Convection-driven porous media flows: Implications for carbon dioxide sequestration

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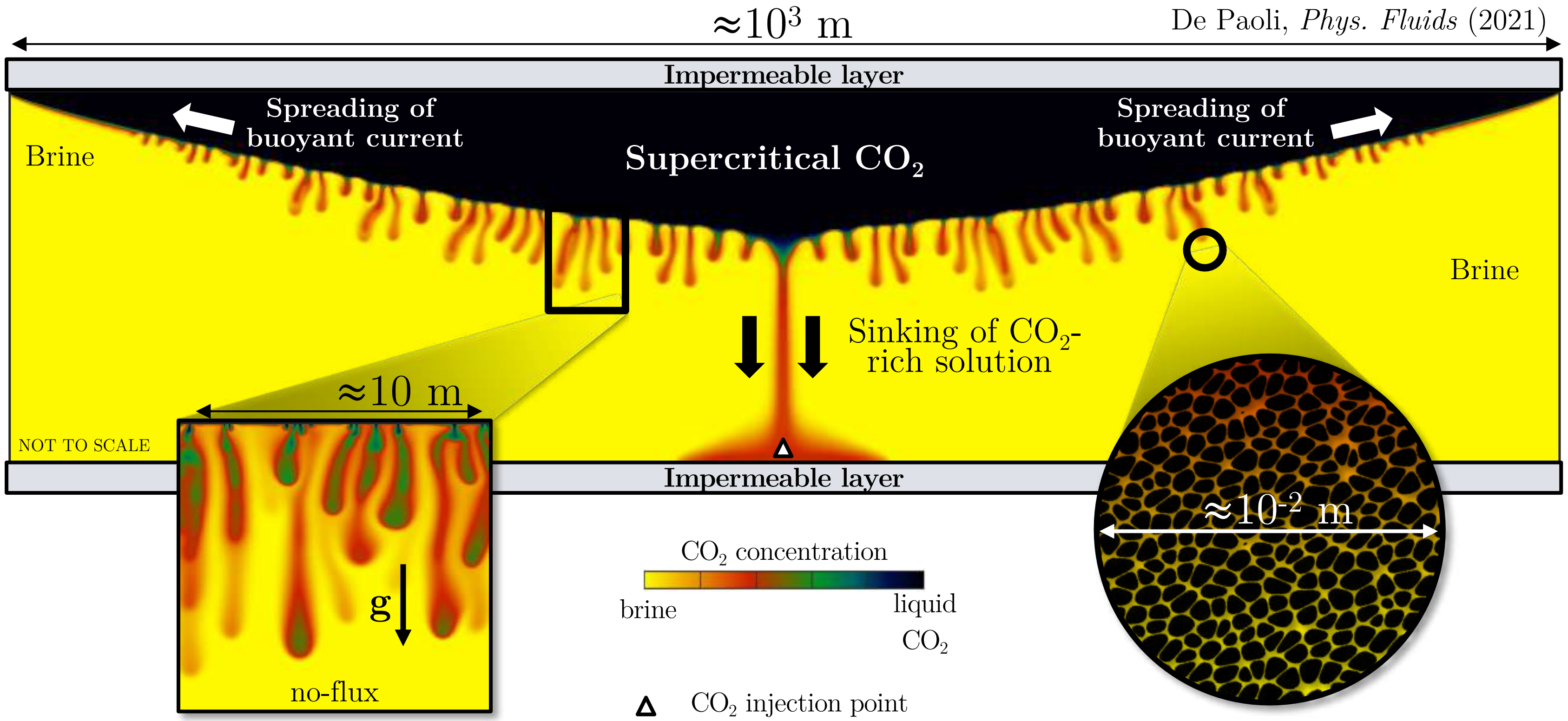
Physics of Fluids

Carbon Capture and Storage

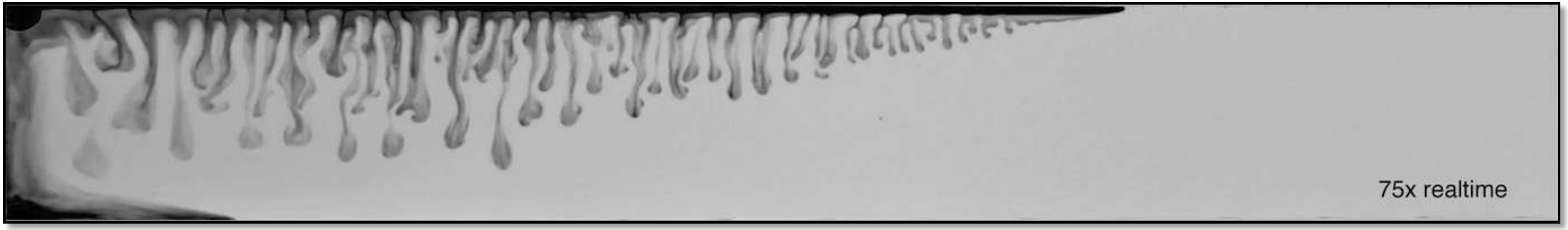
De Paoli, *Phys. Fluids* (2021)



