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Pore-scale distribution of preferential flowpaths in natural rocks with trapped fluid phases

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Heterogeneity in a porous microstructure is, in general, enhanced by the presence of a trapped immiscible fluid phase. Determining the way flow velocities distribute at the pore scale and, in turn, influence the behavior of solute transport, mixing and reaction under such condition is still an open challenge. In the presence of a non-wetting trapped phase, experiments have shown that the isolated ganglia formed after trapping enhance the confinement of the flow into high-velocity preferential pathways, leading to enhanced mixing and reaction rates. However, little attention has been given to multiphase systems in which the trapped phase is wetting. Here, we focus on determining the key parameters affecting the spatial distribution of high-velocity preferential flowpaths in pore spaces characterized by the presence of trapped immiscible wetting or non-wetting fluid phases. We consider three-dimensional reconstruction of natural rocks obtained from micro-tomographic images and use a finite volume-based solver to determine the pore-scale velocity probability distributions of the flowing fluid phases. Trapping is achieved after immiscible two-phase flow processes (drainage and imbibition) leading to a stationary spatial distribution of the fluids. We compare the results achieved for diverse wettability conditions in such settings and use data from fully saturated (single-phase) simulations as a reference for the analysis. Our results suggest that four different features can be observed: high-velocity areas initially present in the single-phase case may be subject to (i) an increase or (ii) a decrease in velocity magnitude, eventually until (iii) velocity vanishes; a high-velocity area may also (iv) appear in the pore space. We find that features (i) and (ii) are promoted when the trapped phase is wetting and the distribution of preferential pathways is expected to be similar to the single-phase conditions. Otherwise, features (iii) and (iv) are mostly promoted when the trapped phase is non-wetting, with a more pronounced impact on the distribution of preferential pathways. We show that this characteristic is linked to the spatial arrangement of the trapped fluid phase, that is in turn associated with the wettability of the trapped fluid. A trapped wetting phase distributes in the dead end and high entry pressure pores as well as in the small crevices and corners of the pore space, and does not obstruct the central body of pores and throats, where the non-wetting phase flows preferentially. Otherwise, a trapped non-wetting phase resides in the form of isolated ganglia that remain in the central body of pores and throats and modifies the distribution of preferential pathways. These observations reveal that wettability is a significant parameter to take into account together with the degree of saturation when characterizing flow in porous media under multiphase conditions, as the distribution of preferential flowpaths is critical to the determination of solute transport, mixing and reaction.