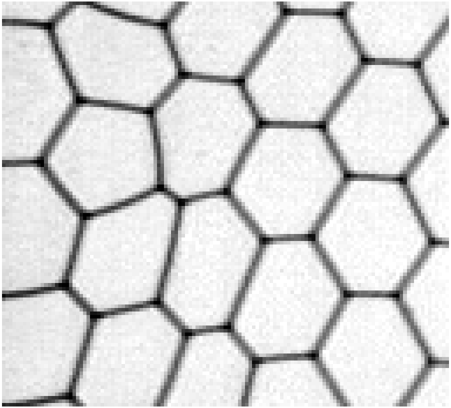
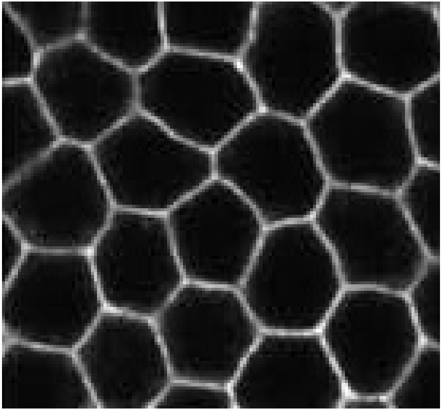
foam - M. Asipauskas *tissue - Blankenship et al.*





