MUSTANG
A MUltiple Space and Time scale Approach for the quaNtification of deep saline formations for CO2 storaGe

Project Number: 227286

Work-Package: WP06

WP Title
Validation Experiment

Deliverable D062
Report on the experiment simulation
-Heletz CO2 injection experiment

The research leading to these results has received funding from the European Community's Seventh Framework Programme [FP7/20072013] under grant agreement n° [227286]

March 14, 2011
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<tr>
<td>Planned delivery date</td>
<td>Jan 31, 2011</td>
</tr>
<tr>
<td>Actual delivery date</td>
<td>March 15, 2011</td>
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<td>Leading participant</td>
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Executive summary

At Heletz, Israel, a series of field experiments, including injection of supercritical (sc) CO2 into a deep saline aquifer, are scheduled to begin 2011, as part of the EU-FP7 MUSTANG project. The aim is to investigate processes governing the fate of geologically stored CO2, including residual trapping and dissolution in formation brine. Field studies are of key importance for assessment of the relative importance of these processes. Test configurations for scCO2 and brine injections/withdrawals include a single-well push-pull test as well as a dipole test allowing control of the flow field and measurements between the two wells. Preparatory tests before CO2 injection include hydraulic testing, standard tracers as well as novel partitioning tracers, and thermal conductivity. Detailed numerical modeling of the tests is critical for a successful design of the field program, the interpretation of the measurements and assessment of parameters affecting the trapping mechanisms. To this end, a suite of numerical models of increasing complexity have been built to address the different field experiment configurations and measurement techniques that will be employed on site. This study presents the results of these modeling studies aimed at optimizing the design of the field testing and relating the various measurements to the in-situ CO2 trapping characteristics of the storage formation. The sensitivity of formation parameters for the residual trapping and dissolution of scCO2 are investigated and effects of formation layering and heterogeneity are assessed.

Keywords

Geological storage of CO2, CCS, modelling, two-phase flow, field experiment, supercritical CO2, trapping, dissolution, saline aquifer, sandstone, heterogeneity
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1. INTRODUCTION

An essential component of the EU FP7 project MUSTANG (www.co2mustang.eu), is the field-scale CO2 injection validation experiment together with its associated testing and monitoring program at the Heletz site in Israel. The general structure of this site is relatively well understood from earlier investigations and the intended target layer for CO2 storage is a lower cretaceous sandstone layer at a depth of approximately 1,500 m, which is overlain by a caprock of low permeability marls and shales. The field experiment comprises a sequence of CO2 and water injections into the target layer together with extensive monitoring of the migration and fate of the injected CO2.

Field experiments are crucial for improving our understanding of CO2 migration and trapping behaviour at the field scale as well as for developing and demonstrating monitoring methods which can delineate the spreading and detect leakages. A key to success in these studies is to design the experiments in such a way that the parameters of interest can be related to measurable quantities, preferably minimizing uncertainty in the estimations. Thorough modelling of the flow and transport of CO2 is therefore important already during the design phase of the experiment. In addition to evaluating models and methods, we are interested in investigating all parameters that influence CO2 transport and fate, particularly in-situ dissolution behaviour and residual supercritical (sc) CO2 trapping.

Two main test configurations are considered: first, a single-well push-pull experiment will be performed using a smaller amount of CO2 (in the order of 100 tons), second, a larger CO2 injection (in the order of 1000 tons) will be performed in a dipole configuration between two wells. In the single-well experiment effects of preferential flow will largely cancel out during the push-pull injection-abstraction sequence, thereby allowing easier interpretation of results and determination of transport parameters (in-situ dissolution, residual scCO2 trapping etc.) with less uncertainty compared to the case of preferential flow affecting the results. In the two-well dipole experiment we will subsequently be able to study the same processes under the influence of geological heterogeneity. Furthermore, here we will also be able to study the spreading over larger volumes, which is additionally needed for testing novel measurement and monitoring methods such as low frequency reflection seismics and custom-designed one-way partitioning tracers being developed within the MUSTANG project. The combination of these two tests allows an effective comparison, which we deem necessary for developing a thorough understanding of the effects of individual processes in complex field settings.

This report presents the progress of the modelling carried out to support the design of these two field experiments and to find optimal test sequences. We will first present a brief general background about the test site and then describe the modelling in two main parts, followed by a brief description of ongoing further developments.

2. BACKGROUND

The experiments are planned to be performed using one existing and one new well, the latter to be drilled at an appropriate distance from the existing well to perform the dipole experiments. Initially
well H-18 in the north-eastern part of the Heletz site was identified as a suitable existing well for the field experiment and was therefore chosen to be reopened and conditioned to be used as the CO2 injection well (Figure 1). Recent failure to reopen H-18 due to unexpected collapse of large sections of the well discovered during the drilling, has however, led to the need of identifying a different well. Because only one new well can be drilled, the experiment needs to be moved to a different part of the Heletz site where a different suitable existing well in good condition for re-entry can be found. Suitable wells in a similar setting to that of H-18 have been identified in the eastern part of the Heletz site (figure 1b), where e.g. wells H-14 and H-16 are possible for re-entry.

Until now most of the modelling efforts have been focussed on H-18. Although it has recently become evident that H-18 cannot be the existing well used in the experiment, the modelling analyses made based on the H-18 setting (Figure 1c) are largely applicable also to other locations in the eastern part of Heletz. A difference, however, is that the considered wells south H-18 (H-14 and H-16) are on the other side of the NW-SE fault seen just north of H-14 in figure 1. While new modelling studies will be performed for the new setting, this report will present the modelling to date, which is based on the H-18 setting (Figure 1c).

To create a dipole along the line of maximum dip, a new well can either be drilled up-dip or down-dip from the existing well along this line. The up-dip well will then be used as abstraction/monitoring well and the down-dip well will be the injection well. In the case of H-18, a combined monitoring and abstraction well was planned to be drilled up dip from H-18, as shown in Figure 1c. The single-well push-pull experiments will be performed only in the injection well, while the dipole injection experiment will, of course, use both wells. In both experiments the injected CO2 is estimated to remain close to the injection well as compared to other existing wells such as H-13 in the case of the H-18-setting or H-9 in the case of the H-14 setting (see Figure 1). Therefore, until hydraulic testing has been undertaken and a new well in the vicinity of the chosen existing well has been drilled, the geological information obtained from the well log of the injection well alone (for now H-18) provides the starting point for our modelling of both CO2 injection experiments. Properties obtained from the H-18 well logs, provide a basis for different conceptual models of the target layer and its variations in the vertical direction, as shown in Figure 2. These models and properties given in Table 1 and Table 2 were used in the modelling aimed at aiding the design of the CO2 injection experiments. The specific models for the push-pull and dipole experiments are described in more detail in the following sections.
Figure 1. Map of the bottom of the target layer for the CO2 injection experiment at Heletz. Well H-18 has been proposed for CO2 injection. The approximate location of the proposed monitoring well is also shown.

