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CO_2 geological storage

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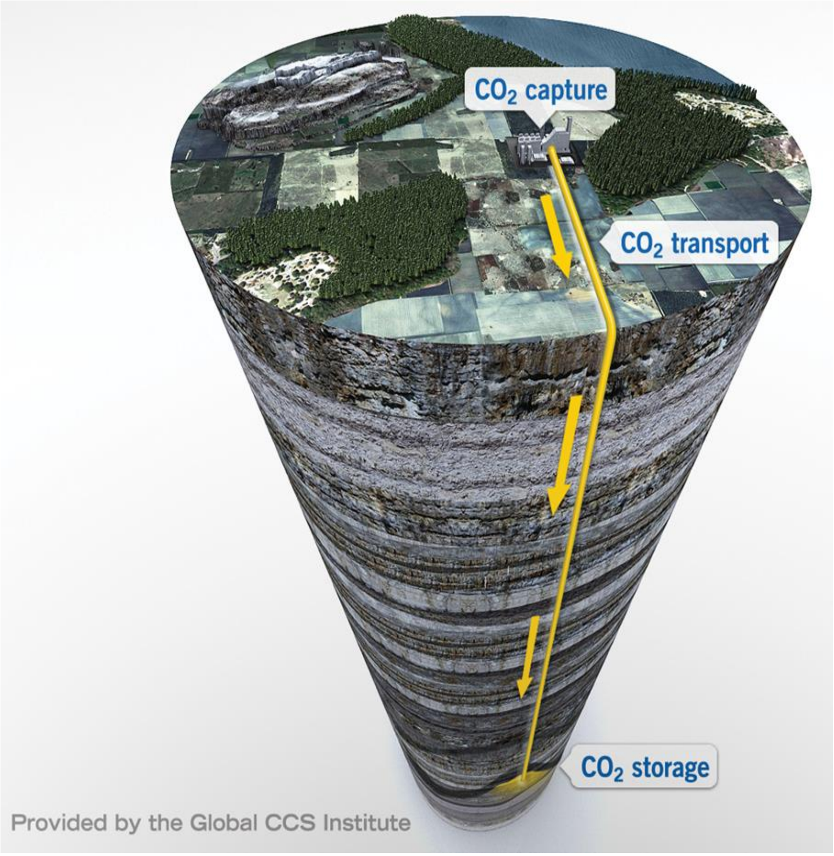
Outline

- what is CCS
- role for global climate goals and present status
- key processes

- Example 1: Determining residual trapping in-situ
- Example 2: How to model CO_2 injection and storage in large scale



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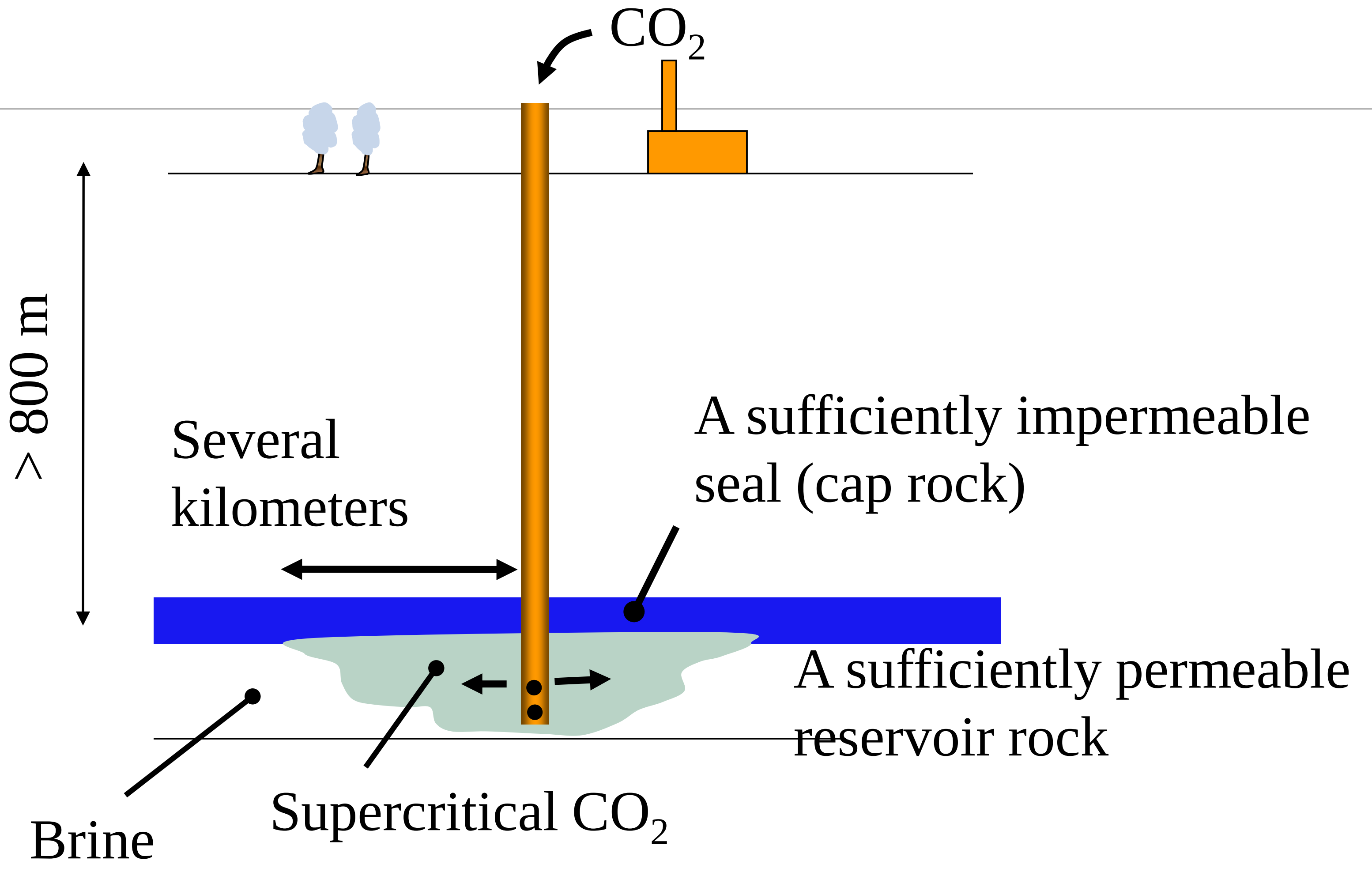
Principle of CCS



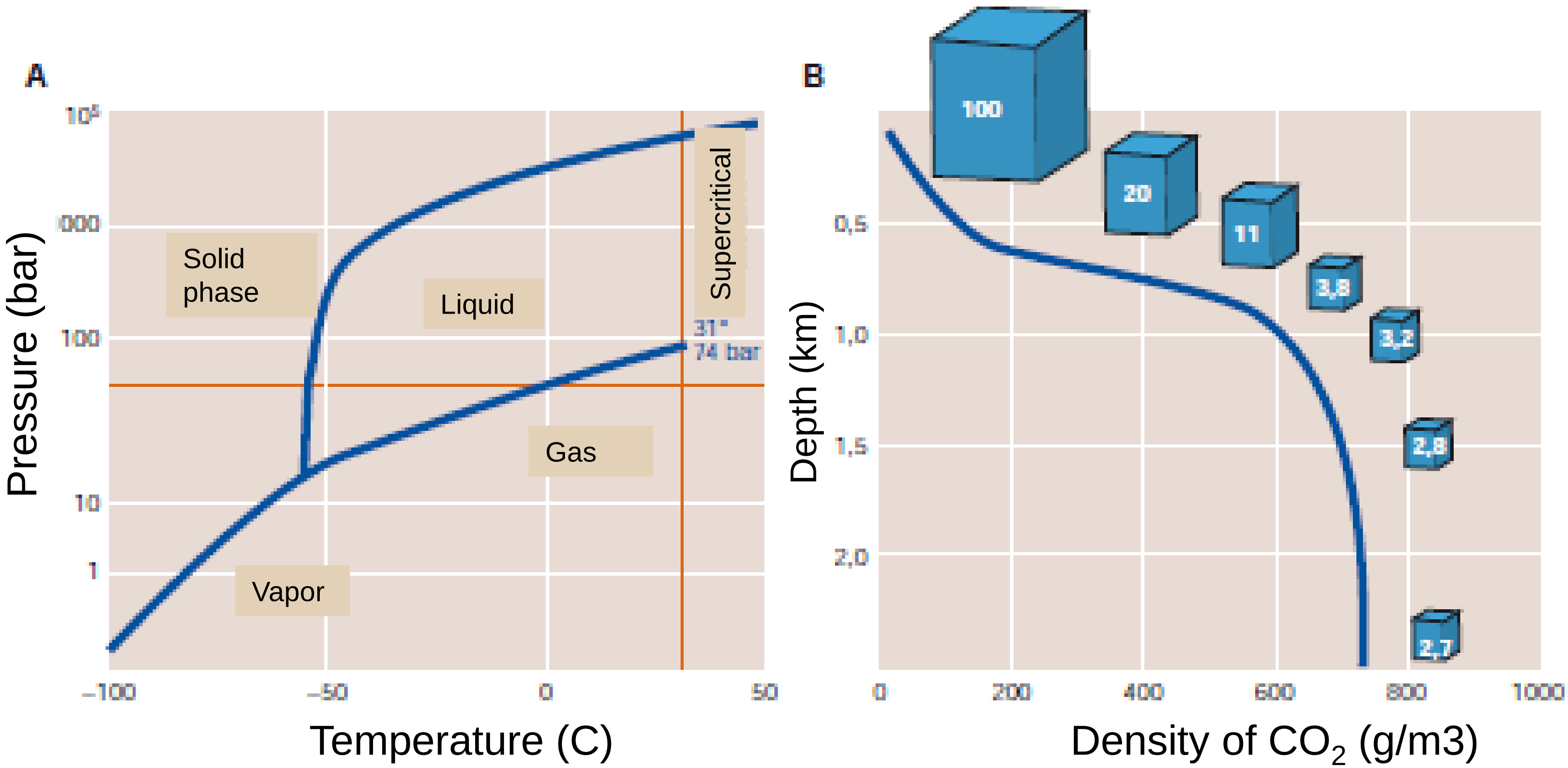
-Density: $\rho CO2/ \rho brine \approx 0.2\text{-}1.0$

-Viscosity: $\mu CO2/ \mu brine \approx 0.03\text{-}0.1$

-Supercritical CO2 an excellent solvent

-Subtle phase changes during leakage

Conditions such that CO_2 naturally in supercritical form – volume decreases



adapted from IPCC, 2004

Estimate of role of CCS in reducing atmospheric CO_2

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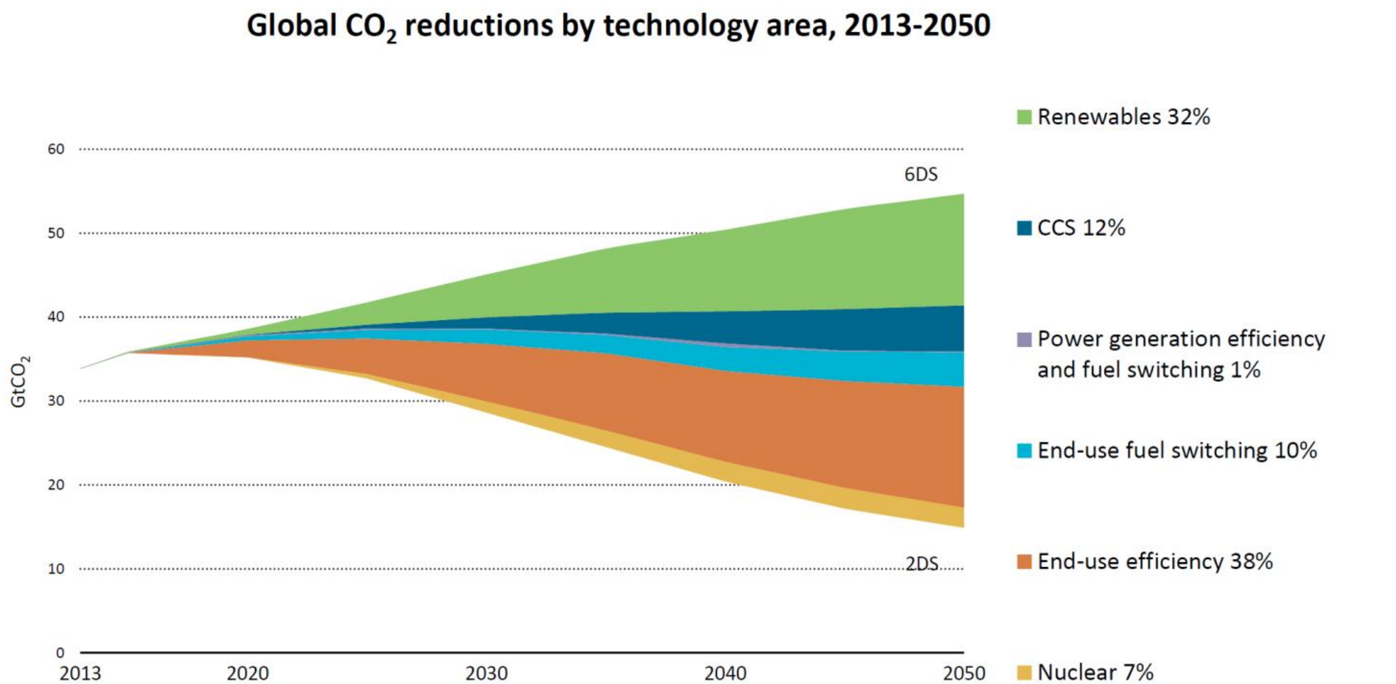
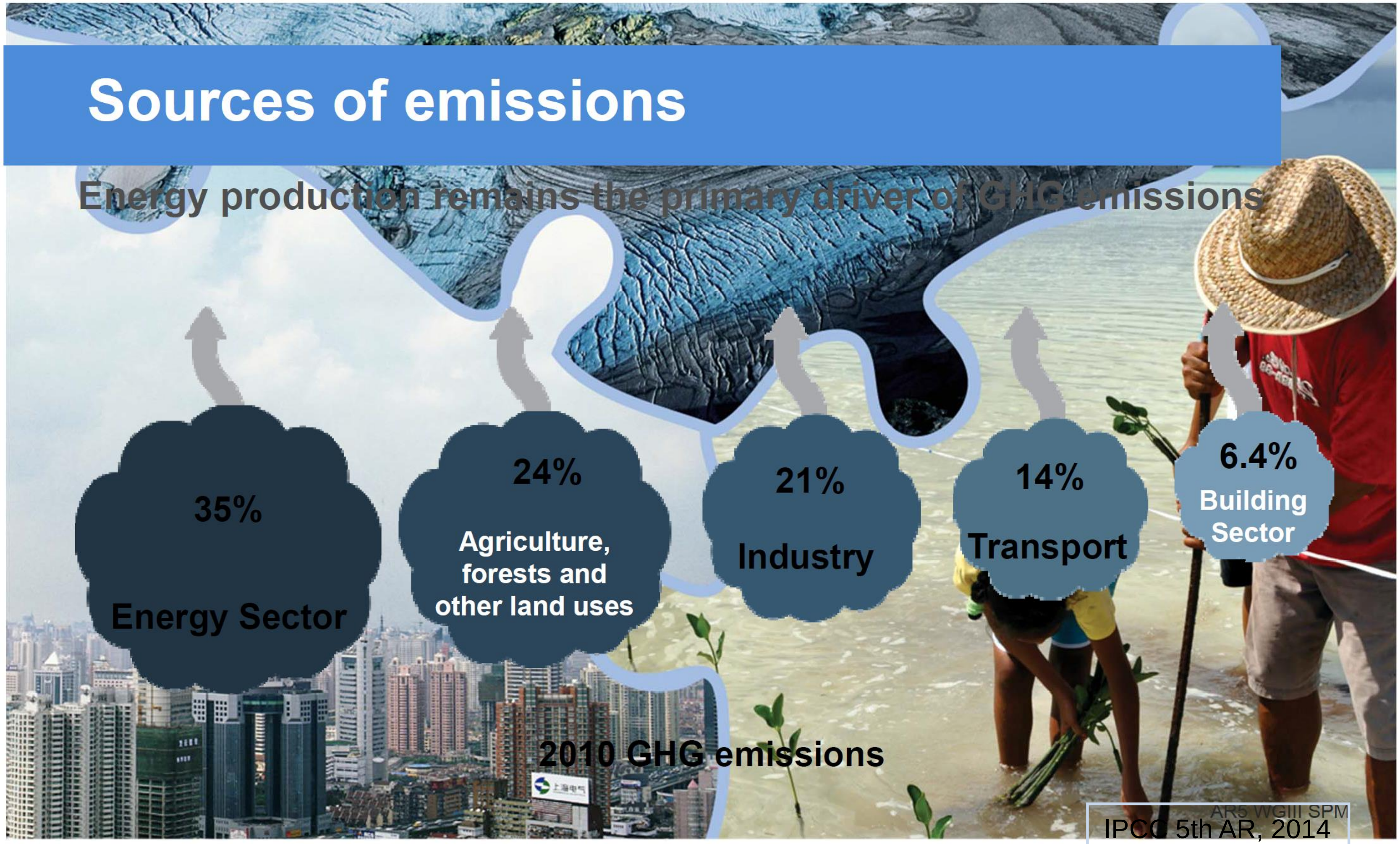
- **IEA ETP**: CCS plays a key role in 2℃ scenario



Source; Tim Dixon, IEAGHG, May 2017

- **Global CCS Institute** assesment (*Major strides in 2017 for CCS*): CCS critical if Paris Agreement climate goals are to met.

Sources of emissions



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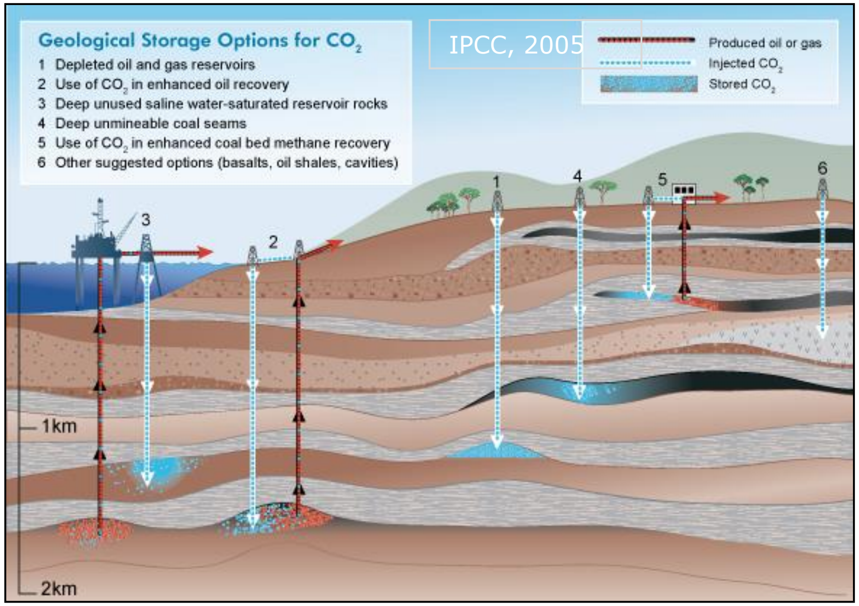
Options for Geological Storage



- deep saline aquifers
- depleted oil and gas fields
- unmineable coal seams
- other options (e.g. basalts)

Depleted oil/gas fields:

- Well understood, lot of data, EOR possibility, proven capability to hold hydrocarbons
- Extensively drilled (leaks?), not sufficient volumetric capacity

Deep saline formations

- Largest overall capacity
- Less previous data, not as well demonstrated (sealing capacity)

Saline aquifers

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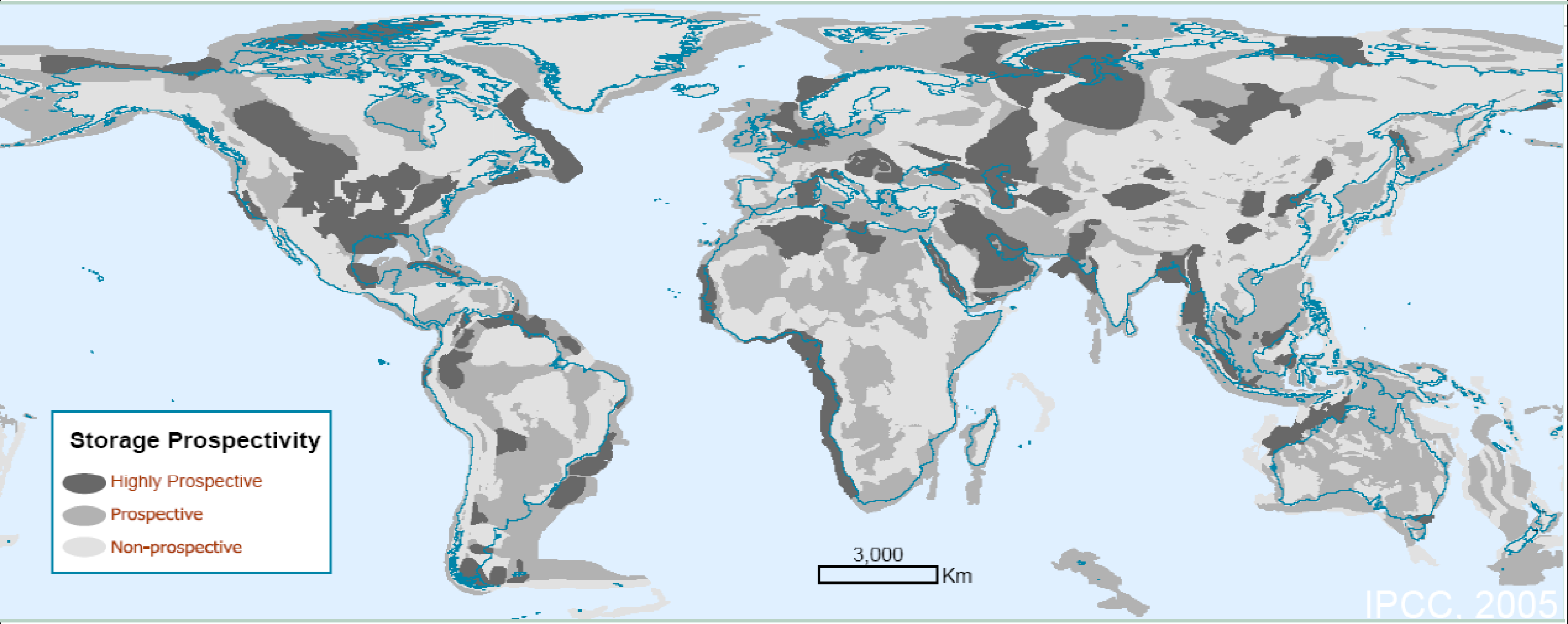
(Geological formations containing water that is too brackish for potable purposes)



Current global estimates suggest CO_2 storage capacity in saline aquifers could be as large as 10,000 billion tonnes.

175 billion tonnes worth of storage would allow us to halt the rate in growth of global emissions for around 50 years.

