EAGE

Th CO2 03

Predictive Modelling Of CO2 Storage In Aquifers: Integrating The Effects Of Boundary Conditions And Saturation Functions

M. Onoja[1]*, S. Shariatipour[1]
[1]Centre for Fluid & Complex Systems, Maudsley House

Summary

In reservoir engineering, the predictive analyses of CO2 sequestration in subsurface formations commonly employ numerical models of subsurface formations. A significant number of work have utilised numerical modelling techniques to predict the impact of the reservoir's boundary conditions and interlayer communication on CO2 storage capacity in aquifers. To the best of our knowledge, no study on the impact of boundary conditions on CO2 storage efficiency has focused on the combined effect of this factor in the reservoir and saturation functions in the caprock. To this end, this study examined the effect of integrating both processes on pressure evolution in the caprock during the numerical simulation of CO2 injection into a deep saline aquifer. Utilising the Sleipner benchmark model, we also showed how varying saturation functions in the caprock can affect the storage efficiency in the reservoir formation.

Introduction

Geological sequestration of carbon dioxide (CO_2) in depleted oil and gas reservoirs, coal formations and particularly deep saline aquifers serves as a promising option for greenhouse gas mitigation (IPCC 2005). Reservoir simulation models continuously play a significant role in assessing the viability of CO_2 storage processes in sub-surface aquifers. The identification of an aquifer's boundary conditions in geological models is necessary for appropriate estimation of the pressure evolution and CO_2 storage capacity. In numerical simulations, an aquifer's boundary condition defines the regime of fluid flow and pressure communication into surrounding geological formations. Flow boundaries can result from reservoir compartmentalization through natural heterogeneity and/or faults. Typically, vertical boundary conditions are defined by low permeability lithologies usually acting as the top seal and the base seal which serve as barriers to flow and pressure communication. Zhou *et al.* (2008) describes three scenarios that can be used to define boundary conditions i.e. open, closed, and semi-closed system. In aquifer models, a closed system will have no pressure communication beyond the lateral and vertical sides of the modelled reservoir while the reverse is the case for an open system. A semi-closed system, however, will only accommodate brine migration into and beyond the overlying and underlying seals.

A significant body of work is available in relation to impact of boundary conditions on CO_2 storage capacity and the dependence of vertical interlayer communication on the permeability of the seals (Bachu 2015). However, there remains a limited degree of the impact of boundary conditions on pressure build-up in low permeability vertical boundaries, such as mudrocks, and the impact of relative permeability curves in these rocks on pressure build-up within them. Mudrocks, often identified as shales, are composed of silt- and clay-sized particles and can be classified as siltstone (with > 66% silt-sized particles), mudstone (clay and silt particles between 33% and 66%) or claystone (with > 66% clay-sized particles). These different types of mudrocks could very well have varying effects on CO_2 and brine flow dynamics. This is one aspect that is rarely considered because fluid flow analysis during CO_2 geo-sequestration are more focused on relative permeability functions in storage formations than in sealing formations. This study examines the effect of the latter in pressure build-up and CO_2 storage efficiency under the three boundary conditions mentioned earlier using reservoir simulation models.

Methodology

Numerical simulations were performed using the Sleipner Layer 9 benchmark model, released in 2011 by Equinor, to study how the sealing lithologies coupled with boundary conditions affect CO_2 storage capacity and security. Sleipner is a commercial CO_2 storage site situated in the Norwegian sector of the North Sea where CO_2 injection into the sandstone-dominated Utsira aquifer commenced in 1996. Wireline log of the Utsira Sand shows a good proportion of clean sand in the reservoir unit with thin mudrock layers which constitute permeability barriers within the reservoir sand. The reservoir consists of an upper "Sand Wedge" unit and a lower "Thick Sand" unit separated by 5-6m thick shale unit. The benchmark model is confined to the Sand Wedge interval of the storage formation bounded vertical by shale layers acting as the top and base seal (Figure 1). In this study, the top seal was modelled with two layers, a top caprock unit and a base caprock unit.