Figure 2. Different vertical models of the target layer around well H-18.
Table 1. Vertically averaged geological properties of the target layer in the vicinity of well H-18.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total sandstone thickness [m]</td>
<td>10.6</td>
</tr>
<tr>
<td>Bottom depth [m]</td>
<td>1632.8</td>
</tr>
<tr>
<td>Final shut-in pressure [Pa]</td>
<td>1.47E+07</td>
</tr>
<tr>
<td>Average porosity [%]</td>
<td>14.3</td>
</tr>
<tr>
<td>Average permeability [m(^2)]</td>
<td>9.7E-15</td>
</tr>
<tr>
<td>Total dissolved solids [mg/l]</td>
<td>53570</td>
</tr>
<tr>
<td>Equivalent NaCl massfraction [-]</td>
<td>0.04988</td>
</tr>
<tr>
<td>Temperature [°C]</td>
<td>67</td>
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</table>

Table 2. Parameters for the characteristic curves.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Residual water saturation (S_{wr})</td>
<td>0.3†</td>
</tr>
<tr>
<td>Residual gas saturation (S_{gr})</td>
<td>0.09</td>
</tr>
<tr>
<td>Pore-size distribution index (\lambda)</td>
<td>0.762†</td>
</tr>
<tr>
<td>Displacement pressure (P_d)</td>
<td>11.82E+03 ††</td>
</tr>
</tbody>
</table>

† based on data for Vosges-1 sandstone (Dana & Skoczylas, Experimental study of two-phase flow in three sandstones. I. Measuring relative permeabilities during two-phase steady-state experiments, 2002).
†† scaled value based on data for Vosges-1 sandstone (Dana & Skoczylas, Experimental study of two-phase flow in three sandstones. I. Measuring relative permeabilities during two-phase steady-state experiments, 2002).

3. PUSH-PULL EXPERIMENT

3.1 Model

The aim of these preliminary simulations is to create a model of the site to facilitate computational pre-testing of the experimental design of the single well push-pull CO\(_2\) injection test. Preliminary simulations are carried out to investigate the feasibility of hydraulic and thermal methods and pumping scheme to determine residual CO\(_2\) saturation and in-situ solubility/dissolution. The objective is further to eventually relate parameters of interest to measurable quantities. For the study the TOUGH2/ECO2N numerical simulator (Pruess, ECO2N: A TOUGH2 fluid property module for mixtures of water, NaCl, and CO2, 2005) was used.

A radially symmetric model for the Heletz site was created. The model represents a simplified version of the site consisting of a 5.8 m deep sandstone formation with a radius of 500 m. The model was homogeneous with parameters based on average formation properties. The total number of grid blocks was 2407 (29x83). A constant boundary condition was assumed.

3.1.1 Assumptions

The model assumptions are shown in Table 1. The capillary pressure and relative permeability curves were expressed by the Brooks-Corey Burdine relationship and used the parameters in Table 2.

Formation heat conductivity under fully liquid-saturated and desaturated conditions were chosen as 4.01 and 2.54 W/m°C, respectively (CWET=4.01 and CDRY=2.54). These values are based on calculations and should be replaced by values from laboratory measurements when available. The
sandstone dry heat conductivity was calculated from the porosity using Somerton (1992). This was corrected for temperature (but not pressure). From this the matrix thermal conductivity was calculated and used to calculate thermal conductivity using equation 7 in Hurter et al. (2007). The MOP(10)=1 alternative expressing heat conductivity as a linear function of liquid saturation was chosen, in accordance with Hurter et al. (2007), who used a linear function.

### 3.1.2 Discretization
A RZ2D-model was created with a vertical discretization of 0.2 m. In the horizontal direction a logarithmic discretization was adapted with finer grid spacing around the well and coarser towards the outer boundary. The boundary grid blocks were given small volumes. To calculate the distance needed for finer discretization (where the plume will spread) a rough calculation for 200 ton CO$_2$ was carried out, Table 3. The distance was approximately 20 m. The model has a radius of 500 m and a total of 2407 (29x83) grid blocks. The well was given a small nodal distance.

Table 3. Calculation of the plume footprint.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$ density [kg/m$^3$]</td>
<td>700</td>
</tr>
<tr>
<td>Volume CO$_2$ [m$^3$]</td>
<td>285.71</td>
</tr>
<tr>
<td>Average CO$_2$ saturation (assumption)</td>
<td>0.3</td>
</tr>
<tr>
<td>Plume area [m$^2$]</td>
<td>954.67</td>
</tr>
<tr>
<td>Plume radius [m]</td>
<td>17.43</td>
</tr>
</tbody>
</table>

### 3.1.3 Boundary conditions
The boundary condition for the outer boundary was obtained through a steady-state simulation, locking the bottom grid block at the final shut-in pressure corrected for the nodal point elevation. It is assumed that there is a zero CO$_2$ mass fraction from the beginning.

### 3.1.4 Initial conditions
An initial (steady state) condition was simulated for the whole model. The boundary was inactivated and given the values obtained in the previous simulation. The left side was assigned to domain 2 (well).

### 3.2 Simulation scenarios
The simulated scenarios include:
- Push-pull experiment with heating, injection of water or/and CO$_2$ and withdrawal of formation fluids. Sequence in accordance with Zhang et al. (In print), but at the moment without tracers (Figure 3). Monitoring of temperature, pressure and mass fraction of CO$_2$ in the aqueous phase in the well was done.
- Different heating scenarios (20, 30 and 50 W/m heating effect) and residual gas saturations.
- Different scCO$_2$ injection volumes impact on e.g. in-situ solubility. Injection of 100, 150 and 200 tons of CO$_2$ during 30, 45 and 60 h respectively was simulated.
- Different discretizations were also tested.
3.2.1 Experimental sequence

Heating (heat1)
The heating was obtained by "injecting" 50 W/m during 48 h into the well elements. An early attempt to "inject" 20 W/m during 48 h in accordance with Freifeld et al. (2009) gave a temperature increase of only some degrees. Injections of 20, 30 and 50 W/m were tested, but for the full sequence the 50 W/m "injection" was used.

Cooling (cool1)
A 96 h cooling period was then simulated using the result from the 50 W/m heat injection simulation.

