Pore-scale mixing and reactions in porous media

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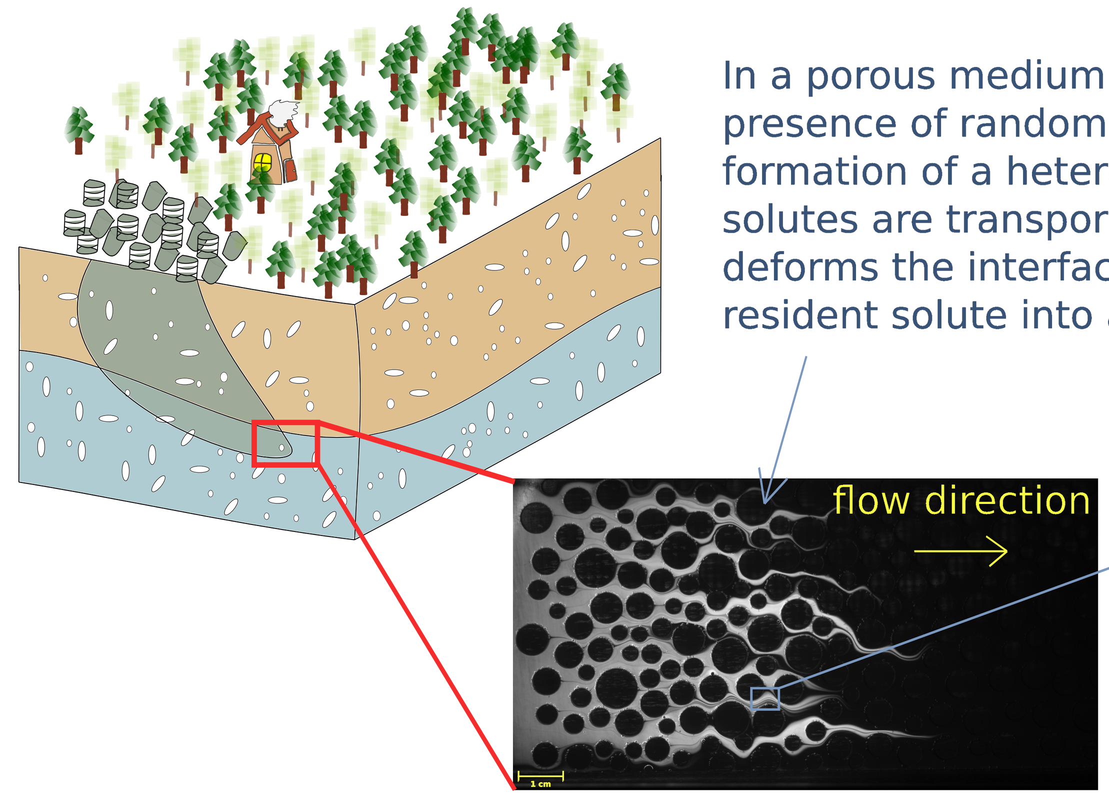
Why pore scale observations?

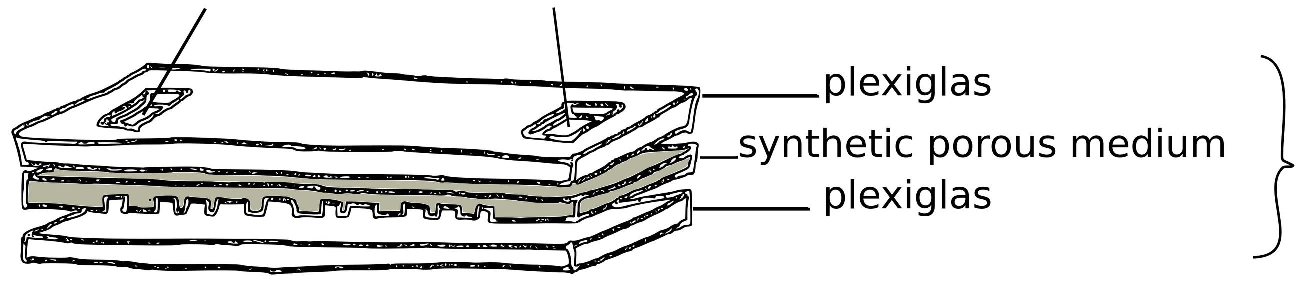


In a porous medium such as a portion of soil the presence of random obstacles (grains) leads to the formation of a heterogeneous flow field. While solutes are transported the contrast of velocities deforms the interface between invading and resident solute into a fingering topography.

