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High Resolution Modelling And Steady-State Upscaling Of Large Scale Gravity Currents In Heterogeneous Sandstone Reservoirs

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Summary

We investigate the impact of small-scale heterogeneities (<10m) and gravity on large scale O(100m) lateral CO2 plume migration at varying capillary number, Nc and gravity number, Ngv. For isotopically correlated heterogeneities, plume migration was slowed signicantly at low Nc and high Ngv. For anisotropic cases akin to sedimentary geological structures, the plume speed was correspondingly enhanced, with breakthrough times reduced by up to 20% at large correlation lengths. Using relative measures, the capillary pressure was found to be the major control on plume migration as opposed to permeability, at low Nc. Using single, homogenized upscaled functions, we were able to capture the effects of small scale heterogeneities at low or high Nc and moderate Ngv. However, the relative enhancement of the impact of heterogeneities at high Ngv (and low Nc) could not be captured using single homogeneous functions for the entire domain. Without including enhanced gravity effects in the upscaling procedure, which generate anisotropic upscaled functions, the full effects of small-scale heterogeneities in gravity segregated flow could be signicantly underestimated in large scale models, leading to inaccurate plume migration estimates.

Introduction

In order to quantify the risk associated with the long-term injection and storage of CO_2 in deep subsurface aquifers, robust and efficient models are required that can evaluate CO_2 plume migration, pressure build-up and trapping mechanisms. Conventionally, subsurface flow models at the aquifer scale employ a continuum approach based on extended Darcy's law, resolving subsurface features at scales of 10s to 100s of meters to tractably simulate plume migration. These models are generally populated with multiphase flow parameters (relative permeability, capillary pressure and trapping) which are derived from viscous limit core flood experiments, measured at high flow rates on subsurface rock cores preferentially selected for homogeneity (McPhee et al. 2015)

While this approach is effective for high capillary number flows occurring in homogeneous media, it breaks down when the capillary number is low and small-scale capillary heterogeneities (i.e. laminae and bedding features below seismic resolution of ~10m) start to impact the flow regime. Recent studies have shown that these heterogeneities can have significant, emergent impacts on buoyant CO_2 plume migration and trapping at the aquifer scale (Li and Benson 2015, Trevisan *et al.* 2017). During the lateral movement of a CO_2 plume underneath a cap rock, in the form of a gravity current, the combined effects of gravity, aquifer topology and small-scale heterogeneities can also cause significant preferential movement of the CO_2 plume (Cowton *et al.* 2018). While it is still unclear as to the full impact of these effects, there are increasing field observations of unexpected plume migration and early CO_2 breakthrough, which are poorly predicted by conventional modelling approaches (see for example the In Salah site, Ringrose *et al*. 2009 and the Sleipner site, Williams & Chadwick 2017). This suggests that capturing the emergent impacts of small-scale heterogeneities and gravity could be key in predicting these phenomena.

A rigorous approach to tractably simulate large scale plume migration incorporating small-scale features is to use equivalent, upscaled multiphase flow parameters. Upscaled functions derived at appropriate flow conditions can capture the underlying small-scale effects whilst allowing grid sizes of 10s-100s of meters, permitting tractable simulation of aquifer scale plume migration. Under this paradigm, the sensitivity to small-scale features and topological variations can be assessed and built into large scale models, allowing more accurate bounds on plume migration uncertainty.

In this work, we use large scale, high resolution numerical simulations of lateral CO_2 plume migration to highlight the emergent impacts of gravity and small-scale heterogeneities. Heterogeneities are generated geostatistically with different isotropic and anisotropic correlation lengths and analysed at varying Capillary and Gravity number. Steady-state upscaling is then used to model the entire domain as one homogeneous unit with equivalent multiphase flow parameters, highlighting the applicability of steady-state upscaling approaches with varying Capillary and Gravity number.