Water injection 1 (wat1)
Injection of water during 1.5 days (36 h) with a salt concentration equal to the formation water salt concentration was simulated. All injections are assumed to be carried out to a temperature equal to that of the undisturbed formation. In reality this is preferable as it minimizes the risk of temperature change related deformations.

Production 1 (pump1)
Production of 5 tons/h of formation fluid during 4 days was simulated.

CO₂ injection (co2)
Injection of 100, 150 or 200 tons of carbon dioxide during 30, 40 and 60 h respectively was simulated. Injection of CO₂ was assumed to occur along the whole depth of the formation, see Table 4.
Table 4. Calculation of injection rate.

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<tr>
<td>Screen length [m]</td>
<td>5.8</td>
</tr>
<tr>
<td>Number of well grid blocks [#]</td>
<td>29</td>
</tr>
<tr>
<td>Length of each grid block [m]</td>
<td>0.2</td>
</tr>
<tr>
<td>CO₂ mass [ton]</td>
<td>100</td>
</tr>
<tr>
<td>CO₂ mass [kg]</td>
<td>100000</td>
</tr>
<tr>
<td>Injection time [s]</td>
<td>108000</td>
</tr>
<tr>
<td>Total injection rate [kg/s]</td>
<td>0.926</td>
</tr>
<tr>
<td>Injection rate per grid block [kg/s]</td>
<td>0.0319</td>
</tr>
</tbody>
</table>

Redistribution (rest1)
A two day recovery period was simulated.

Heating 2 (heat2)
A heat “injection” equal to heat1 was carried out again.

Cooling 2 (cool2)
A cooling period equal to cool1 was simulated.

CO₂ saturated water injection (wat2)
CO₂ saturated water with salt was injected during 36 h to create a residual gas saturation zone.

Redistribution (rest2)
Two days of redistribution was then simulated.

Heating 3 (heat3)
Heating in accordance with heat1 and heat2 was performed.

Cooling 3 (cool3)
Cooling in accordance with cool1 and cool2 was performed.

Water injection 3 (wat3)
Water injection with salt during 36 h was simulated.

Production 2 (pump2)
Withdrawal of formation fluids during 96 h was simulated.
3.3 Preliminary results

Results from the push-pull simulation are shown in Figure 4. Monitoring of temperature, pressure and mass fraction of CO2 in the aqueous phase was done in the bottommost well element.

![Graphs showing temperature, pressure, mass fraction, and gas saturation over time](image)

**Figure 4.** Temperature (left top), pressure (right top), mass fraction of CO2 in the aqueous phase (left bottom) and gas saturation (right bottom) during the experimental sequence as monitored in the bottommost well element.

Results from the 20, 30 and 50 W/m heating scenarios are shown in Figure 5 and Table 5. Figure 5 shows the temperature response when heating with different effects during the first heating event (heat1).
Figure 5. Temperature response during the first heating event using different heater effects.

Table 5. Result from different heating effect scenarios.

<table>
<thead>
<tr>
<th></th>
<th>20 W</th>
<th>dT</th>
<th>30 W</th>
<th>dT</th>
<th>50 W</th>
<th>dT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat1</td>
<td>68.66</td>
<td>1.66</td>
<td>69.48</td>
<td>2.48</td>
<td>71.14</td>
<td>4.14</td>
</tr>
<tr>
<td>Rest1</td>
<td>66.08</td>
<td>66.08</td>
<td>66.08</td>
<td>66.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat2</td>
<td>68.38</td>
<td>2.3</td>
<td>69.94</td>
<td>3.41</td>
<td>71.72</td>
<td>5.64</td>
</tr>
<tr>
<td>Rest2</td>
<td>66.9</td>
<td>66.9</td>
<td>66.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat3</td>
<td>68.64</td>
<td>1.74</td>
<td>69.5</td>
<td>2.6</td>
<td>71.22</td>
<td>4.32</td>
</tr>
</tbody>
</table>

Table 6. Temperature increase during heat injection for different residual gas saturations.

<table>
<thead>
<tr>
<th></th>
<th>0.09</th>
<th>0.19</th>
<th>0.29</th>
</tr>
</thead>
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<tr>
<td>dT (water saturated)</td>
<td>4.14</td>
<td>4.14</td>
<td>4.14</td>
</tr>
<tr>
<td>dT (after CO2 injection)</td>
<td>5.64</td>
<td>5.78</td>
<td>5.78</td>
</tr>
<tr>
<td>dT (residual CO2 saturation)</td>
<td>4.32</td>
<td>4.51</td>
<td>4.94</td>
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Results from the simulations with different residual gas saturation are shown in Table 6. An impact of the residual gas saturation on the temperature response during heating could be seen. Also a reduction in pressure of 1.458 and 6.0302 MPa between the first and second withdrawal could be seen for residual gas saturations of 0.09 and 0.19 respectively.

Simulations of different mass injection of scCO2 (100, 150 and 200 tons, during 30, 45 and 60 h respectively) showed only minor effects on the thermal and pressure responses, see Figure 6. This had however an effect on areal plume extent and on distribution between the phases (solubility), see Figure 7.
Figure 6. Temperature (left top), pressure (right top), mass fraction of CO2 in the aq. phase (left bottom) and gas saturation (right bottom) during the experimental sequence as monitored in the bottommost well element for different amount of injected CO2.

Figure 7. Fraction of total CO2 mass in different phases for different amounts of injected CO2.
3.4 Push-pull experiment concluding remarks

- A radially symmetric model was created to evaluate the push-pull experiment. The simulation results are of a preliminary nature.
- Thermal methods could potentially be of interest when determining the residual saturations as different residual gas saturations in these simulations resulted in different temperature responses. Combined with laboratory measurements this could be used when determining parameters.
- The amount of injected CO2 impacts the distribution between the phases however further simulation studies with tracers could potentially contribute to quantification of in-situ solubility.
- Future studies will incorporate tracers, hysteresis, heterogeneity and reactive transport into the modeling scenario.

4. DIPOLE INJECTION EXPERIMENT

4.1 Pre-experiment modelling background and objectives

The larger CO2 injection experiment was planned to be performed in a dipole configuration using the existing well H-18 for injection and a new well to be drilled up-dip in the target layer for abstraction (see Figure 1 above). The dipole configuration provides control of the flow field of both CO2 and formation brine, and allows the application of cross-hole measurement techniques, including tracers and reflection seismic. Just like in the single-well push-pull experiment, a sequence of CO2 and water injections, in combination with a number of monitoring techniques, is deemed to be an effective strategy for providing information about the flow, transport and reactive processes as well as properties of the target layer controlling the fate of the injected CO2. The planned measurement techniques include hydraulic and tracer tests, reflection seismics and thermal measurements of CO2 saturation.

