mechanical interactions between bacteria and grains in a model soil

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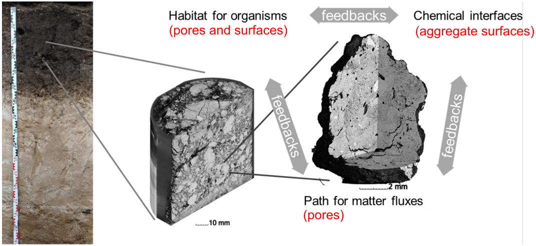
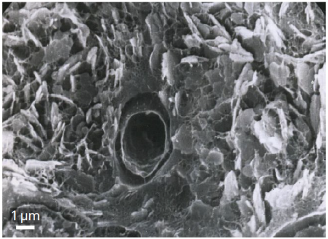
structure $\leftrightarrow$ biology feedback in soil



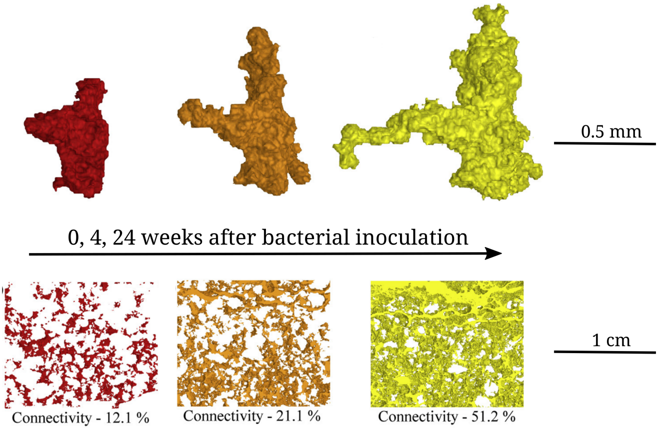
adapted from Schlüter et al. (2020) *Geoderma*



Philippot et al. (2024) *Nat. Rev. Microbiol.*

- continuum of pore scales (sub-μm $\rightarrow$ cm)
- biological activity at each scale feeds back with surface chemistry and transport pathways

bacterial inoculation modifies soil porous structure



Heliwell et al. (2014) *Soil Biol Biochem*

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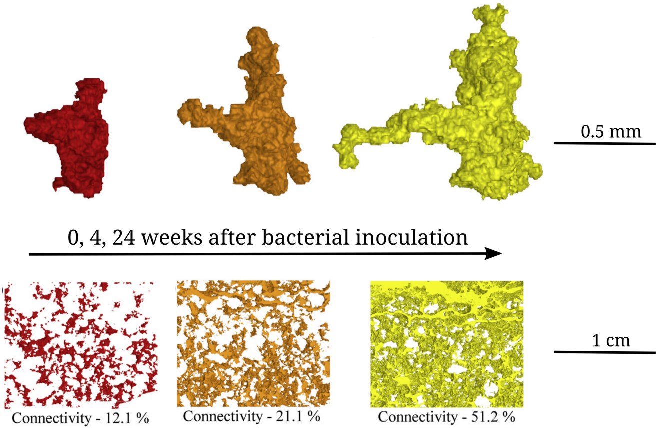
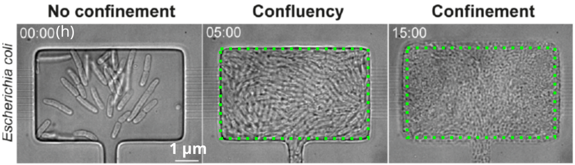
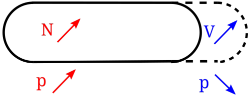


Heliwell et al. (2014) *Soil Biol Biochem*

Bacteria modify pore sizes & increase soil pore connectivity.
Do they mechanically create those spaces?