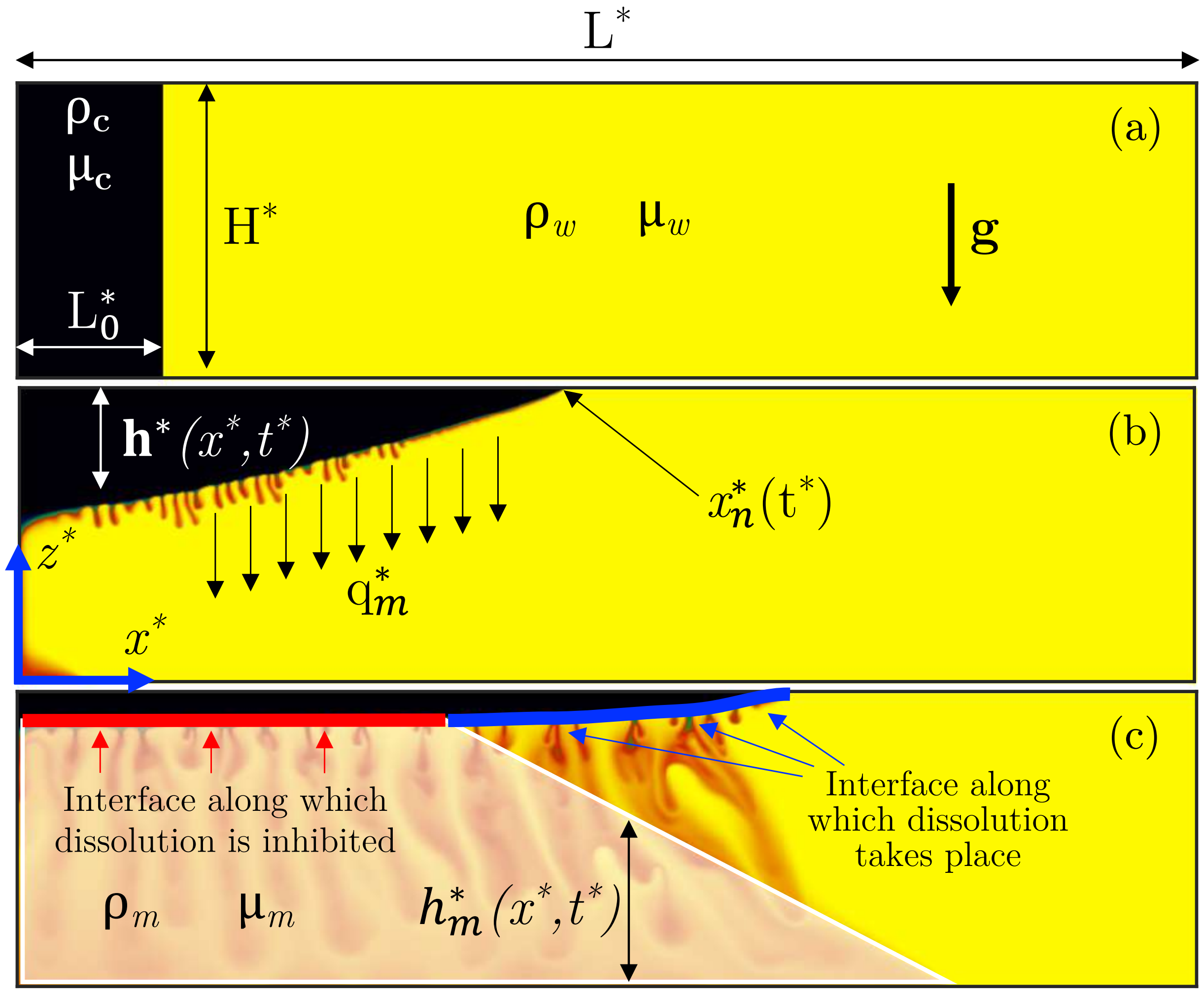
Reservoir properties

- anisotropy and heterogeneities
- finite size of confining layers
- effects of rock properties (mechanical dispersion)
- chemical dissolution and morphology variations
- ...

MacMinn et al., *Geophys. Res. Lett.* (2013)



Multiphase gravity currents with dissolution



De Paoli, *Phys. Fluids.* (2021)

$$\frac{\partial h}{\partial t} - \frac{\partial}{\partial x}\left[(1-f)h\frac{\partial h}{\partial x} - \delta f h_m \frac{\partial h_m}{\partial x}\right] = -\varepsilon_0,$$

$$\frac{\partial h_m}{\partial t} - \frac{\partial}{\partial x}\left[\delta(1-f_m)h_m\frac{\partial h_m}{\partial x} - f_m h \frac{\partial h}{\partial x}\right] = \frac{\varepsilon_0}{X_v}$$

$$f = \frac{Mh^*/H^*}{(M-1)h^*/H^* + (M_m-1)h^*_m/H^* + 1},$$

$$f_m = \frac{M_m h^*_m/H^*}{(M-1)h^*/H^* + (M_m-1)h^*_m/H^* + 1},$$

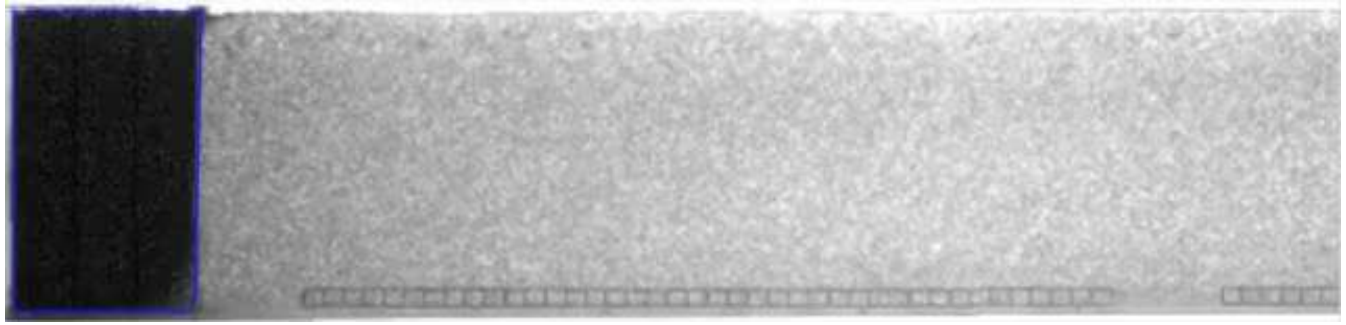
MacMinn, Neufeld, Hesse, and Huppert, *Water Resour. Res.* (2012)

Mobility ratios $M = \mu_w/\mu_c$ and $M_m = \mu_w/\mu_m$

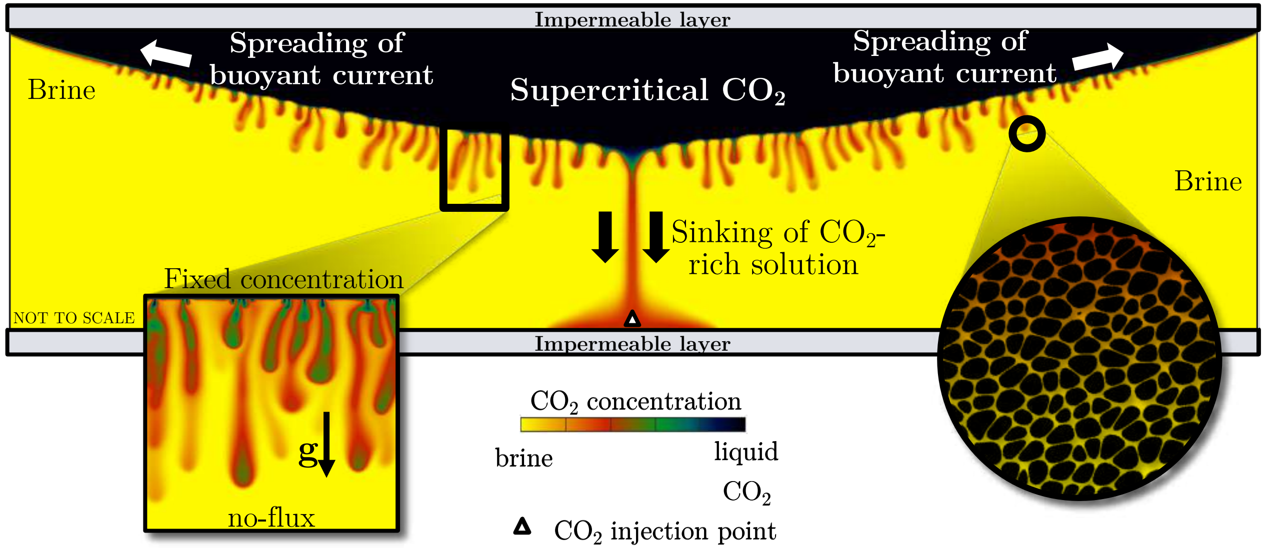
Buoyancy velocity ratio $\delta = W^*_m/W^*$

