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Capillary trapping for geologic carbon dioxide storage – From pore scale physics to field scale implications

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ABSTRACT

A significant amount of theoretical, numerical and observational work has been published focused on various aspects of capillary trapping in CO_2 storage since the IPCC Special Report on Carbon Dioxide Capture and Storage (2005). This research has placed capillary trapping in a central role in nearly every aspect of the geologic storage of CO_2. Capillary, or residual, trapping – where CO_2 is rendered immobile in the pore space as disconnected ganglia, surrounded by brine in a storage aquifer – is controlled by fluid and interfacial physics at the size scale of rock pores. These processes have been observed at the pore scale in situ using X-ray microtomography at reservoir conditions. A large database of conventional centimetre core scale observations for flow modelling are now available for a range of rock types and reservoir conditions. These along with the pore scale observations confirm that trapped saturations will be at least 10% and more typically 30% of the pore volume of the rock, stable against subsequent displacement by brine and characteristic of water-wet systems. Capillary trapping is pervasive over the extent of a migrating CO_2 plume and both theoretical and numerical investigations have demonstrated the first order impacts of capillary trapping on plume migration, immobilisation and CO_2 storage security. Engineering strategies to maximise capillary trapping have been proposed that make use of injection schemes that maximise sweep or enhance imbibition. National assessments of CO_2 storage capacity now incorporate modelling of residual trapping where it can account for up to 95% of the storage resource. Field scale observations of capillary trapping have confirmed the formation and stability of residually trapped CO_2 at masses up to 10,000 tons and over time scales of years. Significant outstanding uncertainties include the impact of heterogeneity on capillary immobilisation and capillary trapping in mixed-wet systems. Overall capillary trapping is well constrained by laboratory and field scale observations, effectively modelled in theoretical and numerical models and significantly enhances storage integrity, both increasing storage capacity and limiting the rate and extent of plume migration.

1. Introduction

The trapping of CO_2 by capillary forces in the pore space of rocks is a key process for maximising capacity and ensuring the integrity of CO_2 sequestration at industrial scales. When CO_2 is injected into a deep subsurface geologic formation it will displace the resident fluid, generally brine and in some cases hydrocarbons, and migrate in response to buoyancy and pressure gradients. As the reservoir brine imbibes back into the pore space pursuant to the migrating CO_2 plume, small isolated blobs of CO_2 will be trapped by capillary forces: this is known as capillary or residual trapping (Fig. 1). The isolated blobs are of the size scale of the pores of the rocks, tens to hundreds of micrometers, and the process is controlled by fluid physics and interfacial forces at the micron scale. Because the trapping, however, is pervasive over the hundreds of meters to hundreds of kilometres of the plume extent it plays a major role in plume migration, immobilisation, storage security and ultimately the capacity for storage resources to safely contain injected CO_2.

The importance of capillary trapping had already been identified in the IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005). Both the extent and rate of trapping made it integral

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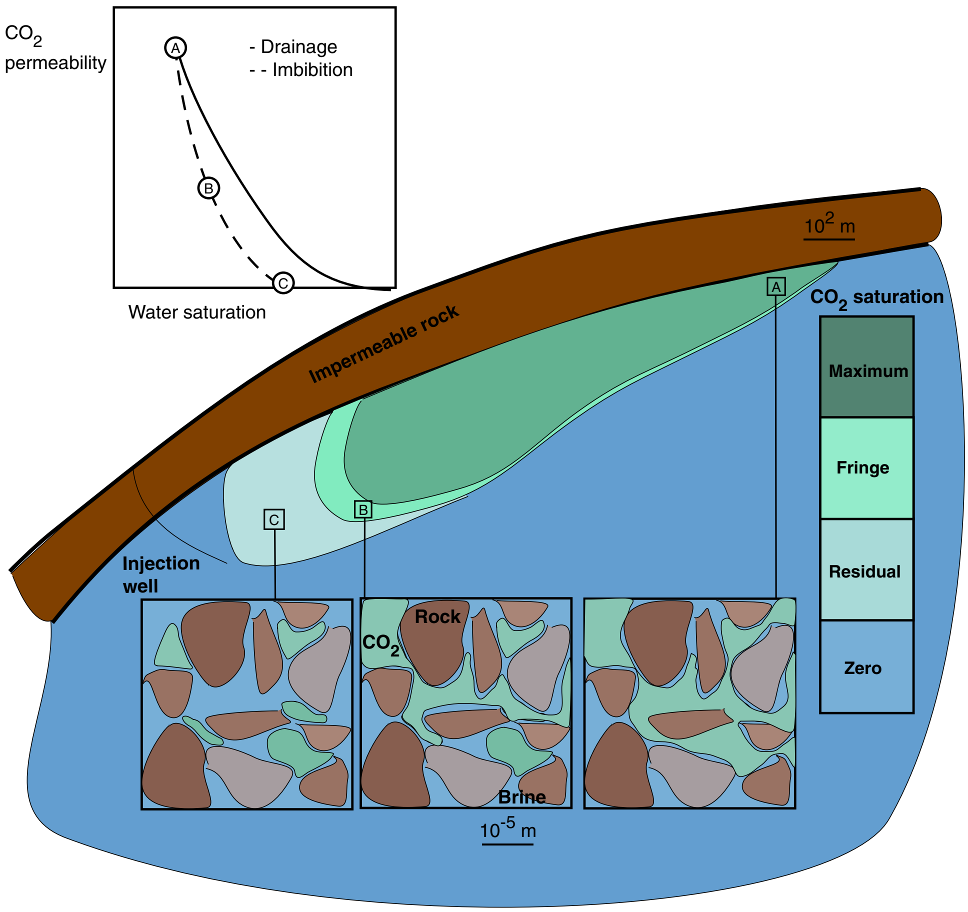

