SIGNIFICANCE OF DIPPING ANGLE ON CO_2 PLUME MIGRATION IN DEEP SALINE AQUIFERS

S.E. GASDA[1], J.M. NORDBOTTEN[1,2] AND M.A. CELIA[1]

[1]Dept of Civil and Environmental Engineering, Princeton University, Princeton, NJ, USA
[2]Dept of Mathematics, University of Bergen, Bergen, Norway

Abstract

Recent investigations regarding CO_2 sequestration in deep, saline aquifers have focused on characterization of the injected plume, its migration within the aquifer over time, and possible leakage out of the aquifer. As part of our efforts to understand and quantify leakage potential in CO_2 storage systems, a semi-analytical solution has been developed that describes the plume shape evolution as well the amount of leakage, with a focus on leakage along abandoned wells. The semi-analytical solutions require a number of simplifying assumptions, including a perfectly horizontal aquifer, negligible capillary pressure, and symmetry of the injection plume. Each of these assumptions can be tested systematically through application of more general numerical simulators. In typical sedimentary basins, it is common to have sloping aquifers with a vertical rise of up to 3-4 km over the total horizontal length of the basin (hundreds of kilometers). In this study, we use a general two-phase numerical simulator to assess the limitations of the assumptions required to derive semi-analytical solutions to these systems. In this presentation we will present results from these simulations and discuss their implications regarding the extent to which CO_2 injection systems can be simplified.

1. INTRODUCTION

It is generally accepted in the scientific community that continuing and increasing anthropogenic emissions of carbon dioxide may adversely affect the environment in the centuries to come [*Houghton et al.*(2001)]. For a variety of political, socio-economical and technological reasons, one of the few immediate options available for mitigation of CO_2 emissions is to dispose of gaseous carbon dioxide in deep, geological formations, a strategy that would effectively sequester CO_2 for hundreds to many thousands of years [*Houghton et al.*(2001)].

Geologic sequestration of CO_2 would include pumping large quantities of gaseous carbon dioxide into formations at sufficient depth such that the CO_2 would be in a supercritical state, which would occur at temperatures and pressures found below approximately 800 m in typical sedimentary basins [*Holloway*(2001), *Bachu*(2000)]. In these deep formations, the injected CO_2, although hundreds of times more dense than at atmospheric pressure, would be less dense and significantly less viscous than the resident brine [*Bachu*(2002)]. Thus, gravity override and viscous instability will cause the CO_2 to bypass the brine along

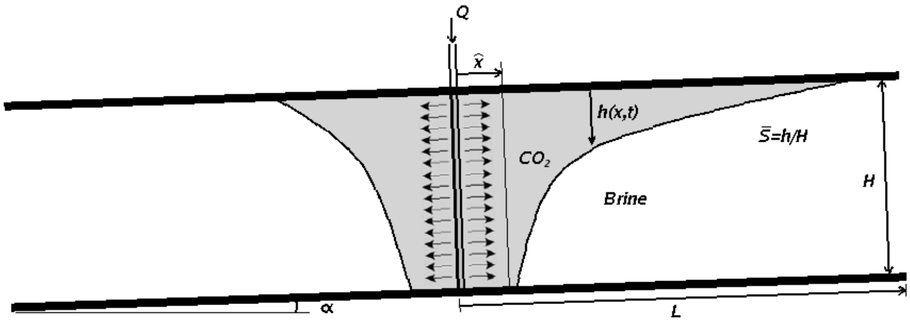


FIGURE 1. Cartoon depicting the CO_2-brine interface, denoted by $h(x,t)$, and the location of the centroid $\hat{x}$ for a typical sloping aquifer.

the bottom of the confining layer and escape vertically if favorable pathways exist such as abandoned wells [*Gasda*(2004), *Gasda et al.*(2004)].