confined bacteria generate large growth stresses



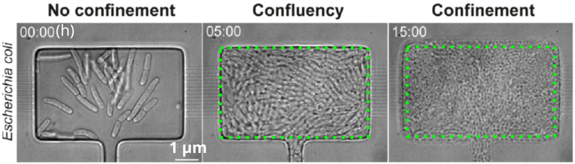


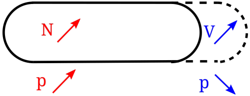
Le Blanc et al. (2024) *bioRxiv*

Turgor pressure

Internal pressure > turgor pressure

confined bacteria generate large growth stresses





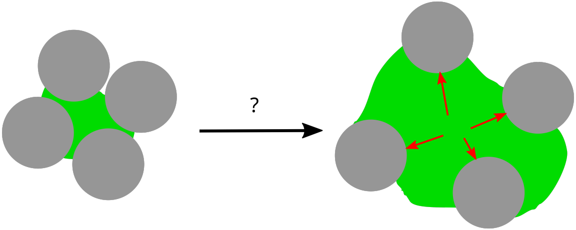
Le Blanc et al. (2024) *bioRxiv*

Turgor pressure

Internal pressure > turgor pressure

What is the interplay between **growth stresses**, **stress relaxation**, and **cavity deformation** in **divided media**?

research question

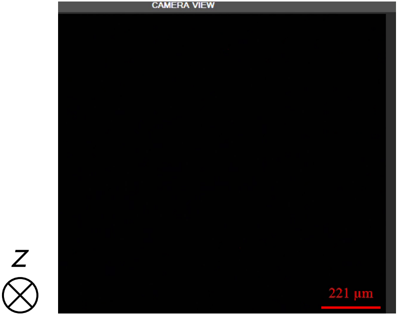


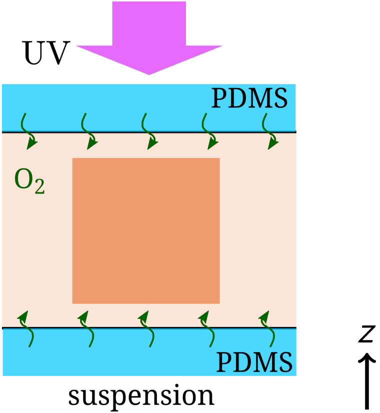
The mechanical action of bacteria on a confining, divided environment has not been directly observed yet.

- Can bacteria deform a granular matrix, and how?
- Which biophysical conditions favour it?

experiments: use **microfluidic techniques** to concurrently observe **bacterial growth** and **position of mobile grains**

particle fabrication—principle

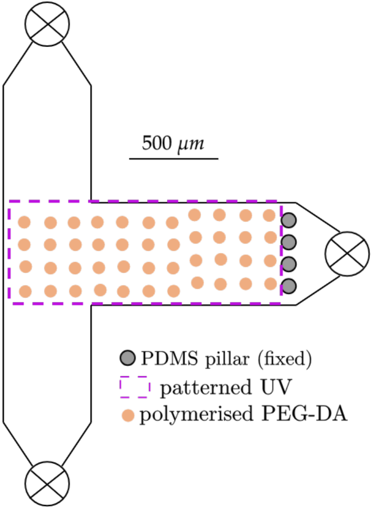




- **PEG-DA**: hydrogel polymerised (hardened) by UV
- UV projected across microfluidic channel according to pattern

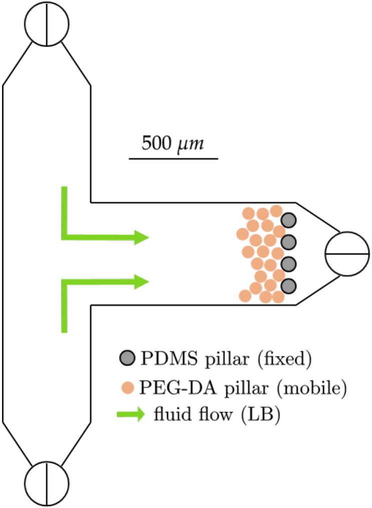
rigid ($\sim$ 10–100 MPa) pillars (40 µm) in suspension

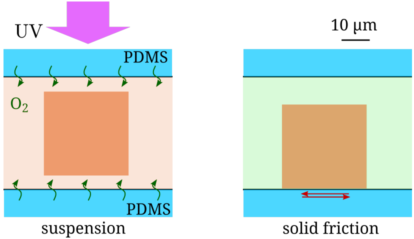
microfluidic chamber—*in situ* particle fabrication



