THE LONG-TERM FATE OF CO_2 INJECTED INTO AN AQUIFER

Erik Lindeberg and Per Bergmo

SINTEF Petroleum Research, NO-7465 Trondheim, Norway

ABSTRACT

Assuming that an underground aquifer is capped by a capillary seal preventing injected CO_2 to migrate into the atmosphere, the CO_2 will eventually accumulate under this seal. The topography of the seal will determine the CO_2 migration on the 1000 years time-scale. CO_2 diffusing into the underlying aquifer column will set up convective currents in the aquifer enhancing the solution rate of CO_2. Most of the CO_2 will have dissolved into the aquifer after between 5 000 and 50 000 years mostly dependent on the vertical permeability of the aquifer and the contact area between CO_2 and brine. On a time scale of several hundred thousand years, molecular diffusion through the capillary seal will be the dominating transport mechanism and will eventually deplete the formation of CO_2 by transporting it into the atmosphere if reactions between CO_2 and rock minerals are neglected. This process will take millions of years, however.

INTRODUCTION

5 million tonnes CO_2 from the Sleipner gas processing plant has been injected into the Utsira formation [1] in the North Sea and eventually 25 million tonnes will be injected before the gas production has ceased. The CO_2 is injected near the bottom of the approximately 200 m thick sand. The migration of injected CO_2 is being monitored by 4D seismic, which shows that the CO_2 is retained in large thin clouds under what is expected to be horizontal semi-permeable shales within the formation. All evidences [2] are indicating that the intermediate shales are not sufficiently tight to prevent most of the CO_2 from migrating to the top seal of the formation after the injection period is over. The topography of the top seal will determine the further migration. The questions how fast CO_2 will dissolve in the brine and what the long-term fate of the CO_2 will be, have been raised and are the subject of this study.

MODELLING

Selection of area for the model

Based on 12 000 x 10 000 m pre-injection seismic maps of the top seal and floor of the formation, and one intermediate shale layer within the formation a reservoir model was constructed. The seismic maps had an initial resolution of 12.5 x 12.5 m. In a previous study [2] a subset of this grid (2000 x 3000 m, coarsened to 25 x 25 m) was used to simulate the near injection site and this model was large enough for predicting the first 10 years of injection. Due to the smooth topography of the top seal (depth variation of less than 80 meter over the 120 km^2 area) the CO_2 will spread over a very large area. To predict the long-term fate of the injected CO_2 this requires the use of a much larger model and using a coarser grid to achieve acceptable computing time. In addition, the resolution has to be sufficiently fine to preserve the dominating migration pattern under the seal. Determining the optimal lateral coarsening and selecting the optimal part of the reservoir was performed in several steps. As a reference, a simulation grid with 25 x 25 m lateral resolution was used. By simulating the migration of CO_2 on a subset of the complete grid consisting of only the upper 30 m of the formation with a 2 m vertical resolution the area could be reduced to a 7.2 x 9.8 km while still containing the CO_2 bubble within the model. Next, the lateral grid was coarsened. With 100 x 100 m grid blocks, the migration pattern was satisfactory maintained. The lateral grid was now limited to approximately

7 000 grid blocks which allowed the use of 52 vertical blocks (Figure 1). With a total of 350 000 grid blocks a satisfactory compromise between resolution and computing speed was achieved when simulating the problem with the parallel option in Eclipse 100 using 10 processors on a SGI Origin 2000.

