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

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## 1 Introduction

Underground sequestration of $CO_2$ produced from localized sources like power plants and oil and gas recovery sites has been proposed as a possible solution to reduce the rate of anthropogenic $CO_2$ emission into the atmosphere [5, 2]. Much of the technology required to inject $CO_2$ into saline aquifers, unminable coal seams, and abandoned reservoirs is already available from the petroleum and mining industry. However, before large-scale storage operations can be initiated, answers to practical questions regarding operational safety and the fate of the injected $CO_2$ need to be answered. The main concern for policy makers and the general public is the risk of leakage, i.e., how likely it is that the injected $CO_2$ (or highly saline brine) will migrate into water resources, active petroleum reservoirs, or back to the surface via conductive features like fractures and faults, through ill-plugged wells [10], or through caprocks broken by the high pressure imposed to the system during the injection operation. 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.

The flow of $CO_2$ in the subsurface is governed by a very complex interaction between physical forces acting on the reservoir fluids and properties of the reservoir rock itself. To determine the fate of the injected $CO_2$, it is necessary to develop effective (numerical) models that can be used to accurately describe the pertinent flow dynamics during injection and the subsequent migration period. Moreover, the 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. Geological heterogeneity is recognized as a major control mechanism within petroleum production [3] and an important constraint on many aspects of quantitative hydrogeology. For this reason, much effort has been devoted to understand and represent geological heterogeneity in flow models, see e.g., [4]. The understanding of the geology of a specific reservoir or aquifer is typically limited and the description of the geological heterogeneity will usually have large uncertainties attached. If flow simulations are to be used to assess risks associated with a storage operation, the numerical flow model must properly account for the impact of uncertainty in the geological description. Yet, academic studies of $CO_2$ injection commonly employ simplified or conceptualized reservoir descriptions, in which the medium is considered (nearly) homogeneous, and instead focus on developing complex flow models, discretization schemes, and solvers.

Within oil recovery, the impact of geological uncertainty on production forecasts has been thoroughly investigated in the SAIGUP project [8, 6, 9], in which an ensemble of synthetic but realistic models of shallow-marine reservoirs were generated and several thousand cases were run for different production scenarios. The results showed that realistic variations in the structural and sedimentological description has a strong influence on production responses. Simulation of $CO_2$ storage involves temporal and spatial scales and density ratios that are quite different from those encountered in oil recovery. Potential storage sites may also have geological characteristics that differ from those seen in producible oil reservoirs. For these reasons, one cannot expect that knowledge of how geological heterogeneity impacts flow predictions of oil-water systems can be carried directly over to $CO_2$-brine systems relevant for $CO_2$ injection scenarios. Nevertheless, we will herein consider a scenario in which $CO_2$ is injected into an abandoned shallow-marine reservoir and use geological realizations generated as part of the SAIGUP project to study the impact of geological heterogeneity on the early-stage