Modelling and simulation of CO_2 leakage mechanisms from geological storage

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Introduction

- Capture of CO_2 in combustion processes and geological storage of the CO_2 could be an important contribution to the reduction of CO_2 emissions.
- Feasibility of a geological storage project depends on how large fraction of the stored CO_2 can be kept out of the atmosphere for a sufficiently long period of time.
- A given amount of escaped CO_2 will have different effects on the global climate depending on the profile of the annual leakage rates associated with the escape.

Scope of the work

- Investigate the mechanisms by which CO_2 may escape from a storage site into the oceans or atmosphere
- Determine the associated escape rate profiles for different mechanisms
- Determine distribution of leakage volumes over time

Model assumptions

- Leakage mechanism studied is buoyancy-driven flow of CO_2 through a percolating network of permeable sand bodies in the caprock

- Distribution of porous sand bodies was created randomly in the aquifer caprock but ratios shale/sand patches are based on studies of the well-logs from the caprock of an aquifer

- Properties of the simulation model were chosen to give a significant leakage over a time period of a few thousand years (which is short enough to be of interest to study the effect of leakage on global climate)

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Model dimensions and simulation tools

- Lateral extent of the model was 72 x 72 cells; The number of layers varies from 38 to 66 layers, depending on the number of shale overburden blocks modeled
- The lateral extent of each cell is 100 m x 100 m
- Number of active cells varies from 196 992 to 342 144
- Irap RMS from Roxar and Eclipse 100 black oil simulation tool from Schlumberger have been used

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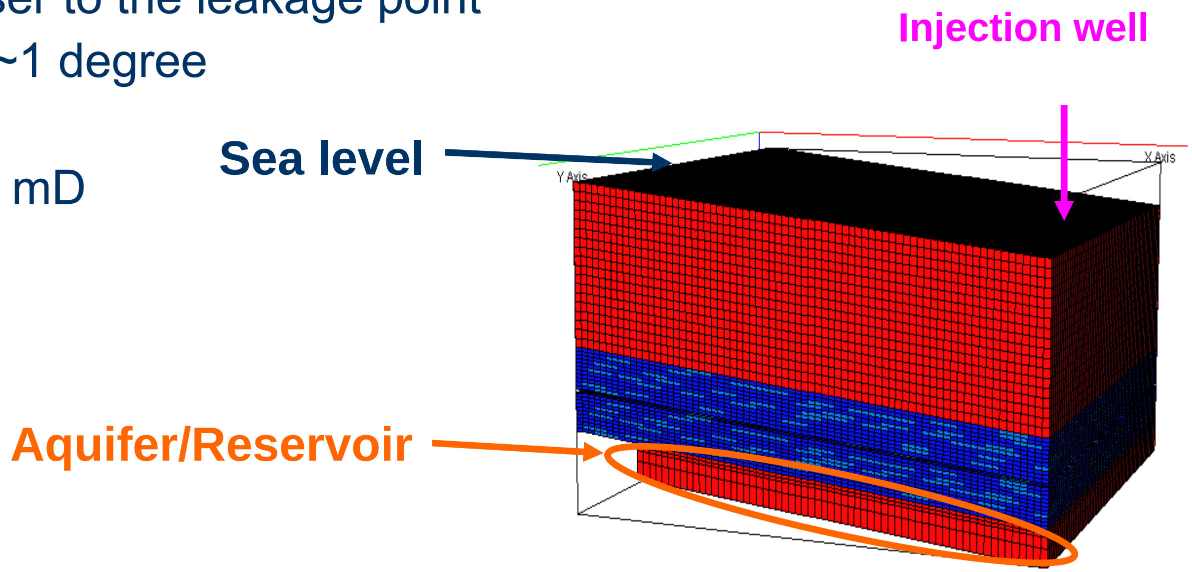
❑ Study sensitivity of calculated leakage profiles with respect to variation of

- ❑ Thickness of the shale layers
- ❑ Flow function hysteresis
- ❑ Injected volumes
- ❑ Permeability of the shales
- ❑ Permeability of the sand patches present in the shale layers

