CO_2 Storage:
Project Development and Capacity estimation

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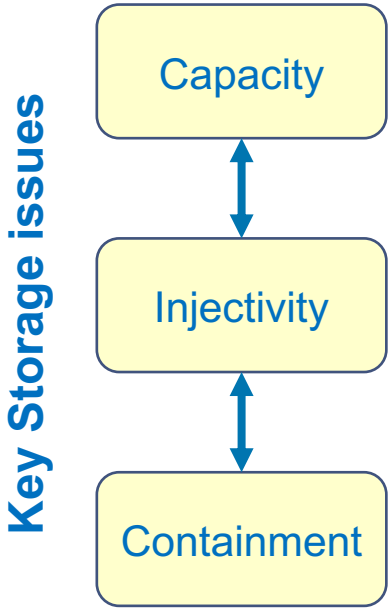
Geological Storage of CO_2

1. The basic concept is to store captured CO_2 underground in reservoirs that would otherwise contain water, oil or gas
2. We need to be deep (greater than 800m) to ensure CO_2 is in a dense form – the super-critical phase
3. These are also the depths where we are confident that natural gas has been trapped for millions of years
4. But the big questions are:
   - Where do we store it?
   - How much CO_2 can we inject?
   - Can we store it safely?
   - Can we store it cost-effectively?

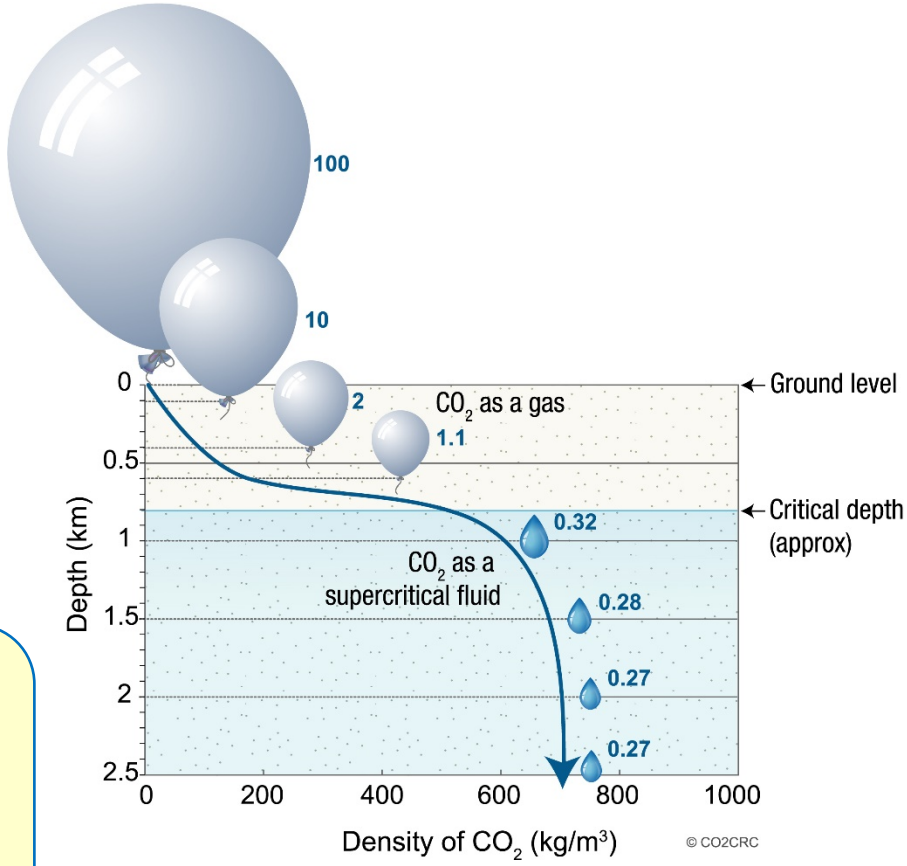


CO_2 at depth

- CO_2 is stored at depths >800m to ensure that CO_2 is in a dense form
- This is also important for storage security, because storage seals become more effective with depth
- CO_2 properties are highly variable, f(P,T)

At standard conditions (ISA) (1.013 Bar & 15°C)

- 1 m^3 of CO_2 has a mass of 1.87 kg
- 1bscf = 28.32 x10^6 m^3
- Mass of 1Bscf = 52959.5 kg (or 53 Tonnes)
- Mass of 1MMscf = 52.96 kg
- So a single well injecting 20 MMscf per day is injecting about 1 tonne of CO_2 per day

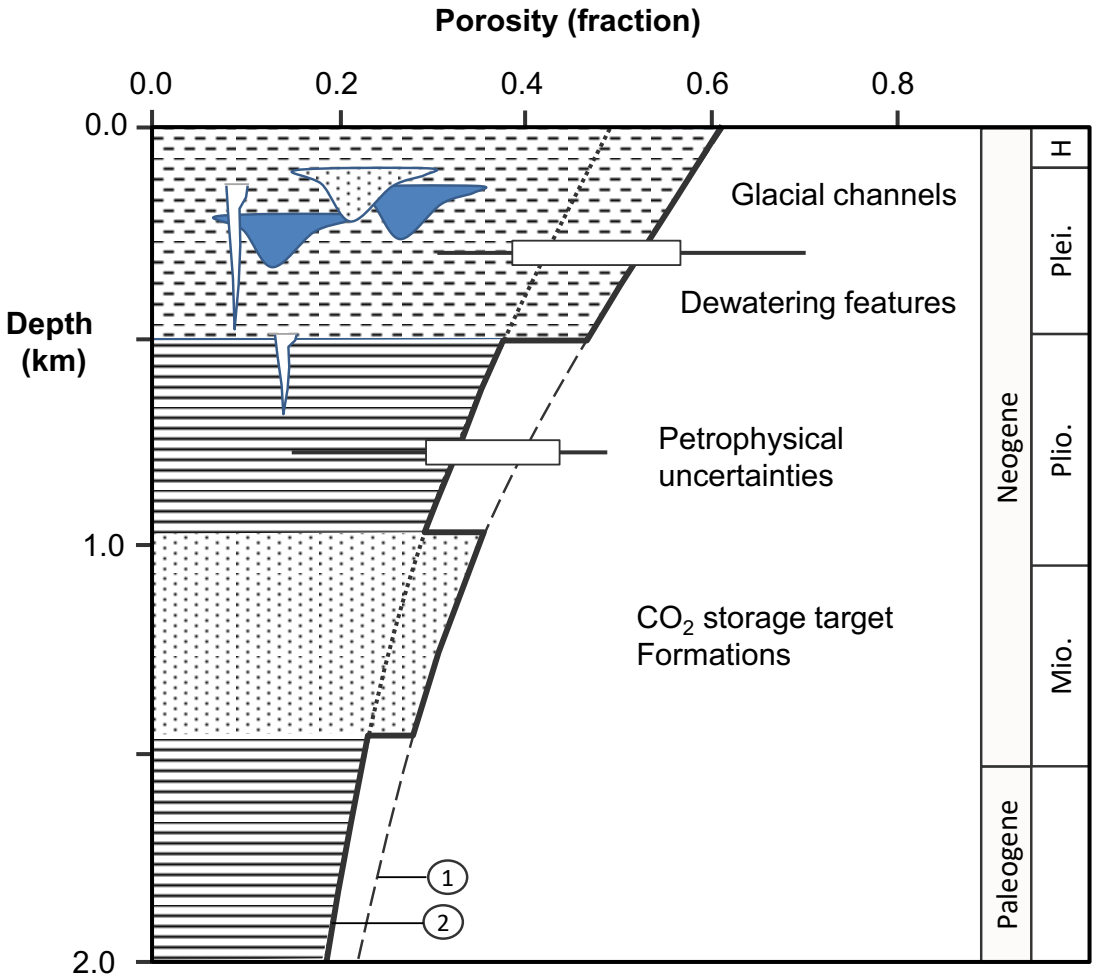


Simplified CO_2 density versus depth diagram (from CO2CRC)

NB. Gas engineers tend to work in standard cubic feet (scf) while CO_2 projects prefer to report mass

