Mineral dissolution and wormholing from a pore-scale perspective

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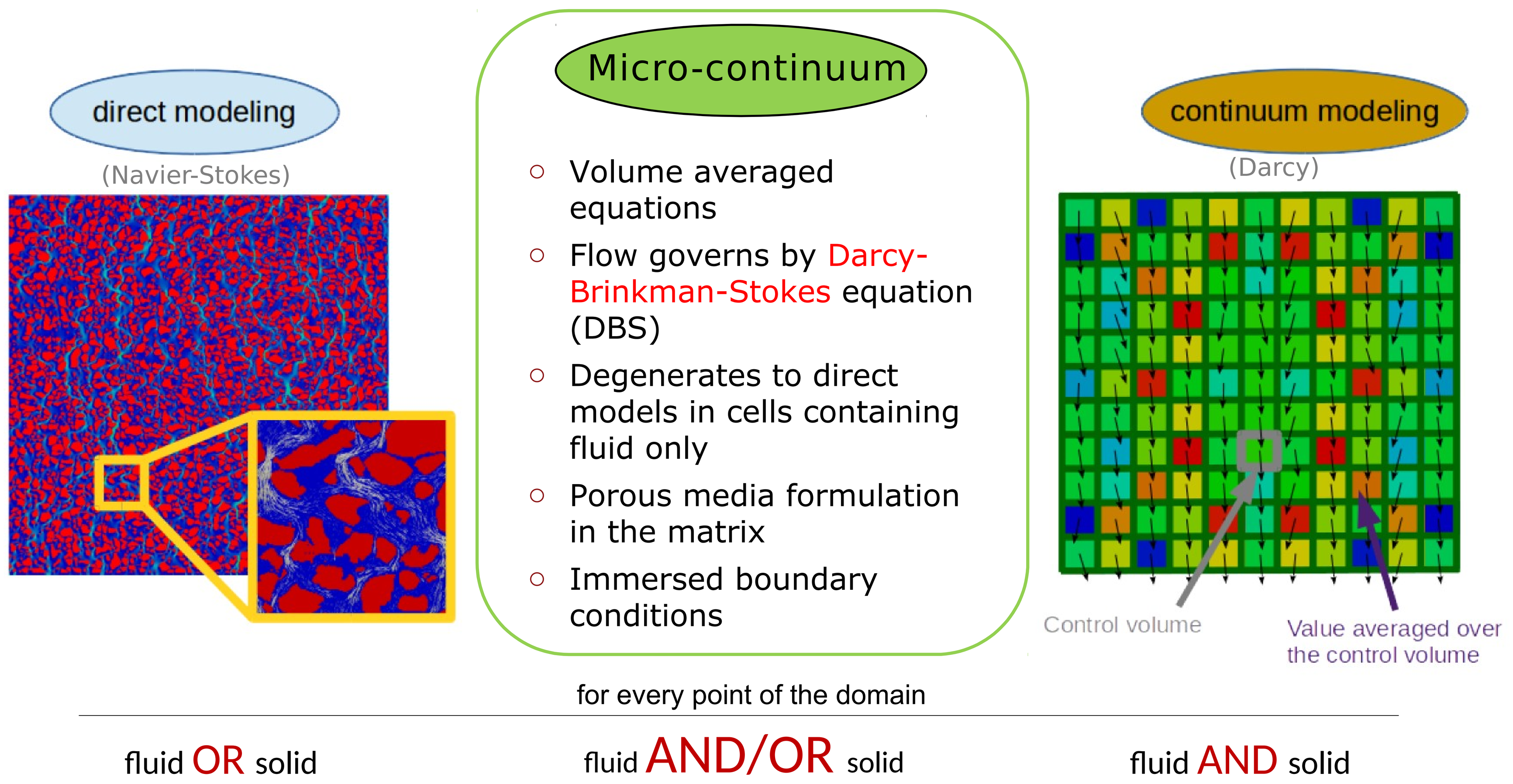
Introduction

- A micro-continuum approach is proposed to simulate the dissolution of solid minerals at the pore-scale. The approach employ a the Darcy-Brinkman-Stokes formulation and locally averaged conservation laws combined with immersed boundary conditions for the chemical reaction at the solid surface.
- The simulation framework is validated using an experimental microfluidic device to image the dissolution of a single calcite crystal. The evolution of the calcite crystal during the acidizing process is analyzed and related to flow conditions, i.e., Péclet and Damköhler numbers.
- Macroscopic laws for the dissolution rate are proposed by upscaling the pore-scale simulations.
- Finally, the emergence of wormholes during the injection of acid in a two-dimensional domain of calcite grains is discussed based on pore-scale simulations.