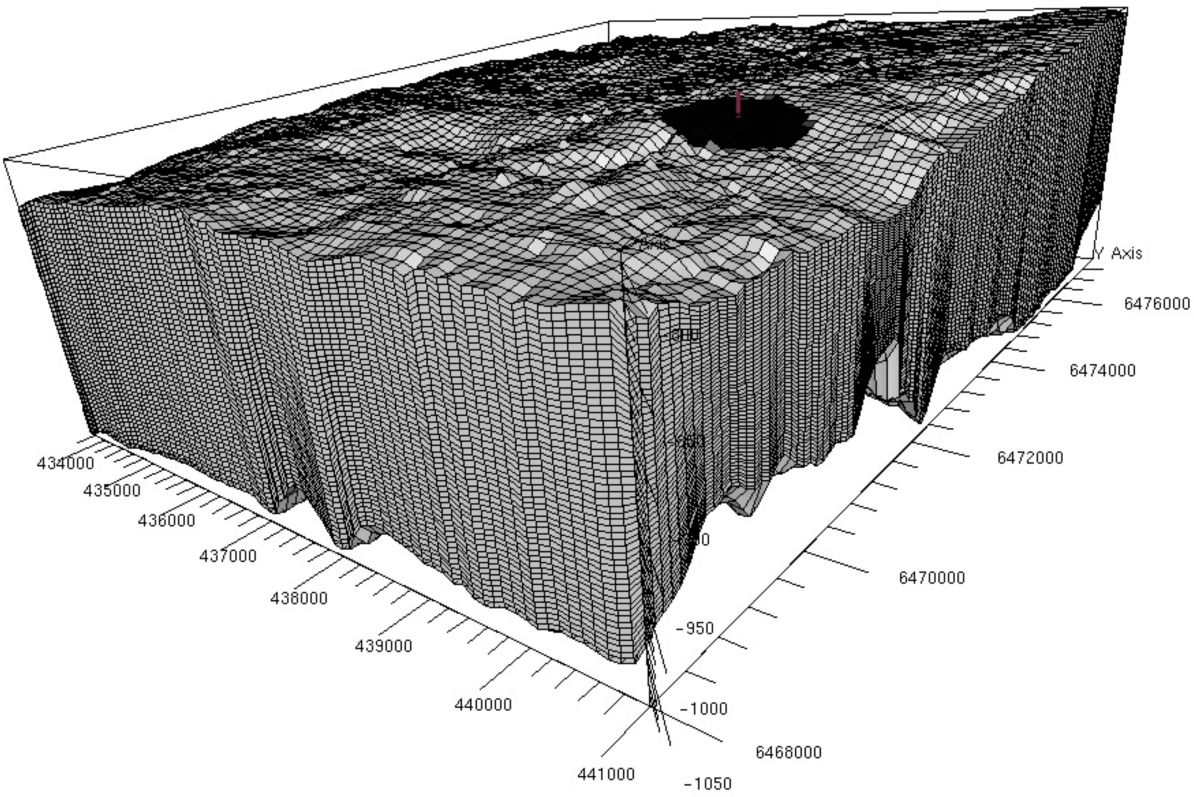


Figure 1: Reservoir grid. The dark spot represent the extension of the CO_2 bubble under the cap seal in year 2011 after 15 years of injection

Simulation of the combined effect of lateral migration and dissolution of CO_2 into the aquifer

The results of the simulation of the fate of the CO_2 bubble resulting from 25 years of CO_2 injection shows that the CO_2 bubble increases in its lateral extension under the cap seal for more than 200 years after the injection has stopped (corresponding to the six first top view pictures in Figure 2). After 200 years the dissolution is the dominating mechanism resulting in a shrinking of the bubble and after another 4800 years the bubbles has completely dissolved. In the base case (Utsira conditions) the horizontal permeability, k_h = 2000 mD. The sand is isotropic, but the semi-permeable shales has been up-scaled through the vertical permeability, k_v = 200 mD. Simulations where both k_v and k_h were reduced with a factor of respectively 0.1, 0.01 and 0.001 was also performed resulting in a much lower dissolution rate. The relative dissolution rates are illustrated in Figure 3.

Induced convective currents in the aquifer column

Molecular diffusion can usually be neglected in reservoir engineering especially when large reservoir models are considered because diffusion is generally negligible compared to other fluxes. In this case with dissolution in an underlying brine column molecular diffusion play a significant role on long time-scales. Due to the special pVT properties of the CO_2/brine system (the density of CO_2 saturated brine is approximately 10 kg/m^3 denser than brine with no CO_2) molecular diffusion from the CO_2 bubble into the underlying brine column will create a hydrodynamic unstable layer setting up convective currents in the brine column [3]. These convective currents will carry dissolved CO_2 down into the column and under-saturated water up to the CO_2/brine contact enhancing the transfer of CO_2 into the brine compared to a transport relaying on molecular diffusion only. Due to the importance of this mechanism, a more thorough examination of the phenomena has been performed by some numerical experiments.