Fig. 1. A sketch of key processes governed by capillary trapping after CO_2 injection has ceased at a storage site. Plume migration is limited by the trapping as large fractions of the plume are immobilised. Capillary trapping is secure over long timescales and avoids buoyant stress on overlying cap rock layers. Trapping is also key to parameterising hysteresis in relative permeability functions – more trapping leads to greater disconnection of fluid ganglia as CO_2 saturation in the pore space decreases (movement from A towards C in the figure) and thus a larger decrease in permeability as a function of saturation.

to storage security relative to other trapping mechanisms (Fig. 2). At the time of the report, the importance of capillary trapping for CO_2 migration and immobilisation had been identified in a small number of numerical studies (King and Paterson, 2002; Doughty and Pruess, 2004), but no laboratory or field observations of the extent of trapping had been published, the pore scale interfacial properties had not been characterised and no methodology incorporated residual trapping in estimations of the storage capacity of individual sites or regions.

In this paper we review the body of work, most of which has been published in the ten years since the IPCC report, that has placed capillary trapping in a central role in nearly every aspect of the geological storage of CO_2. The recently developed tools of digital rock physics has allowed for unprecedented detail in understanding the pore scale physics of CO_2-brine systems. A sizeable and growing database of observations of the key constitutive relationship characterising capillary trapping at the centimetre scale of rock cores now exists for a range of rock types and reservoir conditions. The impact of capillary trapping on plume migration and immobilisation is now well understood from both theoretical and numerical investigations. Where CO_2 storage constitutes an ongoing component of greenhouse gas emissions abatement strategy, governmental agencies now incorporate modelling of residual trapping at field scales for estimations of the capacity of the regional storage resource. The existence and stability of residually trapped CO_2 in reservoir settings has been demonstrated by field scale injection experiments in Japan, the United States and Australia (Xue et al., 2006; Hovorka et al., 2006; Paterson et al., 2011). Combined,

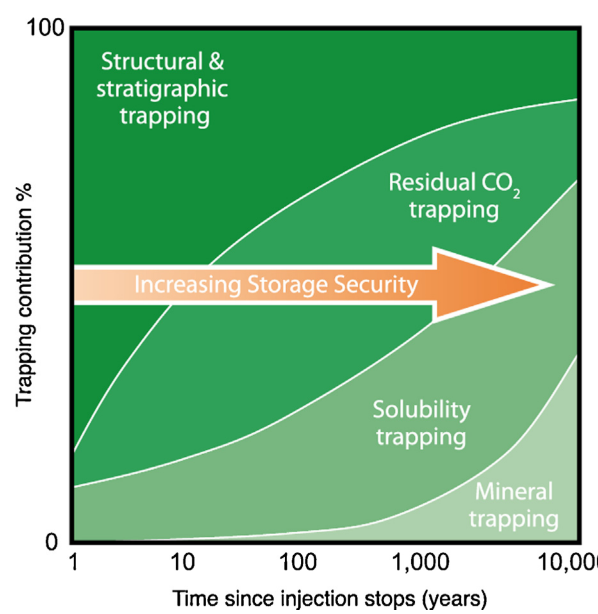

Fig. 2. A schematic of the relative importance of various trapping mechanisms over time, from Benson et al. (2005, 2012). Residual trapping is significant both in the amount of trapping capacity it provides as well as for the speed over which residual trapping takes place, simultaneously with water influx into the migrating plume.