Micro-continuum model



Darcy-Brinkman model

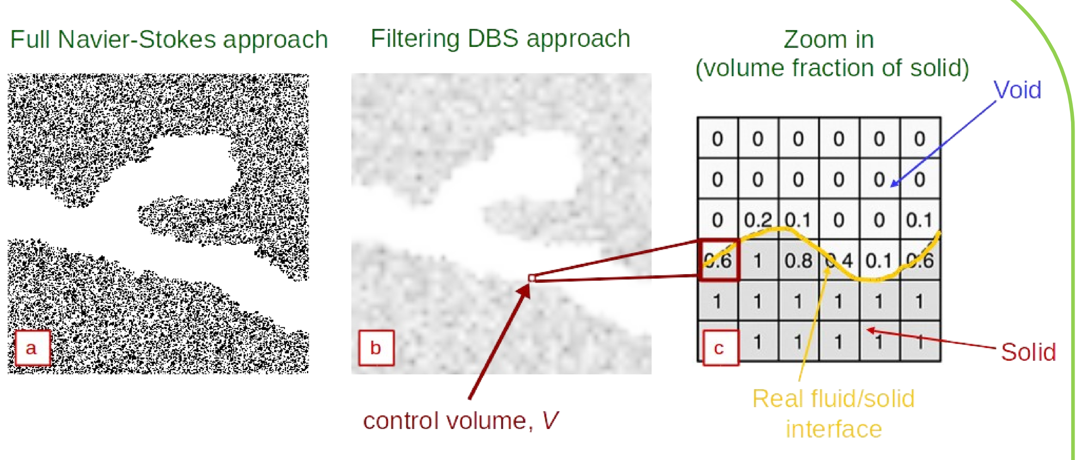
$$0 = -\nabla \bar{p}_f + \frac{\mu_f}{\varepsilon_f} \nabla^2 \bar{\mathbf{v}}_f - \mu_f k^{-1} \bar{\mathbf{v}}_f$$

Mass balance for solid

$$\frac{\partial \varepsilon_s \rho_s}{\partial t} = -\dot{m}$$

Mass balance for fluid

$$\frac{\partial \varepsilon_f \rho_f}{\partial t} + \nabla . \left(\rho_f \bar{\mathbf{v}}_f \right) = \dot{m}$$



Mass balance equation of acid in the fluid

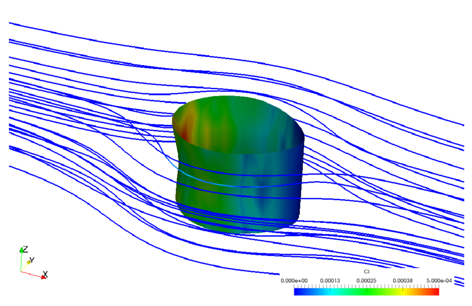
$$\frac{\partial \varepsilon_f \rho_f \bar{\omega}_{f,A}}{\partial t} + \nabla . \left(\rho_f \bar{\mathbf{v}}_f \bar{\omega}_{f,A} \right) = \nabla . \left(\varepsilon_f \rho_f D_A^* \nabla \bar{\omega}_{f,A} \right) - \dot{m}_{f,A}$$