The goal of the pre-experiment modelling is to aid the design of a successful experiment. Specifically this includes: (i) providing a general picture of the CO2 migration and fate, (ii) evaluating key aspects of the experimental design including the location of the observation well and the CO2-water injection schemes, and (iii) identifying key parameters affecting the fate of the injected CO2 and evaluate the relationships between measurable quantities and parameters of interest.

4.2 Model design

A three-dimensional (3D) model of the test site was defined as shown in Figure 8. The model includes the H-18 injection well and the planned abstraction well at different possible distances up-dip in the target layer from H-18. The direction of maximum dip is NW to SE and the dip in the test area is estimated to be on average is 7.8°.
The target layer is heterogeneous and consists of sandstone and shale layers. As more geological data has continuously become available, the models have been updated and refined. Three different vertical models have been employed; (i) 3 sand layers (K, W, A) with two 2 embedded shale layers, (ii) one single sandstone layer having a thickness equal to the sum of three layers (iii) a thinner single sandstone layer of thickness representative of excluding low-porosity (<10%), low permeability parts. A schematic vertical section of the injection-abstraction dipole for the single-layer case is shown in Figure 8. Heterogeneity within the sandstone layers is discussed more in chapter 5 below.

All models are three-dimensional, but assume symmetry over the line of maximum dip, as shown in Figure 8. The modelling was done only for one of these halves to allow finer discretization at the same computational cost. The model has high resolution around the wells, thereby resolving the pressure in the wells which is an important parameter in the planned experiments. In other regions the grid resolution gradually becomes lower and in total approximately 48000 grid blocks are used in the model. The numerical simulator used for the multiphase flow and transport modelling is TOUGH2 (Pruess et al., 1999) with the equation-of-state module ECO2N (Pruess, ECO2N: A TOUGH2 fluid property module for mixtures of water, NaCl, and CO2, 2005).

Figure 8. Top view of the 3-dimensional model used to aid the design of the dipole experiment.

Figure 9. Vertical section of the model through the two wells.
4.3 Injection sequence

The different measurements to be performed require a sequence of different well operations (CO2 and water injections and abstractions, as well as no pumping) in the two wells. How this sequence is specifically defined is restricted by practical constraints on the maximum injection and abstraction rates, as well as the time and pumping regime required to perform specific measurements. However, there is also some room for designing the sequence to maximize the information that can be gained from the experiment, for example with respect to water injections. In Figure 10 we present a first proposal for three different injection abstraction schemes which accommodate the proposed measurement techniques.

The base-case sequence can briefly be summarized as follows: After abstracting water for 1 day to create a flow field towards the abstraction well, the total planned volume of CO2 (1000 tons) is injected in H-18 at a rate of 5 tons/hour, at the same time abstraction is continued in the new well at the same volumetric rate as the injection. During this time pressure P and flux Q of the two fluid phases (water and CO2) are measured in both wells. Then, after the CO2 has been injected, 7 days are allowed for the first thermal conductivity and cross-hole reflection seismics measurements to be performed. During this time no pumping is done in either well in order not to disturb these measurements. Then, 16.3 days into the test sequence, a combined hydraulic and tracer test is performed. Water and tracers are injected for 1 day, generating a pressure signal which is dependent on the spatial distribution of CO2 between the wells. After this, abstraction is continued for 15 days drawing the tracers towards the abstraction well. The thermal conductivity and geophysical measurements are then repeated followed by a new hydraulic and tracer test, etc., as shown in Figure 10.

Two similar injection-abstraction sequences are also tested. In the second scenario we test additional water injection in the injection well for 15 days following the one-day hydraulic test with tracer injection. Additional water may push the CO2 further out in the formation but may also lead to increased dissolution of the CO2 into the aqueous phase. In the third scenario we continuously abstract fluids from the abstraction well, which should produce more migration in this direction.

In the modelling of different injection-abstraction schemes we use the lumped single layer model with a dipole distance of 100m.
Figure 10. Three possible injection abstraction scenarios.

Figure 11 shows the spatial distribution of supercritical (sc) CO2 in the vertical x-z plane through the two wells at 62.3 days after start of injection. The general movement of the scCO2 is radially away from the injection well and updip towards the abstraction well. The water injection during the hydraulic test initially produces a fully water saturated cylinder in the middle of the scCO2 body. After this water injection the scCO2 again moves updip and towards the abstraction well along the target layer ceiling, but the trace of the water injection can still be seen as break in the scCO2 saturation in cross-sections shown in Figure 11. Comparing the base case (Figure 11, top) to the additional water injection scenario (Figure 11, middle), it can be seen that the additional water injection dissolves large amounts of the scCO2. The amount of dissolution primarily depends on the amount of "new" non-CO2-saturated water that comes in contact with the scCO2. This, in turn, depends on the relative movement of scCO2 and brine past each other. At low saturation, the scCO2 body becomes less mobile and the injected water moves through the scCO2 body producing dissolution, while scCO2 saturation goes down and the scCO2 is further immobilized.

Figure 12 shows how the mass of CO2 is distributed between scCO2 and dissolved CO2 in the brine, as well as the amount of CO2 that has been abstracted for the different injection-abstraction scenarios. In all cases the equilibrium dissolution model employed in THOUGH2/ECO2N predicts about 18% of the scCO2 to dissolve during the CO2 injection. The dissolution then continues as the scCO2 and brine continue to move relative to each other. The one-day water injection during the hydraulic test produces only a very short-term increase in the rate of dissolution, but the longer water injection represented by the additional water injection scenario significantly increases the total amount of dissolution compared to the other two scenarios.
Figure 11. Supercritical CO2 in the x-z plane, 62.3 days after start of injections. Top: Base-case injection-abstraction scenario. Middle: Additional water injection scenario. Bottom: Continuous abstraction scenario.

Figure 12. CO2 mass balance. Supercritical, dissolved and abstracted CO2.
Comparing the base case (Figure 11, top) to the continuous abstraction scenario (Figure 11, bottom), it can be concluded that abstraction strongly pulls the scCO2 body towards the second well. More abstraction produces a faster breakthrough of scCO2 and stretches the scCO2 body to the abstraction well. However, the scCO2 does not move beyond the abstraction well as it is pumped out after the breakthrough and onwards. As can be seen in Figure 13, the different injection-abstraction scenarios produce similar areal footprints of scCO2, defined as the maximum horizontal area (occurring at the target layer ceiling) of the scCO2 body. However, in the case of the additional water injection, the scCO2 is at much lower saturation than in the other two scenarios by the end of the simulated time period, as can be seen in Figure 11.

Figure 13. Areal footprint of the scCO2.

