An improved history-match for layer spreading within the Sleipner plume including thermal propagation effects

Gareth Williams[1] and Andrew Chadwick[2]

[1]British Geological Survey, Murchison House, West Mains Road, Edinburgh, UK, NG12 5GG
[2]British Geological Survey, Environmental Science Centre, Keyworth, Nottingham, UK, NG12 5GG

Abstract

CO_2 separated from natural gas produced at the Sleipner field in the North Sea is being injected into the Utsira Sand, a regional saline aquifer of late Cenozoic age, comprising mostly unconsolidated sand of high porosity and high permeability. A number of thin mudstones, typically 1 – 2 m thick, divide the reservoir into nine sand bodies.

CO_2 is injected, via a deviated well, at a depth of 1012 m below sea level, ~200 m beneath the top of the aquifer. Injection commenced in 1996 at a roughly constant rate, with around 15 million tons of CO_2 stored by 2016. The growth of the resulting plume has been monitored using repeat time-lapse 3D seismics acquired in 1999, 2001, 2004, 2006, 2008 and 2010 (Figure 1).

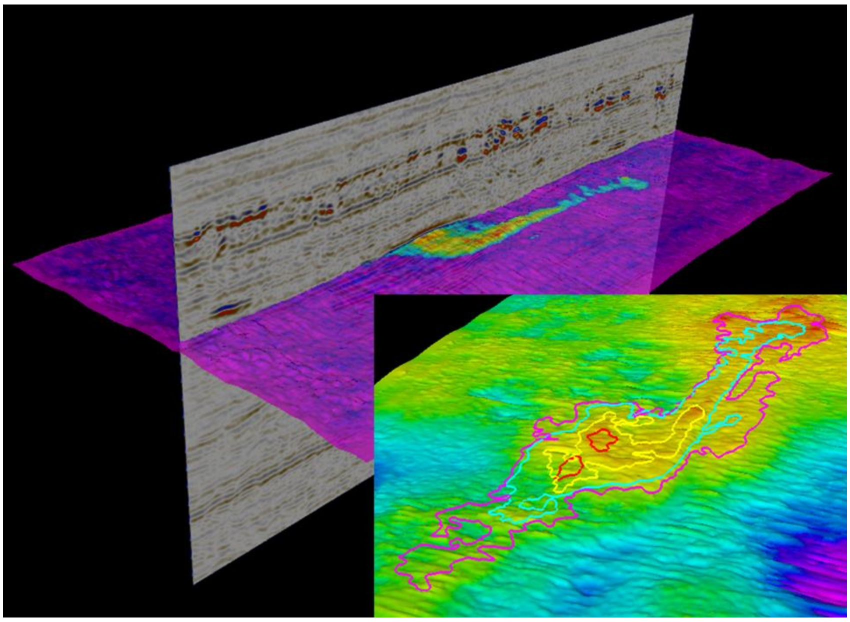

Figure 1 Perspective view of the topmost CO_2 layer in 2006, looking north-west. Inset: Top reservoir (base caprock) surface. Polygons show the mapped extents of the topmost CO_2 layer in 1999 (red), 2001 (yellow), 2006 (blue) and 2010 (pink). Note rapid migration beneath a north-trending linear ridge.

Recent dynamic models of CO_2 plume migration at Sleipner have focused on the topmost spreading layer in the plume. This lies directly beneath the reservoir caprock, and its geometry can be accurately mapped on amplitude slices through successive time-lapse seismic surveys (Figure 1). Studies have attempted to history-match the growth of the topmost layer with varying degrees of success (Chadwick and Noy, 2010; Singh et al., 2010; Cavanagh, 2013; Zhu et al. 2015). Most flow simulations have difficulty in reproducing the rapid northward migration of CO_2 along a prominent linear ridge (Figure 1). Studies have investigated the effects of uncertainties in topseal topography, permeability anisotropy and gas composition (e.g. Chadwick and Noy, 2010; Zhu et al. 2015), with alternative modelling approaches including vertical equilibrium solutions and non-Darcy models (see Cavanagh, 2013). These have had varying success in replicating the observed layer growth rates. This paper explores the effect of two key parameters - injectant temperature and reservoir permeability information which have been previously neglected.

Due to adiabatic compression within the injection tubing, the temperature of CO_2 at the injection perforations is estimated at ~ 48 C (or slightly higher depending on pressure) (Alnes et al. 2011). This is around 13 C above the ambient reservoir temperature at the injection point.

A simple 2D axisymmetric numerical model, with reservoir thickness, temperature, pressure and injection rates similar to Sleipner, demonstrates the thermal effects of injecting CO_2 at 48 C into a cooler reservoir (Figure 2). The warm, buoyant CO_2 rises vertically to the top of the reservoir undergoing Joule-Thomson cooling to a temperature of around 36 C (Figure 2b), some 7-8 C above the ambient reservoir temperature (Figure 2c). The warm CO_2 then spreads laterally beneath the reservoir caprock. Compared with previous modelling, its higher temperature correlates with significantly lower density and viscosity (450 kg/m^3 and $3.0x10^{-5}$ Pa.s respectively), and a consequent increase in buoyancy and mobility.