- channel widths 500 μm
- channel height 50 μm

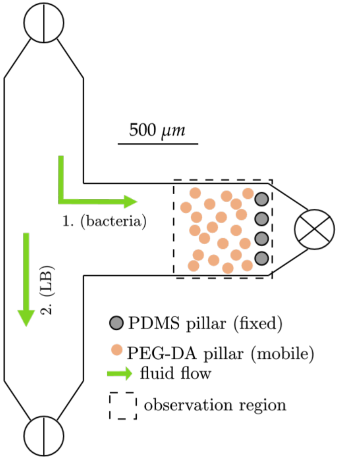
rendering the environment suitable for bacterial growth

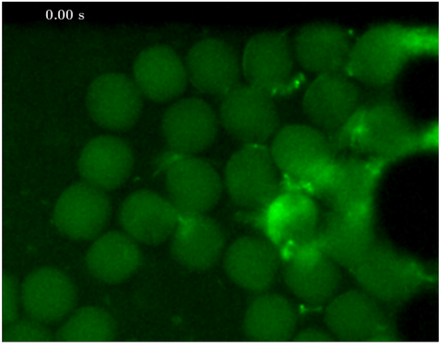




PEG-DA precursor solution rinsed with 50% spent medium → no non-specific adhesion

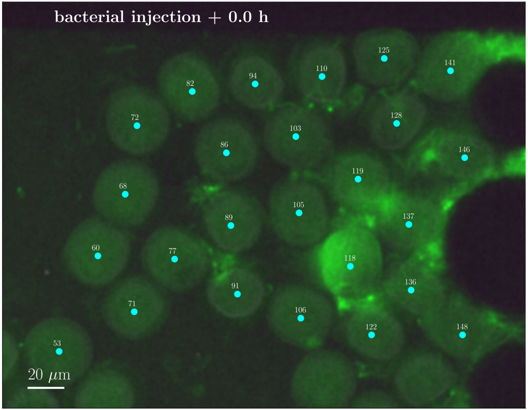
bacterial injection and continuous nutrient supply



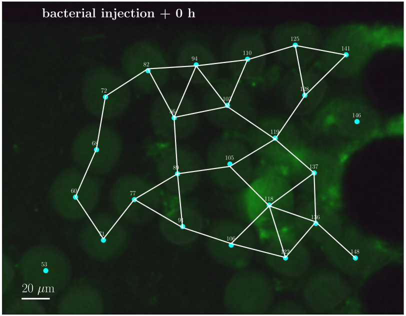


bacteria: *Bacillus subtilis*, expressing GFP (emit green when excited by blue)

bacterial growth and pillar movement



pore widening and movement chains



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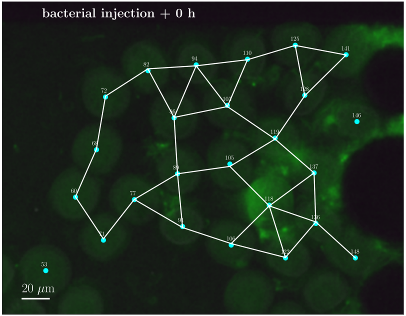