The updip scCO2 migration distance is longest for the continuous abstraction scenario (Figure 14), which is also the only scenario for which the scCO2 breaks through to the abstraction well. The scCO2 body is in the case more elongated along the line between the two wells, while in the base-case and additional water injection scenarios the scCO2 tends to spread more radially.
4.4 Effects of layers and layer permeability

The effects of having different sandstone layers (K, W, A) separated by claystone layers was investigated by including these layers in the 3D symmetrical half model (Figure 8), using a three layer vertical model (Figure 2). While values for average porosity and permeability of each layer has been estimated from core samples and porosity logs, we further investigated the effects of layering by varying the degree of difference in k and $\phi$ between the different layers. For different cases were therefore tested as shown in Table 7. The first model represents the best estimates (BE) of k and $\phi$ for each layer, then we compare this model to all layers having the same average k and $\phi$, referred to as same layer properties (SLP) model, and to two cases where we increase the differences between the layers. According to the estimated value of k, the W layer is the most permeable, with a permeability of approximately 5 times that of the least permeable A layer, while the K layer is of intermediate permeability, having a permeability approximately double that of the A layer. When we test the effect of increasing the permeability differences between layer we keep the A-layer k constant and (i) double the contrast so that: $k(K\text{-layer}) = 4 \times k(A\text{-layer})$ and $k(W\text{-layer}) = 10 \times k(A\text{-layer})$ (K4W10 model) as well as (ii) quadruple the contrast (K8W20 model) as specified in Table 7.

<table>
<thead>
<tr>
<th></th>
<th>Best Estimate (BE)</th>
<th>Same Layer Properties (SLP)</th>
<th>K=Ax4, W=Ax10</th>
<th>K=Ax8, W=Ax20</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\phi$ (md)</td>
<td>$k$ (md)</td>
<td>$\phi$ (md)</td>
<td>$k$ (md)</td>
</tr>
<tr>
<td>K layer</td>
<td>0.145</td>
<td>8.3</td>
<td>0.143</td>
<td>9.7</td>
</tr>
<tr>
<td>W layer</td>
<td>0.163</td>
<td>20.3</td>
<td>0.143</td>
<td>9.7</td>
</tr>
<tr>
<td>A layer</td>
<td>0.133</td>
<td>4.5</td>
<td>0.143</td>
<td>9.7</td>
</tr>
<tr>
<td>Shale</td>
<td>0.039</td>
<td>0.001</td>
<td>0.039</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Table 7. Permeability models for the three layers

As an illustration of the effects of the layering, Figure 15 shows the examples of the spatial distribution of CO2 in the vertical x-z plane through the two wells at 32.3 days after start of injection: scCO2 best estimate (BE) model (Figure 15, top), dissolved CO2 BE model (Figure
15, middle), scCO2 same layer properties (SLP) model (Figure 15, bottom). Comparing the BE model to the SLP model (Figure 15, top and bottom) it can be seen that distribution of the scCO2 is strongly influenced by differences in layer properties. For the BE model the most permeable W-layer dominates the scCO2 migration and at 32.3 days the scCO2 has broken through to the abstraction well in this layer.

Figure 15. CO2 distribution at the x-z plane through the two wells 32.3 days after start of injection: s.c. CO2 saturation best estimate model (top) and same layer properties model (bottom). Mass fraction of CO2 in the aqueous phase BE model (middle).

When further increasing the k contrast as compared to the BE model, there is however no further large change in the scCO2 migration behaviour. This can be seen in Figure 16 showing the maximum updip migration of the scCO2 front, Figure 17 showing the areal footprint and Figure 18 showing the CO2 mass distribution for the different layer permeability models in the three layers (A, W, K). Figure 16 shows that the scCO2 breaks through in the W layer at a similar time in all the models where a k contrast exists and the only model that differs strongly from the others is the SLP model. The results for areal footprint (Figure 17) and mass distribution (Figure 18) show a similar general trend in the sense that the only model that differs strongly from the other models is the SLP model. These findings indicate that in a multilayer system where the scCO2 can freely choose which layer it will preferably migrate into, a relatively small difference in permeability can be enough to cause preferential flow in one layer. However, also for larger permeability contrast the migration behaviour is quite similar. This latter observation is, of course, dependent on the fact that we assume a constant injection rate of scCO2 and if we e.g. instead used a constant pressure boundary for scCO2 injection, the results would not be as similar.
Figure 16. Maximum updip migration of scCO2 front for different layer permeability models.

Figure 17. Areal footprint of scCO2 in the K, W and A layers, for different layer permeability models.
Figure 18. Supercritical, dissolved and abstracted CO2 for different layer permeability models.

With the constant rate scCO2 injection of 5 tonnes/hour for the different k contrasts we instead see differences in the needed injection pressure as illustrated in Figure 19. It can be noted that for the BE model and the average k SLP model very high injection pressures are needed to drive this rate of injection and would most likely not be practical to increase the pressure that much. The tests of higher k in the W and K layers (K4W10 and K8W20 models) show more reasonable injection pressure for this flow rate.

Figure 19. Pressure with time in injection well.
4.5 Effects of dipole distance

To aid the decision on where to optimally drill the new monitoring/abstraction well, different scenarios for the well position were modelled. This modelling was done using the single layer model excluding low permeability parts (see Figure 2). The first modelling scenario here (scenario 1) is a reference case with only injection in well H-18 and no abstraction. For this scenario the new well is modelled as a passive monitoring well located at 50 m distance up-dip from H-18. Comparison with this reference case allows evaluation of the effects of dipole injection-abstraction setup. The following two scenarios have an active abstraction well at 50 m (scenario 2A) and 100 m (scenario 2B) distance, respectively.

Figure 20 shows the supercritical CO2 saturation ($S_{\text{scCO2}}$) in a vertical section through the two wells at the end of the injection-abstraction sequence. Comparing the reference case (Figure 20a, CO2 injection only and passive monitoring well) to the two scenarios with abstraction (Figure 20b and Figure 20c), it can be seen that abstraction draws CO towards the up-dip (new) well, but also prevents CO2 migration beyond it. The dipole configuration can produce a directed movement of the injected CO2. This is deemed to be an important advantage in the field experiment because it will to some extent counteract preferential flow and spreading in unfavourable directions (such directions where the CO2 cannot be monitored) governed by geological heterogeneity in the formation. An important next step as more data is becoming available is therefore to investigate the performance of the dipole configuration in heterogeneous systems.

