Small-scale CO_2 injection into a deep geological formation at Heletz, Israel

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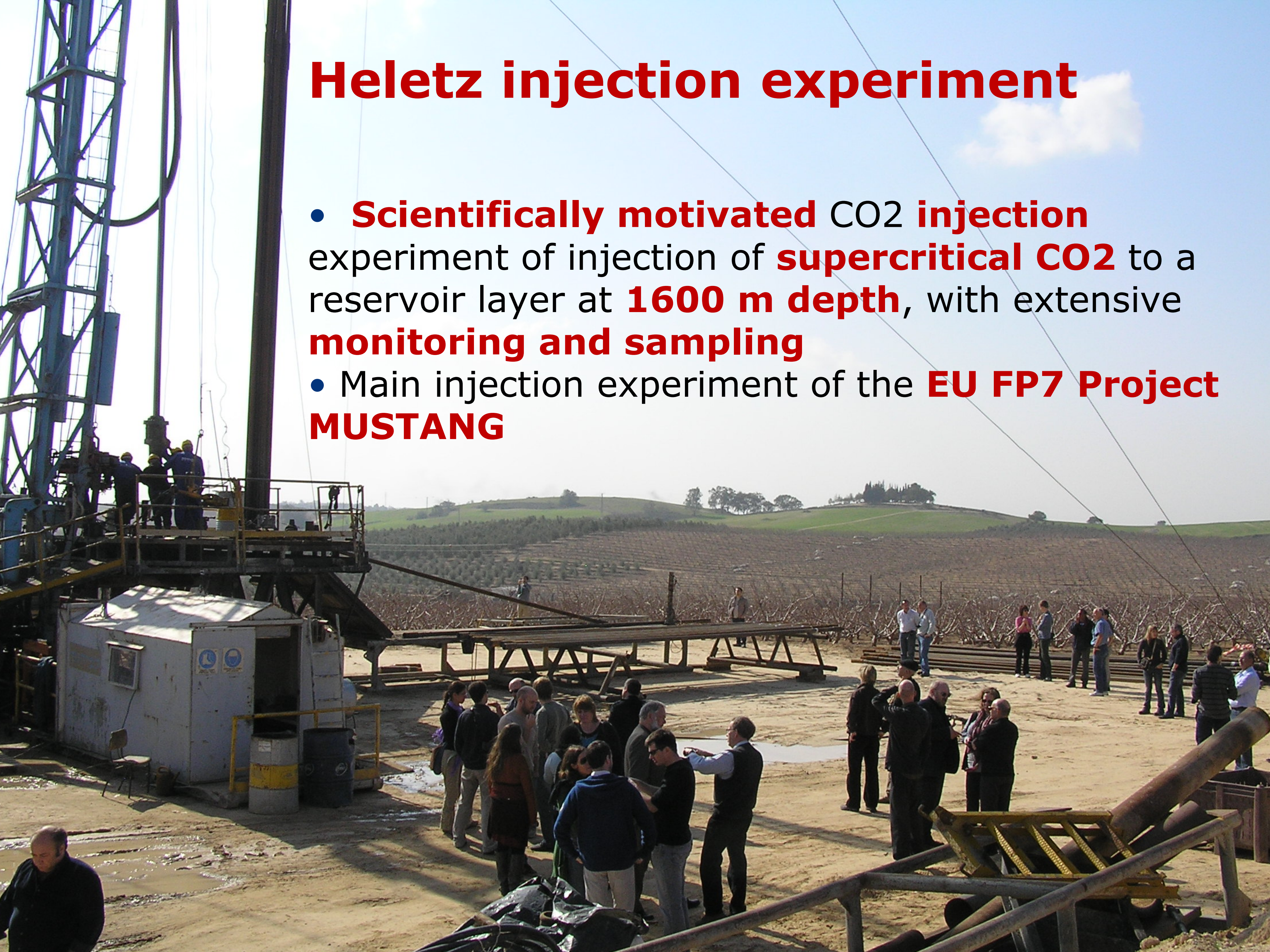
Heletz injection experiment

- **Scientifically motivated** CO_2 **injection** experiment of injection of **supercritical CO_2** to a reservoir layer at **1600 m depth**, with extensive **monitoring and sampling**
- Main injection experiment of the **EU FP7 Project MUSTANG**



Outline

MUSTANG project at large

Heletz injection experiment

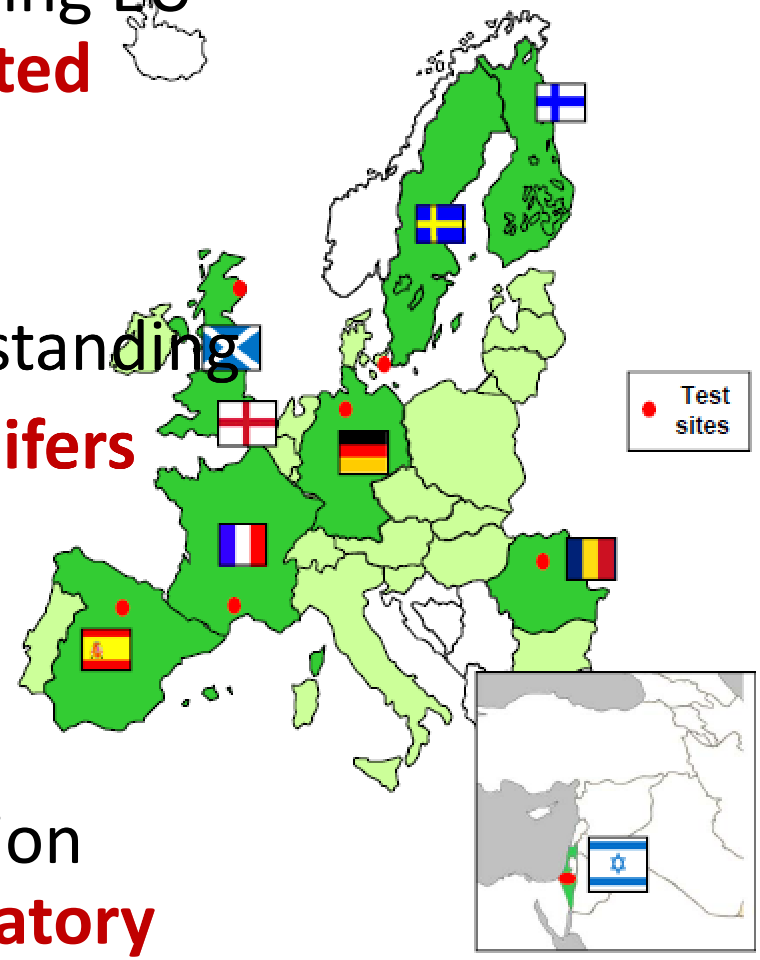
- Background and objectives
- Experimental setup
- Results of the predictive modeling
- Where we are now and the time table

MUSTANG project (www.co2mustang.eu)

- **MUSTANG** is a large scale integrating EU FP7 project, **19 partners, 24 affiliated organizatons**

- **develop methodology** and understanding for the **quantification of saline aquifers** for CO2 geological storage

- **7 test sites**, one deep **injection experiment** and one shallow injection experiment, as well as strong **laboratory experiment**, process understanding and **modeling** components



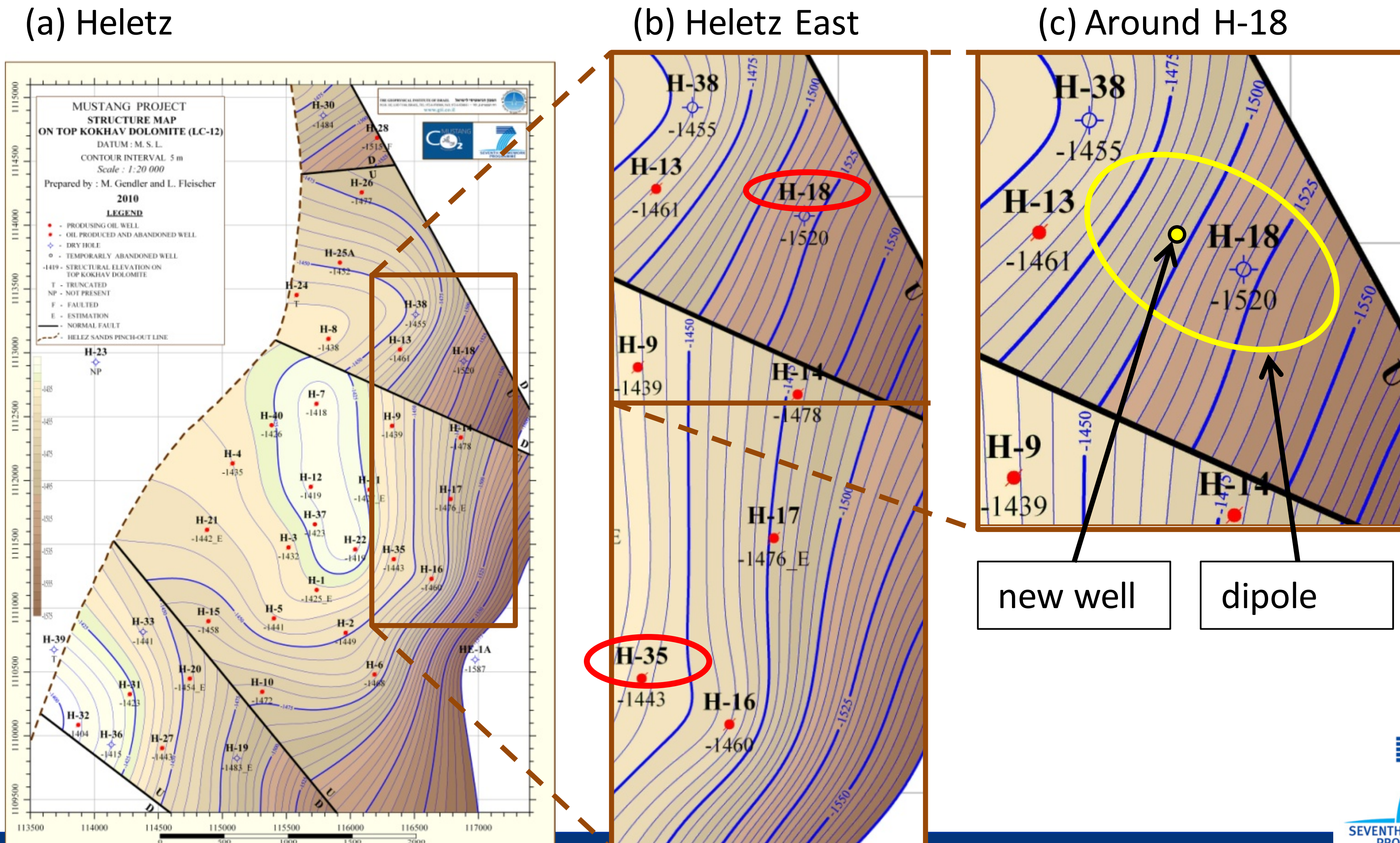
Background to Heletz injection experiment

- **Predictions** regarding the storage potential and the trapping mechanisms for geological storage of CO_2, **rely on model simulations**

