

Introduction

Chaotic mixing in porous media plays an important role in environmental and industrial systems, with important consequences for reactive transport processes. Recent findings by optical imaging (**Fig. 1**) indicate that steady laminar flows through transparent bead packs produce chaotic microscale trajectories like turbulent flow but at low Reynolds numbers. This changes the current paradigm of reactive transport modeling as chaos enhances microscale chemical gradients and controls mixing rates. Yet, proving the existence of chaotic mixing in rocks, key for reservoir and storage applications, is a challenge. We have conducted purpose-designed laboratory experiments to demonstrate chaotic mixing in rocks at high resolutions at Imperial College London and the European Synchrotron Radiation Facility (ESRF).

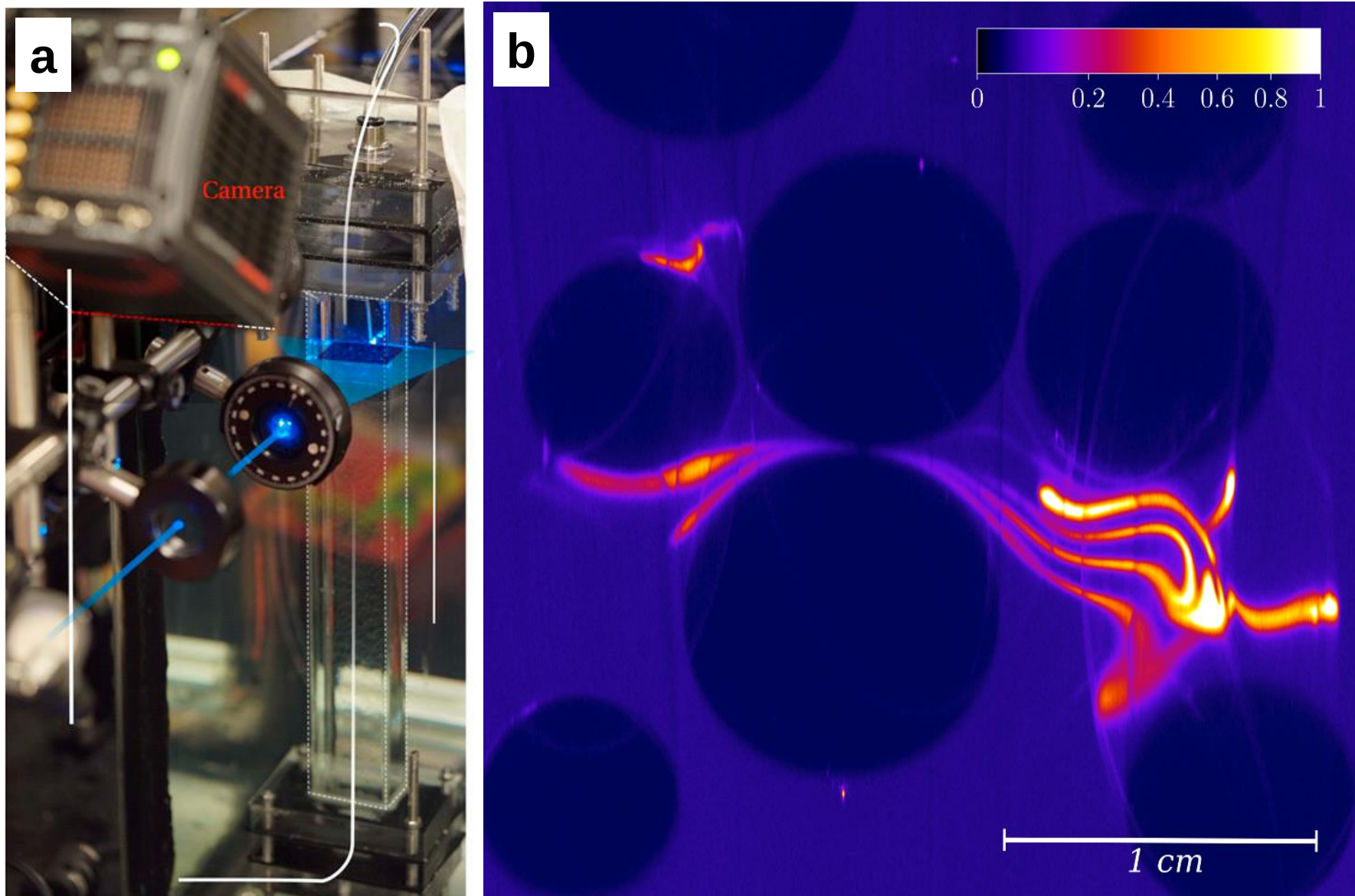


Fig. 1 (a) Experimental setup for three-dimensional imaging of the mixing of a fluorescent solute dye in optically matched porous bead packs. (b) The image shows the deformation of a fluorescent dye (color scale indicates the concentration of dye) while advected by a viscous fluid (glycerin and water) through a 3D random bead pack (blue disks) (Heyman et al. 2020).

Materials & Methods

Experimental phase at Imperial College London

Using a specially built core holder, we have reached $Pe \sim 10^3$ - 10^4 during co-injection of two miscible highly viscous fluids (**Fig. 2**) into natural rock samples (Bernheimer sandstone) and polydisperse bead packs (**Fig. 3**) for two different injection types: (1) point injection and (2) front injection (**Fig. 2**). We have imaged the co-injection of these two fluids in the rock/bead pack using the Heliscan setup at ICL (**Fig. 3**) at a relatively high resolution.