![Figure 20. Vertical section through the two wells showing the supercritical CO2 saturation at the end of injection-abstraction sequence. (a) Reference case with injection only and a passive monitoring well, (b) and (c) abstraction well at 50 m and 100 m distance.](image-url)
Figure 21 shows a horizontal (top) view of the supercritical CO2 saturation in the top of target layer at the end of injection-abstraction sequence. The total area over which the scCO2 spreads defines a footprint of the scCO2 plume. A large and well defined (not jugged by preferential flow fingers) footprint is deemed advantageous for the monitoring of the injected CO2 using surface or cross-hole reflection seismics. It can be seen that in the reference case (Figure 21a, no abstraction) the shape of the (half-) footprint is round with a slight tendency to move up-dip (left in Figure 21) by buoyancy driven flow. The 50 m dipole (Figure 21b) is not predicted to increase the size of the footprint because when the scCO2 arrives at the abstraction well it will also be pumped out. The 100 m dipole (Figure 21c) produces an elongated footprint as the CO2 is drawn to migrate over a longer distance compared to the other two scenarios.

![Image of Figure 21](image-url)  
**Figure 21.** Horizontal of the top of the target layer, showing the supercritical CO2 saturation at the end of the injection-abstraction sequence. (a) Reference case with injection only and a passive monitoring well, (b) and (c) abstraction well at 50 m and 100 m distance, respectively.

Figure 22 shows the calculated total scCO2 areal footprint for the three scenarios as a function of time after start of the experiment. Comparing to the reference case (labelled single-well injection in Figure 22) the shorter dipole distance (50 m) produces a smaller footprint and the larger distance (100m) produces a larger footprint. The use of dipole configuration can hence either reduce or enlarge the footprint, depending on the dipole distance in relation to the amount of injected CO2. Of the three here investigated scenarios the 100 m dipole distance produces the largest footprint and the furthest migration in the up-dip direction.
Figure 22. Areal footprint of the supercritical CO2 as a function of time after start of the experiment.

Figure 23 shows the distribution of CO2 between the supercritical phase and the aqueous phase (dissolved CO2) in the aquifer, together with amount that has been pumped out as a result of abstraction. In the 50 m dipole distance scenario, shown in Figure 23a, the CO2 is predicted to arrive at the abstraction well already after approximately 8 days, and is then started to be pumped out. Consequently, at the end of the experiment (62.3 days) more than a third of the injected CO2 is predicted to have been pumped back out of the formation. For the 100 m dipole case (Figure 23), the CO2 arrives at the abstraction well after approximately 50 days and only a small amount is pumped out.

Under assumption of thermodynamical equilibrium between the fluid phases, the amount of CO2 that dissolves depends mainly on the total volume of formation water that the scCO2 comes in contact with. For the 50 m dipole case (Figure 23a) this volume is smaller than in the 100 m dipole case (Figure 23b) and therefore the amount of CO2 that finally dissolves is also smaller. It can also be noted that after the scCO2 has started to flow into the abstraction well in the 50 m dipole
scenario, most of the scCO2 migration occurs through a volume where the water has already been in contact with scCO2 and is saturated with dissolved CO2. Therefore the dissolved CO2 curve flattens in Figure 23a as only small amounts of additional CO2 can be taken up by the formation water after arrival to the abstraction well.

**Figure 24.** Hydraulic tests for the 50 m dipole scenario. The pressure response for a given water injection rate is compared without any CO2 in the formation (reference water injection) and with CO2 present (injection-abstraction sequence).

Hydraulic tests can provide information about the spatial distribution of supercritical CO2 around the wells where the tests are performed. Because the relative permeability to the aqueous phase decreases in the presence of scCO2, the pressure needed to drive a given injection rate of water depends on the CO2 distribution and saturation in the formation. Here such test is simulated by comparing the pressure in the injection well during a reference water injection performed before any CO2 was injected to the formation, with the pressure signals for the same rate water injections when CO2 is present in the formation at two different times during the abstraction-injection sequence. This test for the 50 m dipole scenario is shown in Figure 24. It can be seen that the pressure is clearly higher for the two hydraulic tests with CO2 present as compared the reference water injection prior to the CO2 injection. While in these simulations, the spatial distribution of CO2 and effective permeability to the aqueous phase are exactly known, in a practical situation many different spatial distributions of CO2 could produce the same pressure signal. Therefore, the pressure responses obtained from these hydraulic tests should be interpreted jointly with all other data collected using other measurement techniques. More work is needed to do this, including model developments for the modelling of different types of tracers to be injected with the CO2 and the water. For the 100 m dipole scenario (not shown) the pressure differences were also clear but the pressure increase was smaller compared to the 50 m dipole. The sensitivity of the pressure response hence also depends on experiment design, including the dipole distance.
4.6 Conclusions

In brief, the conclusions of the dipole experiment modelling based on to date available geological information are as follows:

- The dipole configuration produces a directed movement of the injected CO2.
- The injection/abstraction scenario affects the amount of CO2 that dissolves into the aqueous phase, whereas the choice of layer permeability model has almost no effect on dissolution for the same scenario.
- Additional water injection significantly increases dissolution and leads to removal of a large part of the mobile scCO2.
- Continuous abstraction significantly increases the updip CO2 migration (towards the abstraction well), while dissolution is not markedly increased.
- Having one thick sandstone layer produces farther updip migration and larger areal footprint compared to 3 separate layers of the same total thickness and permeability. This is a result of buoyancy of the scCO2.
- In the same-layer-properties model, the CO2 is relatively uniformly distributed between the different (K, W, A) sand layers. This is a markedly different CO2 migration pattern compared to the 3 other models in which the layers have different properties and the W-layer dominates.
- Increasing the permeability contrast between the layers from that of the best estimate model (K2W5) to that of the K4W10 and K8W20 models does not markedly increase the updip migration of the scCO2 front, nor the areal footprint. This could be a result of the abstraction well blocking further increase in these parameters, however, the amount of abstracted CO2 is also not markedly larger.
- Existence of higher permeability layers significantly reduces the pressure needed to drive injections of CO2 and water.
- A small permeability contrast, represented by the best estimate model, seems to produce the largest sensitivity in the hydraulic (water injection) test, as well as the largest pressure response during fluid abstraction.
- A larger dipole distance (100 m) stretches the scCO2 plume more, a larger areal footprint is produced, and the CO2 arrives later to the abstraction well compared to the 50 m dipole.
- Early arrival means that a lot of CO2 will be pumped out.
- A larger scCO2 areal footprint may be advantageous for delineation of the plume using reflection seismics.
- Hydraulic tests are sensitive to the presence of CO2 which reduces the permeability to water and produces higher injection pressures.
- Combining modelling with the sequence of several measurement methods can reduce uncertainty and provide information about parameters controlling CO2 fate, including:
  - CO2 migration pattern
  - In-situ dissolution behavior
  - Trapped scCO2 saturation
5. ASSESSMENT OF EFFECTS OF HETEROGENEITY

5.1 Introduction
Geological heterogeneity can potentially have a large influence on the migration of the injected CO2. Heterogeneity in permeability (k) can exist at different levels; i.e. both at a larger scale formation or multilayer level as the extent and thicknesses of layers vary within the entire storage formation and at a smaller scale single-layer level as k varies within a given layer of the formation. In this work we investigate the effects of heterogeneity within the target sandstone layer on the migration of CO2 injected to this layer. Below we briefly present the methods employed and the preliminary results of this ongoing work.