Disorder, elasticity, rearrangements

e.g. in foams or biological tissues

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2022

Outline

Motivations

Tissue morphogenesis

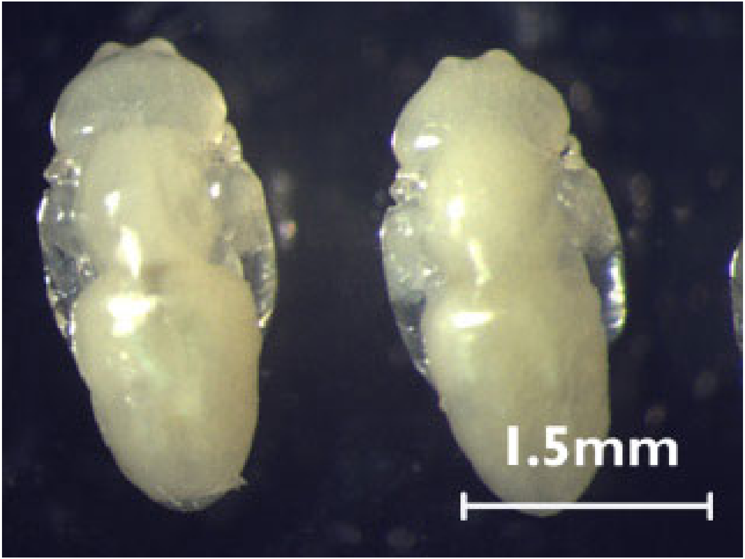
Multi-cellularity and neighbour changes

Fruit fly metamorphosis

Larva → adult

Drosophila melanogaster pupae development

duration : 5 days

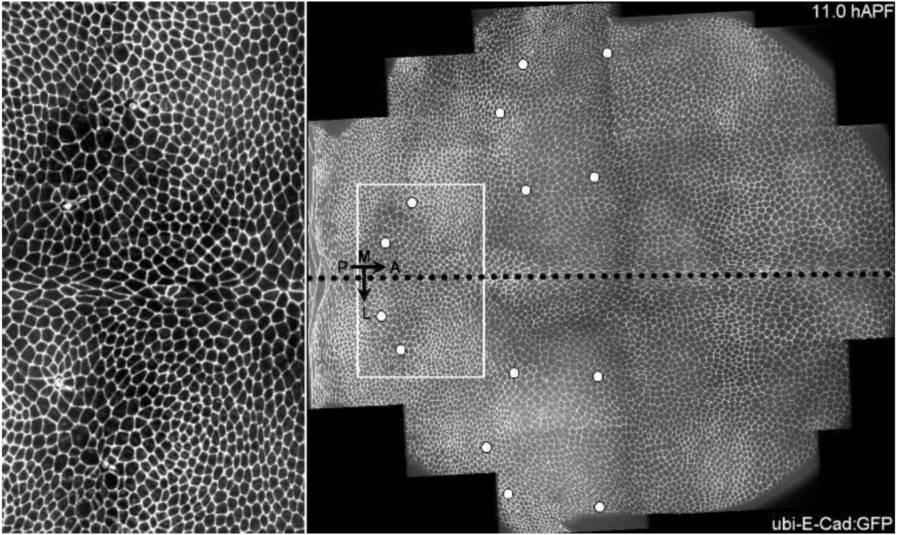


http ://www.exploratorium.edu/

Multi-scale live imaging

Bosveld

zoom waist dorsal thorax neck



1 layer∼7000 cells 12-38h after pupa formation ∼3 decades time & space

Linking scales

cell scale $\longrightarrow$ cell group scale $\longrightarrow$ tissue scale

Linking scales

cell scale ⟶ cell group scale ⟶ tissue scale

statistical physics :
determine the
material parameters

viscosity η
stiffness G
yield strain ε_Y

Linking scales

cell scale ⟶ cell group scale ⟶ tissue scale

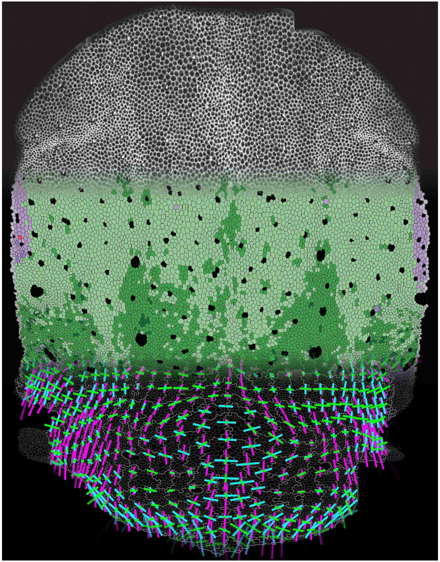
statistical physics :
determine the
material parameters

viscosity η
stiffness G
yield strain ε_Y

continuum mechanics :
determine the
dynamical fields

velocity V
strain ε
stress σ

Continuous description



It enables :

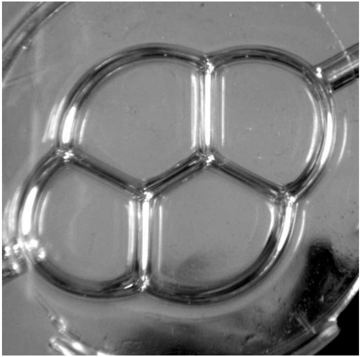
- compare experiments and/or simulations
- average them, determine their variability
- subtract them, determine effect of parameters

It requires :

- fluctuations average out
- cells in group : number $\gg 1$
- thanks to average over space, time and samples

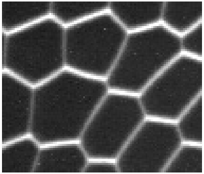
Inert cellular materials

foam as model system



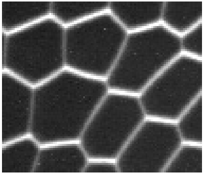
D. Cuvelier

Deform a foam



local energy minimum

Deform a foam



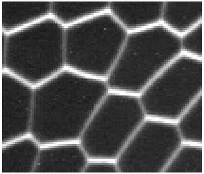
local energy minimum

Small deformation

elastic solid

reversibly comes back
to its initial shape

Deform a foam

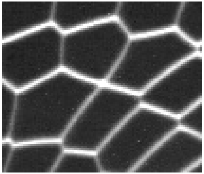


local energy minimum

yield

ε_Y

$\rightarrow$



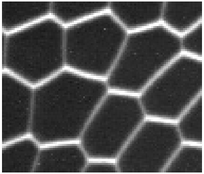
neighbour change

Small deformation

elastic solid

reversibly comes back
to its initial shape

Deform a foam

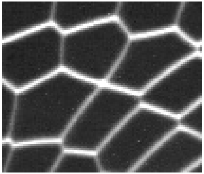


local energy minimum

yield

ε_Y

$\rightarrow$

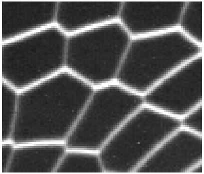


neighbour change

time

τ_R

$\rightarrow$



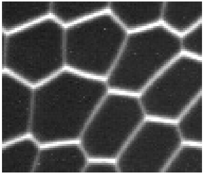
relaxation to other minimum

Small deformation

elastic solid

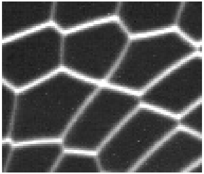
reversibly comes back
to its initial shape

Deform a foam



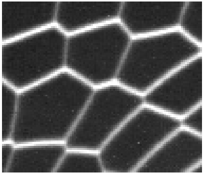
local energy minimum

yield ε_Y $\rightarrow$



neighbour change

time τ_R $\rightarrow$



relaxation to other minimum

Small deformation

elastic solid

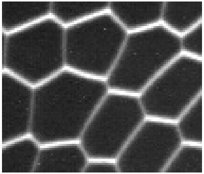
reversibly comes back to its initial shape

