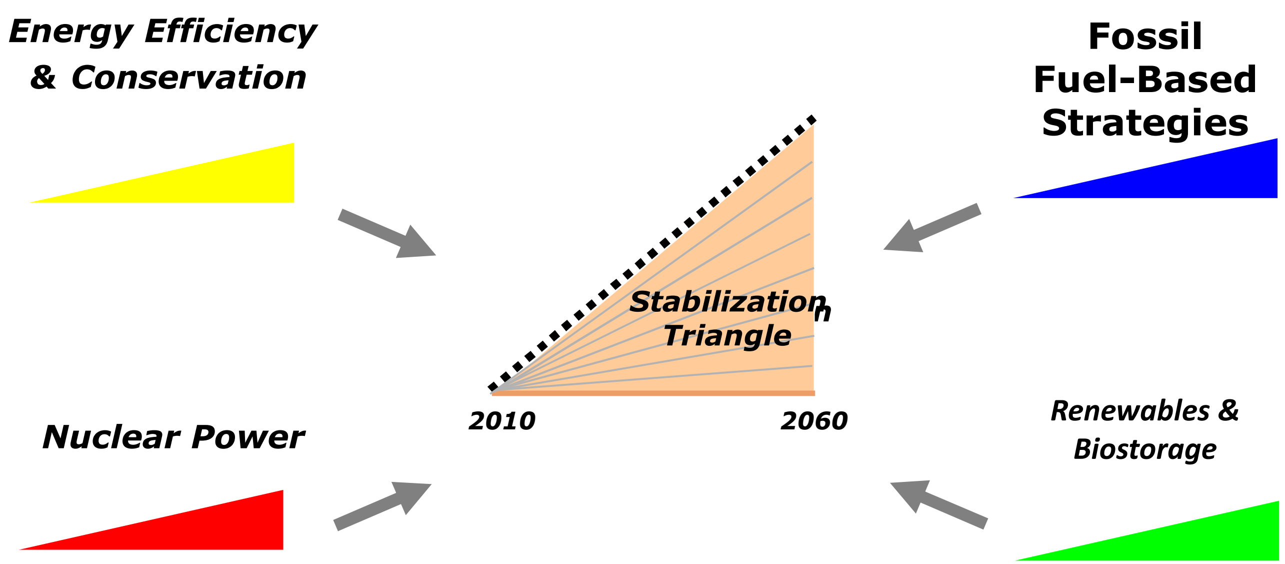
A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO_2 problem should provide at least one wedge.

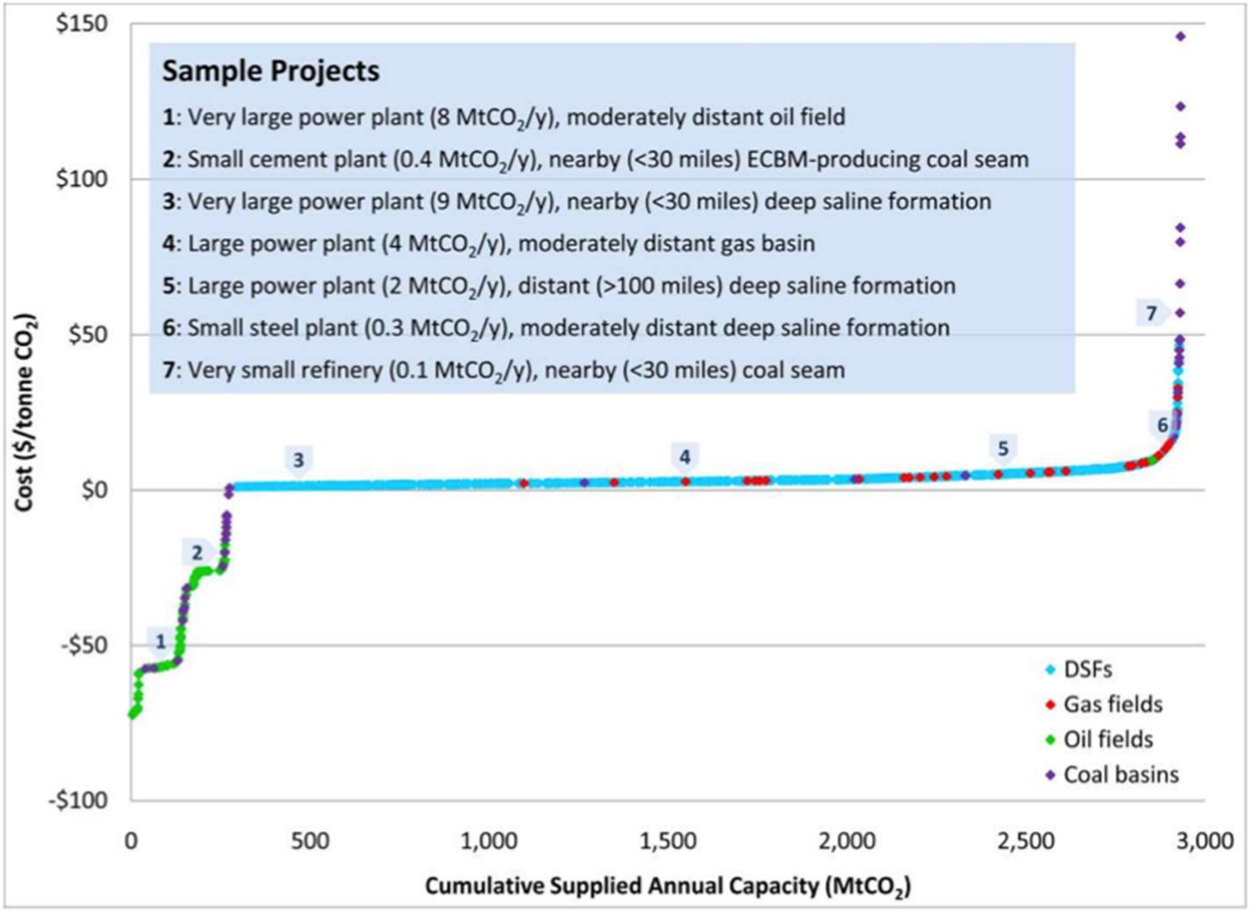
15 Wedge Strategies in 4 Categories



Carbon Mitigation Initiative, Princeton University - http://cmi.princeton.edu/about/