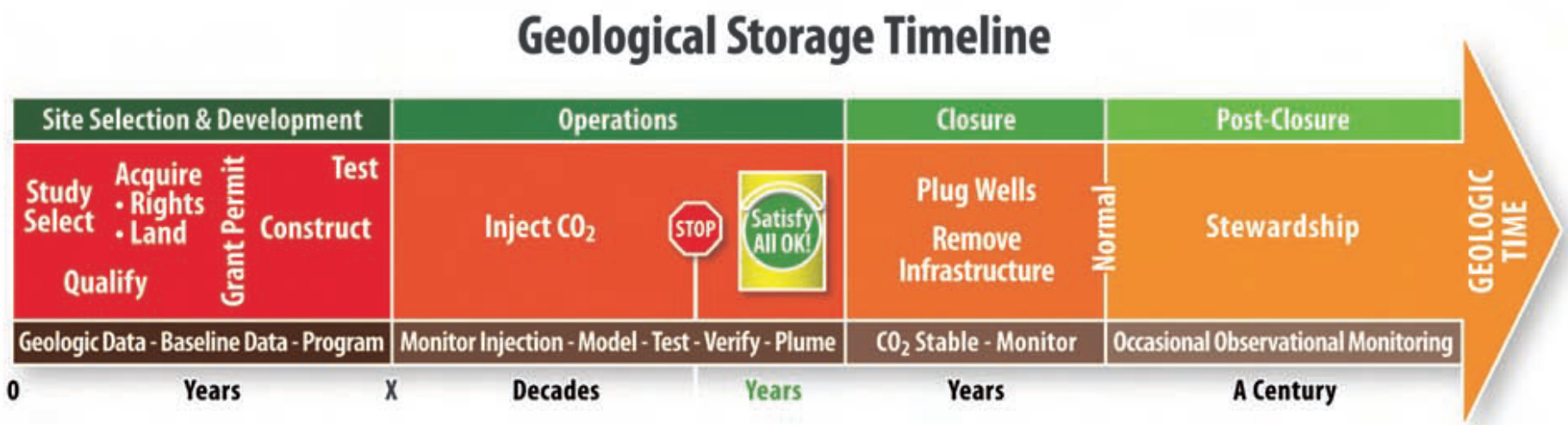
Rock properties versus depth

- Conceptual sketch showing a shallow stratigraphic sequence representative of the North Sea basin.
- Typically a Miocene CO_2 storage target formations could be capped by a Pliocene mudstone sequences forming the main containment system.
- The role of shallow glacial channel and dewatering features in the Pleistocene may be a key issue for assuring storage containment.
- Reference porosity curves are shown based on (1) Sclater & Christie, 1980, and (2) Marcussen et al., 2010.
- The actual porosity and permeability of the shallow basin sequence is variable and uncertain and needs to be determined via site investigation



Overall time-line for CO_2 Storage Projects

1. Site Selection
2. Storage Operation
3. Site Closure
4. Post-closure Stewardship



(from CO_2 Capture Project http://www.CO2captureproject.org/ Cooper et al., 2009)

Containment

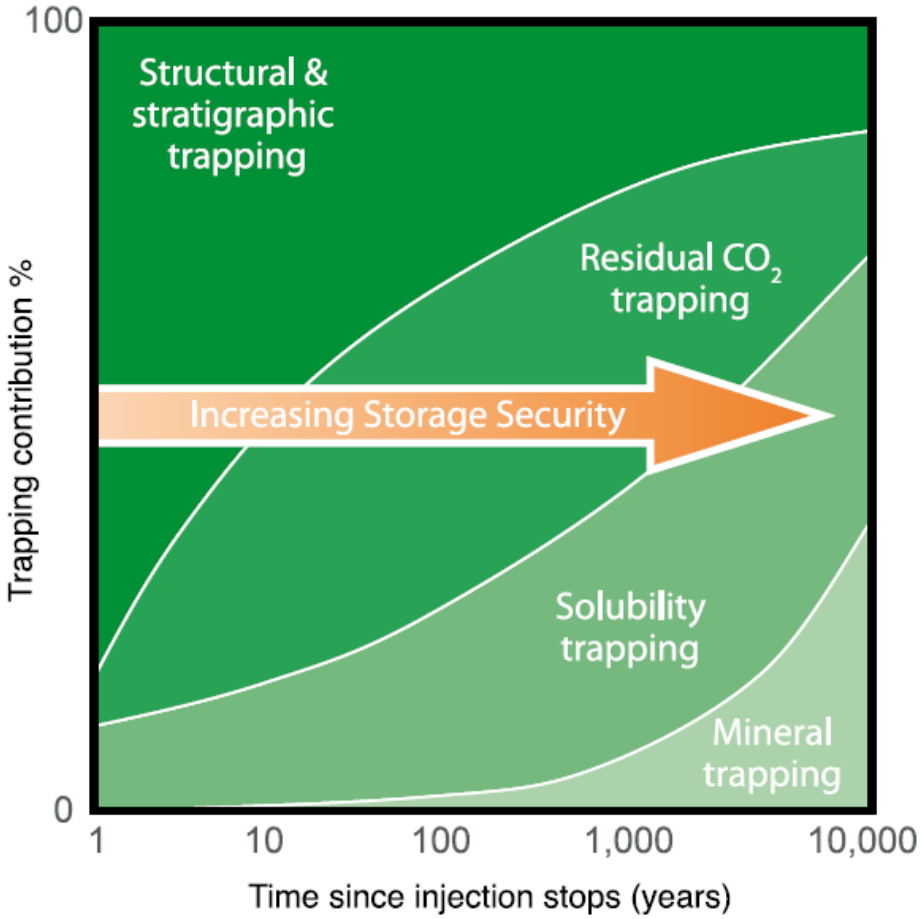
Trapping mechanisms involve both physical and geochemical factors:

- Physical trapping mechanisms related to basin-scale processes:
  - regional structure, basin history and pressure regimes
- Physical trapping mechanisms related to geometry of traps:
  - controlled by rock architecture of the storage complex
- Physical trapping mechanisms related to fluid flow processes:
  - Capillary interfaces between fluids
  - Retention of CO_2 as a residual phase
- Geochemical trapping mechanisms:
  - CO_2 dissolution in brine
  - CO_2 precipitation as mineral phases
  - CO_2 sorption/absorption (e.g. on clay minerals)

Structural and Stratigraphic trapping

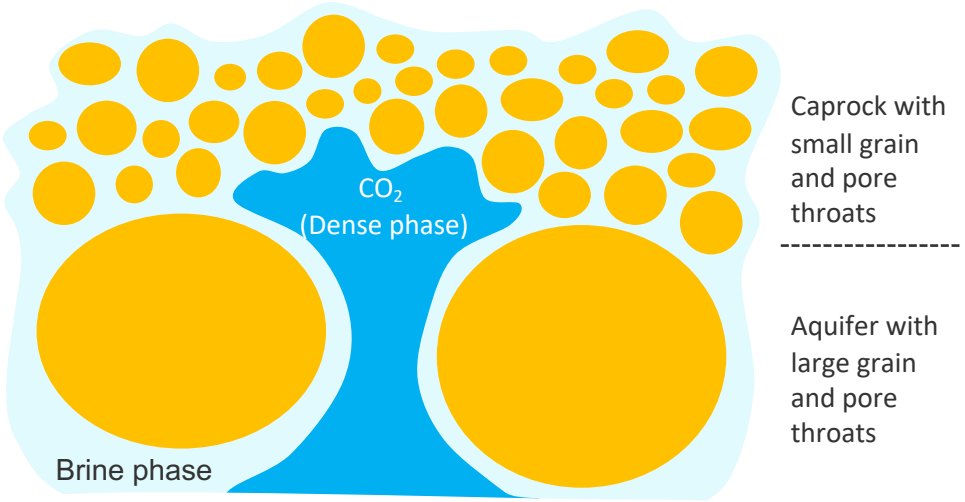
Increasing storage security over time

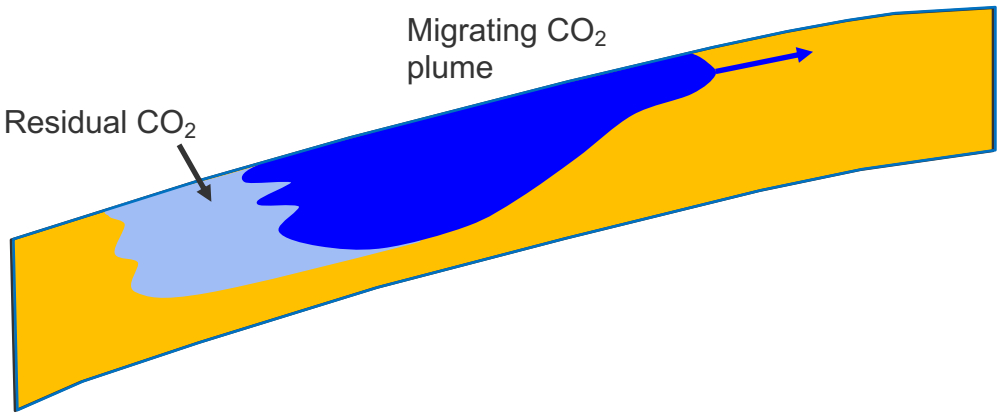
- The IPCC special report (Metz et al. 2005) argued that the various CO_2 trapping mechanisms would work over time to increase storage security in the long term:
    1. Structural and stratigraphic trapping
    2. Residual CO_2 trapping
    3. Solubility trapping
    4. Mineral trapping
- Longer term processes – residual solubility and mineral trapping – would gradually work to "fix" CO_2 permanently in the subsurface