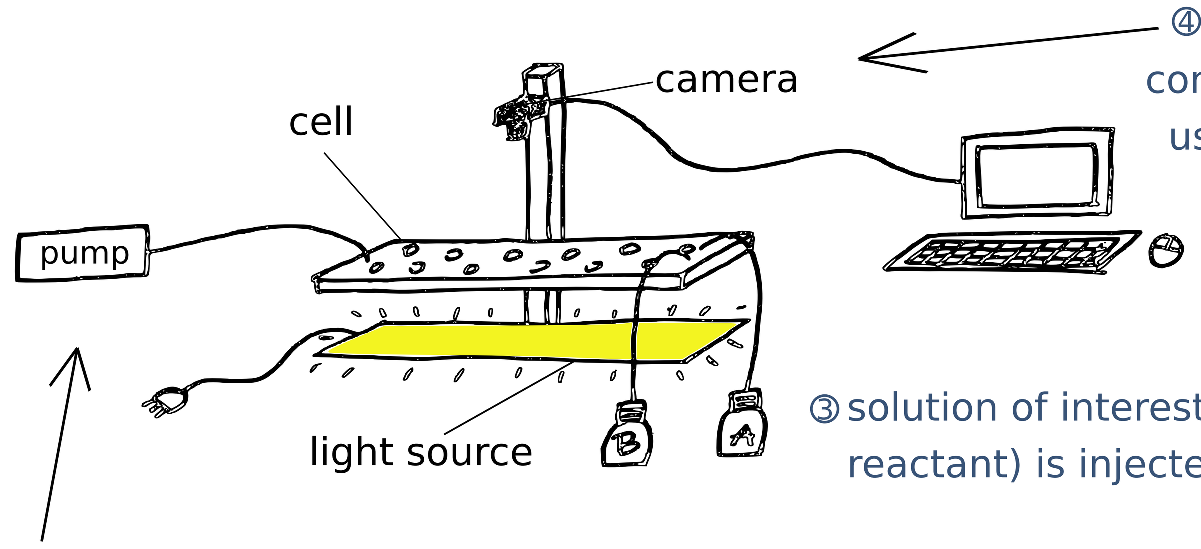
This flow heterogeneity leads to a broad distribution of concentrations within pores. This implies that the concentration gradient varies locally along the interface.

In the case of reacting solutes the reaction is driven by concentration gradients: the reactants get mixed along their front by molecular diffusion. To predict reaction rate the local concentration should be considered at the scale at which mixing happens: the pore scale.

Using millifluidic flow cell



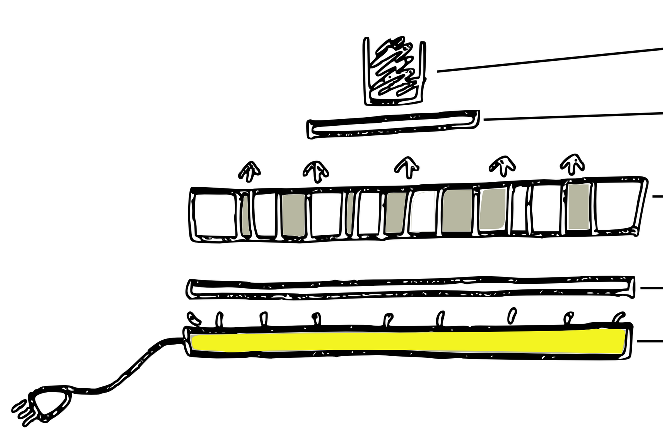
① porous medium is enclosed between two plexiglas plates and saturated



④ image of the displacing concentration field is recorded using a computer controlled camera

③ solution of interest (conservative tracer or reactant) is injected in the medium