The convection was simulated on a 10 m wide and 13 m deep 2D model. This corresponds to the region of the CO_2/brine contact were a 1 m thick CO_2 bubble is resting on top of a brine column at the pressure and temperature corresponding to reservoir conditions in Utsira. Figure 4 shows how CO_2 dissolves in the brine

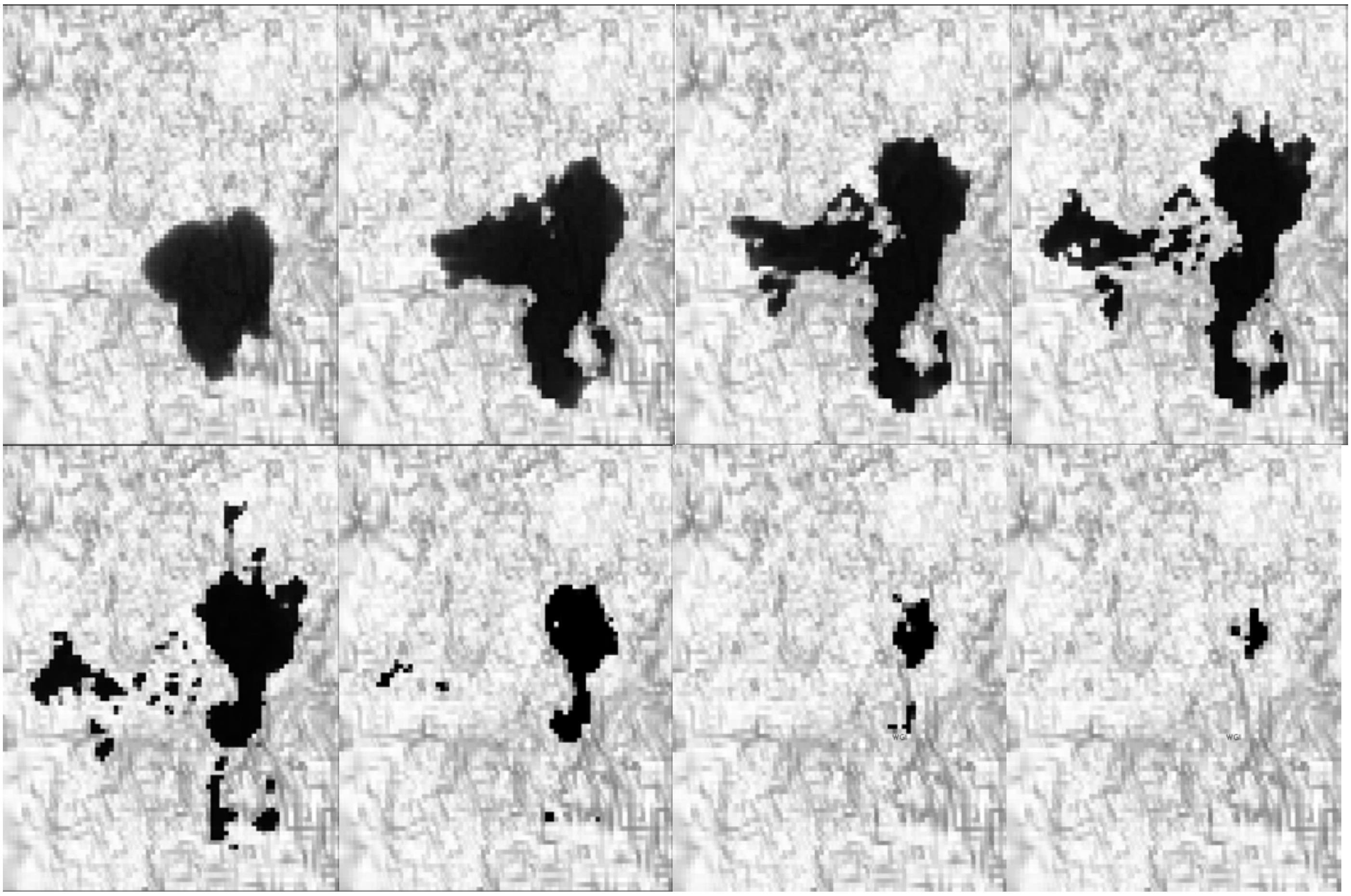


Figure 2: The migration of CO_2 under the cap seal in year 2021 (end of injection), 2050, 2150, 2200, 2520 (maximum), 3620, 5020, and 5820