Large deformation

plastic solid

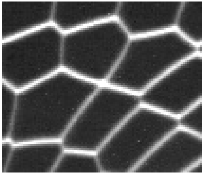
irreversibly sculpted, new shape

Deform a foam



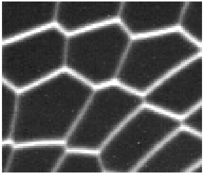
local energy minimum

yield ε_Y $\rightarrow$



neighbour change

time τ_R $\rightarrow$



relaxation to other minimum

Small deformation

elastic solid

reversibly comes back to its initial shape

Large deformation

plastic solid

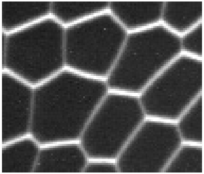
irreversibly sculpted, new shape

Quick deformation rate

viscous liquid

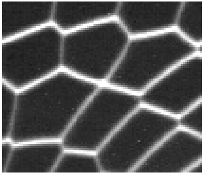
irreversibly flows, stress increases with rate

Deform a foam



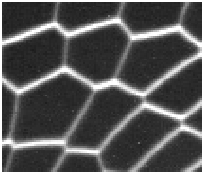
local energy minimum

yield ε_Y $\rightarrow$



neighbour change

time τ_R $\rightarrow$



relaxation to other minimum

Small deformation

elastic solid

reversibly comes back to its initial shape

Large deformation

plastic solid

irreversibly sculpted, new shape

Quick deformation rate

viscous liquid

irreversibly flows, stress increases with rate

no gap, no overlap

$\rightarrow$ deform through rearrangements

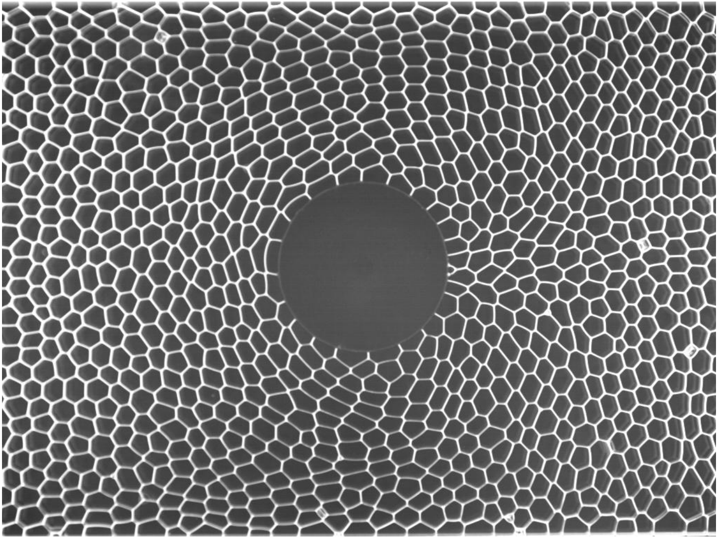
$\rightarrow$ viscous, elastic, plastic (VEP) behaviour

Foam flow around obstacle

Dollet, Raufaste

- heterogeneous : variety of shears and elastic deformations
- can discriminate between models ?

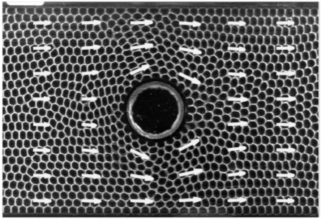
control parameters :
- 2D
- water 1.2%
- monodisperse
- $V = 0.6$ cm/s



