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IMPACT OF GEOLOGICAL HETEROGENEITY ON EARLY-STAGE CO_2 PLUME MIGRATION

Meisam Ashraf[*,§,1], **Knut-Andreas Lie**[*,§,2], **Halvor M. Nilsen**[§,3], **Jan M. Nordbotten**[*,4], **Arne Skorstad**[†,5]

[*]Department of Mathematics, University of Bergen, NO-5008 Bergen, Norway

[§]SINTEF ICT, Department of Applied Mathematics, NO-0314 Oslo, Norway

[†]Norwegian Computing Center, NO-0314 Oslo, Norway

[1]Meisam.Ashraf@uni.no, [2]Knut-Andreas.Lie@sintef.no, [3]HalvorMoll.Nilsen@sintef.no
[4]Jan.Nordbotten@math.uib.no, [5]Arne.Skorstad@nr.no

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Summary. In an effort to determine the influence of geological heterogeneity on CO_2 storage efficiency, we study injection and early-stage migration of CO_2 in 54 different realizations of a shallow-marine reservoir.

1 INTRODUCTION

Academic studies of CO2 injection frequently employ simplified or conceptualized reservoir descriptions in which the medium is considered nearly homogeneous. However, geological knowledge and experience from petroleum production show that the petrophysical characteristics of potential CO2 sequestration sites can be expected to be heterogeneous on the relevant physical scales, regardless of whether the target formation is an abandoned petroleum reservoir or a pristine aquifer. Geological uncertainty introduces tortuous subsurface flow paths, which in turn influence reservoir behavior during injection. It is paramount that the effect of the geological heterogeneity is quantified by the research community. This will facilitate both improved understanding of subsurface flow at operational CO2 injection sites, and allow comparison with simulated flow in ideal homogeneous models and upscaled versions of these.

Within oil recovery, the impact of geological uncertainty on production forecast has been thoroughly investigated in the SAIGUP project [2, 3, 4] focusing on shallow-marine reservoirs. To study different factors, synthetic realistic models were made and several thousand cases were run for different production scenarios. The results showed that realistic heterogeneity in the structural and sedimentological description had a strong influence on the production responses.

The main objectives of CO_2 storage studies are to maximize the injection volume/rate and to minimize the risk of leakage [1]. The problem of CO_2 storage differs from oil recovery prediction not only in the objectives of study, but also in the time scales considered for the process (thousands of years compared to tens of years for CO_2 migration). In addition, the characteristic length scale of the flow is much larger. Working with long temporal and spatial scales and huge amounts of uncertainties poses the question of how detailed the geological description should be. The motivation of this work is mainly to answer two questions related to CO_2 storage:

- How sensitive is the injection and early-stage migration to uncertainty and variability in the geological description?
- What simplifying assumptions are allowed in averaging the geological attributes over scales?

To this end, we use a subset of the synthetic models from the SAIGUP study to perform a preliminary sensitivity analysis for CO_2 sequestration in aquifers. Heterogeneity classes are defined based on different sequence-stratigraphy parameters and levels of shale barriers. We assume two-phase flow with slight compressibility for supercritical CO_2. The injection scenarios are defined based on the objectives outlined above, and important responses are discussed to evaluate the efficiency and risk of the process.

2 Geological descriptions

In this work we question the widespread use of simplified geological descriptions that ignore the detailed heterogeneity in modeling. Our hypothesis is that heterogeneity features like channels, barriers, sequence stratigraphy of facies, and fault intensity/geometry all have a particular effect on flow behavior, both locally and globally, and may significantly alter the injection and migration of CO_2 plumes.

Sound geological classifications and descriptions of key geological features are important to give a realistic description of the sensitivity of CO_2 storage performance. To this end, we have selected four parameter spaces of geological variations from the SAIGUP study [2, 3, 4]. The parameters span realistic intervals for progradational shallow-marine depositional systems with limited tidal influence. In the following, we give a brief description of each.