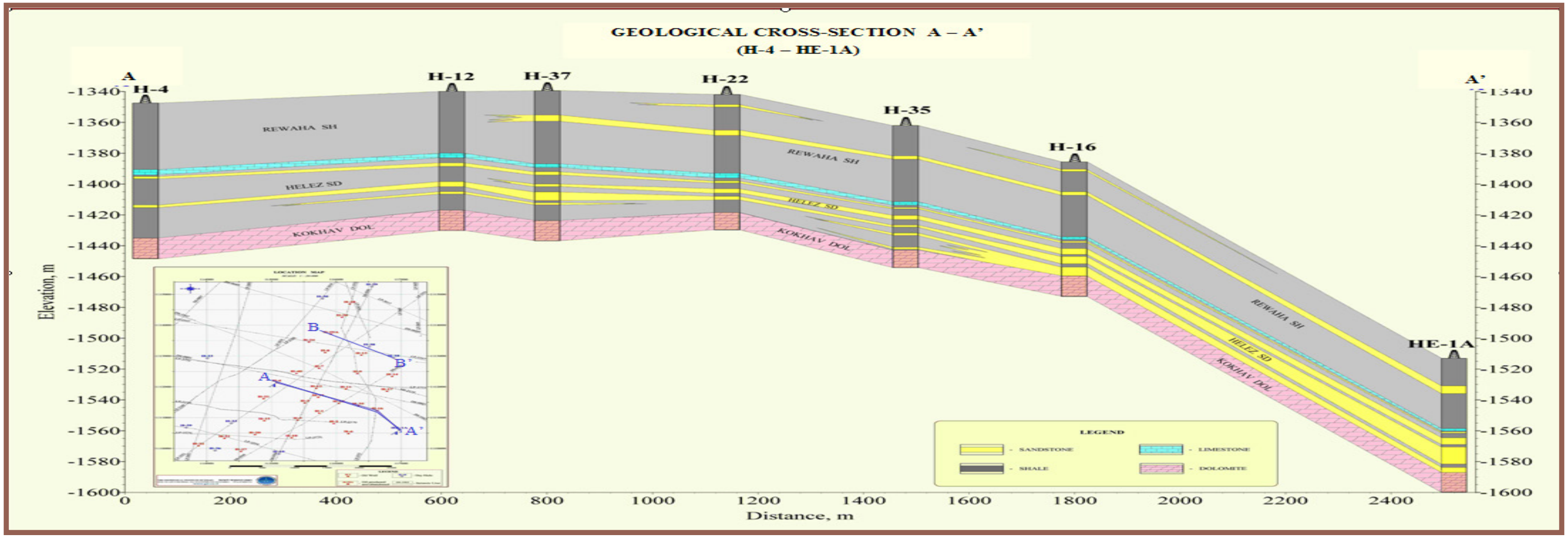
- **Models need careful validation** through well-controlled CO_2 injection experiments

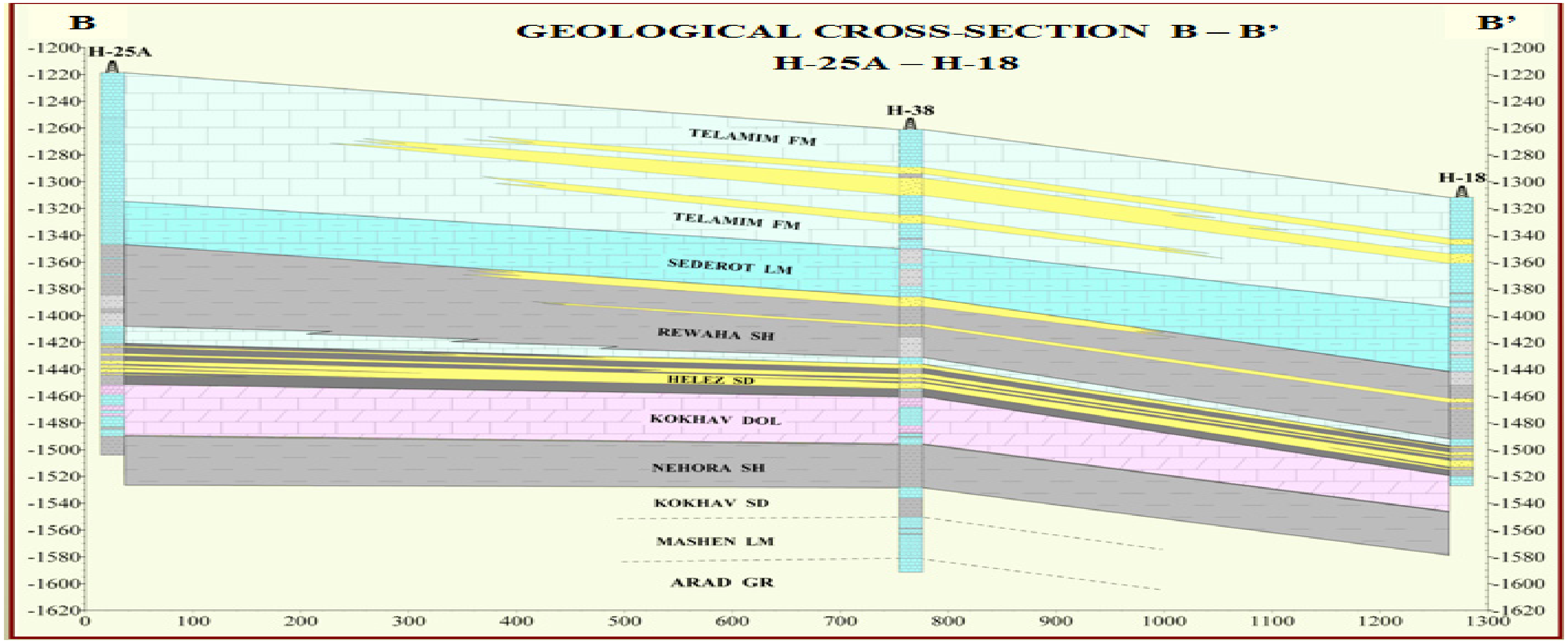
Heletz site

- ❑ **Well-characterized lower Cretacious sandstone**
- ❑ **Target layer at about 1500 m depth**
- ❑ **New well will be drilled to obtain suitable dipole for experiment**



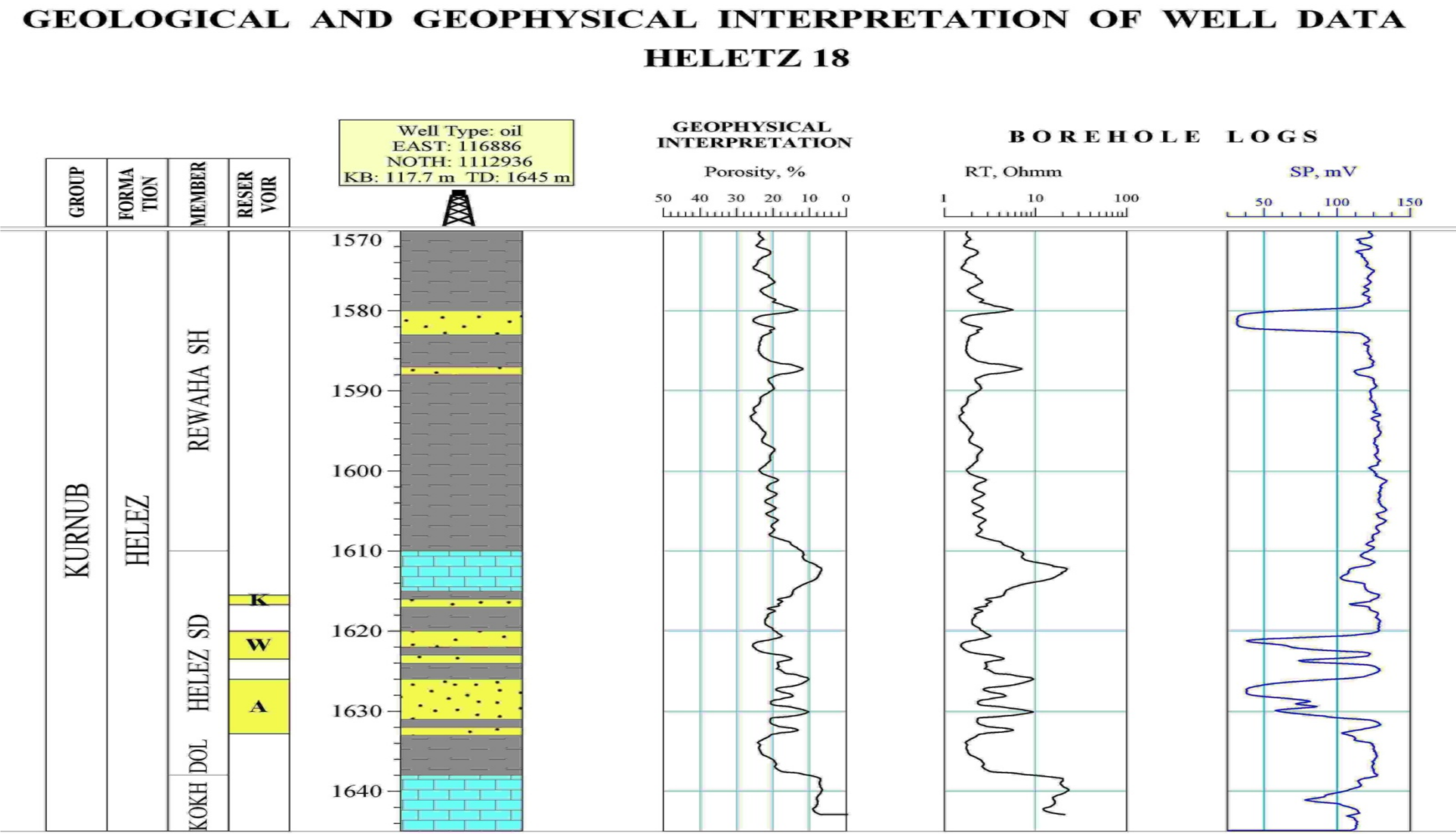
Heletz site - Geology





SEVENTH FRAMEWORK PROGRAMME

Heletz site – Target layers



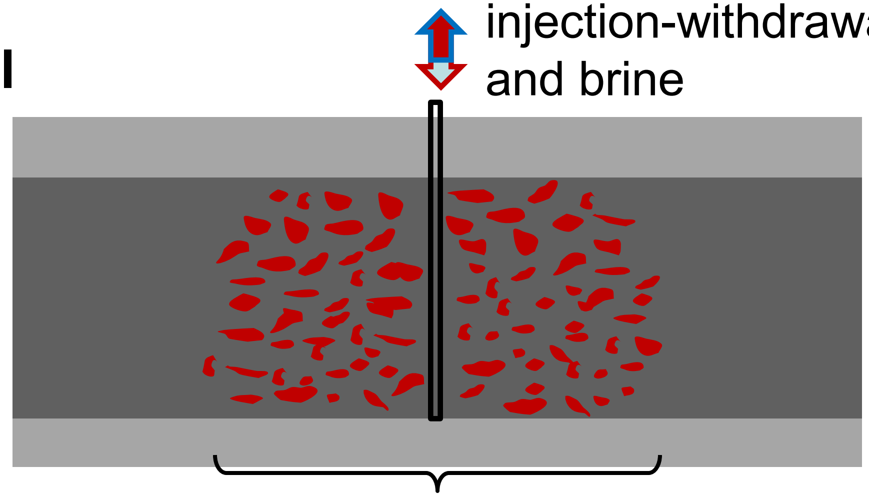
Shtivelman et al, EGU 2011

Objectives of the experiment

- Develop and validate a methodology for estimating **two key trapping mechanisms** of the stored CO_2 (residual trapping and dissolution) **at field scale**.
- Estimate the magnitude of the mixing of the stored CO_2 with the formation fluid.
- Assess the **impact of heterogeneity** on the evaluation of these parameters.
- Construct **comprehensive datasets** to be used **for model validation.**
- Test novel and traditional MMV (Measurement, Monitoring and Validation) technologies.