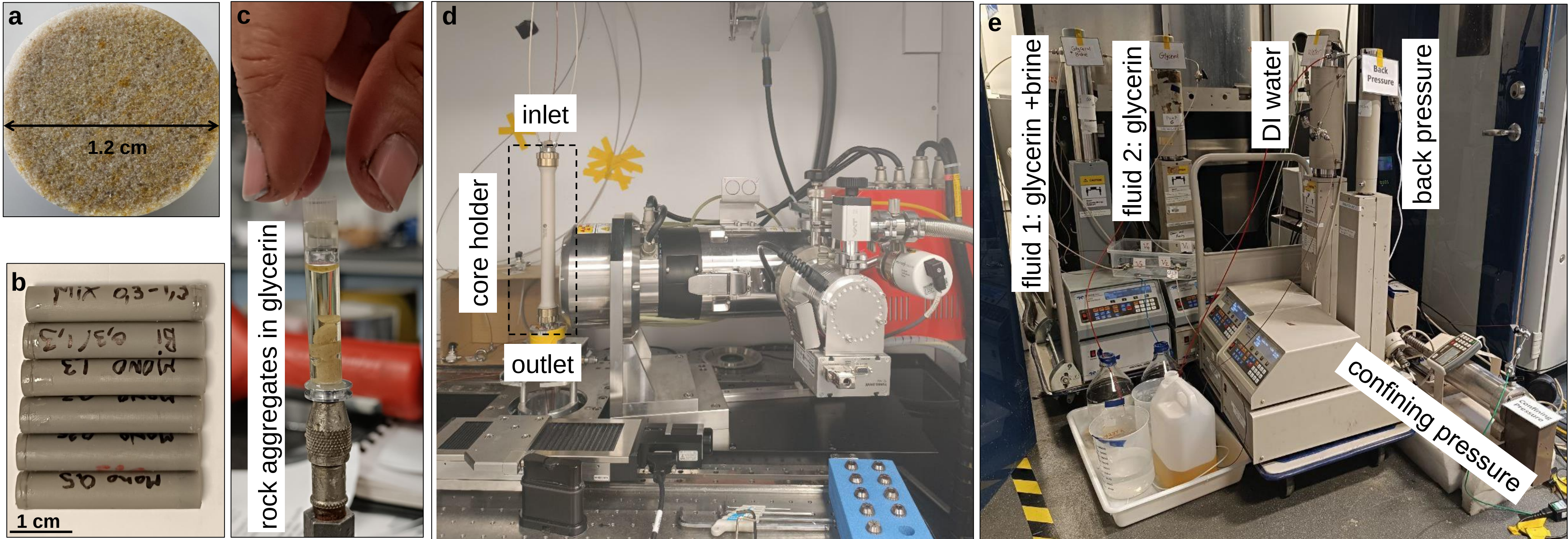
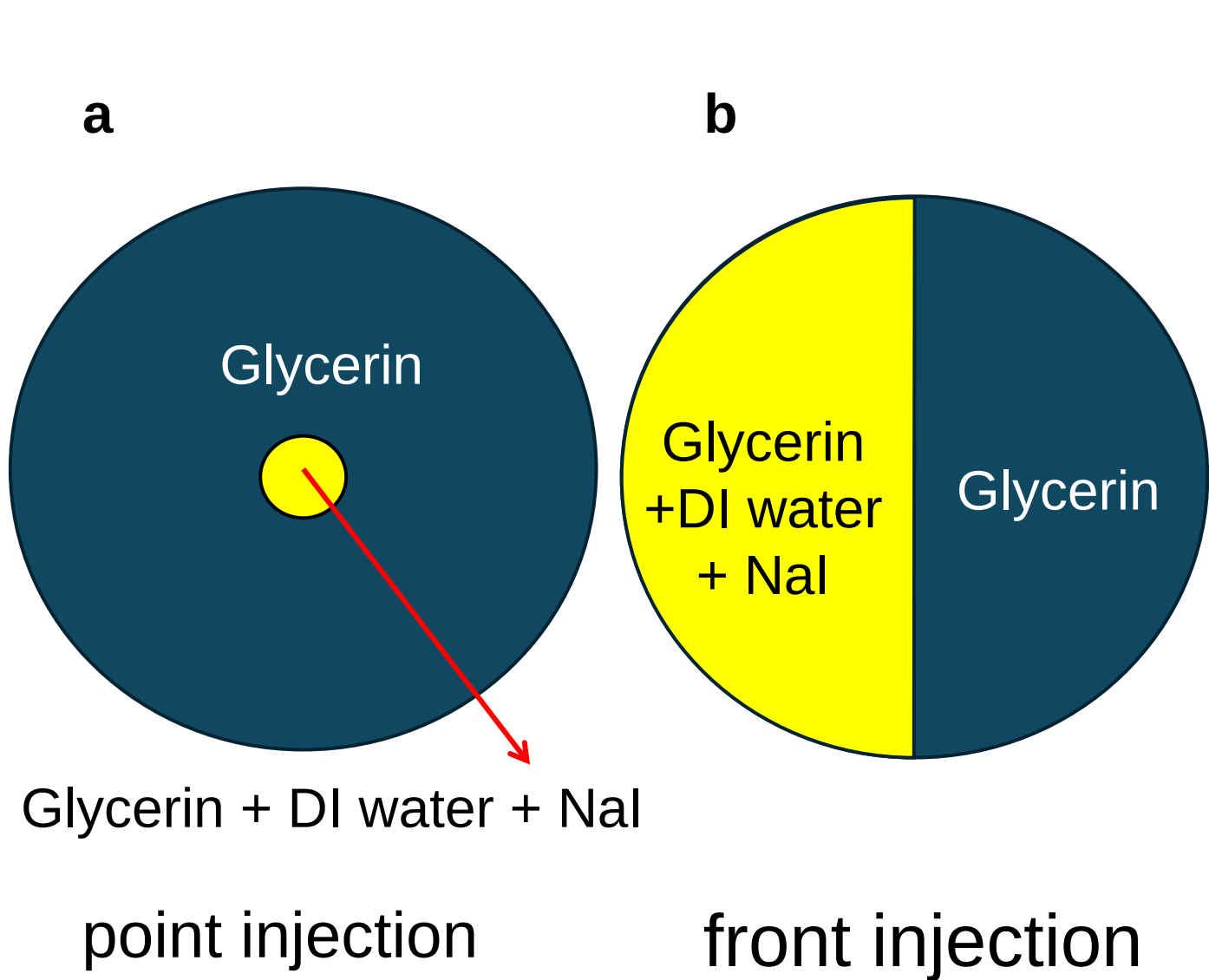


Fig. 3 (a) Bernheimer sandstone core and (b) polydisperse bead packs used for the co-injection of highly viscous fluids. (c) Assessment of the rock-fluid contrast in the CT images. (d) Specially built core holder in the Heliscan setup, used for acquiring CT images with relatively high resolution ($\sim 5 \mu m$) at Imperial. (e) pump setup used for co-injecting highly viscous fluids and applying confining and back pressure.

Preliminary Results

Experiments at Imperial College London

Figure 4 shows preliminary observation on stretching and folding of the higher-density fluid phase (brighter phase: Glycerin + DI water + NaI) while co-flowing with Glycerin (darker phase) inside a polydisperse bead pack (orange spheres) during front injection.