Capillary forces and CO_2 trapping

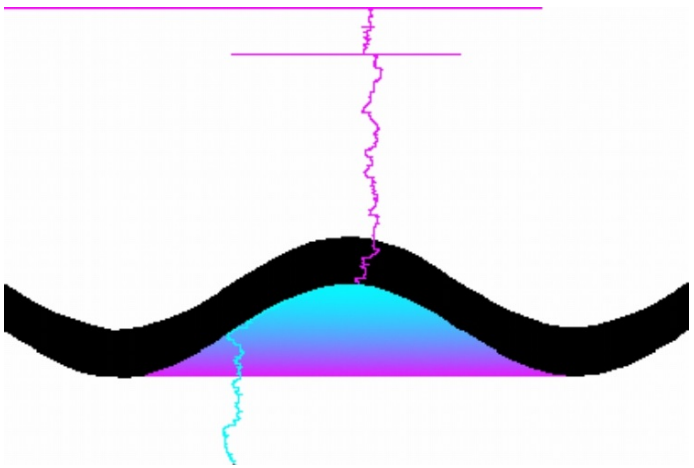
- Capillary forces (interfacial tension) play an important role in trapping of CO_2:
  - Both at the caprock interface (structural trapping)
  - And as residual CO_2 (as the plume migrates upwards)





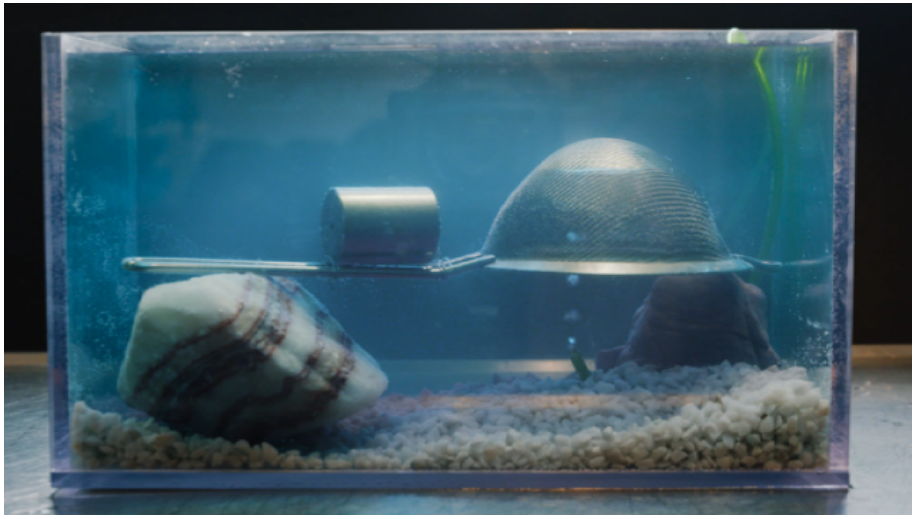
Capillary seals

- The (molecular-scale) capillary force provides the essential and fundamental seal
- A seal will only leak if $P_{fluid} > P_{threshold}$
- The key questions are therefore:
  - the capillary pressure functions for the seal
  - Possible weak points (e.g. faults)



Invasion percolation simulation of trap filled so that fluid buoyancy pressure to exceeds $P_{threshold}$

Laboratory tank demonstration of capillary seal using air and food sieve

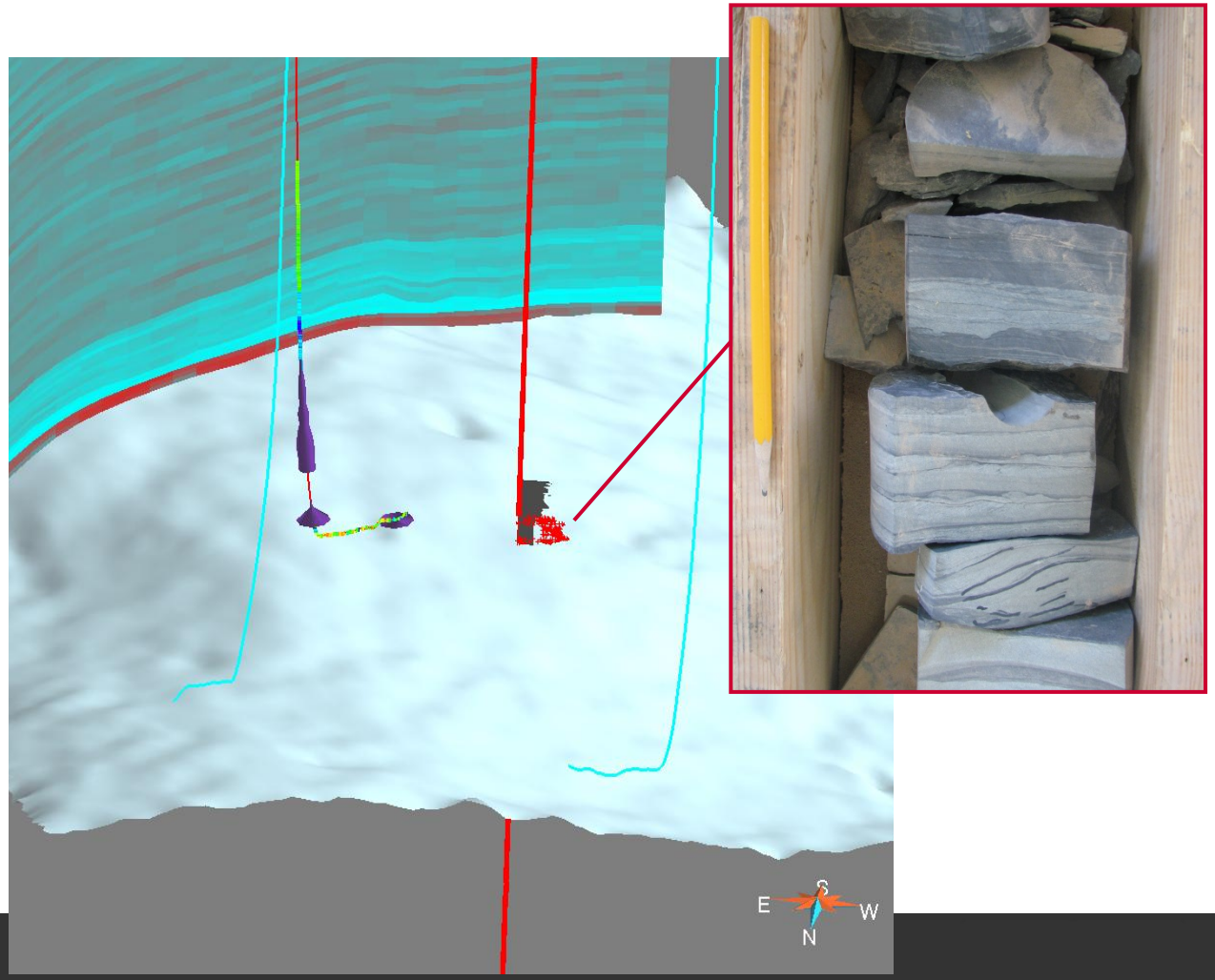


https://www.youtube.com/watch?v=8-dXwakvmsI

Site Characterisation

Illustration site characterization work at the In Salah CO_2 storage site.