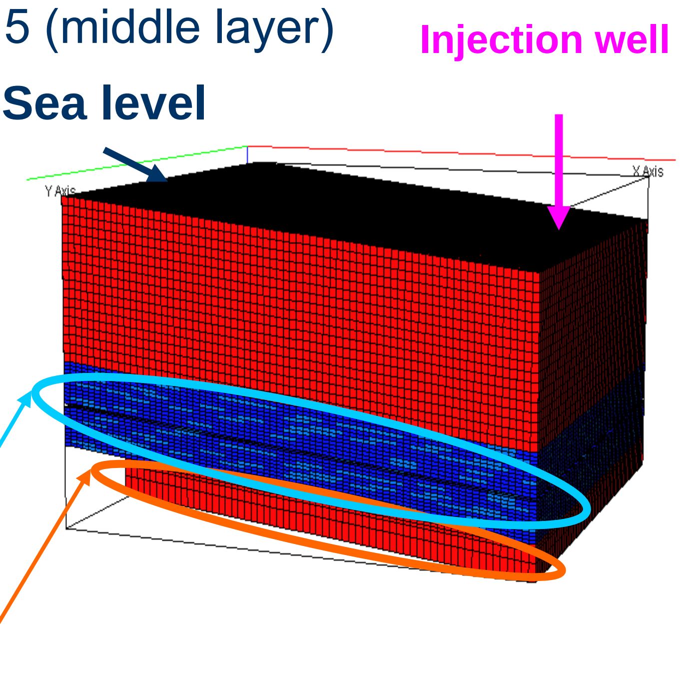
Aquifer model

- Generic aquifer model:
  - Represented by 4 deepest layers of the model
  - Top 800 mss
  - Thickness 100 m
  - Increasing thickness from 10 m (first two layers from top) to 30 and 50 m
  - Inactive blocks are introduced in the reservoir to move the top of the structural trap closer to the leakage point
  - Dip angle aquifer ~1 degree
  - Porosity 25%
  - Permeability 1000 mD

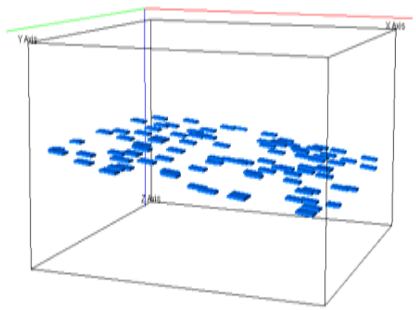


Overburden model

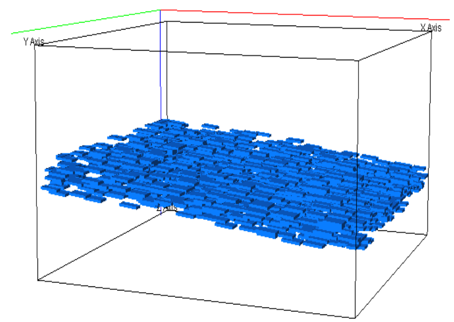
- A basic block of the overburden model - 11 layers
  - Low-permeable shale (from 0 to 10E-5 mD)
  - Patches of sand of higher permeability (10 / 100 / 1000 mD)
  - Sand patches placed randomly in each layer
  - 1 patch of sand consist of 3x4 cells (300 m x 400 m)
  - Sand/shale ratio varying from of 0.203 to 0.5 (middle layer)
  - Average sand/shale ratio for the 11 layers block of 0.23
  - Shale & sand patches layers thickness 10 m (1 overburden block ~110 m)
  - Sand layers thickness in top of any overburden block - 30 m



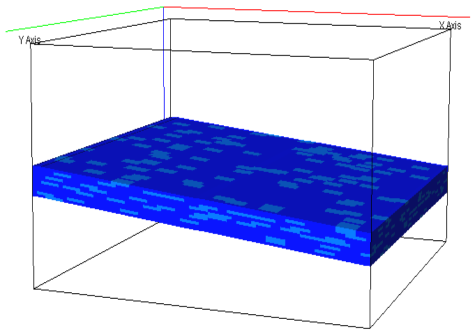
Modelling the overburden structure



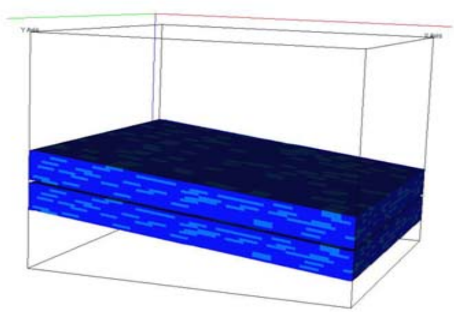
Distribution of sand patches in one layer



