Investigation of gas migration and retention using transparent soil

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Geological storage of carbon dioxide (CO\textsubscript{2}) has the potential to alleviate or defer climate change. The efficiency of geological storage requires retention of CO\textsubscript{2} within the geosphere for an extended period of time, and the release of CO\textsubscript{2} from storage locations could affect groundwater quality in shallow aquifers. A conceptual ground profile illustrating gaseous CO\textsubscript{2} migration in a shallow aquifer is illustrated in Figure 1. CO\textsubscript{2} is released at depth and then migrates upward under buoyancy forces while encountering a number of local and regional heterogeneities. Migration of CO\textsubscript{2} through the ground profile is dependent on retention characteristics of the materials within the profile. Illustrated on Figure 1 are heterogeneities that significantly impact the spatial distribution of CO\textsubscript{2}. The finer layers form capillary breaks, which attenuate CO\textsubscript{2} migration, causing gas pools to develop. Periodically as gas pools fill, gas breakthrough occurs across the fine layers and upward gas migration continues. The majority of the gas within the ground profile is located within the pools. Accurate predictions of spatial and temporal CO\textsubscript{2} distributions requires understanding of gas dynamics and gas breakthrough mechanisms.

![Figure 1. Conceptual ground profile illustrating CO\textsubscript{2} migration following injection.](image)

Experimental investigations of gas dynamics and gas breakthrough benefit greatly from high spatial and temporal resolution measurements of gas content. For this investigation a transparent soil is used, which allows for spatial resolution down to the millimetre-scale as well as temporal resolution of 5 s (insert our multi-phase transparent soil REFs). Transparent soil is formed by matching the refractive index of the soil particles and pore fluid. Use of transparent soil allows for direct observation and quantification of the gas phase throughout the experiments using digital image analysis. Digital image analysis is a two-step process whereby normalized images are formed comparing the current image to
a dry image and a saturated image, followed by conversion of the normalized intensity image to degree of saturation (Sills 2015). A schematic of the experimental apparatus used in this study is given in Figure 2a and a normalized intensity image of a gas injection experiment is given in Figure 2b. The front and back faces of the 147 cm tall by 117 cm wide by 5 cm thick apparatus is constructed of 18 mm thick Perspex. Reference dots along the sides allow for image alignment and the steel bars provide structural reinforcement for the front face. The transparent soil is a fused quartz and is provided in two grain-size distributions (fine and coarse gradations which are both classified as poorly sorted sands) that allow for heterogeneous ground profiles to be constructed. The ground profile used in this study is shown schematically on Figure 2a. The soil is placed using a wet pluviation method through the pore fluid, which is a mineral oil mixture of the same refractive index. Gas is injected at the location shown in Figure 2a at a rate of 30 mL/min, which ensures discontinuous flow (bubble flow) mechanisms dominate. The normalized image (Figure 2b) illustrates the high spatial resolution of the experimental technique for a single digital image of the gas injection experiment. The gas distribution was monitored throughout the experiment, and gas saturations were quantified at the local scale. The focus of this study is a particular filling and emptying event where the observed gas pool emptying behaviour did not follow theoretical (equilibrium-based) predictions.

Figure 2. Gas injection experiment: a) schematic of transparent soil flow apparatus and b) normalized intensity image illustrating the spatial resolution of the experimental method.

Saturation images from a pool filling and emptying event are given in Figure 3 including initial filling (Figure 3a), pool at maximum volume (Figure 3b) and after the emptying event (Figure 3c). The saturation images are taken of the area below the undulating fine layer shown in Figure 2a. The saturation images show gas migrating upward under buoyancy, capillary, and viscous forces, and then spreading laterally after encountering the capillary break (fine layer). The gas migrates along the base of the undulating fine layer and pool formation begins. The pool continues to build below the capillary break, which is indicated as the darker colours on Figure 3. The gas pool continues to grow downward until it reaches its maximum volume just prior to breakthrough, which is shown in Figure 3b. At this point, the suction at the top of the pool reaches the air entry value of the fine layer and gas breakthrough, or pool emptying, initiates. Gas breakthrough continues until the pool empties and only occluded bubbles remain below the breakthrough location. A pocket of trapped gas remains under the left-hand side of the undulation as access to the gas breakthrough point was cut off by the undulating fine layer.
Figure 3. Gas saturation distribution of a pool below a capillary break: a) during filling, b) at maximum pool height, and c) following breakthrough and complete emptying of the pool.

In the event described above, pool filling proceeded as expected, based on a theoretical consideration of buoyancy and capillary forces at equilibrium, while pool emptying did not. A gas pool is expected to fill until the air entry value of the capillary break is reached, which was observed in the experiment. Gas breakthrough continued until only occluded bubbles (soil at residual gas saturation) were observed below the gas breakthrough location, rather than until the suction reduced below the terminal height (suction at which air first becomes disconnected). The results was a complete emptying of the gas pool rather than a partial emptying to approximately one half of the maximum (entry) height.

Given this observed behaviour the implications to temporal and spatial predictions of gas distributions are important to consider. Efficiency of CO$_2$ storage, and protection of shallow aquifers from leaks, requires significant retention of gas below capillary breaks throughout the ground profile. Current understanding provides a framework for significantly larger gas volume storage than those observed in the experiment. The results of this show the high quality data that is available from experiments that employ transparent soil and also provide motivation for understanding the observed behaviour.