1.1. **The effect of slope on CO_2 injection.** The purpose of this study is to examine the extent to which use the simple analytical models (see for example [*Nordbotten et al.*(2005a), *Nordbotten et al.*(2005b), *Nordbotten et al.*(2006), *Saripalli and McGrail*(2002), *Kavetski et al.(2006)*]) or simplified numerical models [*Pruess and Garcia*(2002), *Pruess et al.*(2003), *Gasda et al.*(2005)] can be used to model injection of CO_2 into sloping aquifers. Typical slopes range from a few tenths of a degree to several degrees in many sedimentary basins. In sloping aquifers, buoyancy will drive the plume upslope. This will decrease the large-scale lateral symmetry of an injected plume of CO_2 and pull the outer edge of the plume further upslope than otherwise would be predicted by a solution that assumes a perfectly horizontal aquifer.

In this study, we will examine the effect of slope on CO_2 migration over a range of reservoir characteristics and fluid properties. The horizontal centroid migration of the plume will be used to determine the significance of slope overall. In order to generalize the results, we look for how the upslope migration changes with a dimensionless grouping that takes into account relevant system parameters.

1.2. **System domain.** The domain of interest on which we test the effect of slope (see Figure 1) is a two-dimensional aquifer of constant thickness $H = 50$ m, bounded above and below by impermeable sediments and hydrostatic pressure conditions at some fixed distance L from the injection well in both directions. The formation consists of an isotropic, homogenous medium with constant porosity ϕ equal to 0.15 and permeability k equal to 5×10^{-14} m^2. The slope of the aquifer is obtained by rotating the coordinate system in the x-z plane by an angle α equal to 0.1° and 1°. These numbers are consistent with observations in the Alberta Basin [*Nordbotten et al.*(2005a)]. Following the method of Nordbotten *et al.* (2005b), we choose different density and viscosity values for water, ρ_w and μ_w, and CO_2, ρ_n and μ_n in order to capture the end members of CO_2 sequestration conditions. We characterize these two regimes as *warm, deep* and *cold, shallow* basins and use the viscosity and density values in Table 1. CO_2 is injected into the formation along the center axis of the domain at a rate Q equal to 0.05 kg/m/s. The domain is viewed as one slice of a 600-m injection interval injecting a million tons CO_2 per year, which is representative of the CO_2 emissions of a medium-size coal-fired power plant [*Holloway*(2001)].

Table 1. Fluid properties for CO_2 and brine at different subsurface temperature and pressure conditions

Subsurface Conditions	**Viscosity** [mPa s] (CO_2, Brine)	**Density** [kg/m^3] (CO_2, Brine)
warm, deep	(0.0395, 0.2535)	(479, 1045)
cold, shallow	(0.0577, 1.1875)	(741, 1121)

In order to examine the effect of changing just viscosity or density, we will use all four different combinations of viscosity-density pairings. We will also investigate the effect of two different degrees of slope, 0.1° and 1°, for each pairing, giving a total of eight cases to be tested.

