Experimental Investigation of Salt Precipitation in a Free-Flow/Porous-Media Microfluidic System

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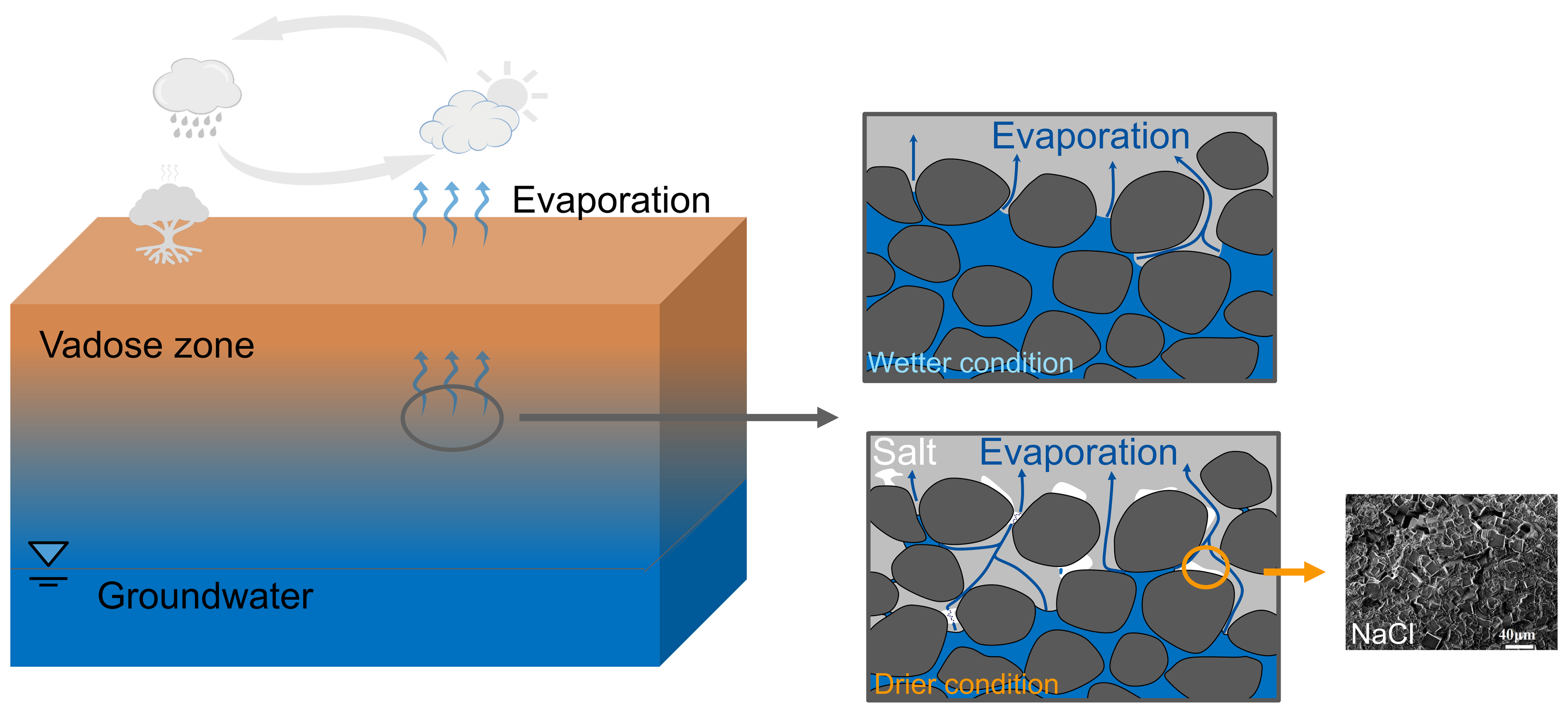
1 Introduction



Schematic of salt precipitation in a free-flow/porous-media system

- ❖ Evaporation in porous media with salt precipitation is an important process that can be encountered in many applications (e.g., soil salinization in arid and semi-arid regions).
- ❖ As water evaporates, the salt concentration increases at the evaporation front. When it exceeds the solubility limit, salt begins to precipitate, forming salt crust with submicronic pores.
- ❖ The salt crust alters pore sizes and connectivity, which in turn affects vapor transport and liquid flow. These coupled processes ultimately shape the evaporation dynamics.

