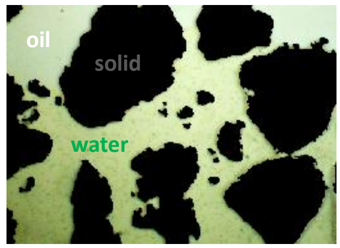
Particle image velocimetry analysis of immiscible two-phase flow through porous media at the pore scale

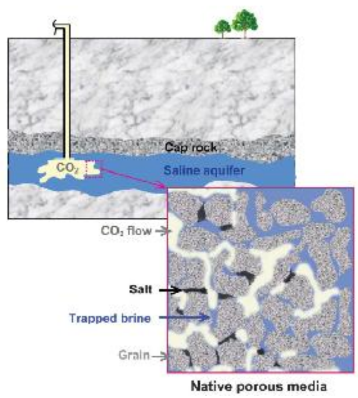


Sophie Roman*, Cyprien Soulaine, Moataz Abu AlSaud, Hamdi Tchelepi, Anthony Kovscek

*sroman@stanford.edu

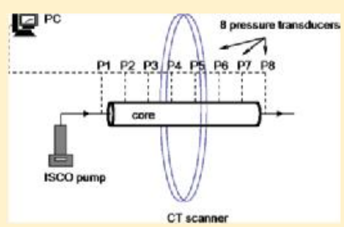
Multiphase Flow in Porous Media

Example of application:
CO_2 injection and sequestration



CO_2 sequestration into deep saline aquifer and pore-scale CO_2 flow in native porous media [1]

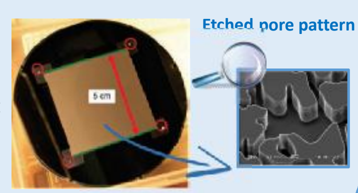
Experimental investigations



Core-scale two-phase immiscible drainage experiments [2]

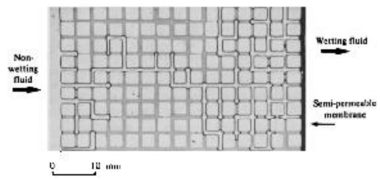
2D Micromodels [3]

- Provide direct visualization of the **pore-scale**
- Valuable to interpret observations at larger scale



[1] Kim et al. (2013) *Aquifer-on-a-Chip: understanding pore-scale salt precipitation dynamics during CO_2 sequestration.* Lab on a Chip 13, 2508.
[2] Aryana and Kovscek (2012) *Experiments and analysis of drainage displacement processes relevant to carbon dioxide injection.* Phys. Rev. E. 86, 066310
[3] Buchgraber et al. (2011) *A microvisual study of the displacement of viscous oil by polymer solutions.* SPE Reservoir Evaluation & Engineering 14, 269280.

Two-phase immiscible flow in micromodels



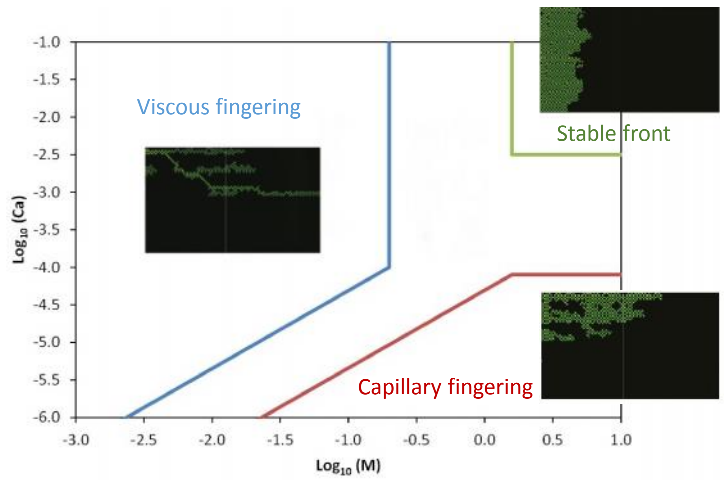
Lenormand, R., C. Zarcone, and A. Sarr (1983). *Mechanisms of the displacement of one fuid by another in a network of capillary ducts*. J. Fluid Mech. , 33753

