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CO2 Plume Behaviour in a Cyclic, Fining Upward Clastic Sequence - Do the Claystone Intervals Seal?

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SUMMARY

We numerically modeled CO_2 plume behaviour in fining upward clastic sequences, using the Middle Buntsandstein of the North German Basin as an example. The aim was to examine how vertical and lateral reservoir heterogeneities influence CO_2 plume development. CO_2 injection was simulated through eight wells around a closed anticlinal structure, each injecting 500,000 m^3 of CO_2 per year over a period of 30 years. Sensitivity studies were carried out on several parameters.

Lateral facies variations with high permeability contrast seem to inhibit CO_2 flow. Where siltstones with a permeability of 1 mD hardly present an obstacle in graded sequences, it forces the CO_2 plume sideways, effectively forming a barrier in rocks with a bimodal permeability distribution. In laterally homogeneous, but vertically fining upward sequences, the CO_2 preferrably moves laterally and updip along the high permeability layers during the injection phase, forming a two-storey plume. However, after injection stops, most of the gas soon overcomes the finer grained, low permeability intervals and migrates vertically into the uppermost part of the reservoir and from there into the structural top. The structural top then fills from top to bottom, and not from bottom to top as one might expect.

Introduction

In Germany, the Middle Buntsandstein formation is one of the reservoir options considered for the potential storage of CO_2. It is made up of a series of fining upward clastic sequences. A typical succession starts with a basal sandstone that grades into siltstones and claystones, followed by another such sequence. This cyclicity can be observed on various scales, from decimeters to several hundreds of meters. Two basal sandstone units are the main target of interest for CO_2 storage exploration: the Volpriehausen and Detfurth sandstones. The reservoir sequence is overlain by thick Upper Buntsandstein halites and claystones, thought to be the main seal for CO_2 containment.

The goal of the present study is to examine whether the whole of the Middle Buntsandstein clastic sequence can be regarded as one reservoir, or whether storage would be restricted to the basal sandstone layers. In other words, do the finer grained siltstone and claystone intervals seal or do they allow the CO_2 to flow through? How do vertical and lateral heterogeneities influence the CO_2 plume in such a multilayered, fining upward reservoir?

Model setup

To answer these questions, we built a 3D geological model of a trap structure typical for the North German Basin, and simulated CO_2 injection into the Middle Buntsandstein sandstone layers for 30 years, continuing to observe for another 100 years after injection shutdown. Two initial model cases were considered (Figure 1).

Model 1: A large scale model, including the whole of the Middle Buntsandstein interval. Two basal sandstones (Volpriehausen and Detfurth Sandstones) intercalated into claystone dominated sequences were considered. Their facies and thus petrophysical parameters were allowed to vary laterally (Figure 1, left).

Model 2: A detailed model of one of the basal sandstones (Detfurth Sandstone). The sandstone has been subdivided into two smaller scale fining upward cycles, grading from coarse sandstone to siltstone. No lateral facies variation has been considered in this case (Figure 1, right).