Reservoir permeability provides for additional uncertainty. Core measurements give a mean value of around 3 Darcy, but borehole pumping tests from the Utsira Sand suggest higher regional permeabilities from 6 to 8 Darcy (Chadwick et al. 2002).. The core samples were taken in Norwegian well 15/9-A23 (Chadwick et al. 2002), but did not include the top sand layer, which crucially has a notably lower gamma-ray count, suggesting a coarser, cleaner lithology.

The uncertainty in CO_2 temperature (and consequently physical properties), and the range of plausible permeability values for the upper sand at Sleipner, allows for an improved history-match (Figure 3). Upper bound values of 8 Darcy horizontal permeability and a CO_2 temperature of 36 C gives an improved match with the top spreading layer imaged on seismic reflection data.

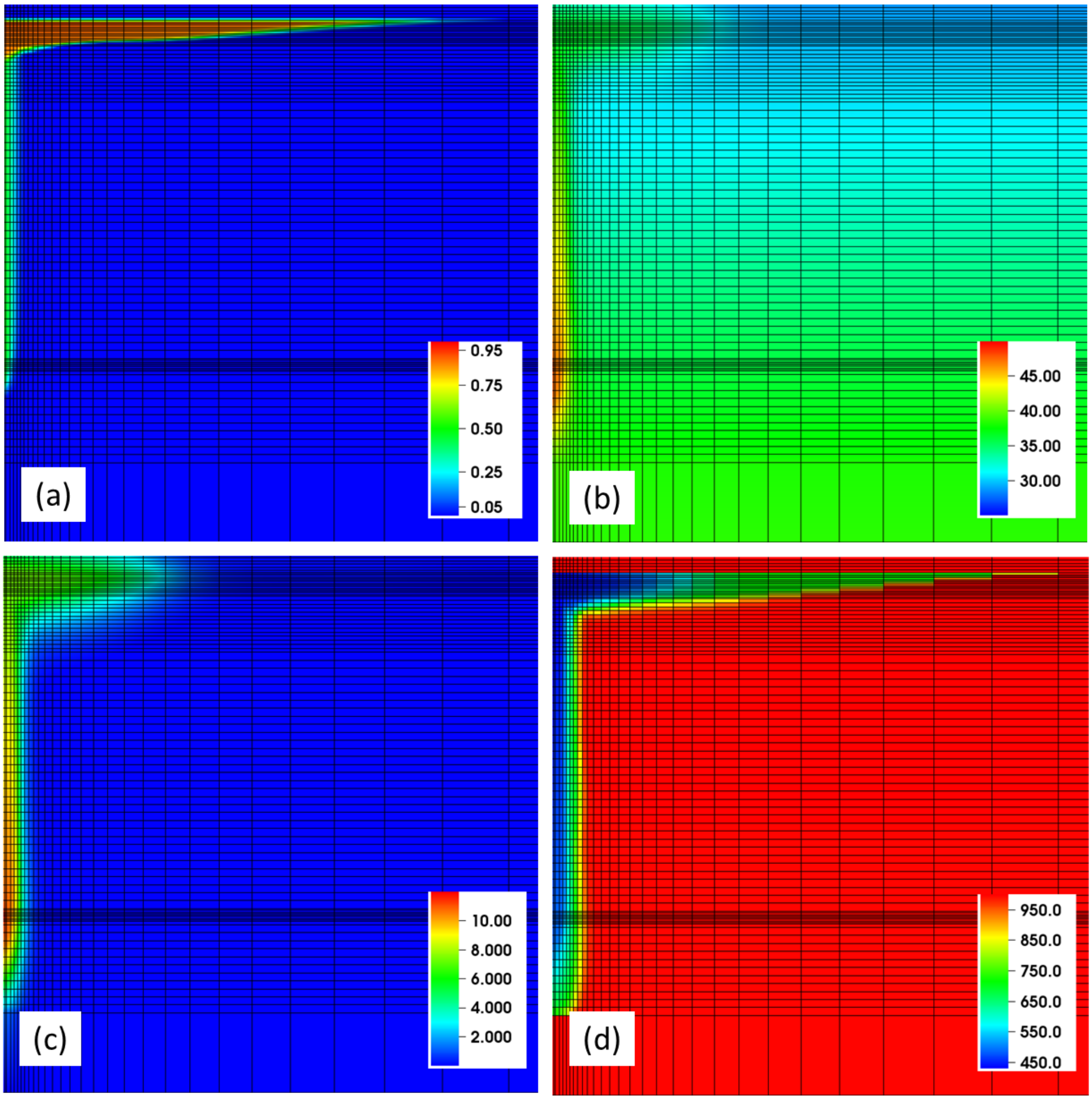

Figure 2. 2D axisymmetric model of CO_2 injected at an initial temperature of 48 C. a) CO_2 saturation b) temperature (C) c) thermal anomaly (C) d) density (kg/m^3) y a