Knowledge gap:

- ➢ Mechanisms governing evaporation in porous media with salt crust remain poorly understood, thereby preventing rigorous representations in mathematical models.

2 Research questions

I. How does precipitated salt affect evaporation behavior in porous media?

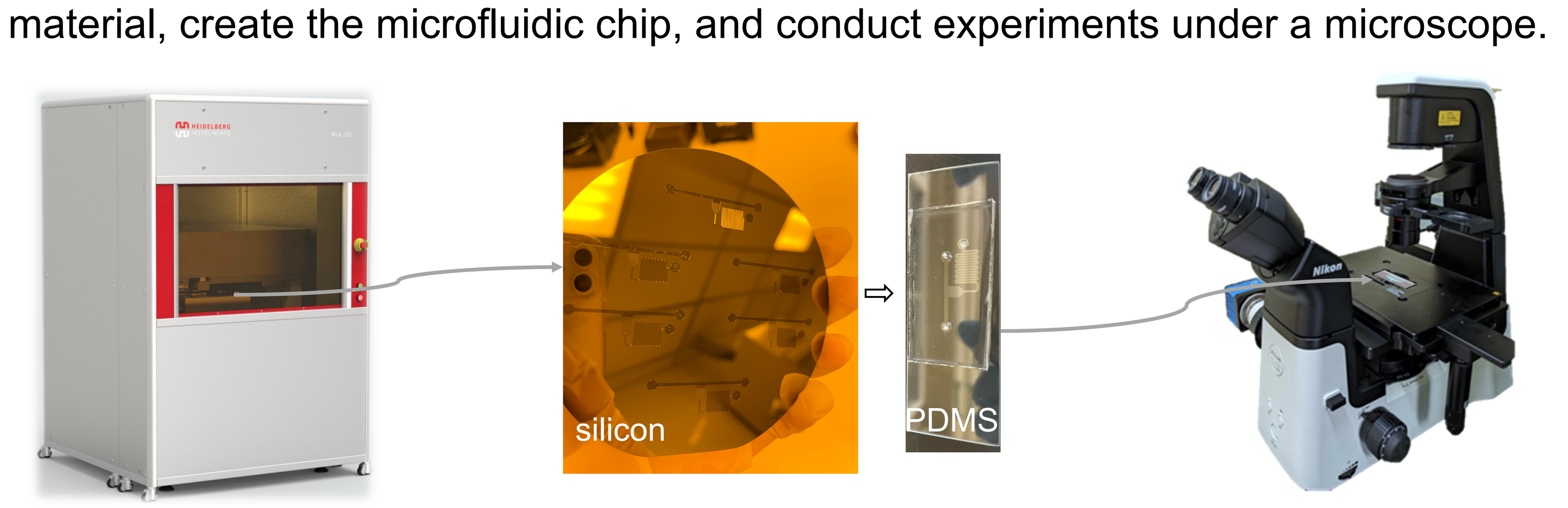
II. For example, how does precipitated salt alter the soil water characteristic curve and the relationship between relative permeability and saturation?

3 Methods

- ❖ We conduct microfluidic experiments to investigate the pore scale evaporation behavior, because many controlling processes in evaporation-driven salt precipitation are acting at the pore scale.
- ❖ Microfluidic experiments conducted under well-controlled conditions with high-resolution visualization offer a powerful approach to elucidating the key processes governing salt precipitation at the pore scale.

