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Two-phase gravity currents in CO_2 sequestration

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Geological carbon capture and storage (CCS), in which compressed CO_2 is injected into deep saline aquifers for permanent storage, forms an integral part of CO_2 mitigation strategies. At representative reservoir conditions CO_2 is buoyant and may therefore leak into surface waters or the atmosphere. The leakage of CO_2 back into the atmosphere may be prevented by the formation of disconnected immobile residual CO_2 in the wake of the migrating plume. Here we constrain the magnitude of residual trapping by considering a two-phase model of the buoyancy driven propagation of a plume of injected CO_2 within a saline aquifer.

The buoyant rise of CO_2 within saline aquifers is the principal mechanism through which CO_2 contacts the host reservoir. Most simplified models of CO_2 migration have assumed that the capillary transition zone is negligible relative to the current thickness and that the fluids are separated by a sharp interface. The results anticipate that such currents quickly become highly localized at the top boundary of reservoirs resulting in a concomitant reduction in residual trapping. However, such single-phase models neglect both the interfacial tension and large viscosity difference between the injected CO_2 and the ambient pore fluid.

The key challenge in two-phase gravity currents is the modeling of the variation in CO_2 saturation with depth within the current. Here we use a standard model that considers the functional dependence of the relative permeability and capillary pressure on saturation to describe the two-phase flow. We anticipate that, after an initial transient, the extent of the current is much greater than its depth and that the capillary pressures within the current are balanced by gravity in this limit. This balance, called gravity-capillary equilibrium, and the fact that flow is predominantly horizontal within the current determine the saturation profile. Realizing that flow is driven primarily by gradients in the hydrostatic pressure, as in single-phase flows, we then use the saturation profile in combination with the relative permeability to determine the dynamics of the two-phase current.

The two-phase model that results is attractive because the formalism captures many of the features of the simpler single-phase models while providing an integrated physical and mathematical framework for the modeling of geological CO_2 sequestration. In particular, by resolving the saturation profile, or capillary fringe, we are better able to estimate the extent and depth of the two-phase current, thus providing more robust estimates of residual CO_2. Such two-phase models lay the groundwork to effective and efficient characterization of storage reservoirs and promise to illuminate the underlying physical processes governing the propagation of sequestered CO_2 in the subsurface.