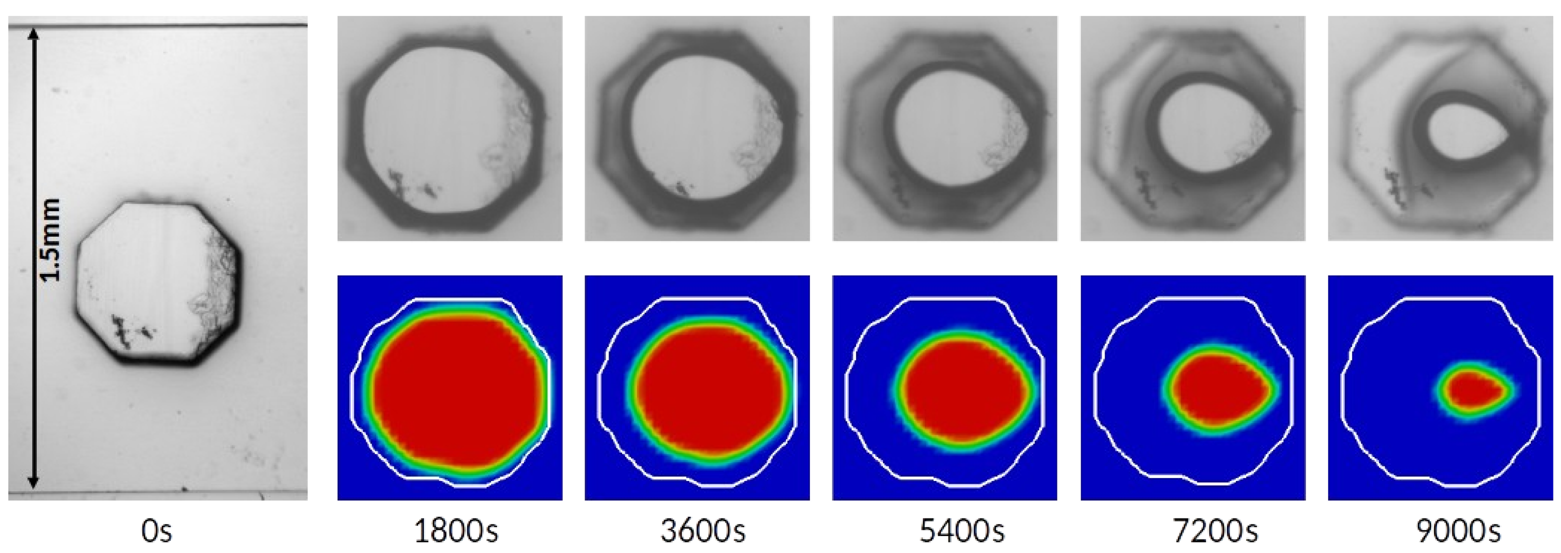
Rate of dissolution

$$\dot{m} = \Gamma \dot{m}_{f,A} \qquad \dot{m}_{f,A} = \rho_f \alpha^* \left(\bar{\omega}_{f,A} - \omega_{eq} \right) \qquad \alpha^* = k a_v = k \left\| \nabla \varepsilon_s \right\|$$

Validation of the model

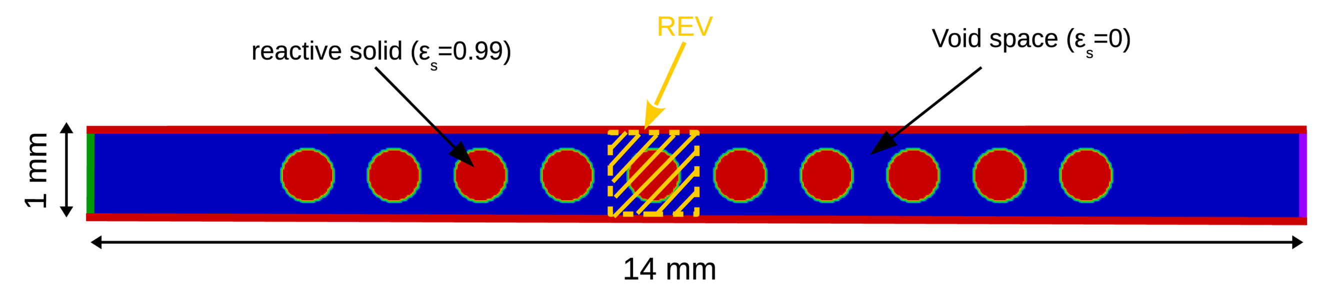
- Dissolution of a calcite crystal in a micro-channel,
- Acquisition of a high resolution dataset to compare with numerical simulations,
- 3D simulations with the micro-continuum approach.