Volume fraction $X_v = \rho_m X_m/\rho_c$

Multiphase gravity currents with dissolution



MacMinn, Neufeld, Hesse, and Huppert, *Water Resour. Res.* (2012)



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$$\varepsilon_0(x) = \begin{cases} 0 & \text{if } \; h(x) = 0 \text{ or } h(x) + h_m(x) = 1 \\ \varepsilon & \text{else,} \end{cases}$$

$$\varepsilon = \frac{q_m^*}{\phi W^*}\left(\frac{L_0^*}{H^*}\right)^2$$

How to determine the dissolution rate q_m^* ?

Dimensionless equations

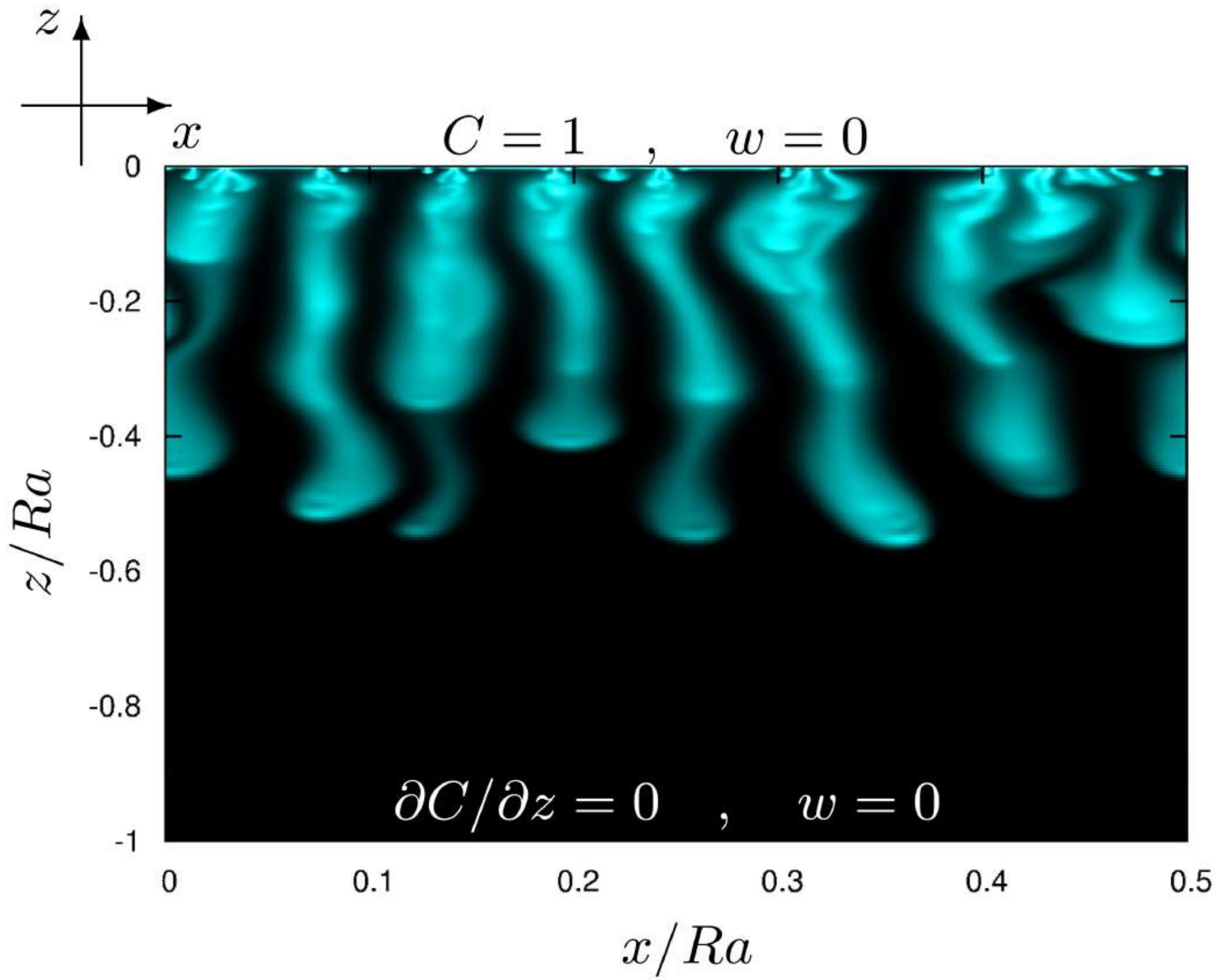
$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = \frac{1}{Ra}\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial z^2}\right)$$

$$u = -\frac{\partial P}{\partial x} \quad , \quad w = -\frac{\partial P}{\partial z} - C$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$$