5.2 Methods

5.2.1 Description of spatial variation in permeability
Detailed porosity logs provide information about the variation in porosity in the vertical direction (measurements every 10 cm) at the locations of the Heletz boreholes. From numerous core measurements of permeability (k) and porosity (φ), an empirical relationship between φ and k has furthermore been formulated. This relationship which is specific for the Heletz target layer sandstone, allows estimation of the vertical variability in k from the porosity log. In order to mathematically describe the heterogeneity in k within the sandstone target layer, an experimental semivariogram approach was used. The semivariogram describes variation in permeability as a function of the distance (h) between two points in a given direction:

\[ \gamma(h) = \frac{1}{2}E[(Z(x+h) - Z(x))^2] \]  \hspace{1cm} (1)  

\[ \gamma(h) = C_0 + \omega \left[ 1 - \exp\left(-\frac{h}{a}\right) \right] \] \hspace{1cm} (2)  

where

\( \gamma = \text{Semivariogram} \)
\( E = \text{expected value} \)
\( Z = \text{random value, observed value} \)
\( x = \text{position vector} \)
\( h = \text{distance between the two points} \)
\( C_0 = \text{nugget factor} \)
\( \omega = \text{sill} \)
\( a = \text{parameter describing variogram range} \)

\( \text{(Niemi, 1994).} \)
\( \text{(de Marsily, 1986).} \)

Figure 25. Permeability distribution of Heletz’s target layer based on combined data.

Figure 1 shows the distribution of permeability. The histogram represents the three wells H13, H18 and H38 data combined. Each well sample consists of the three layers K, W and A which due to the scarce amount of data was therefore also was combined and accounted for as one layer.
Figure 26 Amount of lag pairs for each lag distance

Figure 26 shows the amount of lag pairs used as a base for the Semivariogram shown in Figure 27. As the lag distance increases the variogram becomes dependent on less data creating a decreasing quality of describing the heterogeneity. Therefore the Exponential model was fitted by honouring the lag pairs up to 3.7 meter where the contribution of lag pairs from each well are still rather similar. The parameter setting in order to fit the Exponential model is shown in Table 8.

Table 8 Parameters for the experimental variogram

<table>
<thead>
<tr>
<th></th>
<th>Range parameter</th>
<th>Nugget [Log(k)]</th>
<th>Sill [Log(k)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential Model</td>
<td>0.9</td>
<td>0</td>
<td>0.526</td>
</tr>
</tbody>
</table>

5.2.3 Modelling setup for CO2 injection and migration in the target layer

A 2D setup of the Heletz aquifer has been chosen for this study. The modelled aquifer's resolution is not set as constant and Figure 28 schematically shows the modelled domain and its zones. Zone A is where the CO2 migration takes place and zone B is included as a representation of an infinitely wide aquifer. Vertically, the aquifer consists of 20 elements all 0.5 meters high. Horizontally, the discretization varies with finer discretization near the injection well.
Figure 28 Schematic drawing over the modelled aquifer

The 2D slice is given a thickness of 1 m which results in the following volumes:
Zone A: 310.6 * 1 * 10 = 3106 m$^3$
Zone B (each individual side): 98301.0 * 1 * 10 = 983010 m$^3$

5.2.3 Definition of parameters describing the effects of heterogeneity on CO2 migration

In order to compare and describe the distribution of CO2 in numbers the following definitions and measures used in this work are here defined as follow in table 2.

Table 9 Definitions of parameters describing the effects of heterogeneity on CO2 migration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volumetric storage</td>
<td>the volume of section A occupied by supercritical CO$_2$ (scCO$_2$) in relation to section A's total volume.</td>
</tr>
<tr>
<td>CO$_2$ storage efficiency</td>
<td>Ratio of total injected CO$_2$ mass to volume of formation pore space associated with the maximum spread of scCO$_2$. For our 2D case, the latter volume is defined as: maximum scCO$_2$ migration distance multiplied with depth, width and porosity of the target layer.</td>
</tr>
<tr>
<td>$CO_2$ storage efficiency = $\frac{Total \ injected \ CO_2 \ mass}{(Max. \ spread \ length_{left} + Max. \ spread \ length_{right}) \cdot \ Depth \cdot \ Height \cdot \ porosity}$</td>
<td></td>
</tr>
<tr>
<td>Maximum distribution spread length</td>
<td>the realizations maximum spread length from the injection well.</td>
</tr>
<tr>
<td>Maximum pressure</td>
<td>the maximum pressure within section A at a given time.</td>
</tr>
<tr>
<td>Dissolved CO$_2$ in aqueous phase</td>
<td>the total mass CO$_2$ dissolved in the aqueous phase in relation to the total mass supercritical CO$_2$ injected.</td>
</tr>
</tbody>
</table>
5.3 Results
In the following section we will first show how the scCO2 is spatially distributed after the end of a CO2 injection period (8.3 days) as well as after a period (30 days) of additional redistribution. The amount of injected CO2 is scaled so that the total injection to the one-metre-wide 2D slice domain is comparable to the actual planned injection, producing a migration similar to that along the central plane of the 3D simulations. Here, we will show the results for the homogeneous cases as well as example realizations of the heterogeneous cases. The plots under these sections are plotted with an aspect ratio of 2:1, Y relative X in order to make the viewing easier.
Second, we will show the average results putting all realizations together in an analysis of the most important output parameters. For every different case of heterogeneity we performed at least 40 realizations.