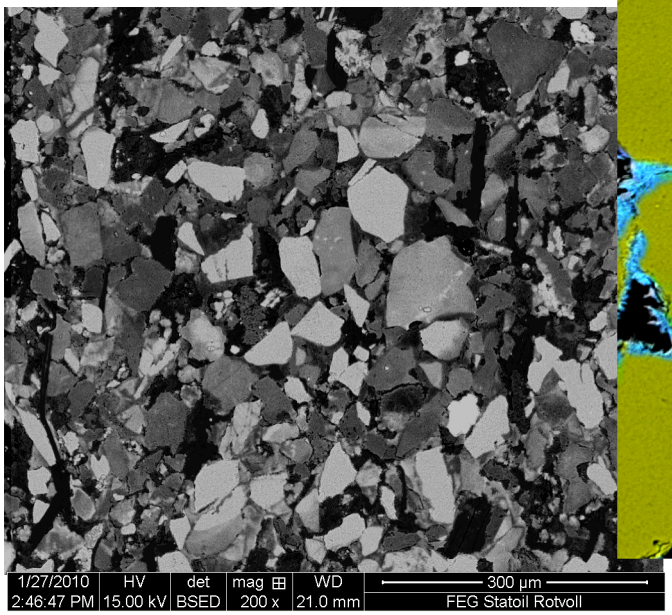
- CO_2 injection wells (blue)
- Appraisal wells with porosity (red), caliper (grey), gamma (color) logs, pre-injection CO_2 gas distribution (purple)
- Core samples (insert)
- Section shows reservoir and caprock porosity (estimated from seismic and well data).
- Surface shows base reservoir mapped from seismic data.
- Courtesy of the In Salah CO_2 Project (Cooper, 2009)



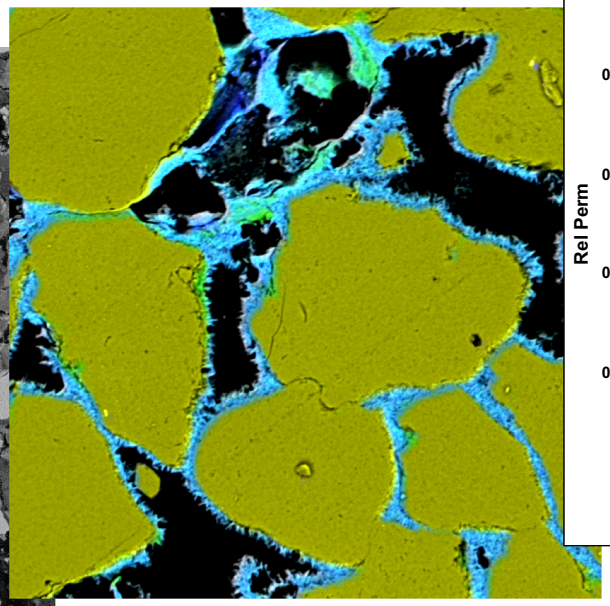
Pore-space Characterisation

- Core analysis, thin section, backscatter scanning electron microscopy (BSEM) mineralogical studies and pore-scale modelling are used to map the pore-space
- Examples from Lopez et al 2011

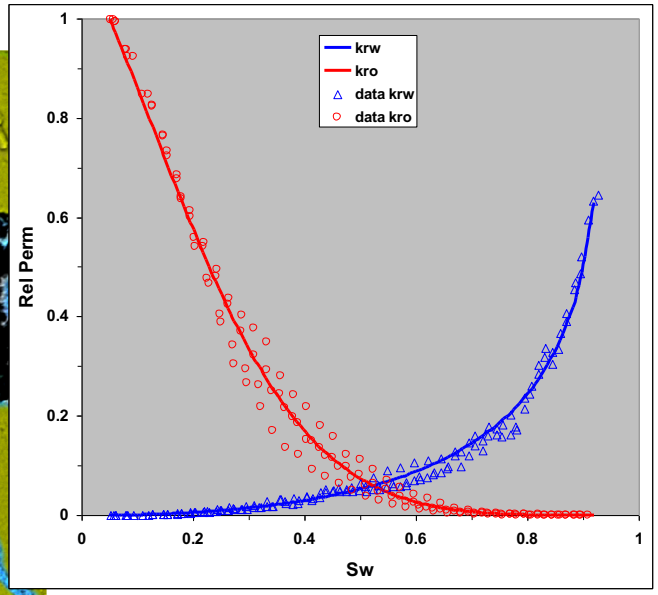
Grain characterisation
(cathodoluminescence)



Mineral identification
(BSEM)



Pore Network Modelling



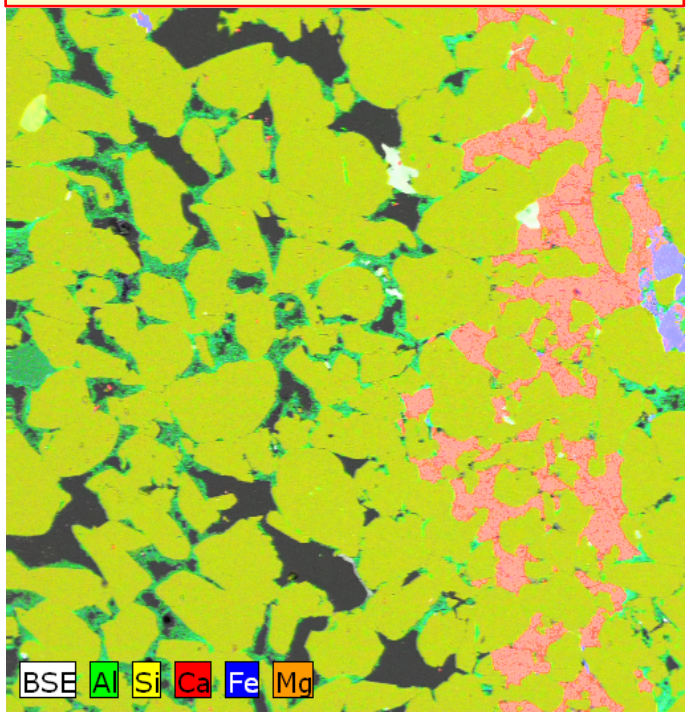
Geochemical Processes

Two main processes concerning the CO_2-minerals reactions in the pore space:

1. CO_2 can precipitate as carbonate minerals (such as calcite and ankerite)
2. CO_2 sorption or adsorption on clay minerals

SEM image of sample from In Salah:

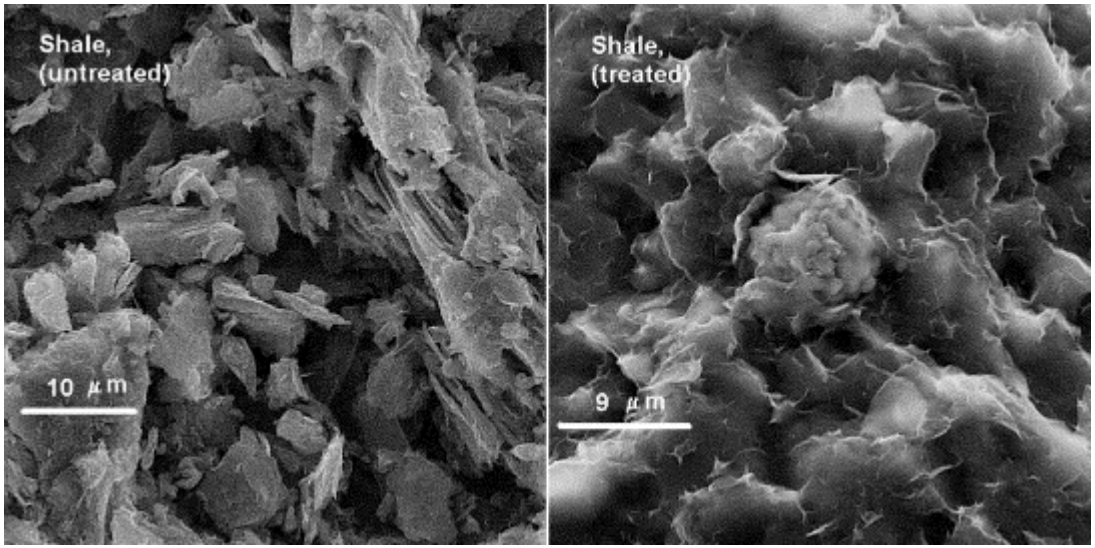
- Cemented fractures filled with Fe-carbonate cements (Ankerite, pink)
- Chlorite grain coatings (green) and quartz sandstone grains (yellow)



Effect of CO_2 reaction with shale (Kaszuba et al, 2003)

A. Before

B. After reaction with CO2

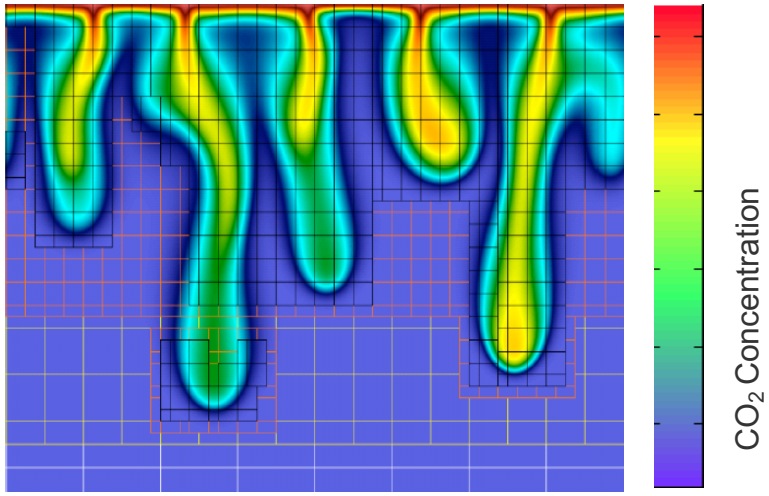


CO_2 Dissolution

- CO_2 dissolution in brine has an important potential to assist and stabilise long-term storage, but estimates of the effect vary enormously
- We know that convective mixing >> molecular diffusion
- The diffusive boundary layer needs to achieve a critical thickness before convection can occur
- Critical time (t_c) for onset of convection and the characteristic wavelength (λ_c) are estimated to be in the range of:
  - 10 days < t_c < 2000 Years
  - 0.3 m < λ_c< 200 m
  - Riaz et al., 2006.