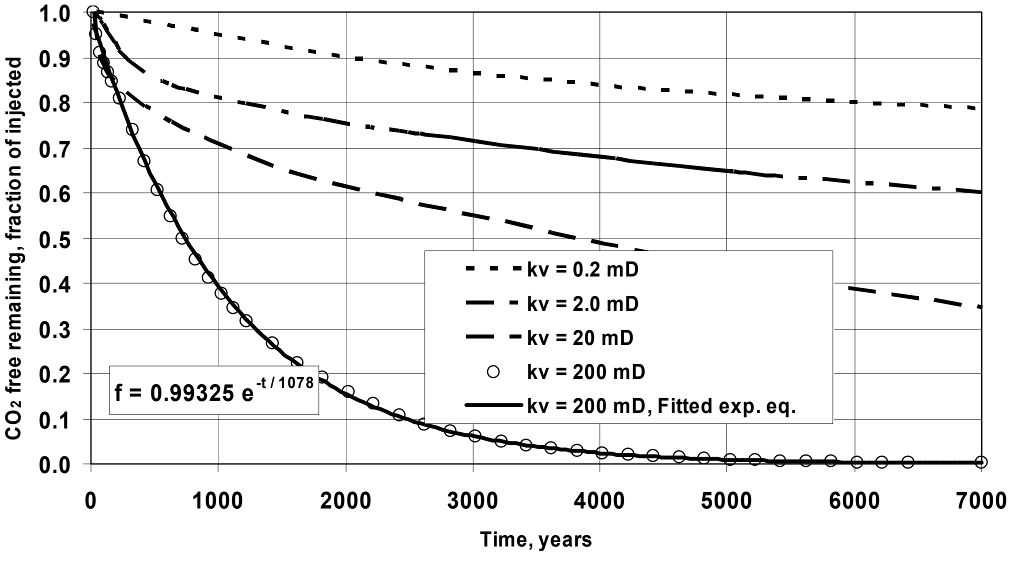


Figure 3: The reduction of free CO_2 as function of time at varying permeabilities. $k_v/k_h = 0.1$ for all tests.

column in one-year intervals. The initially sharp boundary between the gas bubble (black) and the brine (white) is gradually becoming diffuse and after two years, the first instabilities are seen in the diffusion zone. Plumes with a characteristic minimum width are formed. These consist of brine with high concentration of CO_2. They penetrate into the brine with less CO_2 and gradually coalesce into larger plumes. New small plumes are formed which also merge into larger entities during migration. The effective dissolution rate is dependent on the horizontal grid. By reducing the grid block size stepwise, the minimum grid block size was determined from how the solution converged. The horizontal grid block size had to be approximately 0.2 of the wavelength of the initial formed plumes to give an acceptable convergence. The following simulations were performed with a gird of 200 x 340 grid blocks and with a grid block size of 4 x 5 cm.