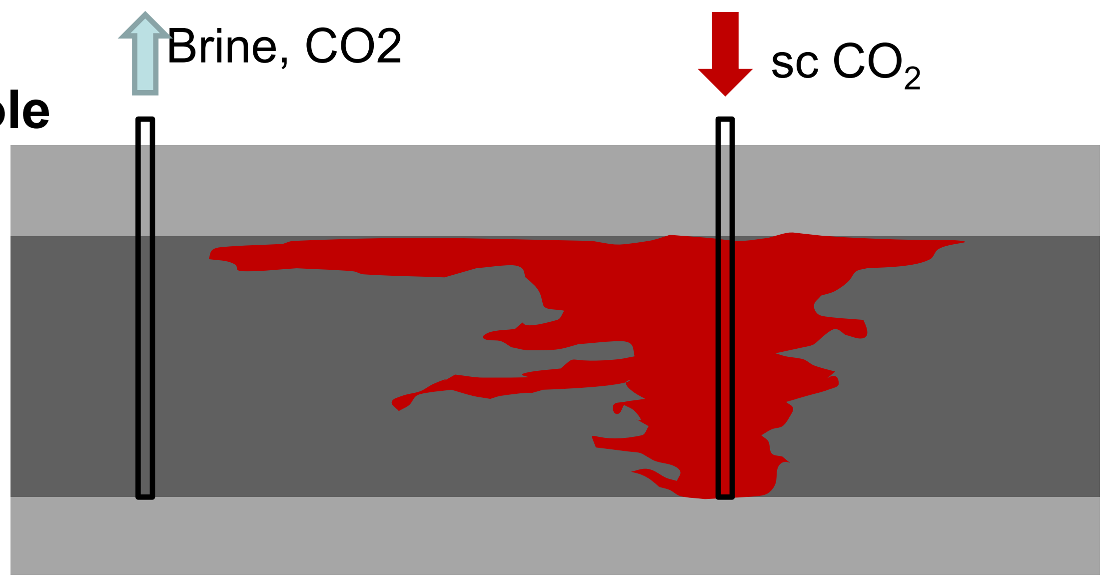
Main CO2 injection scenarios

1. push-pull



- ❑ Reduced influence of formation heterogeneity

2. dipole



- ❑ Heterogeneity affects migration and trapping

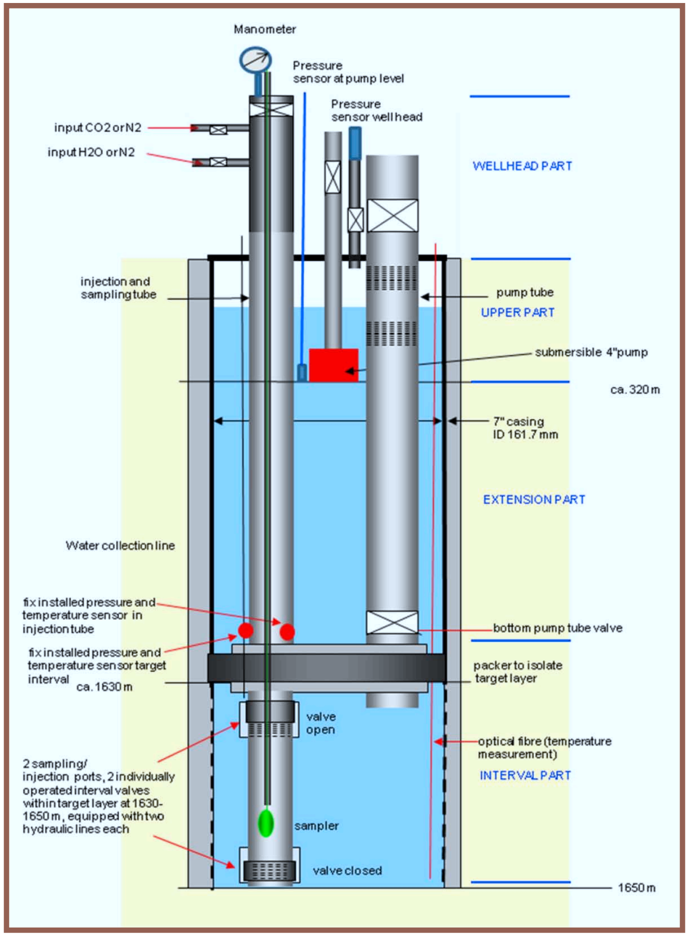
Steps prior to injection experiment

- **Re-entry** of an **existing well** (H18, H35).
- **Drilling of a new well** at distance of 30-70 meters.

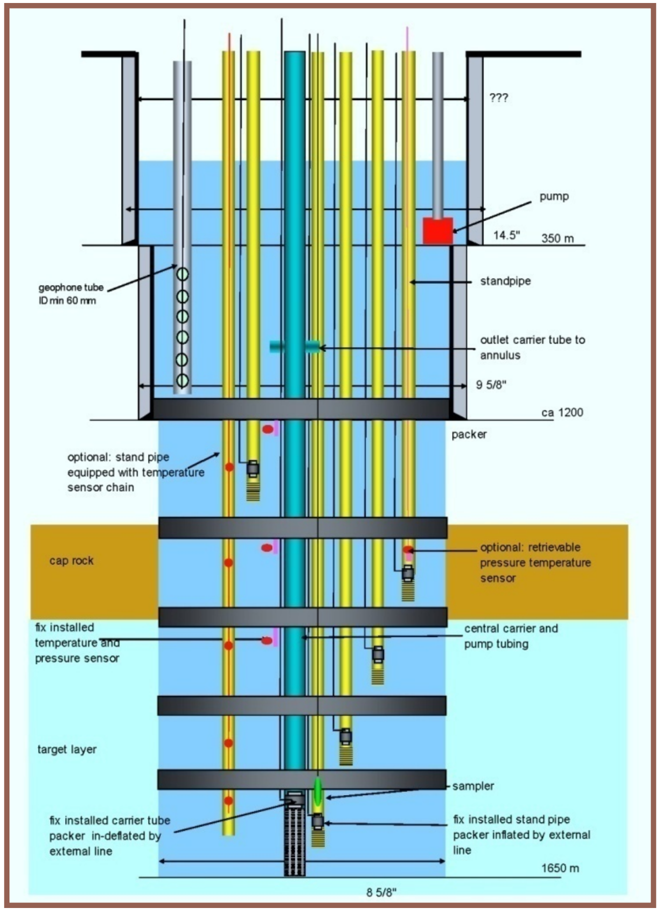
- **Instrumentation** of the wells (design by UU, EWRE, VIBROMETRIC and SOLEEXPERTS).

- **Monitoring and measurement technologies**:
  - pressure and temperature sensors with online data acquisition system,
  - optical fiber for continuous temperature measurement,
  - fluid sampling at various horizons (preserving the in depth pressure conditions),
  - geophones to be installed in the wells and
  - seismic survey on the ground.
- Laboratory facilities on site

Injection / monitoring wells



Injection well



Monitoring well

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Tests to be done

Pre-injection characterization

- Single-well hydraulic tests, flow logging, thermal logging and push-pull tracer tests
- Hydraulic and tracer tests in the two-well system

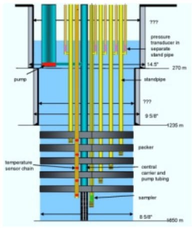
CO2 injection

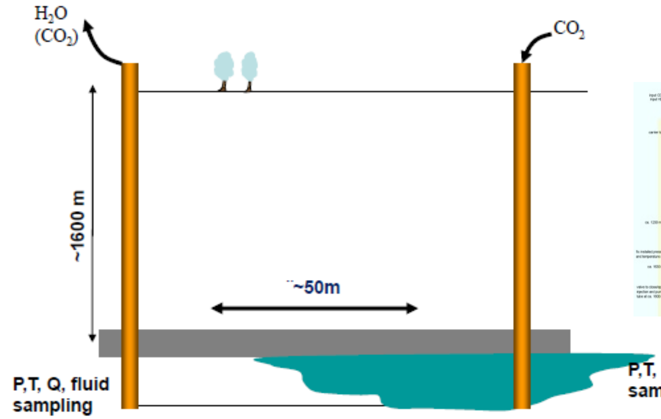
- Push-pull (single-well) experiment of water, CO_2 and tracers in the water and the CO_2
- Injection of water and CO_2 in a directed flow system (established by pumping in the monitoring well)