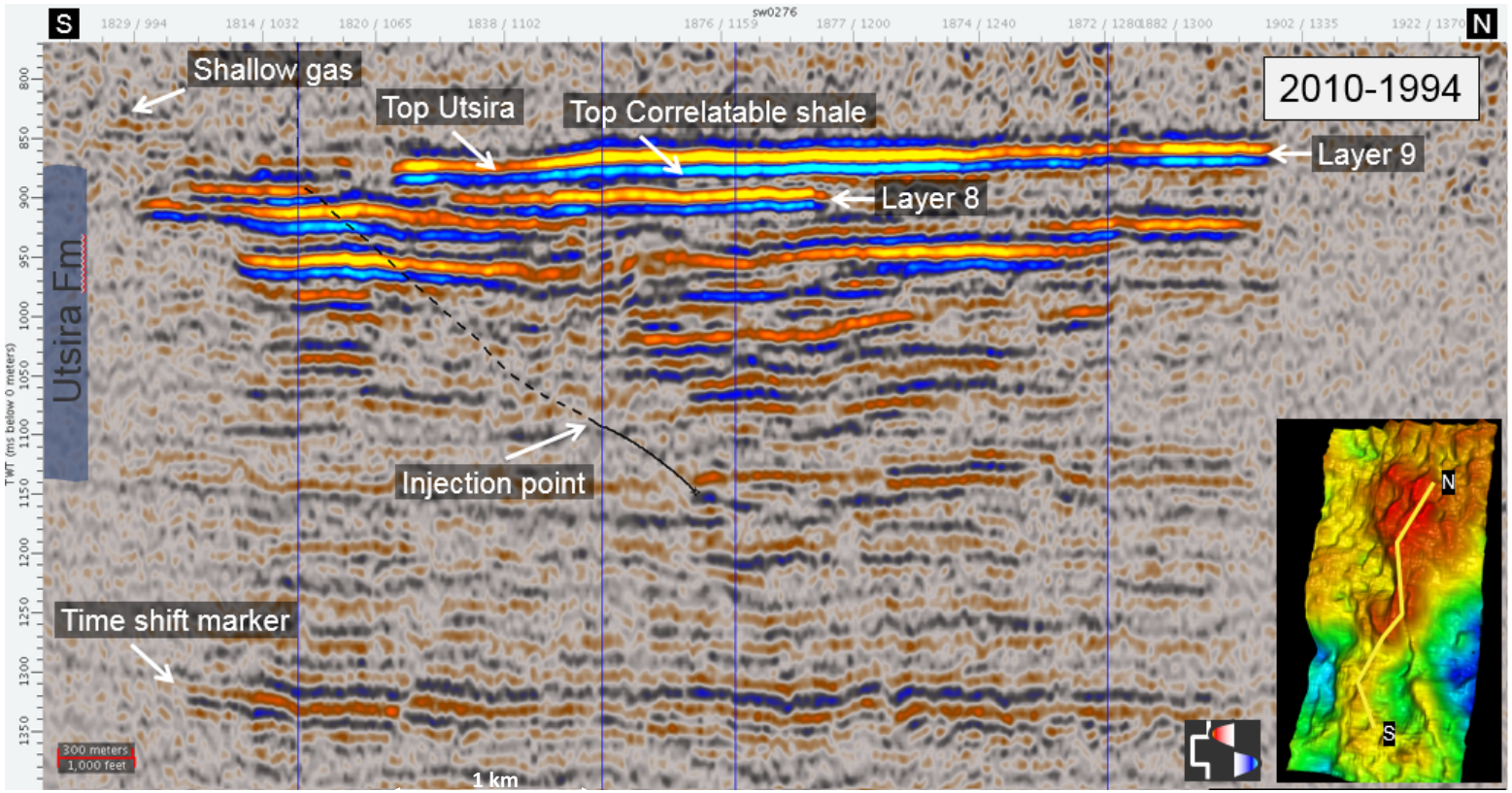
Scope for reducing these ranges using:

- ➢ Field Case Histories
- ➢ Large-scale lab experiments
- ➢ Good geological models



Density-driven flow in CO_2 storage in saline aquifer, Pau *et al*, 2010.

Sleipner time-lapse difference datasets

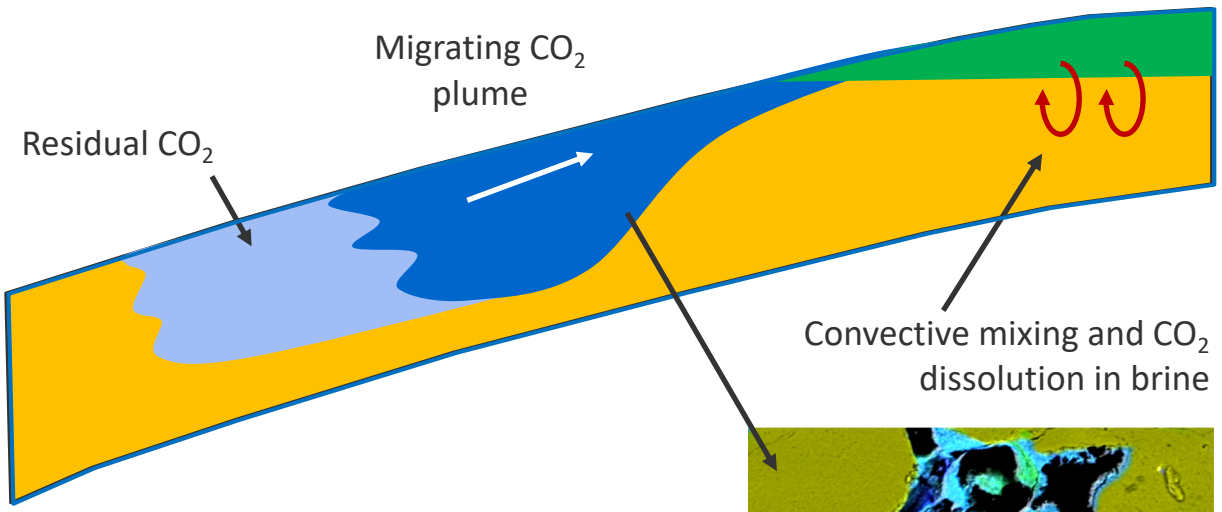


- Sleipner time-lapse seismic data, showing amplitude difference between 2010 and 1994 surveys.
- Bright amplitudes reveal presence of CO_2 complicated by effects of time-shifts and thin layer effects (Furre et al. 2015).

So what happens underground?

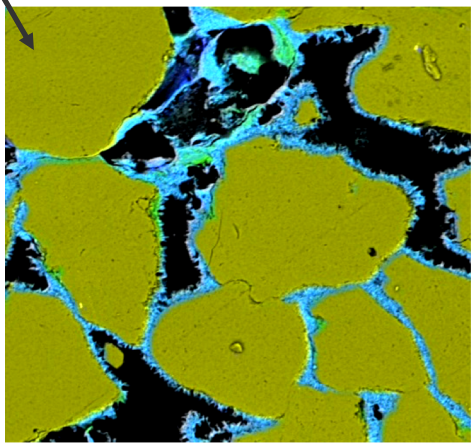
What can we learn from Sleipner about CO_2 trapping mechanisms?