Governing parameter

$$Ra = \frac{gH^* k_v \Delta\rho^*}{\mu \Phi D}$$

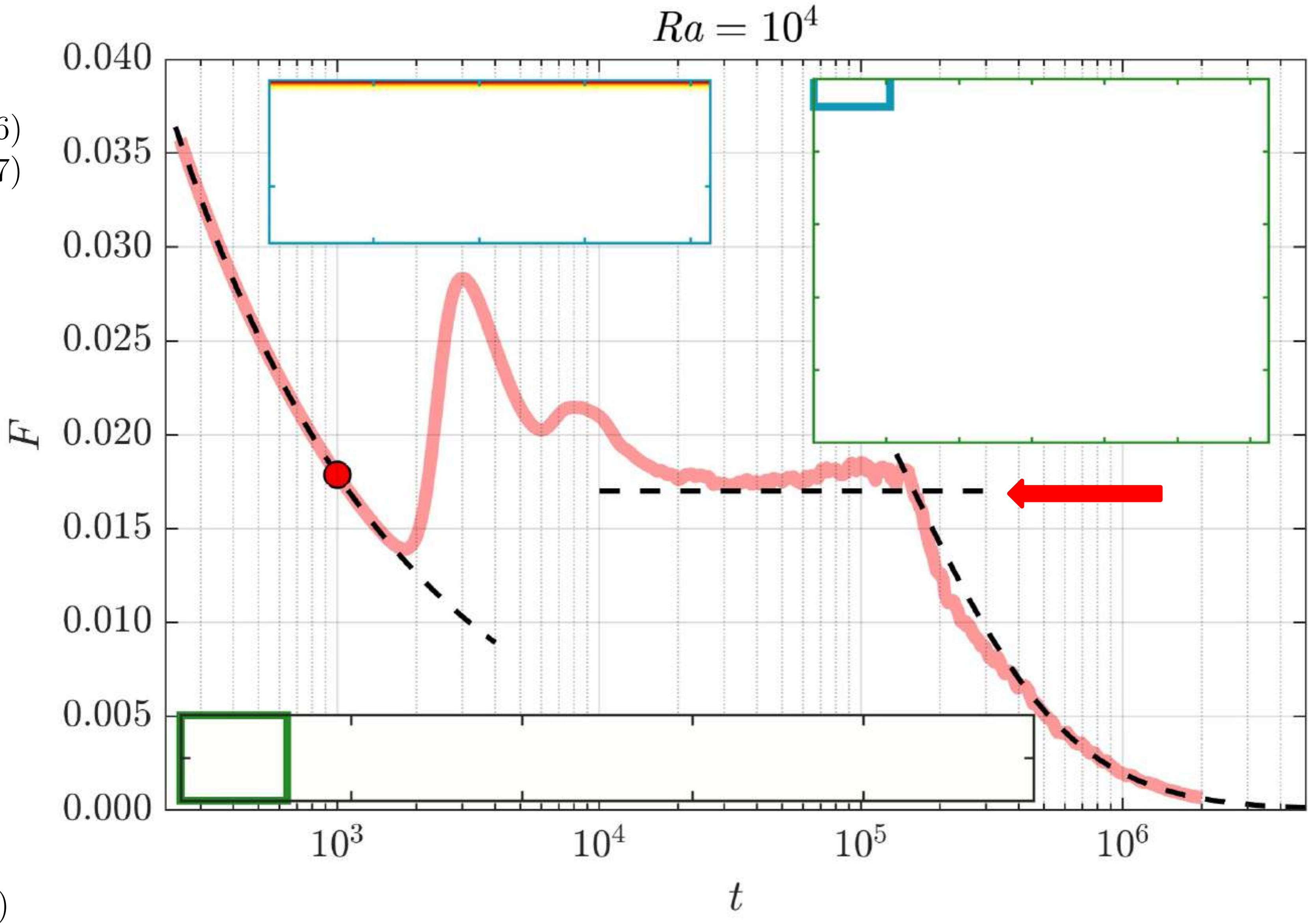


Convective dissolution process

De Paoli, Zonta and Soldati, *Phys. Fluids* (2016)
De Paoli, Zonta and Soldati, *Phys. Fluids* (2017)

$$F(t) = \frac{1}{L}\int_0^L \left.\frac{\partial C}{\partial z}\right|_{z=0} dx$$

Examples of model extension: effect of **anisotropy** of the medium



See also Slim, *J. Fluid Mech.* (2014)
Hewitt, Neufeld & Lister, *J. Fluid Mech.* (2013)

Convection in anisotropic media

Examples of model extension:
effect of **anisotropy** of the medium

Sedimentary rocks: Rocks formed by stratification

Assumptions:

1. Homogeneous porous medium
2. Anisotropic porous medium
   - Principal directions of the permeability tensor aligned with the reference frame

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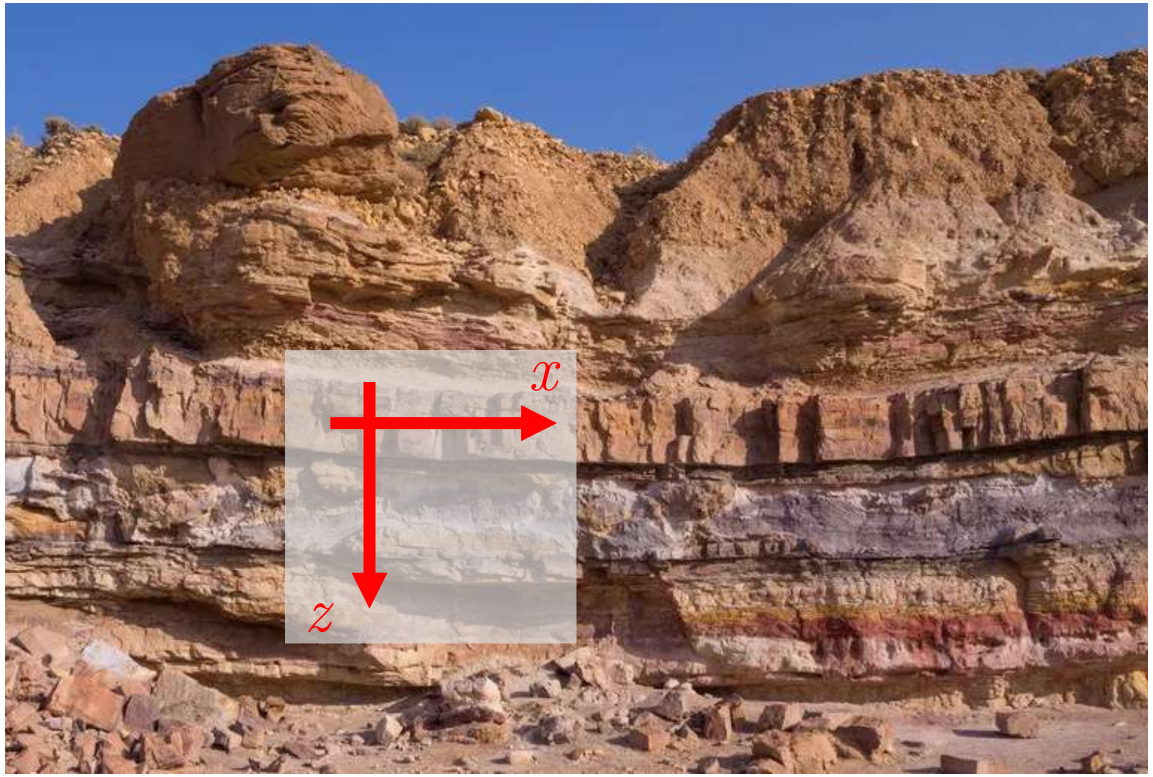
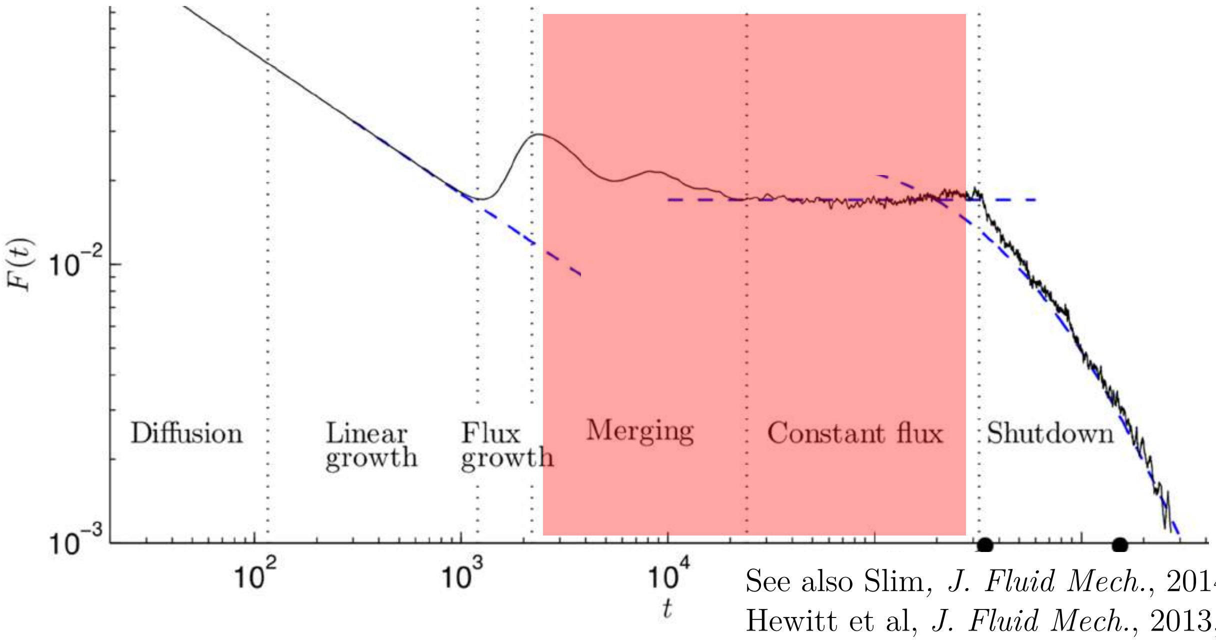