Statistical measurements

Aubouy, Marmottant

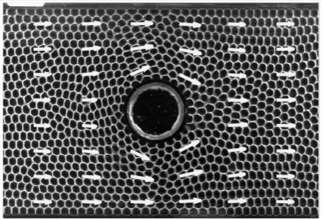
Velocity



Statistical measurements

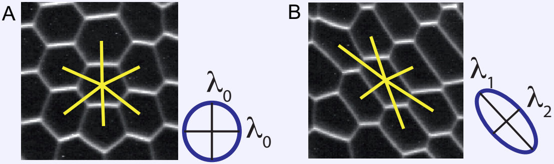
Aubouy, Marmottant

Velocity



Texture

Bubble shape and packing



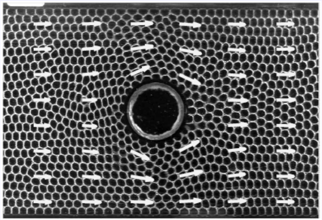
isotropic
circle

anisotropic
ellipse

Statistical measurements

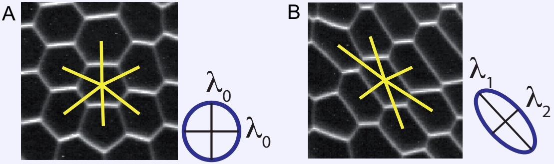
Aubouy, Marmottant

Velocity



Texture

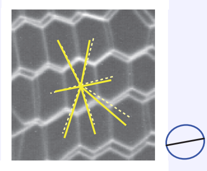
Bubble shape and packing



isotropic circle

anisotropic ellipse

Velocity gradient

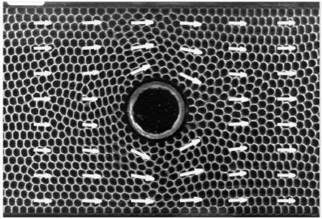


Shape change

Statistical measurements

Aubouy, Marmottant

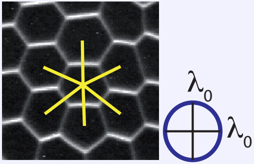
Velocity



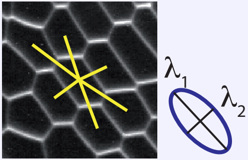
Texture

Bubble shape and packing

A



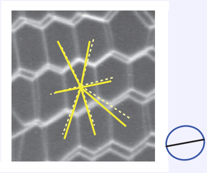
B



isotropic
circle

anisotropic
ellipse

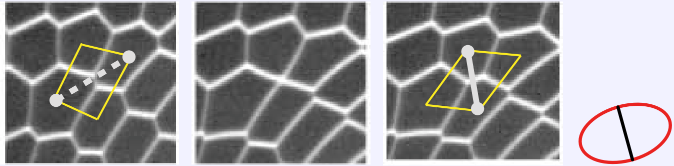
Velocity gradient



Shape change

Plasticity

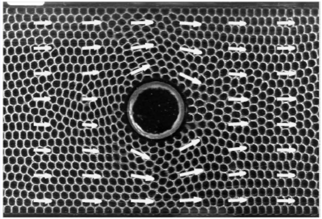
Neighbour change



Statistical measurements

Aubouy, Marmottant

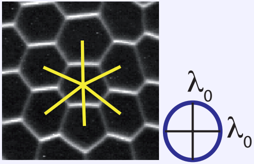
Velocity



Texture

Bubble shape and packing

A



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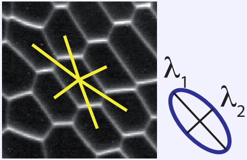

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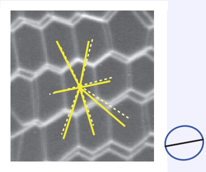
anisotropic ellipse

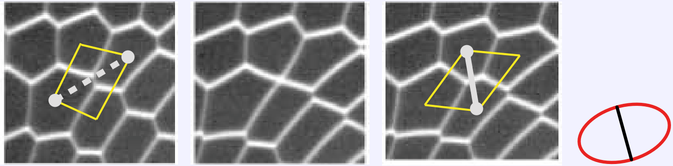
Velocity gradient



Shape change

Plasticity

Neighbour change



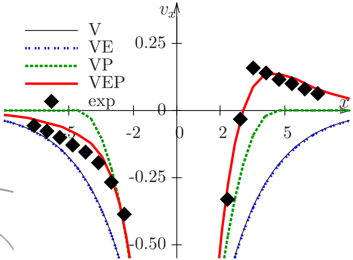
deformation rates : total = elastic + plastic

Prediction ?