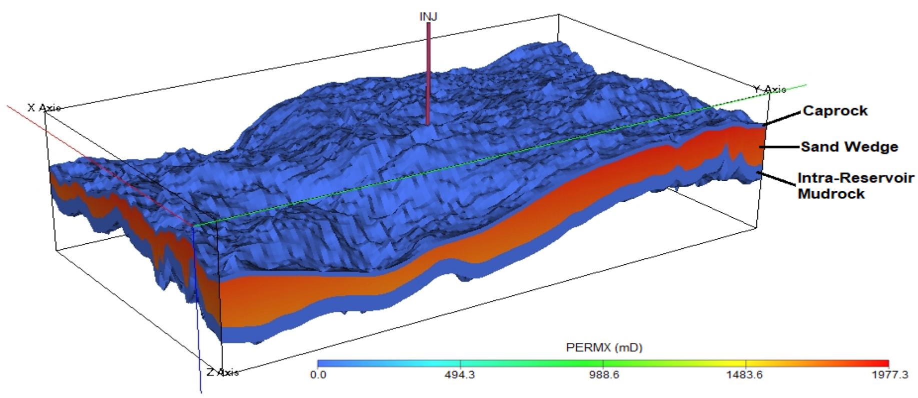

Figure 1 *The storage site model showing estimated horizontal permeability and the injection well.*

The Sleipner benchmark model is particularly useful because it is a real case study with sufficient calibration data (see Singh *et al.* 2010) to investigate uncertainties in CO_2/brine flow dynamics and storage efficiency. It is imperative to stress here that the case-study simulations presented in this paper are not based around the monitoring results for the real injection project as we do not attempt to obtain exact history matches of the Sleipner monitoring data. Nevertheless, the rock and fluid property dataset used in this study, with the exception of the saturation functions, were based broadly on Singh *et al.* (2010). Relative permeability curves for the CO_2/brine flow dynamics in sandstone, siltstone, mudstone, and claystone were based on the description of relative permeability functions in siliciclastic units by Onoja and Shariatipour (2018) using Van Genutchten's formulation (Figure 2). Residual brine saturations, S_{wr}, of 0.3 and 0.605 were adopted for the sandstone and mudrocks respectively.

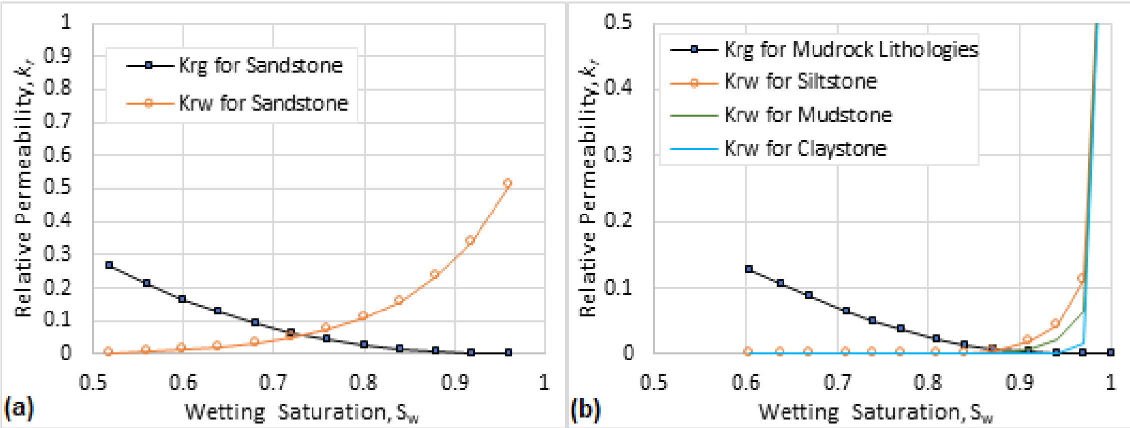

Figure 2 *Relative permeability curves for (a) the sandstone, and (b) the mudrock lithologies.*