2. SOLUTION METHODS

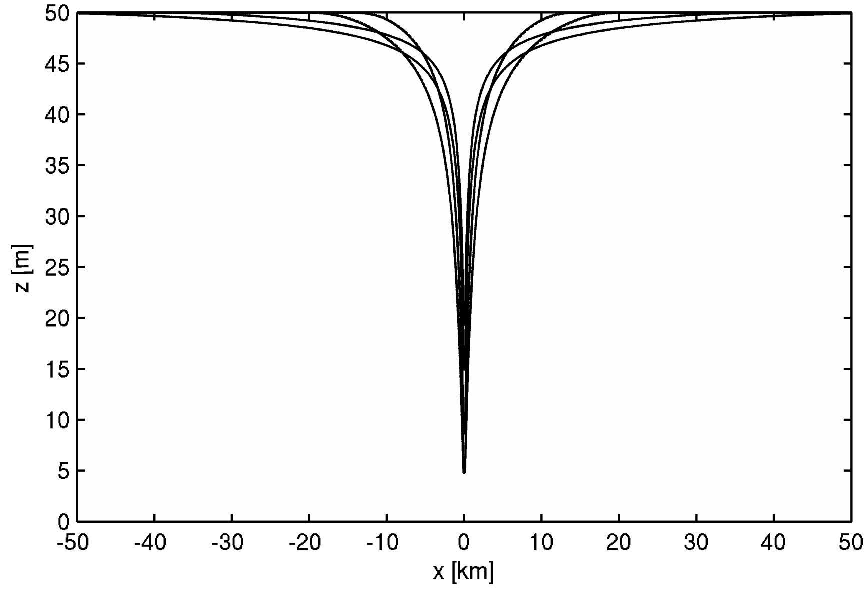
We use two different methods to solve this system, first in one dimension, where the equations are vertically-averaged by assuming flow to be essentially horizontal with respect to the aquifer, and then in two dimensions, where no assumptions are made about direction of flow.

The 1D system is derived following Lake (1989), where the assumption that the two fluids are completely segregated with a sharp interface leads to a solution for location of the interface $h(x,t) = H\bar{S}(x,t)$ for a given time t (Figure 1). We also obtain average relative permeability functions that are linear functions of average saturation. Physical capillary pressure is considered to be negligible, however, the assumption of a sharp interface coupled with vertical averaging leads to a psuedo-capillary pressure. In the 2D model, we assume, for simplicity, zero residual saturations for both phases, with a cubic function to represent the dependence of local relative permeability on phase saturation. As with the vertically-averaged model, capillary pressure is assumed to be neglible.

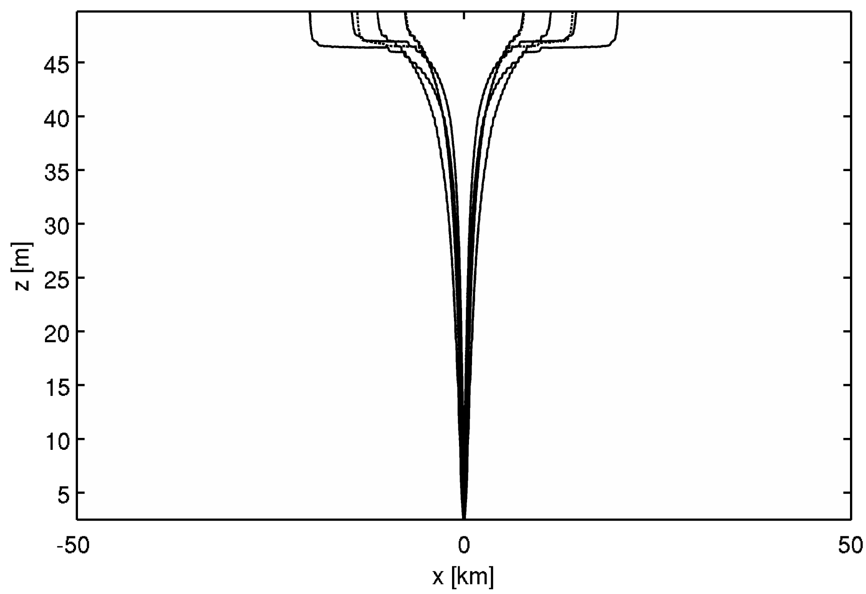
Both the vertically averaged model and the full 2D model are solved using the IMPES method, where the pressure equation is solved implicitly and the transport is solved explicitly. We discretize the space dimension in cartesian coordinates using a finite-difference approximation with a sufficiently refined grid to ensure a converged solution. In regard to stability of the solution in time, the pressure solution is a steady state solution due to the incompressibility of the fluids, whereas the timestep used to compute the saturation in the explicit step is controlled by a CFL condition. We use the upstream value of relative permeability at the cell edges.