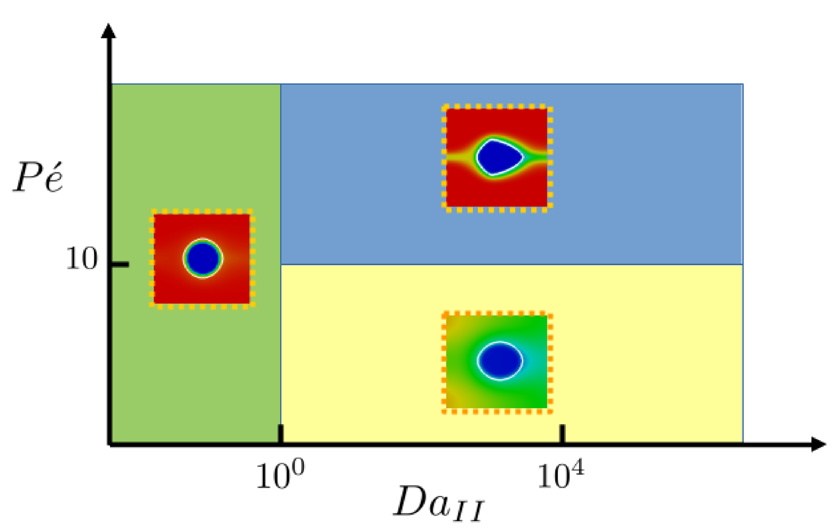


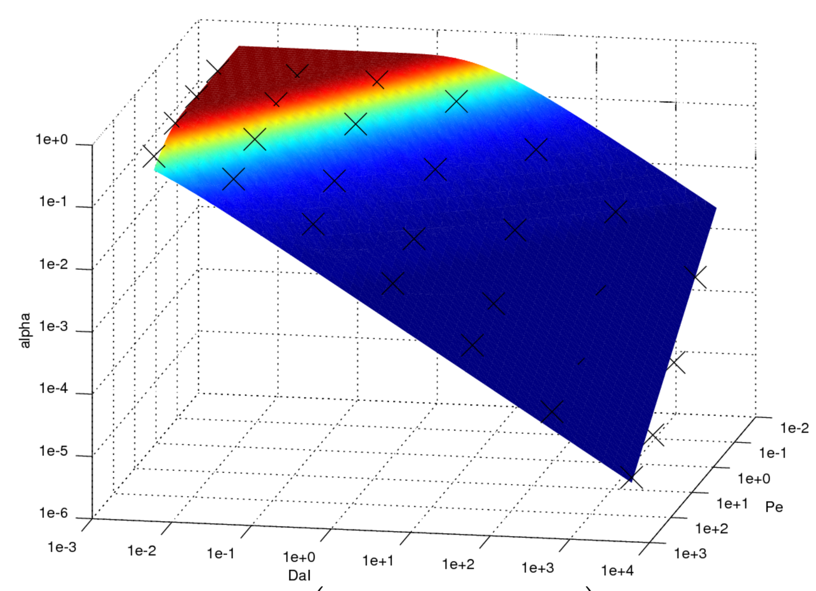
Upscaling dissolution processes

- The DBS framework is used to investigate the effective properties of a porous medium model,
- First, the pore-scale problem is solved on a geometry made of a succession of REV. Then, the results are volume averaged on a REV,
- Identification of 3 dissolution regimes according to the injection flow rate and the mineral reactivity,
- Characterization of a correction factor, alpha, that reduces the surface area accessible to the acid according to the hydrodynamics conditions.



$$\langle \dot{m}_A \rangle = A_e k \alpha \left(\langle C_A \rangle - C_{eq} \right)$$