Using the ECLIPSE 300 compositional module, a simulation of seven years of CO_2 injection at a rate of 300,000 tonnes/yr and an additional seven years of post CO_2 injection was conducted to investigate how the change of relative permeability to brine in the mudrock affects pressure and CO_2 saturation predictions in the model. Nine models were run with the three types of mudrock highlighted in this text as the shale units under closed, semi-closed, and open boundary conditions (Table 1):

Table 1 *Description of the simulation cases used in the study.*

	Closed Boundary	**Semi-Closed Boundary**	**Open Boundary**
Claystone	Case 1A	Case 2A	Case 3A
Mudstone	Case 1B	Case 2B	Case 3B
Siltstone	Case 1C	Case 2C	Case 3C

Results

Simulation results showed that the injection rate was maintained through the injection period across all cases shown in Table 1. As expected, overpressure is highest in the closed system and lowest in the open system during the gas injection period. This is due to brine acting as a pressure transmission medium within the modelled domain. Hence, the higher the restriction of brine flow beyond the boundaries of the domain, the higher the overpressure in the domain. For the entirely closed system, vertical pressure communication was restricted beyond the domain's boundary, resulting in the dominance of gravity forces over buoyant forces on brine flow in the model. For the semi-closed and open systems however, the reverse was the case (Figure 3). Pressure builds-up in the caprock as a response to CO_2 injection in the underlying aquifer. At the end of CO_2 injection, pore pressure was seen to be evenly distributed across the base layer of the caprock in the closed and open system for all caprock variations, unlike the semi-closed which portrayed the highest magnitude of overpressure in the injection zone of the claystone caprock and lowest in that of the siltstone caprock (Figure 4). This phenomenon was attributed to the functional dependency of pressure distribution, within sedimentary formations, on the rock's microstructural features such as the pore size distribution or the average grain size composition. While pressure effectively permeates the base layer of the caprock, the resulting fabric of the overlying layer influences brine migration through the base layer. A greater restriction of brine flow through the base layer and into the top layer in the claystone caprock, compared to the mudstone and siltstone caprocks, resulted in the higher overpressure regime in **Case 2A** (see Table 1). This was attributed to the restriction in the upward path of brine migration which was due to the smaller pore spaces in claystone caprock hence the expansion of formation fluid in the base layer of the caprock.

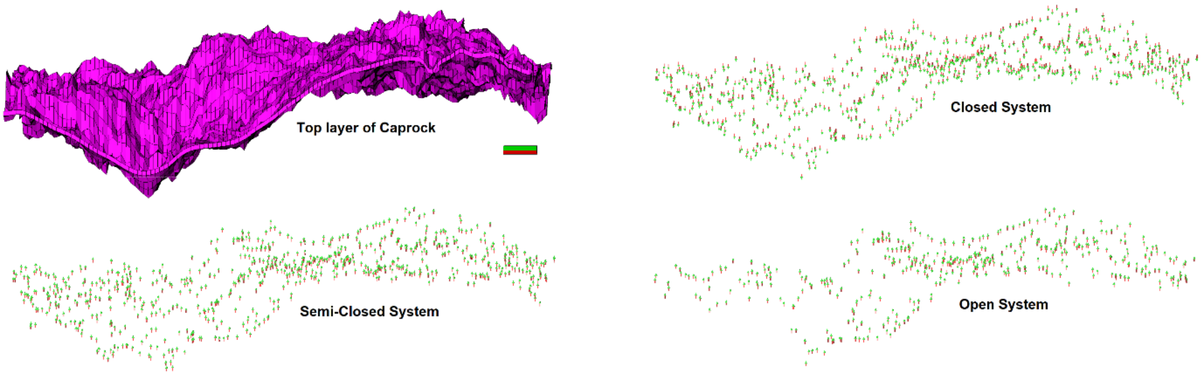

Figure 3 *Brine flow vectors in the top layer of the caprock at the end of CO_2 injection for varying boundary conditions.*