Costs of storage are low compared to the costs of capture

Recent estimates for the UK put costs at £11-20/tCO_2, much associated with capex for transport infrastructure



Cost supply curve of transport and storage estimated for China. From Dahowski et al. (2009) Regional Opportunities for Carbon Dioxide Capture and Storage in China, PNNL-19091

Remedy for policy: Oxburgh Report 2016

There are three failures to address

1) **Expense** : create a national CCS company, who develop the first full chain capture-transport-storage infrastructure in each region. Delivery at £85/MWhr. This company is sold to investors when proven liquid operations

2) **Wider application:** CCS is essential on power, heat, transport

3) **A firm market** for storage of CO2 is created, by means of a Certificate on all producers of fossil carbon entering the UK. That carries an Obligation to store a national percentage of CO2, starting 1%, rising to 100% mid century

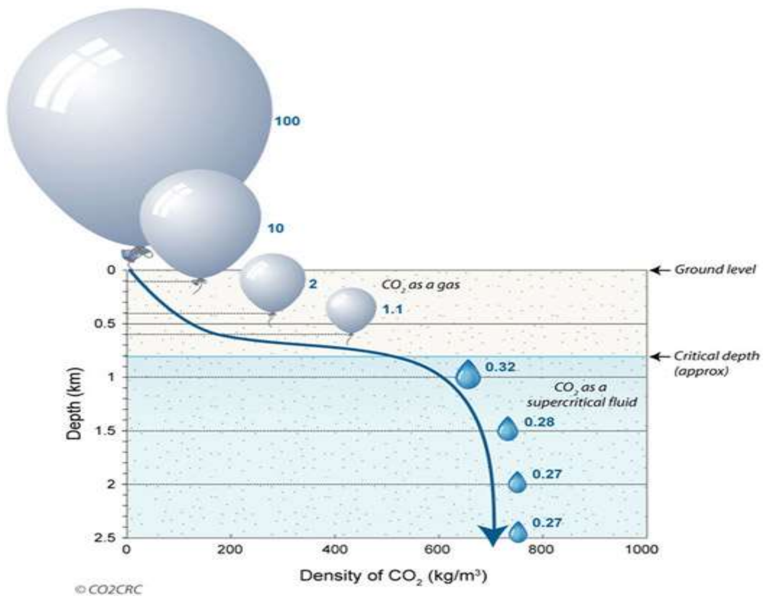
Properties of CO_2 in the subsurface and long-term fate

Critical point of CO_2 is 31^{o}C and 72 atm (7.2 MPa).

CO_2 will be injected deep underground at supercritical conditions (depths greater than around 800 m): CO_2 is relatively compressible; density less than water, similar to oil; low viscosity – around10% of that of water.

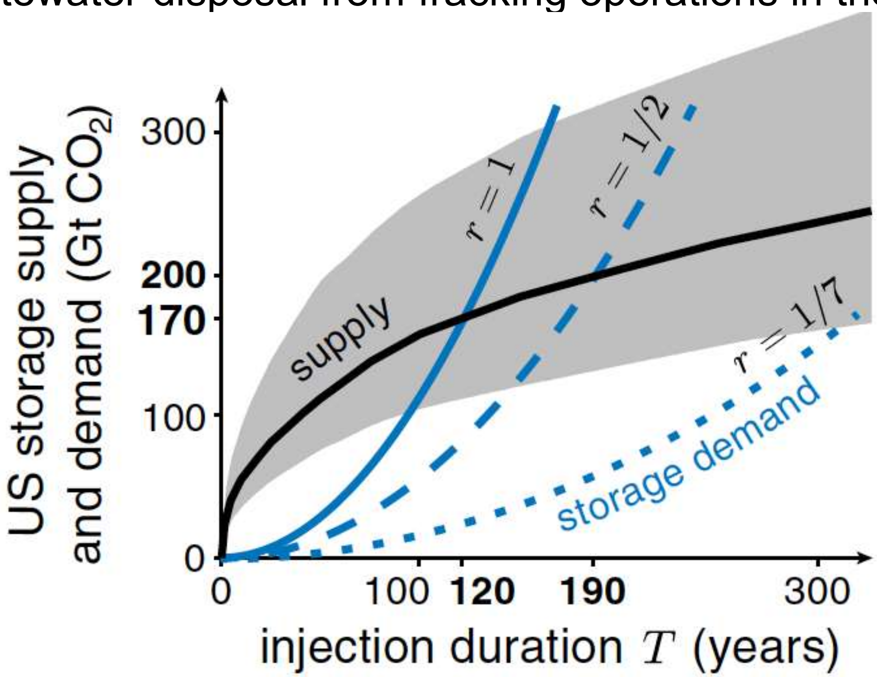
What happens on injection?

1. Pressure increase (fracturing, induced seismicity)
2. Buoyant movement (escape through caprock)
3. Capillary trapping (strands CO_2 in the pore space)
4. Dissolution (CO_2-rich brine sinks)
5. Reaction (forms solid carbonate)