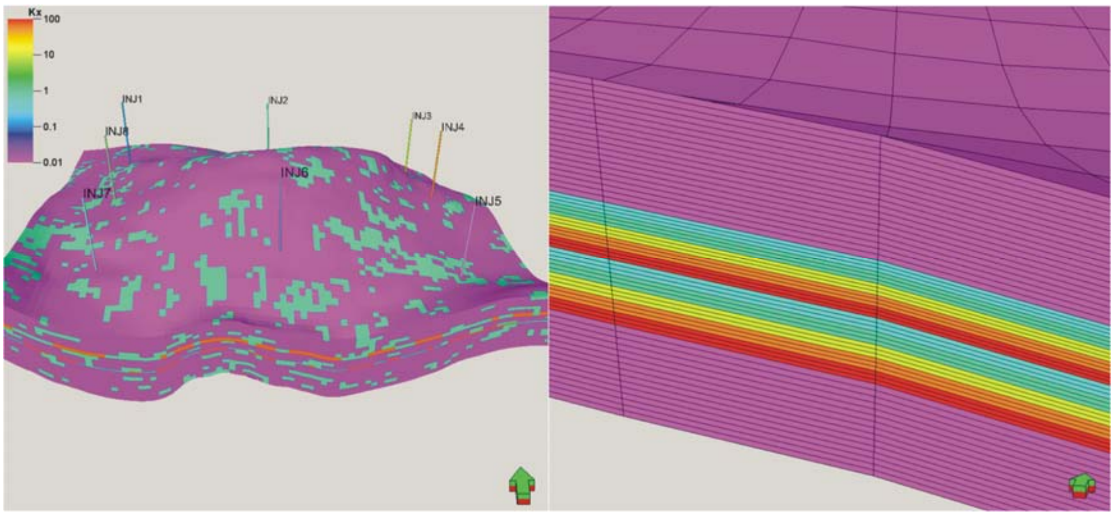

Figure 1 *Initial geological model. Left, Model 1A with lateral facies variation and injector well locations. Right, detail of Model 2A with vertical facies refinement of main sandstone layer. Color code indicates permeability distribution in both models. Arrows point north.*

The model size is 21 km x 16 km, with a horizontal grid cell size of 250 m. In a first simulation run, we modeled the petrophysical parameters to be as close to reality as possible, using published regional data (Run A). To generalise results, we added a second set of model simulations where the permeabilities were 10x higher than in the original case (Run B). We thus have four models, Model 1A, 1B, 2A and 2B. Permeability values of Run A are indicated in Figure 1. To account for lateral heterogeneity and updip migration effects, we simulated eight injector wells evenly spaced around the structure. The injection rate was an industrial scale, constant 500,000 m^3 per day per well for 30 years.

Results

In Model 1A, the migration of CO_2 was dominated by the heterogeneous permeability distribution in sandstone layers, which has regions of 60mD and 1mD (Figure 1, left). The overlying claystone layers were sealing. In Model 1B, CO_2 did leak through the claystone layers. In neither version did the CO_2 reach, let alone fill, the structural trap.

In the low permeability version of the detailed sandstone model (Model 2A), free CO_2 moves laterally and updip along the high permeability layers during the injection phase, forming a two-storey plume. As soon as injection stops, the free gas rapidly overcomes the low permeability siltstone obstacle, accumulating in the upper half of the reservoir. After 130 years, all gas has almost completely disappeared from the lower part. The overlying claystone layers were sealing.

With higher permeabilities (Model 2B), the two-storey plume can only be observed in the immediate vicinity of the wells in the early years of injection. Most of the gas soon overcomes the siltstone obstacle and migrates vertically into the uppermost part of the reservoir, and from there laterally and updip into the structural trap. The structural trap then fills from top to bottom, and not from bottom to top as one might expect. Note that the overlying claystone layers did not seal in this case (Figure 2).

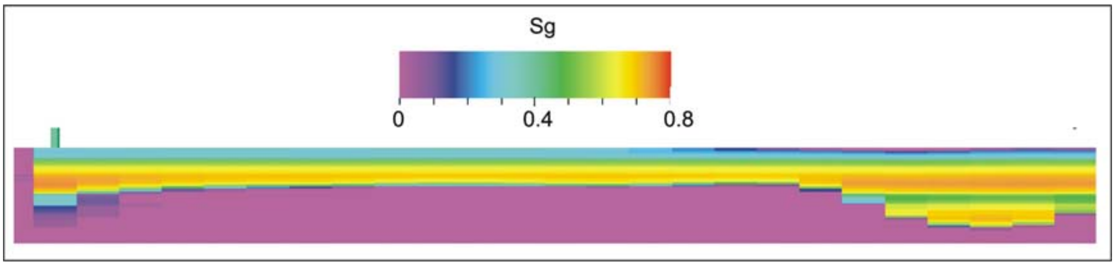

Figure 2 *Flattened view of CO_2 gas saturation in Model 2B after 30 years of injection. Injector is on the left (green), the structural trap on the right hand side of the model.*

One of the main findings is that lateral permeability contrasts seem to inhibit CO_2 migration. While 1 mD regions formed a barrier to CO_2 migrating laterally in Model 1, they did not form a barrier to CO_2 moving vertically in Model 2.

We have also carried out sensitivity studies on various model parameters. Diffusion does not seem to impact the results much. Hysteresis effects lower the gas saturation at the top of the structure. Pressure boundary conditions are important. In all models, we have multiplied the porosity of the outermost cells round the edges by 100, effectively adding 25 km of reservoir in all horizontal directions. As in all numerical simulations, the size of the grid cells also plays an important role.