Have we overestimated saline aquifer CO_2 storage capacity ?

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van der Meer & Egberts formula for CO_2 capacity

Pressure builds up in order to liberate pore volume for dense phase CO_2

- **Formula applied to a closed aquifer [OTC 19309, 2008]**

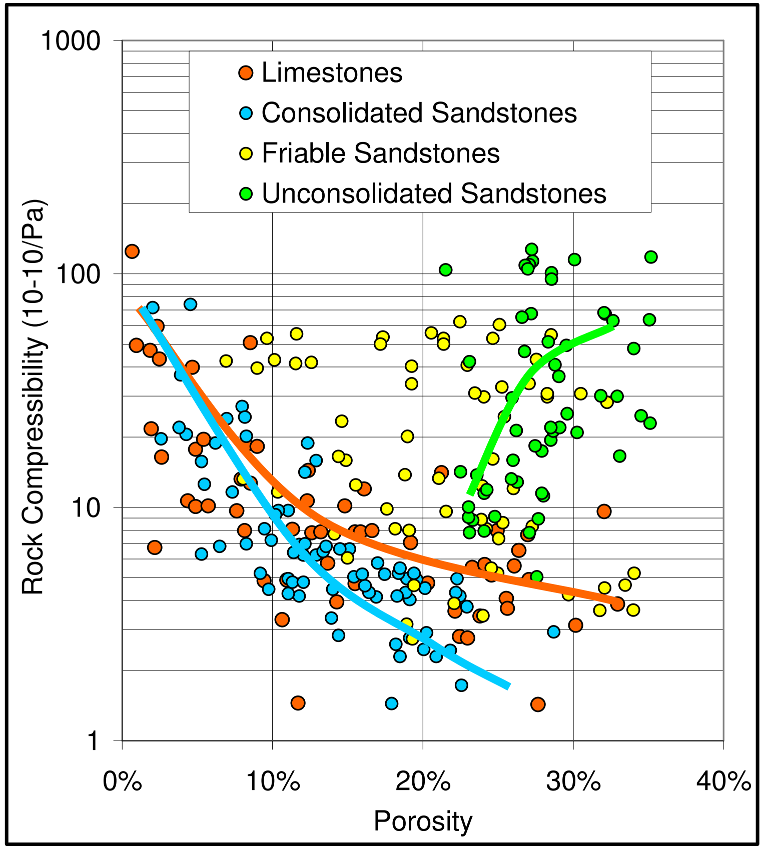
$$M_{CO_2} = \rho_{CO_2} \times V_p \times (C_r + C_w) \times \Delta P$$

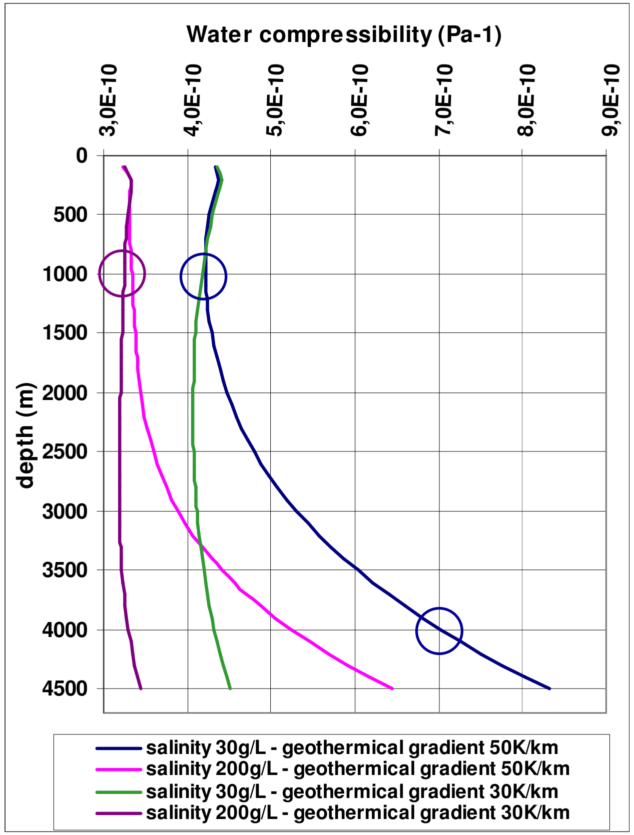
  - M_{CO_2} : CO_2 storage capacity of the aquifer
  - ρ_{CO_2} : CO_2 density at storage conditions
  - V_p : pore volume of the aquifer (initial water volume), at basin scale
  - C_r and C_w : rock and water compressibility
  - ΔP : maximum pressure increase