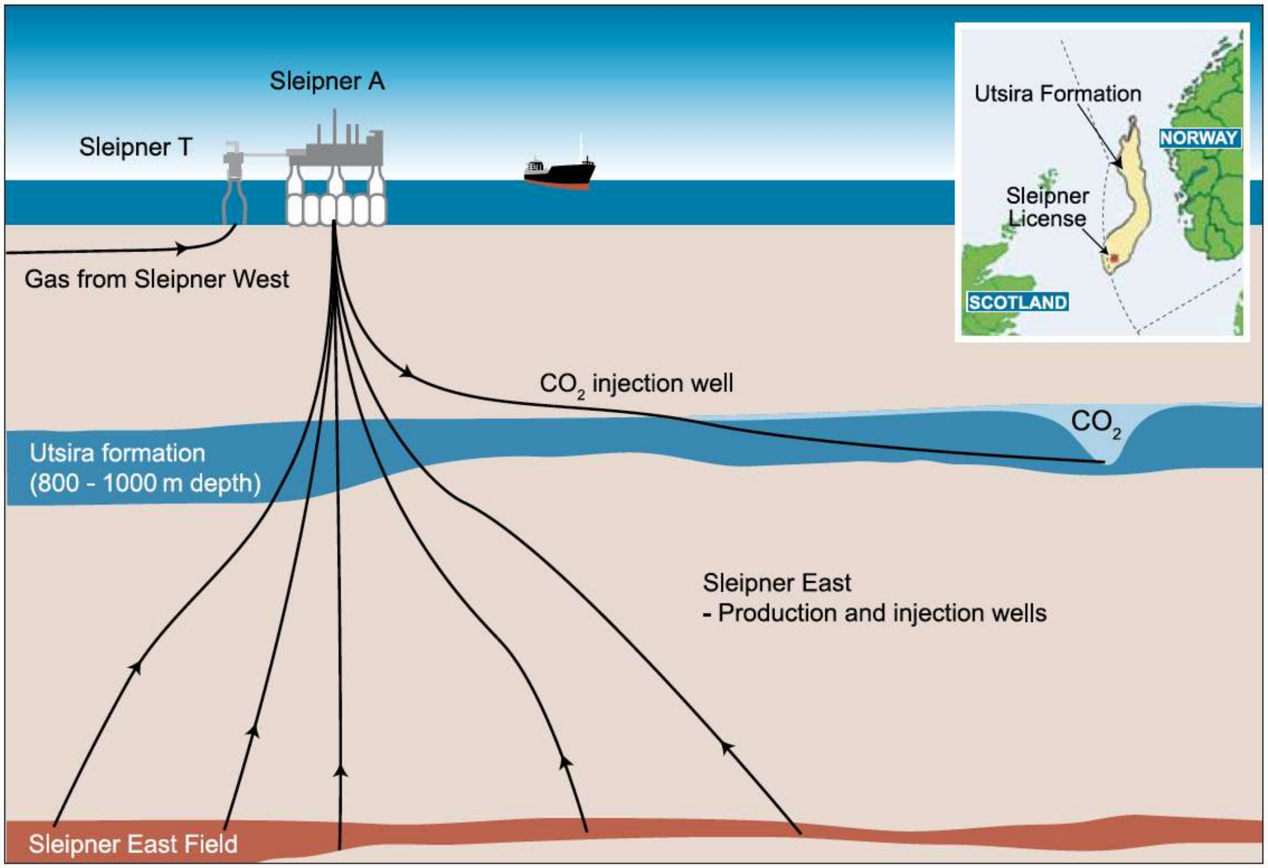
Pressure buildup limits injection rate

Pressure buildup may lead to induced seismicity: volume added to the subsurface increases pressure and can cause fault slippage. Similar problems encountered in wastewater disposal from fracking operations in the US.



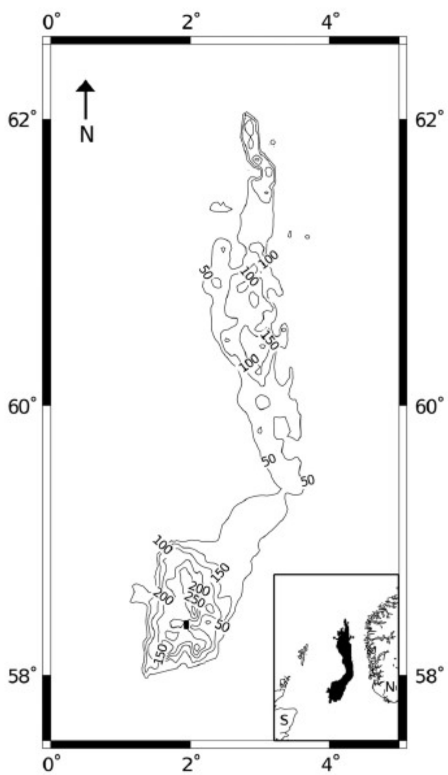
Szulczewski et al. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *PNAS.* **109**, 14, 5185-5189