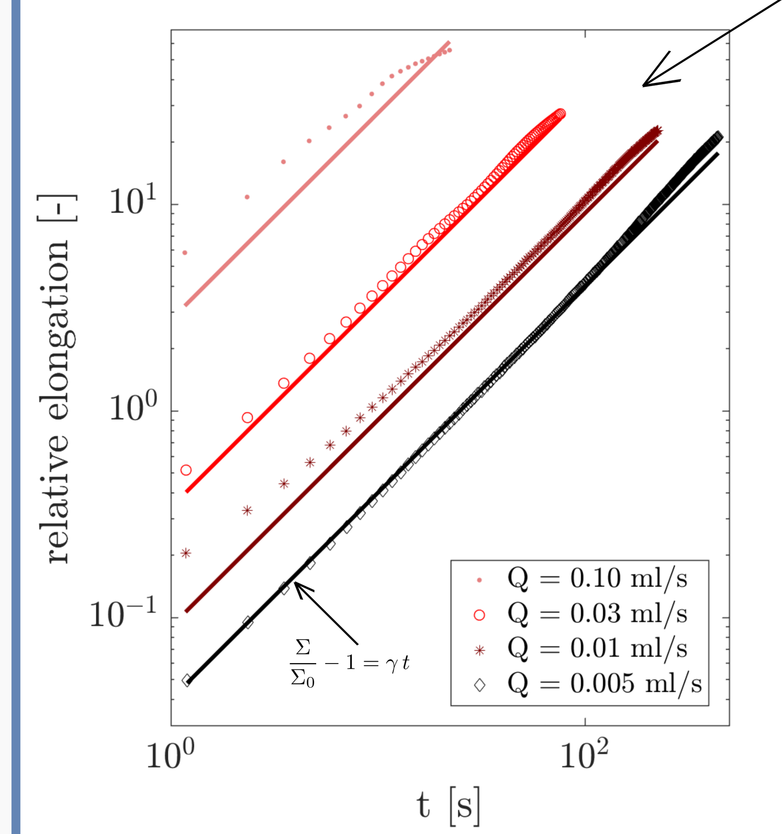
② flow is created using a syringe pump



Fluorescein is used as conservative tracer; the fluorescent tracer is excited by a light source at a wave length of 494 nm and emits back at 512 nm, a pair of low-pass and band-pass filters allows that only the signal emitted by the tracer reaches the camera lens.

How solutes are transported ?

The displacement of a conservative and fluorescent tracer in a synthetic porous medium is visualized using classical photography.



Time evolution of the measured interface between tracer and resident water for different flow rates. As the concentration field moves forward the heterogeneous structure of the medium stretches the interface in the local flow direction, this results in increasing the length of the interface.

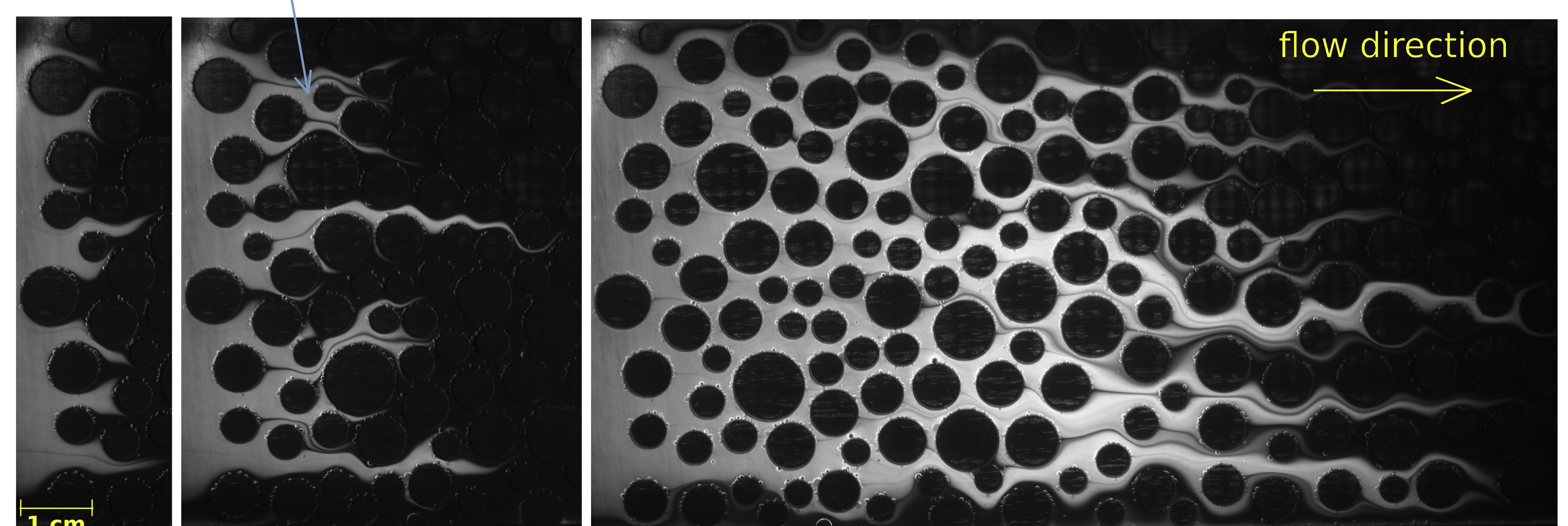
This evolution is well described by a linear growth model (solid line)