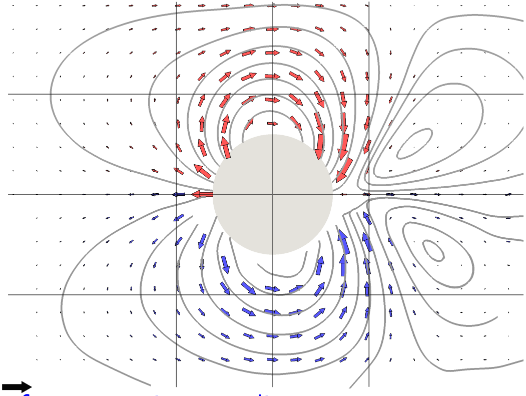
Cheddadi

speed along the main axis $y = 0$
referential moving with the foam

visco-elasto-plastic model
main parameter : yield strain



prediction : continuous model



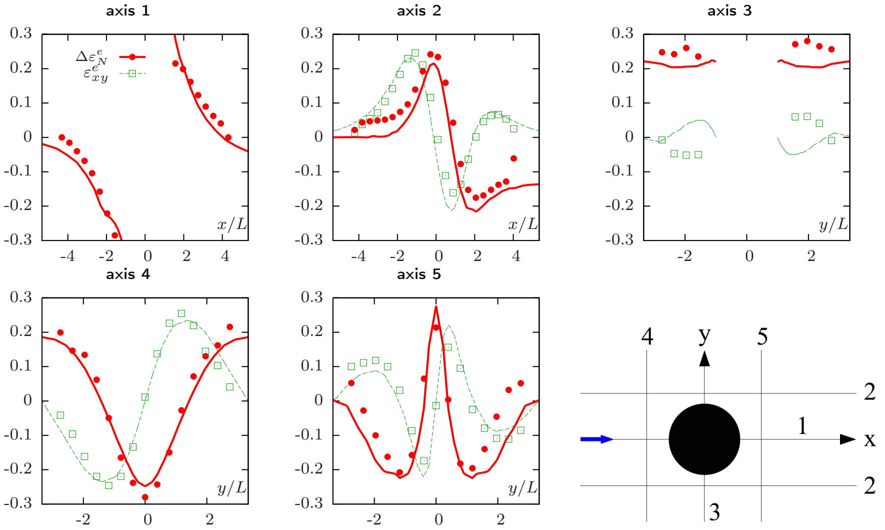
dry foam experiment : discrete measurements

Good agreement

- amplitude of **v**
- orientation of **v**
- recirculation zones
- up/down asymmetry
- $v = 0$ point
- overshoot

Graphs of elastic strain tensor

xx − *yy* and *xy* components



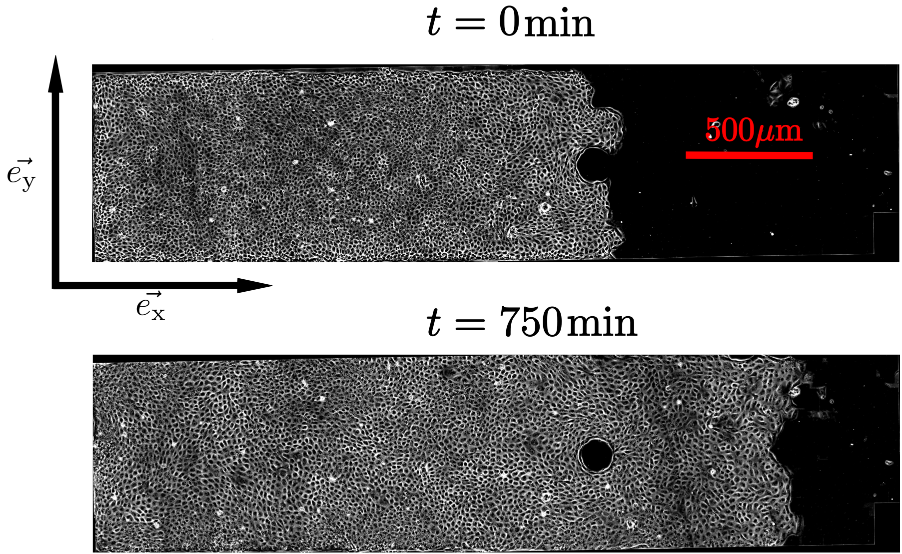
Agrees on **position** and **amplitude** of local extrema

Cell monolayer

around an obstacle

Migration around an obstacle

Tlili

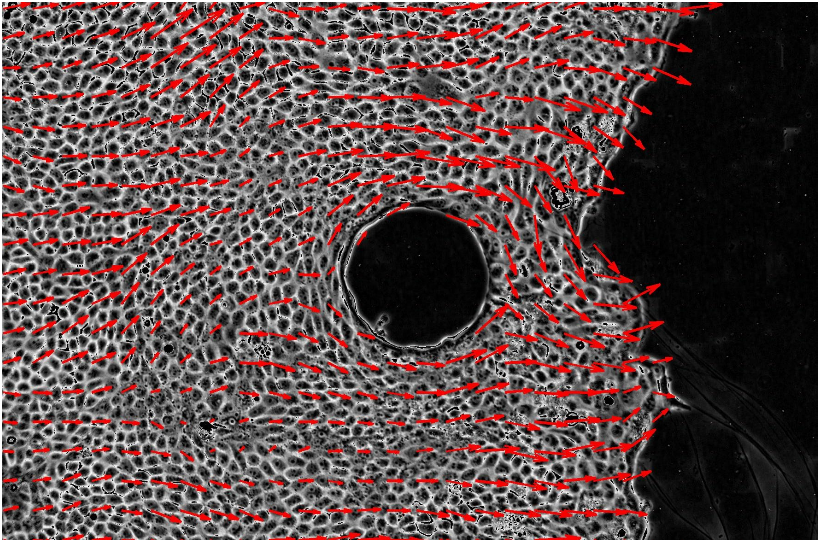


Velocity field

Tlili

image correlation : "particle image velocimetry"