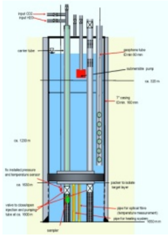
Supporting laboratory testing

- Rock properties, fluid samples at in-situ conditions

Geophyscical monitoring

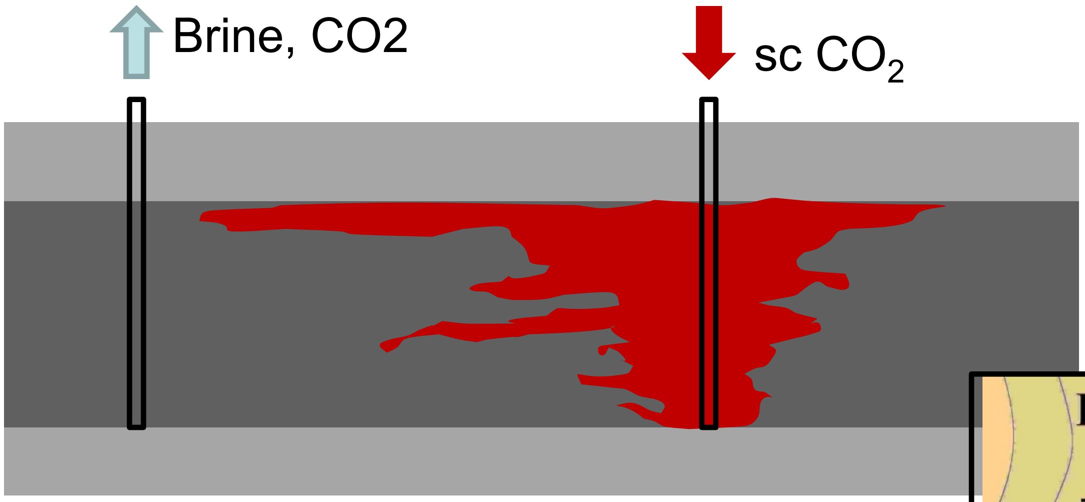


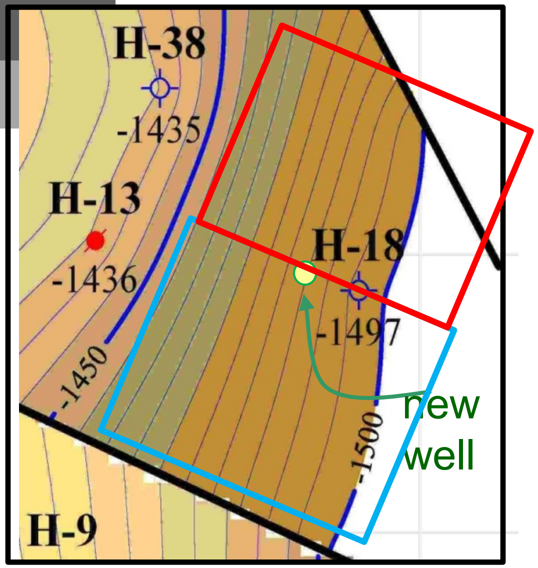


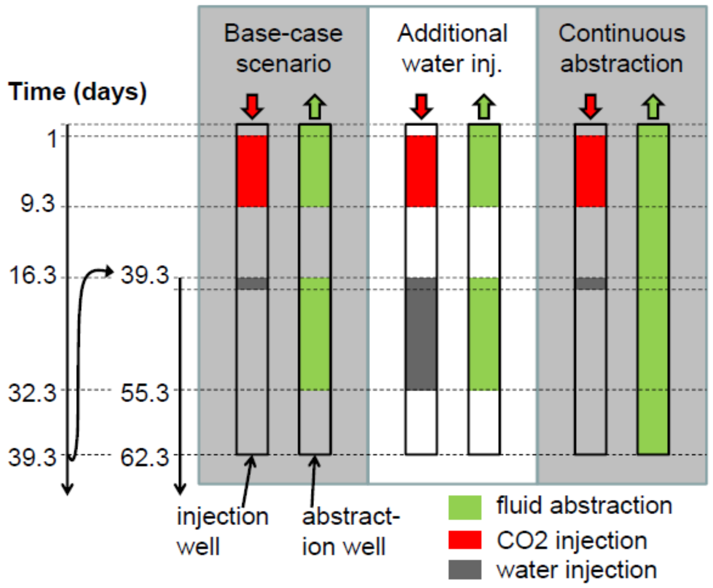


Contributing: EWRE, UU, Lapidoth, GII, UGÖTT, KIT, CNRS, ImaGeau, CSIC, Vibrometric, UEDIN, Stanford Univ, Solexperts, (Halliburton, CO2CRC, LBNL)

Modeling of dipole experiment





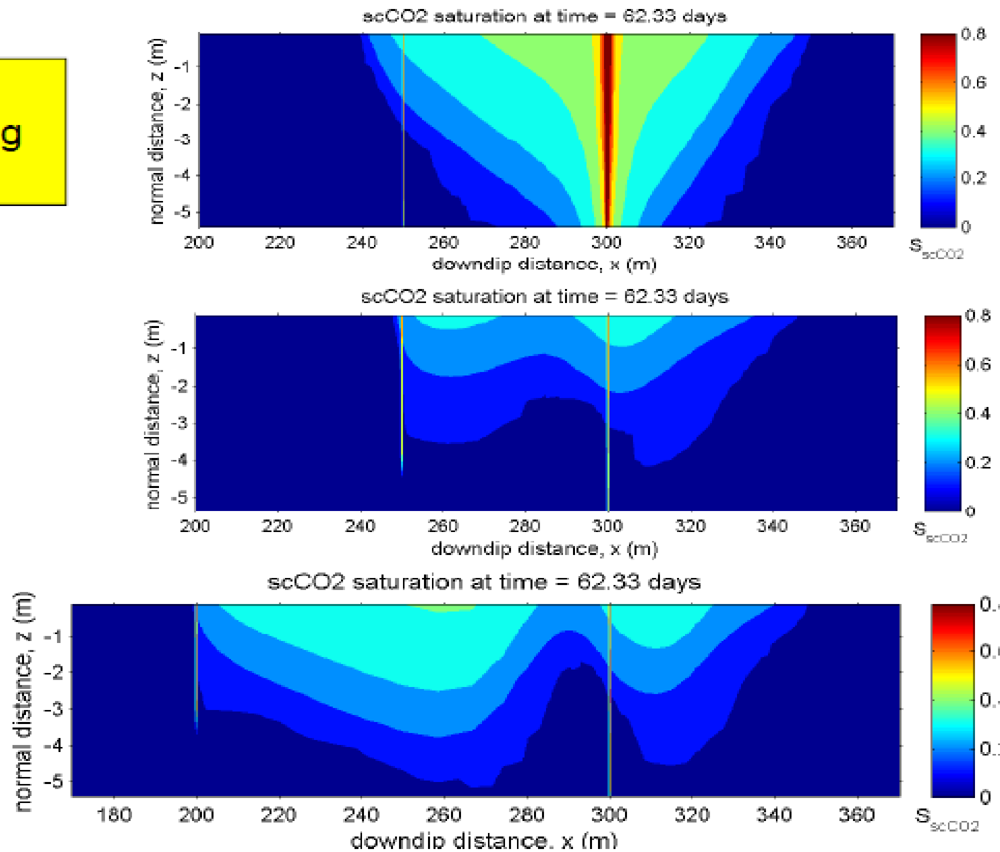


Effect of dipole distance

passive monitoring well

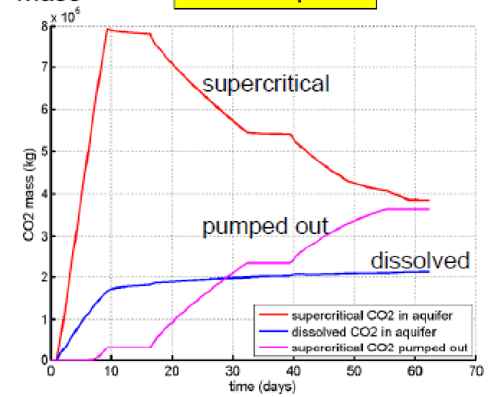
50 m dipole

100 m dipole



CO2 mass

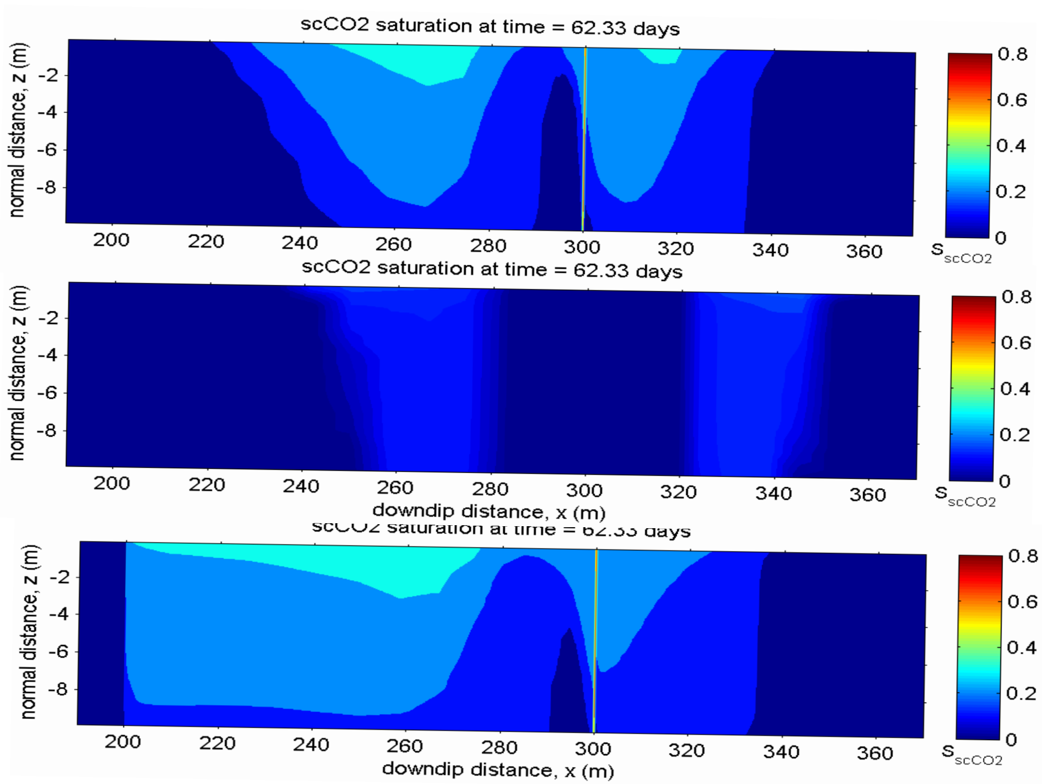
50 m dipole

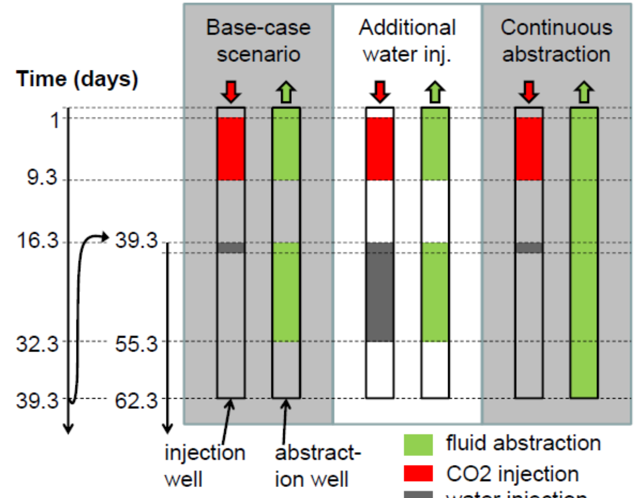


time

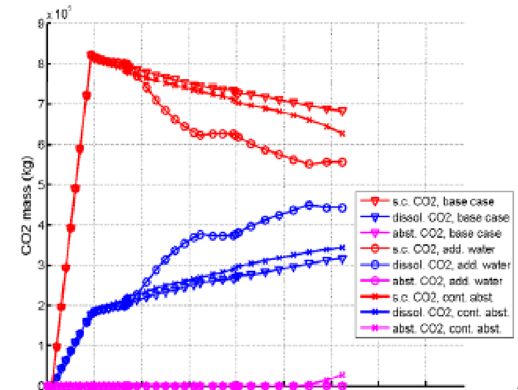
- **Injection-abstraction dipole produces a directed movement**
- **Larger dipole distance (100 m) stretches the scCO2 plume more, and the CO2 arrives later to the abstraction well**
- **Early arrival means that a large portion of CO2 will be lost, if abstraction (to draw the tracers) continues**

