A microfluidic study of drying of bacteria-laden brines

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Introduction

Cycles of drying and rewetting in salt-bearing building stones are a major driver of weathering, primarily through the crystallization of salt [1]. To reduce such damage, microorganism-based treatments have been used as sustainable and compatible consolidation strategies [2]. Yet the coupled biogeochemical processes in porous stone—spanning biofilm growth, mineral nucleation, transport, and evolving interfaces—remain complex and multiscale [3]. To examine these mechanisms directly, microfluidic models provide controlled, pore-scale visualization of drying fronts, liquid–gas interfaces, and salt crystallization [4]. Here, we employ microfluidic analogues of stone to study pore-scale interactions between a denitrifying bacterium (*Paracoccus denitrificans*) and sodium-sulfate crystallization during evaporative drying.

Materials & method

Bacterial strain and growth mineral medium: In this study, we used *Paracoccus denitrificans*—a facultative anaerobic, denitrifying bacterium capable of forming biofilms and generating biogas and biominerals [4]. The stock was grown aerobically in LB broth at 25 °C, 100 rpm for 3 days, then diluted ~1:10 into a mineral medium. The medium contained (in g/L) [5]: $Na_2HPO_4{\cdot}7H_2O$ (8.5), KH_2PO_4 (3), NaCl (0.5), $MgSO_4$ (0.24), $CaCl_2$ (0.011), CH_3OH (4), and KNO_3 (0.72).

Bacteria-laden brine: A 100 g/L sodium sulfate (Na_2SO_4) brine was prepared and autoclaved at 121 °C for 25 min. A bacteria-laden brine was prepared by blending the bacterial suspension in mineral medium with the brine at a 1:1 (v/v) ratio.

Experimental procedure: The micromodel (**Fig. 1**) was pre-saturated with a fluorescent bacteria-laden brine. To isolate bacterial effects, control runs were performed with pure brine, mineral medium, and a mixture of brine and medium. Conditioned air (24°C, 45 % RH) was supplied at 20 std cm^3/min through an open inlet channel; all other boundaries were sealed (no-flow). Images were acquired with a ZEISS fluorescence microscope. Each run was terminated at near-complete drying.

Image analysis: Time-lapse images were processed in ImageJ/Fiji and segmented in Avizo to quantify the temporal evolution of liquid saturation.

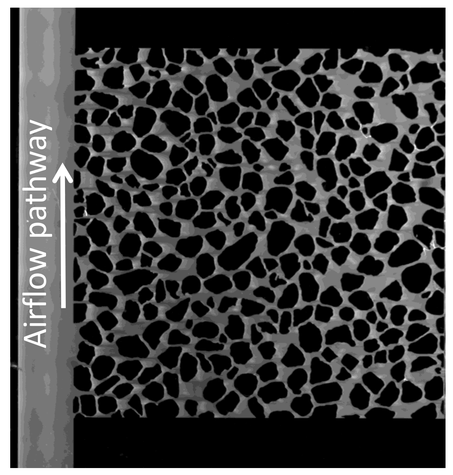

Fig. 1: Plan-view micromodel (1 cm × 1 cm) with 60 µm channel depth.

Results

Fig. 2 shows drying curves for the tested fluids derived from image analysis of the micromodel experiments. Evaporation was slower for the Na_2SO_4 brine and the brine–medium mixture, whereas the mineral medium and the microbial brine evaporated faster (medium > microbial brine). Salt precipitation (**Figs. 3**) reflected these trends: pure brine and the brine–medium mixture produced extensive crystallization, severe pore-throat clogging, and occasional complete blockage. In contrast, chips saturated with mineral medium showed only limited, localized crystallization. For the brine–medium–bacteria (microbial brine) case (**Fig. 4**), the confocal laser microscope revealed pronounced biomass adsorption on pore walls, distortion of liquid-gas interface due to bacterial cell accumulation, and suppressed salt crystallization, suggesting that microbial coverage modifies nucleation sites and crystal growth pathways.

Controls: Drying of bacteria-free liquids

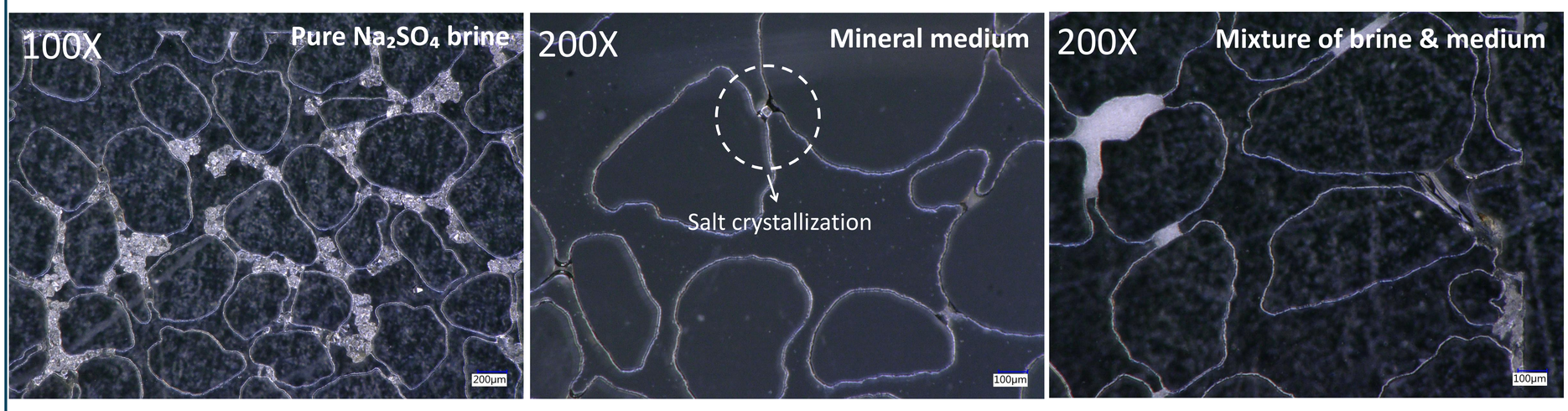

Fig. 3: Salt crystallization features and patterns for bacteria-free fluids.