Mathias, S. 2017

Global CCS facilities in operation or under construction for permanent storage

Source: Global Status of CCS 2017; Global CCS Institute

1 BSCSP Basalt	16 MGSC Sugar Creek EOR Phase II	31 SECARB - Stacked Storage Project Cranfield Phase II
2 Carbfix	17 MGSC Tanquary ECBM Phase II	32 SECARB - Mississippi Saline Reservoir Test Phase II
3 CarbonNet	18 Mountaineer	33 South West Hub (Collie South West Hub)
4 CIDA China	19 MRCSP Appalachian Basin (Burger) Phase II	34 Surat Basin CCS Project (Previously Wandoan)
5 CS Energy Callide Oxyfuel Project	20 MRCSP Cincinnati Arch (East Bend) Phase II	35 SWP San Juan Basin Phase II
6 CSEMP	21 MRCSP Michigan Basin Phase II	36 Teapot Dome, Wyoming
7 Fenn/Big Valley	22 Nagaoka Pilot CO2 Storage Project	37 Total Lacq
8 Frio, Texas	23 Otway I (Stage I)	38 West Pearl Queen
9 JCOP Yubari/Ishikari ECBM Project	24 Otway II Project (Stage 2A,B)	39 WESTCARB Arizona Pilot (Cholla)
10 K12B	25 PCOR Lignite	40 WESTCARB Northern California CO_2 Reduction Project
11 Ketzin	26 PCOR Williston Basin -Phase II (NE Mcgregor Field)	41 WESTCARB Rosetta-Calpine test 1
12 Marshall County	27 PennWest Energy EOR Project	42 WESTCARB Rosetta-Calpine test 2
13 Masdar/ADCO Pilot project	28 Recopol	43 Western Kentucky
14 MGSC Ioudon Field EOR Phase II	29 SECARB - Black Warrior Basin Coal Seam Project	44 Zerogen Project
15 MGSC Mumford Hills EOR Phase II	30 SECARB - Central Appalachian Coal Seam Project	

Compliments: John Gale, IEAGHG

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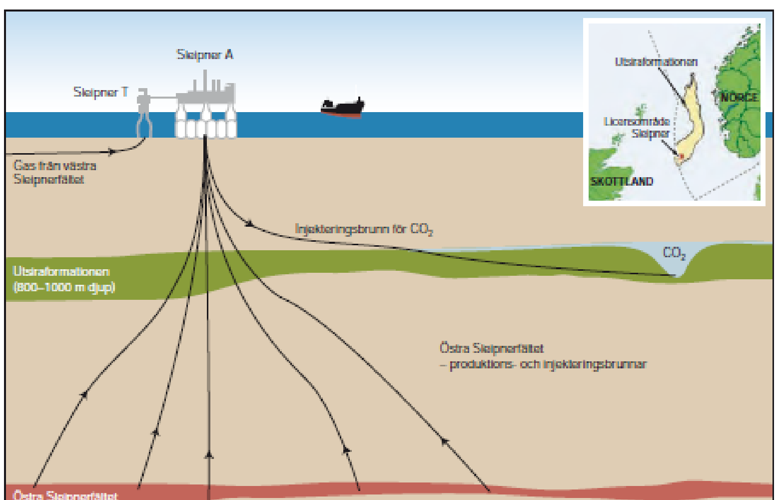
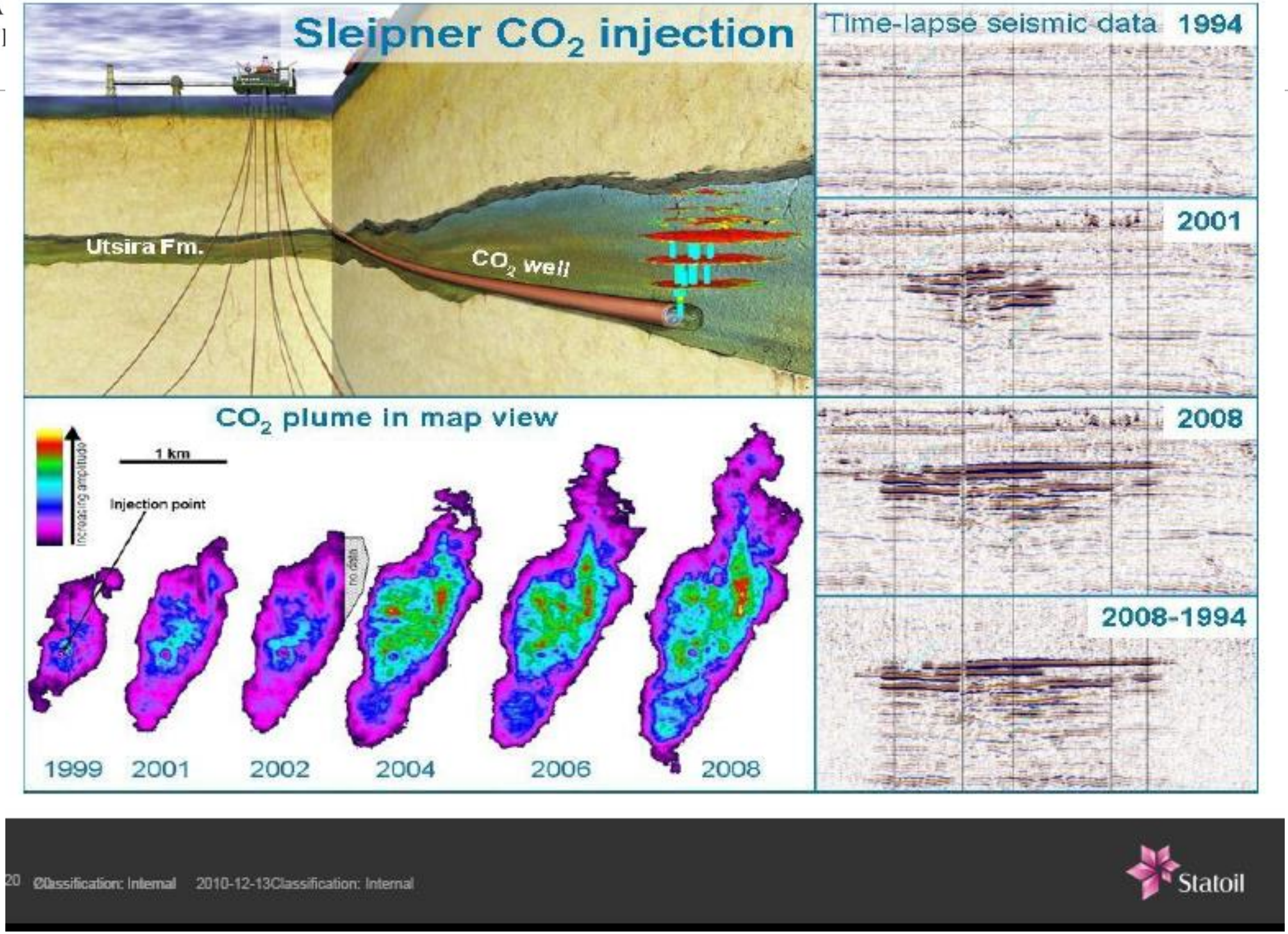
Example of flagship industrial project - Sleipner (North Sea)

- longest running environmentally motivated CCS project
- operating since 1996
- Ideal storage reservoir (uniform, thick, extensive, high porosity, high permeability reservoir layer, thick seal of shale

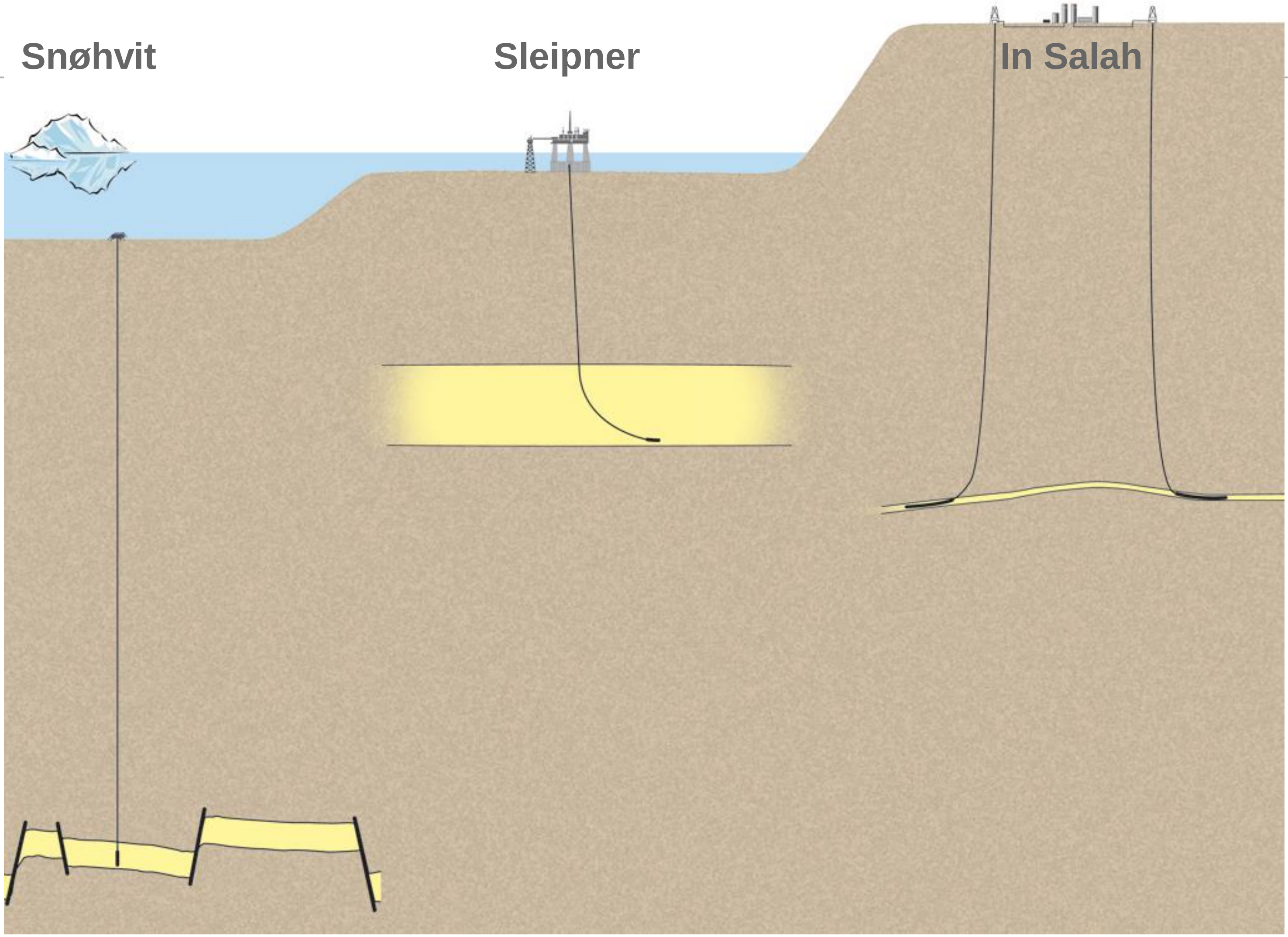


Seismic monitoring to observe the plume at Sleipner



T. Torp, 2011

Statoil's CO_2 Storage Sites



Compliments; Tore Torp/ Statoil

How is CO_2 stored in the deep aquifer?

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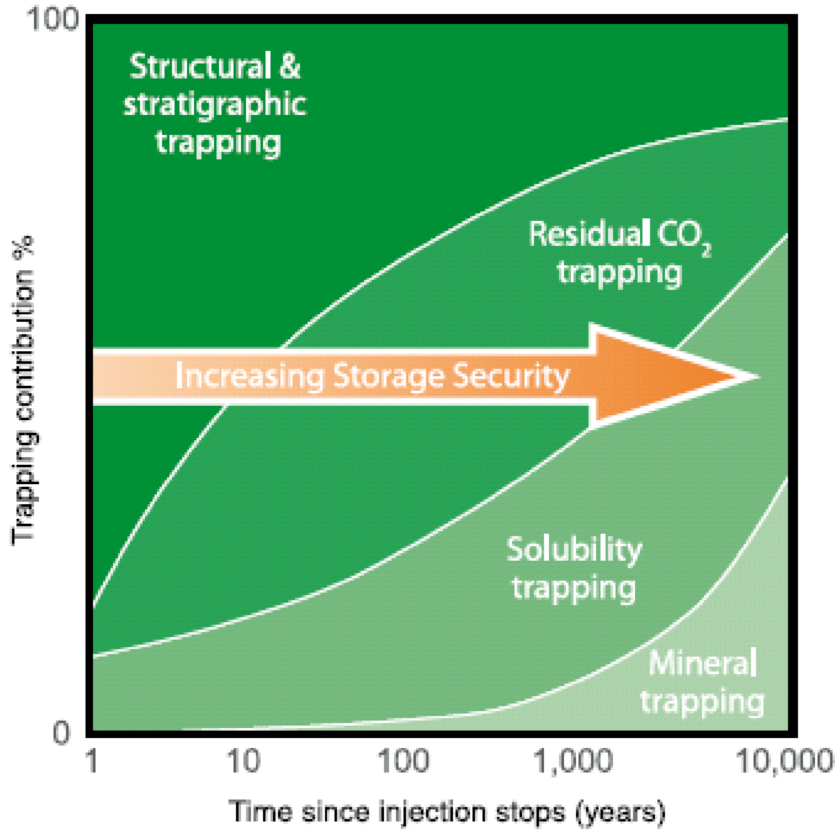
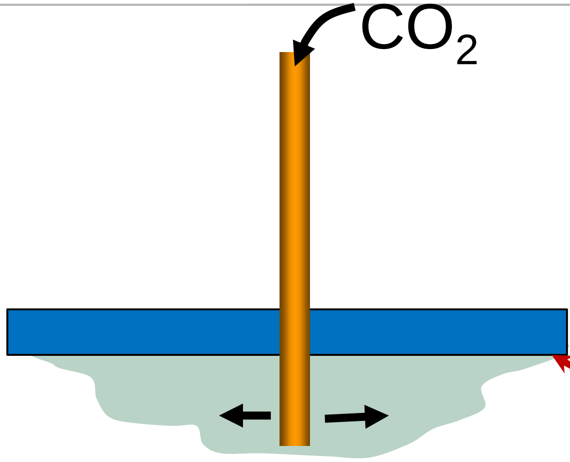


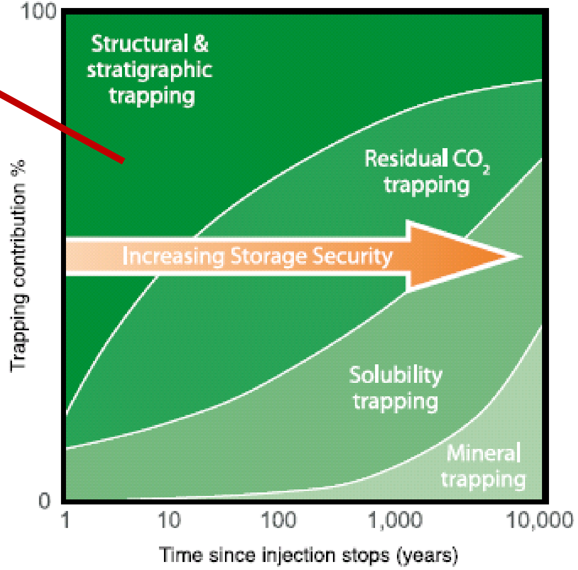
Figure 5.9 Storage security depends on a combination of physical and geochemical trapping. Over time, the physical process of residual CO_2 trapping and geochemical processes of solubility trapping and mineral trapping increase.

IPCC (2005)

How is CO_2 stored in the deep aquifer?



CO_2 gets physically trapped beneath the sealing cap-rock and low permeability layers



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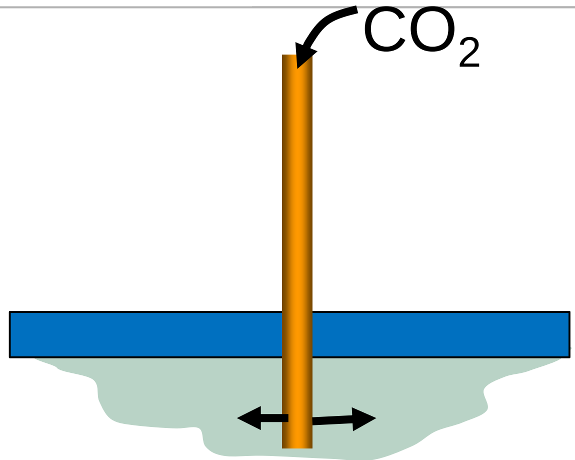

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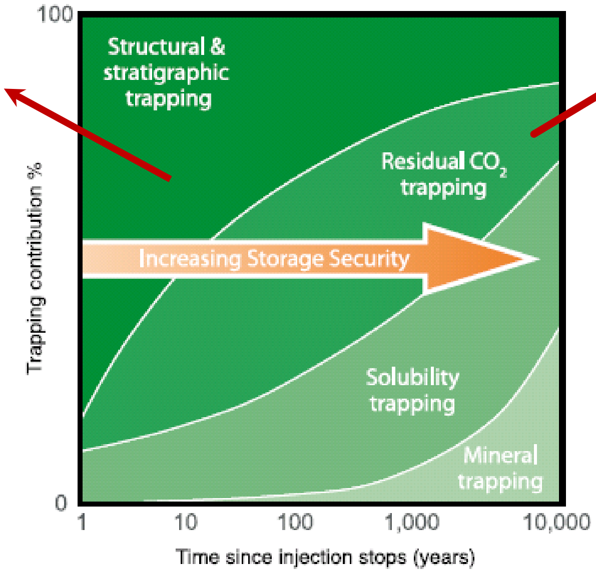

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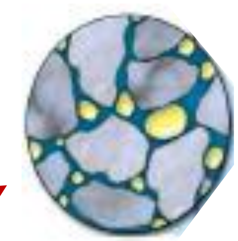
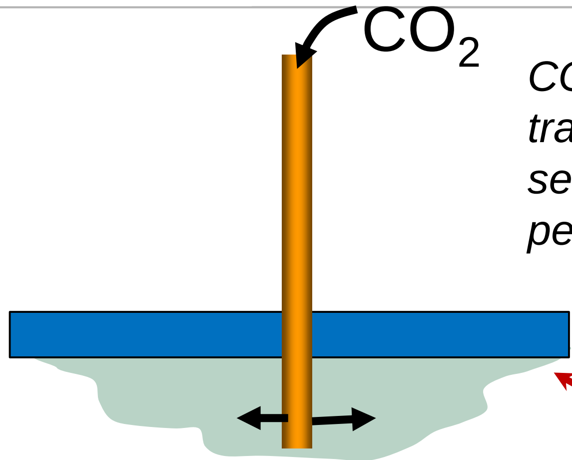


CO_2 gets trapped as immobile isolated residual ’blobs’ in the pore space

How is CO_2 stored in the deep aquifer?



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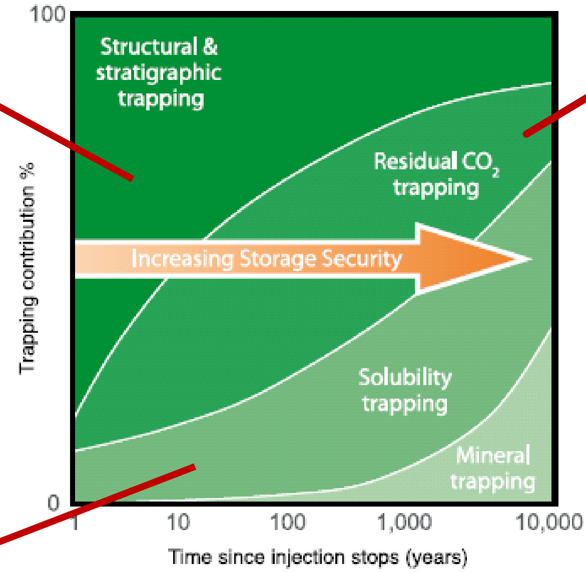

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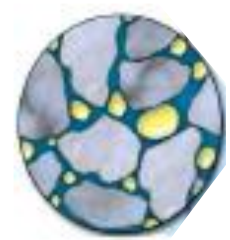
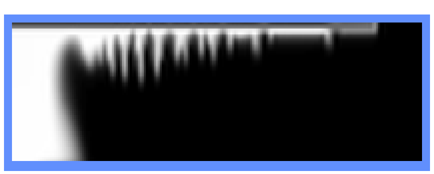


CO_2 gets trapped as immobile isolated residual 'blobs' in the pore space

CO_2 dissolves into water



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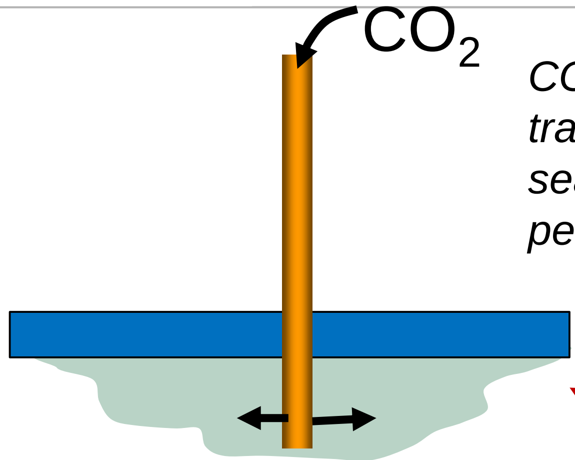
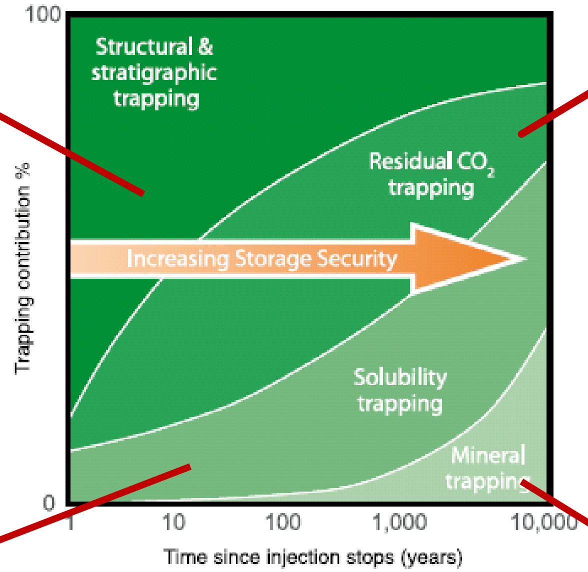


CO_2 gets physically trapped beneath the sealing cap-rock and low permeability layers



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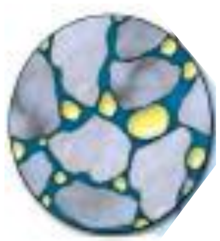