Injection/abstraction schemes



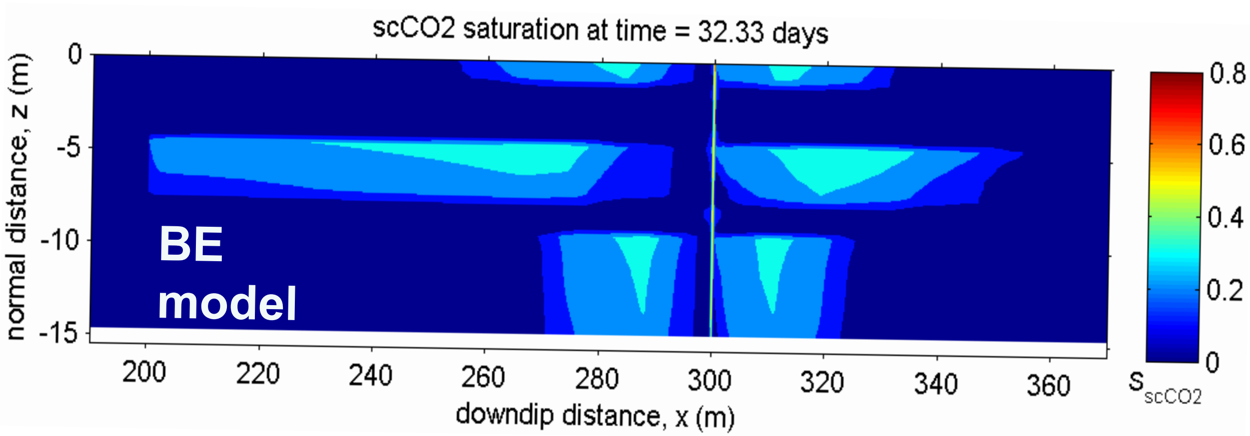


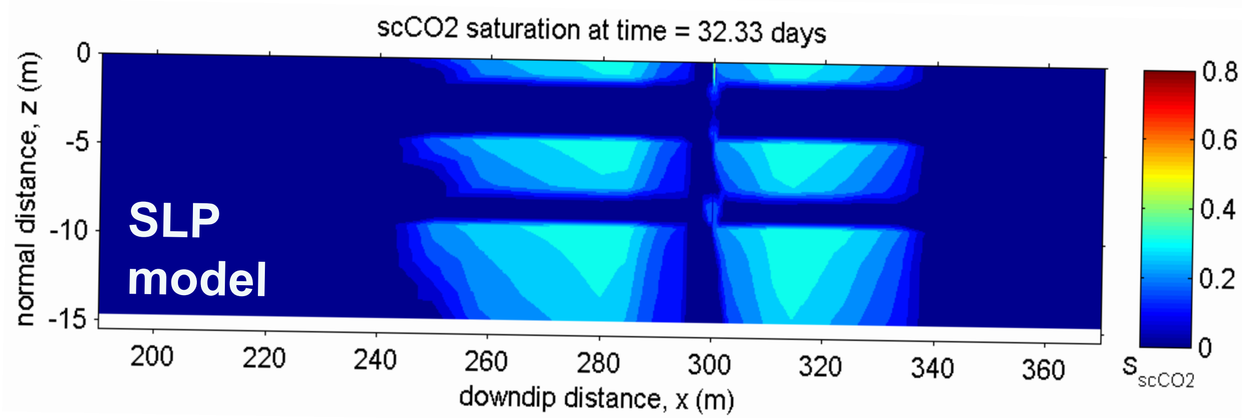
phase distribution

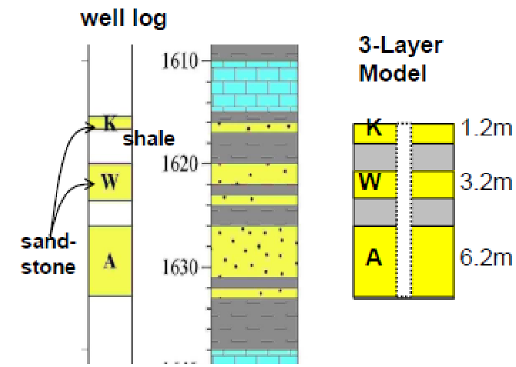


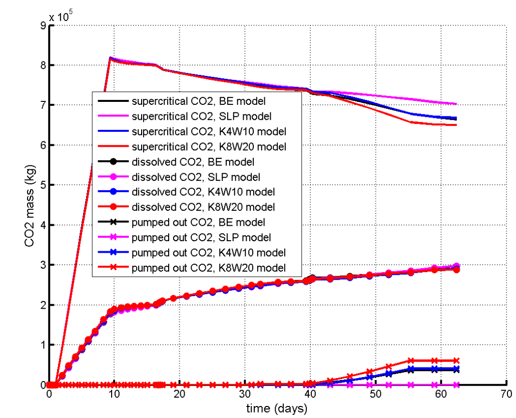
- ❑ **Additional water injection significantly increases dissolution and leads to removal of a large part of the mobile scCO2**
- ❑ **Continuous abstraction significantly increases the CO2 migration updip towards the abstraction well, while dissolution is not markedly increased**

Effect of layering



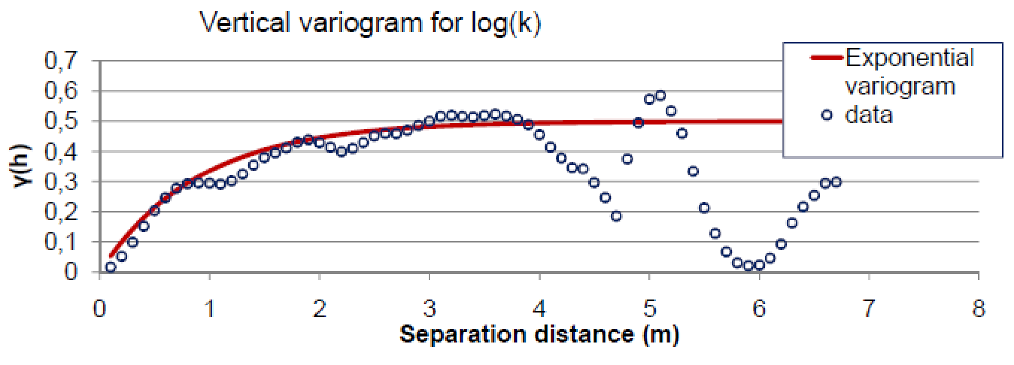






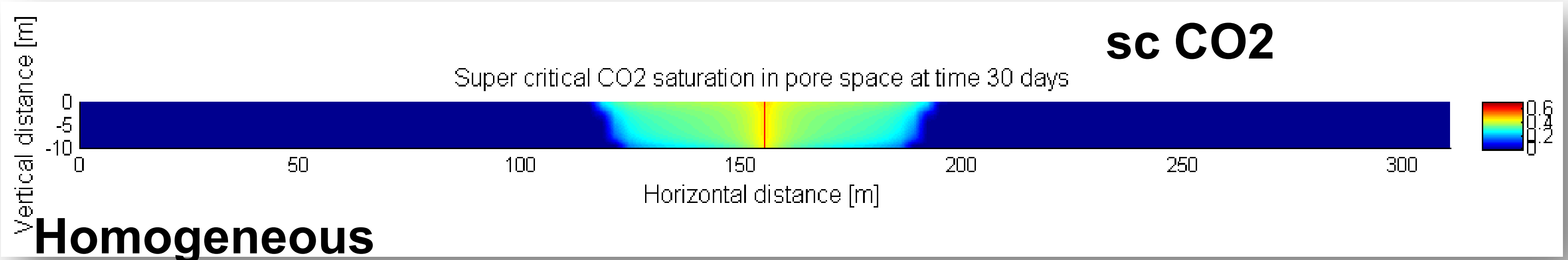
- ❑The permeability contrast between layers doesn't affect dissolution
- ❑ A layer with higher permeability will dominate the CO2 migration

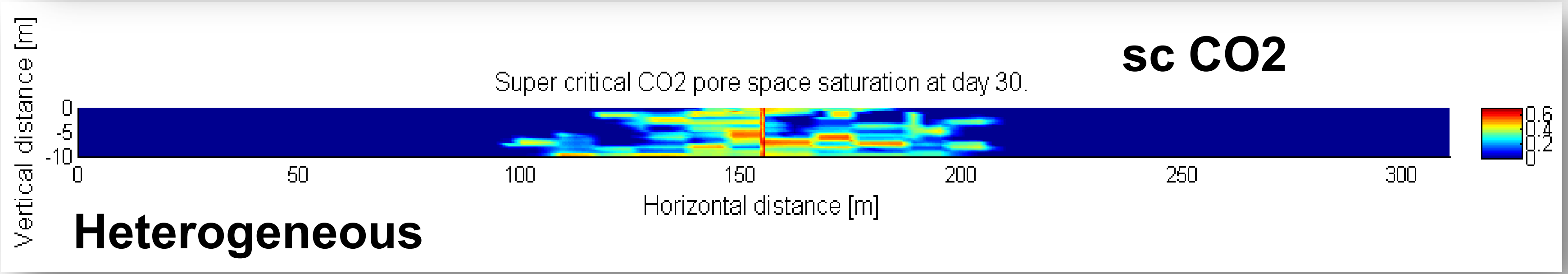
Effect of heterogeneity in sandstone



Example:
σ^2 (log k)=0.5, λ =2.7 m

Assume $\lambda_{horiz} = \lambda_{vertical}$
-> need further study



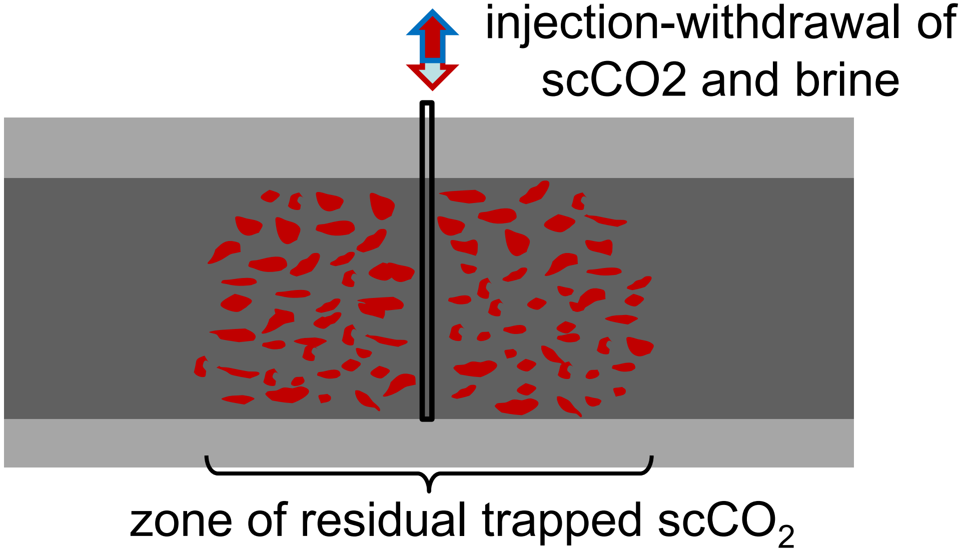


- **Higher permeability, variance and horizontal correlation length increase the maximum scCO2 migration distance for a given amount of injected CO2**

SEVENTH FRAMEWORK PROGRAMME

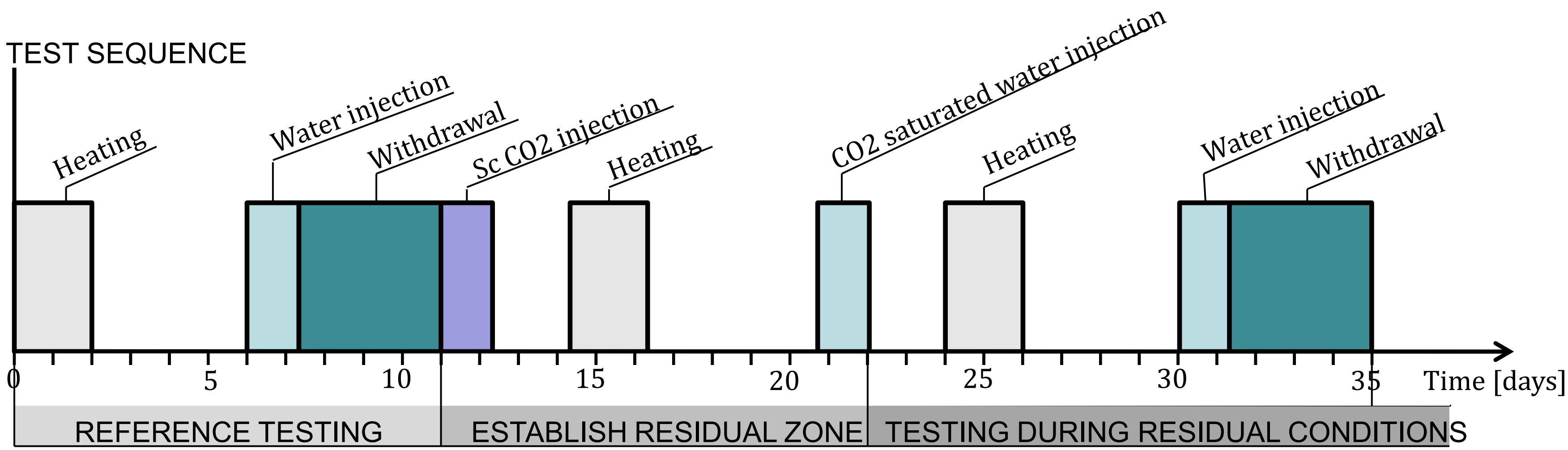
Push-Pull CO2 injection experiment

- test aims at determining residual phase trapping by a specific test sequence using a test sequence, an approach similar by Zhang et al. (2011).