Lobosity: Lobosity is defined by the plan-view shape of the shore-line. As a varying parameter, lobosity indicates the level at which the shallow-marine system is dominated by each of the main depositional processes. Two depositional processes are considered in the SAIGUP study: fluvial and wave processes. The higher amount of sediment supply from rivers relative to the available accommodation space in the shallow sea, the more fluvial dominant the process will be. As the river enters the mouth of the sea, it can divide into different lobes and branches. Wave processes from the sea-side smear this effect and flatten the shoreline shape. Less wave effect produces more pronounced lobe shapes around the river mouths. Very high permeability and porosity can be found in

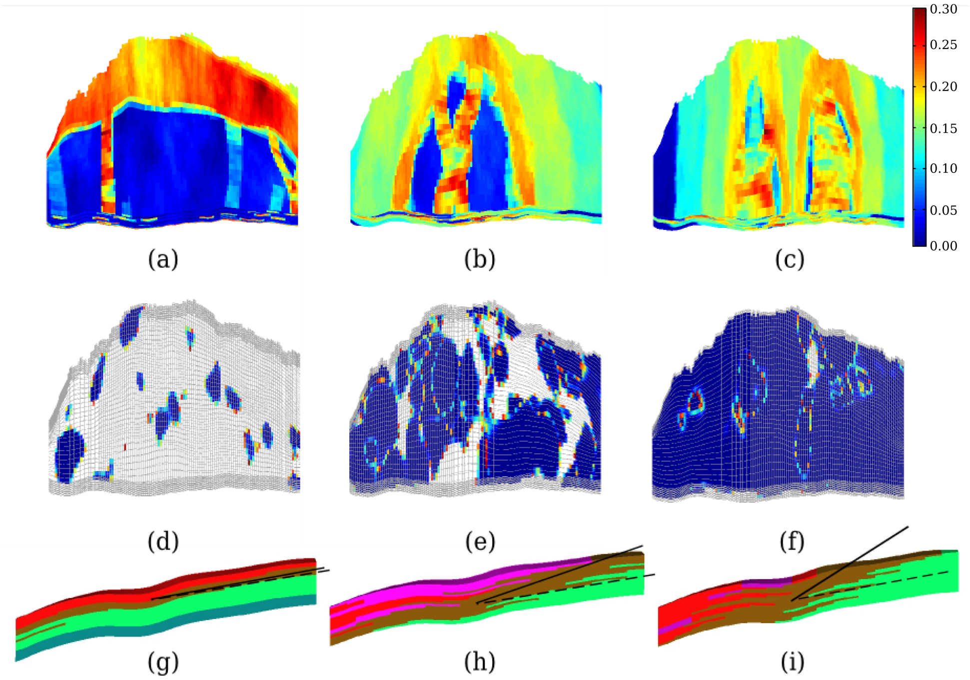

Figure 1: Different geological features considered in this study. Top row shows 'lobosity' in porosity distribution: (a) flat shore-line, (b) one lobe, (c) two lobes. The middle row shows 'barrier' by the distribution of zero transmissibility multipliers: (d) low, (e) medium, (f) high. The lower row shows 'aggradation' in rock-type distribution: (g) low angle of interface between the transitional rock-types leads to parallel layers; this angle is increasing in cases (h) and (i), which correspond to higher levels of aggradation. An up-dip progradation direction is shown in (b), and if the lobe flips over the long axis, we will have down-dip progradation.

the channeling branches, while dense rock with low permeability fills the space between them. Reservoir quality decreases with distance from the shoreface. We expect that the level of lobosity can have a considerable effect on the CO_2 injection and plume size in the aquifer. In this study, models of three levels of lobosity are used: flat shoreline, one lobe and two lobes, see Fig. 1.

Barriers: Periodic floods result in a sheet of sandstone that dips, thins, and fines in a seaward direction. In the lower front, thin sheets of sandstone are interbedded with the mudstones deposited from suspension. These mud-draped surfaces are potential significant barriers to both horizontal and vertical flow. In the SAIGUP domain used here, these barriers were modeled by transmissibility multipliers in three levels of zero value percentage: low (10%), medium (50%), and high (90%). We use the same variations in this study, see Fig. 1.

Aggradation: In shallow-marine systems, two main factors control the shape of the transition zone between the river and the basin: amount of deposition supplied by the river and the accommodation space that the sea provides for these depositional masses. One can imagine a constant situation in which the river is entering the sea and the flow slows down until stagnation. The deposition happens in a spectrum from larger grains depositing earlier in the land side to fine deposits in the deep basin. If the river flux or sea level fluctuates, the equilibrium changes into a new bedding shape based on the balance of these factors.

In the SAIGUP study, the progradational cases are considered in which, for example, the river flux increases and shifts the whole depositional system into the sea. The angle at which the transitional deposits are stacked on each-other because of this shifting, is called aggradation angle. Three levels of aggradation are modeled here: low, medium and high (Fig. 1). As we will observe later, aggradation can have a dramatic influence on the injection and migration process.