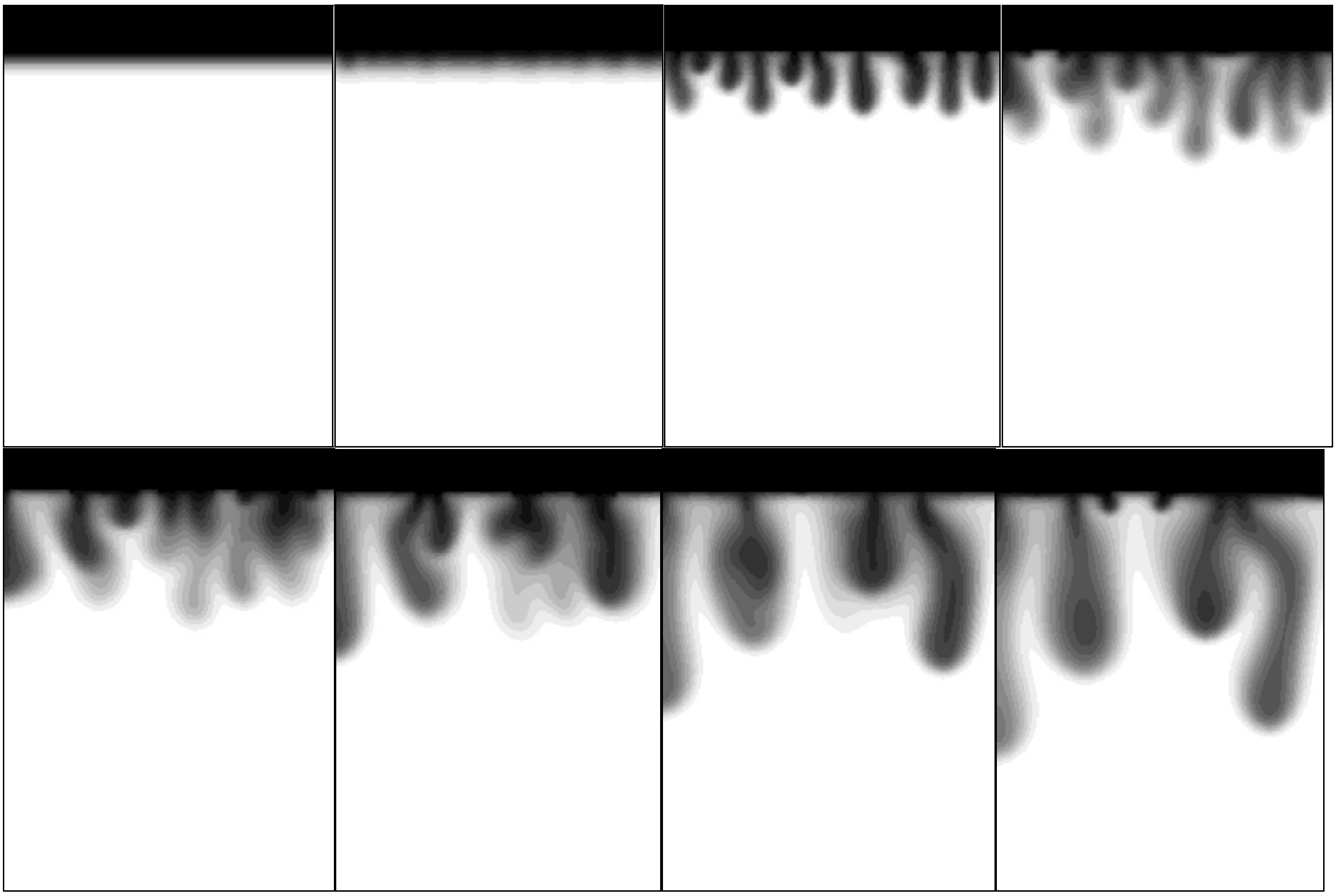


Figure 4: Profile of the convection of high-density plumes of CO_2-rich brine into the brine column below

Numerical experiments on models with different permeabilities, *k*, and viscosities, μ, were performed. In Figure 5 an example is plotted with a table of simple empirical relations for convection and onset of convection that were found. The plume convection is much stronger than diffusion only, but somewhat weaker than a pure Darcy flow, probably due to transverse mixing.