Main steps:

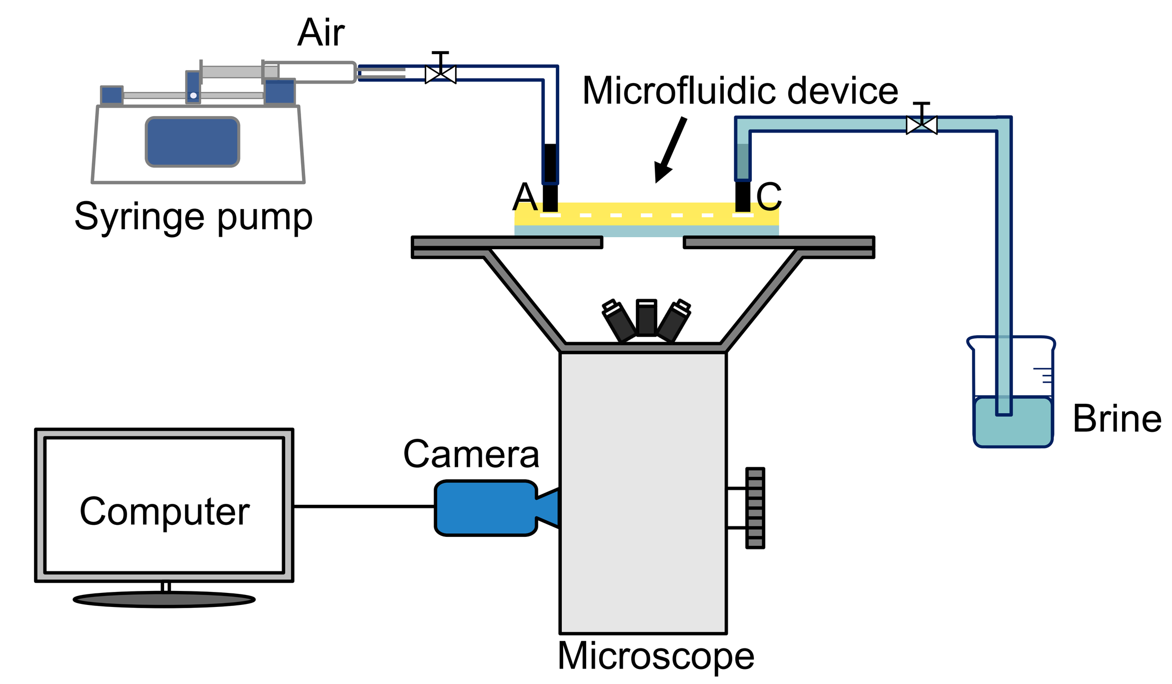
- ➢ We use photolithography to transfer the design onto a transparent and stable material, create the microfluidic chip, and conduct experiments under a microscope.



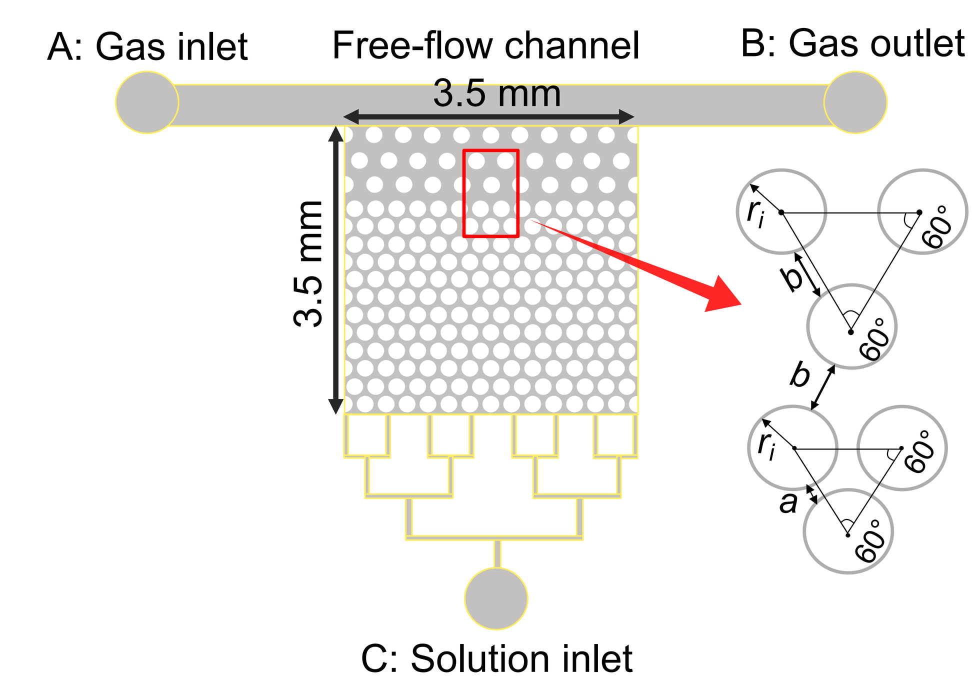
Lithography tool | Patterned chips | Inverted microscope