- Physical trapping
- Residual trapping
- CO_2 dissolution
- CO_2 precipitation



Sleipner CO_2 storage metrics
(as of 2010 seismic survey)

	Mass (Mt)	Fraction of pore space occupied (ε)	
Total injected	12.18	0.048	5% efficiency
Free phase	11±0.5	0.044	
Dissolved phase	1.2±0.5	0.004	10% dissolved



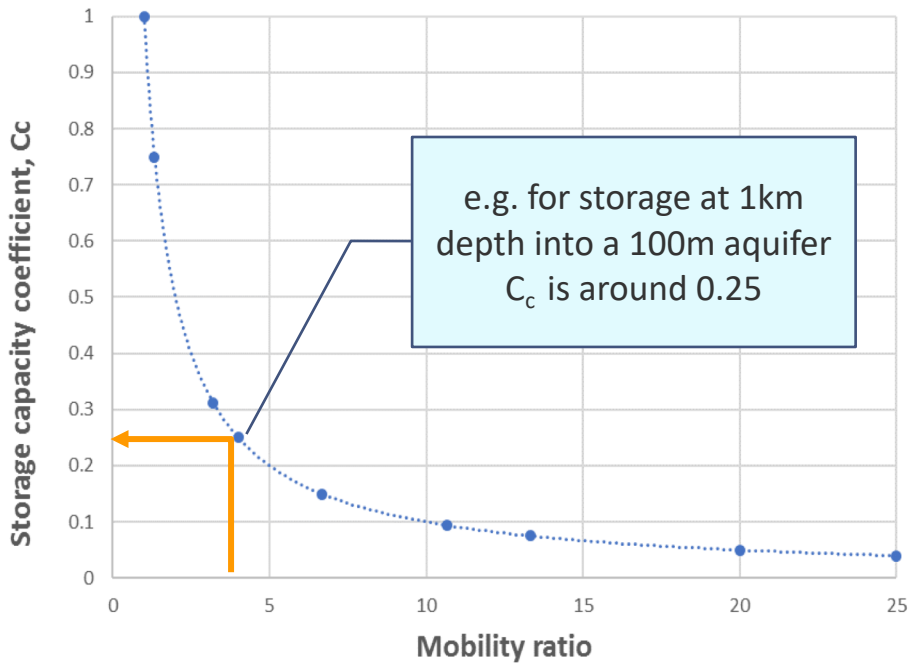
Mineral/pore-space reactions

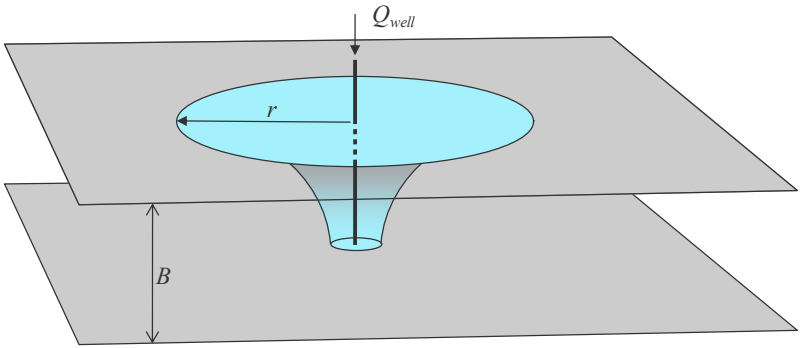
Analytical models for a CO_2 plume

- For a vertical well injecting at a rate Q_{well} into a horizontal saline aquifer unit, with thickness *B*, the CO_2 plume will expand with a 'curved inverted cone' geometry with a radius, *r* (Nordbotten et al. 2005).
- When the flow is viscous dominated:

Mobility ratio

$$r_{\max} = \sqrt{\frac{\lambda_c}{\lambda_b}\frac{Q_{well}\,t}{\pi\,B\phi}}$$

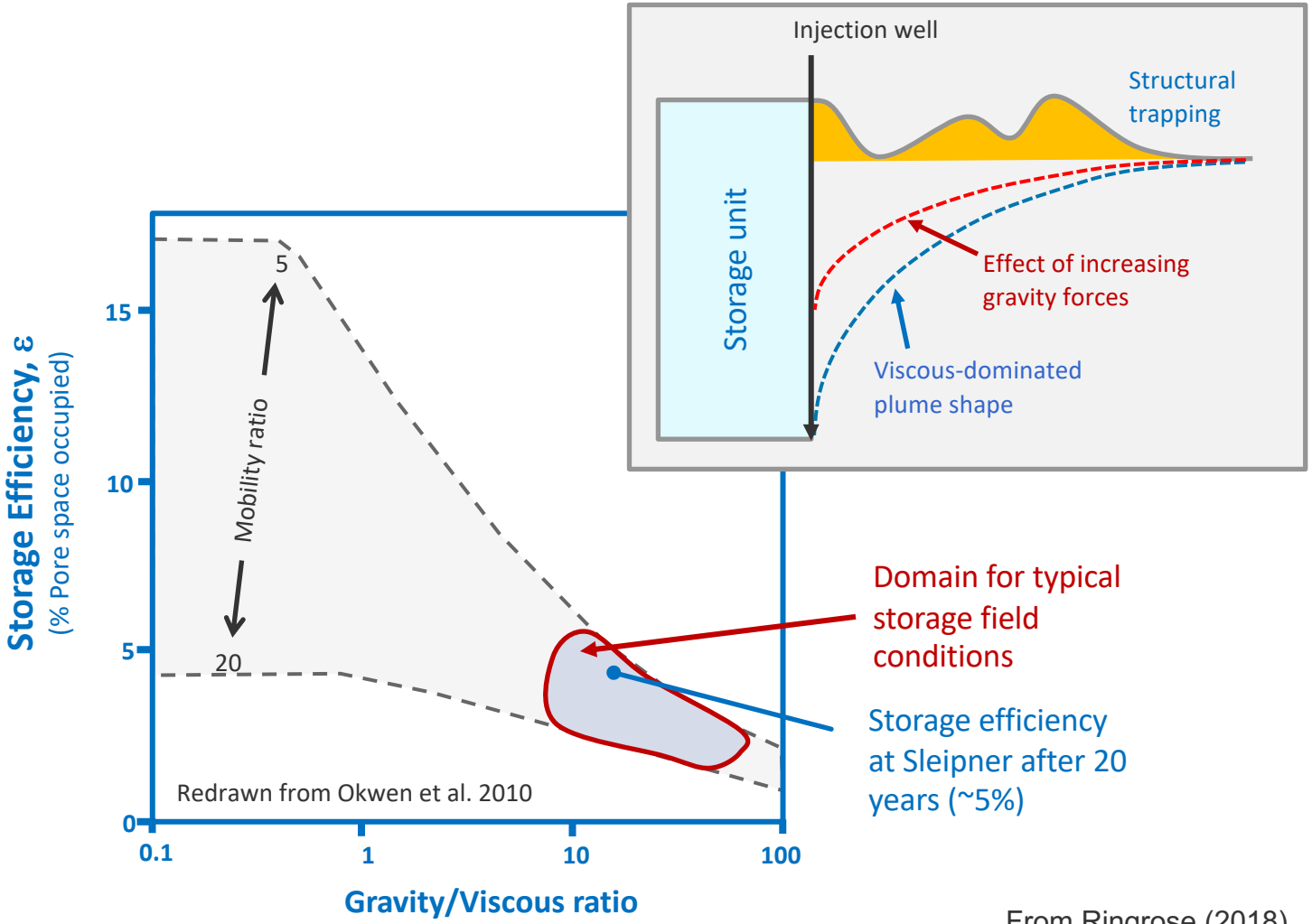




However, the shape of the cone and the efficiency depends on the gravity/viscous ratio:

$$\Gamma = \frac{2\pi\,\Delta\rho\,k\,\lambda_b\,B^2}{Q_{well}}$$

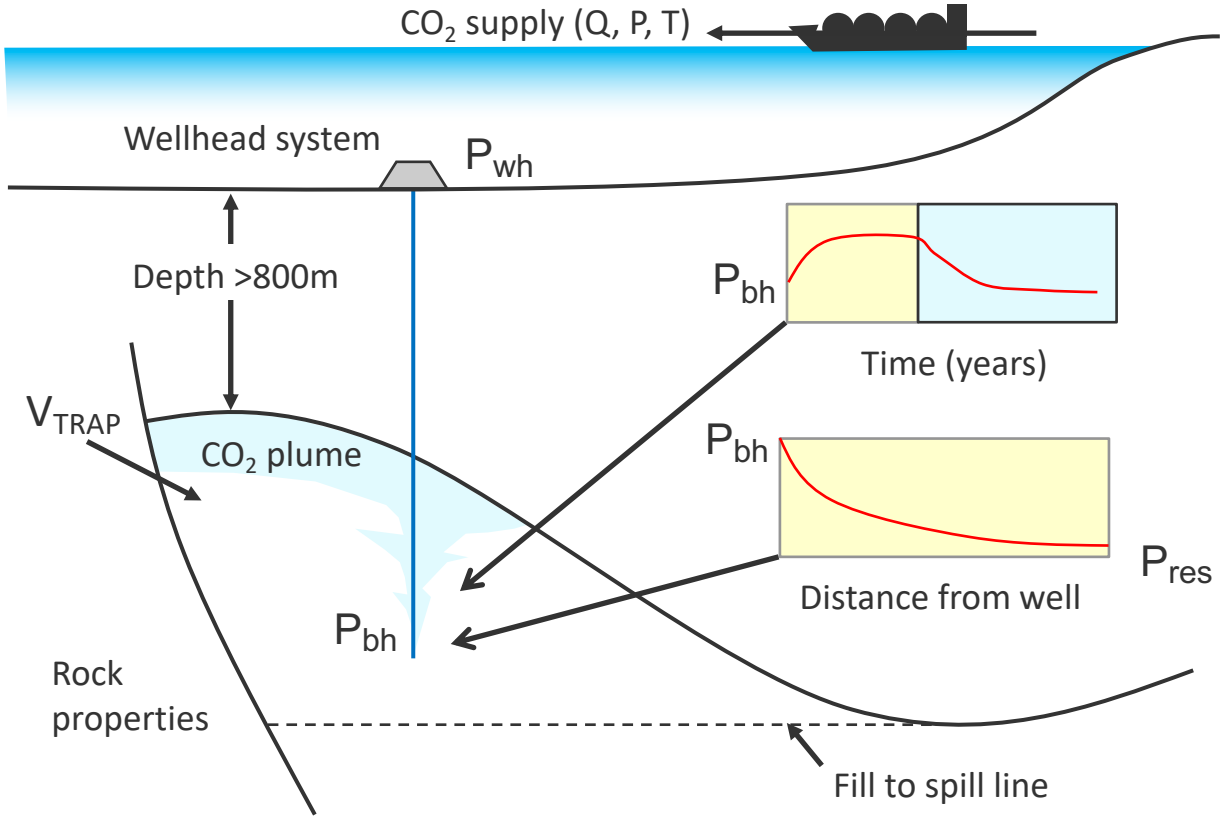
Effects of mobility and buoyancy on capacity