3. RESULTS

We analyze the effect of slope by tracking the horizontal migration of the centroid of the plume $\hat{x}$ over time. We present results from simulations performed using both the vertically-averaged model and the full 2D model for the eight different combinations of slope, viscosity and density values described previously.



(a) 1D simulations results



(b) 2D simulations results

FIGURE 2. CO_2-brine interface for 1D and 2D solutions at 4050 days: from inner to outer (i) *warm, deep* for viscosity and density; (ii) *warm, deep* viscosity and *cold, shallow* density; (iii) *cold, shallow* viscosity and *warm, deep* density; (iv) *cold, shallow* viscosity and density. Locations are shown for 0.1° (solid lines) and 1° (dotted lines) sloping aquifers.

3.1. **Location of the CO_2-brine interface.**

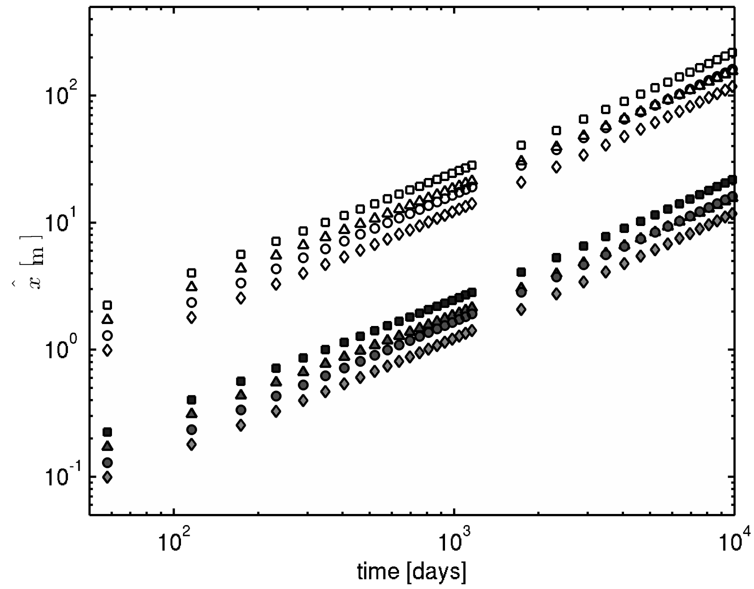
3.1.1. *Vertically-averaged simulations.* We first examine the CO_2-brine interface for all cases at an intermediate time (Figure 2(a)). We see visual evidence of the inherent instability of the interface and gravity override in that the CO_2 overruns the resident brine. For the more unstable viscosity ratios (*cold, shallow* viscosity values), the interface extends 3 times farther and gives a much thinner finger than the more stable cases. We also remark that the difference in density contrast between *warm, deep* and *cold, shallow* cases leads to similar interface shapes but different volumes of CO_2 behind the interface. Because the injection is on a mass basis, the cases with *cold, shallow* values for density are injecting CO_2 with a 1.5 times higher density than for the *warm, deep* cases, which results in a lower injected volume for the same injected mass. The effect of slope is very small, shifting the interface upslope by a fraction of a percent.

3.1.2. *2D simulations.* Next, we examine the saturation profiles from the 2-dimensional simulations using the 50% saturation contour. Because we have neglected capillary pressure, the 50% saturation line is a good proxy for the location of the interface between CO_2 and brine and thus can be compared directly with the vertically-averaged results. The resulting 2D profiles for each of the eight cases (Figure 2(b)) are similar in nature to the vertically-averaged solutions. The 2D results show that increased viscous instability for the cases with *cold, shallow* viscosity values results in interfaces that extend about 1.5 times farther than more stable systems (*warm, deep* viscosity values), compared with a factor of 3 for the vertically-averaged simulations. In regard to the effect of slope and density differences on the CO_2-brine interface, we find that the results from the 2D simulations are consistent with those of the vertically-averaged simulations.

