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Oscillating Flow Leads to Sustained and Enhanced Mixing-Induced Mineral Precipitation in Porous Media

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Mixing-induced mineral precipitation significantly influences various natural and engineered processes such as carbon mineralization, aquifer recharge, and enhanced geothermal systems. Traditionally, this process has been viewed as self-limiting due to the formation of a thin precipitate layer along the mixing interface, which inhibits further fluid mixing and subsequent precipitation [1]. However, our recent work shows that fluid inertia can significantly enhance mixing-induced precipitation [2]. In this study, we introduce a novel mechanism whereby oscillatory flow sustains and dramatically amplifies mixing-induced mineral precipitation in porous media, even under creeping flow conditions.
We performed microfluidic experiments and pore-network modeling to explore the impact of oscillating flow on mixing-induced mineral precipitation in porous media. Barium chloride and sodium sulfate solutions were co-injected into porous microfluidic chips at an oscillating injection rate, maintaining a constant total flow rate and a 10% flow rate difference between the two solutions. The flow rate between the two inlets alternates every 30 minutes, ensuring periodic flow rate oscillations. Precipitation dynamics were captured in real-time using an inverted fluorescence microscope with brightfield imaging, while fluid mixing was characterized through fluorescence imaging. Additionally, X-ray micro-CT scans provided detailed 3D morphology and spatial distribution of the precipitated minerals. Our results demonstrate that oscillating flow conditions prevents the formation of a mixing barrier and actively enhances transverse precipitation across the porous media. As the flow oscillates, precipitation continuously expands transversely, resulting in a broad precipitation zone with porous precipitates. This is in contrast to the thin, dense precipitation layer formed under steady flow conditions. X-ray micro-CT images confirm that the precipitates exhibit microporosity, resulting in dual porosity and a heterogeneous permeability field. These experimental findings align closely with the pore-network modeling results, validating the observed phenomena.
This study highlights the crucial role of flow conditions in controlling spatiotemporal dynamics and patterns of mixing-induced precipitation in porous media. These findings have important implications for various natural and engineered processes where understanding and control of mineral precipitation is critical.

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References

[1] Zhang, C., Dehoff, K., Hess, N., Oostrom, M., Wietsma, T. W., Valocchi, A. J., … & Werth, C. J. (2010). Pore-scale study of transverse mixing induced CaCO3 precipitation and permeability reduction in a model subsurface sedimentary system. Environmental science & technology, 44(20), 7833-7838. [2] Yang, W., Chen, M.A., Lee, S.H. and Kang, P.K., 2024. Fluid inertia controls mineral precipitation and clogging in pore to network-scale flows. Proceedings of the National Academy of Sciences, 121(28), p.e2401318121.

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