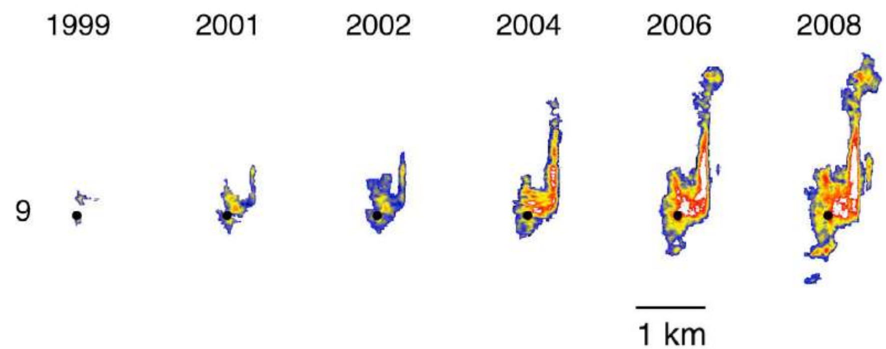
After injection buoyancy drives flow



IPCC (2005) Special Report on Carbon Capture and Storage

Observations at Sleipner – Norwegian North Sea

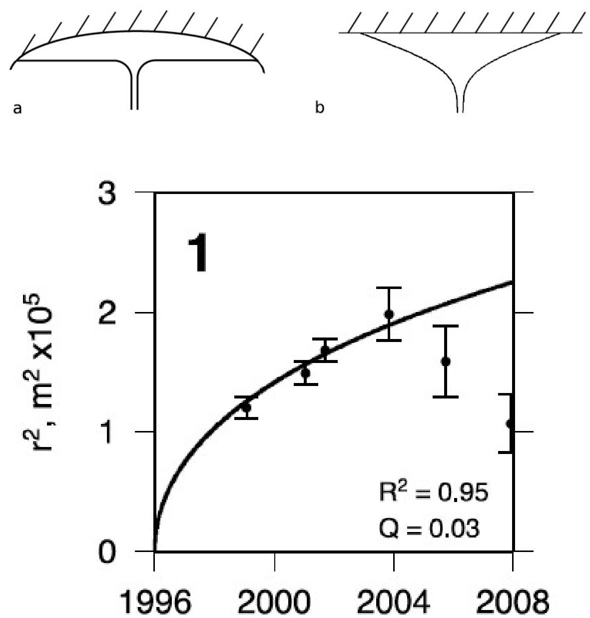


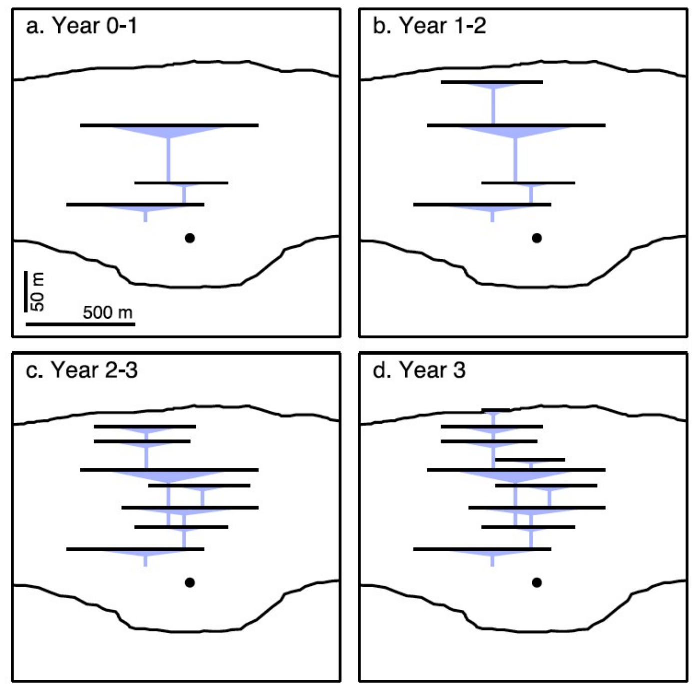


Boait et al. (2012) Spatial and temporal evolution of injected CO_2 at the Sleipner Field, North Sea. *Journal of Geophysical Research*, **117,** B03309

Simple flow processes can describe plume evolution

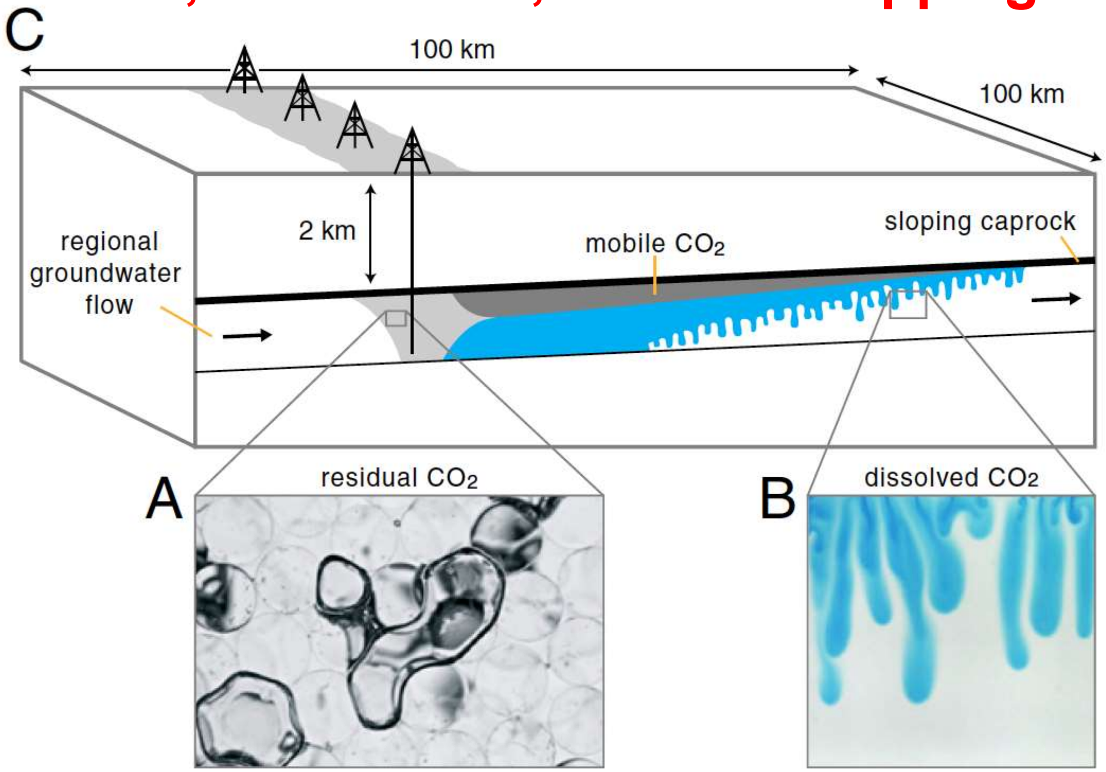
Semi-analytical models to estimate risk of migration and leakage





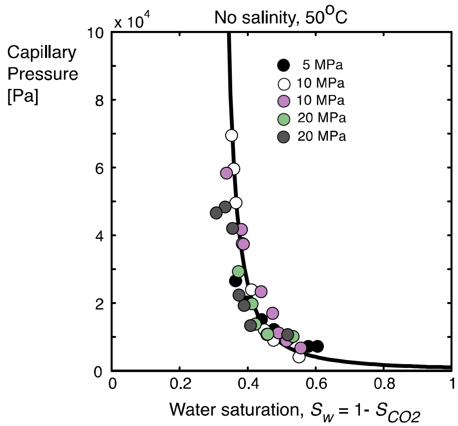
Boait et al. (2012) Spatial and temporal evolution of injected CO_2 at the Sleipner Field, North Sea. *Journal of Geophysical Research*, **117,** B03309

How does CO_2 move and how is it trapped – Structural, dissolution, residual trapping