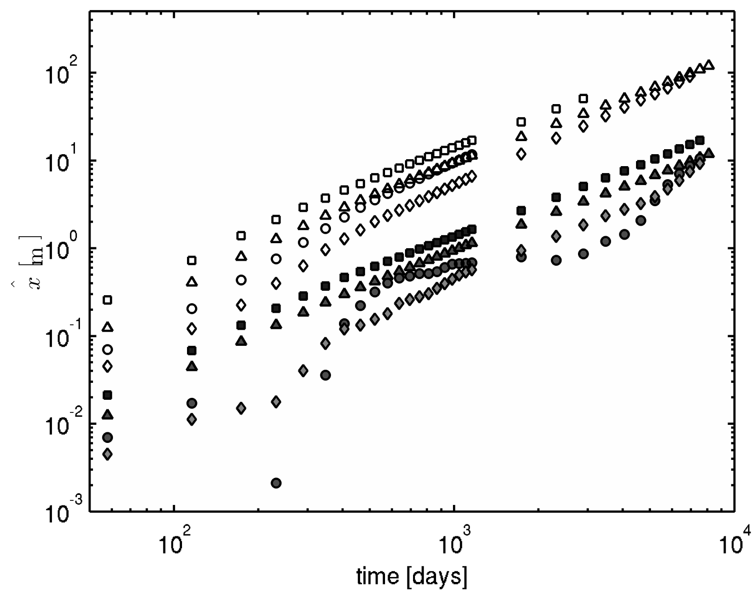
A comparison of the shape of the interfaces from both the vertically-averaged and 2D simulations shows that close to the injection well, the interfaces match up well, but farther from the well, the vertically-averaged solution tapers off more gradually and extends farther (due to mass conservation) than the 2D solution, which forms a thick tongue that ends abruptly. This difference is related to the treatment of relative permeability in the vertically-averaged model, which uses a sharp interface assumption such that the saturations are piecewise constant. Therefore, only end point relative permeabilities are considered. In the full 2D model there is a diffuse edge of the plume, leading to a lower total mobility at the front for concave relative permeability functions. We have observed in related simulations that the curvature of the relative permeability functions is related to the thickness of the CO_2 tongue observed in Figure 2(b).

3.2. **Location of the horizontal centroid.**

3.2.1. *Vertically-averaged simulations.* Given the same set of fluid properties, the nature of the centroid displacement is remarkably similar, regardless of slope (Figure 3(a)). The only difference is that the velocity of migration increases by a factor of 10 for each factor of 10 increase in aquifer slope, which, on a log-log scale, translates to a shift in the y-axis by one log unit. Comparing the effect of different CO_2 viscosity values, we see that the position of the centroid is always farther upslope for lower viscosity systems (*warm, deep* values) than for higher viscosity systems (*cold, shallow* values), which means there is less of an effect of slope on the centroid with less mobile CO_2 being injected into the system.