Rhododendrites/Wikimedia Commons/CC BY 4.0

Heat flux and dissolution rate

isotropic medium



See also Slim, *J. Fluid Mech.*, 2014
Hewitt et al, *J. Fluid Mech.*, 2013,
De Paoli et al., *Phys. Fluids*, 2016, 2017

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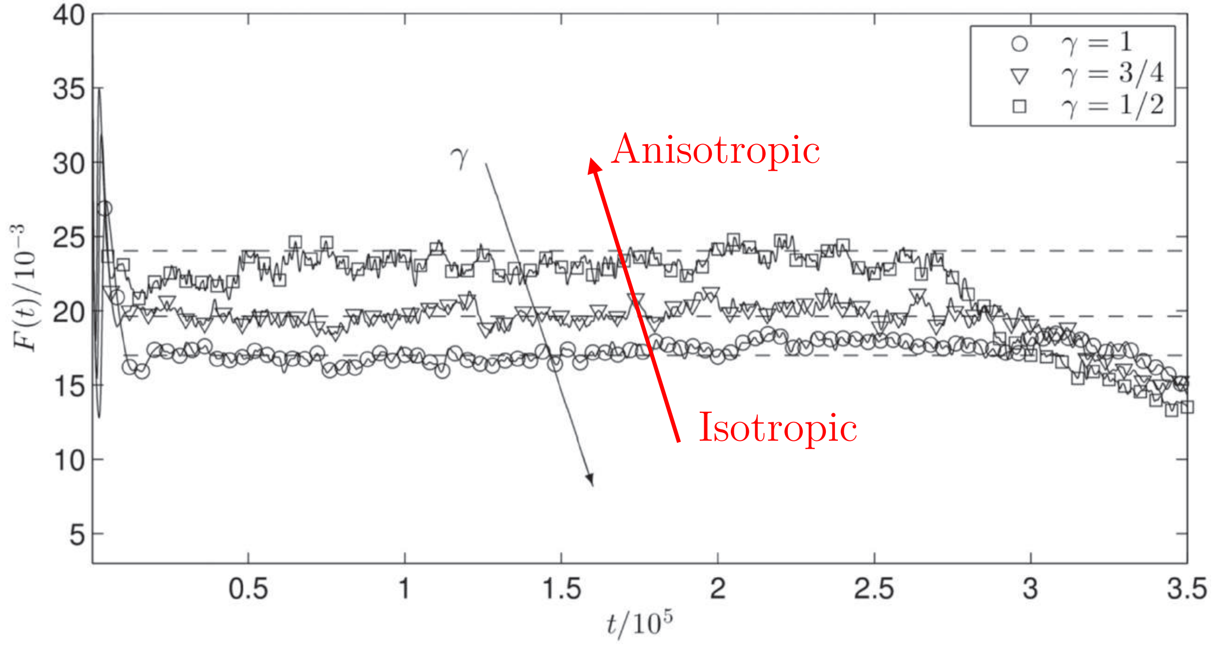
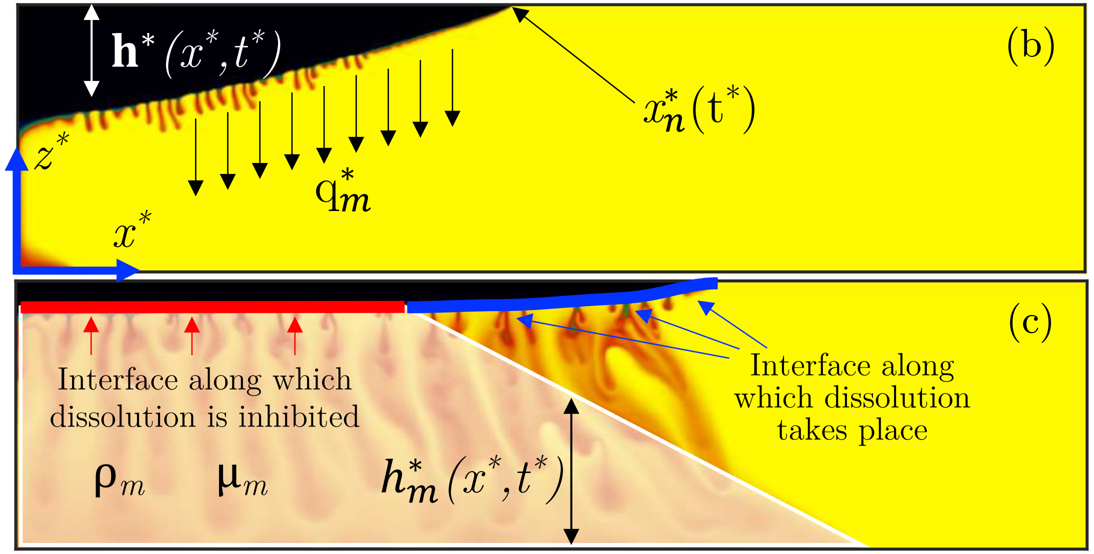