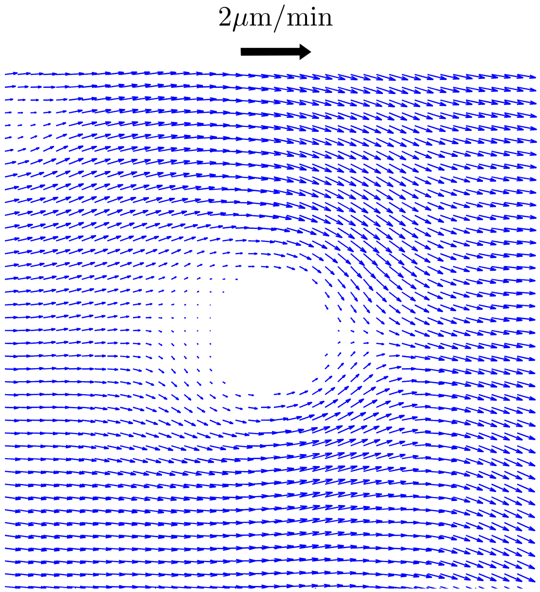
no need to identify ("segment") cell contours



Averaged velocity field

Tlili, Durande

average
over time
and/or over
experiments

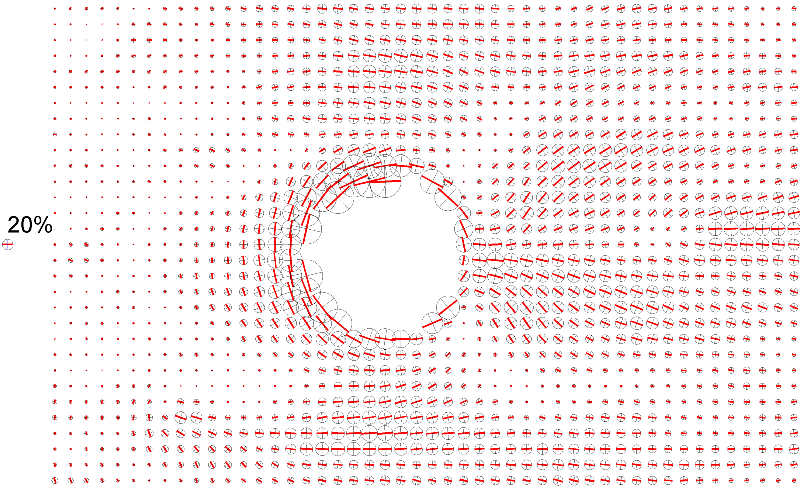


Deformation field

Tlili, Durande

cell shape : "Fourier transform"

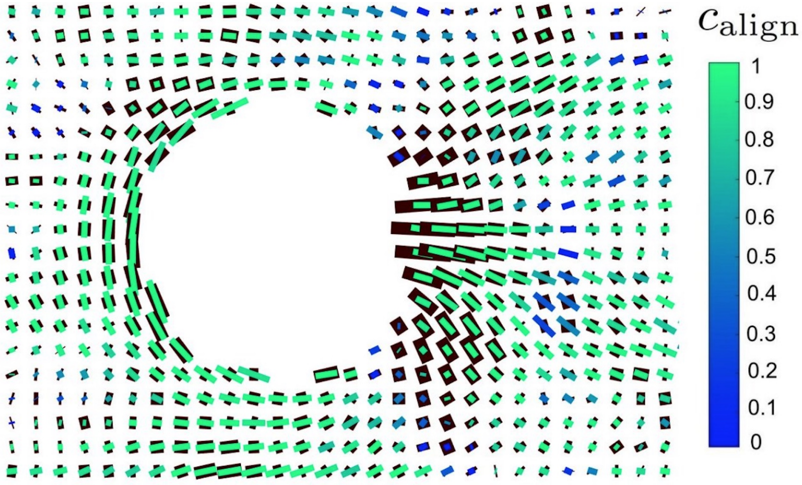
no need to identify ("segment") cell contours