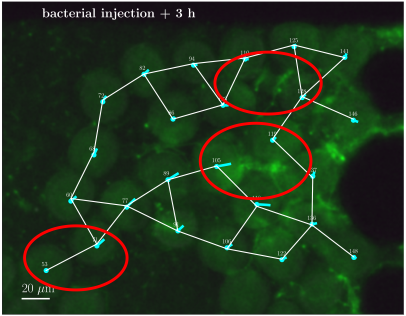

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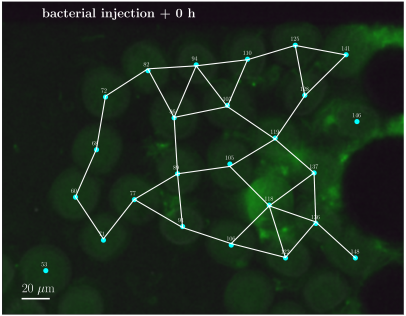
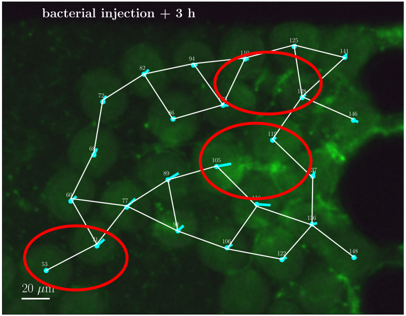
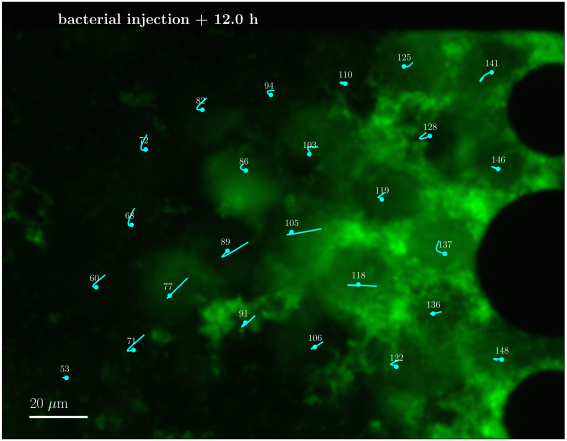




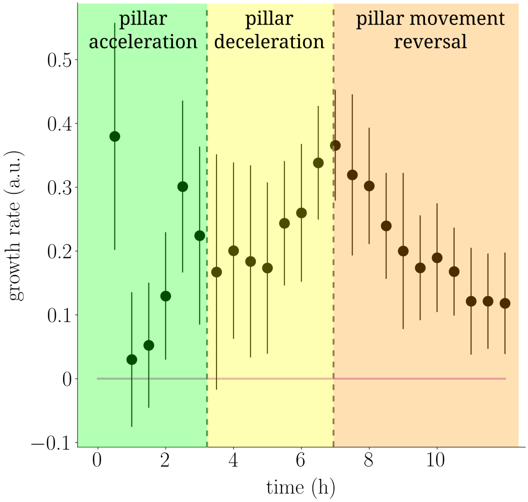
- pillars move when in a bacterial density gradient...
- and when there is free space to move into

idea: bacterial colonies deform soft particle chains

movement reversal

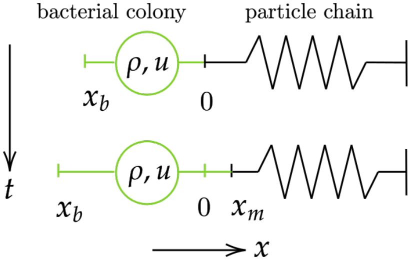


movement reversal is concurrent with growth slowdown



around 7 h after bacterial injection, change in **growth rate** and in **pillar movement direction**

growth pressure when “partially” confined



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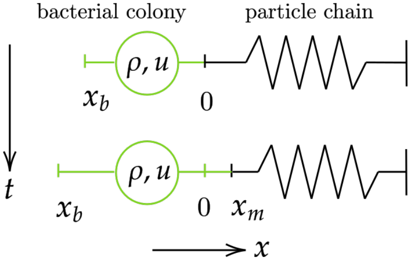

governing equations of bacterial colony:

$$\partial_t \rho + \partial_x(\rho u) = \frac{1}{\tau_g}\rho \quad \text{growth}$$

$$-\partial_x p + \eta \, \partial^2_{x^2} u = 0 \quad \text{Stokes flow } (\eta = \eta(\rho)\eta(\phi))$$

$$p = \Pi(\rho),\ \partial_\rho \Pi > 0 \quad \text{constitutive}$$

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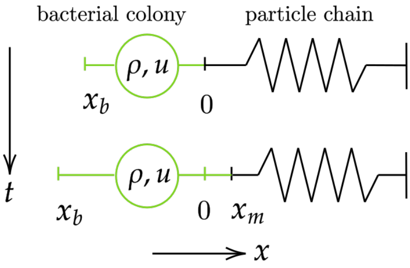