Convection-dominated $F(t) = 0.017$

Strong influence of γ on flux

$$q_m^* \equiv F(t) = 0.017\gamma^{-1/2}$$

Effect of anisotropy



Darcy-scale simulations:

dissolution rate $q_m^* \sim \gamma^{-\frac{1}{2}}$

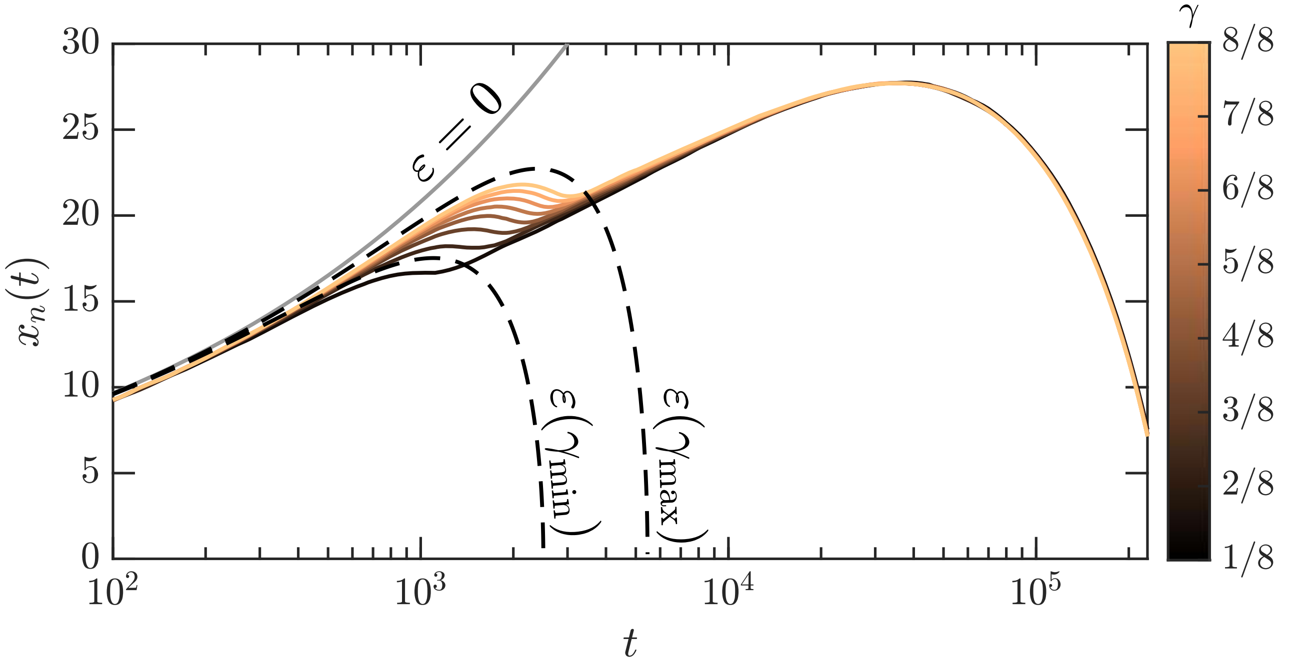
dissolution increases with the anisotropy of the medium