From Ringrose (2018)

Issues for injection pressure management

- CO_2 supply – rates, pressures, temperatures
- Reservoir depth, water depth
- Storage site capacity
- Well design
- Site performance (plume behaviour)
- Reservoir properties
- Overburden & seal charactersitics
- Regional aquifer



Storage Capacity Estimation

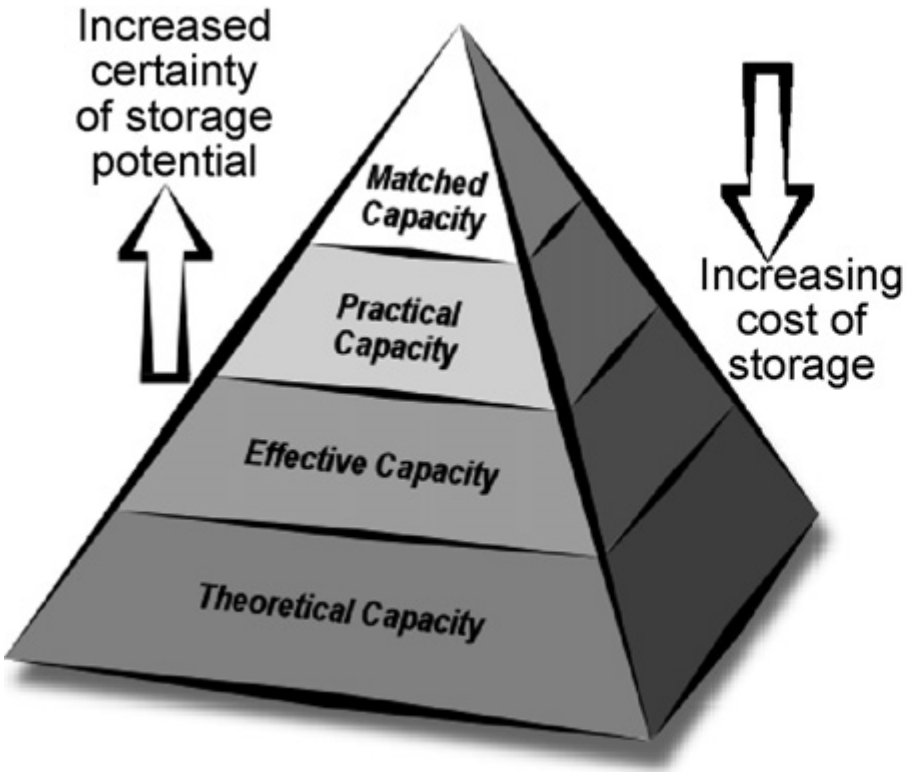
- Many efforts and studies have been completed to map potential CO_2 storage formations and estimate the storage capacity, such as
  - The EU GeoCapacity Project on European Capacity for Geological Storage of Carbon Dioxide (2008; http://www.geology.cz/geocapacity)
  - The North American Carbon Storage Atlas (2012; www.nacsap.org) (USA, Canada and Mexico)
  - The CO_2 atlas for the Norwegian Continental Shelf (2014; www.npd.no/en/Publications/Reports/Compiled-CO2-atlas/)
  - Other national CO_2 storage databases including UK, Australia and Brasil
- These national government-sponsored projects have set out to prepare nations for future large-scale CO_2 storage activities
- In general, there is plenty of theoretical capacity:
  - The North American estimate is over 2,400 billion metric tons (Gt)
  - Greater North Sea basin has mapped capacity of 160 Gt
- However, there is also much debate about how realistic these estimates are:
  - ➢ We need to understand the basis for CO_2 storage capacity estimates

Storage Capacity Estimation

Bachu et al (2007) provide a valuable review of the methods used in CO_2 storage capacity estimation

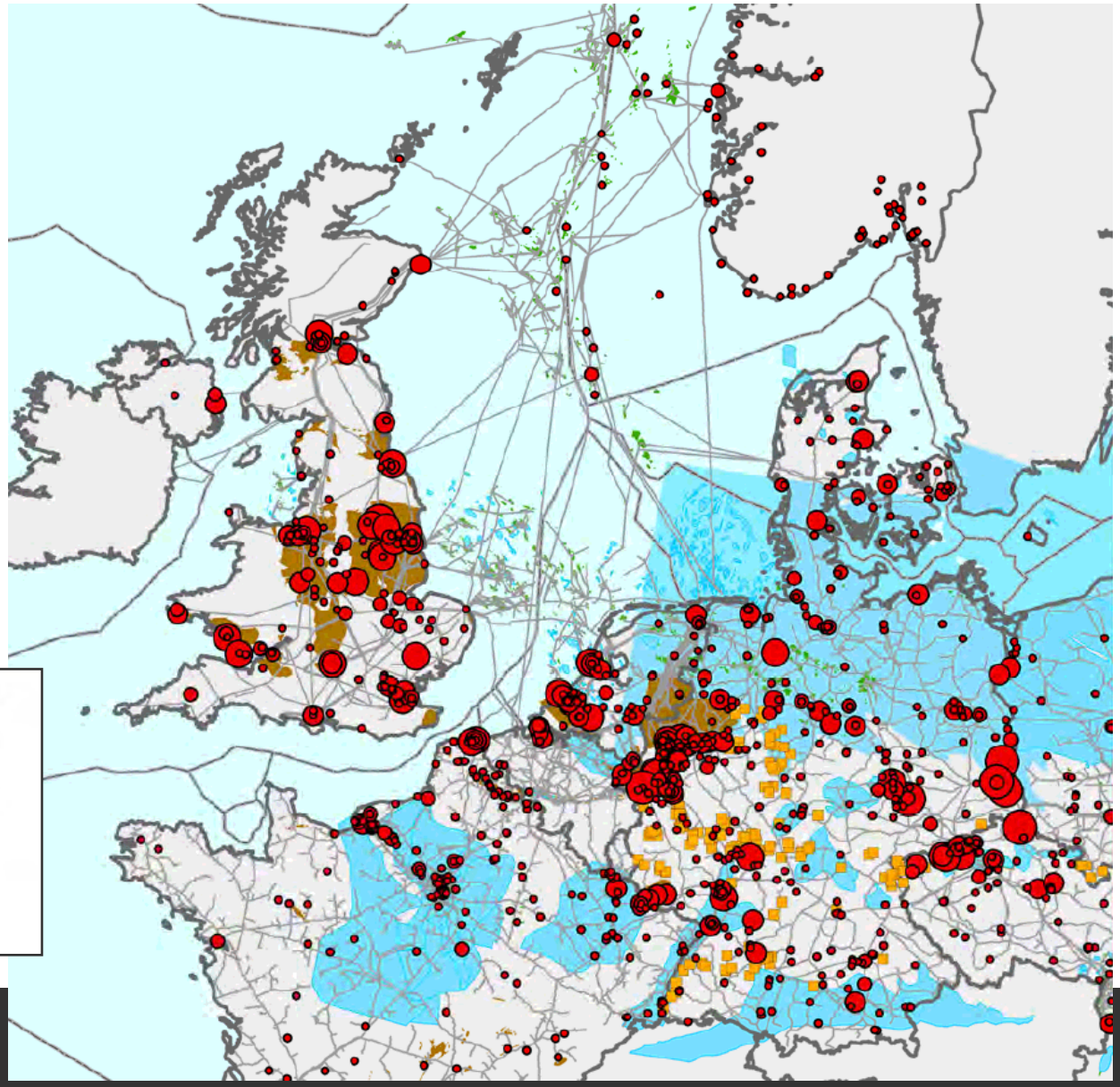
- There are several different types of estimate which can be summarized by the Techno-Economic Resource–Reserve Pyramid
- We need to differentiate:
  - Theoretical capacity (the physical limit)
  - Effective capacity (a more realistic estimate using cut-off criteria)
  - Practical capacity (taking into account economic, technical and regulatory factors)
  - Matched capacity (site-specific storage for specific CO_2 capture plants)