Comparison

Tlili

Cell rearrangements & cell deformation fields

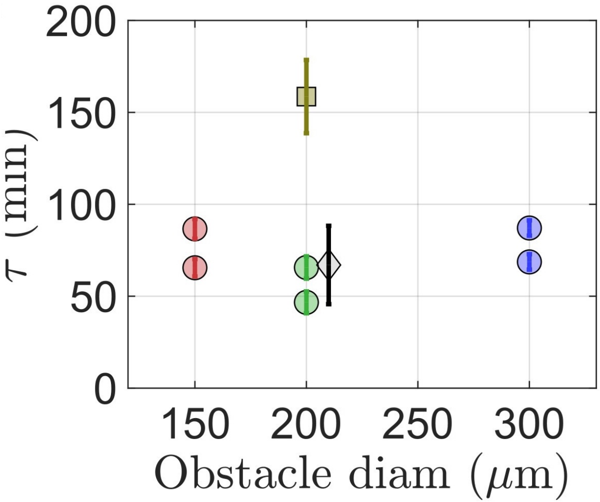


visco-elastic liquid behaviour

visco-elastic time 70 min

Visco-elastic time

Tlili



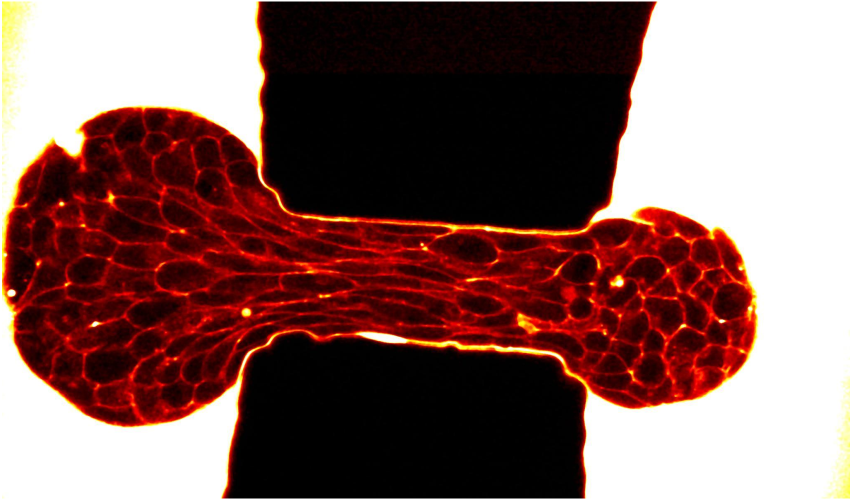
τ independent on obstacle size & independent on division rate

slowed down by myosin inhibitor, related to cell rearrangements

Cell aggregate

through a constriction

Aspire a cell aggregate

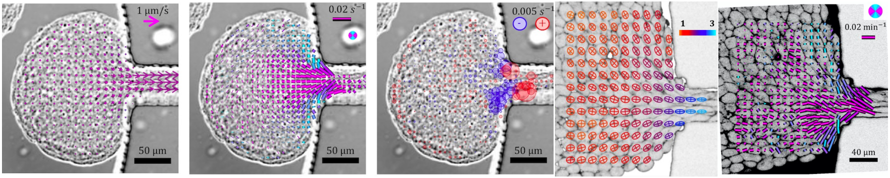


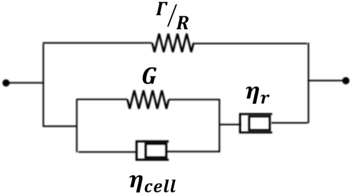
- 1 movie = 3 experiments : constriction, divergence, elasto-capillarity
- heterogeneous : induced cell rearrangements, many informations
- measure and link : cell shape, neighbour changes, local viscoelastic properties

All measures without segmentation

Tlili

velocity shear compression shape plastic





cell group scale visco-elastic relaxation time	τ_r	10^3 s
cell group scale viscosity	η_r	10^5 Pa.s
elastic modulus	G	10^2 Pa
cell scale visco-elastic relaxation time	τ_{cell}	10^2 s
cell scale viscosity	η_{cell}	10^4 Pa.s
aggregate scale capillary modulus	(Γ/R)	10^2 Pa

η_r from previous experiments

Elasto-capillar number ~ 1

Conclusion

Summary of approach

Objects with disorder, elasticity, rearrangements

- Very general applications : bubbles in foam, cells in tissue, grains in polycrystal, atoms in glass, drops in emulsion, magnetic domains, packed soft objects, etc
- total deformation rate
  = elastic deformation rate
  + plastic deformation rate
- experiments and simulations which vary in space
- coarse grain $\rightarrow$ continuous description
- compare experiments and/or simulations

Summary of results

How do objects with disorder, elasticity flow ?