- **Aquifer volume fraction available for storage (storage efficiency)**

$$E = (C_r + C_w) \times \Delta P$$

Rock and water compressibilities





Rock compressibility Newman, 1973

Rock type	Phi	C_r *1/Pa*
Consolidated SST	20%	3×10^{-10}
Unconsolidated SST	30%	80×10^{-10}
Limestone	20%	5×10^{-10}

Rowe & Chou water properties

Depth	NaCl	temp.	C_w *1/Pa*
1 km	30 g/l	50 °/km	4×10^{-10}
1 km	200 g/l	30 °/km	3×10^{-10}
4 km	30 g/l	50 °/km	7×10^{-10}

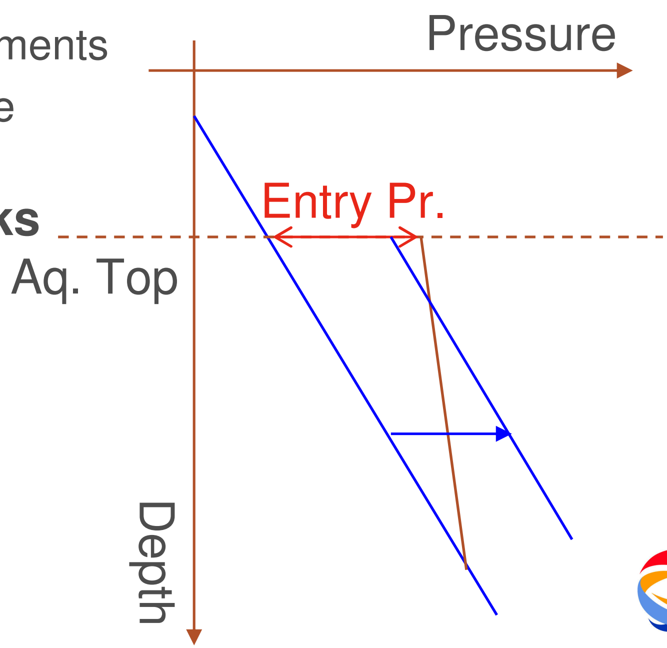
Maximum average pressure increase

- Standard cap rock fracturation gradients

	Low	High
Fracturation gradient	15 MPa/km	20 MPa/km
Maximum injection pressure, 90% safety	13.5 MPa/km	18 MPa/km
Maximum pressure increase to hydrostatic	3.5 MPa/km	8 MPa/km

- **Comments on geomechanical integrity**
  - Reduced frac gradients in shallow (<1 km) environments
  - Fault stability may decrease max pressure increase

- **CO_2 capillary entry pressure into the cap rocks**
  - May become critical if aquifer is pressurized
  - Utsira cap rock experimental value :
    1.7 MPa ≈ **2.1 MPa/km** << 3.5 MPa/km
    [Springer, GHGT8, 2006]