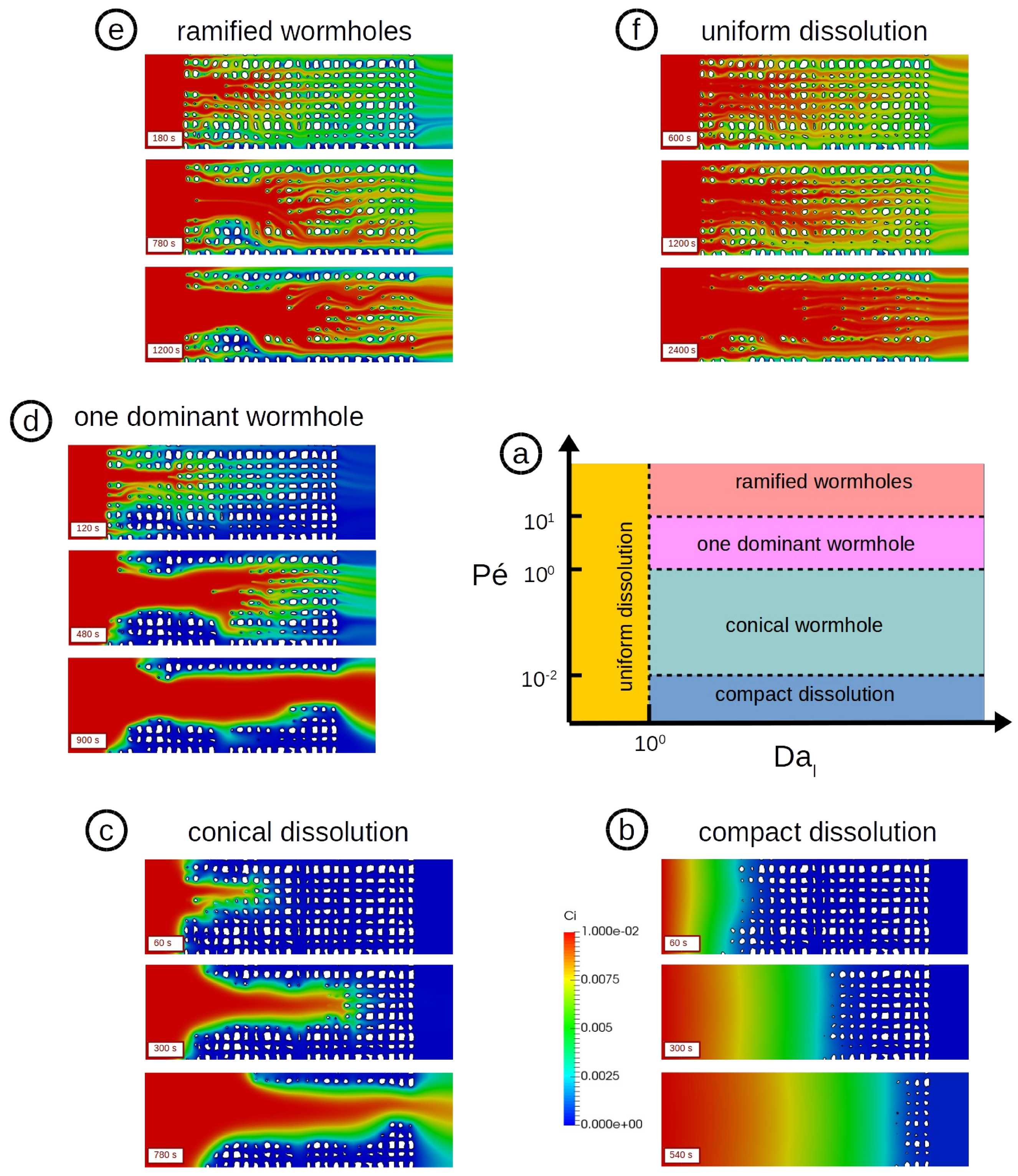




$$\alpha = 1 - \exp \left(-Pe^{-n} \left(\frac{Da_{II}}{Pe} \right)^{-m} \right)$$

Emergence of dissolution wormholes

- Identification of 5 dissolution regimes according to the injection flow rate and the mineral reactivity,
- Emergence of dissolution instability due to the local heterogeneities in the velocity profile,
- Direct consequences on the mean dissolution rate and the permeability/porosity relationship.



Acknowledgements

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References

Soulaine and Tchelepi, *Micro-continuum approach for pore-scale simulation of subsurface processes*, Transport in Porous Media (2016)

Soulaine et al., *Mineral dissolution and wormholing from a pore-scale perpective*, Journal of Fluid Mechanics (under review)