Methodology

2D geostatistical models of permeability K, porosity φ, and entry pressure P_e, are generated in a domain size L_x = 66m, L_y = 5m, shown in Figure 1. The fields have a grid resolution of 0.1m, with correlation lengths r_x and r_y generated using elliptical averaging and scaled to have fixed mean μ, and standard deviation σ, for each realization. The geostatistical fields have typical aquifer properties, with log normal permeability $\mu(K)$ = 7.29 ln(mD), σ(K) = 0.38 ln(mD), normal porosity $\mu(\varphi)$ = 0.29, $\sigma(\varphi)$ = 0.02, and capillary pressure which follows a Leverett - J scaling with permeability, i.e. $J(S_w) = \frac{P_c(S_w)}{\gamma\cos(\theta)}\sqrt{\frac{K}{\varphi}}$, where γ = 40 N.m and $\theta = 50°$. The characteristic $P_c(S_w)$ follows a Brooks-Corey function with λ = 0.75, P_e = 7 kPa and $S_{w,irr}$ = 0.12, typical of sandstone rock. Single Chierici relative permeability functions are used throughout the domain, with parameters A = *11*, L = *1.22*, B = *2.3*, M = 0.6 and $k_{rg}(S_{w,irr}) = k_{rw}(S_{gr}) = 1$.

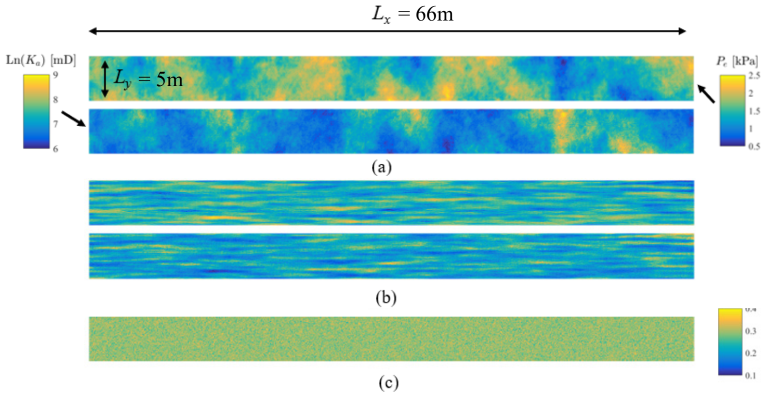


Figure 1 *(a-b) Geostatistical entry pressure fields (top) and permeability fields (bottom). (a) – Isotropic, $r_x = r_y$ = 5m. (b) – Anisotropic, r_x = 0.4m, r_y = 5m. (c) Porosity field.*

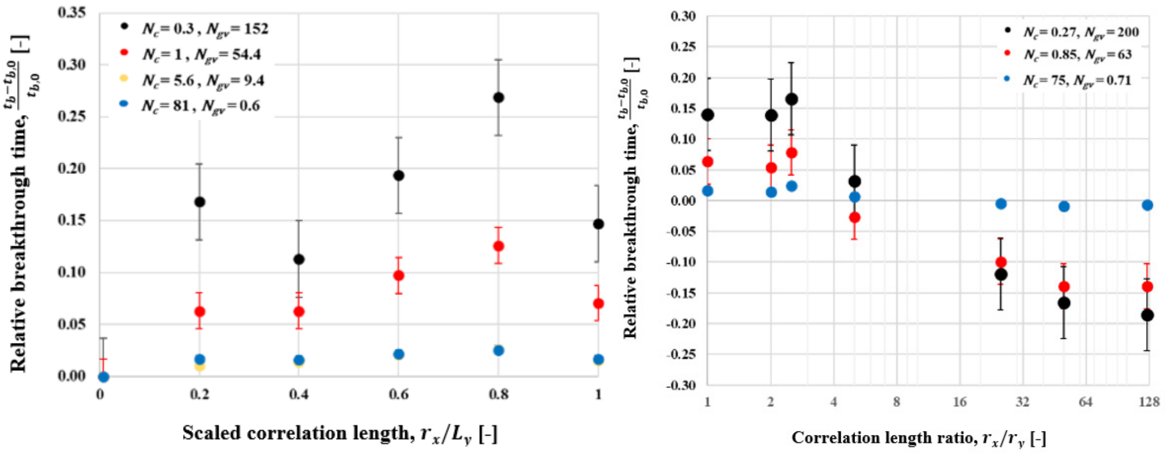
CO_2 is injected along the left domain boundary at a constant rate and hydrostatic pressure is maintained at the right boundary. Zero normal flux is enforced at the top and bottom boundaries. We measure the breakthrough time t_d, of the CO_2 plume through the right boundary as a non-dimensional function of pore-volumes injected. Numerical simulations are performed in CMG IMEX assuming isothermal, immiscible fluids with T = 80 °C, μ_{CO2} = 0.064 mPa.s, μ_{brine} = 0.41 mPa.s, ρ_{CO2} = 746 kg/m^3, ρ_{brine} = 1025 kg/m^3.