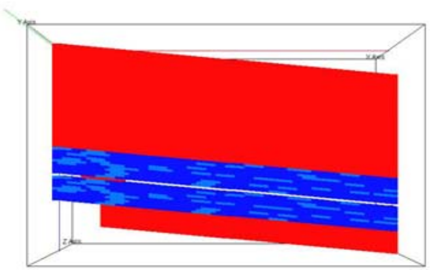
Distribution of sand patches in one overburden block



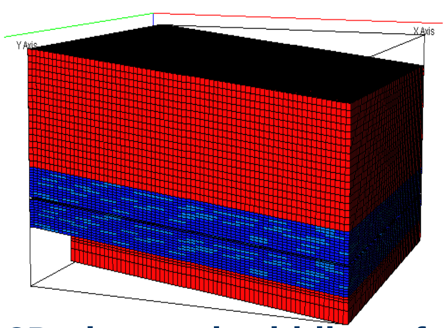
One overburden block



Two overburden blocks

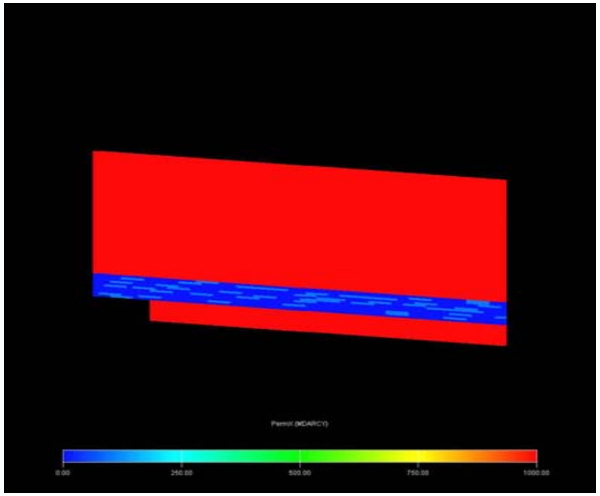


Longitudinal cross section through the model containing two overburden blocks shale and sand body patches

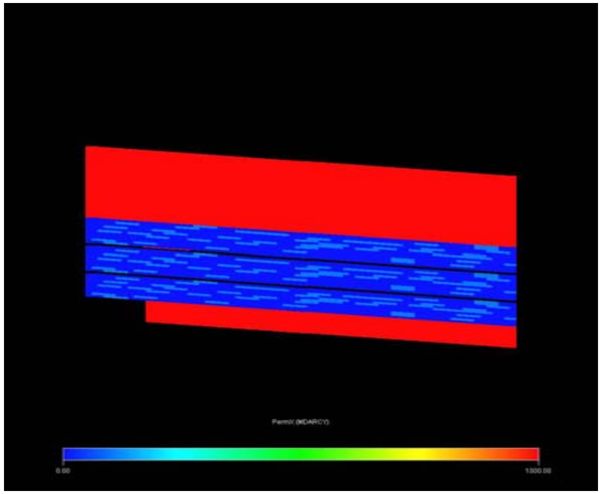


3D view and gridding of the model containing two overburden blocks shale and sand body patches

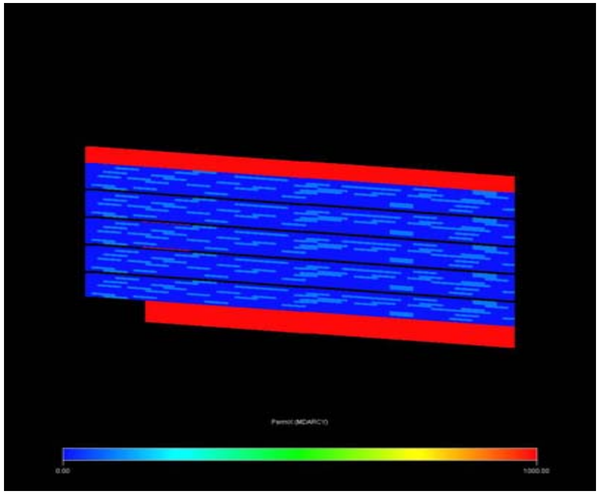
Examples of models with 1, 3 and 5 blocks overburden shale/sands



1 block overburden
(11 layers)