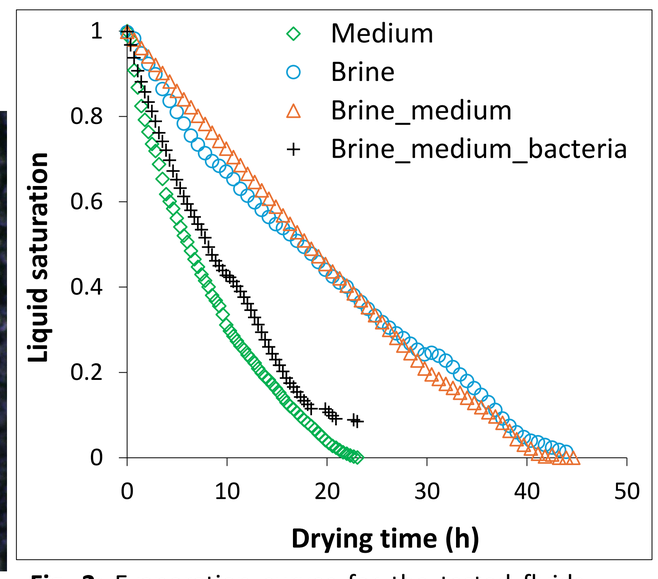

Fig. 2: Evaporation curves for the tested fluids, derived from micromodel image analysis..

Drying of bacteria-laden brine (Brine–medium with *Paracoccus denitrificans*)

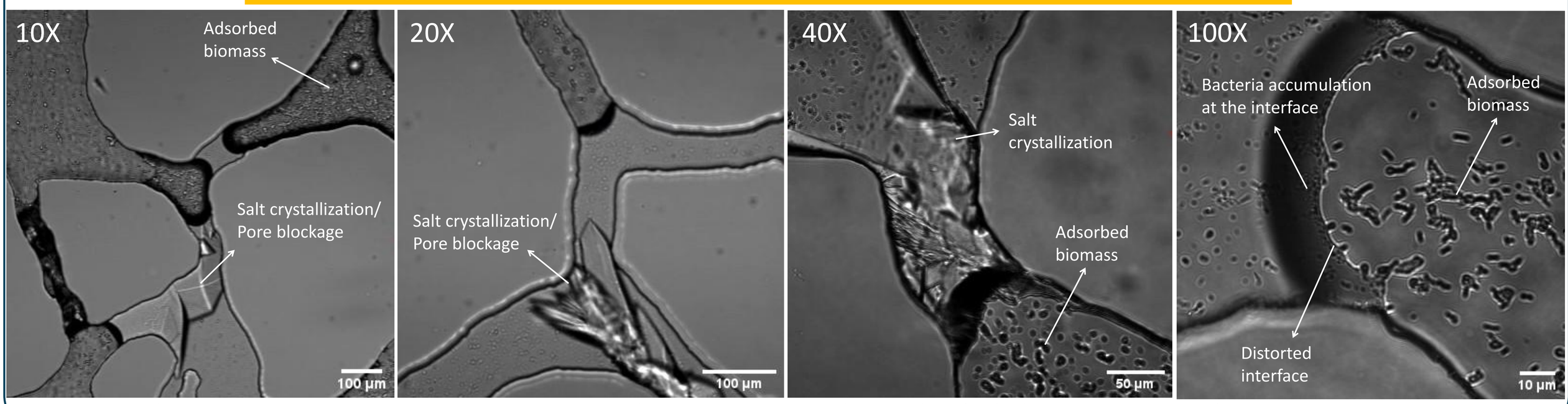

Fig. 4: Evidence of biomass aggregation, bacterial adsorption on walls, and salt crystallization during evaporation of microbial brine (confocal laser scanning microscopy).

Conclusions

- **Composition determines the pathway:** Fluid composition controls drying toward either pore-blocking crystals or more open, film-like coatings.
- **Bacteria suppress bulk salt growth:** Denitrifying bacteria change salt nucleation toward wall-associated biomass and scattered microcrystals, leading to varied evaporation rate.
- **Transport-precipitation coupling:** Partial or complete pore blockage by crystals diverts air–liquid flow pathways and alters local evaporation; Biomass films keep more pathways liquid-conductive, sustaining drying.
- **Interface dynamics:** Time-resolved imaging links drying-front pinning/depinning to subsequent crystal bursts or biomass accumulation.

Acknowledgement

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References

[1] R.J. Flatt, F. Caruso, A.M.A. Sanchez, G.W. Scherer, Chemo-mechanics of salt damage in stone, Nature Communications, 5 (2014) 4823.

[2] W. De Muynck, N. De Belie, W. Verstraete, Microbial carbonate precipitation in construction materials: A review, Ecological Engineering, 36 (2010) 118-136.

[3] X. Liu, R.J. Koestler, T. Warscheid, Y. Katayama, J.-D. Gu, Microbial deterioration and sustainable conservation of stone monuments and buildings, Nature Sustainability, 3 (2020) 991-1004.

[4] P. Bacchin, J. Leng, J.-B. Salmon, Microfluidic Evaporation, Pervaporation, and Osmosis: From Passive Pumping to Solute Concentration, Chemical Reviews, 122 (2022) 6938-6985.