We use the Capillary number, $N_c = \frac{r_c \Delta P}{L_x \sigma(P_e)}$ and equivalent Gravity number, $N_{gv} = \frac{\Delta\rho g L_x}{\Delta P}$ to describe the multiphase flow regime in the presence of capillary heterogeneities. ΔP is the pressure drop over the domain length L_x, r_c is the correlation length, $\sigma(P_e)$ is the standard deviation of entry pressure, $\Delta\rho$ is the fluids' density difference and g is gravitational acceleration. Quoted N_c and N_{gv} represent upper bounds for the different realizations and correlation lengths at a given flow rate at CO_2 breakthrough. We compute upscaled properties by homogenizing the 2D domain using capillary limit upscaling (Braun et al. 2005). Macroscopic percolation concepts are used to calculate the equivalent capillary pressure and single-phase flow simulations are used on the associated phase permeability fields to calculate equivalent, horizontal relative permeabilities assuming capillary equilibrium (or viscous dominated flow). We use the same grid size in the upscaled cases as in the fine scale cases to eliminate numerical dispersion effects, however all grid cells use the same equivalent functions representing a homogenized unit.

Results

The breakthrough times of the CO_2 plume for different permeability and entry pressure fields at varying N_c and N_{gv} are shown in Figure 2. Reported times are relative to the corresponding case with homogeneous entry pressure field (it still has variations in permeability).

The presence of small-scale capillary pressure heterogeneities has slowed the CO_2 plume and increased the breakthrough time for isotropic correlated fields at small N_c and high N_{gv}, with the reverse true for anisotropic fields with large horizontal correlation lengths. The major control on the plume migration and associated breakthrough time at low N_c is the capillary pressure heterogeneity, since the results are relative to corresponding cases that still contain permeability heterogeneity. As N_c is increased and N_{gv} decreased, the relative breakthrough time drops to zero, indicating that each realization behaves as the homogenous case without capillary pressure heterogeneity. The variation between each realization also decreases with increasing N_c since the flow is less impacted by the specific heterogeneity structure when viscous forces start to dominate. The reduced breakthrough time in anisotropic domains suggests that sedimentary structures such as cross bedding and laminae can cause preferential flow solely due to capillary pressure heterogeneities under strong gravity forces. This could explain field cases in sedimentary sandstones (Sleipner, Frio, In Salah), where preferential flow has been observed.



(a) (b)

Figure 2 *CO_2 plume breakthrough time as a function of correlation length, N_c and N_{gv}. (a) Isotropic correlation lengths (b) Anisotropic correlation lengths. Breakthrough times are relative to the corresponding case with homogeneous P_e field. Error bars refer to the range of breakthrough times found from 5 different geostatistical realizations (at high N_c these are within the symbols).*

Results of the steady-state upscaling methods are shown in Figure 3. The average transverse CO_2 saturation in the domain highlights that capillary limit upscaling can capture the global saturation and plume migration for cases where N_c and N_{gv} are low (Figure 3b and c). In figure 3a when N_{gv} is high and the plume segregates almost immediately upon entering the domain, the upscaling methods fail to capture the plume migration. Gravity acts to enhance the impacts of capillary heterogeneity, which are not captured by upscaling using single homogenized functions (i.e. not tensors). In the heavily segregated case, the tip thickness of the gravity current is of the order of the size of the heterogeneity. This means the heterogeneities have a much larger relative impact on the plume migration than if the plume were allowed to travel in 2D through the domain, as in Figure 3b. When gravity segregation and capillary heterogeneities are coupled, the impact on plume migration (whether it is speed reduction or enhancement in anisotropic cases) are magnified far beyond cases without segregation. At the limit of very high flow rate in figure 3d, high N_c and low N_{gv}, which typically occurs near the well-bore, the plume migration is well described by viscous limit upscaling.