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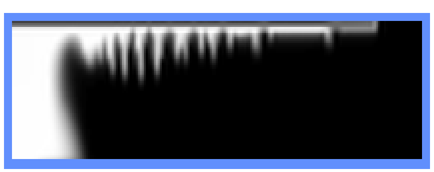
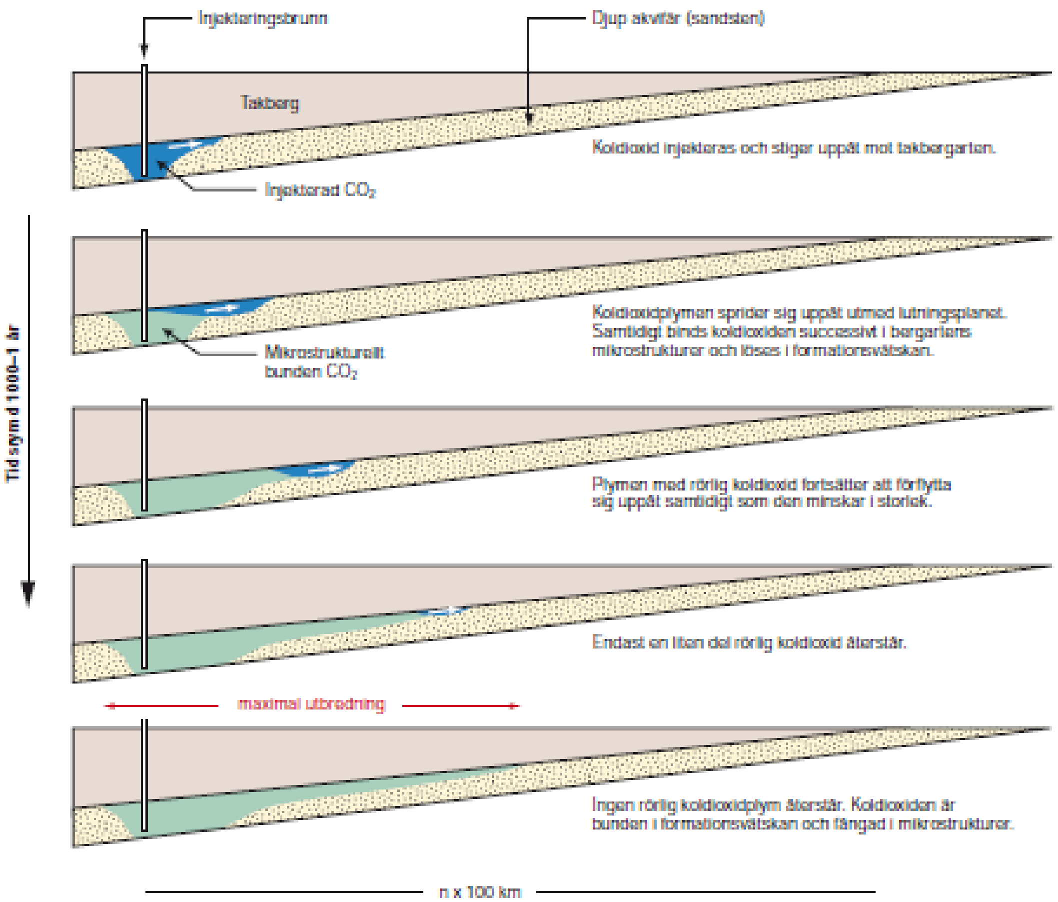
CO_2 dissolves into water



CO_2 converts into solid minerals

Evolution from mobile to residual CO_2



Erlström et al, SGU (Swedish Geological Survey) report 131

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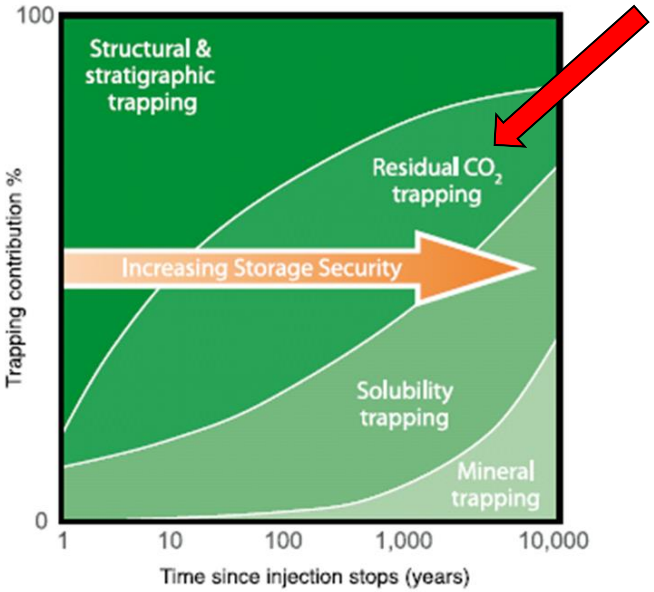
Processes to be modelled

- multiphase non-isothermal flow of brine and CO_2 (TOUGH2/ECO2N, ECLIPSE, PFLOTRAN)
- coupled to hydromechanics (important not to damage the cap-rock, or to create induced seismicity) (TOUGH2/FLAC 3D)
- coupled to reactive chemistry (dissolution and precipitation processes) (TOUGHREACT)
- special challenge: large scale of the domains to be modelled, while the key underlying processes are affrected by small-scale behavior (approaches of increasing accuracy: simplified analytical/semianalytical models > full 3D models e.g. TOUGH-MP)

For TOUGH codes see:http://esd1.lbl.gov/research/projects/tough/

Determining residual trapping

- Residual saturation is a site specific property and its magnitude has a big impact on storage capacity
- Can be determined
  - in the laboratory on core samples
  - from field experiments
- We address this at Heletz, Israel CO_2 injection site data



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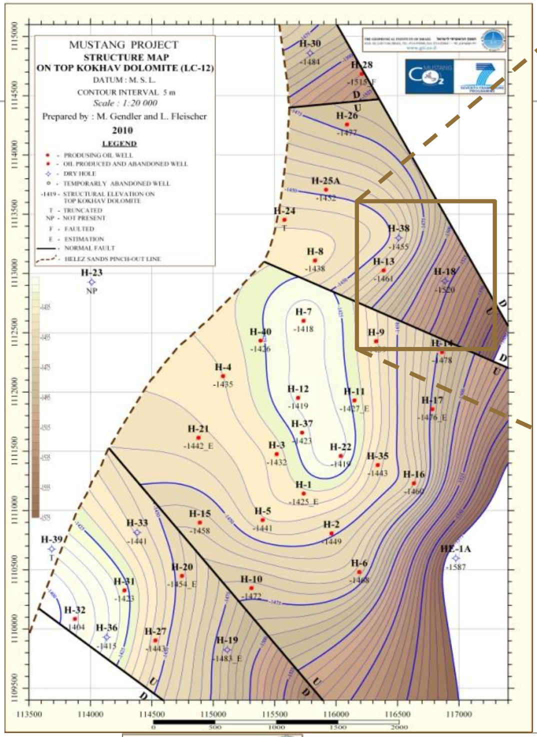
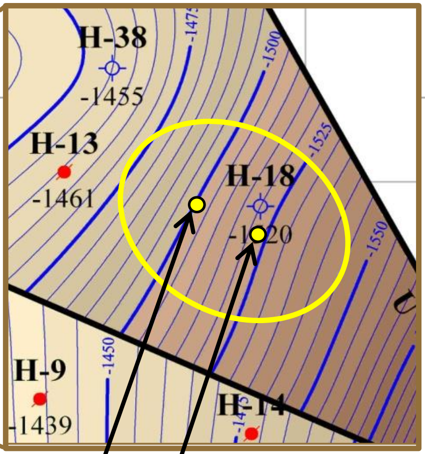
Heletz CO2 injection site

- Scientifically motivated CO_2 injection experiment site of scCO2 injection to a reservoir layer at 1600 m depth, with comprehensive monitoring and sampling
- Developed in the frame of EU FP7 projects MUSTANG and TRUST
- Well characterized

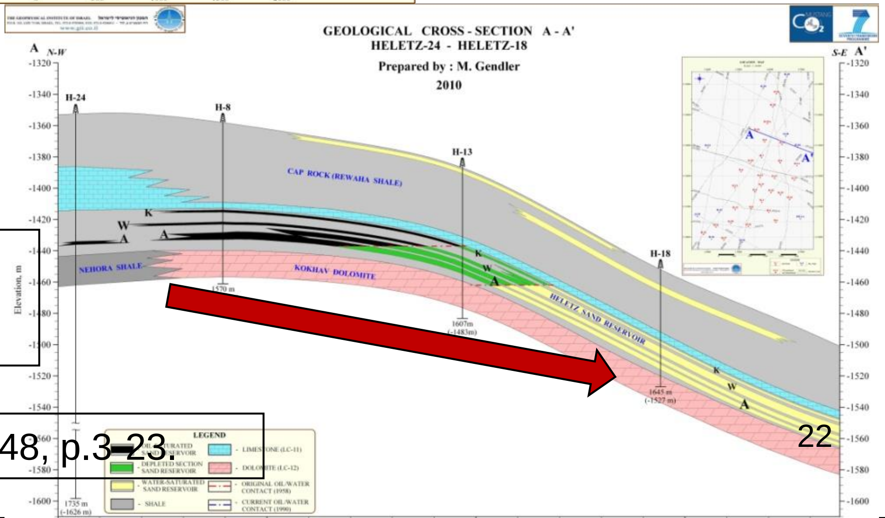
Heletz



Heletz North



wells for CO2 injection experiments

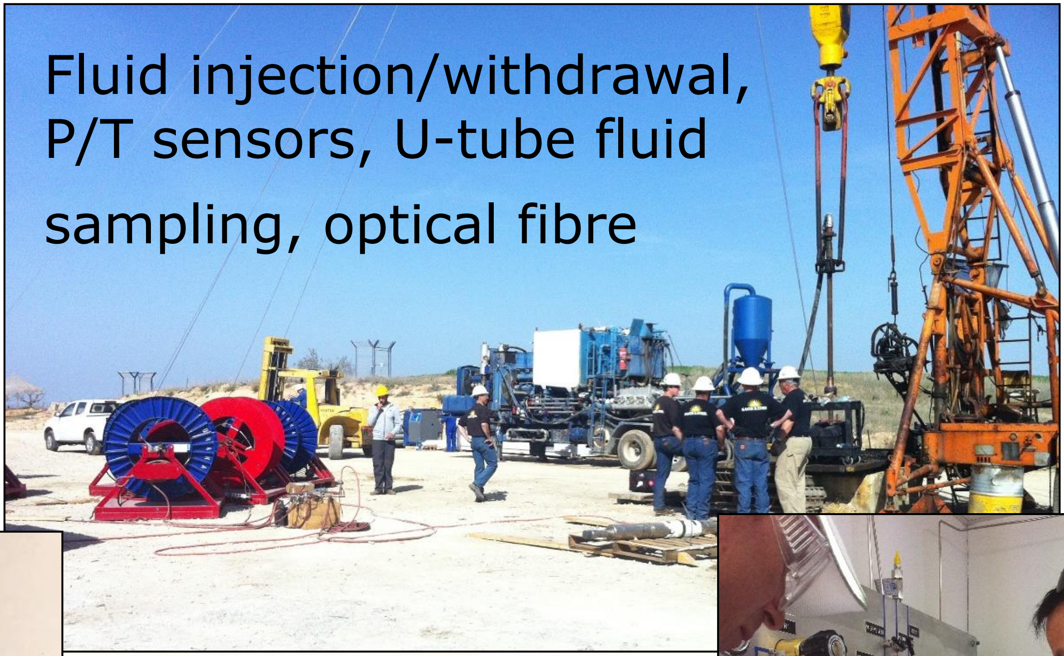


Target reservoir layers of total ~11 m thickness

Niemi et al (2016) Intnl Jour Greenhouse Gas Cntrl, Vol. 48, p.3-23

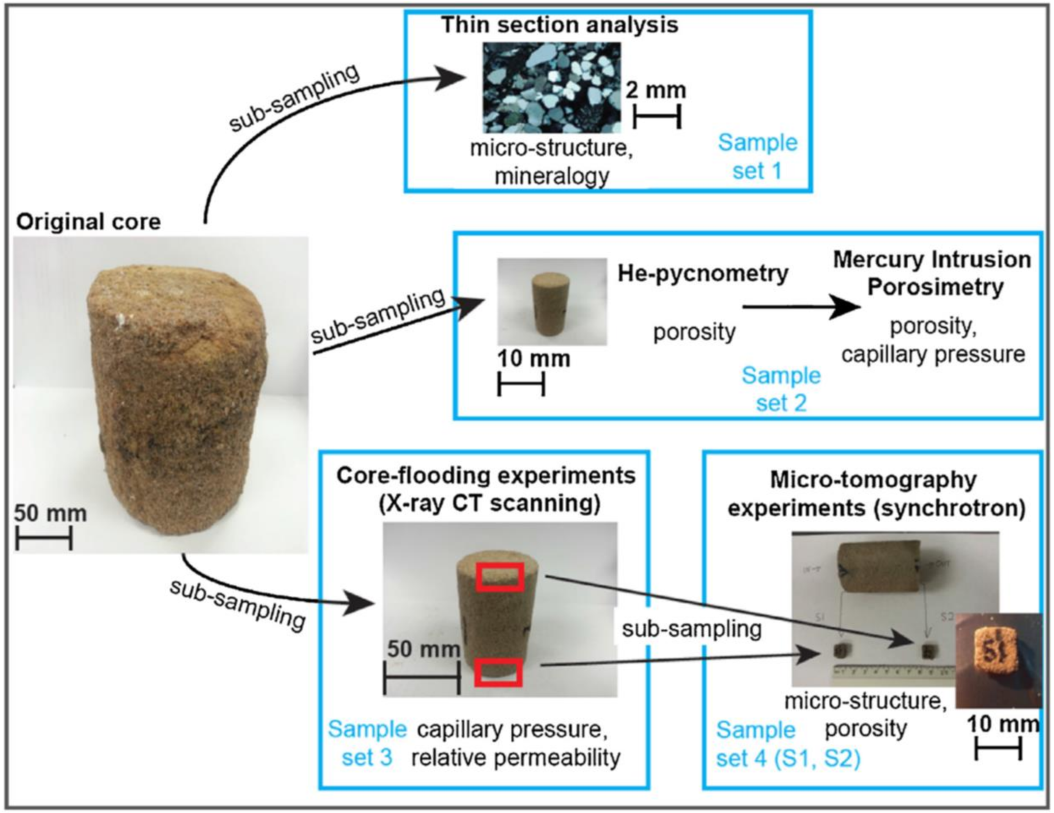
Heletz – well instrumentation and injection system

Fluid injection/withdrawal, P/T sensors, U-tube fluid sampling, optical fibre

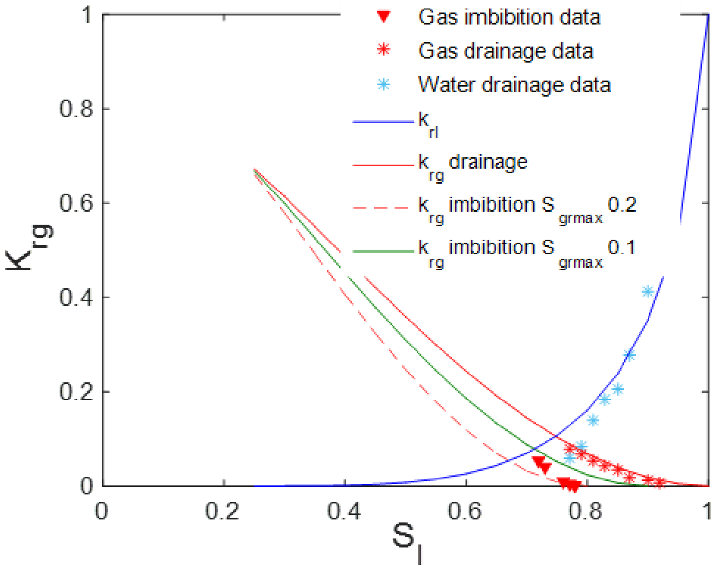


Determining residual saturation in the laboratory

- work flow for the laboratory analysis (Hingerl et al., 2016)



- laboratory determined relative permeability functions for Heletz cores (Hingerl et al., 2016)



Hingerl et al. (2016) Intnl Jour Greenhouse Gas Cntrl, Vol 48.Pp 69-83.

Principle of determining residual trapping in-situ

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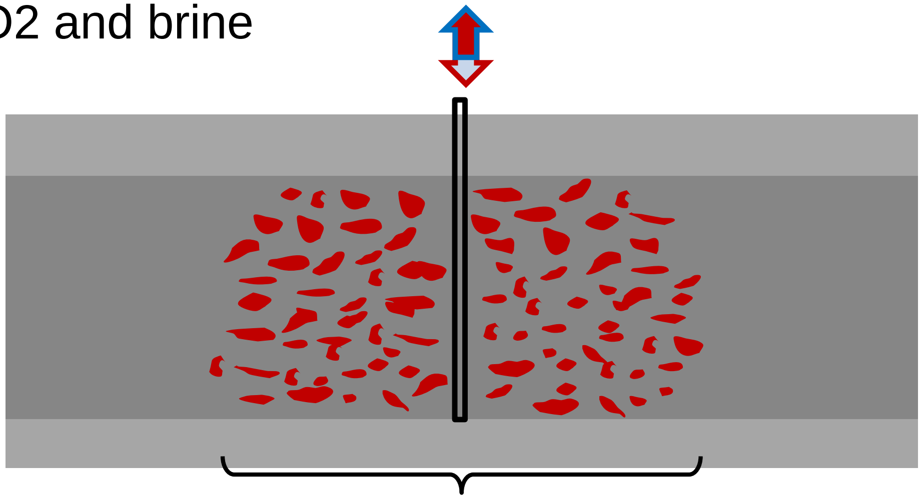


- Hydraulic tests
- Tracer tests
- Thermal tests

Estimate of residual trapping when performed with and without residually trapped CO_2

e.g. Yang et al. (2011) IJGCC Vol4, p 5044-5049, Rasmusson et al. (2014) IJGGC Vol 27, p155-168)

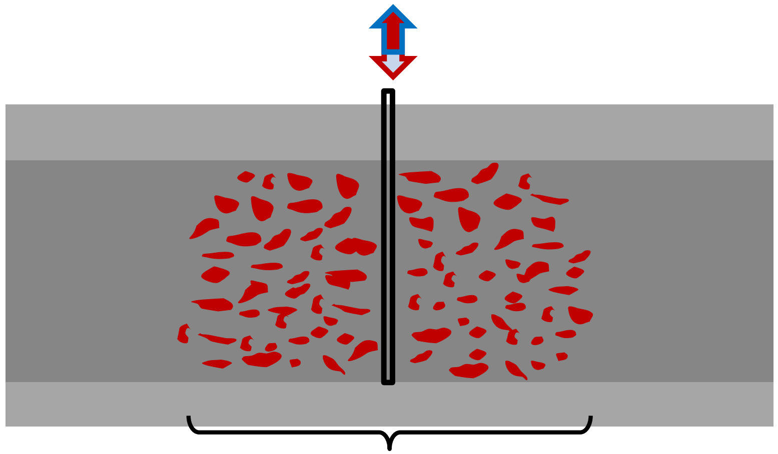
Otway, Australia experiment demonstrated that pressure signal was an effective measure for differentiating residual saturation of gas (S_{gr})

Paterson et al, 2011. CO2CRC report RPT11-3158

Creating the residually trapped zone

Option 1: Inject CO_2, then pump it back and leave the residual zone behind

Option 2: Inject CO_2, then inject CO2 saturated water to push the CO2 further and leave the residual zone behind



At Heletz, option 1 was used in first experiment, the achievement of residual zone was followed by evolution (i) tracers[1] and (ii) pressure difference in the borehole test interval (pressure difference between the upper and lower sensor relates to the fluid composition (CO2/water) in the interval, Option 2 in the second one

[1] Rasmusson et al (2014) Analysis of alternative designs for push –pull …Int. J. of Greenhouse Gas Control. Vol 27, pp 155-168

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Residual Trapping Experiment I (Sept 2016) - Test sequence

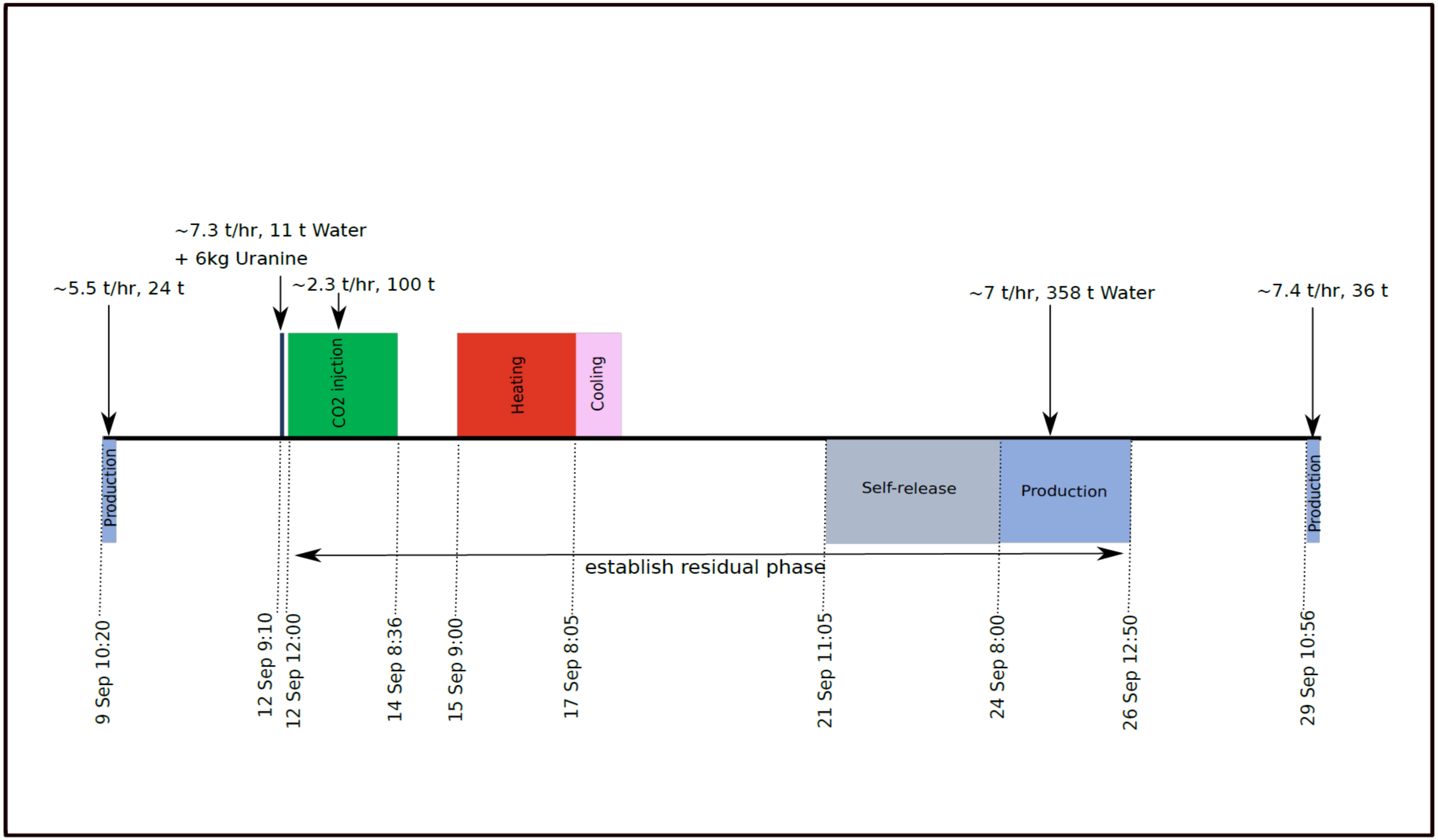
1) Hydraulic withdrawal test for getting the pressure response **prior** to creating the residual CO2 zone

2) Inject indicator tracer (Rasmusson et al, 2014)
3) Inject 100 tons of CO2
4) Withdraw of fluids **until residual saturation is reached** (follow both the tracer and the evolution of pressure difference in the well)

5) Hydraulic withdrawal test for getting the pressure response **after** creating the residual CO2 zone

- P/T was continuously monitored
- CO_2 mass flowrate, temperature, pressure and density recorded
- DTS was recorded during the entire sequence;
- Downhole fluid sampling and measurement of high pressure pH and low pressure alkalinity and gas composition, as well as measurement of partial pressure of CO_2 were measured during the production phase.