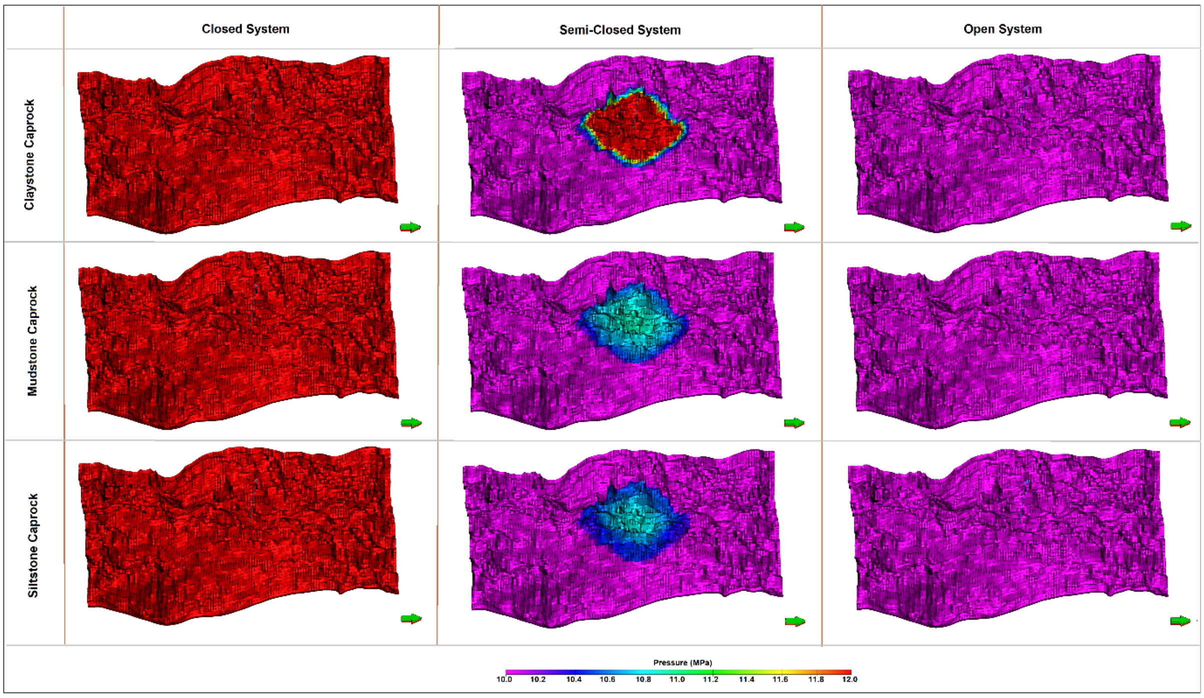

Figure 4 *Overpressure in the base layer of the caprock simulated in the first year of post-CO_2 injection.*

CO_2 in free form within the base layer of the caprock was also seen to be greater in the semi-closed system than in the open and closed systems (Figure 5). The flow boundary conditions of the semi-closed system which encourages vertical fluid migration enabled the gas to permeate into the top layer of the caprock at the end of the simulation period. However, this was not the case in the closed system, where gravity forces dominate, and in the open system, where lateral regime of fluid flow counteracts the vertical regime. The degree of the CO_2 component in the top layer of the semi-closed system was based on the concentration of CO_2 in the base layer and hence was greater for the siltstone caprock, followed by the mudstone caprock and finally the claystone caprock. This also follows the argument that the displacement of the wetting brine in the original porosity of the rock matrix by the non-wetting phase is under the influence of capillary and viscous forces. Due to the relatively larger pore throats in slit-rich mudrocks over clay-rich mudrocks, the capillary forces are lower in the siltstones than in claystones thus accommodating greater CO_2 fracture flow through the rock fabric.