Orders of magnitude of storage efficiency

		Cap. entry pressure controlled	Standard case	Compres-sive basin	Unconso-lidated sandstones
Rock compressibility	*1/Pa*	$5{\times}10^{-10}$	$5{\times}10^{-10}$	$5{\times}10^{-10}$	$80{\times}10^{-10}$
Water compressibility	*1/Pa*	$4{\times}10^{-10}$	$4{\times}10^{-10}$	$5{\times}10^{-10}$	$5{\times}10^{-10}$
Total compressibility	*1/Pa*	$9{\times}10^{-10}$	$9{\times}10^{-10}$	$10{\times}10^{-10}$	$85{\times}10^{-10}$
Max pressure increase	*MPa/km*	2.1	3.5	8.0	3.5
Storage efficiency E	*%/km*	0.2	0.3	0.8	3.0

- **Large impact of rock compressibility and maximum pressure increase**
- **Key assumptions**
  - No pressure loss near wells (possibility to build up pressure homogeneously)
  - No CO_2 dissolution into the formation water
  - Closed aquifer, no water flow out of the aquifer

Impact on storage capacities – Utsira example

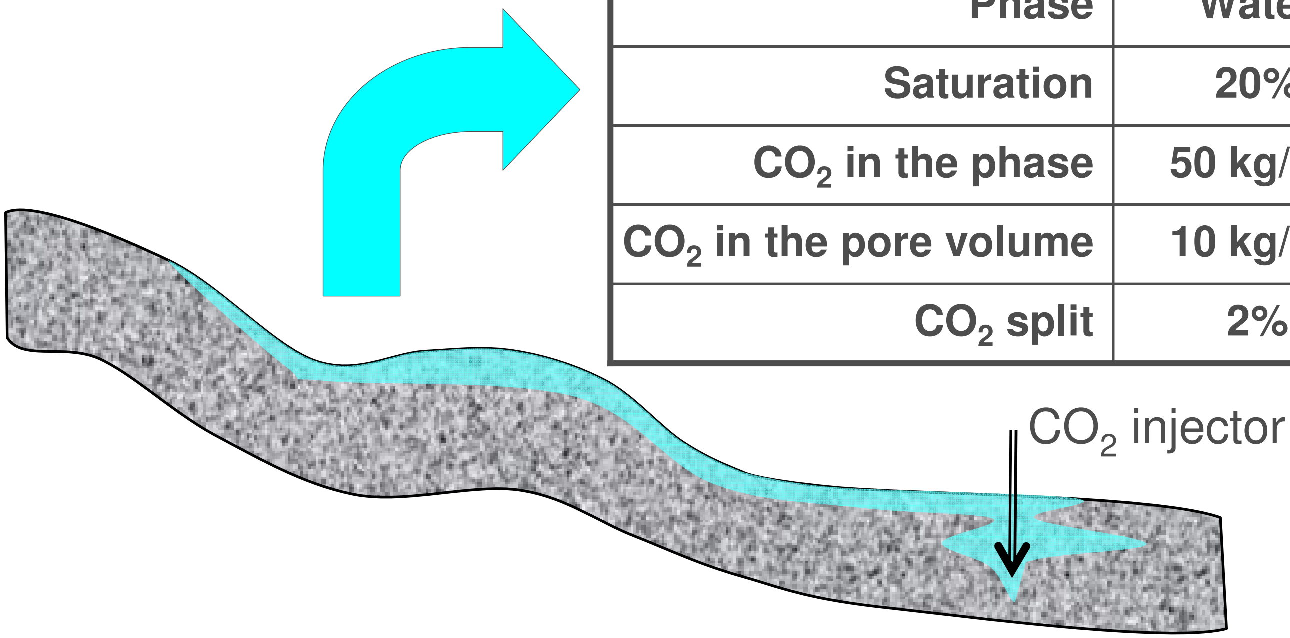
- Utsira CO_2 storage capacities

	published figures		*pressure formula*	
	GESTCO *(full cap.)*	SACS *(traps)*	*Conso-lidated*	Unconso-lidated
Pore volume, km^3	918	600	*600*	600
rock compress., 1/Pa			*5×10^{-10}*	80×10^{-10}
water compress., 1/Pa			*4×10^{-10}*	4×10^{-10}
max pressure, MPa			*1.7*	1.7
E	6%	0.11%	*0.15%*	1.4%
CO_2 volume, km^3	55	0.66	*0.92*	8.6
CO_2 mass, MT	42 356	400	*550*	5 140

