# Impact of Geological Heterogeneity on Early-Stage $CO_2$-Plume Migration: Sensitivity Study

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## 1 Introduction

Sedimentary basins consist of thick piles of lithified sediments that provide large volumes that can be used to store carbon dioxide produced from localized sources as a possible means to reduce the rate of anthropogenic emission into the atmosphere [25, 18]. Sedimentary basins contain fluids (mostly brine) whose flow is controlled by high-permeable strata through which the fluids can flow and low-permeable strata which inhibit fluid flow. How efficient the geological storage of $CO_2$ will be, is determined by how the low and high permeability strata are stacked inside the sedimentary basin [24]. Carbon dioxide injected deep in a sedimentary basin will form a plume that has a lower density than the formation brine and hence will migrate upward by buoyancy forces. The most secure type of geological storage is therefore provided in depleted petroleum reservoirs that contain stratigraphic and structural traps that have held hydrocarbons for million of years. Unfortunately, oil and gas reservoirs do not contain sufficient pore volumes to store the large amounts of $CO_2$ that are required to significantly reduce current and future carbon emissions. A more viable solution is to use saline aquifers that have very slow flow rates and offer large volumes of pore space. Aquifers are typically connected to the surface through permeable strata, and the injected $CO_2$ may therefore in principle travel in the up-dip direction and eventually leak out through sedimentary outcrops. In practice, this process will take millions of years because of the long distances involved. Moreover, as the plume migrates upward, some of the $CO_2$ will be trapped as small droplets between rock grains (residual trapping), some of it will dissolve into the formation water (dissolution trapping), and some of it will react with rock minerals and become permanently trapped. In general, the flow of $CO_2$ in subsurface rocks is governed very complex interactions between physical forces acting on the reservoir fluids and properties of the reservoir rock itself. It is therefore necessary to develop effective (numerical) models that can be used to accurately describe the pertinent flow dynamics and provide a detailed inventory of injected volumes. Numerical models must also properly account for geological heterogeneity—i.e., variations in hydraulic conductivity and fluid storage—and how this heterogeneity influences the flow dynamics.

The main concern for policy makers and the general public is the operational safety and the risk of leakage, i.e., how likely it is that the injected carbon dioxide (or highly saline brine) will migrate into water resources, into active petroleum reservoirs, or back to the surface through ill-plugged wells [43], through caprocks broken by the high pressure imposed to the system during the injection operation, or via conductive features like fractures and faults. Likewise, there is a concern about pressure buildup, which may extend much further than the injected $CO_2$ plume (the effluent of $CO_2$ into brine). In other words, the operator of a potential injection site needs to maximize storage volumes while minimizing leakage risks and effects on areas surrounding the injection point. Over the last two decades, there have been a large number of simulation studies of $CO_2$ sequestration, including in particular, studies of pilot projects like Sleipner [13, 7, 12, 40, 9], In Salah [8, 11, 46], Ketzin [21, 34, 29, 30, 45], or Johansen [2, 6, 19, 17, 52]).

Geological heterogeneity is recognized in many studies as a major control mechanism that influences flow from small laminated scales to large global scales. Stratigraphic heterogeneity, for instance, is dependent on the depositional environment, and affects the geometry and spatial distribution of depositional facies as well as the spatial permeability distribution within facies. Practically, including all details of every scale into flow simulation model is impossible. Moreover, the understanding of the geology of a specific reservoir or aquifer is typically (surprisingly) limited: experience from the