$$\Sigma = \Sigma_0 \left(1 + \gamma t\right)$$

interface length

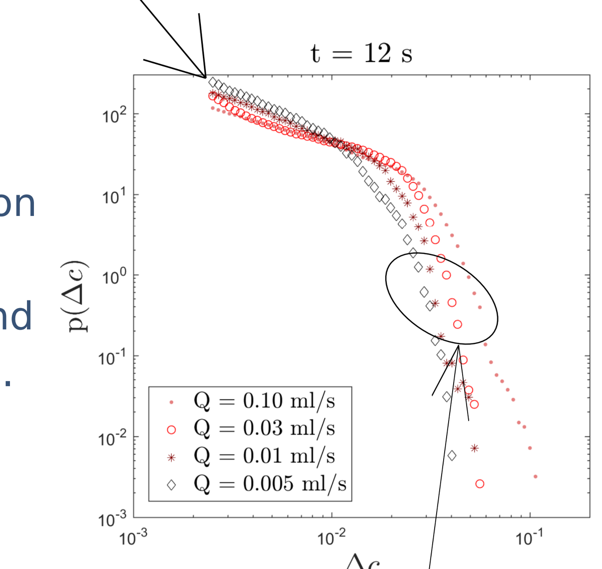
stretching rate that is proportional to the applied flow rate

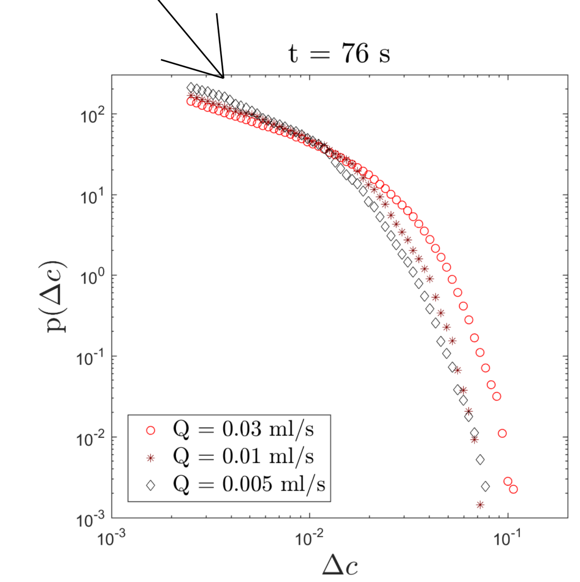
Light intensity recorded by the camera is related to tracer concentration through a calibration procedure.



t_0 = 0 s t_1 = 12 s t_2 = 76 s

From the concentration field, gradient of concentration field and its PDF are computed.