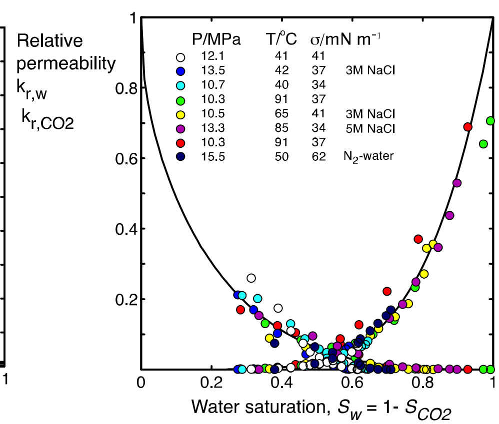


Szulczewski et al. (2012) Lifetime of carbon capture and storage as a climate-change mitigation technology. *PNAS.* **109**, 14, 5185-5189

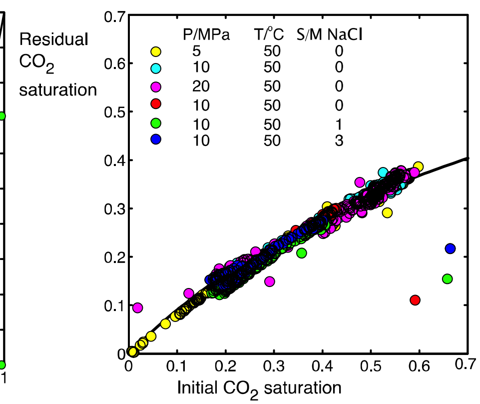
Three important flow properties



Capillary pressure:
Pressure difference between phases



Relative permeability:
How fast does it move?



Residual trapping:
Limits on movement, how much is trapped

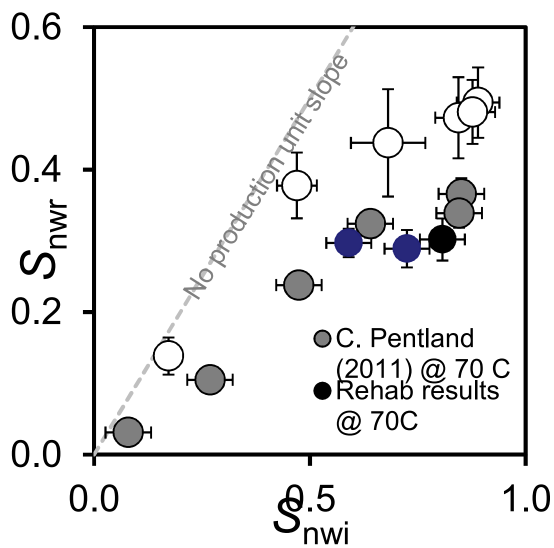
Imperial College multi-scale imaging lab

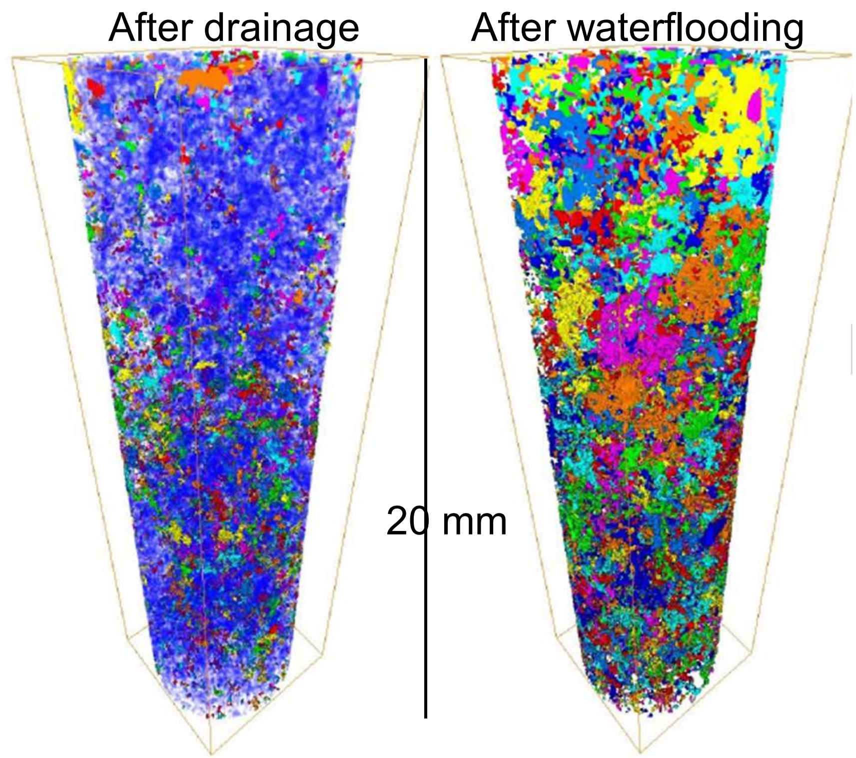
Start with the fundamentals – understand processes experimentally at the pore scale.
Micron-to-metre imaging with *in situ* displacement at reservoir conditions.

Trapped CO_2 clusters – colour indicates size

How much is trapped and how much can be stored?

Results in sandstones (Doddington, Bentheimer and Berea).