Conclusions

In this work, we have investigated the impact of small-scale heterogeneities and gravity on lateral CO_2 plume migration. For isotopically correlated heterogeneities, plume migration was slowed signicantly at low N_c and high N_{gv}. For anisotropic cases akin to sedimentary geological structures, the plume speed was correspondingly enhanced, with breakthrough times reduced by up to 20% at large correlation lengths. Using relative measures, the capillary pressure was found to be the major control on plume migration as opposed to permeability, at low N_c. Using single, homogenized upscaled functions, we were able to capture the effects of small scale heterogeneities at low or high N_c and moderate N_{gv}. However, the relative enhancement of the impact of heterogeneities at high N_{gv} (and low N_c) could not be captured using single homogeneous functions for the entire domain. Without including enhanced gravity effects in the upscaling procedure, which generate anisotropic upscaled functions, the full effects of small-scale heterogeneities in gravity segregated flow could be signicantly underestimated in large scale models, leading to inaccurate plume migration estimates.

Acknowledgements

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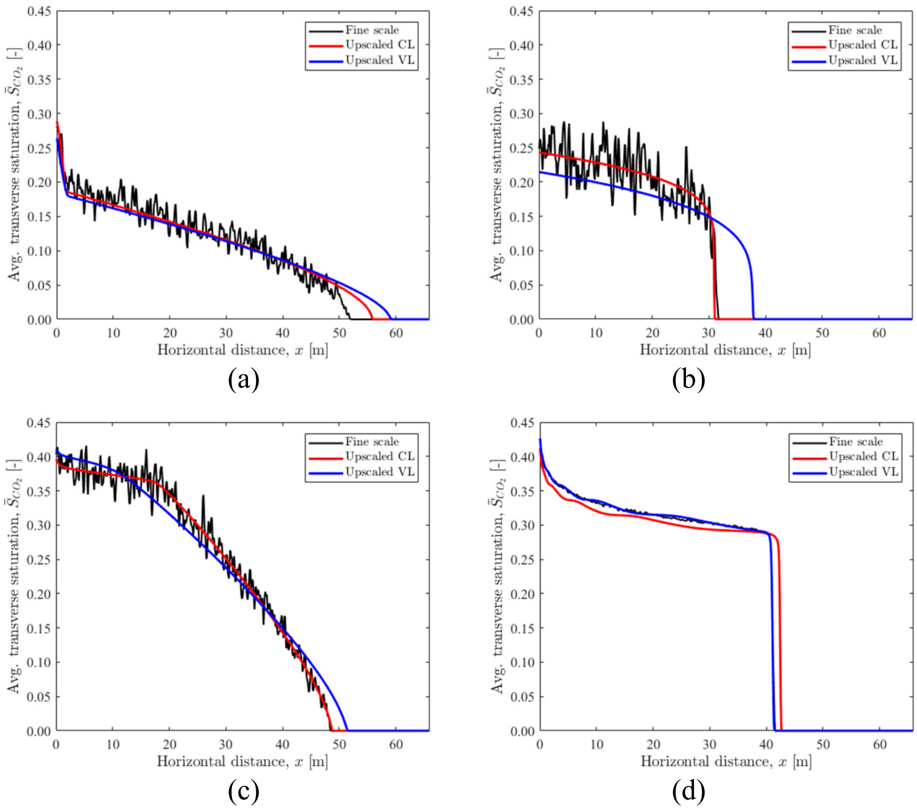

Figure 3 *Average transverse CO_2 plume saturation through the domain for isotropic permeability and entry pressure fields $r_x = r_y = 0.4m$. (a) $t_d = 0.1$, $N_c = 0.08$, $N_{gv} = 80$. (b) $t_d = 0.1$, $N_c = 0.08$, $N_{gv} = 0$. (c) $t_d = 0.2$, $N_c = 0.2$, $N_{gv} = 8$. (d) $t_d = 0.2$, $N_c = 35$, $N_{gv} = 0.05$.*

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