Viscosity ratio: $M = \mu_{nw}/\mu_w$

Capillary number:
$Ca = \mu_{nw}.u_{nw} / (\sigma_{nw\text{-}w}.\cos\theta)$

nw: non-wetting, *w*: wetting

Zhang et al. (2011), *Influence of Viscous and Capillary Forces on Immiscible Fluid Displacement (…)*, Energy & Fuels 25, 3493-3



Micro-dynamics of two-phase flows

- Aim: to investigate the mechanisms of displacement of one fluid by another in micromodels at the pore-scale
- Direct numerical simulations of multiphase flows at the pore scale are still in development and need validation

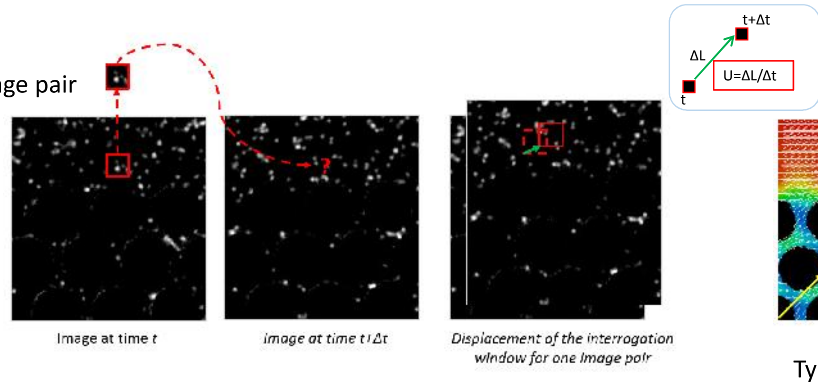
The **Particle Image Velocimetry** (PIV) technique, used to obtain instantaneous velocity measurements, appears useful and relatively unexplored to understand and quantify the mechanisms involved at the pore scale

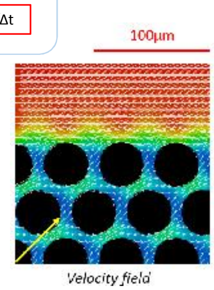
- PIV allows for quantitative comparisons between experimental and numerical data
- Previous studies: complex and expensive optical systems, simplified geometries, PIV measurements have not been validated

Particle Image Velocimetry (PIV)

To measure the displacements of tracer particles seeded in the fluid in a fixed time interval

Image pair





Typical PIV result

- The images are divided in a uniform grid of so-called interrogation windows.
- The image patterns in the interrogation windows in the images at *t* and *t+Δt* are compared statistically.
- The procedure is repeated for all interrogation windows resulting in a uniform grid of displacement information.
- The same procedure is repeated for several image pairs and the results are averaged.

*Adrian, R. J. and J. Westerweel (2011). *Particle Image Velocimetry*. Cambridge University Press.

Outline

I/ Introduction

II/ Experimental Setup

III/ Single Phase Flow: validation of the micro-PIV measurements in micromodels

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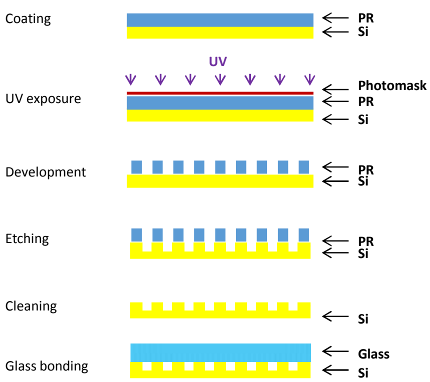
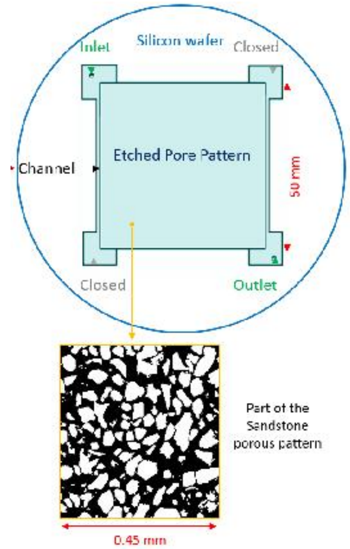
Experimental Setup: Micromodels