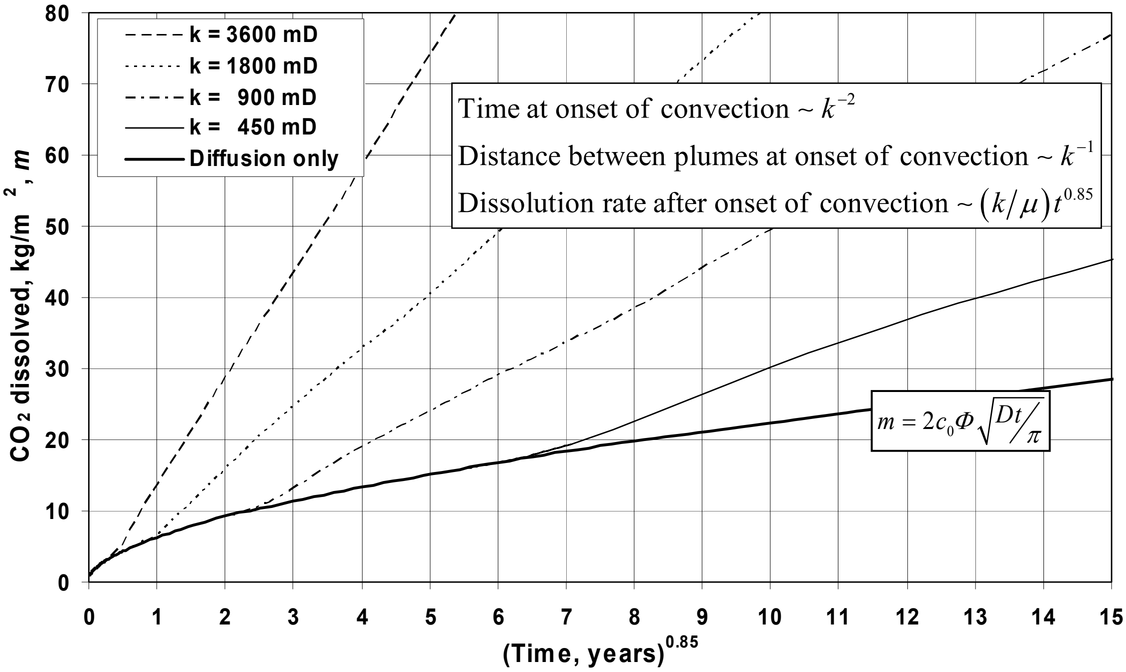


Figure 5: Dissolution of CO_2 due to convective flow. In this example $\mu = 0.885$ mPa s, diffusion coefficient, $D = 2.06 \cdot 10^{-9}$ m^2/s, the porosity $\Phi = 0.38$ and the solubility of CO_2 in brine, $c_0 = 52.94$ kg/Sm^3

Induced convective currents in a 3D reservoir case

In the reservoir simulations above the shrinkage of the CO_2 bubble is due to convective dissolution of CO_2 at the CO_2 /brine interface. Considering the high resolution of the grid needed to give a fair representation of the problem and that the lateral grid block size is 100 m x 100 m in the reservoir simulation, the question of how accurate the CO_2 dissolution is represented must be addressed. In Figure 5 the plume of dissolved CO_2 is illustrated at different time-steps. In the first 100 years no significant convection occurs. This artefact is due to that the convection will not start before the instability is so large that it can be represented by the large plume wavelength (200 m). When this instability is reached the convection progresses in the same way as illustrated before with coalescing plumes. The convection delay of approximately 100 years does not play a significant role considering all the other uncertainties of the reservoir model, however. The explanation for the slower dissolution rate in the reservoirs (Figure 3) within lower permeability is not only due to the slower induced convection, but also because the CO_2 distributes over a smaller area resulting in a smaller contact area between CO_2 and brine.