Progradation: The final factor varied is the progradation or the depositional-dip direction. Two types are considered here: up and down the dominant structural dip. Since the model is tilted a little, this corresponds to the lobe direction from flank to the crest or vice-versa (Fig. 1). This has a potential influence on the CO_2 flow from the injection point up to the crest.

3 Simulation workflow

A fully automated workflow was designed for this study, starting from variational parameters in the SAIGUP models and ending into comprehensive result outputs based on the objective of the work. As a first step, 54 representative cases are studied using a commercial simulator (Eclipse). However, the parallel aim of future work is to develop fast simulation methods that are suitable for performing thousands of runs, using e.g., a vertically-averaged formulation [5].

4 Scenario design

After studying several scenarios for a typical CO_2 injection, we ended up using an injector down in the flank and hydrostatic boundary conditions on the sides, except the faulted side on the crest (Fig. 2). No-flow boundary conditions are imposed on the top and bottom surfaces of the model. The well is completed only in the last three layers.

Simple linear saturation functions with zero capillarity are used. This can be justified because the permeability contrast in channels has the dominating effect on the flow. Also, simple PVT data for a slightly compressible supercritical CO_2 is used. To model the hydrostatic boundaries in Eclipse, high multipliers are used to magnify the pore volume of the outer cells in the model. About 40MM m^3 of supercritical CO_2 is injected for thirty years, which amounts to 20% of the models' pore volumes. After the injection period, seventy years of early plume migration is simulated.

5 Results

As our objective function, we seek to maximize the CO_2 storage volume and minimize the risk of leakage. These quantities are measured indirectly by various simulation outputs

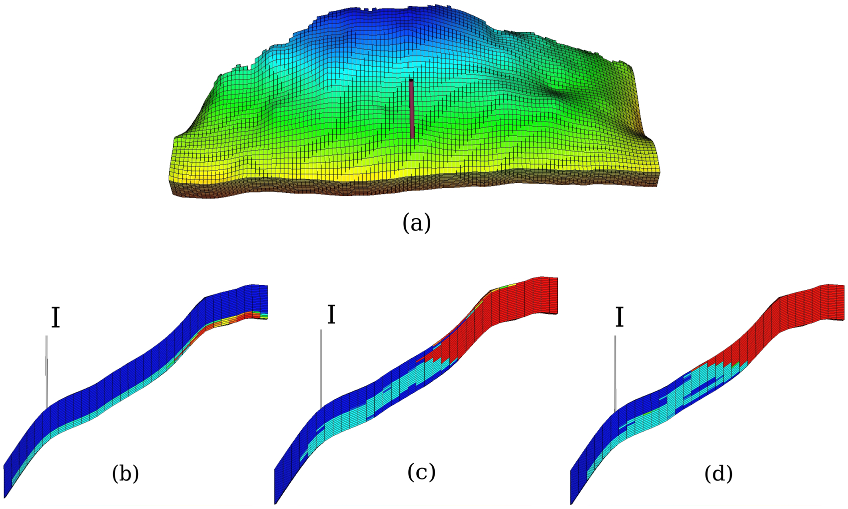

Figure 2: (a) Model geometry and well position. Model dimensions are 3km×9km×80m with 20 layers. The bottom row shows the side view of CO_2 distribution (in red) at the end of simulation in different aggradation cases, from low (b) to high (d). The vertical direction is exaggerated.

that are discussed below.

In all outputs, we recognize the effect of aggradation. Cases with low aggradation have continuous facies layering parallel to the horizontal direction of the grid. Because the three lowest layers, in which the well is completed, are sealing in the cross-layering direction, the flow is forced to stay in the same layers rather than accumulating in the crest (Fig. 2).

Reservoir pressure: The pressure response in general shows a sharp jump at the start of injection and a declining trend during the injection and plume migration. Pressure behavior of different cases at the end of the injection period is shown in Fig. 3. Low aggradation cases show higher pressure.

Boundary fluxes: The flux out of the open boundaries is a measure of the sweep efficiency of the CO_2 plume. As channeling can lead to early CO_2 breakthrough at boundaries, we prefer cases with less fluxes out of the boundaries. The down boundary that is closer to the injector is a potential loss for the injected volume (Fig. 4). Again, the flow is led readily to the boundaries in cases with low aggradations .

Total mobile/residual CO_2: If the CO_2 saturation is below the critical value, it will be immobile in the bulk flow, although not in the molecular sense. Less mobile CO_2 means less risk of leakage and more residual volumes (with saturations less than the critical) resulting from a more efficient volume sweep as preferable (Fig. 4). We use critical saturation of 0.2 for both water and CO_2.