4 Microfluidic Experiments

Microfluidic visualization experiment system



The design of the microfluidic device



- The micromodel consists of a porous region, a free-flow channel, a brine reservoir supplying salt water to the porous region as evaporation occurs, two inlets (A and C), and one outlet (B) that is open to the atmosphere.
- The microfluidic device has a thickness of approximately 45 μm.

Objectives:

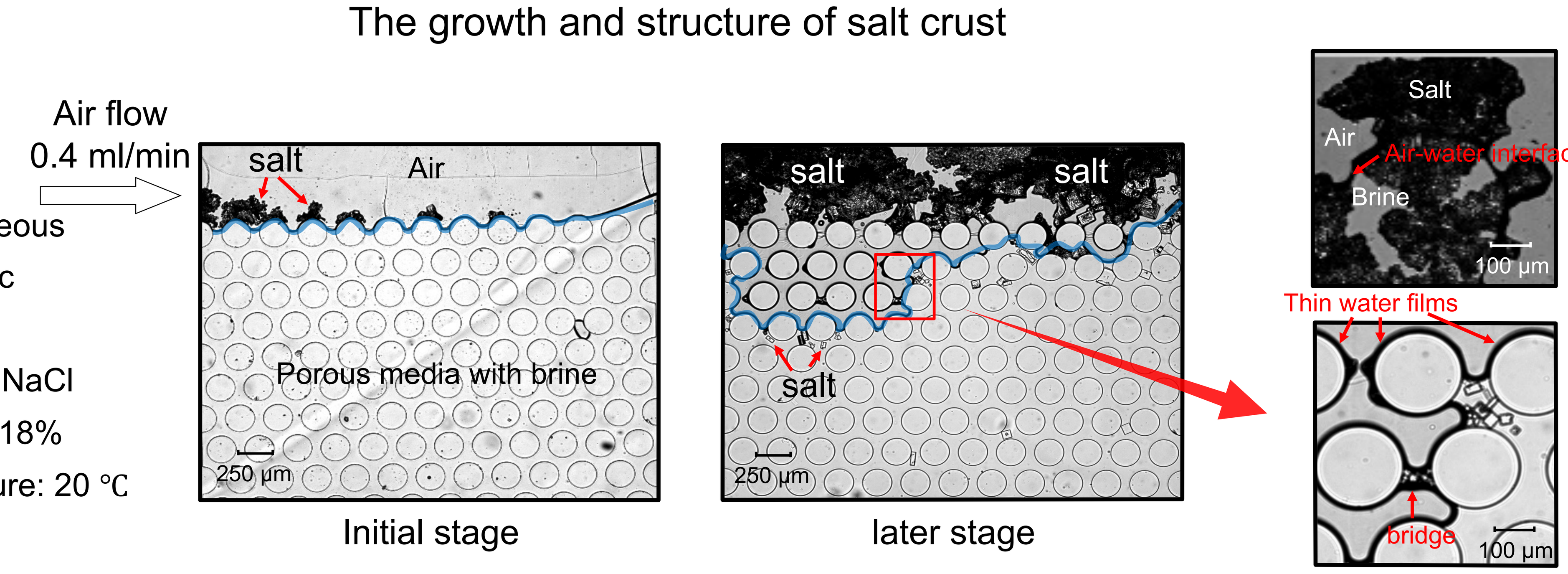
- ➢ Observe and quantify the evaporation and salt precipitation behavior in free-flow/porous-media micromodels.
- ➢ Investigate the impact of microfluidic micromodels with different heterogeneities and different salt compositions on precipitation patterns and dissolution dynamics.
- ➢ Provide a comprehensive dataset for refining and validating mathematical models to simulate evaporation and salt precipitation in such systems.