Residual Trapping Experiment I - Test sequence



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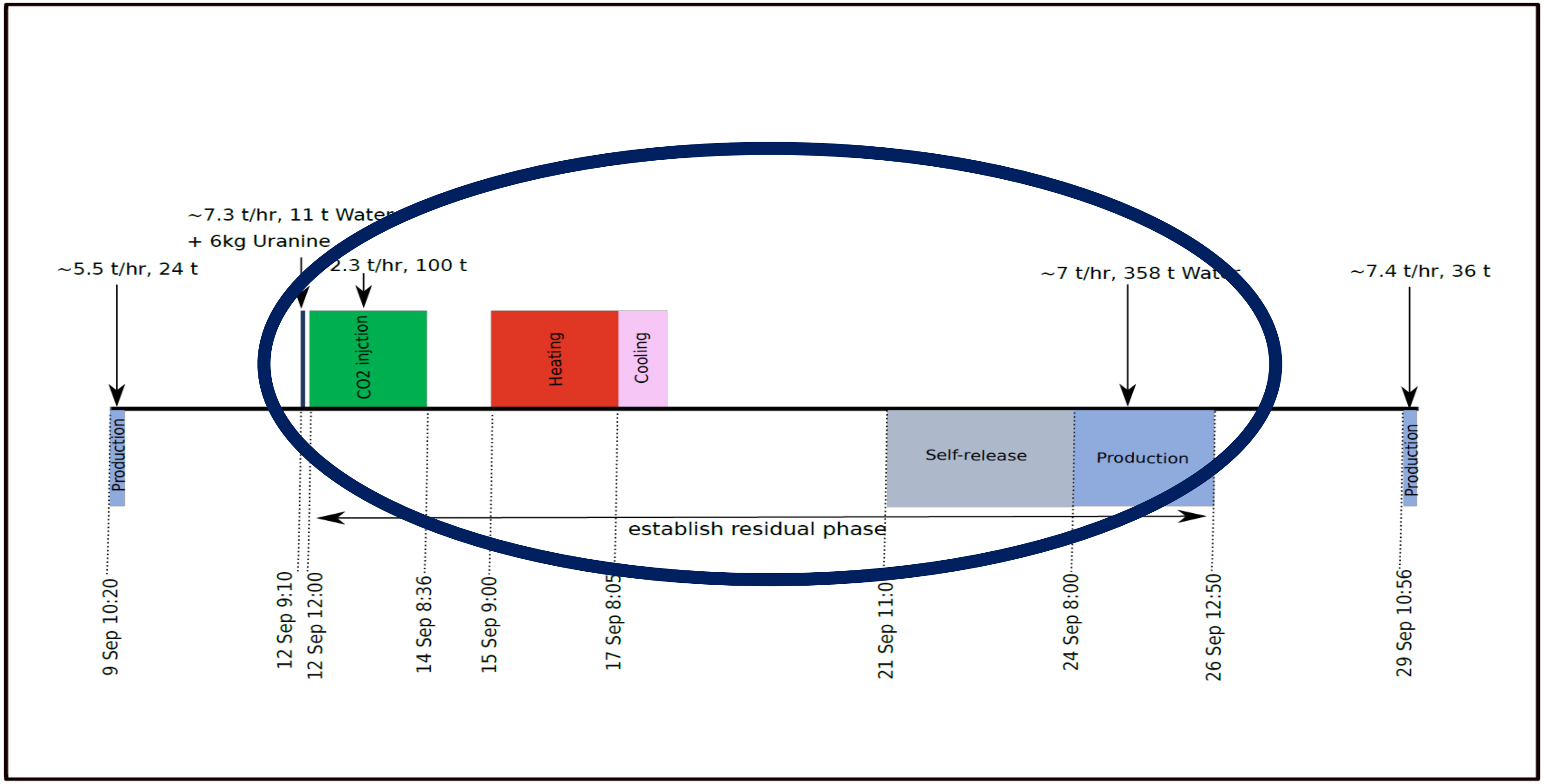
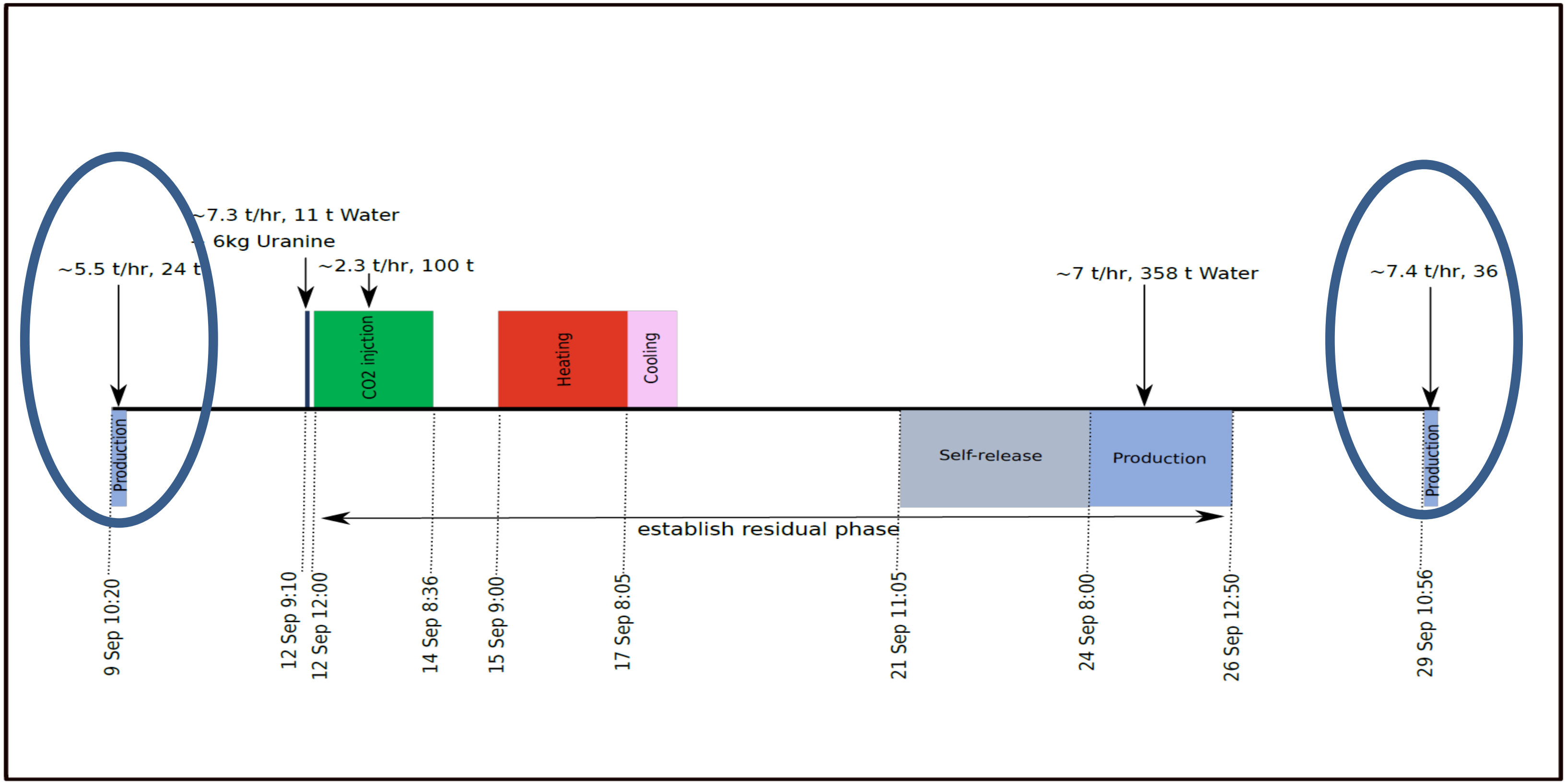


Residually trapped zone created by CO2 injection, followed by self-release and active pumping

Residual Trapping Experiment I - Test sequence



Hydraulic withdrawal/recovery tests before and after creating the residually trapped zone

Heletz - Residual Trapping Experiment I

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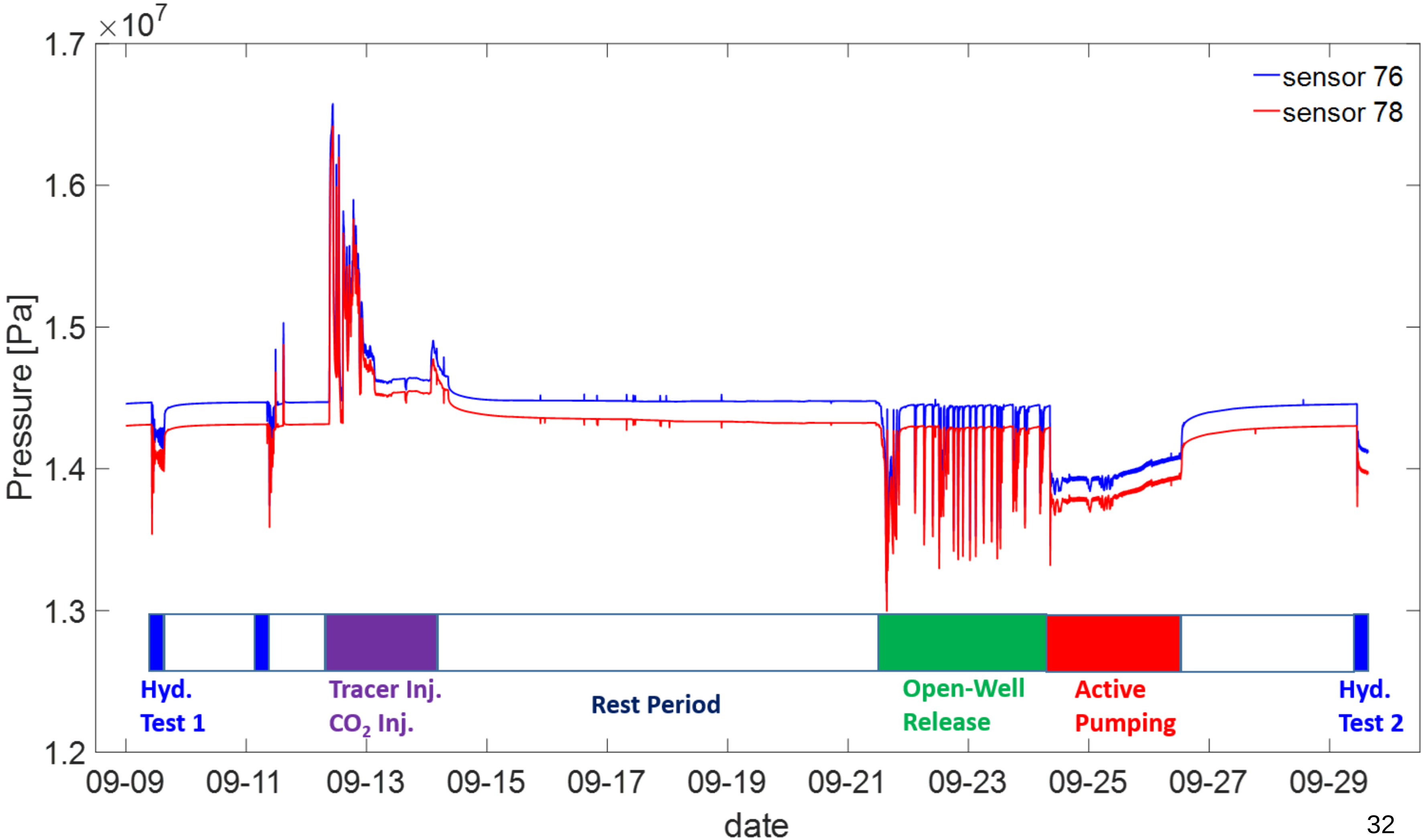
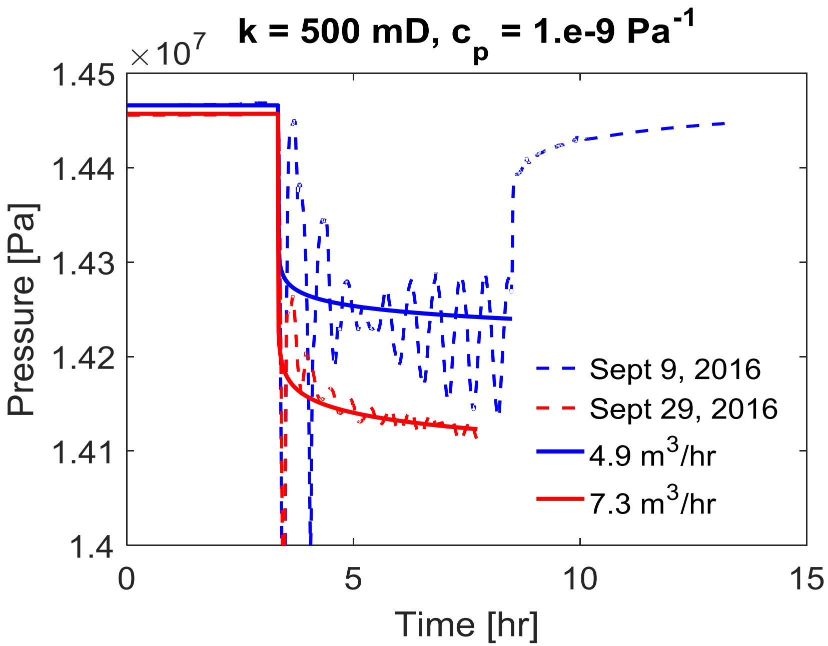
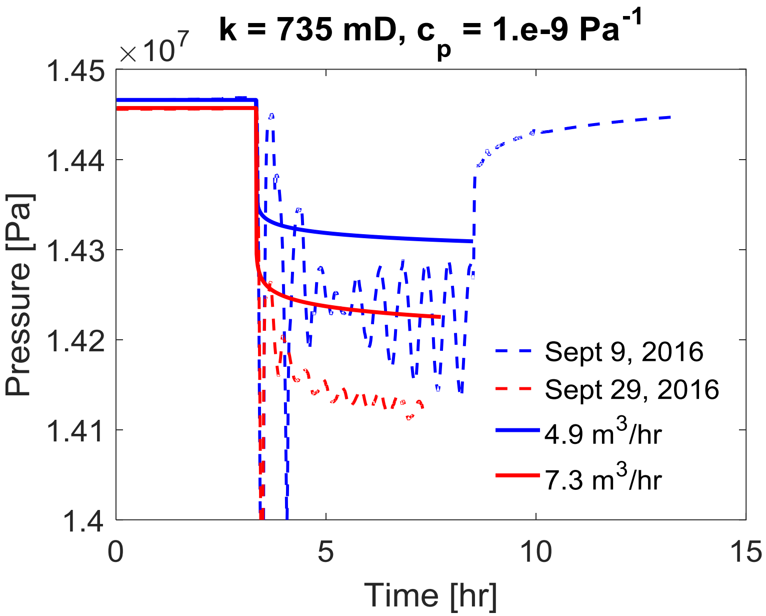
Measured pressure sequence



First estimate of the pressure response – analytical solution

- analytical solution with Theis, fit the hydraulic
test data before and after creating the residual zone





- The result indicates that there is very little effect of CO2, the difference in pressure decrease can be explained by the difference in pumping rate

Full physics TOUGH2 simulation of the entire test sequence

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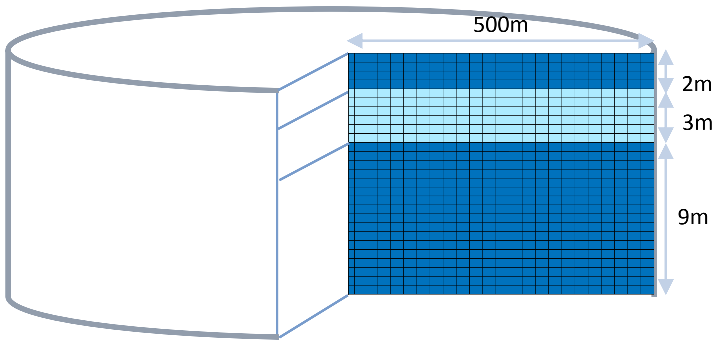
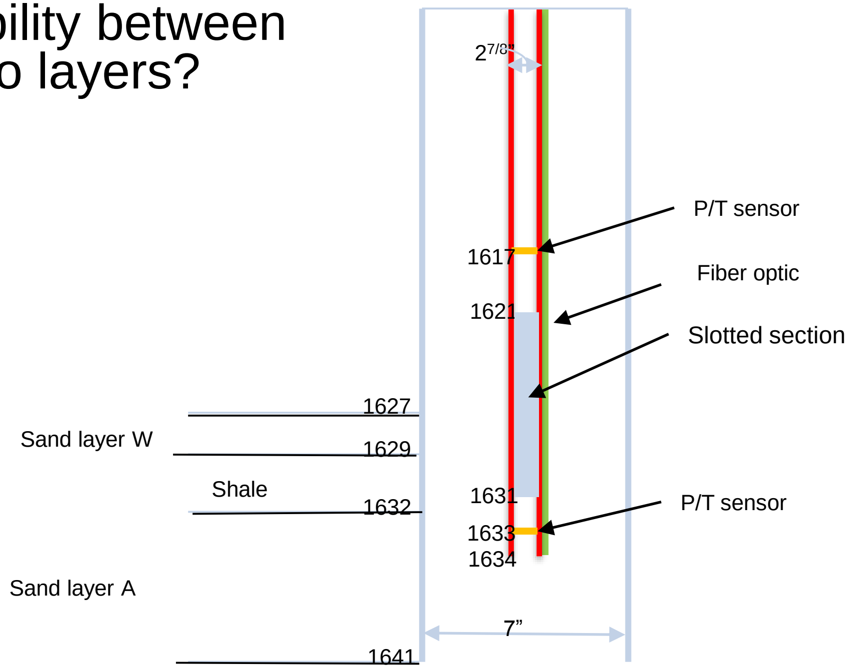
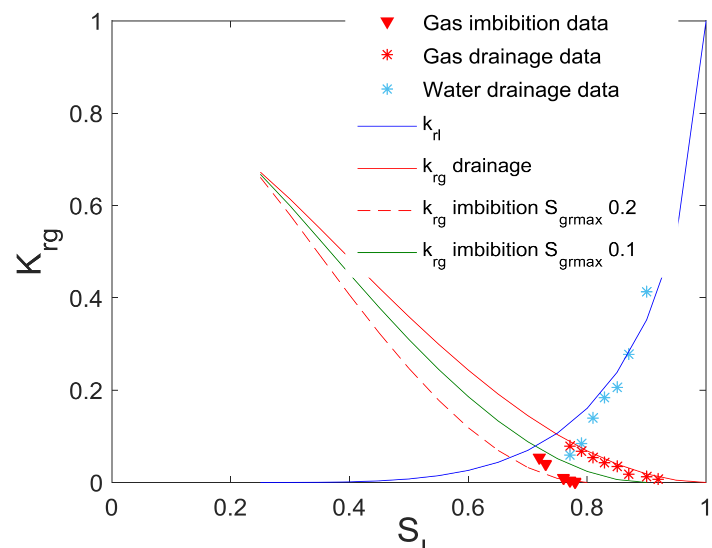
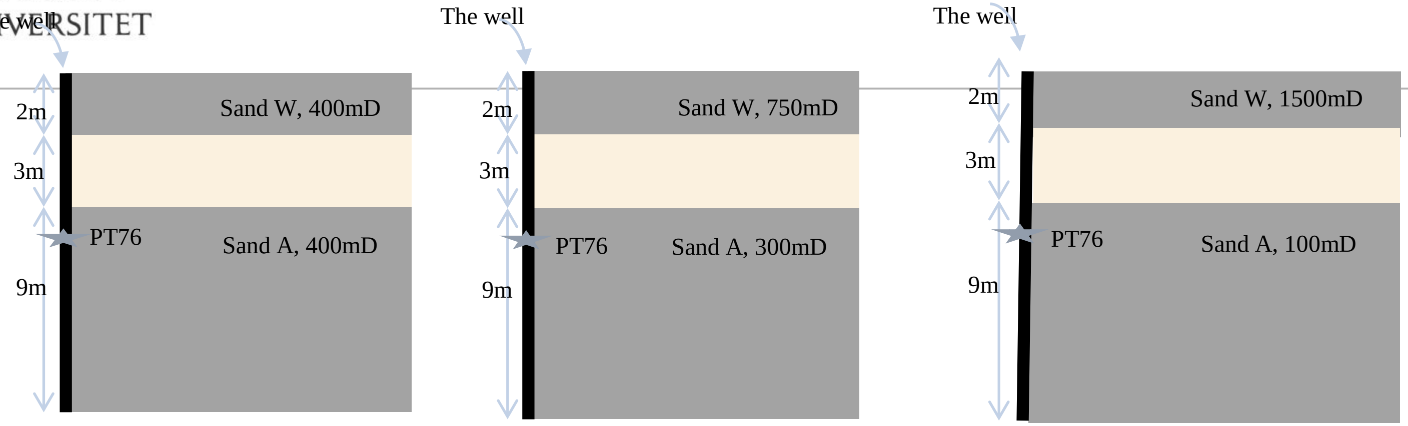
- Vary the properties permeability, porosity, characteristic two-phase functions incl. residual saturation and thermal properties within the range of measured data
- We had good data constrains from previous site characterization programme
- Variability between the two layers?