Connected CO_2 volumes: To estimate the risk of leakage from the caprock, we

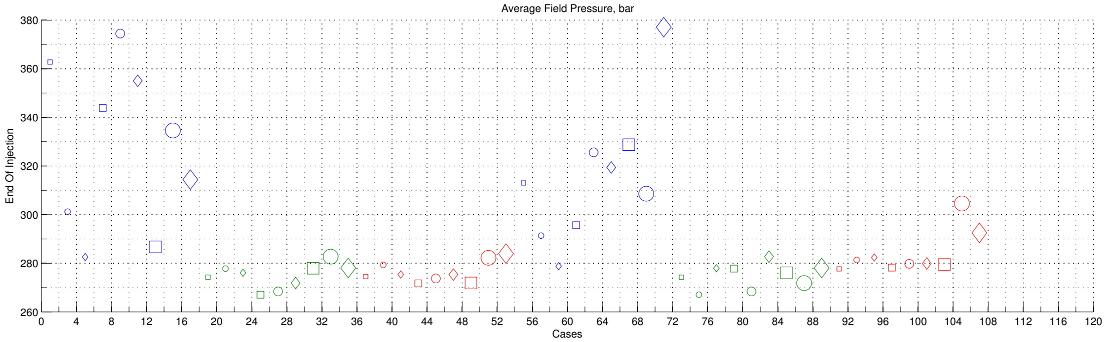

Figure 3: Average reservoir pressure plot for all cases. Colors represent 'aggradation' level: blue for low, green for medium, and red for high levels. Size represents 'barrier': small for low, medium for medium, and large for high level of barrier. Marker shape represents 'lobosity': square for flat shore-line, circle for one lobe, and diamond for two lobes. The first half of the case numbers refer to 'progradation' up-dip towards the crest, and the second half represent 'progradation' down-dip.

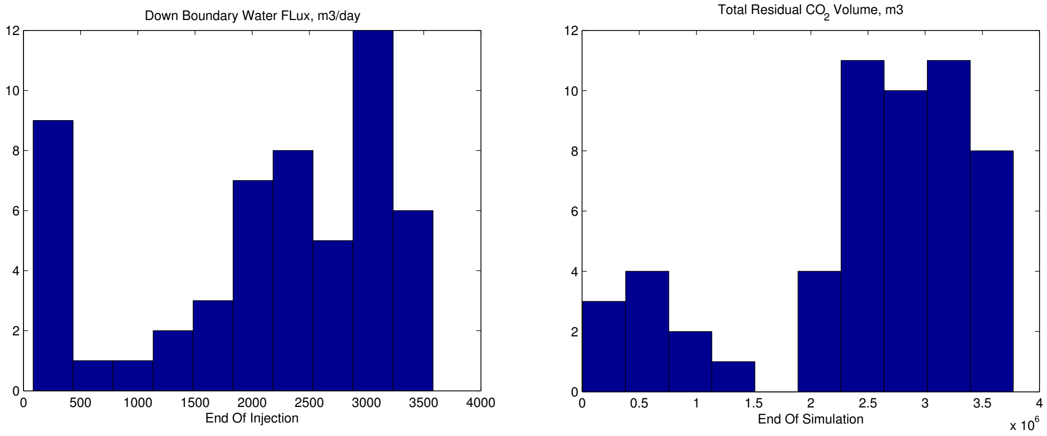

Figure 4: (a) Flux histogram for down boundary: cases with low aggradation show high values. (b) Total residual CO$_2$ volume; cases with low aggradation show less values in a separate family.