Large impact of rock compressibility

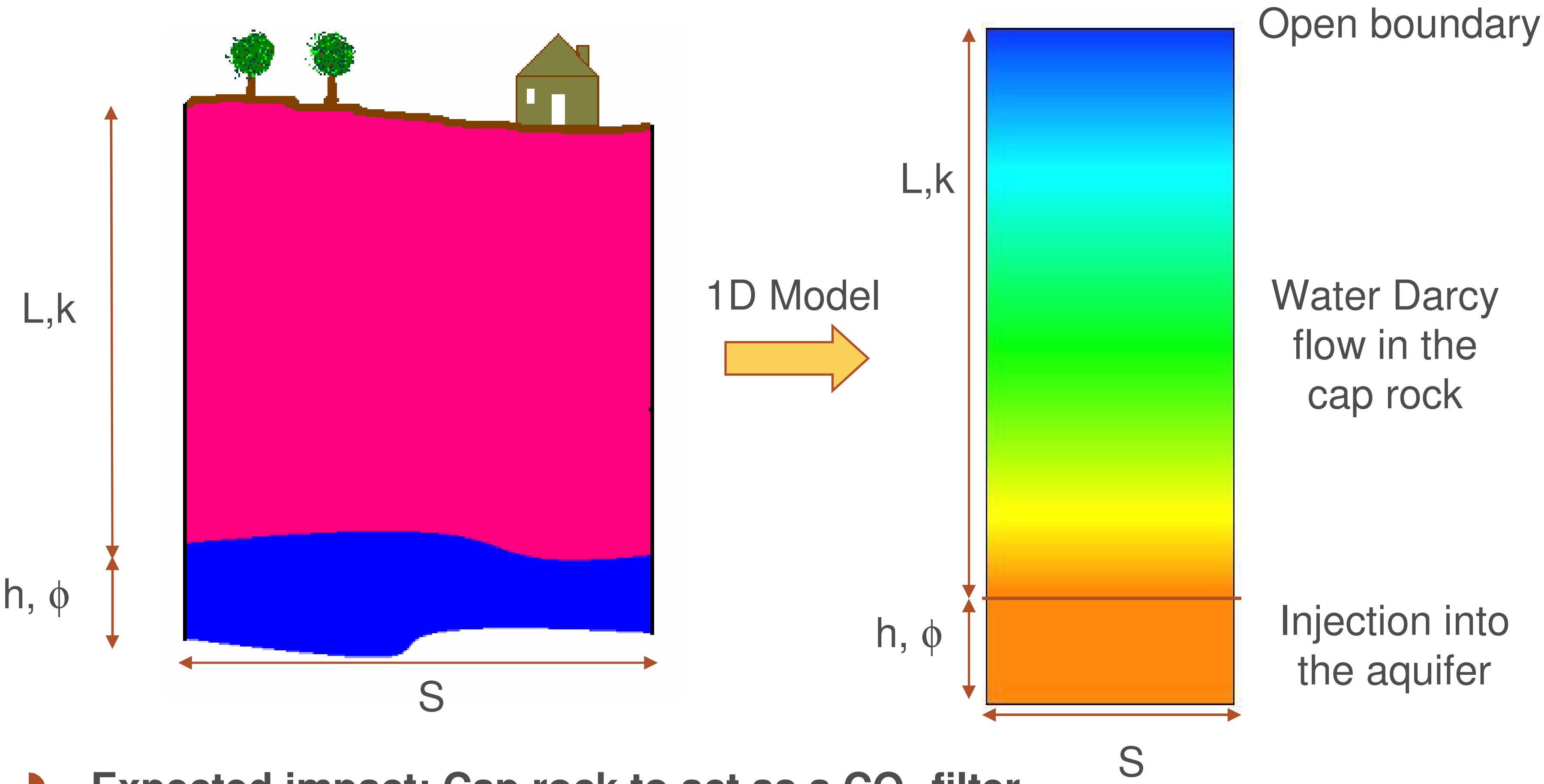
Can CO_2 dissolution change the picture ?