- Microfabrication of 2D etched-silicon micromodels



Etching depth: 12µm
Micromodel surface: water-wet

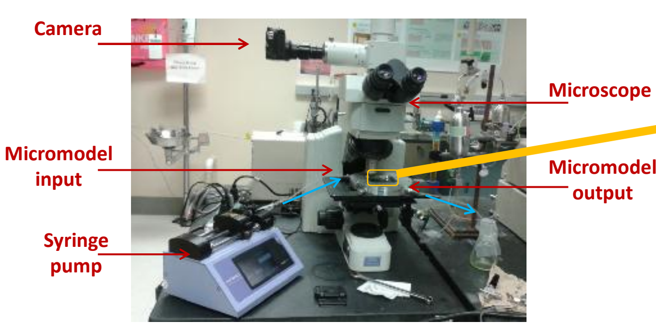
- Micromodels

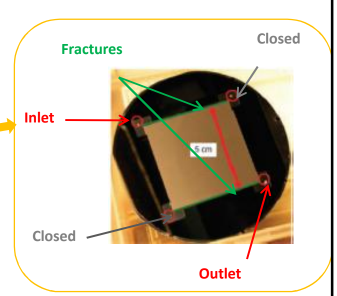


Sandstone pattern
(grains 30-200µm)
Pore throats<7µm

Buchgraber, M., et al. (2012). *Creation of a dual-porosity micromodel for pore-level visualization of multiphase flow*. Journal of Petroleum Science and Engineering 86-87.

Experimental Setup





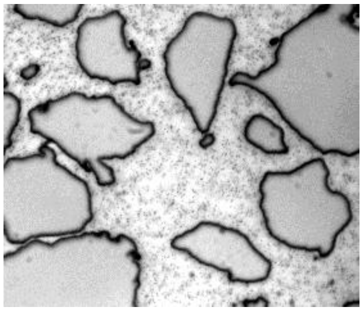
The water is seeded with **Carboxylate Modified Latex Microparticles**:

- 1µm diameter: to follow the flow without disturbing it
- negatively charged, hydrophilic: minimize particle aggregation and binding to the walls
- particle density ≈ water density, to avoid sedimentation.

→ Sequences of images of the flow are recorded

Image processing

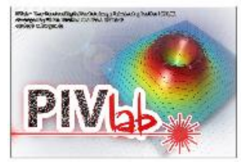
50µm



Original image sequence
X200

After image processing: bright particles, dark background and grain detections

- Noise removal
- Correction of light intensity fluctuations
- Calculation of the background image
- Grain detection
- Subtraction of the background and the grains



*PIV tool for MATLAB**

*Thielicke, W. & Stamhuis, E. J. (2014): *PIVlab - Time-Resolved Digital Particle Image Velocimetry Tool for MATLAB* (version: 1.35)
**Lindken, R. et al. (2009), *Micro-particle image velocimetry (µ-PIV): Recent developments, applications, and guidelines*, Lab Chip 9(17) 2551-2567

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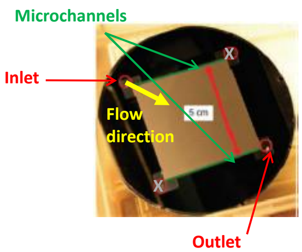
PIV measurements in micromodels: validation

In the case of fully saturated micromodels, 2D direct numerical simulations are performed with OpenFOAM (Cyprien Soulaine, SUPRI-B).
The numerical results are compared with the data provided by PIV measurements.

