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Push-pull flows reveal the scalar signature of chaos in porous media

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Recent works have shown that laminar flows through porous media generate Lagrangian chaos at pore scale, with strong implications for a range of transport, reactive, and biological processes in the subsurface. The characterization and understanding of mixing dynamics in these opaque environments remains an outstanding challenge. We present a novel experimental technique based upon high-resolution imaging of the scalar signature produced by push-pull flows through various porous materials (beads, gravels, sandstones) at high Péclet number. We show that this method provides a direct image (see below) of the invariant unstable manifold of the chaotic flow, while allowing a precise quantification of the incompleteness of mixing at pore scale. In the limit of large Péclet numbers, we demonstrate that the decay rate of the scalar variance is directly related to the Lyapunov exponent of the chaotic flow. Thus, this new push-pull method has the potential to provide a complete characterization of chaotic mixing dynamics in a large class of opaque porous materials.