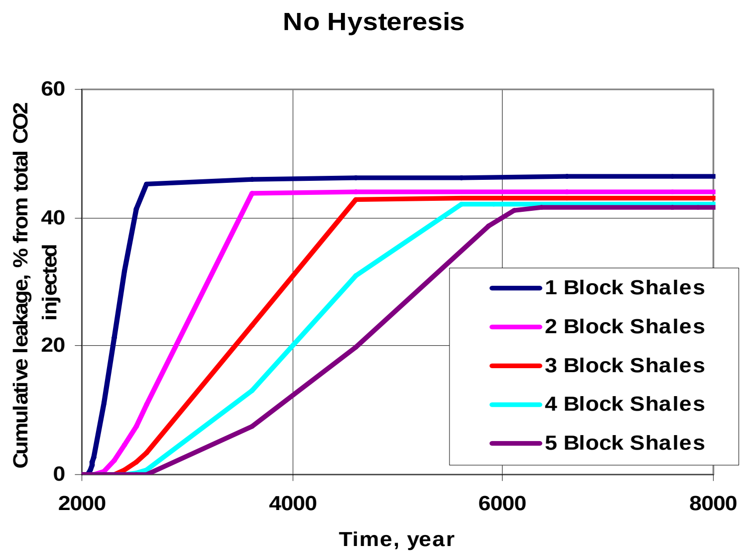
3 blocks overburden
(33 layers)

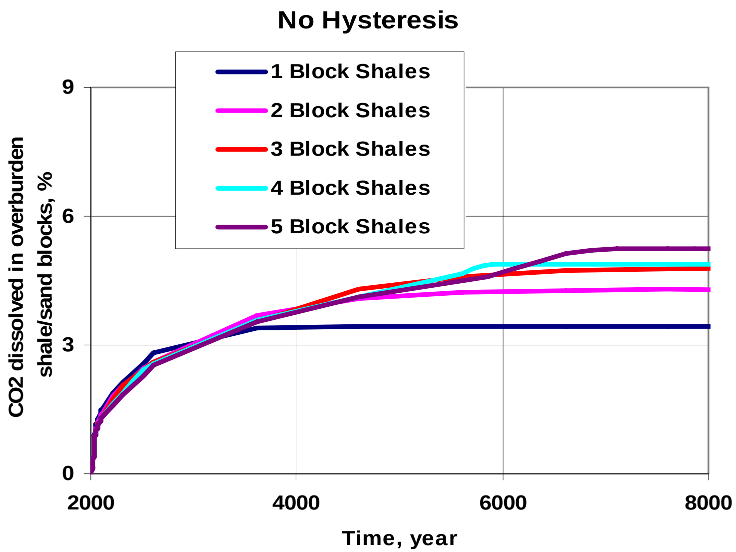


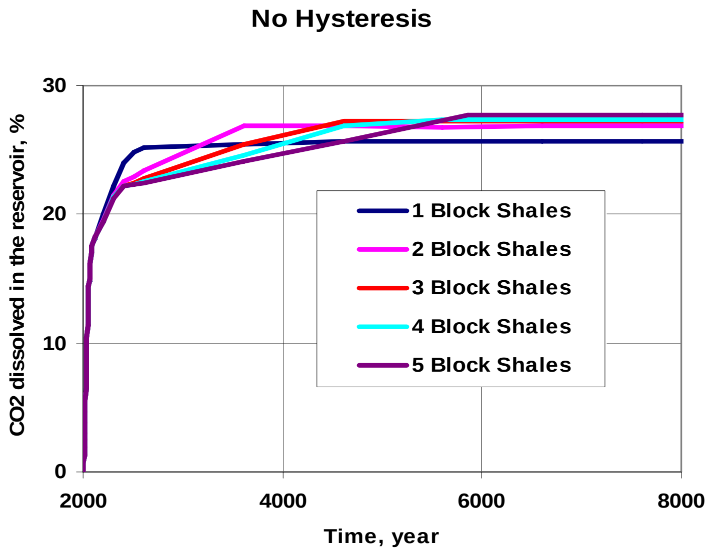
5 blocks overburden
(55 layers)

Effect of adding more shale blocks to the model

- Increasing number of shale blocks
  - Slow down the escape rates;
  - delay leakage;
  - Increase fraction of CO_2 in dissolved state in the overburden blocks and reservoir;
  - Increase time elapsed before a steady state is reached for the CO_2 in the reservoir and overburden shales