Experiment

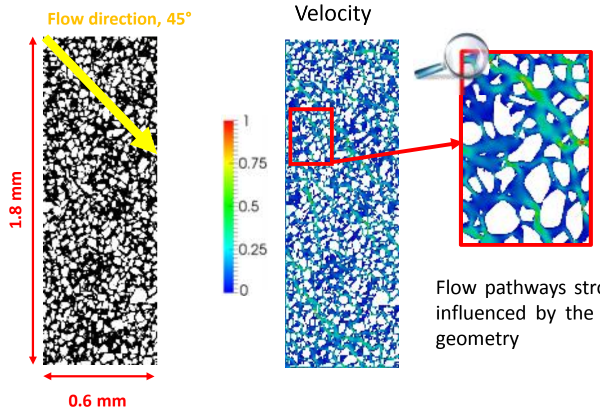


Fluid: water seeded with micro-particles

Q=1.10^{-4} to 1.10^{-3}mL/min

Numerical Simulation

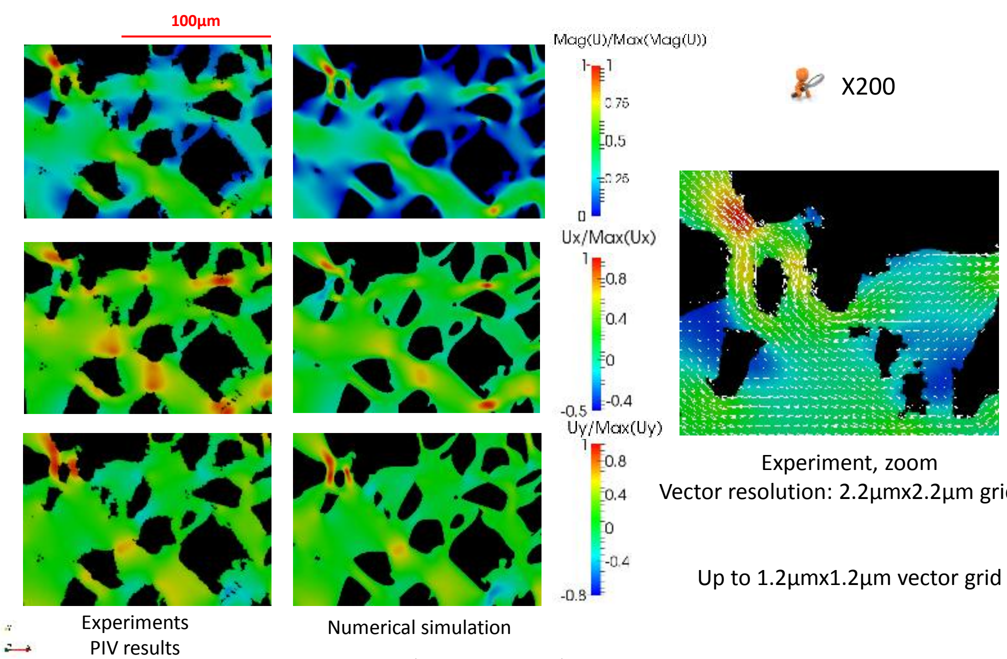
periodic boundary conditions



Flow pathways strongly influenced by the pore geometry

PIV measurements in micromodels: validation

Sandstone pattern: single phase flow



Experiments
PIV results

Numerical simulation

Experiment, zoom
Vector resolution: 2.2µmx2.2µm grid

Up to 1.2µmx1.2µm vector grid

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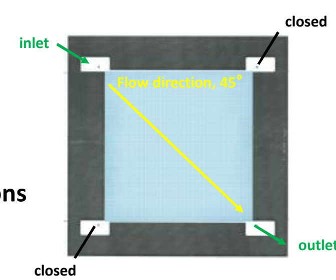
Two-phase flow experiment



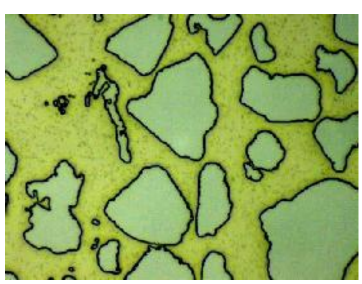
Fluid properties

Wetting fluid: 65%water, 35%glycerin +UV-dye + particles
Non-wetting fluid: n-heptane
Viscosity ratio: µnw/µw=0.145