5.3.1 Base case
Homogeneous
Permeability: 26.9 mD

Figure 29 a) Injection 8.33 days, b) Redistribution 30 days

Figure 5a represents the distribution of scCO2 right at the end of the injection phase while Figure 5b represents the distribution after additional 30 days of redistribution time. As a comparison to the homogeneous case shown in Figure 29, Figure 30 shows the resulting scCO2 distributions for an example realization of spatially correlated heterogeneous permeability following an exponential variogram of mean of k=26.9 mD and sill 0.526. In this base case we assume that the horizontal and vertical spatial correlations are equal, using the same range value in the horizontal direction as the one obtained for the vertical direction. The permeability distribution can thus be summarized as:

| Mean permeability: 26.9 mD | Sill: 0.526 | Horizontal range: 0.9 m | Vertical range: 0.9 m | Realization no.3 |
5.3.2 Effect of range
Next we investigate the effects of increasing the horizontal range by a factor 10. Figure 31 shows the resulting scCO2 distributions for an example realization of the same mean k=26.9 mD and sill = 0.526, but horizontal range 9.0m. The parameters can be summarized as:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability</td>
<td>26.9 mD</td>
</tr>
<tr>
<td>Sill</td>
<td>0.526</td>
</tr>
<tr>
<td>Horizontal range</td>
<td>9.0 m</td>
</tr>
<tr>
<td>Vertical range</td>
<td>0.9 m</td>
</tr>
<tr>
<td>Realization no.</td>
<td>23</td>
</tr>
</tbody>
</table>

5.3.3 Effect of mean permeability
Finally, we investigate the effect of a higher mean permeability both for the homogeneous and heterogeneous cases. Figure 32 shows the homogeneous case, where Figure 32a represents...
the distribution of scCO$_2$ right at the end of the injection phase and Figure 32b represents the distribution after additional 30 days of redistribution time.

Figure 32 a) Injection till 8.33 days, b) Redistribution 30 days

Figure 31 shows the resulting scCO$_2$ distributions for an example realization of the same higher mean $k$ of 269 md and sill = 0.526, but horizontal range 9.0m. Figure 33a shows the permeability field for realization 3, Figure 33b shows the scCO$_2$ distribution right at the end of the injection phase and Figure 33c shows the scCO$_2$ distribution after additional 30 days of redistribution time. The parameters can be summarized as:

<table>
<thead>
<tr>
<th>Permeability: 269.0mD</th>
<th>Sill: 0.526</th>
<th>Horizontal range 0.9m</th>
<th>Realization no.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical range 0.9m</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 33 a) Permeability distribution, b) injection 8.33 days, c) redistribution 30 days.

5.4 Discussion and preliminary conclusions

The following preliminary discussion and conclusions is based on the analysis of data representing the median values of 40 randomized realizations output after a simulation run of 8,33 days CO$_2$ injection followed by 30 days of re-distribution time.
5.4.1 Effects on maximum migration distance
When storing CO\textsubscript{2} geologically, the maximum migration distance is an important parameter to consider, particularly if there would exist any cap rock discontinuities or fault zones neighbouring the storage site causing a potential threat of leakage. While no such problems are deemed to exist for the Heletz injection experiment, it is still of interest to investigate how the presence of heterogeneity in the target layer can affect this parameter. Accordingly, Figure 34 shows the effects on maximum scCO\textsubscript{2} migration distance of mean k, horizontal range (correlation length) and sill (variance in log(k)).

![Figure 34 Maximum scCO\textsubscript{2} migration distance.](image)

The results shown in Figure 34 indicate that heterogeneity increases the maximum migration distance from the injection well, and that the horizontal range has a positive correlation to the maximum migration distance of the scCO\textsubscript{2}. The results for different average permeability indicate that for the homogeneous cases, a ten times higher mean permeability (increase of k=26.9 to k=269) produces a large increase in the maximum migration distance while for the heterogeneous cases the corresponding increase is somewhat smaller. For example; the homogeneous case k=26.9 in Figure 34 compared with the homogeneous case k=269 shows an increase of 21 meter while the corresponding cases with heterogeneity for a horizontal range 2.7 meters (Figure 34, k=269 sill=0.526 compared with k=26.9 sill=0.526) only shifts at around 10-15 meter as the permeability is increased by a factor 10.

5.4.2 Effects on storage efficiency
The parameter used to describe the storage efficiency is the ratio between total injected mass of CO\textsubscript{2} and the volume of the target layer out to the maximum horizontal length to which scCO\textsubscript{2} has migrated. The latter can accordingly be defined as the sum of maximum spread length on each side of the injection well multiplied by the height, width and porosity of the target layer. A lower storage efficiency value indicate a less effective use of the aquifer space while a larger value suggests the contrary. This parameter is correlated with the maximum migration distance but differs in the sense that it depends on the migration in both directions from the injection well.

Figure 35 shows the effects on storage efficiency of the different parameters describing the spatial distribution of k; mean k, horizontal range (correlation length) and sill (variance in log(k)).
When comparing the results described in Figure 35 for homogeneous mean $k=26.9$ with mean $k=269$ it seems clear that a lower permeability results in a significantly higher storage efficiency which also can be observed by comparing the scCO2 distribution of Figure 29b with Figure 32b. Comparing the homogeneous case of mean $k=26.9$ with its corresponding case of heterogeneity the results indicate a decrease in storage efficiency when heterogeneity is introduced. This effect is smaller for the higher permeability scenario ($k=269$ mD). In this case of higher permeability buoyancy has a larger effect on the scCO2 migration compared to the lower permeability case, the buoyancy flow towards the ceiling of the formation produces a preferential flow pattern along the ceiling which reduces storage efficiency. In all the tested cases of heterogeneous $k$ distributions, the results indicate decreased storage efficiency as the horizontal range increases which can be seen in Figure 35 as well as by comparing Figure 30b and c with Figure 31b and c.

A more preferential flow pattern reduces storage efficiency. Heterogeneity produces some preferential flow, the extent and pattern of which is dependent of the heterogeneity characteristics (properties of the $k$ distribution). However, heterogeneity also counteracts buoyancy flow and the preferential flow pattern along the ceiling of a layer that is seen in the homogeneous cases. It can be concluded that the net effect of heterogeneity on storage efficiency depends on the importance of buoyancy flow, which, in turn, is dependent on the permeability. The preliminary results presented here indicate that a low permeability, a short horizontal range and a small variance in log($k$) (sill) increase the storage efficiency.

### 6. FUTURE DEVELOPMENTS

Future developments which are currently being addressed in the modeling of both the push-pull experiment and the dipole injection experiment include:

- Detailed parameter sensitivity analysis to better identify key parameters affecting the flow and transport of the injected CO2 and to aid the experimental design by relating measurements to the parameters of interest.
• Model developments to include novel, one-way partitioning tracers in the numerical simulator
• Model developments to include hysteresis in the constitutive relations of capillary pressure and relative permeability
• Continued modelling to further study effects of geological heterogeneity and layering in the target formation, particularly addressing the effects of different kinds of heterogeneity in the formation
• Modeling studies (and developments) to investigate the effect of chemical reactions of the fate of the injected CO2
• Further studies on the effects of different boundary conditions
• Effects of rate-limited dissolution of the scCO2 into brine

References