Sedimentary rocks are anisotropic

$$\gamma = \frac{k_v}{k_h} < 1$$

$\gamma = 1$ isotropic

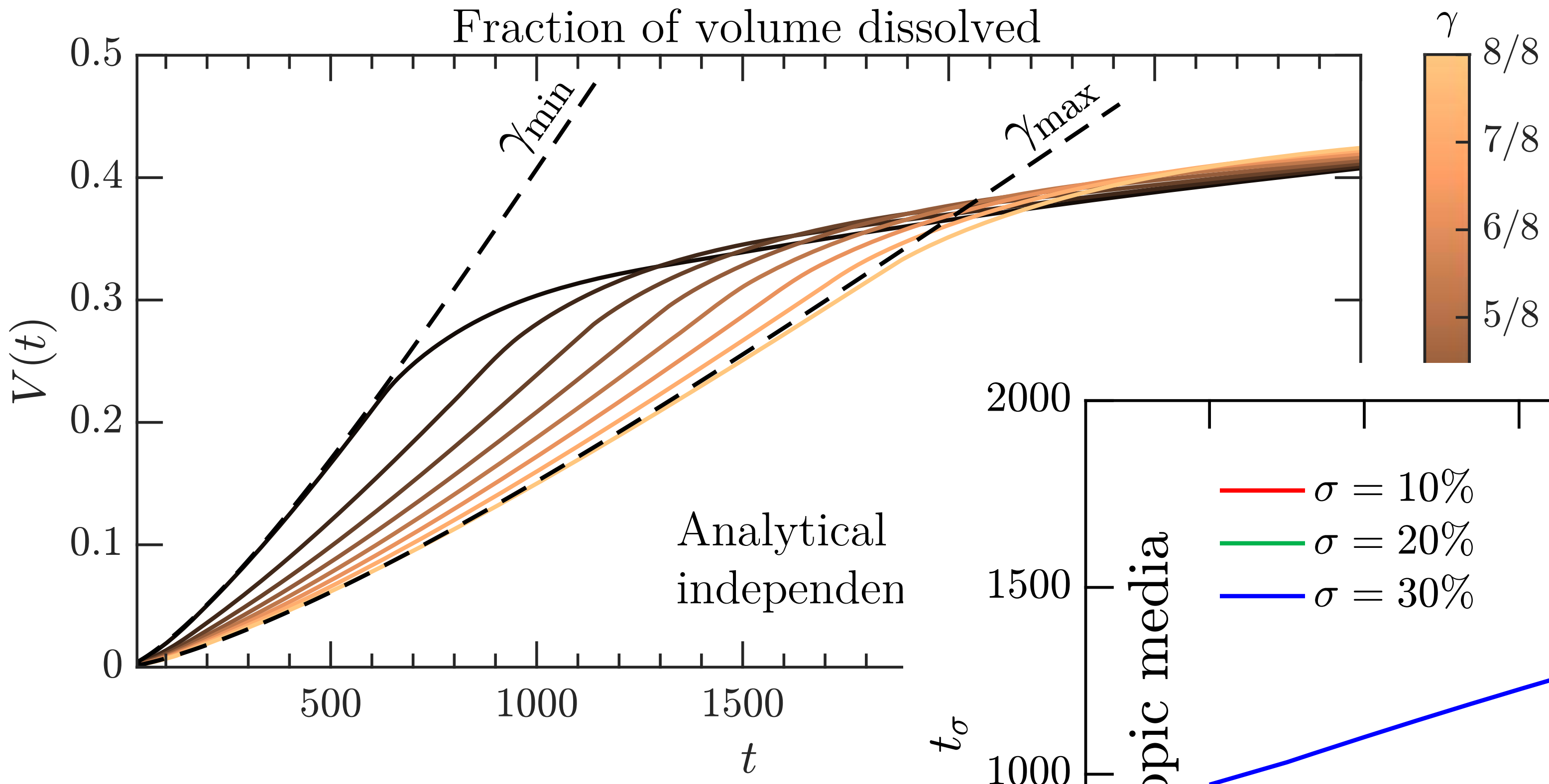
$\gamma = 1/8$ strongly anisotropic



Analytical solution in case of
- no-dissolution
- independent currents

De Paoli, Zonta & Soldati, *Phys. Fluids* (2016, 2017)

Effect of anisotropy



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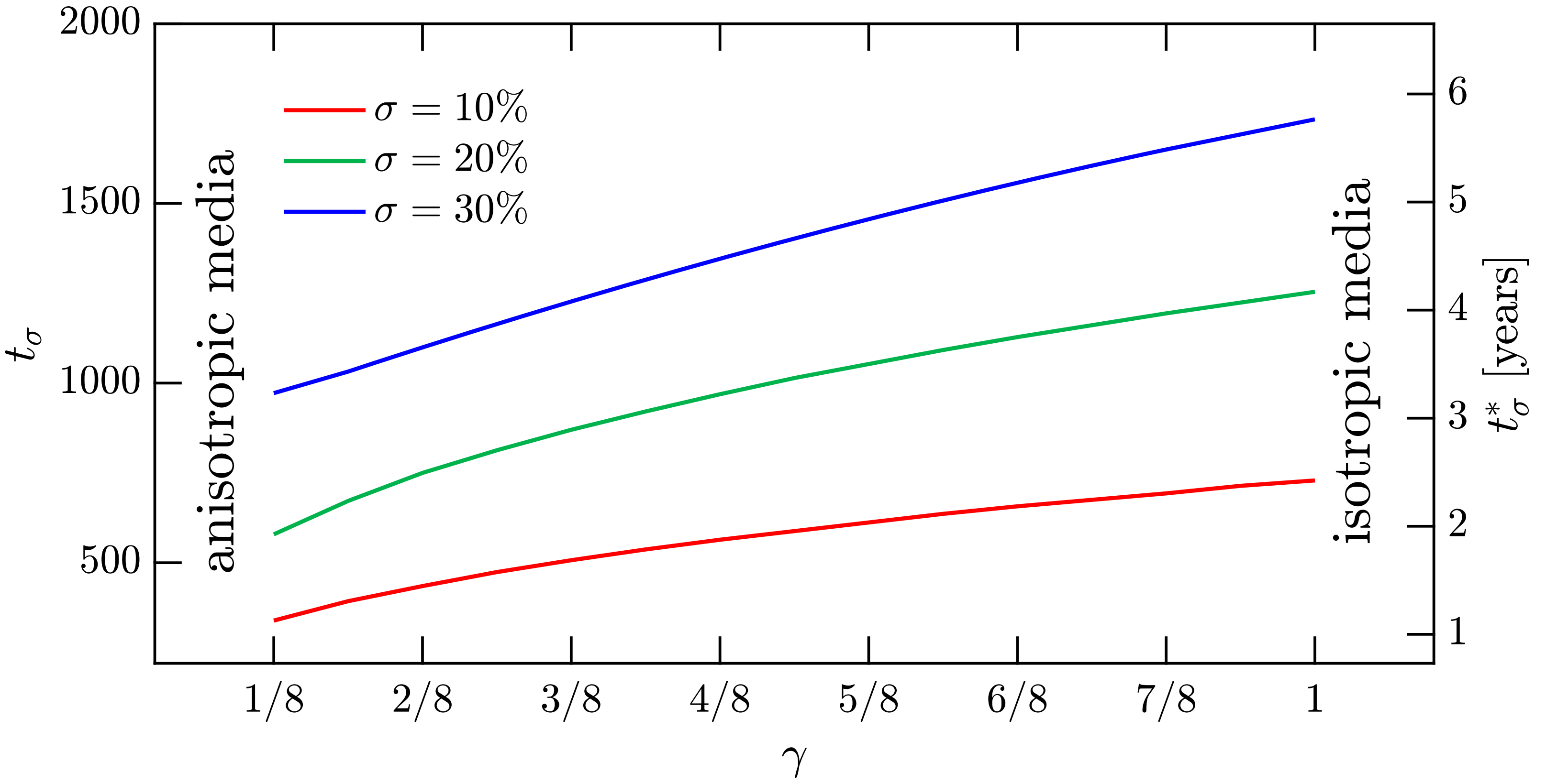
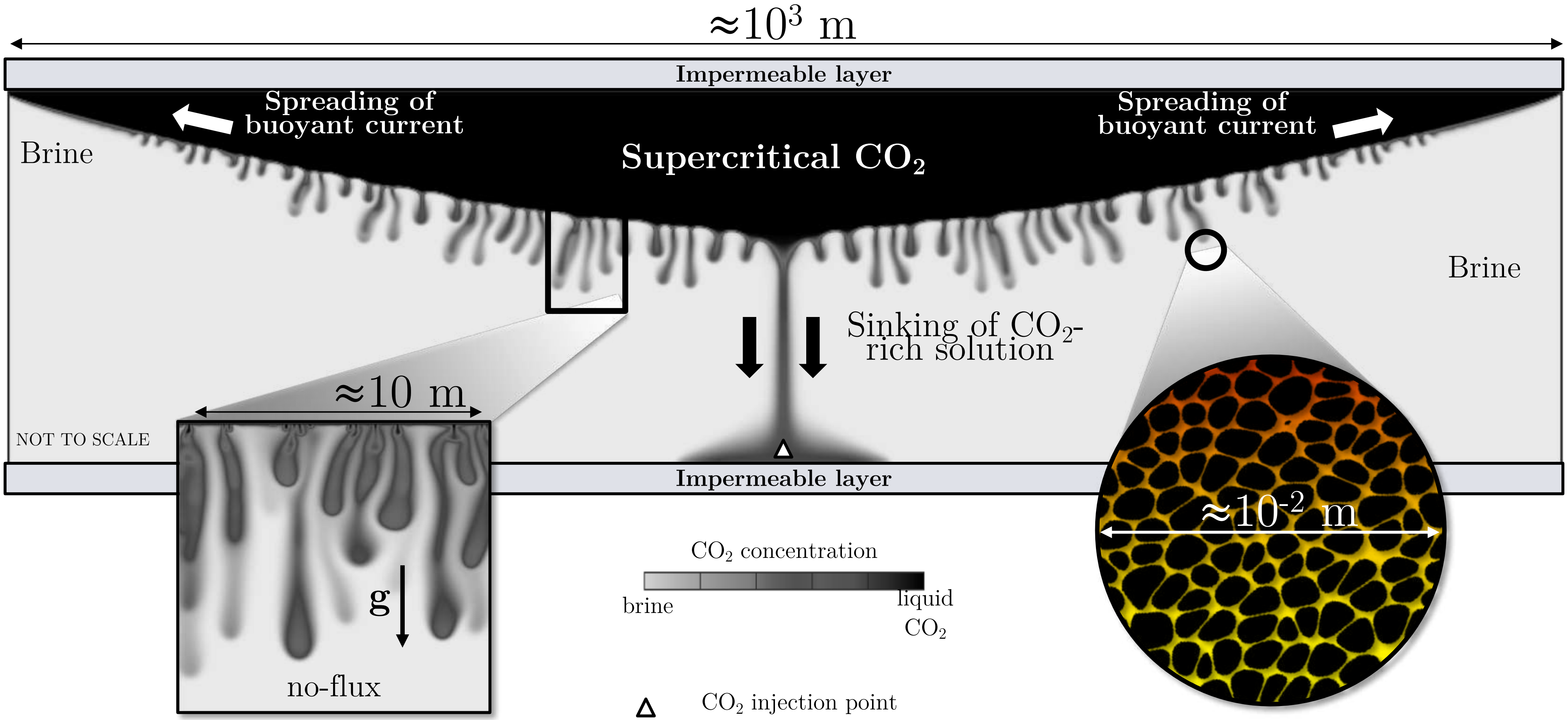