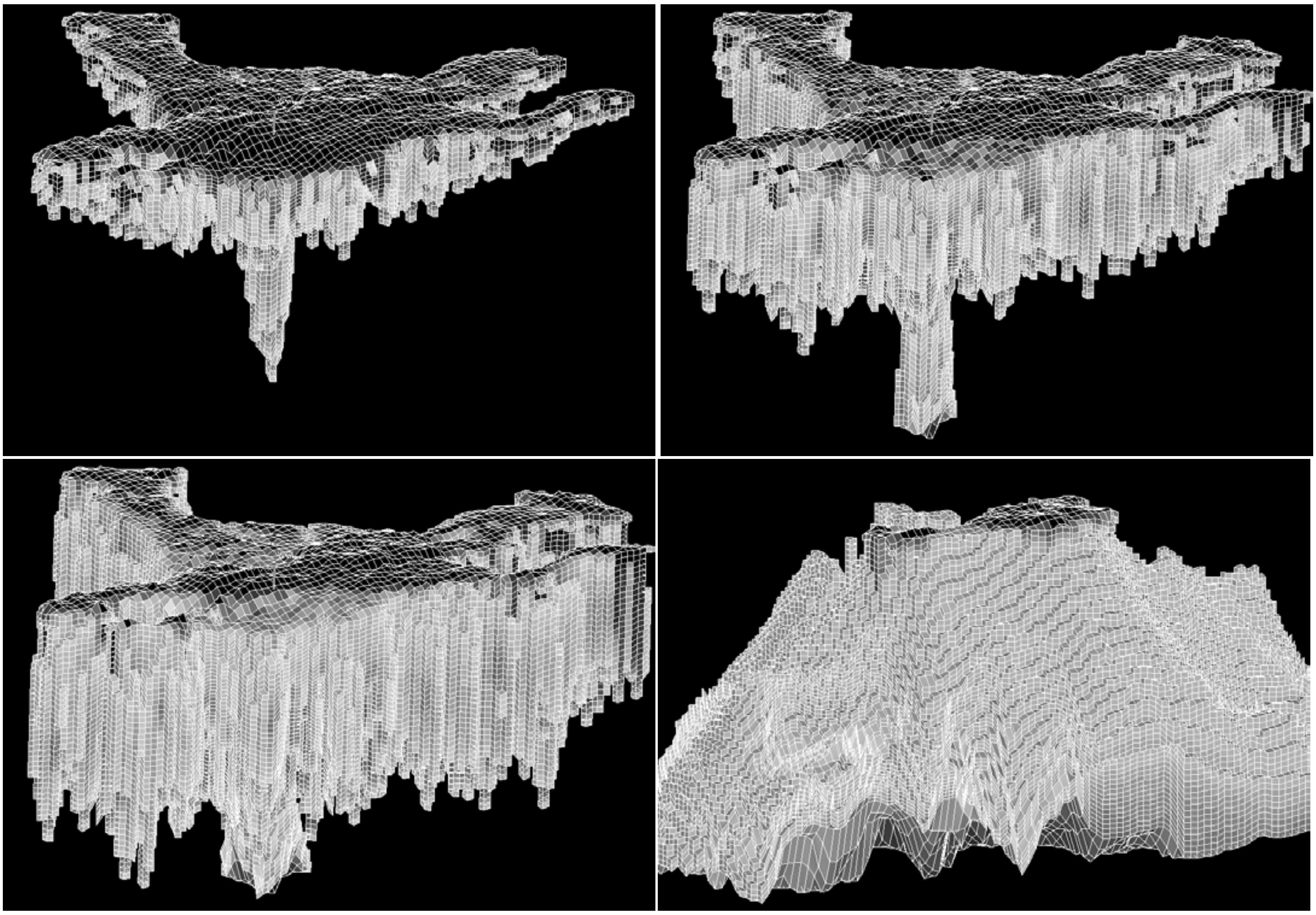


Figure 5: A 3D view of the convection of CO_2 rich brine plumes into the column below at year 2220, 2420, 2620, and 5020 when all the plumes have coalesced in to one single plume unit. The big plume in the middle on the upper two pictures is near to the injection site.

DIFFUSION OF CO_2 THROUGH THE OVERBURDEN INTO THE BIOSPHERE

A capillary seal in a shale or mudstone is an effective barrier for CO_2 in gas phase due its high capillary entrance pressure. These seals provide, however no restriction for molecular diffusion because their pores are saturated with brine and they can have a large porosity. Above Utsira there is a 700 m thick overburden between the seafloor and the aquifer. The concentration profile of CO_2 in the overburden is obtained by solving the one-dimensional diffusion equation for a porous medium with tortuosity, τ;

$$\frac{\partial c}{\partial t} = D_e \frac{\partial^2 c}{\partial z^2}, \; c(0,t) = c_{0,} \; c(Z,t) = 0 \; \textit{for all times } t, \textit{ and initially } c(z,0) = 0 \qquad (1)$$

