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Correlative characterization of fluid flow and solute transport in disordered porous media via fast micro-computed tomography

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The study of fluid-flow and solute transport in natural porous media has applications across diverse geological environments, such as soils for contaminant remediation and rocks for subsurface gas (CO_2 or H_2 storage). Transport processes drive chemical reactions in fluids; however, the inherent disorder of natural porous media introduces heterogeneities in physico-chemical properties across a wide range of length scales. This disorder results in heterogeneous velocity fields, which in turn produce complex and difficult-to-predict solute concentration distributions, leading to the so-called "non-Fickian"behavior.

Solute transport in rocks is often studied using 4D imaging techniques such as X-ray and neutron-based computed tomography. While these methods enhance our understanding of non-Fickian transport [1], their limited spatial resolution (>1 mm) precludes direct observations at the pore-scale where the mixing processes originates. The development of fast X-ray CT imaging allows direct visualization of pore-scale processes at much finer spatial and temporal resolution (approx. few µm and 10 sec). However, quantitative analysis of the imagery obtained by these approaches is still lagging, with significant potential for optimization in geological applications.

Here, we analyzed a comprehensive 4D dataset obtained via fast micro-computed tomography from tracer tests conducted in two sintered glass beadpacks (6 mm diameter, 20 mm length) with irregular grain and pore structures [2,3]. Tracer experiments were performed at two Péclet numbers (Pe = 2.7 and 5.4), with scans acquired over a 6 mm × 5 mm window at spatial and temporal resolutions of 13 µm and 15 seconds, respectively. We found that the pore space must be clustered into larger sub-volume elements—at least 700 times the voxel size in this case—to enable reliable quantification of flow and transport properties. The dataset was rigorously evaluated using concentration profiles associated with each clustered pore-volume element (PVE) to produce arrival-time maps (as proxy for flow heterogeneity) and mixing maps (as proxy for transport heterogeneity). While slice-averaged properties could be well predicted by a simple transport model (the Advection Dispersion Equation, ADE), significant variability was observed at individual PVE locations. This variability became more pronounced at higher Pe primarily due to the emergence of flow channeling. Our findings demonstrate that fluid flow—primarily driven by pore connectivity and pore-size heterogeneity—does not necessarily dictate solute transport dynamics. The distinct features of the arrival-time maps and the mixing maps indicate that both data-sets are necessary to fully capture the solute transport process. As such, these results highlight the benefits of further developing correlative characterisation techniques in the study of solute transport in porous media.

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