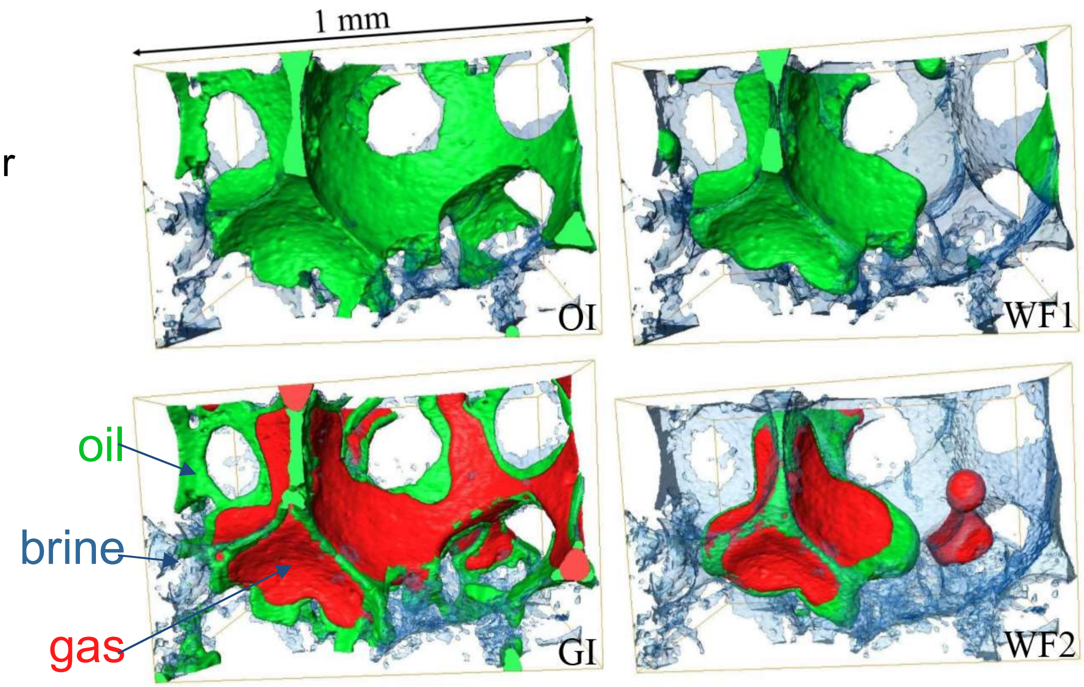


Pentland *et al., Geophysical Research Letters (*2011)
Andrew *et al., IJGGC*, (2014)

In three-phase flow see enhanced trapping

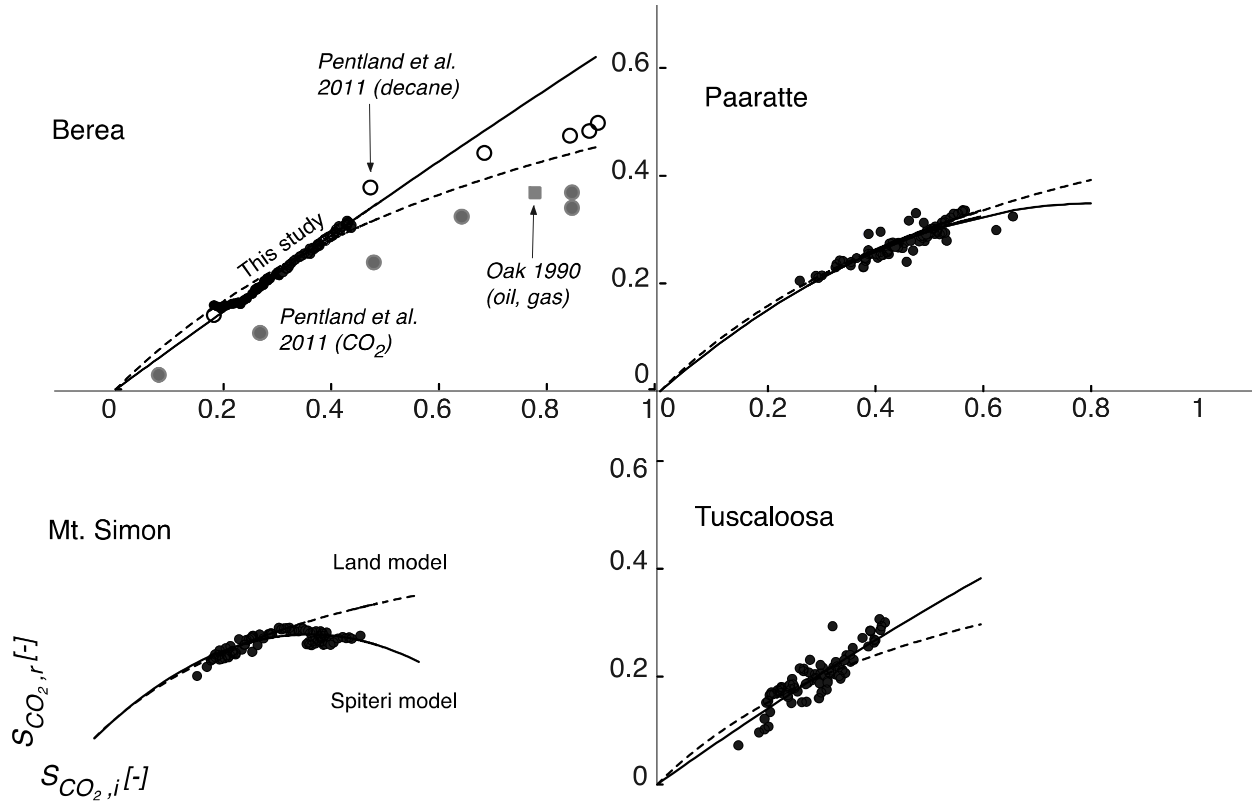
What about storage in depleted oilfields?

Here oil spreads as a layer between water and gas and enhances trapping – more storage plus additional oil recovery.



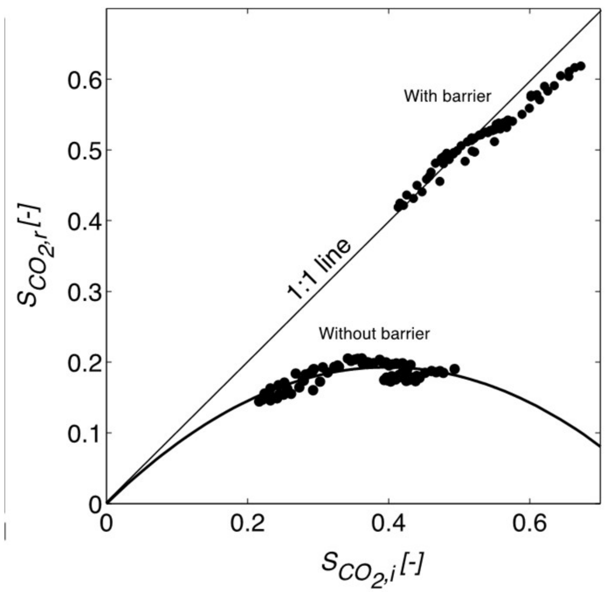
So what is the residual saturation in relation to initial?