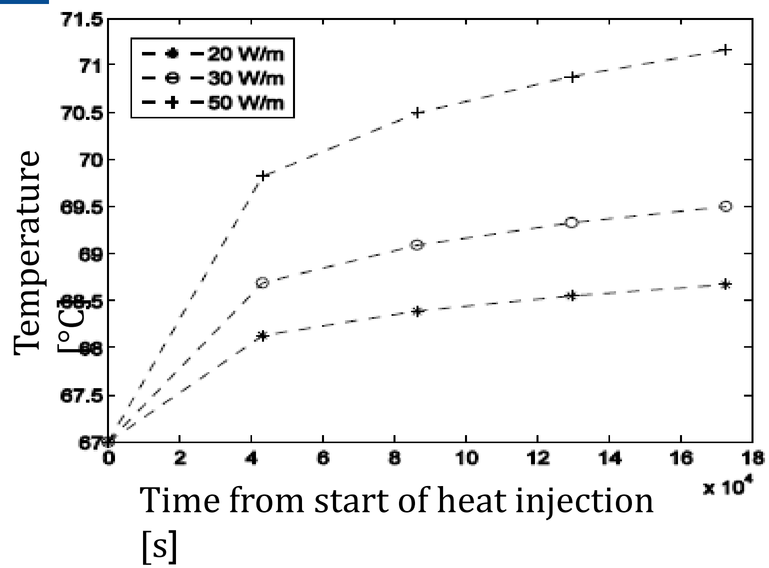
Reference: Zhang Y., Freifeld B., Finsterle S., Leahy M., Ennis-King J., Paterson L., Dance T, 2011, Single-well experimental design for studying residual trapping of supercritical carbon dioxide. International Journal of Greenhouse Gas Control, 5, 88-98.

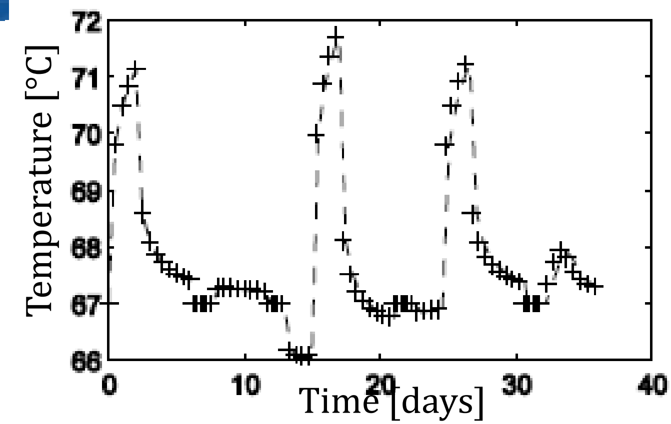
Simulation of push-pull experiment

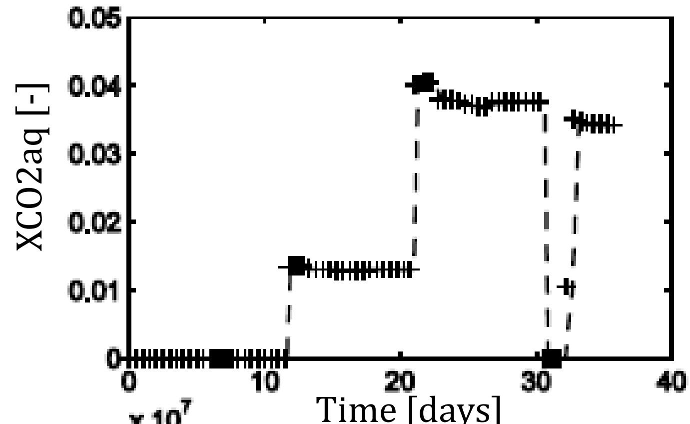


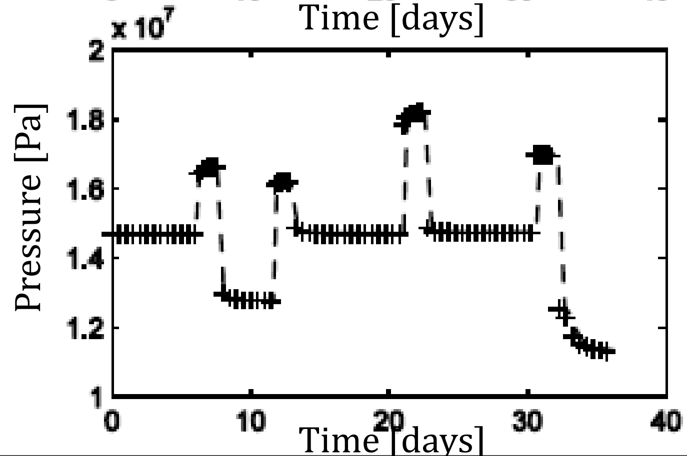
- Simulations with **different assumed residual CO2 saturations**, **heater effects** and amount of injected CO_2 has been carried out using TOUGH2/ECO2N, to see the effect on temperature and pressure response.

Simulation of push-pull experiment



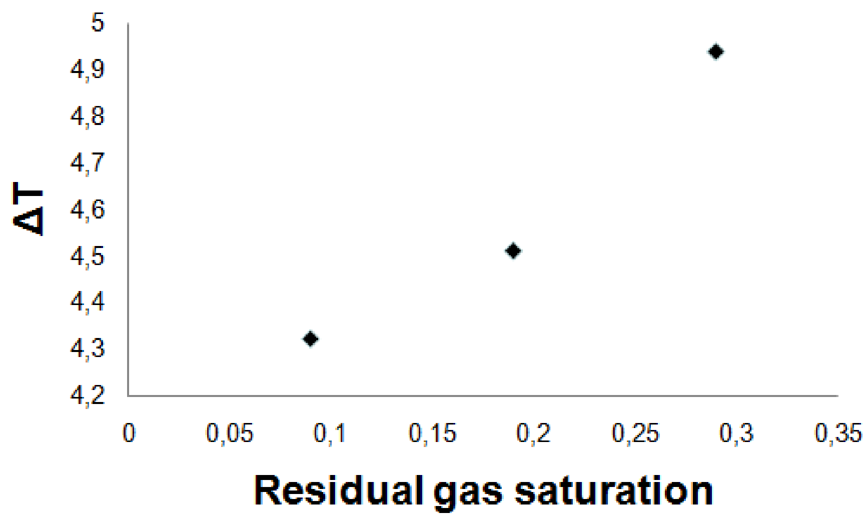


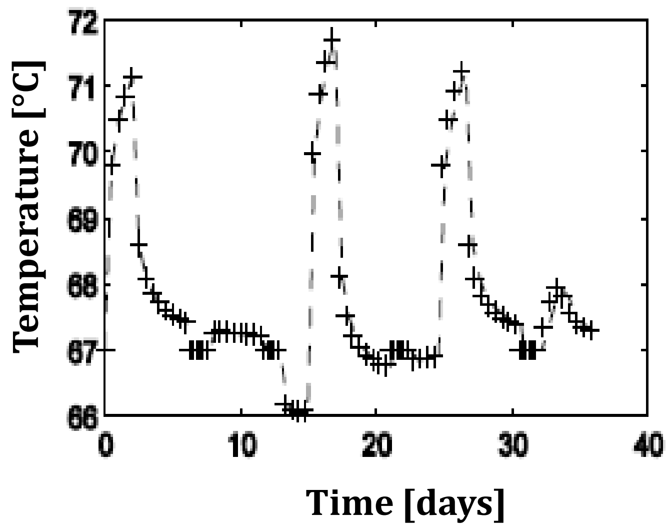


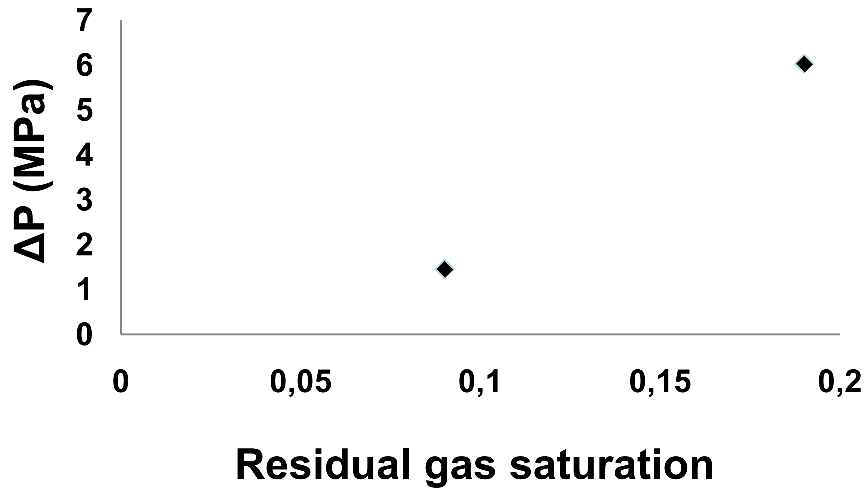


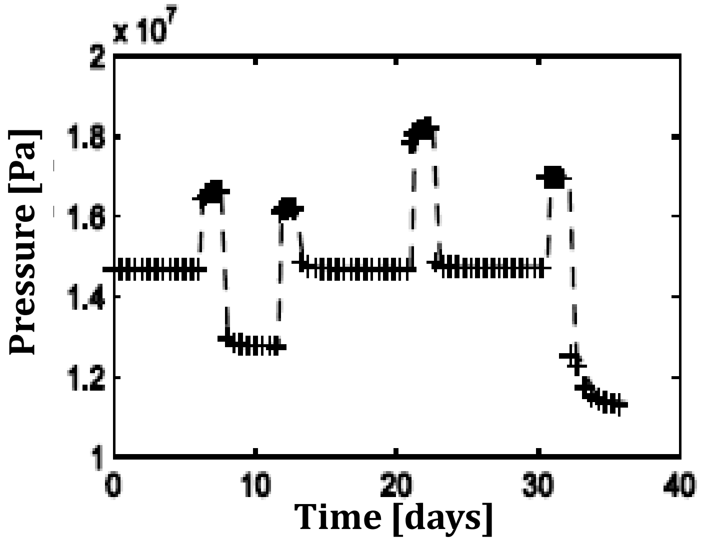
Example of simulated temperature, pressure and dissolved CO2 saturation responses

Effect of residual saturation on observed temperature and pressure









SEVENTH FRAMEWORK PROGRAMME

Modelling of combined well-reservoir CO_2 flow

- Estimate conditions needed at the well-head to ensure at least the desired injection flow rate into the formation
- impact of different formation conditions