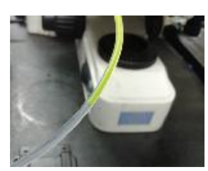
Representative of CO_2/brine system under aquifer conditions

Drainage experiment

1) Micromodel saturated with the wetting fluid
2) Injection of the non-wetting fluid at $2.5.10^{-3}$mL/min
3) Acquisition of movies at different locations in the micromodel



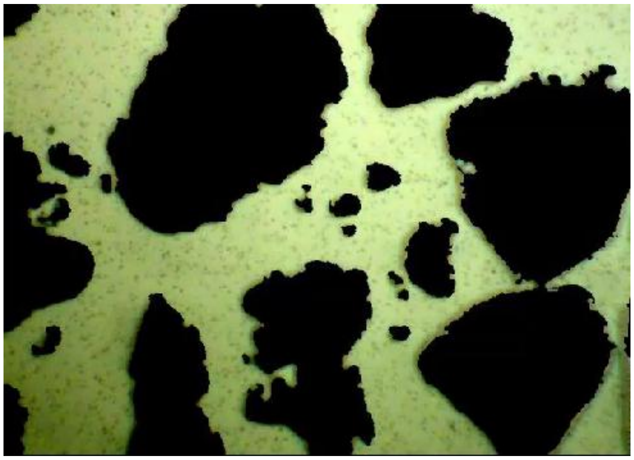
Advancing non-wetting phase



Oil pushing dyed water before entering the micromodel

Microdynamics of two-phase flow

50µm



Green: water /glycerin + particles
White: n-heptane
Black: grains

Flow instabilities due to interface migration may induce pressure instabilities that propagate further downstream → perturb the wetting phase before the passage of the interface*

Flow direction *Sequence of images after image processing*

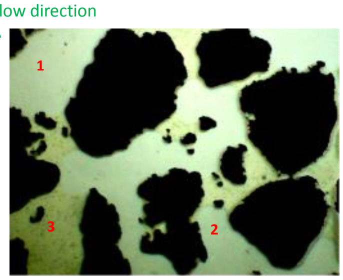
Blois, G, Barros J., Christensen K. (2015). A microscopic particle image velocimetry method for studying the dynamics of immiscible liquid-liquid interactions in a porous micromodel.* Microfluidics and Nanofluidics, 1-16

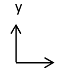
Microdynamics of two-phase flow

µ-PIV results

Displacement along x (Ux) and along y (Uy) of the wetting phase as a function of time for 3 positions in the porous medium