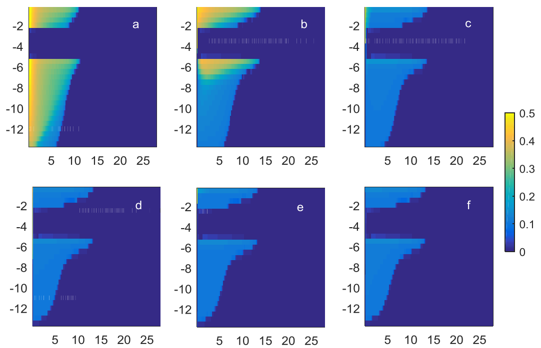


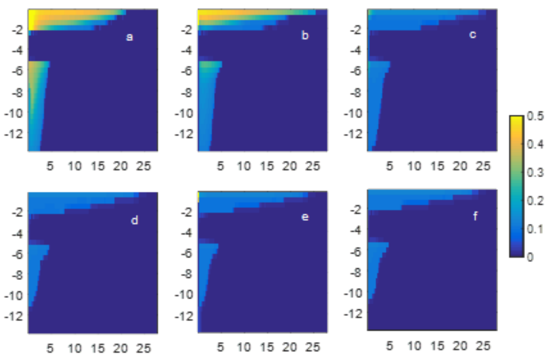
Examples of data constrains



- Examples of permeability fields that fulfill the first hydraulic test and are consistent with earlier hydraulic data from in-situ well-tests and from cores

- Gas residual saturation varied between 0.05 to 0.2, with and without hysteresis





Example of the effect of the residual saturation on pressure response of the hydraulic test

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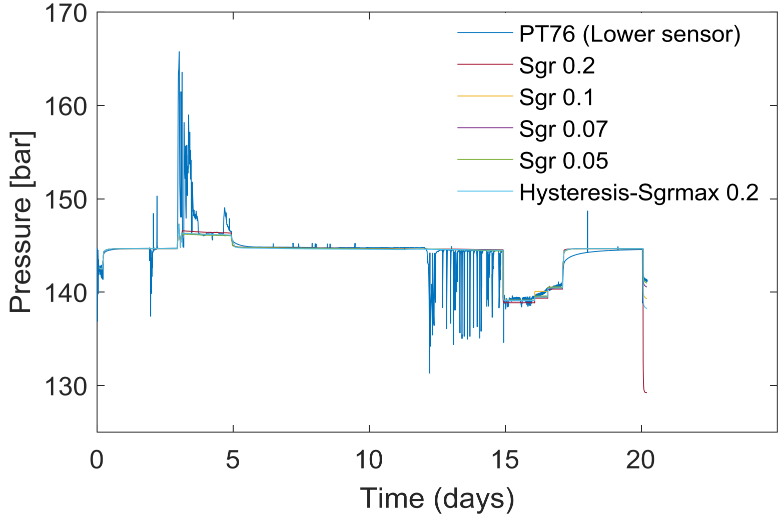
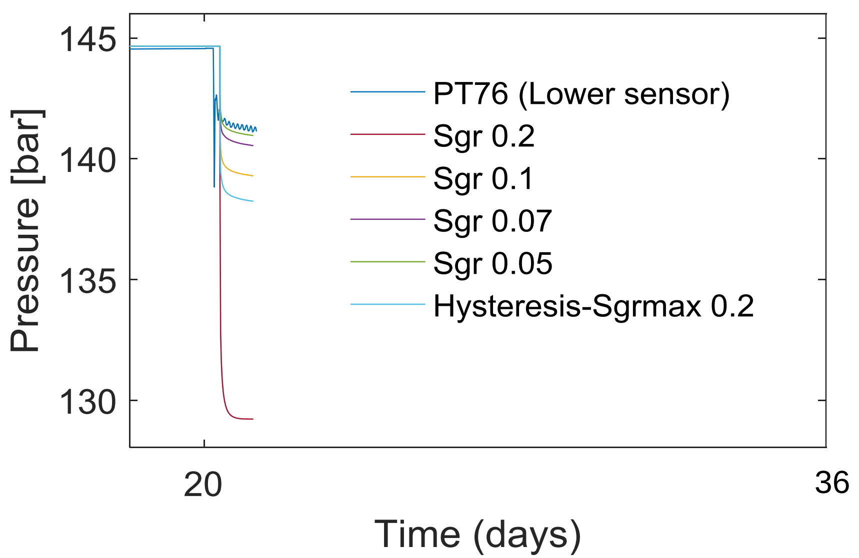
- k= 400 mD in both layers, residual trappig varied

- Simulation results of the pressure response at the location of the sensor PT76 during the whole experiment

- The smaller the residual saturation the closer the agreement





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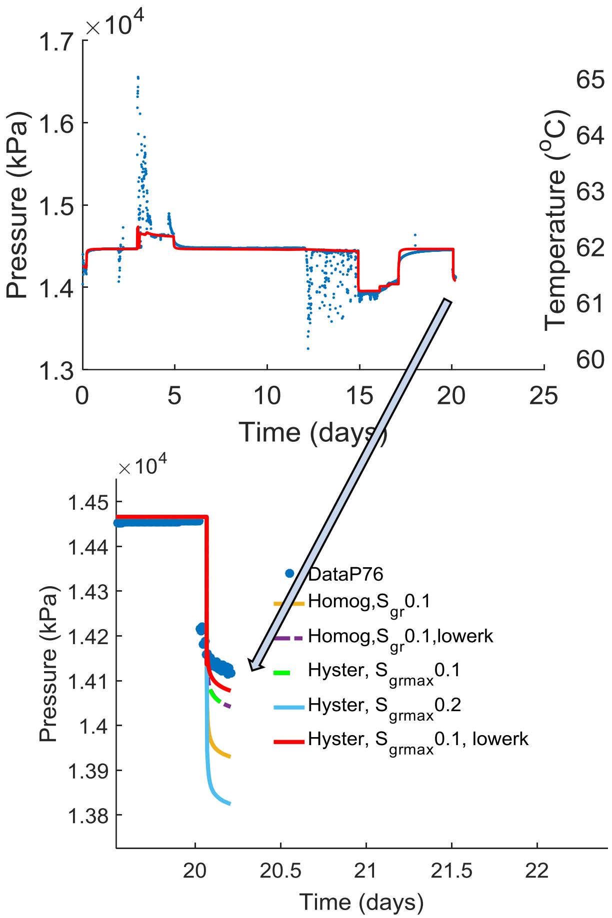
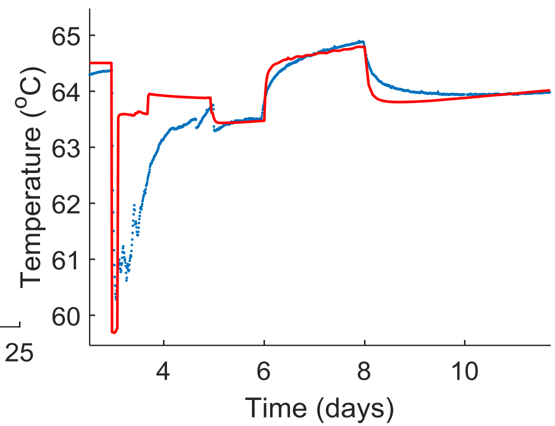
Model with best overall agreement

Pressure

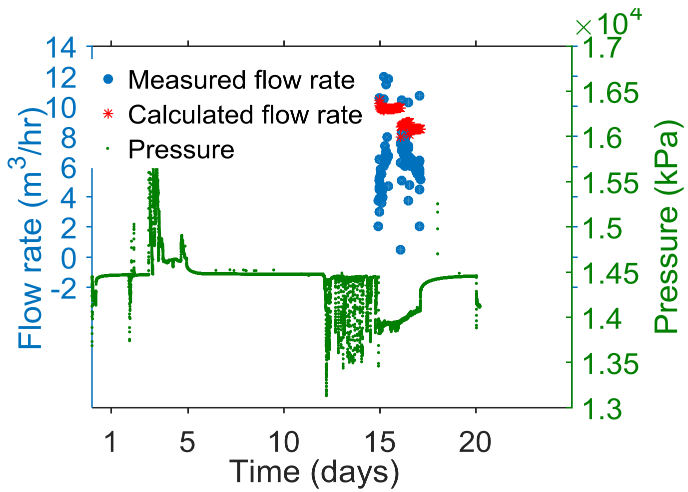


Temperature

during injection and heating



Flow rate



- Hysteretic relative permeability with residual trapping of 0.1,
- k=400 mD in both layers and
- reduced flow into the lower layer

Modeling of Residual Trapping Experiment I – understanding the self release of CO2 and water after opening the well

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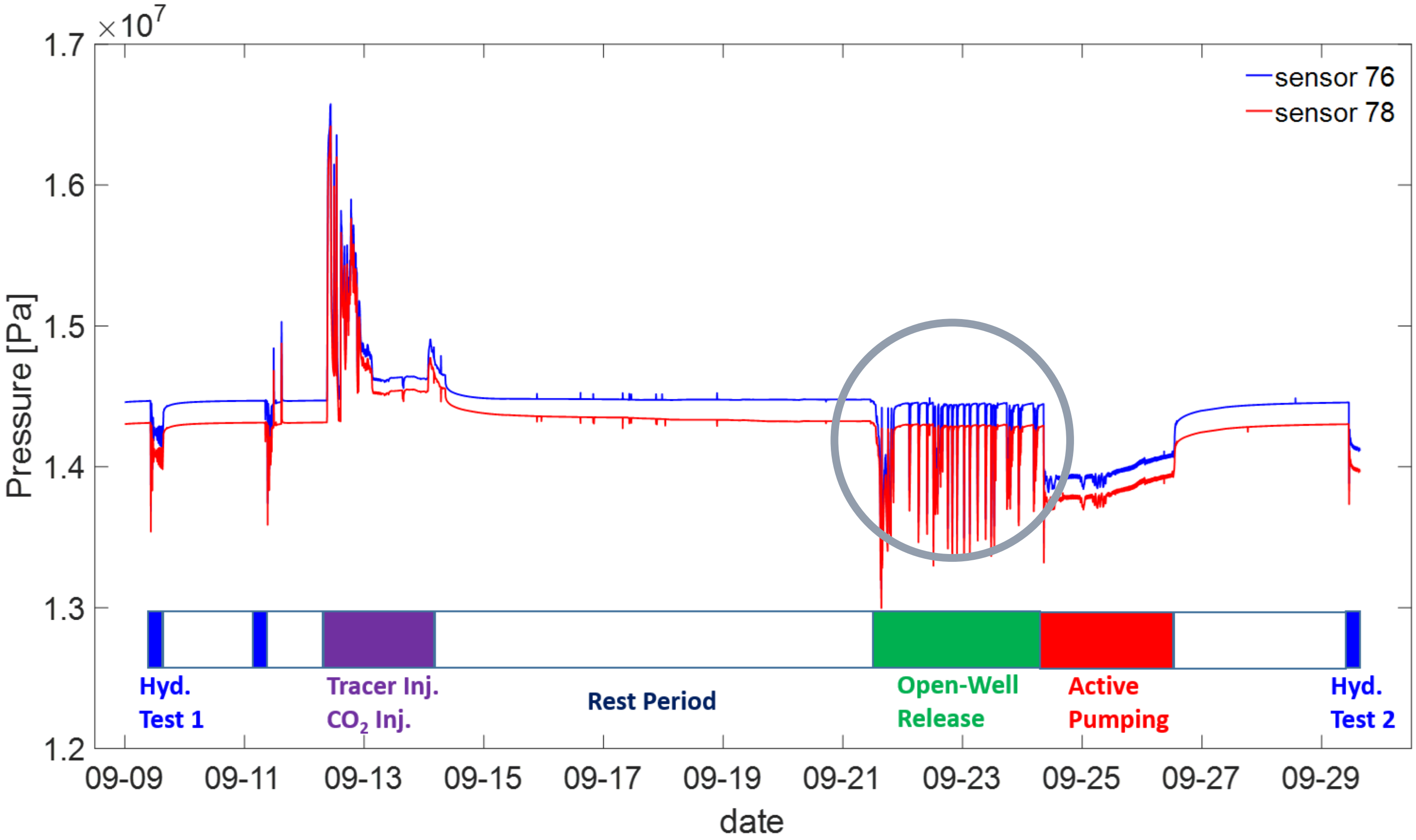
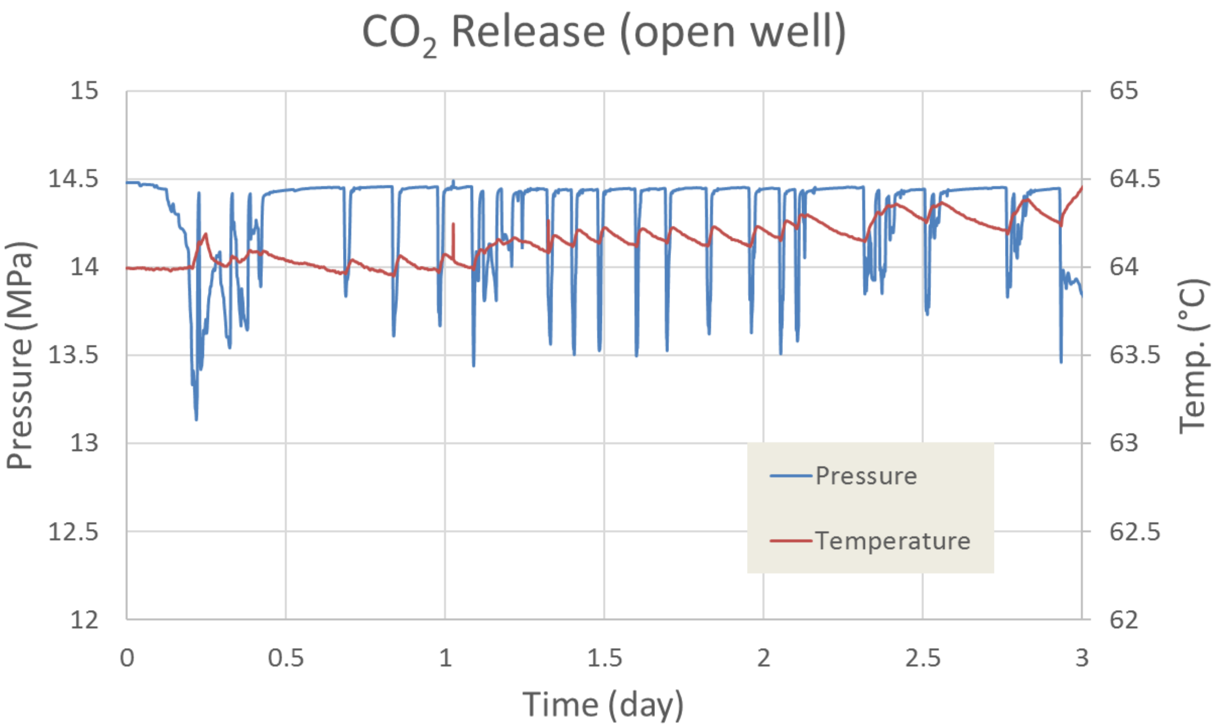


Detailed modeling of this to get a better estimate of CO2 lost during this stage as well as overall state of the system

Residual Trapping Experiment I – self release period

- Monitored pressure records at 1633 m depth shows ‘geysering’ type periodic release of CO_2 and water to the surface
- Temperature fluctuations correspond to the leakage events
- Reduction of temperature occurs due to the endothermic effect of CO_2 exsolution and Joule-Thomson cooling.



Coupled wellbore–reservoir simulator

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Wellbore-flow

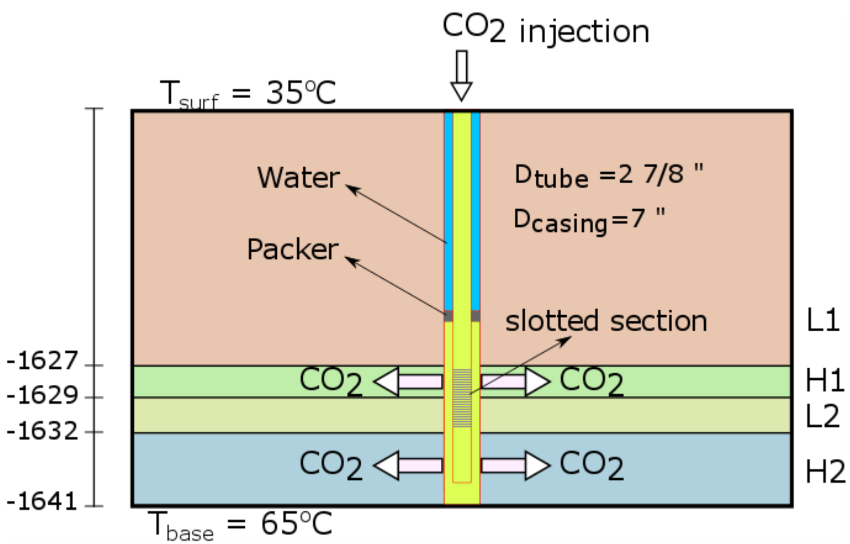
one-dimensional
Drift-Flux
Model (DFM)
(T2Well)

Reservoir-flow

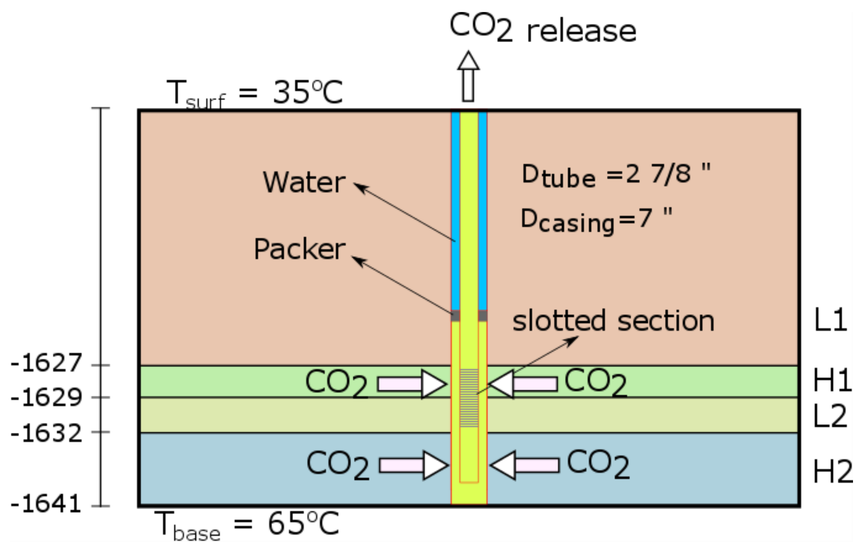
standard multiphase
Darcy’s law
(ECO2N) for CO2,NaCl and
Water

Conceptual model of Heletz experiment

Case1: CO_2 Injection



Case2: CO_2 Release



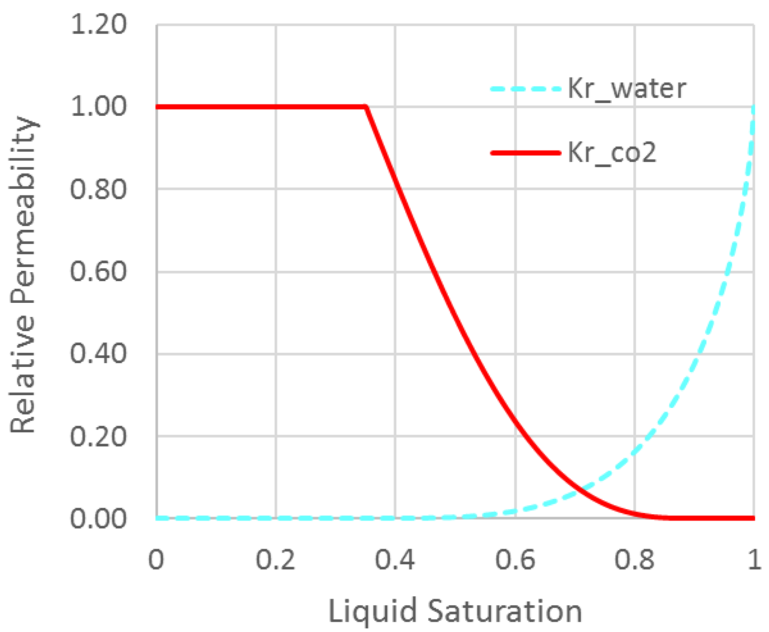
Self release model – choise of residual trapping model

Two scenarios:

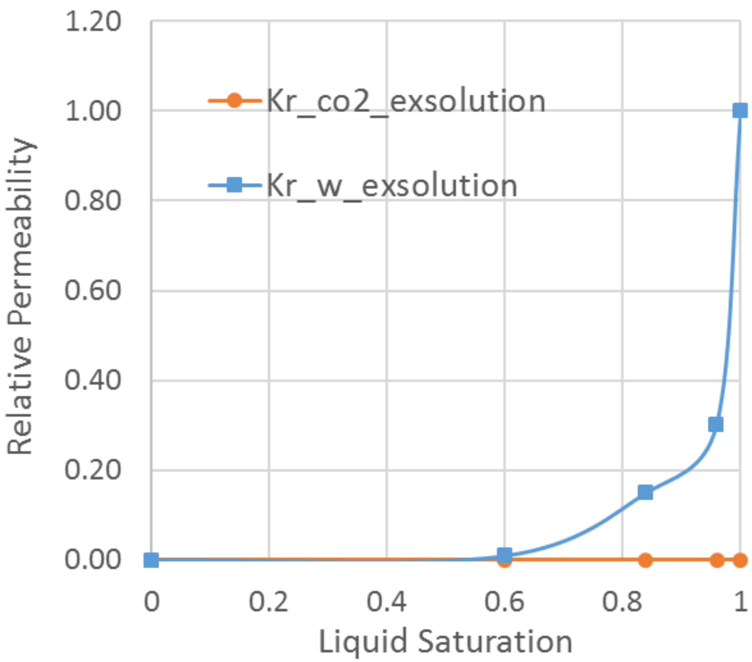
1. The relative permeability is defined based on Heletz core samples by Hingrel. et al (2016);