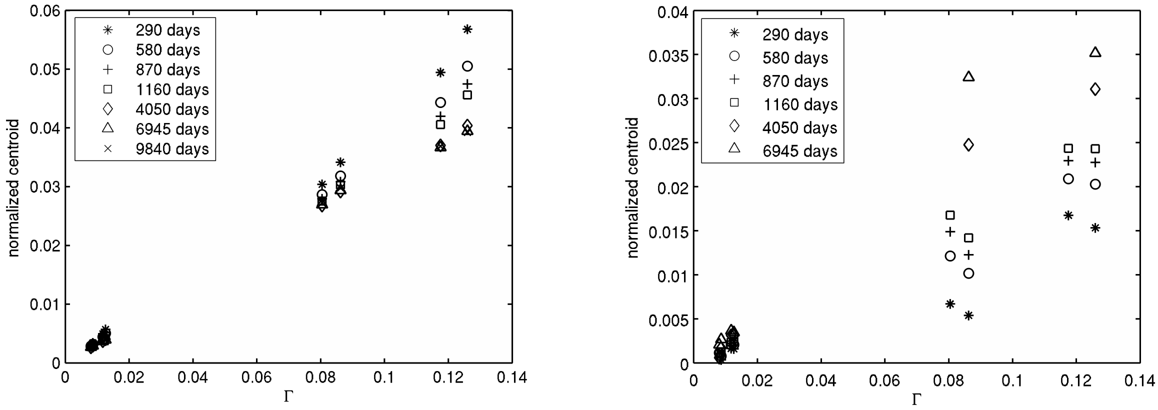


(a) 1D simulation results



(b) 2D simulation results

Figure 3. Horizontal position of centroid for 1D and 2D simulations over time for different combinations of fluid properties: (i) *warm, deep* for viscosity and density (squares); (ii) *warm, deep* viscosity and *cold, shallow* density (triangles); (iii) *cold, shallow* viscosity and *warm, deep* density (circles); (iv) *cold, shallow* viscosity and density (diamonds). Locations are shown for 0.1° (filled) and 1° (open) sloping aquifers.



(a) 1D simulation results

(b) 2D simulation results

FIGURE 4. Dependence of horizontal centroid position on the dimensionless grouping Γ for 1D and 2D simulation results at four different times. Centroid position is normalized by the location of a piston-like CO_2 front at time t.

The effect of changing density values from a lower contrast (*cold, shallow* values) to a higher contrast (*warm, deep* values) decreases the upslope migration of the centroid.

3.2.2. *2D simulations.* We find that the 2D simulations give similar trends to the vertically-averaged simulations in terms of centroid migration for different degrees of slope, and different values for viscosity and density (Figure 3(b)). The 2D data show that the centroid does not move as far at early times (as much as an order of magnitude difference), but, by later time, has reached approximately the same location as in the vertically-averaged simulations. It is likely that the treatment of relative permeability functions in the 1D model that is causing the difference in shape of the plume between the 1D and 2D solutions is also affecting the upslope migration of the centroid.

4. DIMENSIONLESS ANALYSIS

The results for centroid migration for the various cases described above can also be represented by dimensionless characterization. The dimensionless grouping we use to describe the system is a type of gravity number, which we define as $\Gamma = (k \Delta\rho g \sin\alpha) \,/\, (Q \mu_n)$. We also normalize the centroid position by the position of the CO_2-brine interface for a piston-like displacement in a horizontal aquifer, determined from the volume of fluid injected per height of the aquifer and the porosity of the aquifer.

We find there is a strong linear dependence between normalized centroid position and the dimensionless grouping for the results from 1D simulations (Figure 4(a)). The slope of the linear trend is 0.32 for the vertically-averaged simulations. In comparison, the data from 2D simulations shown in Figure 4(b) show a trend towards a linear dependence with Γ, but the slope of the linear trend is smaller than that of the vertically-averaged results.

Again, we believe that the overall difference in these results is caused by the relative permeability effect discussed previously.

5. CONCLUSIONS

We find that the upslope migration of the plume centroid is directly proportional to the buoyancy drive for the system, which means an increase in permeability, density contrast and slope or a decrease in injection rate or CO_2 viscosity will enhance upslope migration. In this study, we conclude that the effect of slope is insignificant for typical conditions in sedimentary basins in North America because the centroid moves only a small fraction of the total extent of the plume over a 30-year injection period. But, the implications of this study are that a significant increase in buoyancy drive, for example a high permeability aquifer as in the Utsira formation or a high slope as in the Frio Formation, will lead to a more pronounced upslope migration which may need to be taken into account in a simplified semi-analytical model.

Comparing results for the vertically-averaged and 2D simulations, we conclude that the different methods give similar trends in the data qualitatively speaking, but the difference in solution shape has a significant effect when comparing the speed of centroid migration and the relationship to the dimensionless grouping. This discrepancy requires further analysis to explain the differences between the results of the 1D and 2D models.