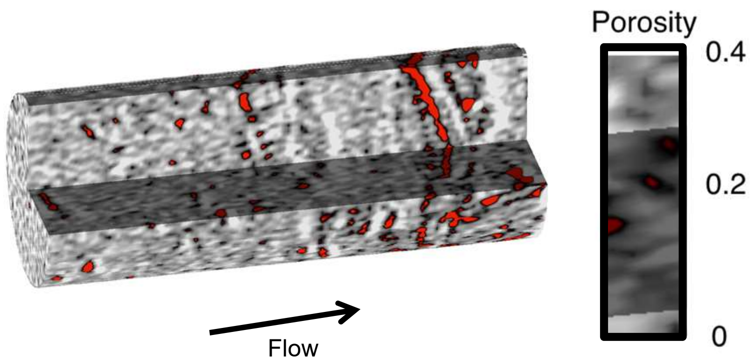
About 50% - So migration distances about two times emplacement.



Krevor et al. (2011) Relative permeability and trapping of CO2 and water in sandstone rocks at reservoir condition, *Water Resources Research* **48**, 2, W02532

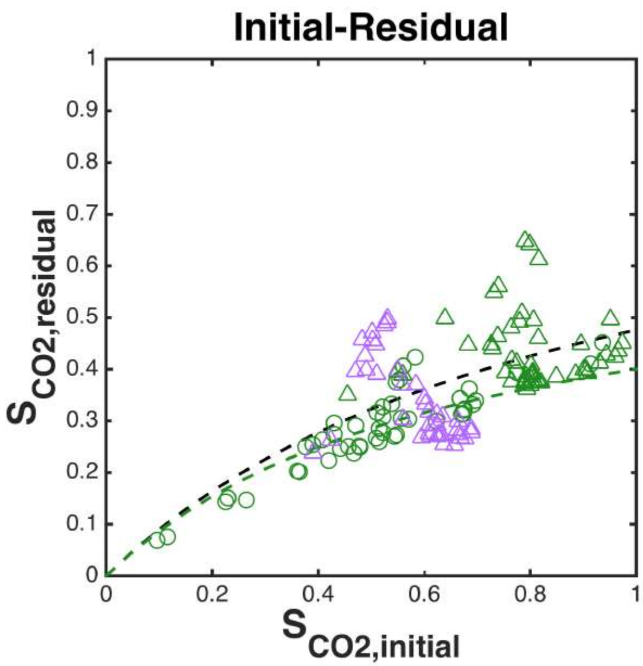
Rock heterogeneity leads to even more trapping