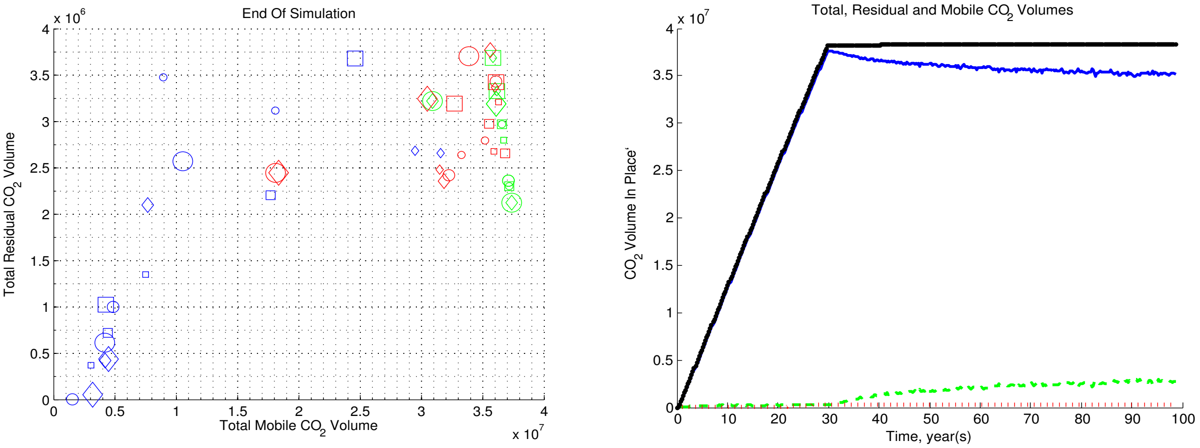

Figure 5: CO_2 volumes. Left: residual versus mobile volume at the end of simulation. Most of the green colored cases follow a linear trend, which is expected because the injected CO_2 must be conserved if no CO_2 leaves the system. For the rest of the cases, some CO_2 goes out of boundaries. Right: Total CO_2 volumes with time plotted for one case. Green curve is the residual volumes, dotted red denotes volumes that have left the domain, solid blue is mobile volumes, and the solid black shows the summation, which is the total volume and stays constant after injection because no more CO_2 is added to the system.

assume that all mobile CO_2 connected to a leakage point will escape out of the reservoir. Hence, it is preferable if the total mobile CO_2 volume is split into smaller plumes rather than forming a big mobile plume. Though the area exposed to potential leakage points will increase by splitting the plume, yet the volume reduction is overtaking the area effect.

On the other hand, the split CO_2 plumes can sweep more cross-areas than a big single plume. The no-flow faulted side can be considered to be connected to an imaginary large volume available for long-term plume migration. Thus, it makes sense to talk about plume sweeping cross area. Larger areas leave more residual CO_2 in the tail of the plume. Hence, we looked at the largest plume size, the number of plumes, and other statistical parameters. The number of plumes at the end of simulation for all cases are given in Fig. 6. Two-lobed cases include more branching channels which result in more plume numbers. Also barrier effect increases the lateral distribution of the plume.

6 Conclusions

Herein, we have reported on a preliminary study of the influence of various geological parameters on the injection and early-stage migration of CO_2 in progradational shallow-marine systems. Large variations in the flow responses show the importance of considering uncertainty in the geological parameters. In particular, our results highlight how variation in aggradation and barriers significantly change the flow direction within the medium. Therefor we believe that effort should be put into detailed geological modeling of potential injection sites. This way, one can better balance the influence of simplifications made in the models of geology and flow physics.

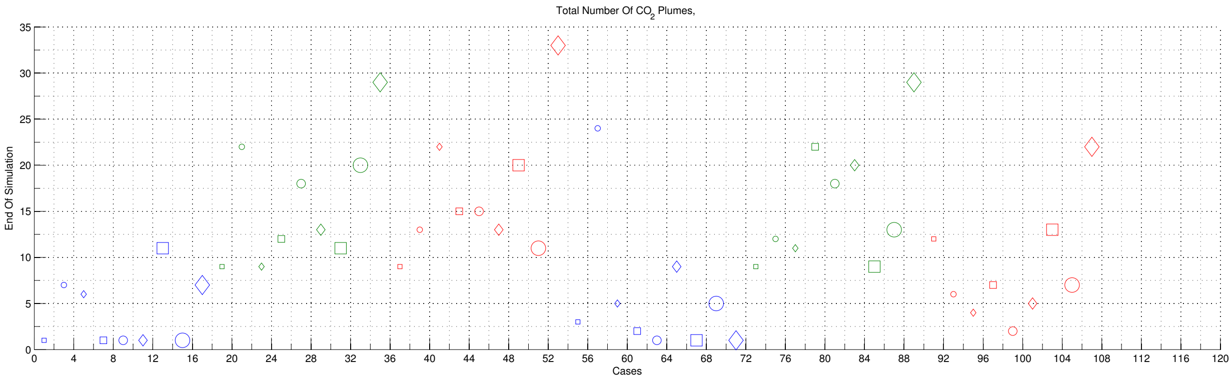

Figure 6: CO_2 plume number at end of simulation, see explanation in Fig. 3.

Finally, we stress that these are very preliminary conclusions drown from a limited number of simulations performed on a suite of synthetic models that were made to study petroleum production. A more thorough investigation should generate new synthetic geological realizations that are more representative of typical injection sites.

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