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Non-invasive imaging of solute redistribution below evaporating surfaces using 23Na-MRI

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Evaporation from porous media is a key phenomenon in the terrestrial environment and is linked to accumulation of solutes at or near the evaporative surface. It eventually leads to salinization, soil degradation and weathering of building materials, topics with high economic impacts. Although the detrimental effects manifest on different scales from pores to the field, the key to understanding is found on the pore scale since pore system connectivity and structure control the solution behavior near the evaporation surface. A thorough understanding requires the development of physical models describing the most relevant processes and their validation by experiments. Vice versa, new experimental observations promote the further development of the physical models.

In this context, the current study aims at the understanding of solute accumulation near evaporating surfaces for model porous media at the cm-scale. Analytical and numerical modelling predict the development of local instabilities due to density differences during evaporation in case of saturated porous media with high permeability, which eventually causes density-driven backflow through fingering [Bringedal et al. TPM 2022]. To experimentally investigate this process, we performed experiments on sand packings with a diameter of 3.1 cm and a height of 4 cm prepared with two types of porous media: F36 (medium sand) and W3 (fine sand/silt) with porosities of 0.37 and 0.39, respectively. The intrinsic permeability of the two packings differed by two orders of magnitude, i.e. 2.9×10-11 m2 for F36 and 5.6×10-13 m2 for W3. Using magnetic resonance imaging (23Na-MRI), we monitored the development of solute accumulation and subsequent backflow with high spatial (1 mm) and temporal (1 hr) resolution during evaporation with a continuous supply of water at the bottom of the samples (wicking conditions).

Significant differences between the 23Na enrichment patterns were observed for the two types of sand. F36 sand produced an initial enrichment at the surface within the first hour, but soon after a downwards moving plume developed, hence redistributing NaCl back into the column. This was attributed to density driven backflow made possible by the high permeability. The backflow caused a good mixing of the solute during the observation period of 120 h. 1D concentration profiles with depth obtained from the 3D imaging showed that the average concentration reached only 2.5 mol/L, well below the solubility limit of 6.13 mol/L. In contrast, for fine W3 sand with lower permeability, enrichment only took place in a shallow near-surface zone of a few mm with a maximum concentration of 5.1 mol/L after 73 hours of evaporation. No fingering occurred although the mean evaporation rate was similar to that of the F36 sand. These results highlight the major role that porous media properties play in solute redistribution near evaporating surfaces, which was predicted by theory and now confirmed experimentally. The findings encourage further investigations involving different porous media with systematic variation of hydrological properties and the coupling of experimental results to numerical modelling.

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