2. The relative permeability is assumed to be reduced due to exsolution effect from Zuo. et al (2012);

Scenario 1



Scenario 2



Model results – for pressure

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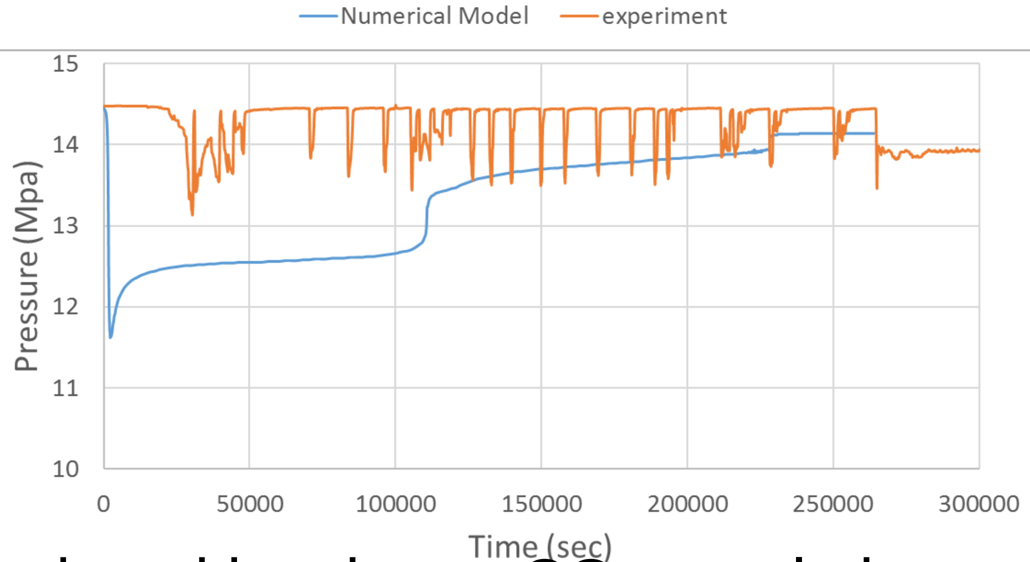
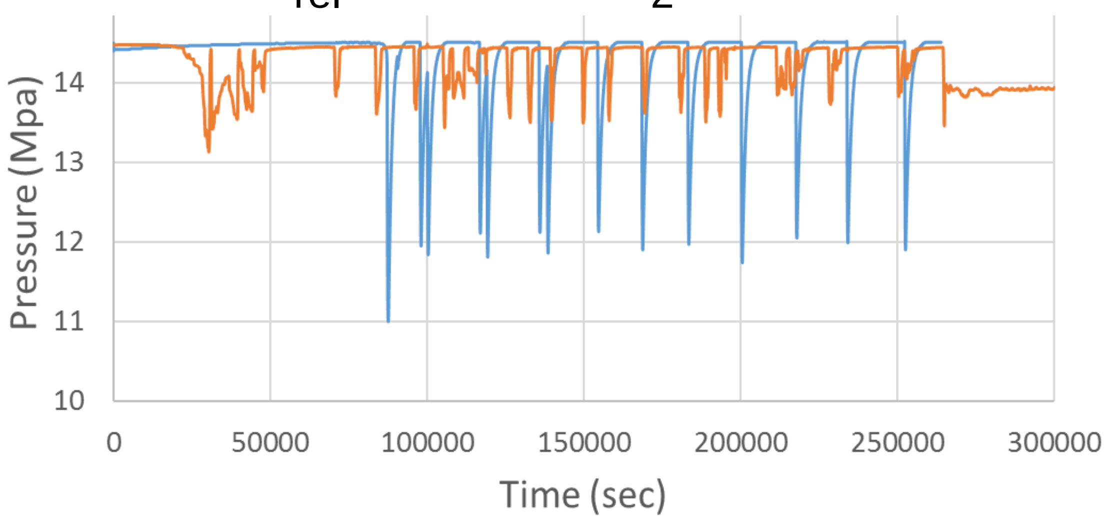
k_{rel} as measured on core



reduced k_{rel} due to CO_2 exsolution



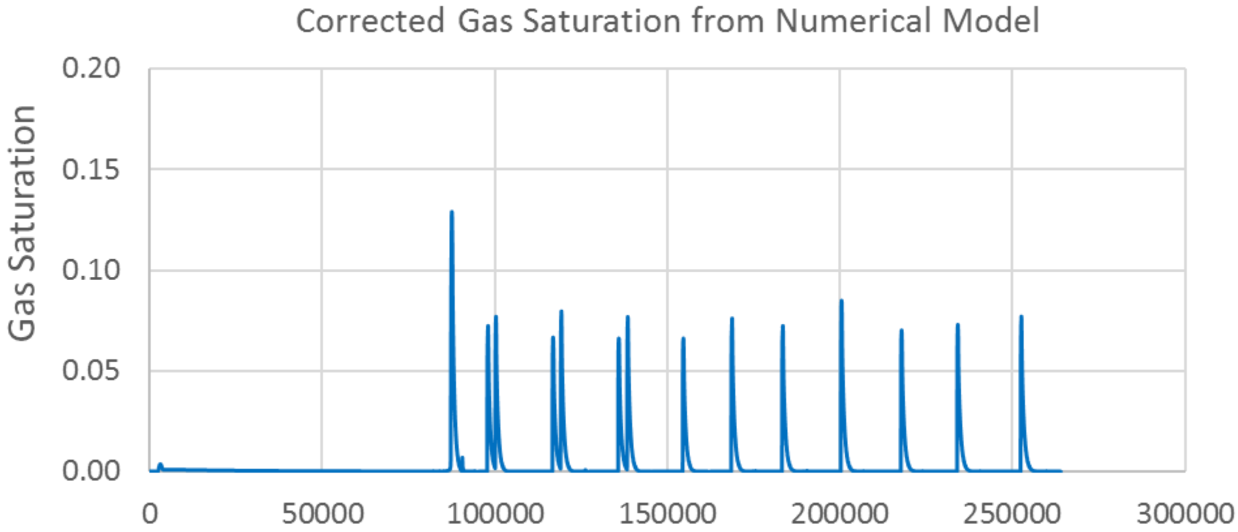
- gas flow into the wellbore is because of exsolution of CO_2 saturated water due to pressure reduction;

- reducing water relative permeability and setting CO_2 relative to very value could capture the behaviour;

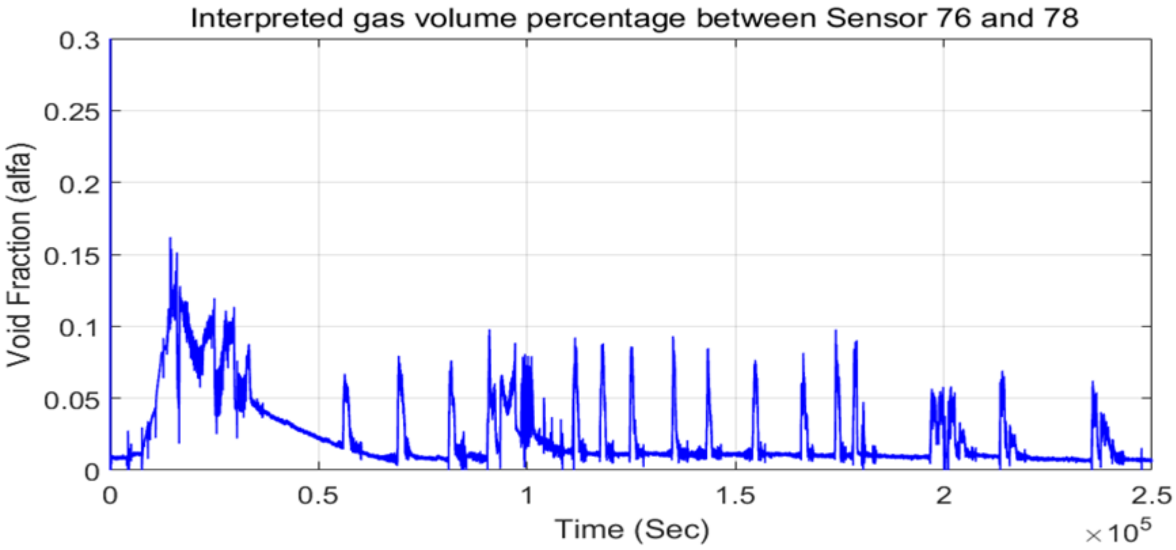
- The pressure must be corrected by pressure loss in unsaturated part of well;

Model Results – gas saturation in the well at reservoir horizon

model



data



Residual Trapping Experiment II (Aug – Oct 2017) – Test Sequence

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1) Hydraulic injection/withdrawal of water and partitioning tracers Kr and Xe for getting the pressure and tracer response **prior** to creating the residual CO2 zone

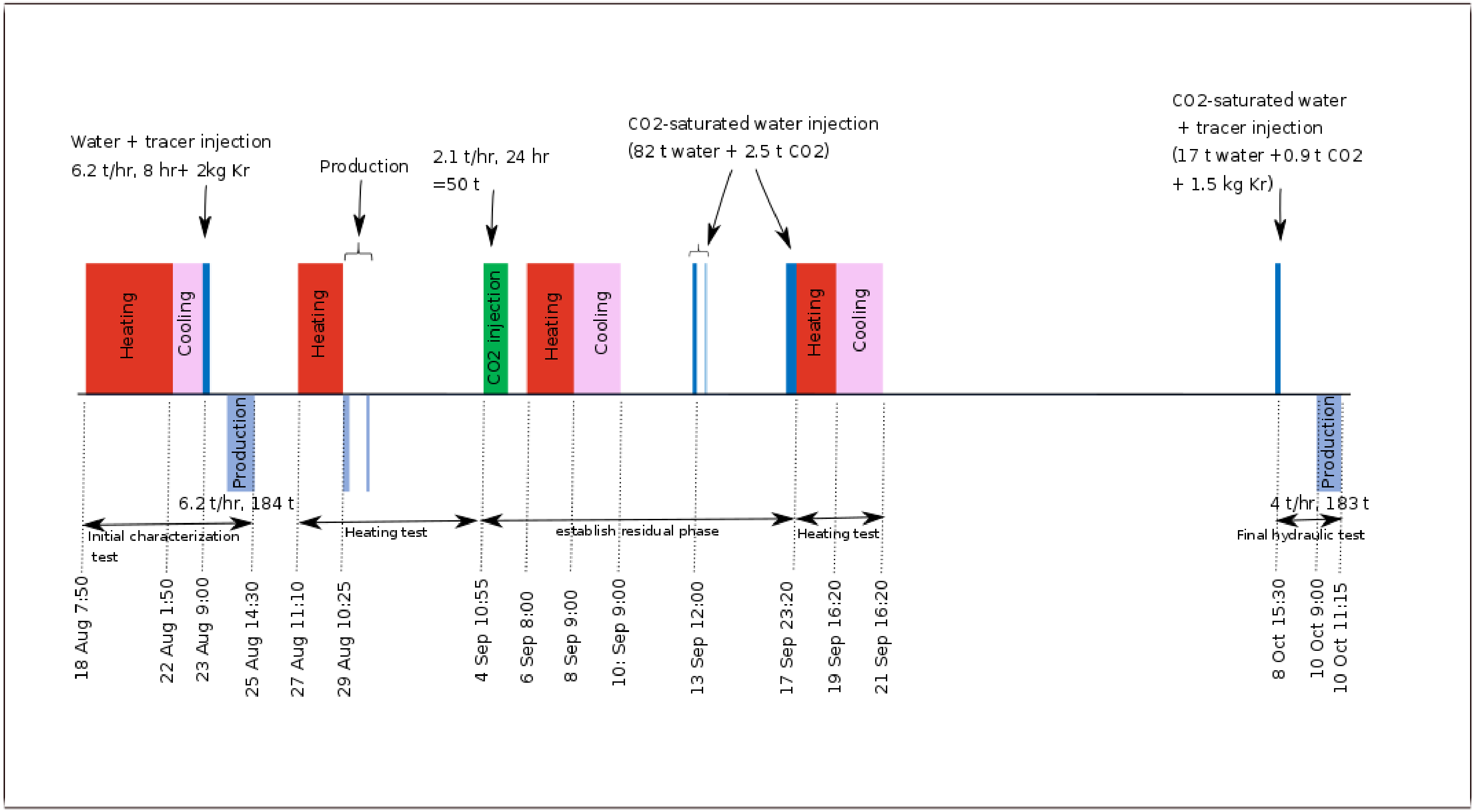
3) Inject 100 tons of CO2

4) Inject water saturated with CO2 to push away the mobile CO2, **to generate the residually trapped zone**

5) Hydraulic injection/withdrawal of water and partitioning tracers Kr and Xe for getting the pressure and tracer response **after** creating the residual CO2 zone

- P/T was continuously monitored
- CO_2 mass flowrate, temperature, pressure and density recorded
- DTS was recorded during the entire sequence;
- Downhole fluid sampling and measurement of high pressure pH and low pressure alkalinity and gas composition, as well as measurement of partial pressure of CO_2 were measured during the production phase.
- Tracer concentration analysis

Residual Trapping Experiment II (Aug – Oct 2017) – Test Sequence



Residual Trapping Experiment II (Aug – Oct 2017) – Test Sequence

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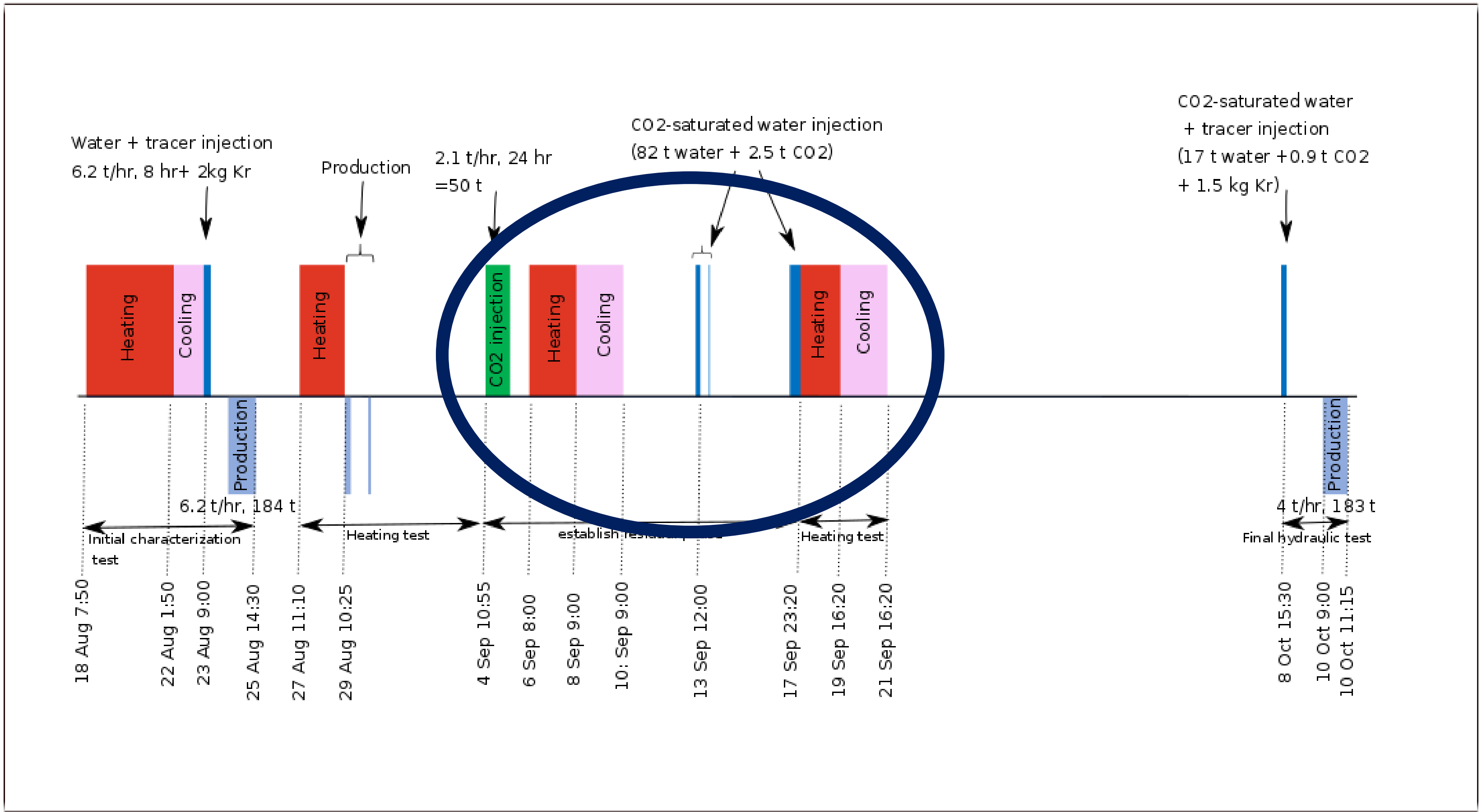
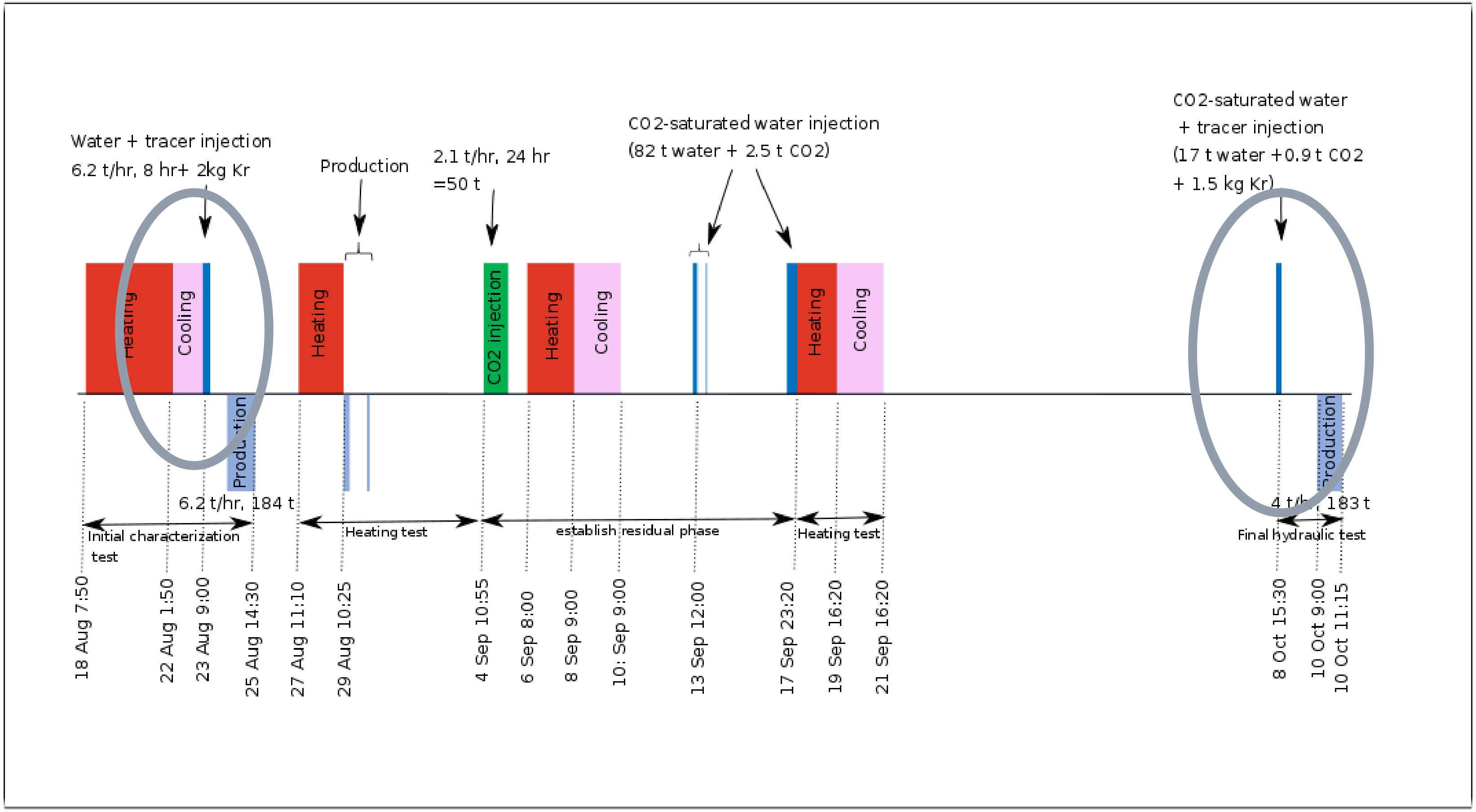


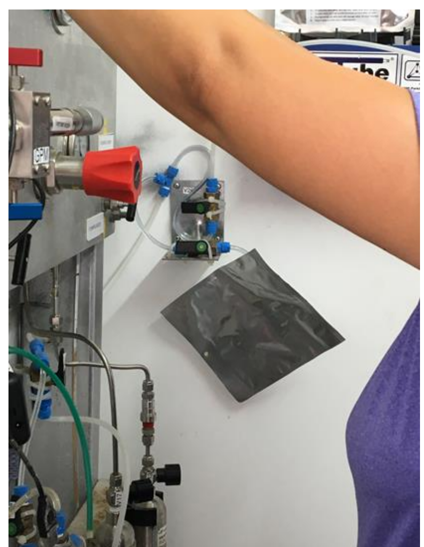
Residually trapped zone created by CO2 injection, followed by injection of CO2 saturated water

Residual Trapping Experiment II (Aug – Oct 2017) – Test Sequence



Injection/withdrawal of water+gas partitioning tracers Krypton and Xenon before and after creating the residual zone

Tracer injection and sampling - Residual Trapping Experiment II (Aug–Oct 2017)



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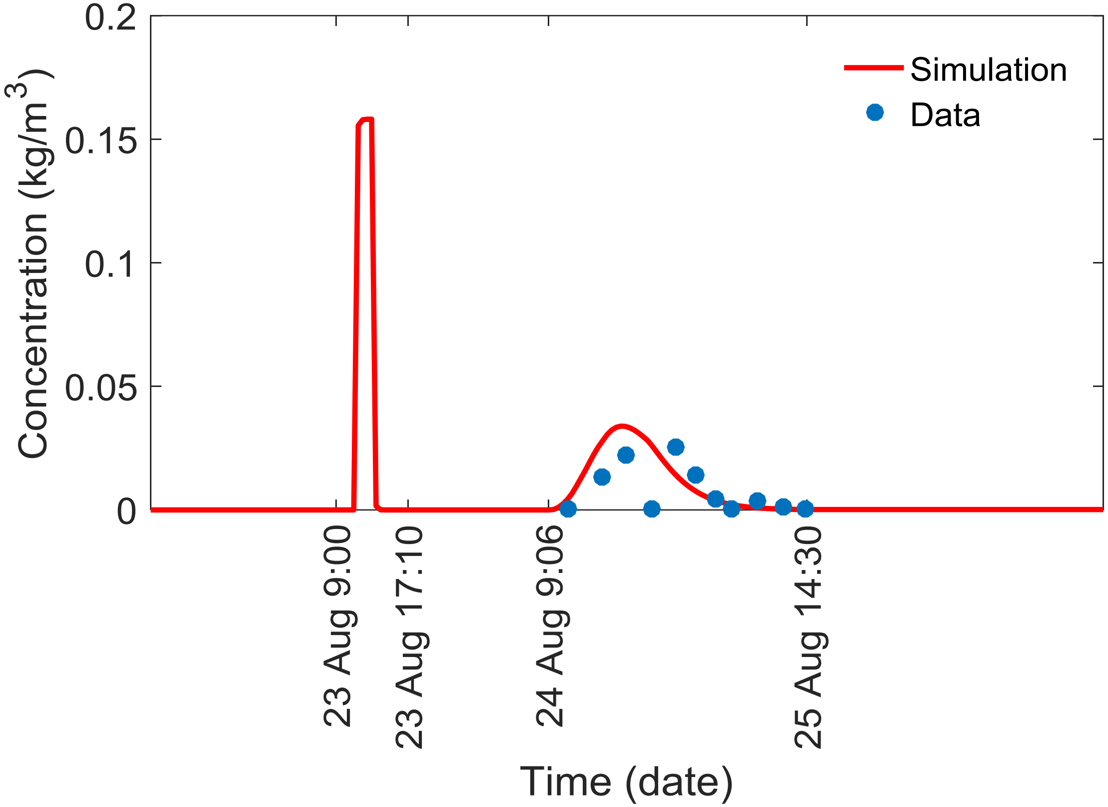
Residual Trapping Experiment II (Aug – Oct 2017) – Tracer information

Test	Injection				Abstraction			
	Duration (hr)	Water (m3)	Rate (m3/hr)	Kr (kg)	Duration (hr)	Water (m3)	Rate (m3/hr)	Kr (kg)
Test 1-Single phase	8.5	50.499	5.96	2	30	183.8	6.13	1.37
Test 2-two phase	5.5	18	3.27	2	11.5	88.27	7.68	0.6
Test 3-Single phase	6.3	60.1	9.4	3.02	78.5	374.8	4.8	1.96

For single phase tests the recover rate was 68,5% and 65% and for the two-phase test 30% (due to partitioning to CO_2)