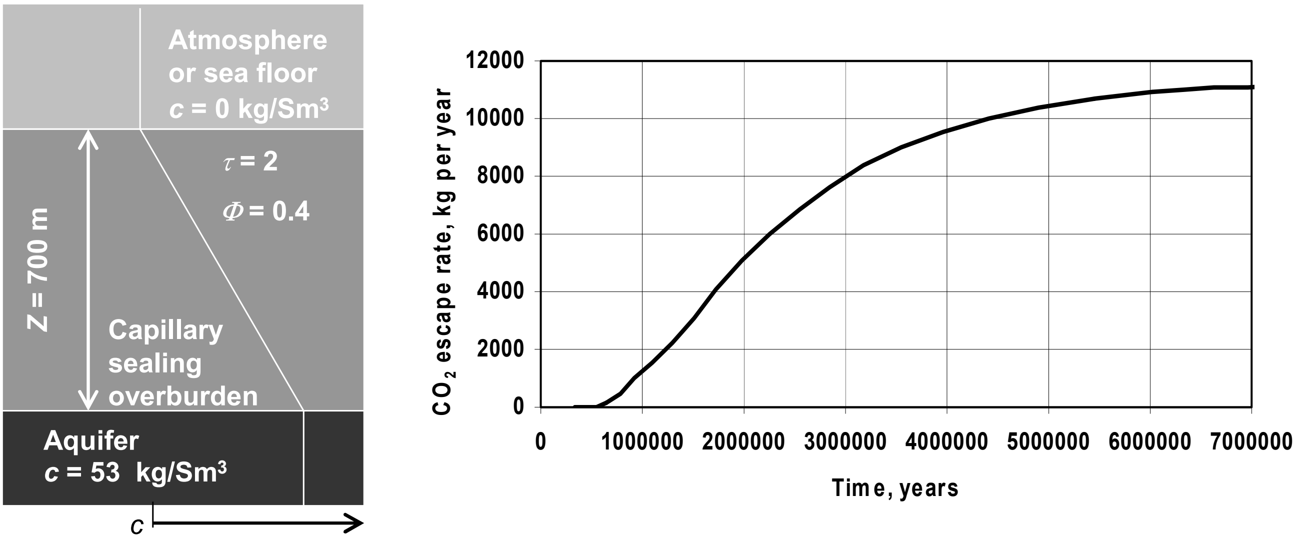
where c is the concentration of CO_2, z is the height-coordinate, and $D_e = D / \tau$ is the effective diffusion coefficient. The bulk diffusion coefficient of CO_2 in brine D, is set equal to $2\cdot10^{-9}$ m^2/s. At these boundary conditions, Eqn. 1 has the solution

$$c(z,t) = c_0\left[1-\frac{z}{Z}-\frac{2}{\pi}\sum_{n=1}^{n=\infty}\frac{1}{n}\sin\left(\frac{n\pi z}{Z}\right)e^{-D_e t\left(\frac{n\pi}{Z}\right)^2}\right] \qquad (2)$$

The flux, J, in a porous medium with porosity, Φ, from the top seal of the formation into the atmosphere is obtained by combining the flux equation and the derivative of Eqn. 2 for $z = Z$:

$$J = -D_e\Phi\left(\frac{\partial c}{\partial z}\right)_{z=Z} = D_e\Phi c_0\left[\frac{1}{Z}+\frac{2}{Z}\sum_{n=1}^{\infty}(-1)^n e^{-D_e t\left(\frac{n\pi}{Z}\right)^2}\right] \qquad (3)$$

The escape rate as function of time is plotted in Figure 6 assuming that the CO_2 bubble has a constant radius of 2 000 m. It will take more than 500 000 years for the CO_2 to reach the surface and the maximum flux rate is not achieved until the steady state concentration profile is reached after several million years. This illustrates the effective trapping of CO_2 in an aquifer as soon as it has dissolved in the brine and suggests that injection of CO_2-saturated brine could be a feasible option for CO_2 storage if the seal integrity is questionable.



6: Molecular diffusion through the overburden seal. The escape rate is calculated from Eqn. 3 assuming that the CO_2 source is a bubble with constant radius of 2 000 m

CONCLUSION

The long-term fate of CO_2 in an aquifer will strongly depend on the topography of the cap rock. The CO_2 will eventually dissolve in the brine and this dissolution is mainly controlled by induced convective currents. If mineral reactions and hydrodynamic activity are neglected, the dissolved CO_2 represents the ultimate trapping of CO_2 because molecular diffusion of CO_2 through the overburden rocks is too slow to have any climate impact at a time-scale shorter then the long ice-age cycle (100 000 years).

REFERENCES

1. Zweigel, P., Hamborg, M., Arts. R., Lothe, A., Sylta, Ø., Tømmerås, A. (2000). In: *Proceedings of 5th. International Conference of Greenhouse Gas Technology*, pp. 366-371
2. Lindeberg, E ., Bergmo, P., Ghaderi, A., Zweigel, P., Lothe, A., (2000), In: *Proceedings of 5th. International Conference of Greenhouse Gas Technology*, pp. 372-377
3. Lindeberg, E.G.B, Wessel-Berg, D. (1997) *Energy Convers. Mgmt.* **38** S229.