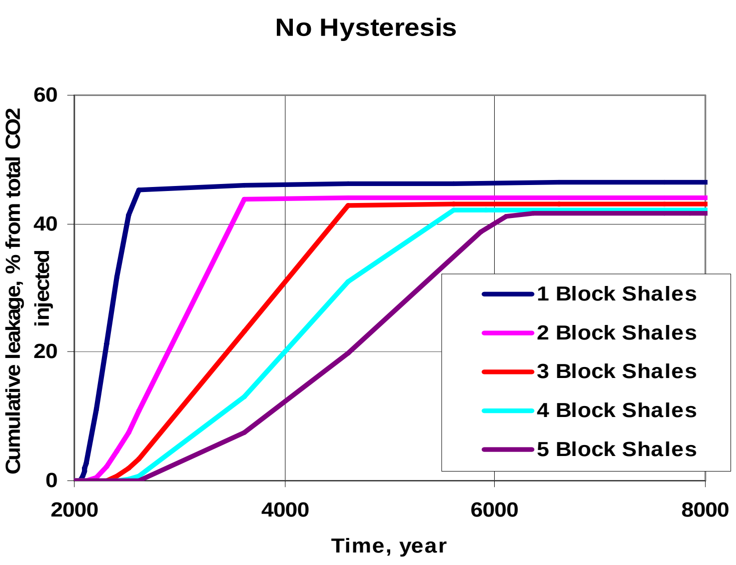


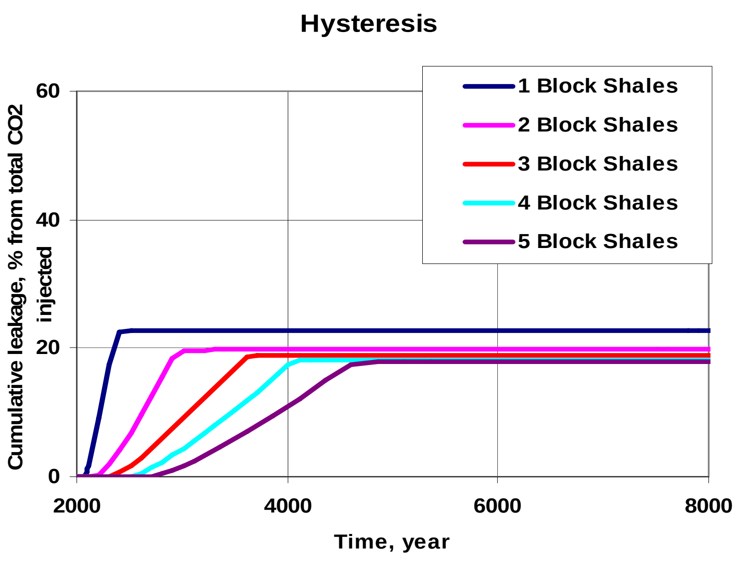




Effect of hysteresis

- more CO_2 is retained as dissolved gas in the reservoir;





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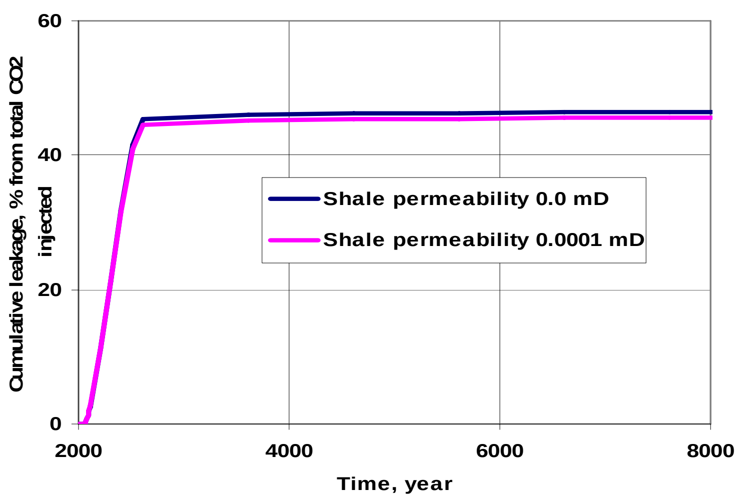
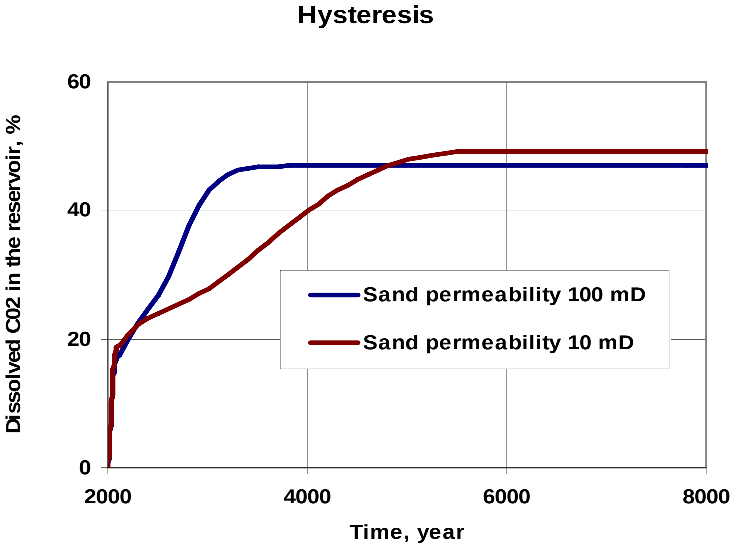
Effect of adding permeability to the shale in the overburden blocks