Residual Trapping Experiment II – Krypton breakthrough first tracer experiment

Injection sampling

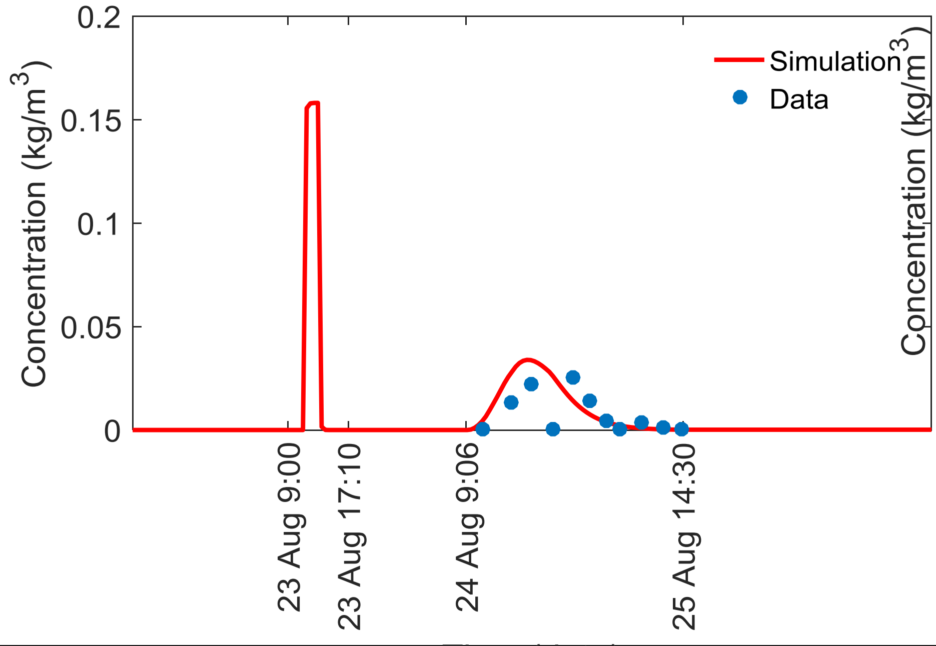


measured breakthrough and TOUGH2 model result with the model developed based on RTE I

Residual Trapping Experiment II – Krypton breakthrough

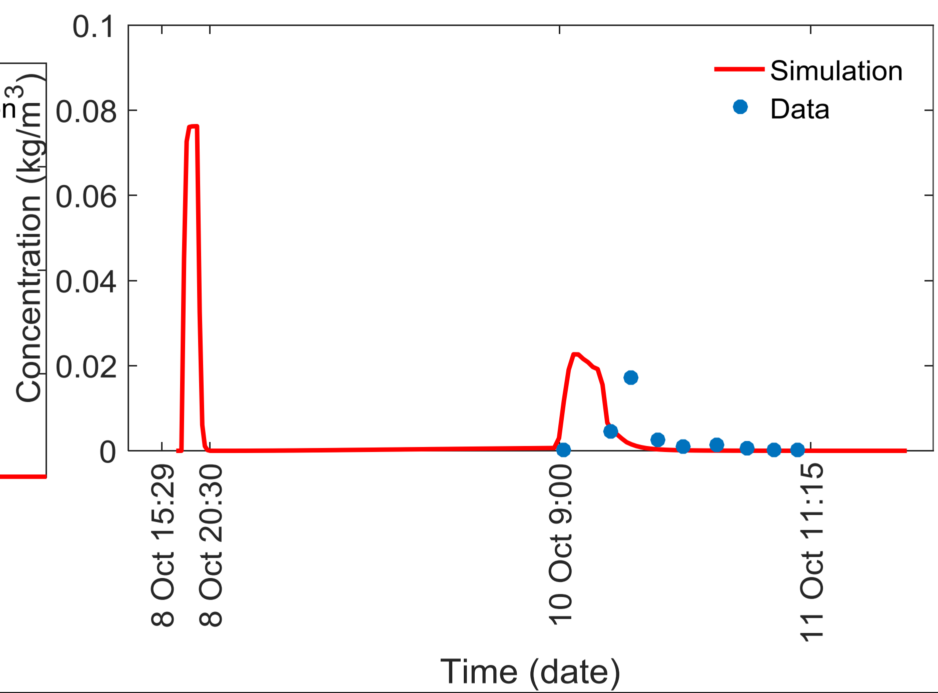
measured and modelled breakthrough without CO2

>Very good agreement without any calibration of the RTE I model



measured and modelled breakthrough with trapped CO2

> modelling still in progress; total tracer partitioned into CO2 correct, but timing not yet perfekt)



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Conclusions from the Residual Trapping Tests I and II so far

- Two distinctly different residual trapping field experiments carried out and analysis underway

- Results so far indicate similar characteristics in terms of CO2 residual trapping

- **Test I (hydraulic test)** shows residual trapping of the order of 0.10 when hysteresis included, proportionally more CO_2 goes into the upper reservoir layer

- Analysis of coupled well-reservoir behavior: the oscillating pressure/temparature pattern can be explained by CO_2 exsolution, as well as reduced gas and liquid permeability due to exsolution

Conclusions from the Residual Trapping Tests I and II so far

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- **Test II (partitioning tracer test)** successfully completed and meaningful tracer breakthrough curves obtained. Tracer recovery without CO2 68%, with CO2 about 30%. Analysis underway, but indicate similar trapping than Test I

- **Together** these tests should provide a good understanding of CO_2 residual trapping at Heletz and provide procedures and methods for other sites as well

Insight is also being gained by means of pore-network modeling

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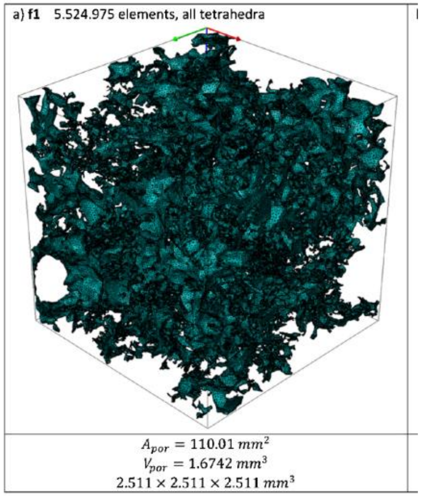
Pore network modeling is used to analyze the residual trapping in cores of different permeability, where two-phase properties/pore structure have been experimentally determied

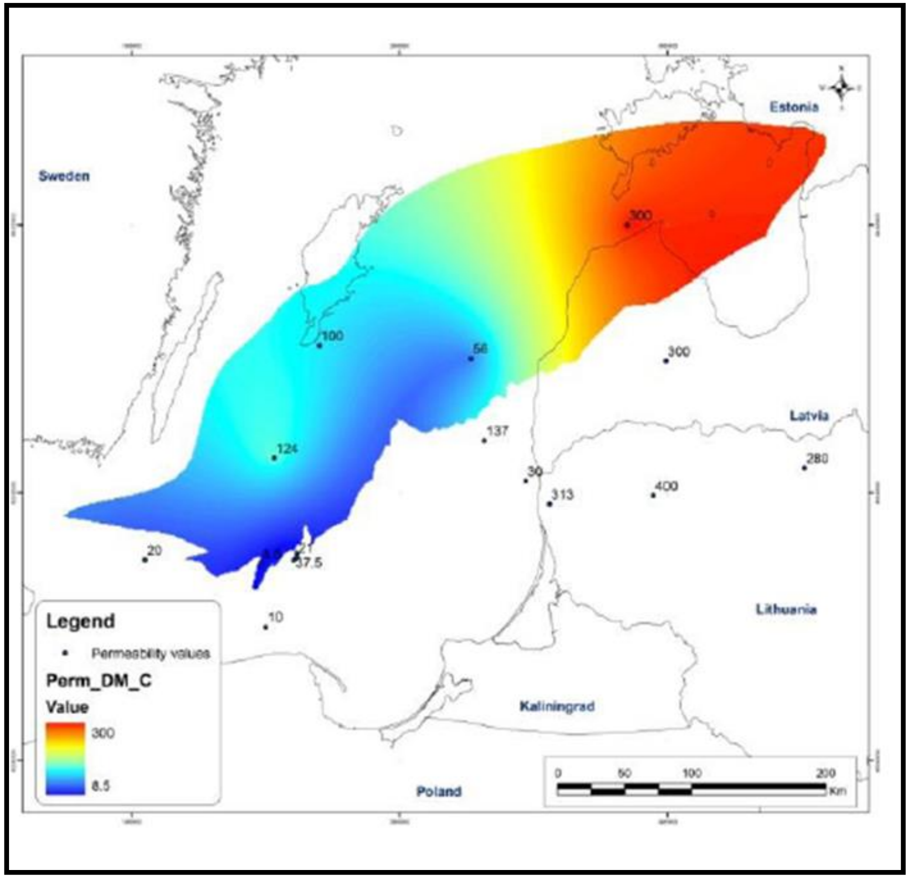
- the model has been succesfully fitted to the Stanford University experimental data on 100mD core (Rasmusson et al., 2018)
- work is in progress to model the trapping on a 450 mD core analyzed by Göttingen University (Tatomir at al., 2016)



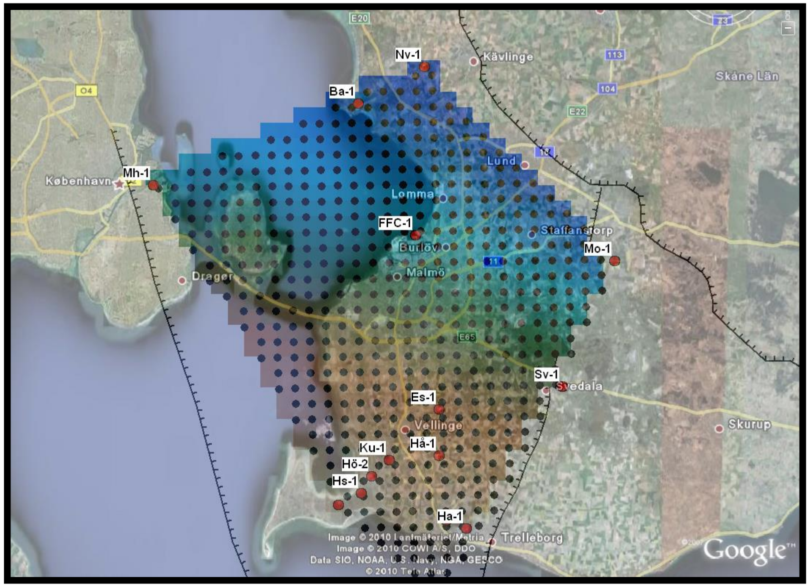
Tatomir et al. (2016) An integrated core-based Analysis for the characterization of flow, transport and mineralogical paramters at Heletz CO2 pilot CO2 storage reservoir. International Journal of Greenhouse Gas Control (2016) Vol 46 pp. 24-43.

Rasmusson et al. (2018). Modeling of residual trapping at pore scale – example application to Heletz data. International Journal of Greenhouse Gas Control. Accepted with minor revision

A few words of how to handle the large scale of the domains to be modelled when making predicition for real sites



Dalders Monocline Baltic Sea



South-West Scania Sweden

Yang et al. (2015) International Journal Greenhouse Gas Control, Vol. 43, p. 149-150,	Tian, et al. (2016).) Greenhouse Gases: Science Technology, Vol. 5, no 3, p. 277-290, 6(4): 531-545.)

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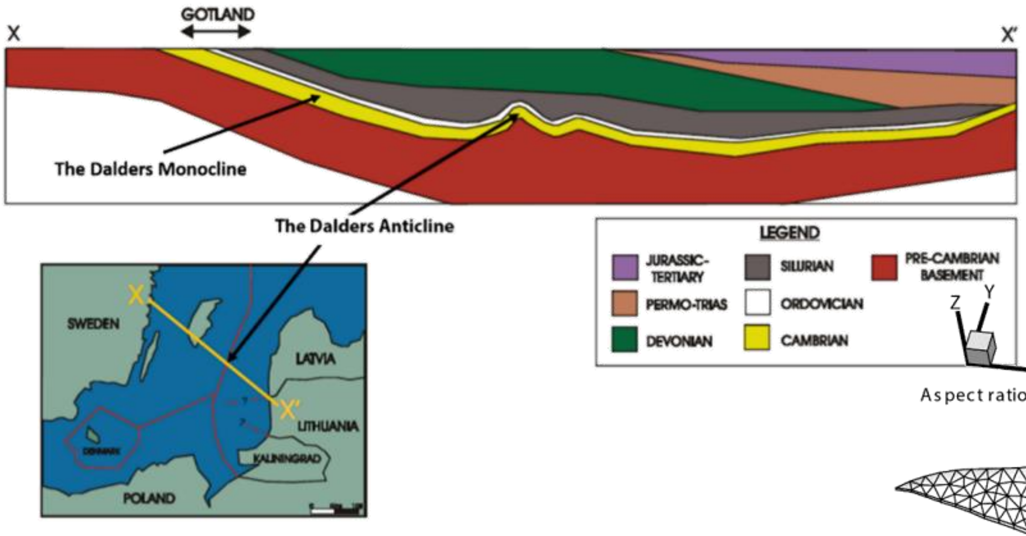
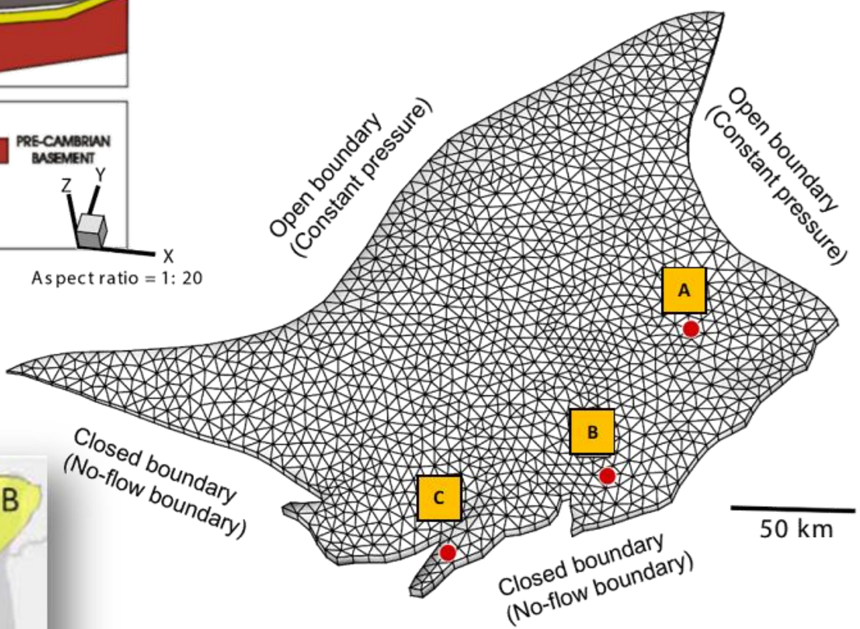
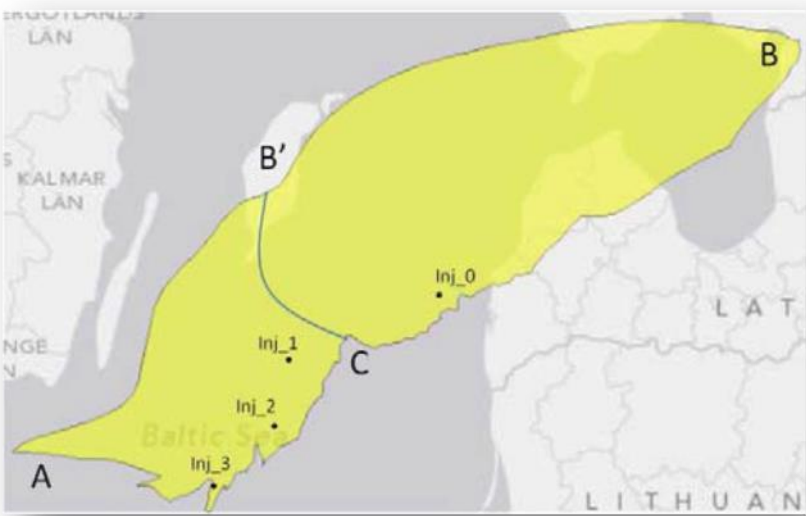
Modeling approaches available

- **Full-physics** models (TOUGH2, ECLIPSE etc.) for 3D systems
- **Simplified models for two-phase flow region**
- Analytical and semi-analytical models for idealized systems (pressure response etc.)
- Simplified models for plume evolution (vertical equilibrium, invasion-percolation etc)
- **Simplified models for the far field** (single-phase flow)

Example of large scale real site simulation : Capacity estimation for Dalders Monocline (Baltic Sea)







Use of models of increasing level of complexity

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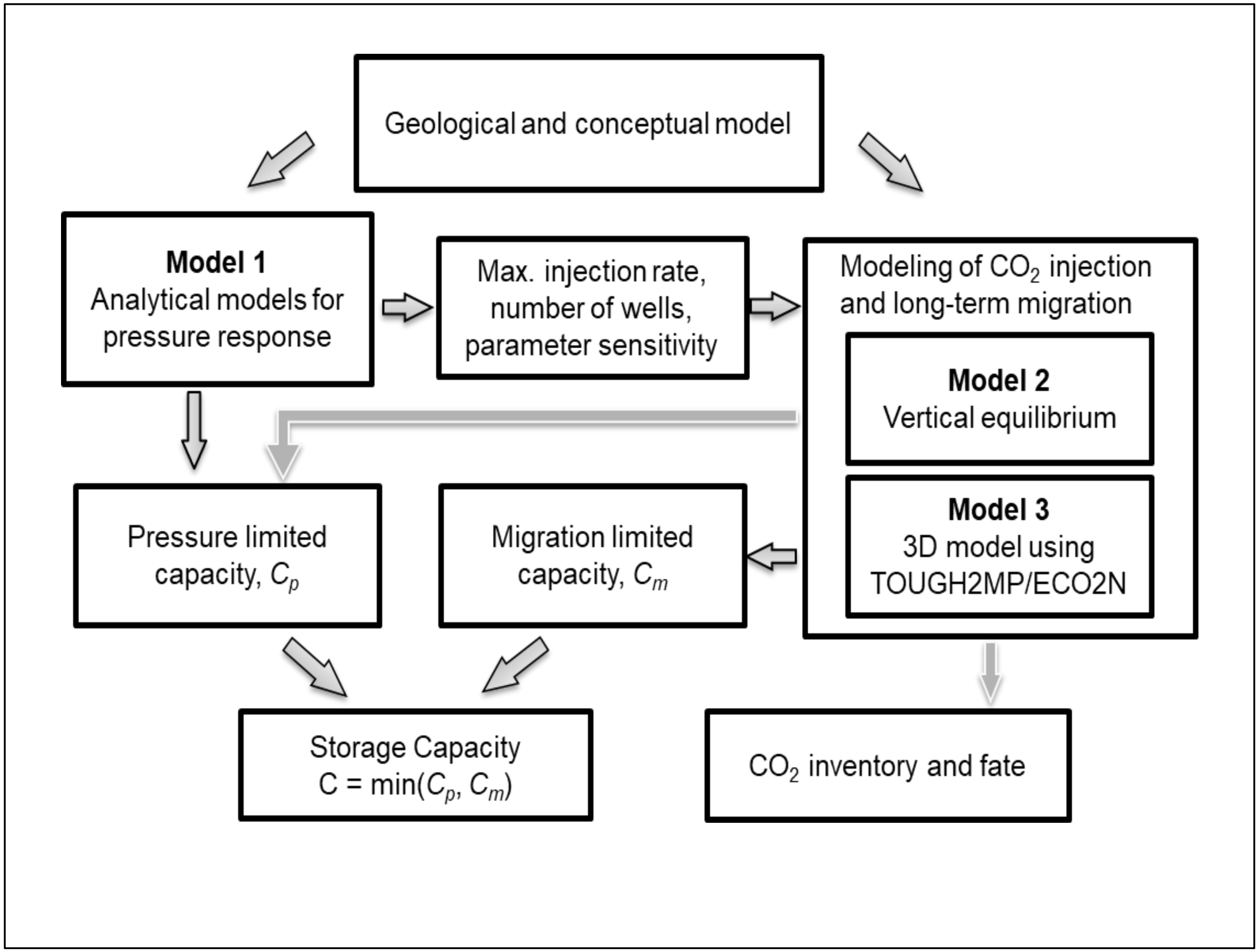
1. **Semi-analytical model for two-phase flow** (Mathias et al., 2011)
- approximate solution for brine-CO2 two-phase flow for pressure (sharp interface, vertical equilibrium, no capillarity..)

2. VE model (Gasda et al., 2009;Nordbotten et al., 2005)
- Assume vertical equilibrium of pressure, formulation of vertically averaged models (vertically integrated input parameters, vertically integrated fluid saturations as output)

3. TOUGH2 (-MP) / ECO2N
- TOUGH2-MP (T2MP) is a massively parallel version of TOUGH2 code



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Porosity and permeability of Dalders Monocline

SLR

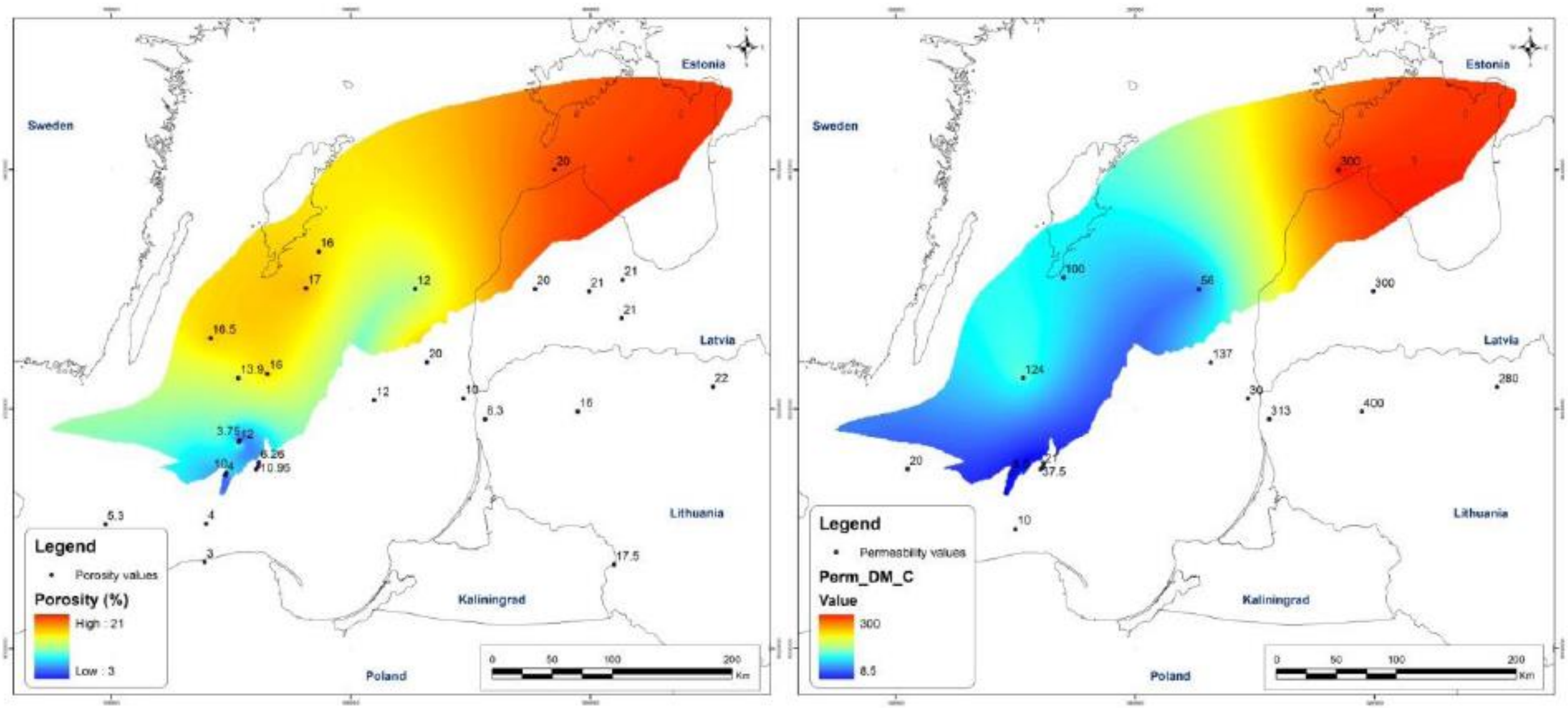

Figure 13 Porosity (to the left) and Permeability (to the right) of the Dalders Monocline.