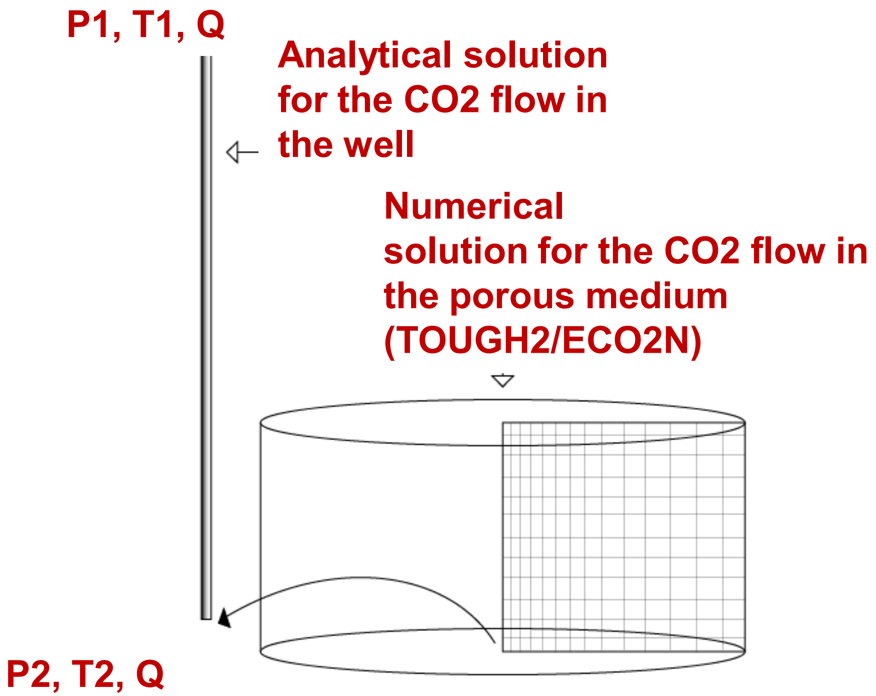


Illustration of the project

Method

- Analytical solution for one-dimensional CO2 flow in the pipe, solving equations of mass, momentum and energy conservation

  P1, T1 =F (P2, T2, Q)

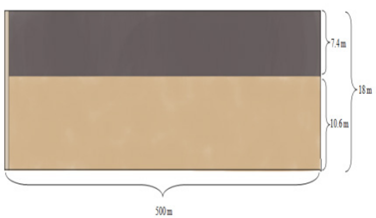
- Numerical solution for CO2 flow in the reservoir

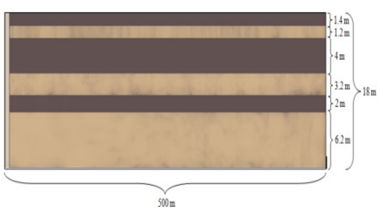
  P2, T2 =F (Q, k, other formation properties)

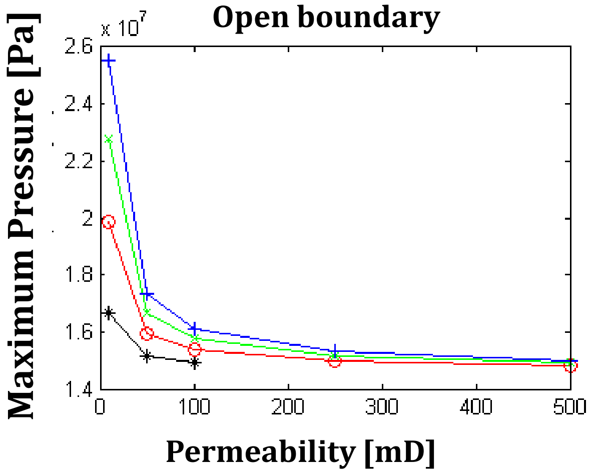
M. Kitron-Belinkov, K. Rasmusson, M. Rasmusson, F. Fagerlund, A. Niemi, J. Bensabat and J. Bear

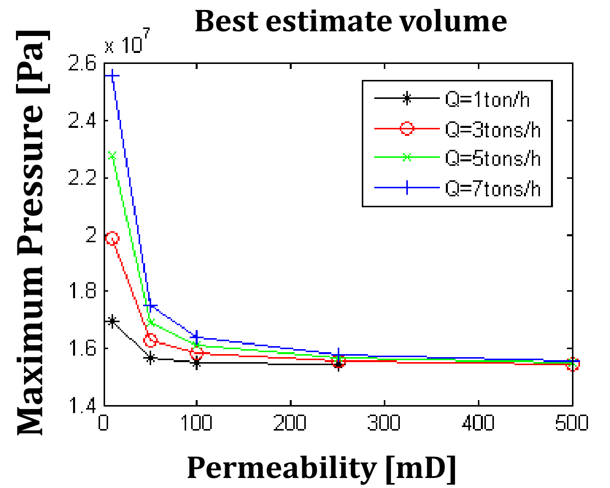
Modelling well-reservoir CO_2 flow

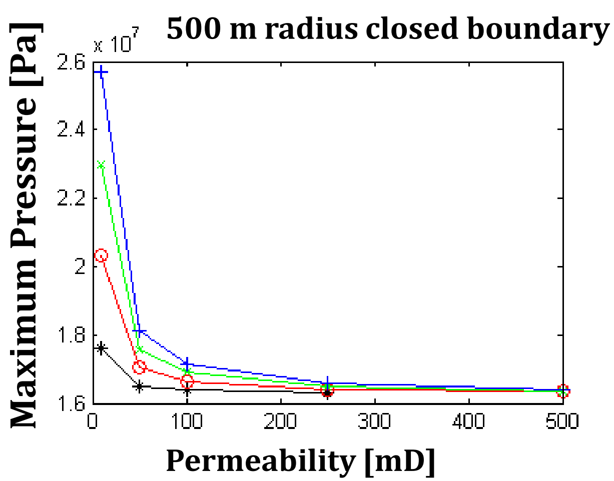
Example: maximum pressure in the injection element (well bottom) during injection for different outer boundary conditions of the reservoir (multilayered model)

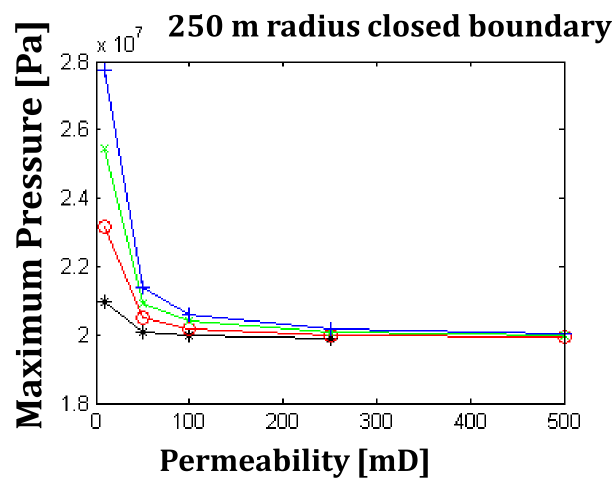










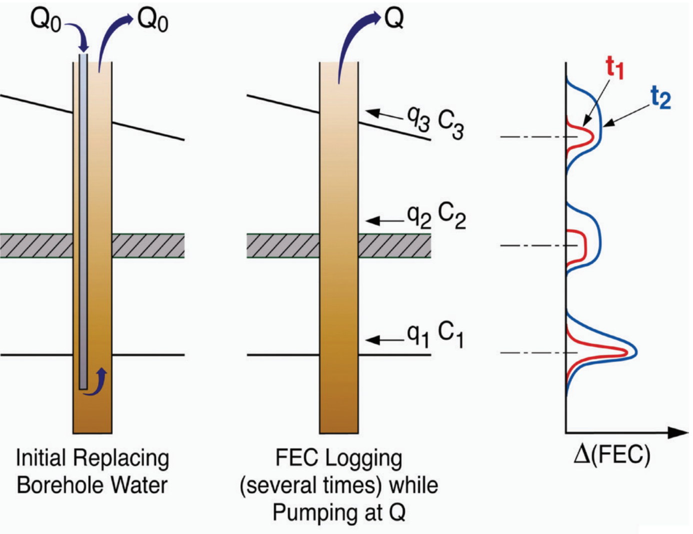


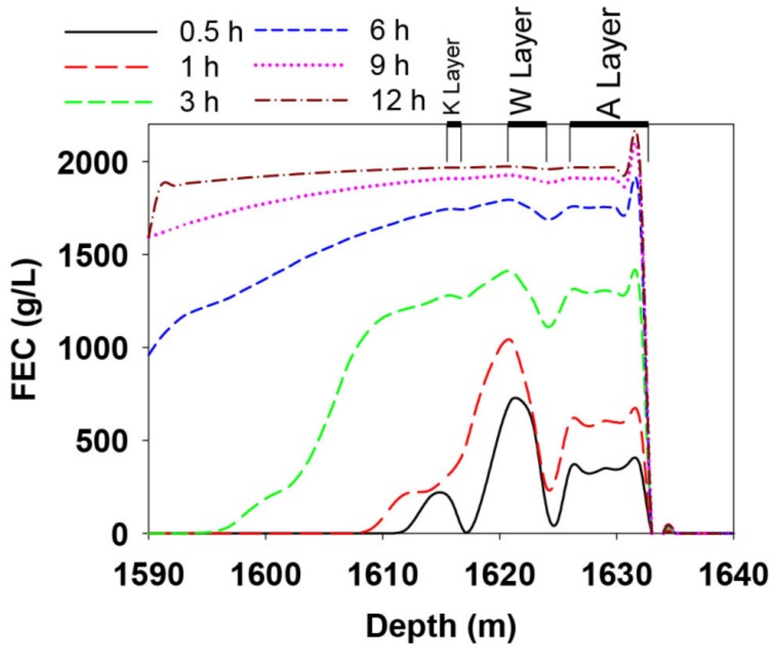
SEVENTH FRAMEWORK PROGRAMME

Flowing FEC method for determining conductivity

Flowing FEC Method

Flowing FEC (Fluid Electrical Conductivity) is fast way (as low as 12 h of experiments) to get detailed permeability structure and internal heterogenity of a target layer.





FEC profile obtained from Salinity logging method (for well H18)

Area under each peak ≈ $q_iC_i \times \Delta t$
Skewness of peak upwards → q_i
Reproducing the two features → q_i and C_i; then $q_i \rightarrow T_i$

Sharma P., A. Niemi, C.F. Tsang, J. Bensabat, P. Pezard and F. Fagerlund: Flowing Fluid Electric Conductivity Logging Method for Characterizing the Hydraulic Conductivity Structure of a Target Layer for CO_2 Injection. EGU 2011.