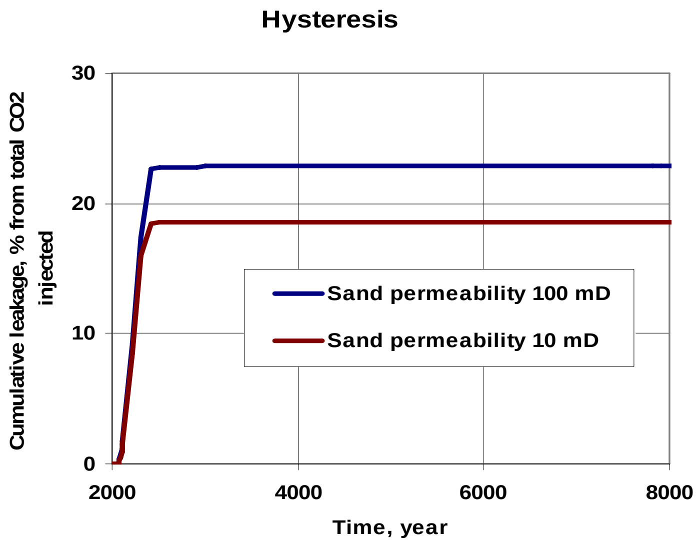
- CO_2 enters the shale also by viscous flow and not only by diffusion;
- The difference in total escape is smaller, with 0.9% less CO_2 escaped from the model; for a given permeability of the shale of 10E-5 mD the process is too slow to make any difference when compare with zero shale permeability case

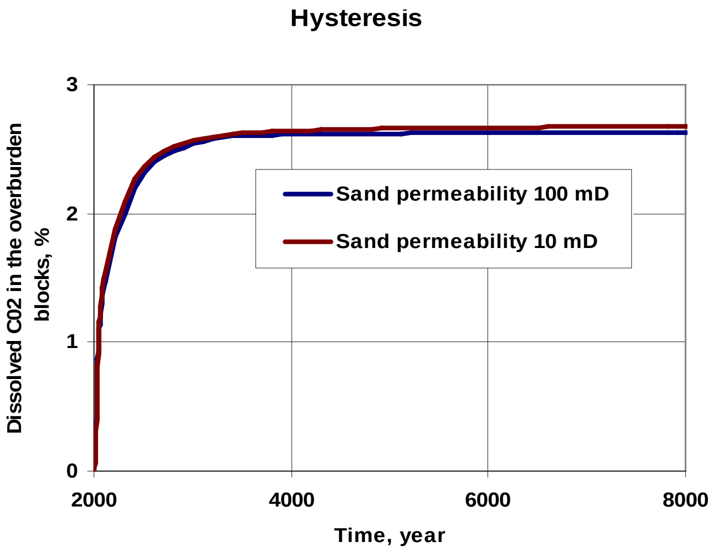


Effect of changing sand body permeability in the overburden shale blocks

- Decreasing permeability shows:
  - The time before steady state is reached in reservoir is longer
  - The final amount of CO_2 retained in the reservoir and/or shales is not significantly affected;
    - Due to the increased contact time between CO_2 and water