First estimate of reservoir <u>pressure behaviour</u> - simplified two phase model (after Mathias et al.)

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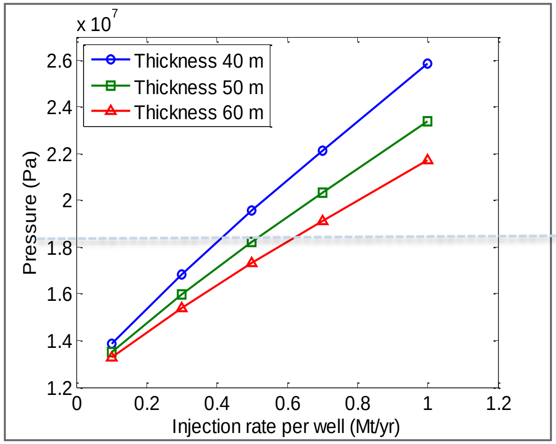
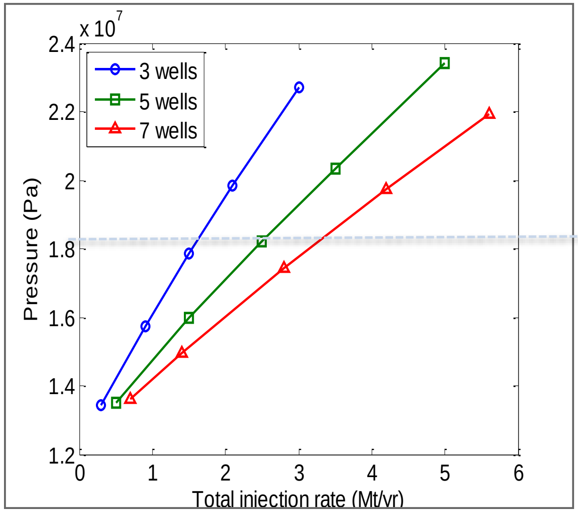
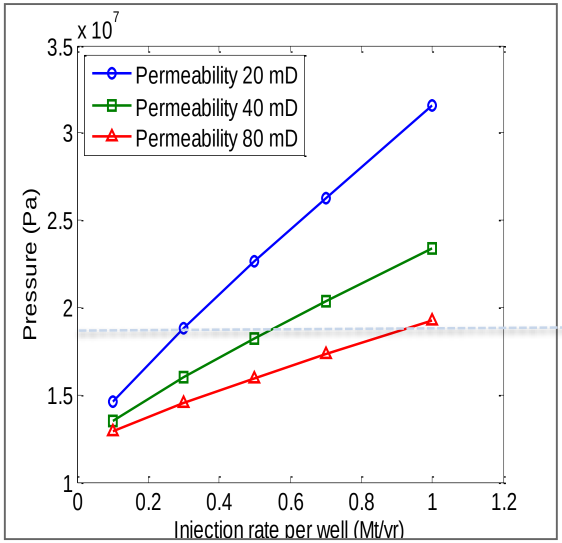
- CO_2 injection rates per well are governed by reservoir thickness and permeability;
- The base case injection capacity is 2.5Mt per annum
- Increasing the number of wells will increase the injection rate







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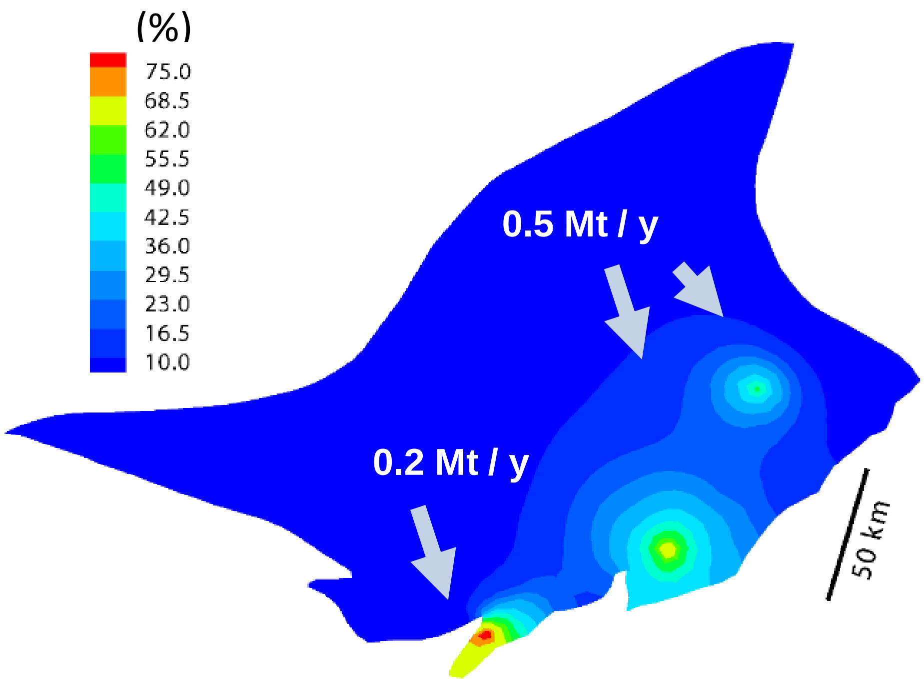
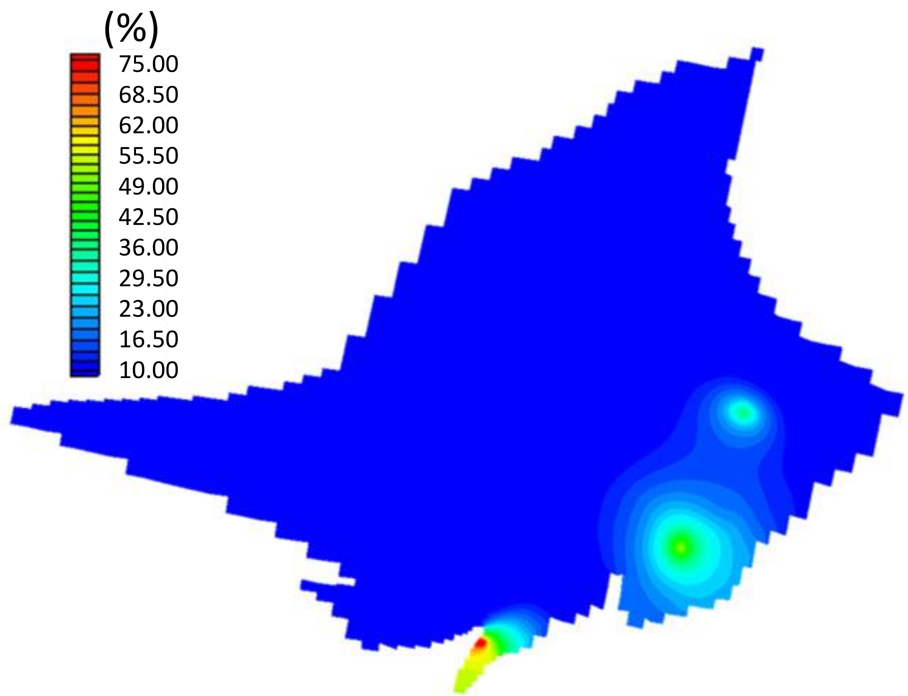
Pressure evolution with full TOUGH2 simulation and VE-approach

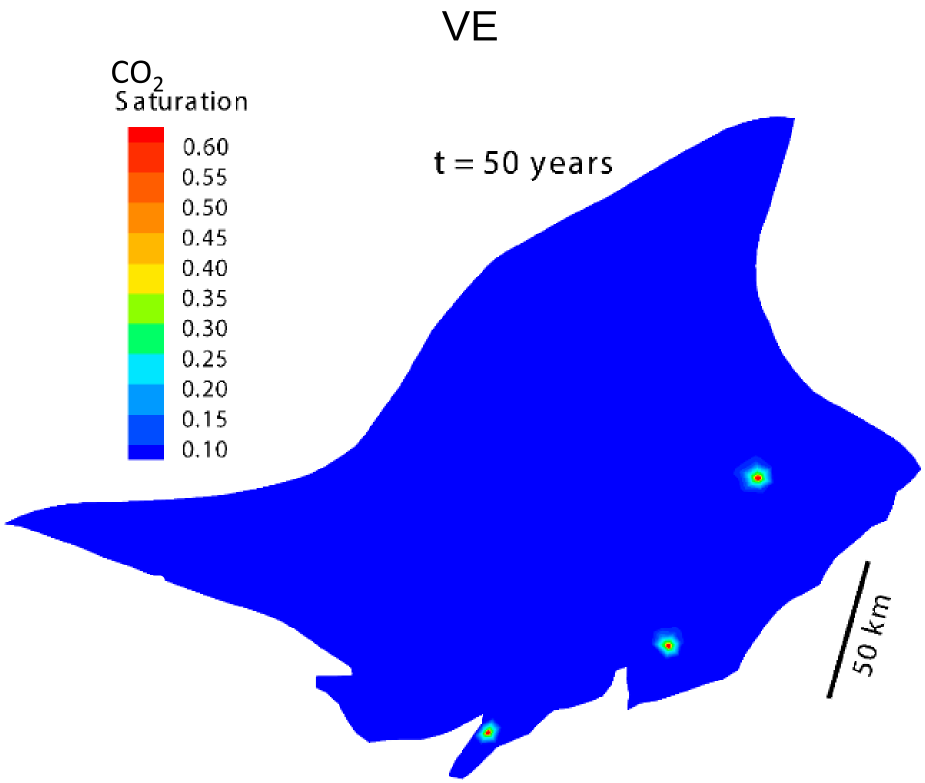
VE

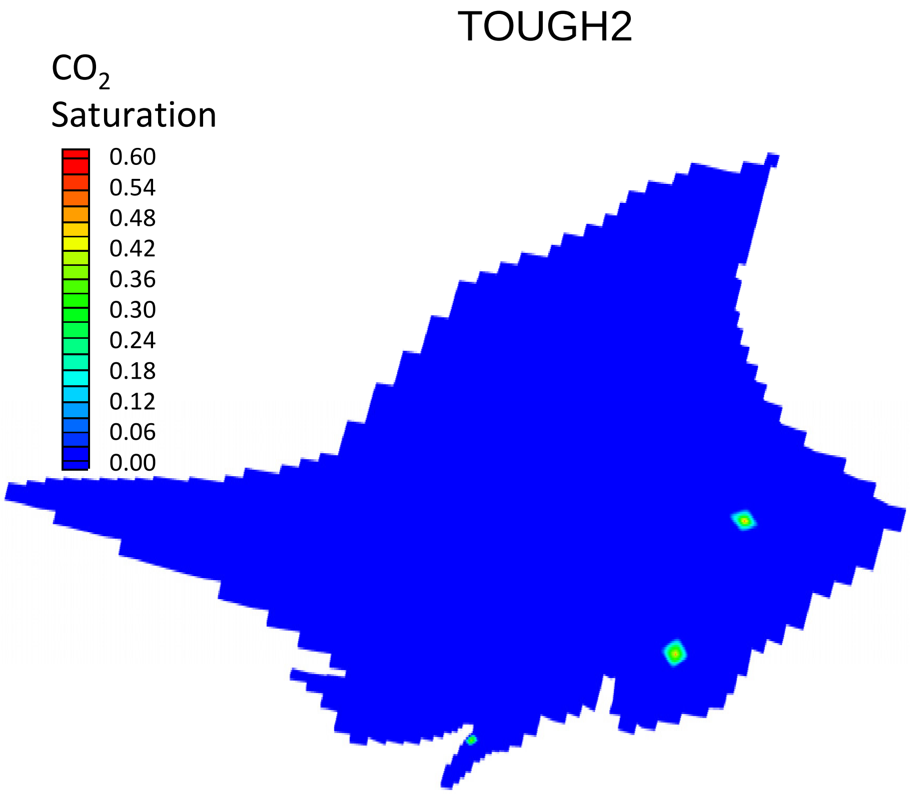


TOUGH2

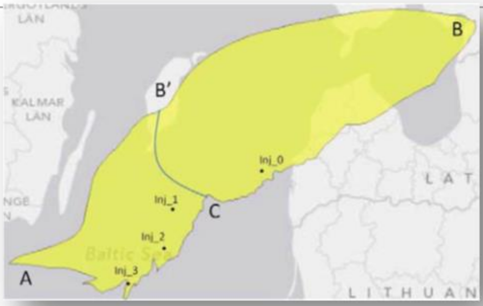


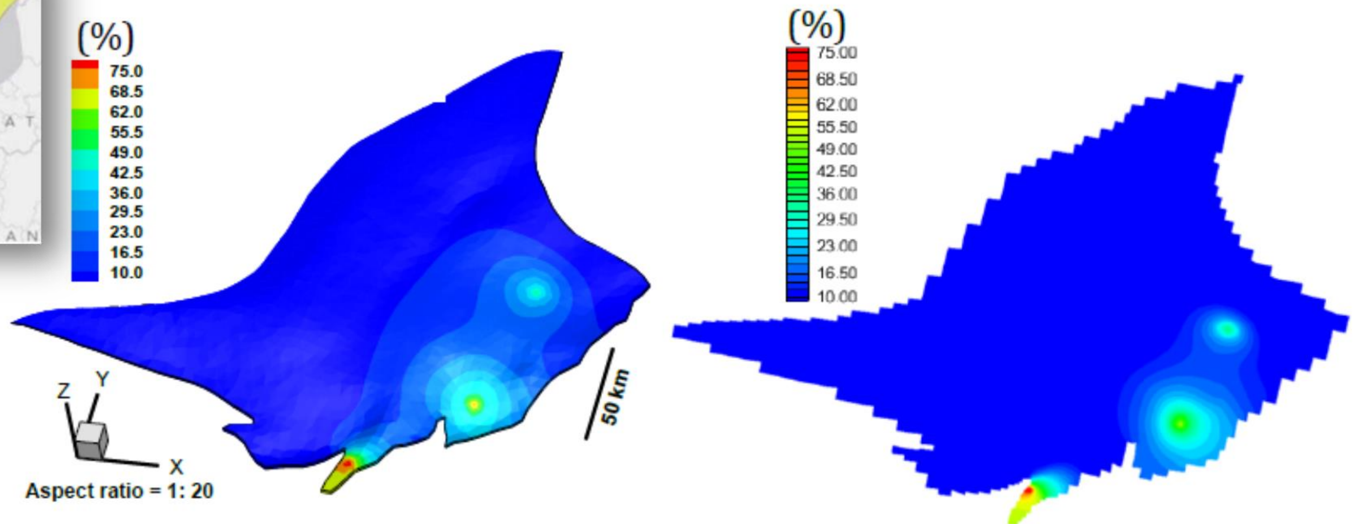
Plume migration with full TOUGH2 simulation and VE-approach



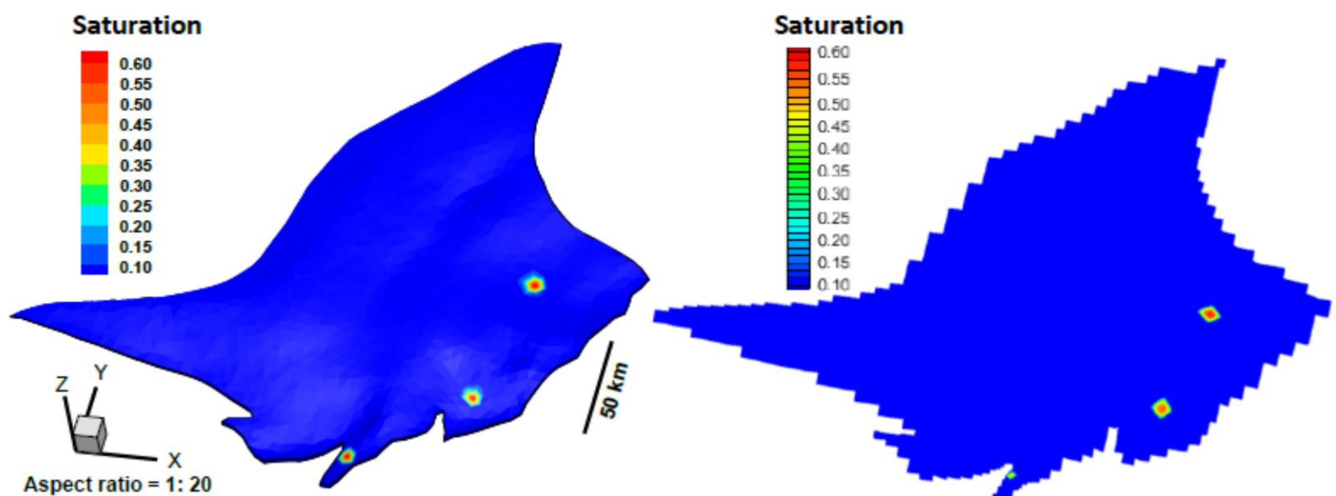


Example of simulated overpressure and CO2 saturation distributions – areal view



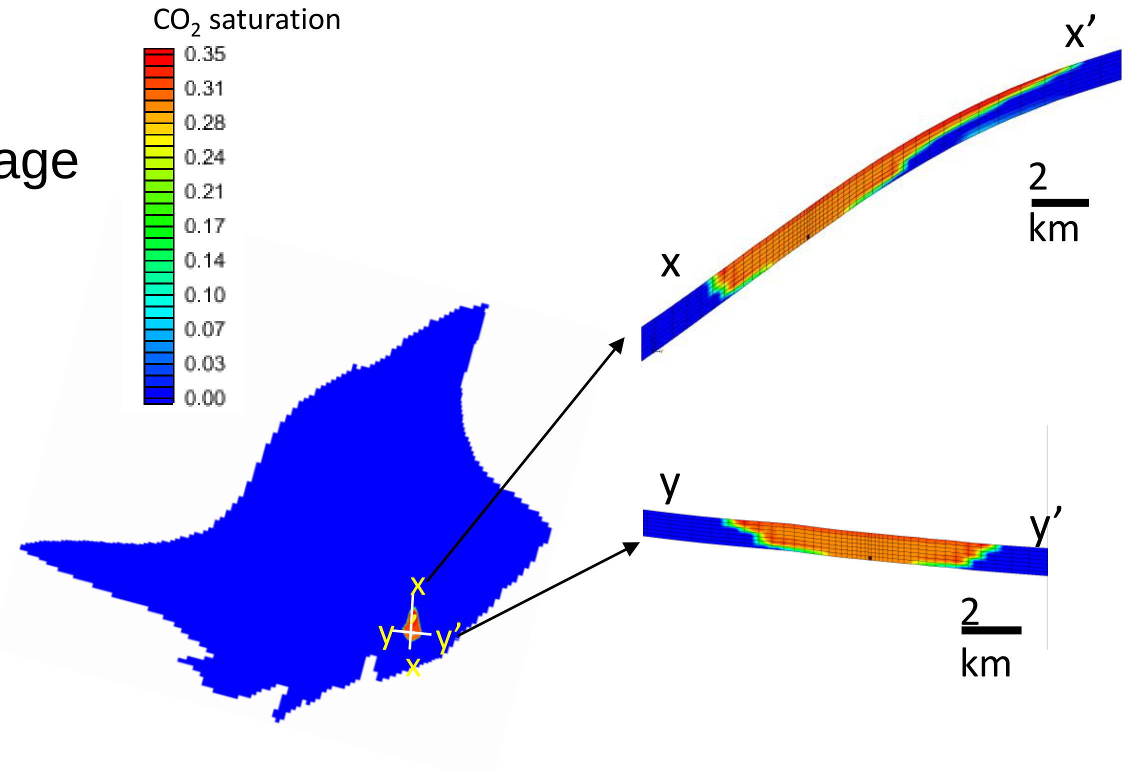


(b)



3D presentation of plume migration (TOUGH2 simulation)

- Under the current injection scenario, the dominant constraint for the CO_2 storage potential is the pressure buildup.



Capacity of 100 Mt based on:

- 4 injection wells;
- 0.5Mt CO_2 / year per well;
- 50-year injection duration.

> Dalders Monocline is a pressure limited system

Especially acknowledged co-workers

Jacob Bensabat, EWRE, Israel
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Maryeh Hedayati, UU
Zhibing Yang, UU and Wuhan University, China
Lily Perez, EWRE
Stanislav Levchenko,, EWRE
Fritjof Fagerlund, UU
Chin-Fu Tsang, UU and LBNL, USA
Sally Benson, Stanford University, USA
Ferdinand Hingerl, Stanford University
Tian Liang, UU
Byeonju Jong, UU
Rona Ronen, EWRE
Yoni Goren, EWRE
Igal Tsarfis, EWRE
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Maria Rasmusson, UU
Lehua Pan, LBNL, USA
Alexandru Tatomir, Göttingen University, Germany
Martin Sauter, Göttingen University
and all TRUST partners

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Swedish Energy Council project 43526-1.

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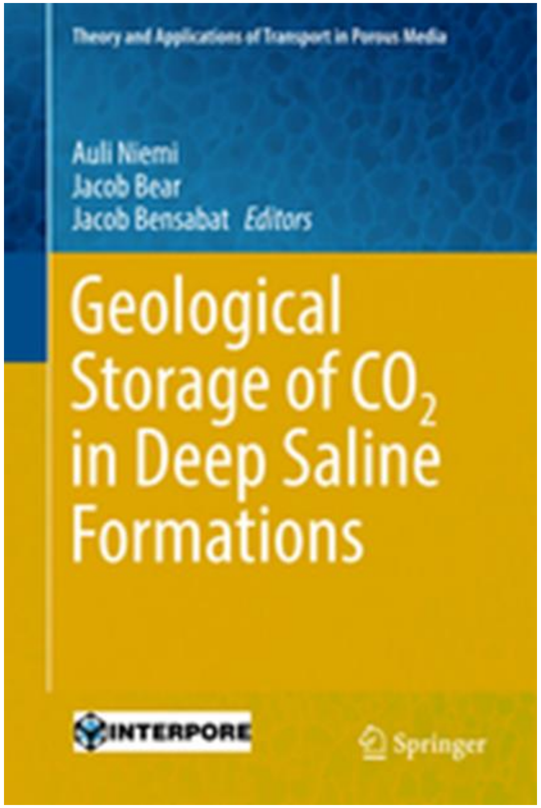
Related Reading

Niemi, A., Bear, J. and Bensabat, J. (Editors) (2016) GEOLOGICAL STORAGE OF CO2 IN DEEP SALINE FORMATIONS. Book to be published 2016, In Press.

Publisher Springer. 600p.



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Thank you for your attention!

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