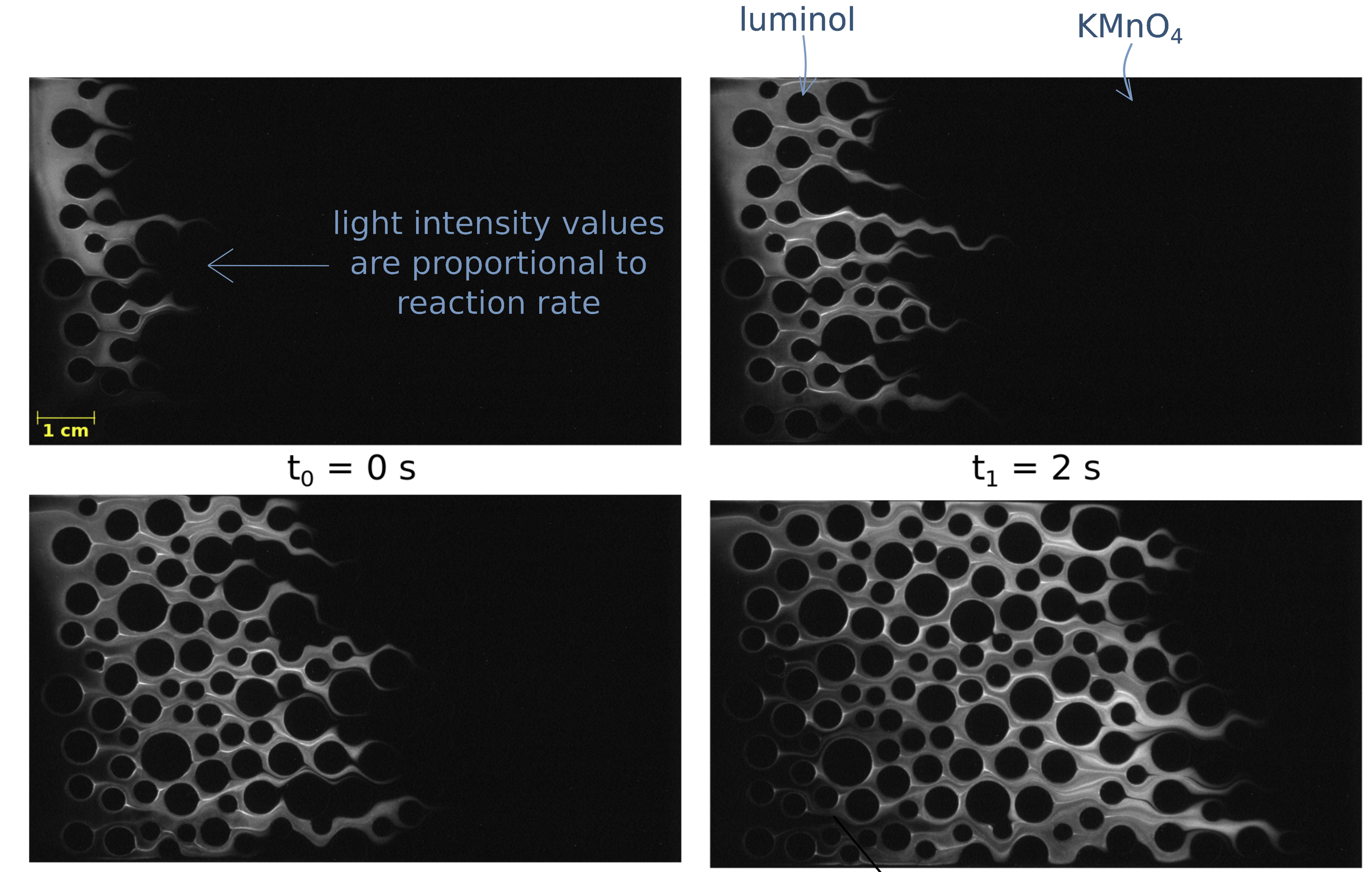




PDFs tend to be sorted by flow rate: higher flow rates lead to higher concentration gradients. This indicates that higher flow rates keep sharper gradient for longer.

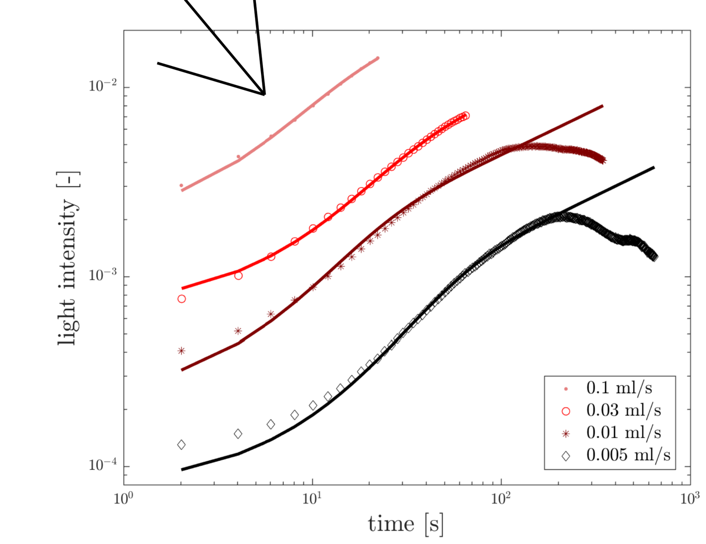
Where do chemicals react?

The displacement of a reactive front produced by the chemiluminescent reaction between luminol and $KMnO_4$ is observed. The reaction kinetics is A+B -> C and is faster than the transport process.



t_0 = 0 s t_1 = 2 s t_2 = 5 s t_3 = 11 s

The measure of the reaction rate is well described by a model (solid line) based on mass conservation. The model defines the reaction rate as a function of average concentration gradient and interface length.



average concentration gradient

$$\frac{dM_C(t)}{dt} = I(t) \approx D\,\frac{c_0}{s(t)}\Sigma_0\left(1+\gamma t\right)$$

Time evolution of mass of product C, measured by the light intensity of the reaction between solutes A and B.

front length with stretching rate γ measured during the conservative experiment

Work in progress...

- run the experiment in a longer porous medium to observe the regime of coalescence of the fingers
- run both conservative and reactive experiments in unsaturated conditions
- link the distribution of concentration to the distribution of reaction rates
- replace the chemical reaction by a biological one and observe the consumption of nutrient by microbial population (attend the talk "Flow through confined micro-structures in presence of microbial growth " #17598 at 11:15)