Long-term predictions
of real-scale reservoirs

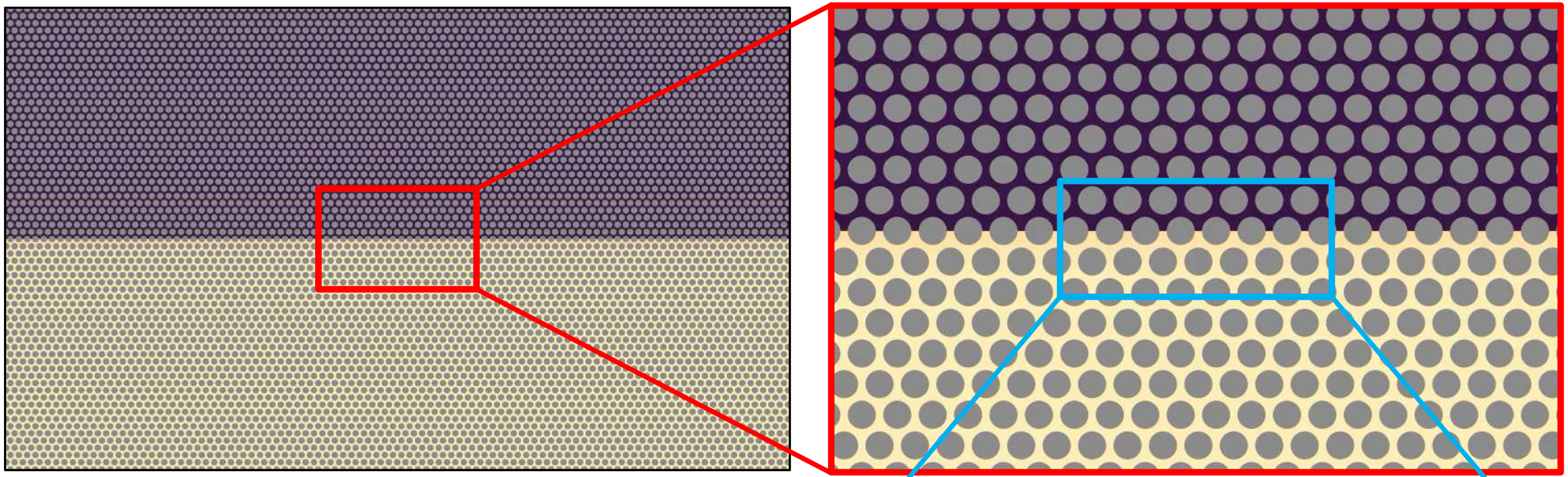
Carbon Capture and Storage

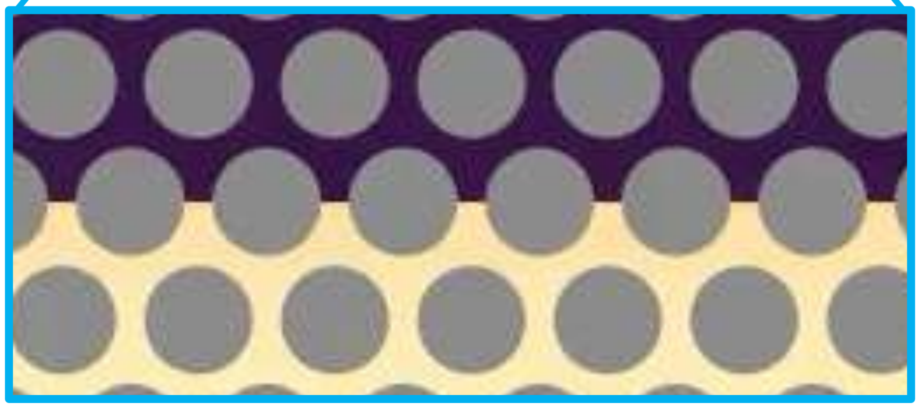


De Paoli, *Phys. Fluids* (2021)

Pore-scale dynamics

arxiv.org/abs/2310.04068





T32:1: Rayleigh-Taylor instability in confined porous media, **De Paoli**, Howland, Verzicco & Lohse

Mon, Nov. 20th
16:25, Room 158AB

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PREPRINT

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High-resolution images, movies and slides are available upon request to m.depaoli@utwente.nl