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Drainage front zonation - viscous effects on phase entrapment and drainage timescales

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The invasion characteristics during drainage of porous media are determined by the interplay of capillarity, gravity, and viscous forces that depend on the flow process and boundary conditions. Rapid drainage gives rise to formation of two regions: Behind a region marked by fast invasion events that contribute to the propagation of the drainage front, a second viscous-limited region is formed with liquid structures draining at larger time scale ('detained liquid phase'). A theoretical framework was developed to characterize the onset and extent of zonation based on continuum scale force balance. Beyond a characteristic distance (viscous length L_V) from the front, drainage becomes viscous limited leading to apparent phase entrapment draining over a secondary timescale. The characteristic viscous length L_V depends on hydraulic properties of the medium and the applied flow rate q_0. A large ratio between q_0 and hydraulic conductivity shortens L_V and leads to larger fraction of apparent entrapped liquid phase at closer distance from the front. For L_V reaching zero the entire pore space becomes viscous limited, defining a criterion for unstable flow. The concept of zonation provides a tool for estimating (i) the viscous length L_V, (ii) the fraction of entrapped liquid phase, and (iii) secondary drainage timescale as functions of medium type and flow rate. Theoretical predictions were compared to drainage experiments at different flow rate and for different porous media, confirming pressure relaxation and liquid redistribution towards the front after stop of drainage. These observations reveal the separation of drainage mechanism and timescales where part of the liquid was detained by viscous forces. The measured redistribution pattern and time evolution were in good agreement with theoretical predictions.