CO_2 flooded area		
Phase	Water	CO_2
Saturation	20%	80%
CO_2 in the phase	50 kg/m^3	500 kg/m^3
CO_2 in the pore volume	10 kg/m^3	400 kg/m^3
CO_2 split	2%	98%



- **CO_2 dissolution will not change the pressure issue**
  - limited CO_2 dissolution in CO_2 flooded area due to small volume of water contacted
  - long time required to contact larger volume of water, over industrial project time
  - let us not forget that dissolved CO_2 occupies volume anyway

Can formation water flow to the cap rock ?



- **Expected impact: Cap rock to act as a <u>CO_2 filter</u>**
  - Water can flow out of the reservoir through the cap rock
  - <u>CO_2 is retained in the storage aquifer</u> due to a capillary barrier

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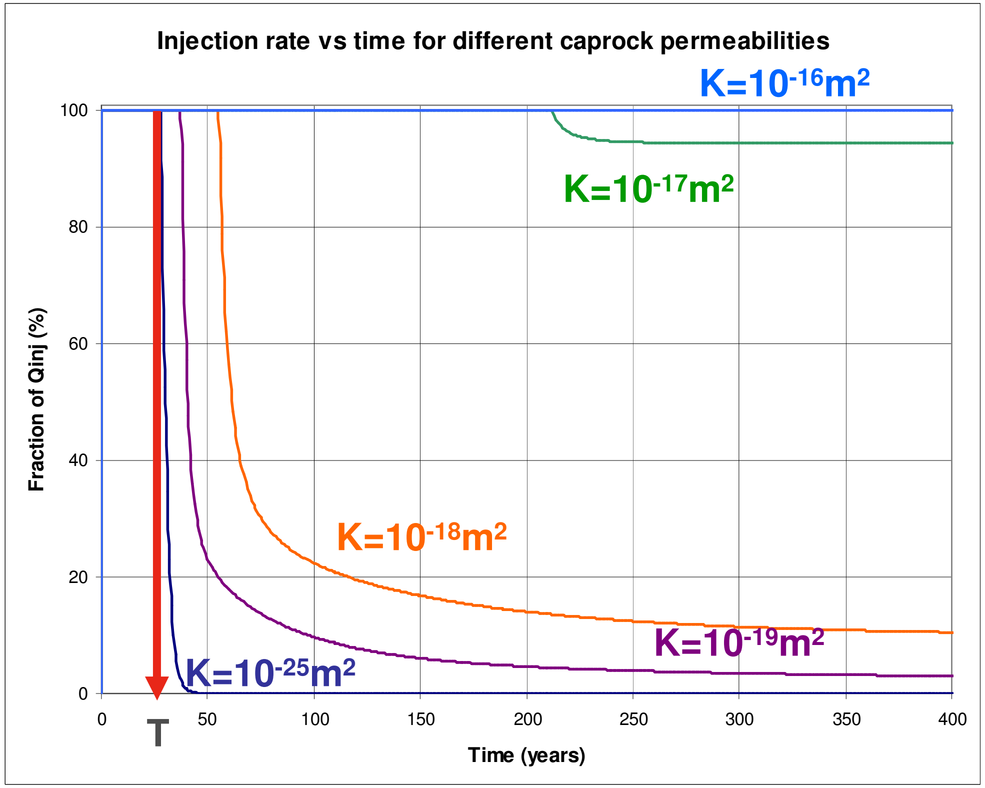
Can formation water flow to the cap rock ?

$$\begin{cases} Q_{Inj} = \dfrac{S\times h\times\phi\times(C_r + C_w)\times\Delta P}{T} \\ Q_{cap} = \dfrac{S\times k}{\mu_w}\times\dfrac{\Delta P}{L} \end{cases}$$