boundary conditions:

$$p(x_b) = \eta \partial_x u, \quad \text{free surface}$$

$$p(x_m) = k x_m, \quad \text{elastic surface}$$

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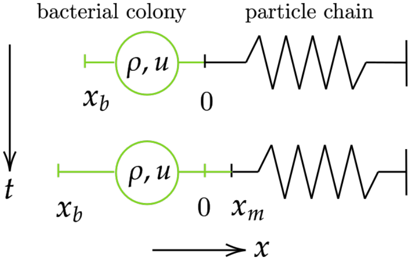

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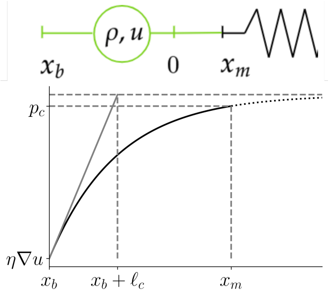
at confluence, $p, u = 0 \Rightarrow$

$$\frac{\partial \rho}{\partial t} > 0 \Rightarrow \frac{\partial p}{\partial t} > 0$$

bacteria generate growth pressure
that drives biomass flow towards the edge of the colony

bacterial division vs. advection times

- after confluence, **growth pressure gradient** towards the wall, where $p = p_c$.



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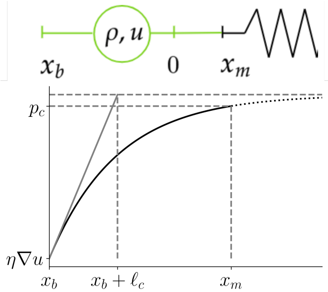


- after confluence, **growth pressure gradient** towards the wall, where $p = p_c$.

$$\frac{\partial p}{\partial t} \propto \frac{1}{\tau_g} - \frac{p_c}{\eta}$$

pressure at wall (p_c)

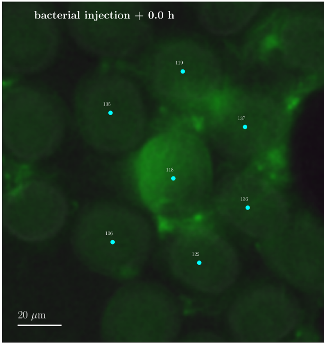
effective viscosity (η)

division time (τ_g)

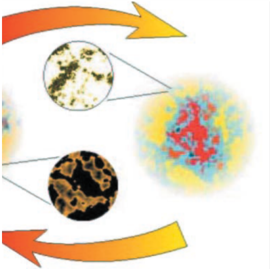
- if $\tau_g < \eta / p_c$, bacteria generate pressure faster than they flow, **compressing** the spring $\Rightarrow \frac{\partial p}{\partial t} = k\dot{x}_m > 0$
- if $\tau_g > \eta / p_c$, bacteria flow faster than they divide & the spring **relaxes** $\Rightarrow \frac{\partial p}{\partial t} = k\dot{x}_m < 0$

summary

- pores where bacterial microcolonies were intercepted have **widened** before shrinking back
- toy model: balance growth vs. self-flow ⇒ non-monotonous motion
- hypothesis: **fast bacterial growth** favours restructuration by elastically transmitting growth stresses to grains
- current work
  - quantify these stresses
  - understand behaviour at short (1-2 h) times
- perspectives: emerging tension from EPS production? emerging cohesion in the medium?



perspective



ıodel for self-organization in the soil-microbe com-
es at a location in soil, and the potential microbial
ases, leading to local depletion of oxygen (left-hand
concentration represented as in Fig. 3). Increased
ıanges the local structure, creating a more open
is leads to enhanced rates of oxygen supply (right-
strate is used up, activity declines and the structure
e closed state. The open and closed states may
onfigurations for oxygen supply in a high potential
n) and protection from desiccation and predation in
ity regime (closed).

Young & Crawford (2004) *Science*

acknowledgments

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GEOSCIENCES Rennes

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