The results of these detailed pore-scale considerations will be used to identify relevant processes and find relations between pore-scale and macro-scale parameters, and to improve the macro-scale models.

5 Preliminary Results

The growth and structure of salt crust

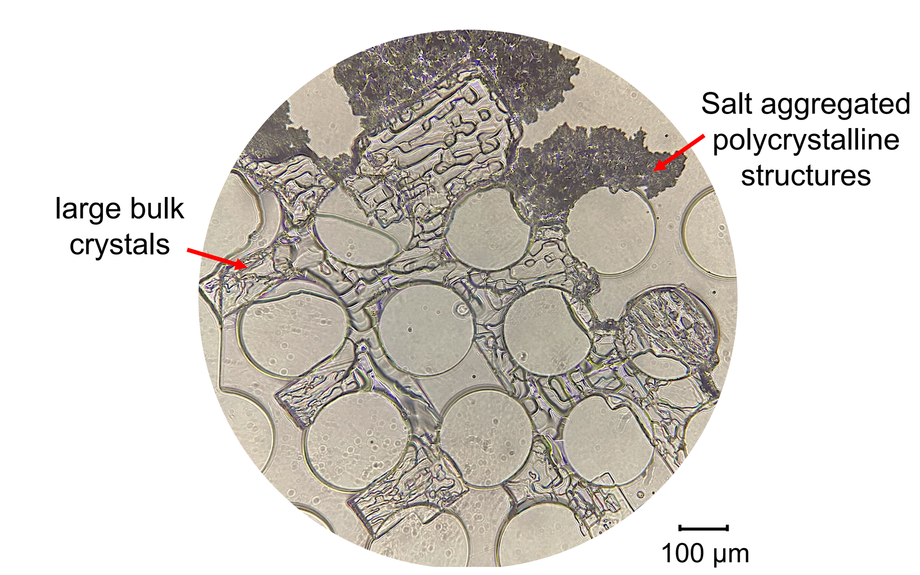
- Homogeneous
- Hydrophilic
- Saturated
- Brine: 2M NaCl
- Humidity: 18%
- Temperature: 20 ℃



Initial stage | later stage

- ➢ In the saturated free-flow/porous-media system, salt precipitation initially occurs at the surface of the porous medium.
- ➢ The resulting salt crust acts as a porous structure, drawing water upward and facilitating further salt deposition in a tree-like growth pattern.
- ➢ Thin water films and liquid bridges play a crucial role in transporting brine and sustaining salt crust formation.

Observed high crystallization pressure



- ➢ The high crystallization pressure causes the PDMS device to degrade, resembling the deterioration of building materials due to salt precipitation.

6 Summary

- ➢ We have developed a microfluidic platform that enables the systematic investigation of evaporation and salt precipitation at the pore scale.
- ➢ Through microfluidic experiments, we observed the evaporation-driven salt precipitation in a free-flow/porous-media porous medium.
  - The porous salt crust absorbs water and promotes further salt deposition.
  - Thin water films and liquid bridges play a crucial role in transporting brine and sustaining salt crust growth.
  - High crystallization pressure causes significant degradation of the PDMS device, highlighting the necessity of using harder materials (e.g., NOA81) for such experiments.

7 Future Work

We will combine pore-scale modeling and experimental observations to explore improved representations for

- ➢ **Soil characteristic curve**: Use a quasi-static pore network model to simulate the variation of capillary pressure at different saturations. This is done by considering the pore structure and fluid surface tension, applying the Young-Laplace equation to derive the relationship between capillary pressure and saturation.
- ➢ **Relationship between relative permeability and saturation**: Use tube and bundles of tube models to simulate fluid flow in porous media and calculate relative permeability (k_r) at different saturations (S). Changes in the porous media with saturation directly affect relative permeability, revealing the k_r-S relationship.