Use of Tracers

See **posters** session

- Ghergut et al ’Single-well and interwell tracer test design for CCS pilot site assessment’
- Ghergut et al ’Dual tracer push-pull test for quantifying residual CO2 interface area and saturation’

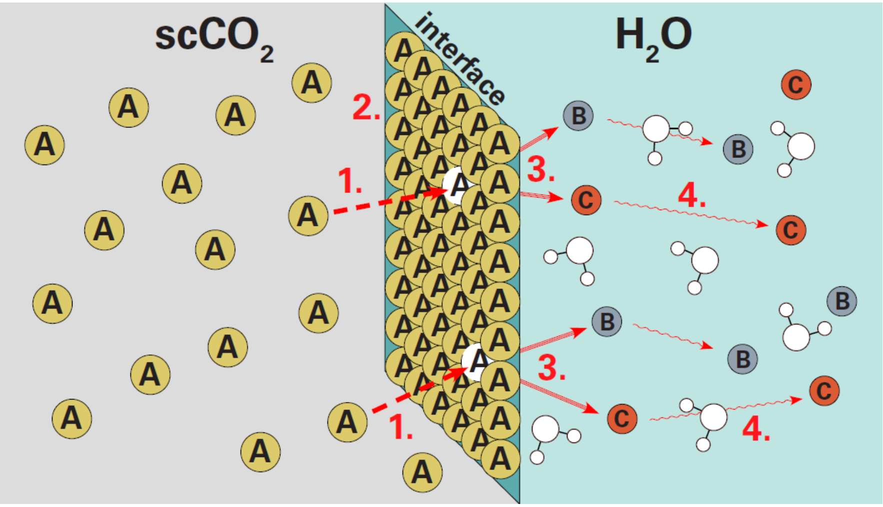
In the following a few words about **KIS tracers** under development

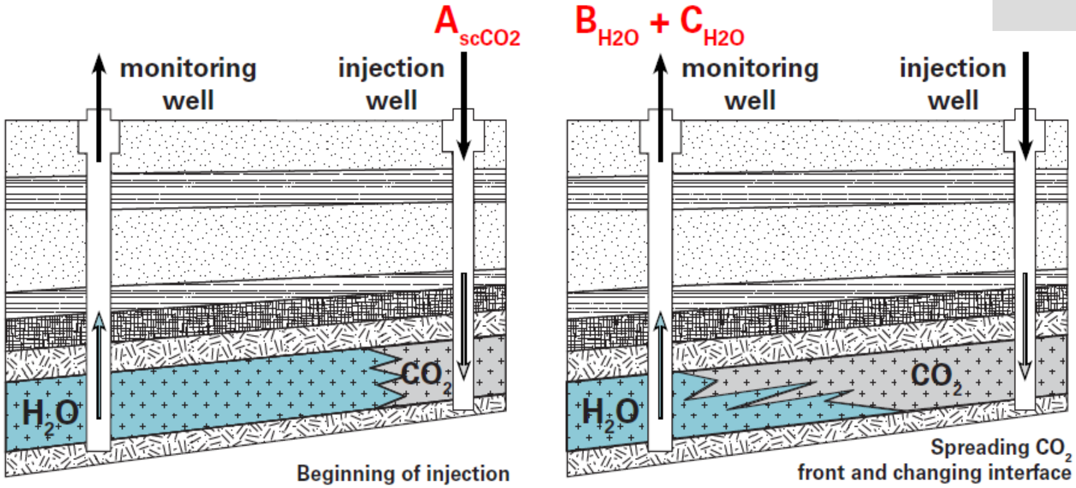
Applying reactive Esters as KIS-Tracer (kinetic interfacial sensitive tracer)

Tracer reaction at interface:

$$A_{CO2} + H_2O \longrightarrow B_{H2O} + C_{H2O}$$

Reactive Ester (KIS)	Water (Brine)	Product 1 (Acid)	Product 2 (Alcohol)



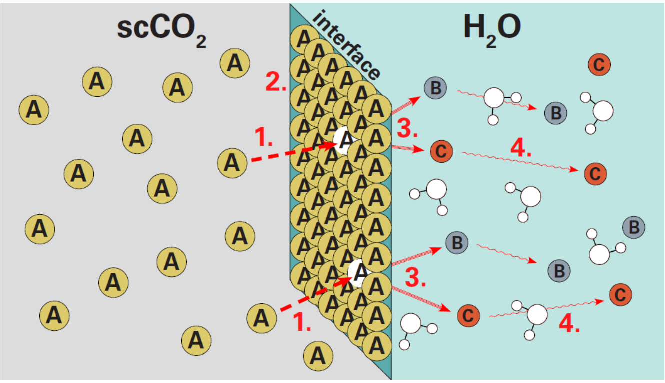


- **KIS-Tracer**
  - Interface-sensitive
  - Time-dependent
  - Kinetic coefficients

In contrast to Partitioning-Tracers which are:

volume-sensitive & based on equilibrium reaction (= transient studies difficult)

KIS-Tracer design



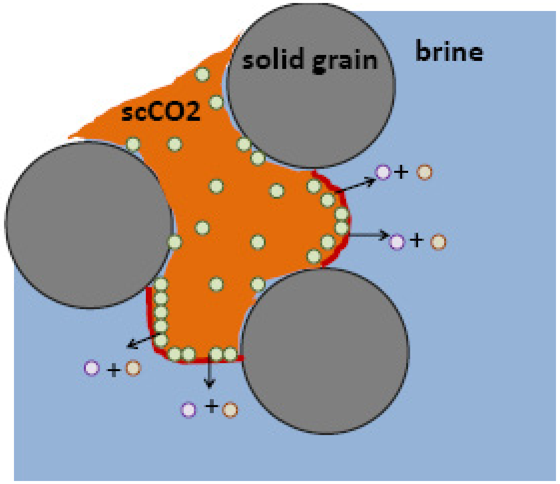
Design and synthesis of new chemical compounds (esters) that meet the following requirements:

- **occupation at interface of Langmuir isotherm type**
  - → constant amount of A
- **partitioning of A,B and C between phases must be negligible**
  - → KIS Tracer: $scCO_2$ soluble, non-polar, high logKow value
  - → reaction products: ionic, highly water soluble
- **k_diff >> k_reac (diffusion rate to interface is faster than reaction rate)**
  - → reaction rate controlled by temperature and molecule type
  - → reaction rate is limiting step

KIS Tracer will allow to study:

- Influence of pressure stimulation on mixing (meso scale lab)
- significance of fingering effects at field scale
- residual saturation of CO_2

Modeling of KIS-tracers



$$(-nS_r\beta_l)\frac{\partial T}{\partial t}+\left(n\frac{\partial S_r}{\partial s}\right)\frac{\partial p_g}{\partial t}+\left(nS_r\frac{1}{K_l}-n\frac{\partial S_r}{\partial s}\right)\frac{\partial p_l}{\partial t}+\nabla[-\frac{k_r^l k}{\mu_l}\cdot(\nabla p_l+\rho_l\mathbf{g})]-\frac{1}{\rho_l}Q_l=0$$

The gas equation is written as

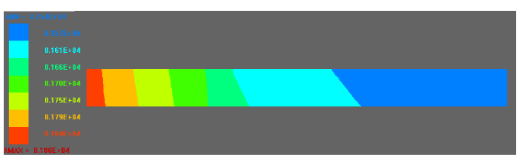
$$n(1-S_r)\frac{\partial(\ln\rho_g)}{\partial T}\frac{\partial T}{\partial t}+\left[n(1-S_r)\frac{\partial(\ln\rho_g)}{\partial p_g}-n\frac{\partial S_r}{\partial s}\right]\frac{\partial p_g}{\partial t}+n\frac{\partial S_r}{\partial s}\frac{\partial p_l}{\partial t}$$

$$+\nabla[-\frac{k_r^g k}{\mu_g}\cdot(\nabla p_g+\rho_g\mathbf{g})]+[-\frac{k_r^g k}{\mu_g}\cdot(\nabla p_g+\rho_g\mathbf{g})]\cdot\nabla(\ln\rho_g)-\frac{1}{\rho_g}Q_g=0$$

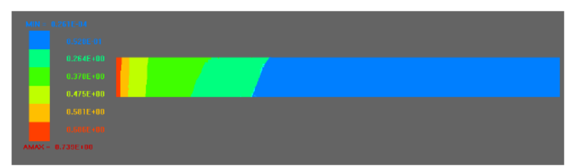
The heat transport equation is defined as

$$[(1-n)\rho_s c_s+nS_{re}\rho_l c_l+n(1-S_{re})\rho_g c_g]\frac{\partial T}{\partial t}-\nabla\cdot[\rho_g c_g T\frac{k_r^g k}{\mu_g}(\nabla p_g+\rho_g\mathbf{g})]$$

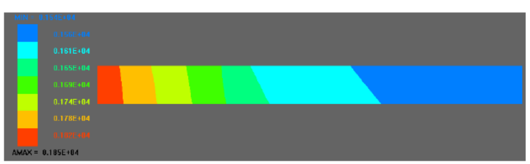
$$-\nabla\cdot[\rho_l c_l T\frac{k_r^l k}{\mu_l}(\nabla p_l+\rho_l\mathbf{g})]-\nabla\cdot(k_T\nabla T)-Q_T=0$$



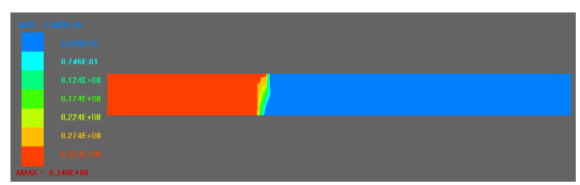
The distribution of gas pressure



The distribution of CO2 saturation



The distribution of water pressure



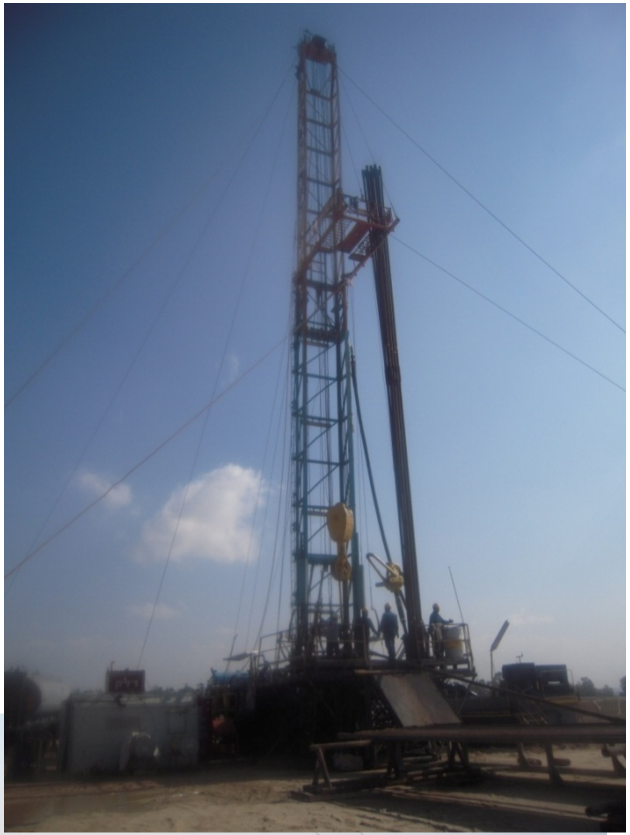
The concentration of tracer in CO2

Fagerlund, Tong et al, 2011

Where are we now

- Intensive planning work completed, including monitoring system design, modeling, permit applications

- Field activities underway since Nov 2010
  - Opening of the Well H18 (Nov to Feb 2011) was not succesful
  - Re-evaluation of data March-April
  - Opening of H35 now essentially complete



- **Well opening complete**

- **Well preparation and drilling of second well summer 2011, pre-experiment testing summer - autumn 2011**

- **Injection experiments winter 2012**

Mustang Partners and SIRAB

MUSTANG PARTNERS

MUSTANG SIRAB

International advisors

Industries/ end-users

Regulators

Thank you!