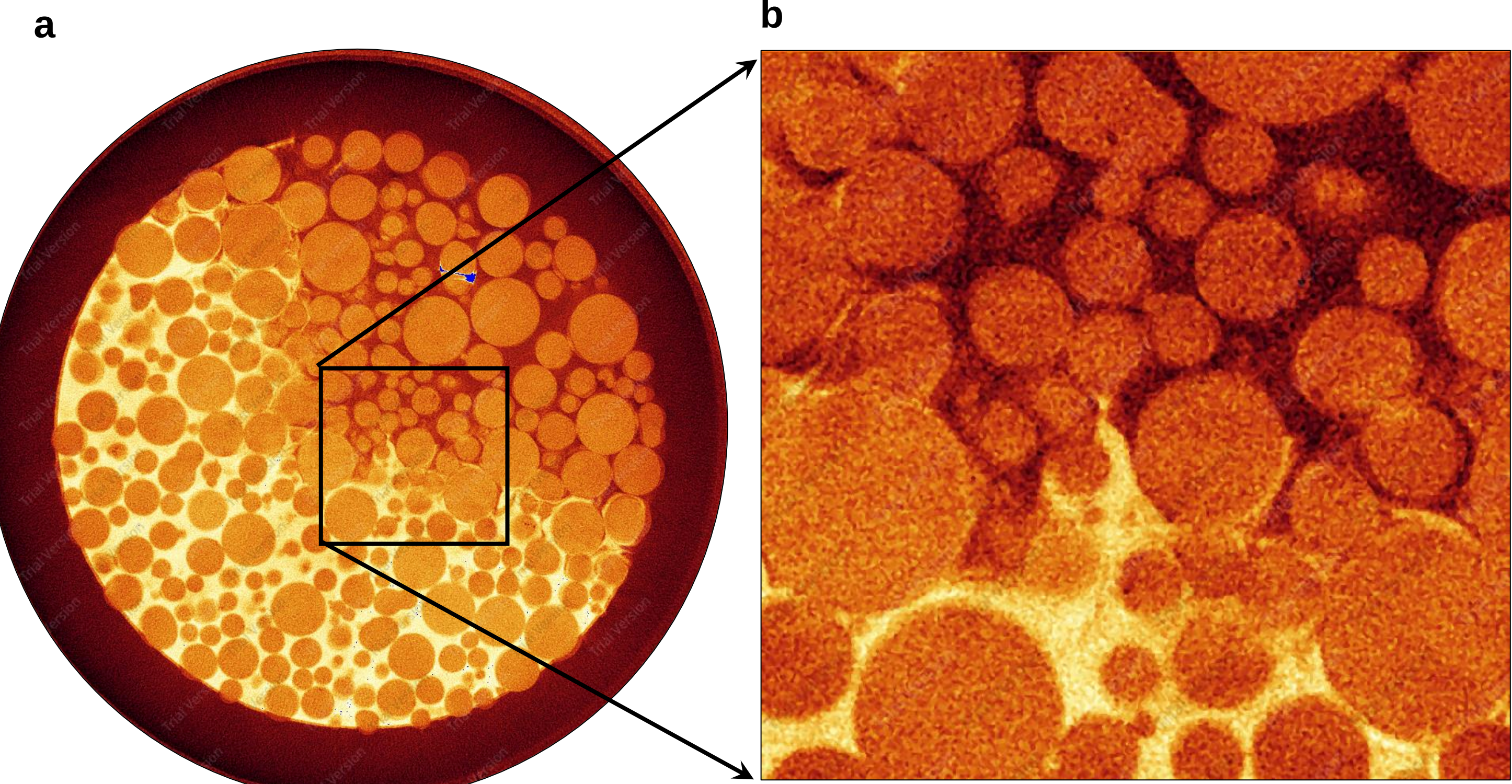


Fig. 4 Stretching and folding of the higher-density fluid phase (brighter phase: Glycerin+NaI) co-flowing with Glycerin (dark phase) inside a polydisperse bead pack (orange spheres) during front injection.