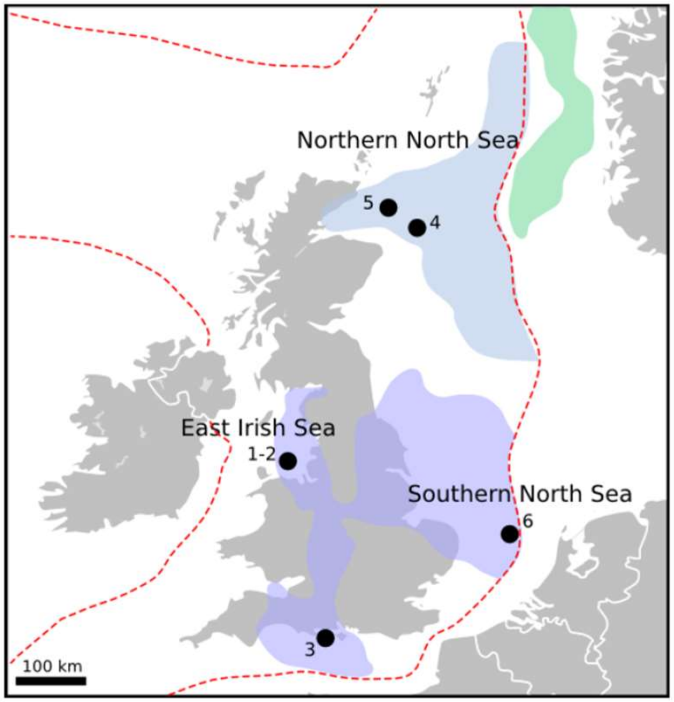




Krevor, Pini, Li, Benson (2011), Geophysical Research Letters GL048239

In UK rocks, less, but still significant trapping, around 40%



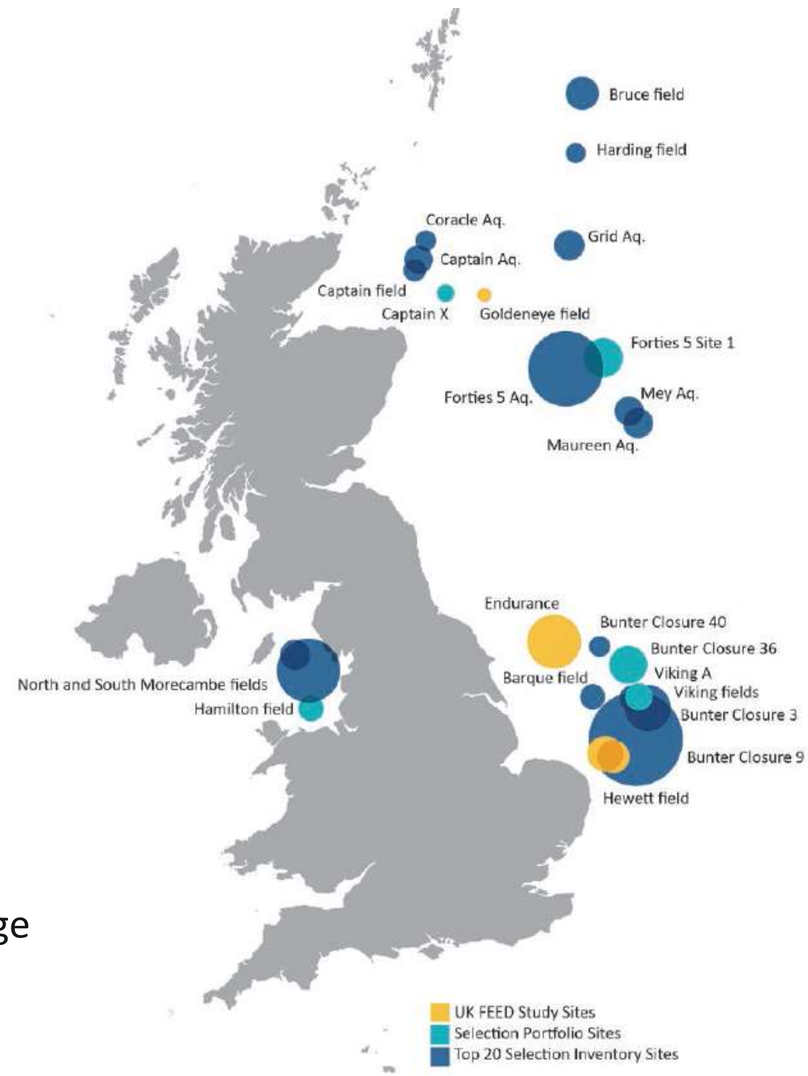


Reynolds *et al.* WRR (2018)

Where would CO_2 storage happen in the UK?

Offshore in the same areas of the North, Central, and Southern North Sea that have significant oil & gas

Total capacity of prioritised sites: 1.6 Gt CO_2

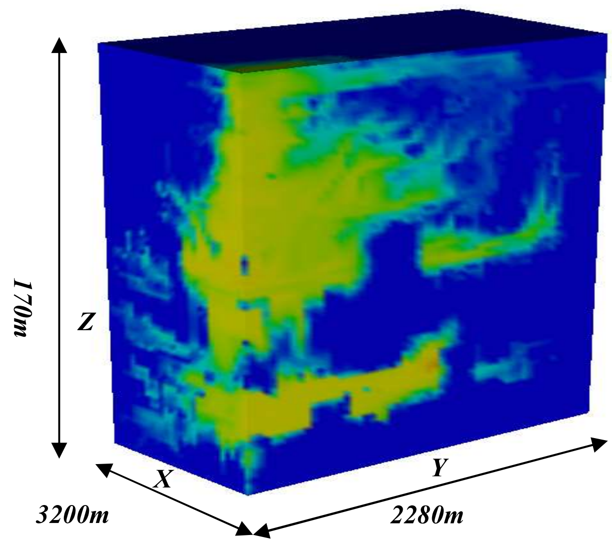


Energy Technologies Institute (2016) Progressing Development of the UK's Strategic Carbon Dioxide Storage Resource

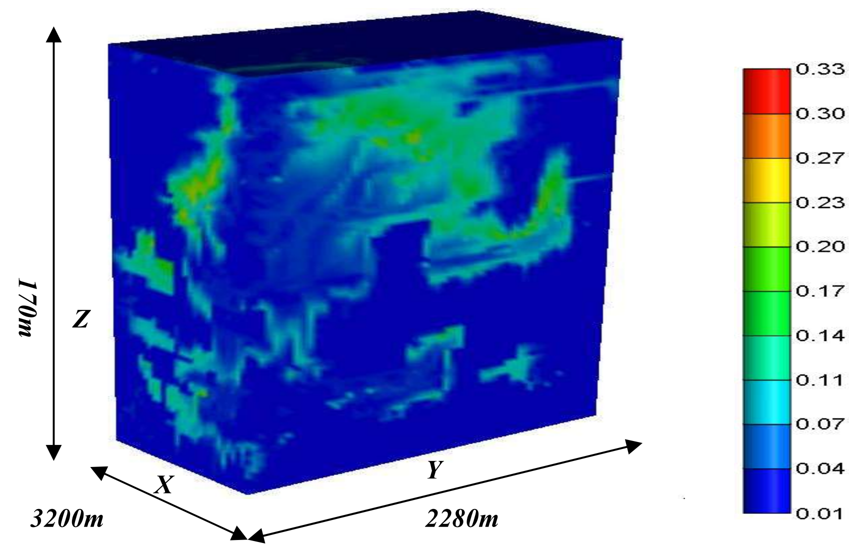
Injection design

Not passive injection/monitoring: Production wells to relieve pressure; Injection of brine to trap CO_2; Enhanced trapping in oilfields.

Shown below: 20 years of water and CO_2 injection followed by 2 years of water injection in realistic geology: 95% of CO_2 trapped after 4 years of water injection



Trapped CO_2 saturation



Mobile CO_2 saturation

Qi *et al.*, *IJGGC*, (2009)

Overall summary

- Subsurface reservoirs provide storage potential for ~10^3 Gt CO_2 worldwide, enough for several 25 Gt “wedges”
- Several physico-chemical processes work together to result in a stabilisation of subsurface CO_2 – impermeable caprocks, resistance to movement, residual trapping, dissolution into the brine.
- The movement and trapping of CO_2 is now well understood from both a physical perspective and a modelling perspective
- Field scale pilot projects have largely validated our understanding of how to predictively model CO_2 migration and trapping
- Analogue field sites demonstrate that CO_2 can remain stable in gaseous form in the subsurface for at least ~1Ma

Without CCS we are condemned to dangerous climate change.

Acknowledgements

Sam Krevor, Imperial College, and Stuart Haszeldine, Edinburgh University

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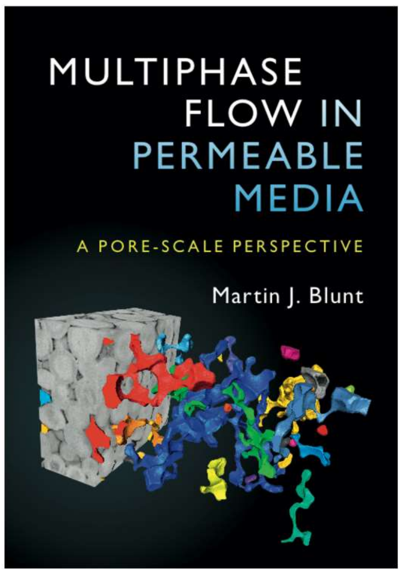
Qatar Petroleum



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