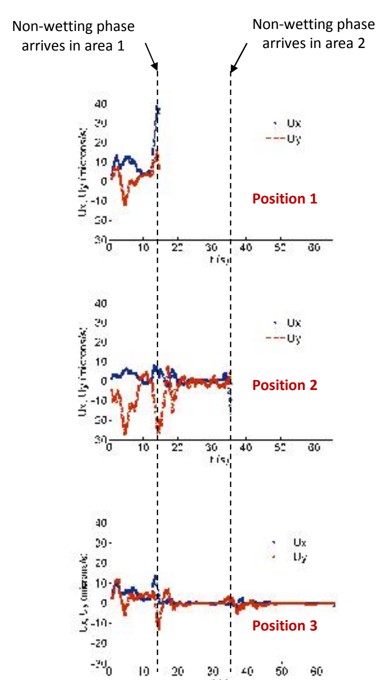
Flow direction





50µm

Last image of the sequence



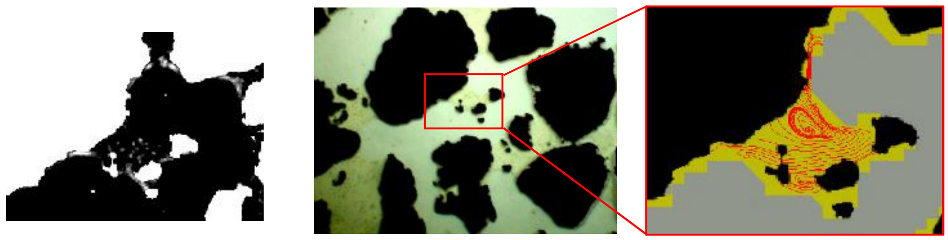
Microdynamics of two-phase flow

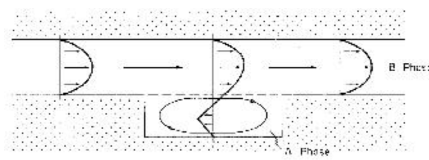
Observation and measurement of recirculation intensity

Driven cavity flow due to the shear stress resulting from the non-wetting phase that is still flowing.

→ Are viscous dissipation terms really negligible at larger scale?

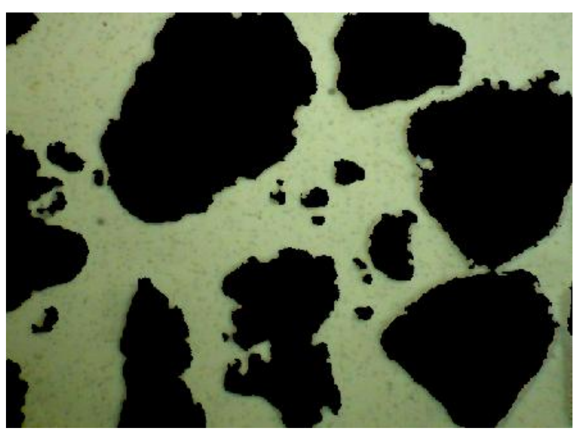
→ What are the consequences on multicomponent mass transport?





Rose, W.. (1960). Fluid flow in petroleum reservoirs: III. Effect of fluid-fluid interracial boundary condition.* Illinois State Geological Survey, 1-18

Microdynamics of two-phase flow
Interface tracking



Interface > **500** µm/s
Wetting phase: **20-100** µm/s

"Slow motion" of the advancing interface (highlighted in red)

→ Further investigations are needed to describe such fast jumps and their consequences

→ The micro-PIV setup developed offers new possibilities to characterize the complex microdynamics of the jumps.

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Conclusion

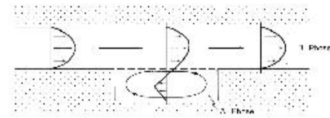
- Single phase flow: good agreement between experiments and numerical simulation
- PIV measurements in micromodels have been validated and optimized
- High resolution of velocity vectors : less than 2µmx2µm vector grids

We have a tool to investigate two-phase flow mechanisms in micromodels <u>quantitatively</u> with high accuracy

- The micro-PIV measurements during a drainage experiment have already shown interesting and complex behaviors
  - Oscillations of the wetting fluid before the passage of the interface
  - Dissipative recirculations during two-phase flow

Future work

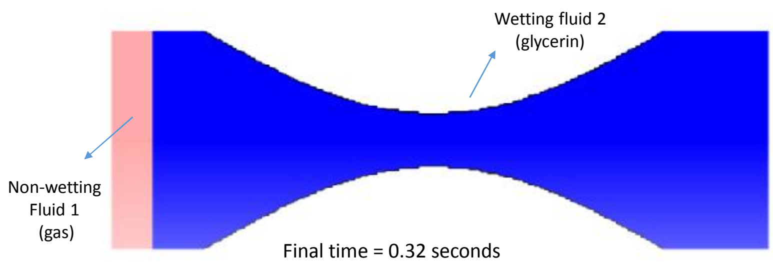
- Particles in both phases



- Quantification of re-circulations
- Parametric study of two-phase immiscible flows in simple geometries, comparison with direct numerical simulations under development

Converging-diverging tube drainage

(Numerical simulation, Moataz Abu AlSaud, SUPRI-B)



grid: 360 by 120

Thank you for your attention!

Questions?

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