There are also various adaptations of this pyramid (e.g. for different stages of exploration and development)



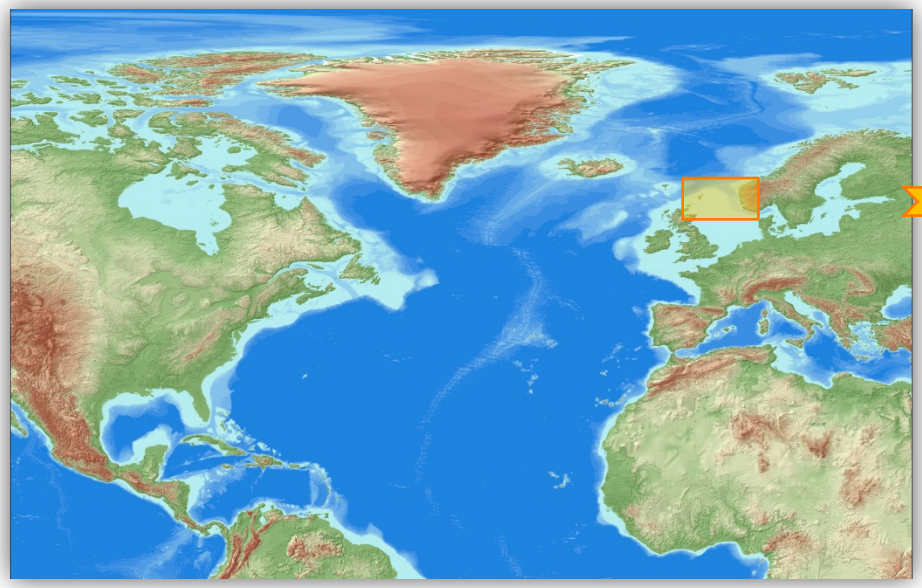
Matched Capacity

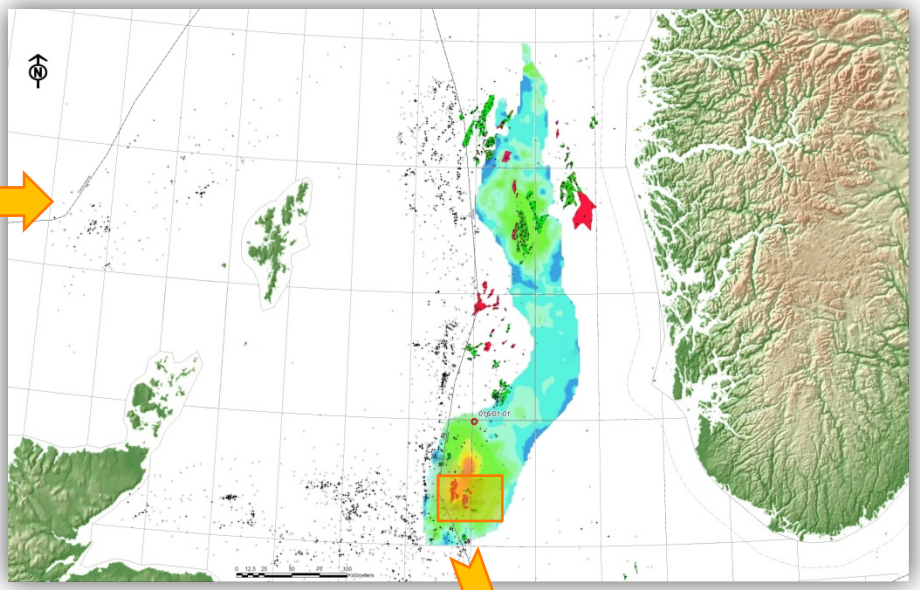
- Map of CO_2 emissions, infrastructure and storage capacity in NW Europe (from www.geocapacity.eu)

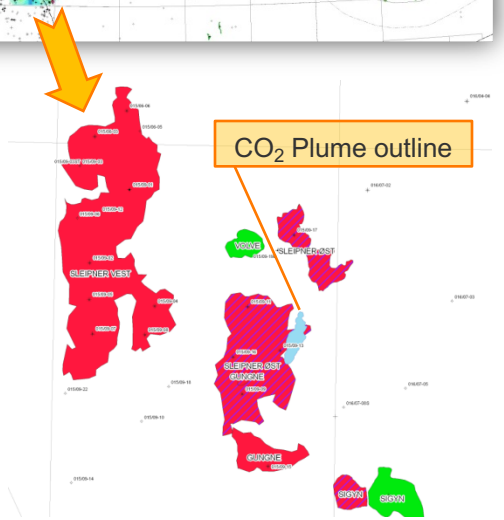


Sleipner site overview

Regional mapping of Utsira formation (Miocene)





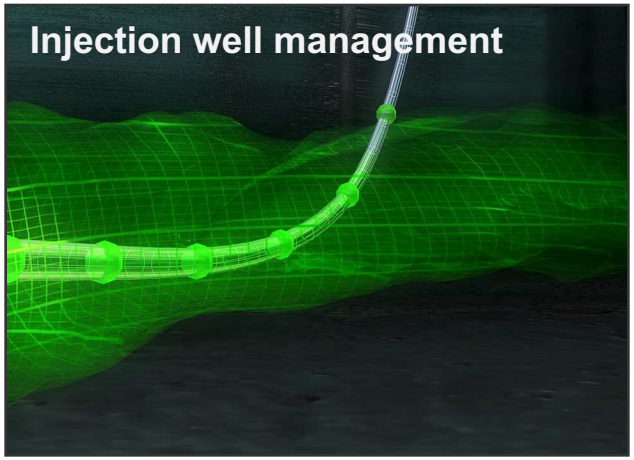


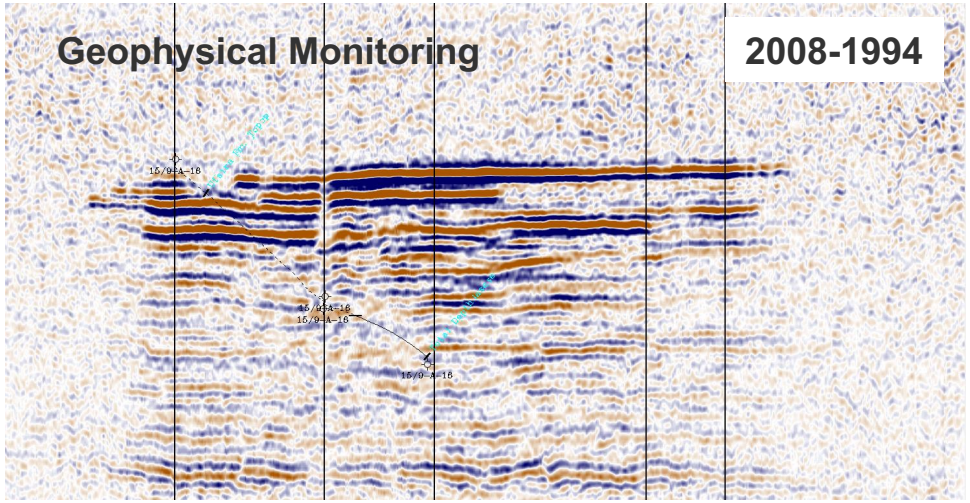
- CO_2 from the Sleipner field is stored in the Utsira Formation, North Sea
- Reservoir unit at 800-1100 m depth
- One CO_2 injector - 36 meter perforation at ~1012 meter (TVD)
- >17Mt CO_2 have been injected (Jan 2019, ~0,9M per annum)
- Background to site selection given by Baklid et al. (1996)
- Regional resource mapping found in Norwegian CO_2 Storage Atlas
  https://www.npd.no/en/facts/publications/co2-atlases/co2-atlas-for-the-norwegian-continental-shelf/

Final words: Experience from CO_2 Storage projects

Operational experience (saline aquifers) reveals several important learnings:

- Injection rates of 0.3-0.9Mt CO_2/year/well
- Injectivity and capacity highly dependent on reservoir properties revealed during site operation
- Geological heterogeneity means that flexible well solutions will be required
- Rock mechanical response to P_{inj} may be a critical factor
- Importance of pressure and fluid management
- Need for fit-for-purpose reservoir monitoring portfolio





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