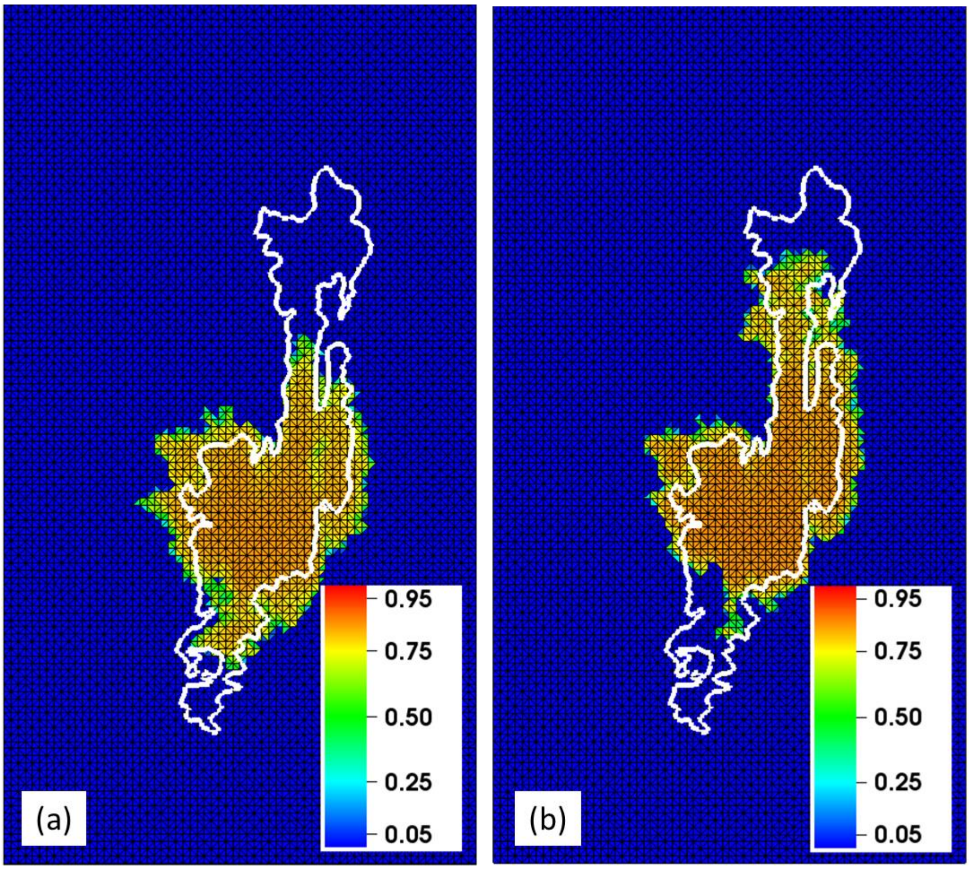

Figure 3. Modelled gas saturation in the top sand in 2010. The CO_2-water contact observed on the seismic data is shown as a white line for comparison. (a) Reservoir model with uniform 3 Darcy permeability and CO_2 at reservoir temperature. (b) Reservoir model with uniform 8 Darcy permeability and CO_2 at 36 C.

Acknowledgements

The work was carried out under the DiSECCS project, funded by the UK Engineering and Physical Sciences Research Council, and is published with permission of the Executive Director, British Geological Survey (NERC). Statoil Petroleum AS, ExxonMobil Exploration & Production Norway AS and Total E&P Norge AS are thanked for provision of the seismic data.

References

Alnes, H., Eiken, O., Nooner, S., Sasagawa, G., Stenvold, T., Zumberge, M., 2011. Results from Sleipner gravity monitoring: Updated density and temperature distribution of the CO_2 plume. Energy Procedia 4, 5504–5511. doi:10.1016/j.egypro.2011.02.536

Cavanagh, A., 2013. Benchmark Calibration and Prediction of the Sleipner CO_2 Plume from 2006 to 2012. Energy Procedia 37, 3529–3545. doi:10.1016/j.egypro.2013.06.246

Chadwick, R. A., Kirby, G. A., Holloway, S., Gregersen, U., Johannessen, P., Zweigel, P. And Arts, R. 2002. Saline Aquifer CO2 Storage (SACS2). Final report: Geological Characterisation of the Utsira Sand reservoir and caprocks (Work Area 1). British Geological Survey Commissioned Report, CR/02/153

Chadwick, R.A., Noy, D., Arts, R., Eiken, O., 2010. Latest time-lapse seismic data from Sleipner yield new insights into CO_2 plume development. Energy Procedia 1, 2103–2110.

doi:10.1016/j.egypro.2009.01.274

Singh, V.P., Cavanagh, A., Hansen, H., Nazarian, B., Iding, M., Ringrose, P.S., 2010. Reservoir Modeling of CO_2 Plume Behavior Calibrated Against Monitoring Data From Sleipner, Norway, in: SPE-134891-MS. Society of Petroleum Engineers, SPE. doi:10.2118/134891-MS

Zhu, C., Zhang, G., Lu, P., Meng, L., Ji, X., 2015. Benchmark modeling of the Sleipner CO_2 plume: Calibration to seismic data for the uppermost layer and model sensitivity analysis. International Journal of Greenhouse Gas Control. doi:10.1016/j.ijggc.2014.12.016