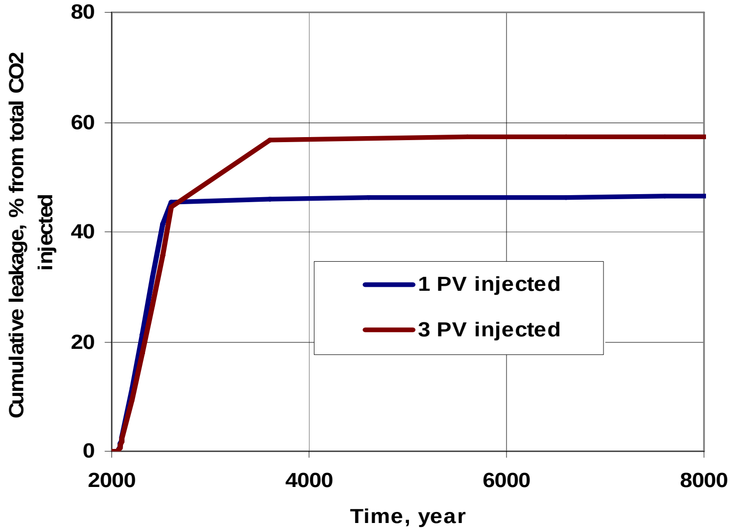






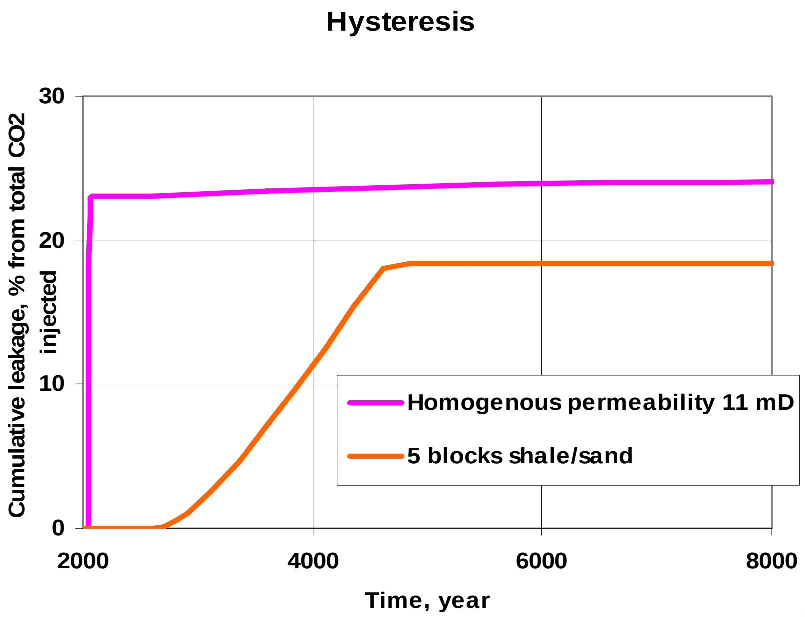
Effect of increasing amount of injected CO_2

- Increasing amount of injected CO_2 from 1 to 3 PV:
  - The total fraction of escaped CO_2 increases from 46% to 54%
  - CO_2 as free gas present for longer period of time in the reservoir
  - Fraction of gas retained in dissolved state in reservoir / overburden blocks is smaller



Effect of up-scaling the shale blocks

- If each shale block is replaced with a block of layers with the average vertical permeability of the shale block of 11.6 mD, the movement of CO_2 changes character completely:
  - The injected CO_2 immediately starts to rise through the low-permeable block of layers;
  - Since hysteresis is included, and since the injected CO_2 still contacts a large amount of water, the total escape is not much larger than for the model with overburden shale blocks;



Generalisation of simulation results into an analytical equation

We searched for an analytical equation which can provide the following information:

- **Offset time** before any leakage is observed at the surface/sea bottom
- **Total leakage** declining with increasing offset time
- **Leakage rate** profile characteristic for each mechanism

Generalisation of simulation results into an analytical equation

We found that one possible equation for the leakage having characteristics mentioned on previous slide could be a gamma distribution function multiplied by a constant A, to give the total escape from present to infinity. Including offset time $t_0 > 0$ the equation can be written:

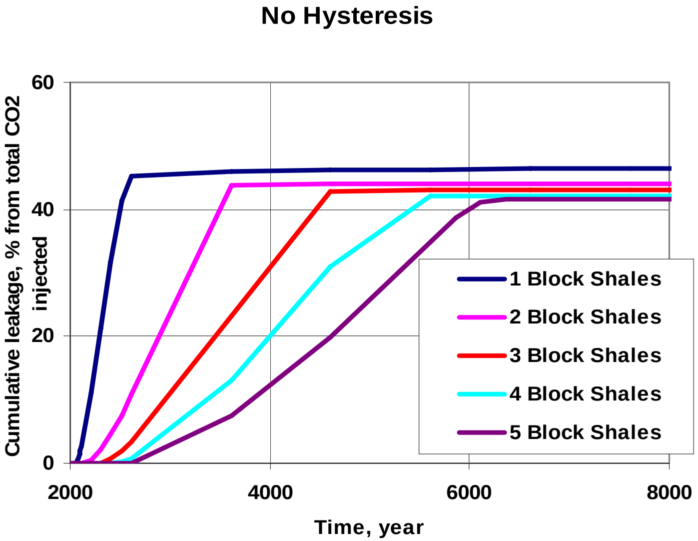
$$f(t,\alpha,\beta) = \frac{A}{\beta^{\alpha}\Gamma(\alpha)}(t-t_0)^{\alpha-1}e^{-\frac{t-t_0}{\beta}}$$

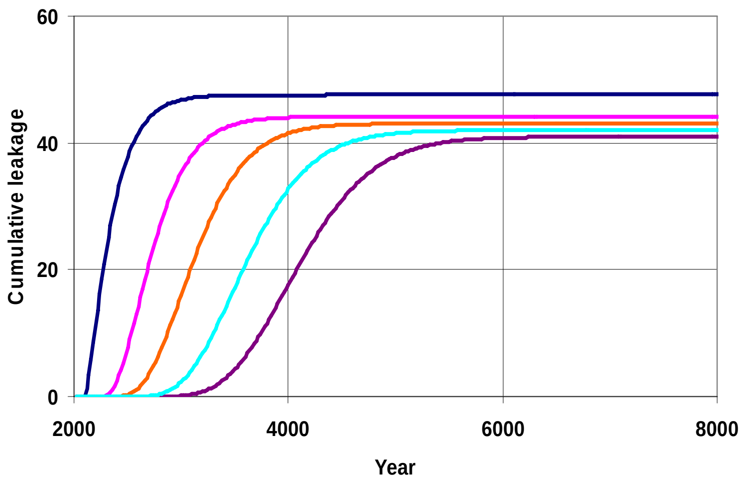
The mean of the distribution is $\mu = \alpha\beta + t_0$ and the spread of the distribution can be characterised by the standard deviation $\sigma = \beta\sqrt{\alpha}$

The dependence of A on the offset time can be defined by formula $A = A_0 e^{-t_0/\tau}$

❑ Above equation is not unique. It can provide offset time before leakage, total cumulative leakage and leakage rates, but there may be other functions which can give the same information and results.

Representation of the distribution function for different parameters





$$f(t,\alpha,\beta)=\frac{A_0 e^{-t_0/\tau}}{\beta^{\alpha}\Gamma(\alpha)}(t-t_0)^{\alpha-1}e^{-\frac{t-t_0}{\beta}}$$

- Curves represented in the right picture have been obtained for different $t_,$ α and β
- τ is set to 2000 years and A_0= 0.5 , is considered suitable for the leakage without hysteresis

Summary and conclusions

- It has been developed a conceptual model of leakage through a percolating network of permeable bodies in the overburden. Some caprock well logs indicate that the mechanisms studied in this work are relevant for CO_2 storage.

- It has been developed a simulation model for study of this leakage mechanism, and examined sensitivity to parameters variation.

- It has shown that the calculated leakage rates may be approximated by simplified expressions. This would allow a Monte Carlo simulation of storage quality and determine cumulative leakage rates for a large collection of storage sites.

- The results will be useful for input into calculations of climate effects of non-perfect storage. This will in turn be used to determine the requirements for storage quality.

Acknowledgements

- This publication forms a part of the BIGCO2 project, performed under the strategic Norwegian research program Climit.
- The authors acknowledge the partners: StatoilHydro, GE Global Research, Statkraft, Aker Kværner, Shell, TOTAL, ConocoPhillips, ALSTOM, the Research Council of Norway (178004/I30 and 176059/I30) and Gassnova (182070) for their support.

Thank You for Attention!
Questions?...