Acknowledgement

This work was sponsored in party by a grant from BP and Ford Motor Company through funding of the Carbon Mitigation Initiative at Princeton, and by the National Science Foundation through a graduate fellowship to S. Gasda. We also thank Stefan Bachu of the Alberta Geological Survey for his important contributions to this work.

References

[*Bachu*(2000)] Bachu, S. (2000), Sequestration of CO_2 in geological media: criteria and approach for site selection in response to climate change, *Energy Conv. Manag.*, *41*, 953–970.

[*Bachu*(2002)] Bachu, S. (2002), Sequestration of CO_2 in geological media in response to climate change: road map for site selection using the transform of the geological space into the CO_2 phase space, *Energy Conv. Manag.*, *43*, 87–102.

[*Gasda*(2004)] Gasda, S. E. (2004), CO_2 sequestration into a mature sedimentary basin: determining the capacity and leakage potential of a saline aquifer formation, *Master's Thesis*, Dept. of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey.

[*Gasda et al.*(2004)] Gasda, S. E., S. Bachu and M. A. Celia (2004), Spatial characterization of the location of potentially leaky wells penetrating a deep saline aquifer in a mature sedimentary basin, Env. Geology, 46(6-7), 707–720.

[*Gasda et al.*(2005)] Gasda, S. E. and M. A. Celia (2005), Upscaling relative permeabilities in a structured porous medium, Adv. Water Res., 28(5), 493–506.

[*Holloway*(2001)] Holloway, S. (2001), Storage of fossil fuels-derived carbon dioxide beneath the surface of the earth, *Ann. Review Energy Env.*, *26*, 145–166.

[*Houghton et al.*(2001)] Houghton, J. T., Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, and D. Xiaosu (eds.) (2001), *Climate Change 2001: The Scientific Basis*, Third Assessment Report of the IPCC, Cambridge University Press, New York.

[*Kavetski et al.(2006)*] Kavetski, D., J. M. Nordbotten, M. A. Celia, and S. Bachu (2006), Analysis of potential CO_2 leakage through abandoned wells using a semi-analytical model, to appear in *Proceedings of the 16th Conference on Computational Methods in Water Resources, Copenhagen, Denmark, 2006.*

[*Lake*(1989)] Lake L., *Enhanced Oil Recovery* (1989), Upper Saddle River, New Jersey, Prentice Hall.

[*Nordbotten et al.*(2005a)] Nordbotten, J. M., M. A. Celia, S. Bachu, and H. K. Dahle (2005), Semianalytical solution for CO_2 leakage through an abandoned well, *Env. Sci. Tech.*, *39*(2), 602–611.

[*Nordbotten et al.*(2005b)] Nordbotten, J. M., M. A. Celia, and S. Bachu (2005), Injection and storage of CO_2 in deep saline aquifers: analytical solution for CO_2 plume evolution during injection, *Trans. Por. Med.*, *58*(3), 339–360.

[*Nordbotten et al.*(2006)] Nordbotten, J. M., and M. A. Celia (2006), Similarity solutions for fluid injection into confined aquifers, to appear in *J. Fluid Mech.*.

[*Pruess and Garcia*(2002)] Pruess, K., and J. Garcia (2002), Solutions of test problems for disposal of CO_2 in saline aquifers, *Tech. Rep. LBNL-51812*, Lawrence Berkeley Natl. Lab., Berkeley, CA.

[*Pruess et al.*(2003)] Pruess, K., T. F. Xu, J. Apps, and J. Garcia (2003), Numerical modeling of aquifer disposal of CO_2, *Soc. Pet. Eng. J.*, *8*(1), 49–60.

[*Saripalli and McGrail*(2002)] Saripalli, P. and P. McGrail (2002), Semi-analytical approaches to modeling deep well injection of CO_2 for geological sequestration, *Energy Conv. Manag.*, *43*(2), 185–198