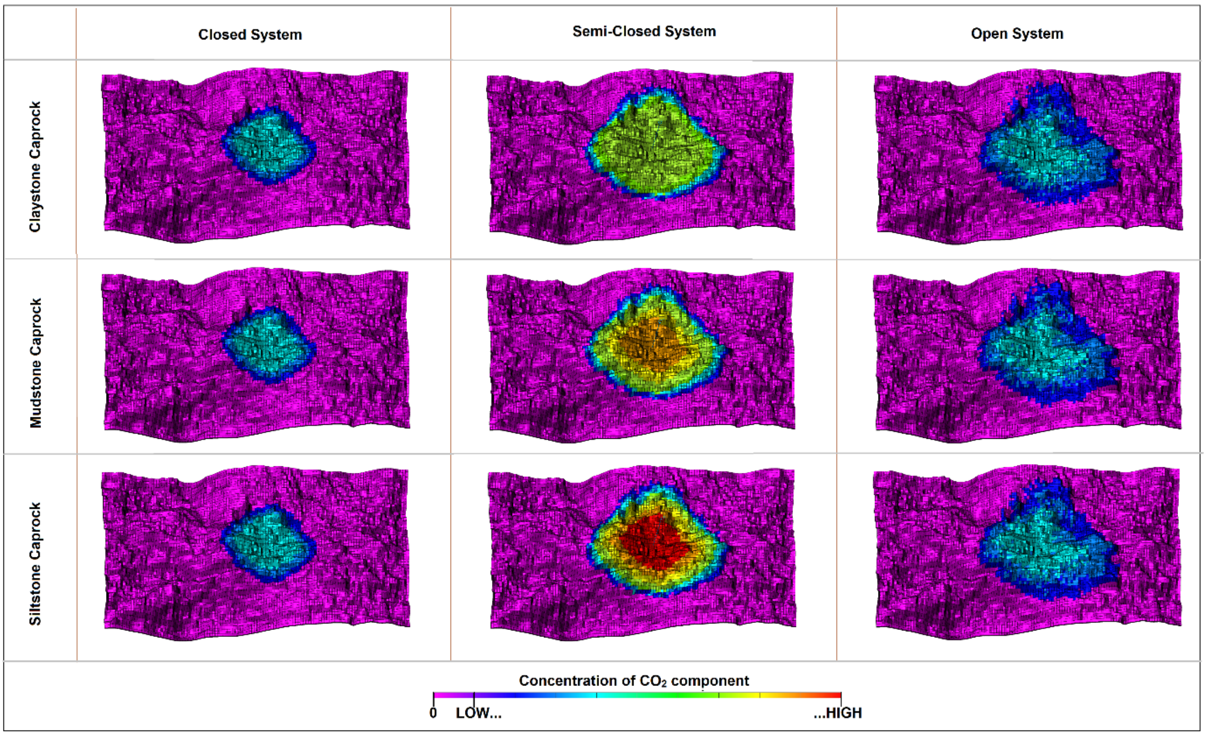

Figure 5 *Concentration of mobile CO_2 in the base layer of the caprock at the end of simulation.*

Conclusions

This study shows that the most efficient mechanism for gas transport through mudrocks is the pressure-driven volume flow of the mobile gas phase. The ease of such pressure-driven flow through silt-rich shale barriers, as opposed to clay-rich shale barriers, portrays the importance of relative permeability functions in low permeability units. Hence, adopting this approach for the simulation of CO_2 permeating through shale barriers in a reservoir formation will enhance precision in the predictive analysis of gas breaking through interlayer baffles.

Acknowledgements

The authors would like to thank the FMFMRC for financial support and Equinor for permission to publish data from the Sleipner project. We acknowledge Schlumberger for the use of ECLIPSE and Petrel software.

References

Bachu, S., [2015] Review of CO_2 storage efficiency in deep saline aquifers. *International Journal of Greenhouse Gas Control*, **40**, 188–202.

IPCC [2005] *IPCC Special Report on Carbon Dioxide Capture and Storage*. Prepared by Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Onoja, M.U. and Shariatipour, S.M. [2018] The impact of gradational contact at the reservoir-seal interface on geological CO_2 storage capacity and security. *International Journal of Greenhouse Gas Control*, **72**, 1–13.

Singh, V. P., Cavanagh, A., Hansen, H., Nazarian, B., Iding, M. and Ringrose, P. S., [2010] Reservoir Modeling of CO_2 Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway. *SPE 134891*

Zhou, Q., Birkholzer, J.T., Tsang, C.F. and Rutqvist, J. [2008] A method for quick assessment for CO2 storage capacity in closed and semi-closed saline formations. *International Journal of Greenhouse Gas Control*, **2**, 626–639.