The cap rock can expulse a volume of formation water equivalent to the injected volume of CO_2 if:

$$k > Lh\times\frac{\phi\times(C_r + C_w)\times\mu_w}{T}$$



- **Modelling results**
  - Flow through cap rocks can be significant, for permeabilities over 10^{-18} m^2 , but
  - It requires an assessment of permeability distribution in the cap rock at basin scale
  - Vertical permeability can be severely reduced by local lower permeability layers

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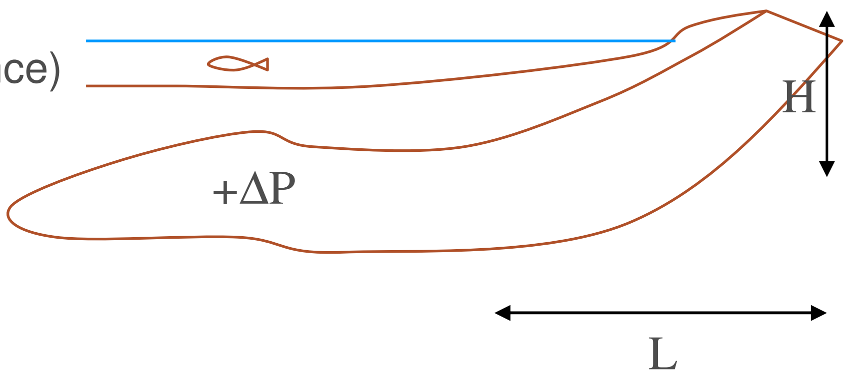
Can formation water flow to open boundaries ?

- **Water flow due to the pressure increase**
  - Increasing with the tilt (to decrease the distance)

$$Q_w \approx \frac{S \times k}{\mu_w} \times \frac{\Delta P}{L}$$



- **CO_2 front velocity to the open boundary**
  - Also increasing with the tilt

$$v_{CO_2} \approx \frac{1}{\phi} \times \frac{k}{\mu_{CO_2}} \times \frac{\Delta\rho \times g \times H}{L}$$

- **Significant water flow not necessarily easy to obtain**
  - Distance to open boundary & small tilt required to avoid CO_2 migration
  - Large scale connectivity assessment (faults, permeability, …)

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Is the storage efficiency formula an issue ?

- **Large scatter in storage efficiency E using a pressure approach**
  - E from 0.2 to 3% of the pore volume per km of burrial
  - **beware the rock compressibility value** (unconsolidated sandstones)

- **Global Storage Capacities in aquifers**

	Capacity, Gt	Efficiency	Comment
Worldwide	**1000 – 20 000**		IPCC 2005, IEA 2008
Australia	**740**	**19%**	Geodisc, Bradshaw et al, 2004
Alberta	**1000 – 4000**	**≈ 9%**	Bachu & Adams, 2003 (dissolution – 54 kg/m³)
USA	**900 – 3400**	**1-4%**	DOE Atlas, 2008 (15%-85% confidence range)
Norway offshore	**up to 480**	**≈ 4.4%**	Joule II, 1996

Capacity assessments require consistant approaches accounting for pressure

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Conclusion - Recommendations

- **1st order estimate: Aquifer storage capacity based on the ΔP formula**
  - screening estimate only
  - based on water pore volume below 800-1000 m depth
  - based on <u>rock compressibility</u> and maximum pressure aquifer data
- **2nd order estimate: Acount for well pressure losses and water flow**
  - perform reservoir flow models with relevant well pattern
  - incorporate the water volume expected to contribute to the water flow, ie cap rock and basin scale aquifer
  - connectivity features should be included (faults, low permeability layers)
  - do not use constant pressure boundary conditions on local flow models !
- **Consider water production to control pressure build up**
  - Flett et al., SPE 116372, 2008
  - Yang, SPE 115236, 2008
  - Lindeberg & Vuillaume, GHGT9, 2009

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