ESRF experiments

Experiments have been performed at ESRF at different resolutions (6.5, 1.45 and 0.7 μm) for natural rocks and synthetic porous media

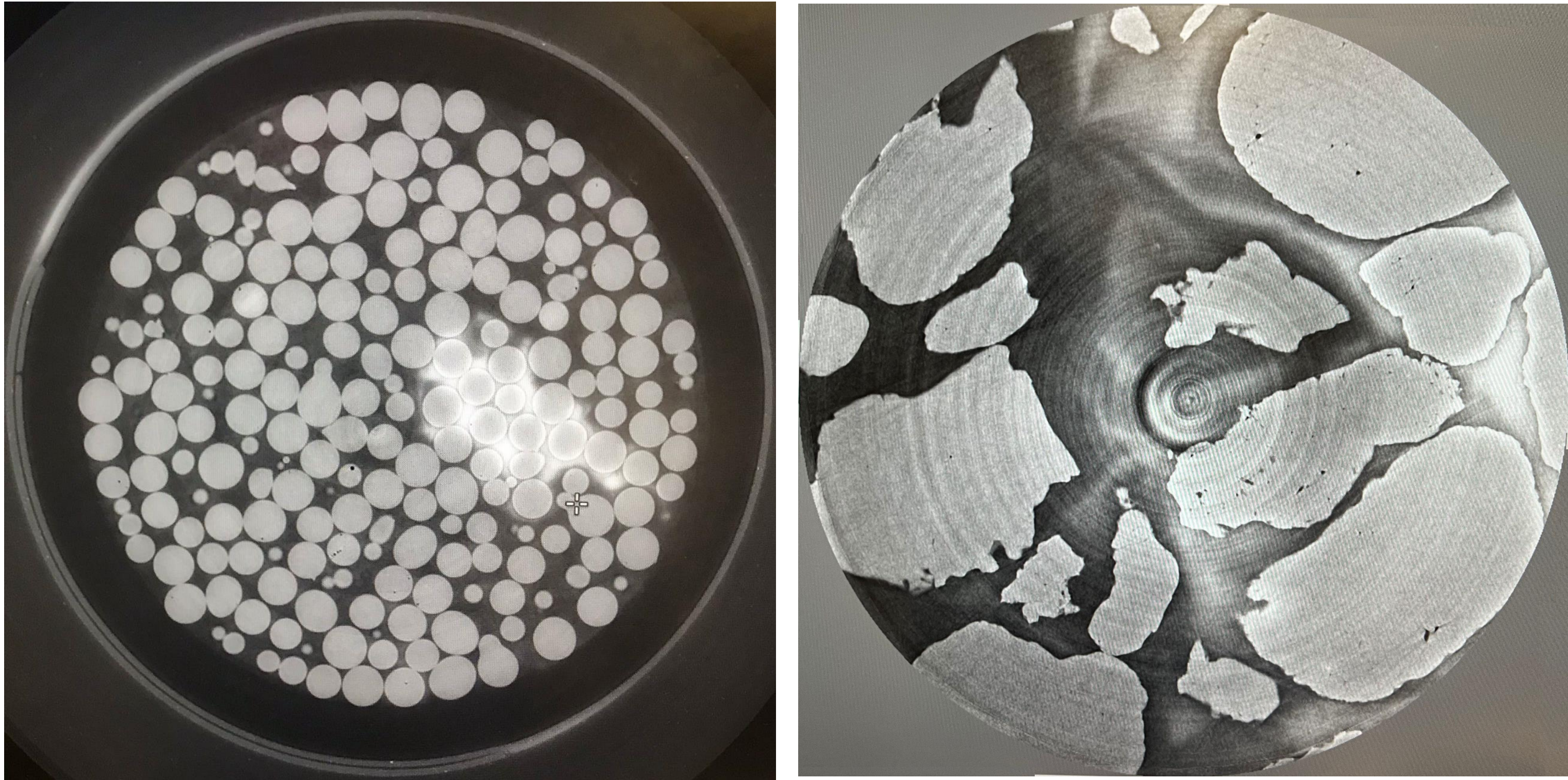


Fig. 5 Raw images of pointwise injection into a beadpack sample (left) and zoom of front injection into a sandpack sample (right) showing mixing

References

Heyman, J., et al. (2020). Stretching and folding sustain microscale chemical gradients in porous media. Proceedings of the National Academy of Sciences, 117(24), 13359-13365.
Heyman, J., et al. (2023). Fluid Stretching and Folding in 3D Porous Bead-Packs. Album of Porous Media, 75.
Aquino, T., et al. (2023). Fluid-solid reaction in porous media as a chaotic restart process. Physical Review Letters, 130(26), 264001.