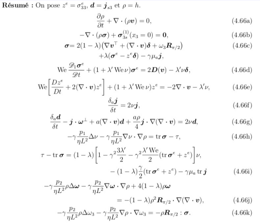
- powerful statistical tools to analyse data
- cellular structure → emergent solid behaviour
- inert case → coarse-grain & model predicts flow
- activity → emergent collective migration
- extract rheological equations and parameters

Perspectives

in progress

Model

Shourick



Résumé : On pose $z^e = \sigma^e_{33}$, $\boldsymbol{d} = \boldsymbol{j}_{s3}$ et $\rho = h$.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \tag{4.66a}$$

$$-\nabla \cdot (\rho \boldsymbol{\sigma}) + \boldsymbol{\sigma}^{(1)}_{3s}(x_3 = 0) = \boldsymbol{0}, \tag{4.66b}$$

$$\boldsymbol{\sigma} = 2(1-\lambda)\big(\nabla \boldsymbol{v}^\top + (\nabla \cdot \boldsymbol{v})\boldsymbol{\delta} + \omega_3 \boldsymbol{R}_{\pi/2}\big) + \lambda(\boldsymbol{\sigma}^e - z^e \boldsymbol{\delta}) - \gamma \mu_a \boldsymbol{j}, \tag{4.66c}$$

$$\mathrm{We}\, \frac{\mathscr{D}_1 \boldsymbol{\sigma}^e}{\mathscr{D} t} + (1 + \lambda' \,\mathrm{We}\, \nu)\boldsymbol{\sigma}^e = 2\boldsymbol{D}(\boldsymbol{v}) - \lambda' \nu \boldsymbol{\delta}, \tag{4.66d}$$

$$\mathrm{We}\left[\frac{D z^e}{D t} + 2(\nabla \cdot \boldsymbol{v}) z^e\right] + (1 + \lambda' \,\mathrm{We}\, \nu) z^e = -2\nabla \cdot \boldsymbol{v} - \lambda' \nu, \tag{4.66e}$$

$$\frac{\delta_a \boldsymbol{j}}{\delta t} = 2\nu \boldsymbol{j}, \tag{4.66f}$$

$$\frac{\delta_a \boldsymbol{d}}{\delta t} - \boldsymbol{j} \cdot \boldsymbol{\omega}^\perp + a(\nabla \cdot \boldsymbol{v})\boldsymbol{d} + \frac{a\rho}{4} \boldsymbol{j} \cdot \nabla(\nabla \cdot \boldsymbol{v}) = 2\nu \boldsymbol{d}, \tag{4.66g}$$

$$-\gamma \frac{p_1}{\eta L^2} \Delta \nu - \gamma \frac{p_1}{\eta L^2} \nabla \nu \cdot \nabla \rho = \mathrm{tr}\, \boldsymbol{\sigma} - \tau, \tag{4.66h}$$

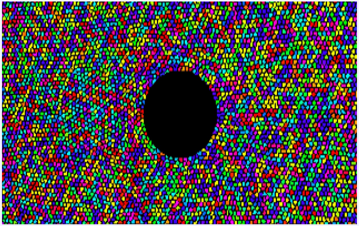
$$\tau - \mathrm{tr}\, \boldsymbol{\sigma} = (1-\lambda)\left[1 - \gamma^2 \frac{3\lambda'}{2} - \gamma^2 \frac{\lambda' \,\mathrm{We}}{2} (\mathrm{tr}\, \boldsymbol{\sigma}^e + z^e)\right]\nu, - (1-\lambda)\frac{\gamma}{2}(\mathrm{tr}\, \boldsymbol{\sigma}^e + z^e) - \gamma \mu_a \,\mathrm{tr}\, \boldsymbol{j} \tag{4.66i}$$

$$-\gamma \frac{p_2}{\eta L^2} \rho \Delta \boldsymbol{\omega} - \gamma \frac{p_2}{\eta L^2} \nabla \boldsymbol{\omega} \cdot \nabla \rho + 4(1-\lambda)\rho \boldsymbol{\omega} = -(1-\lambda)\rho^2 \boldsymbol{R}_{\pi/2} \cdot \nabla(\nabla \cdot \boldsymbol{v}), \tag{4.66j}$$

$$-\gamma \frac{p_2}{\eta L^2} \rho \Delta \omega_3 - \gamma \frac{p_2}{\eta L^2} \nabla \rho \cdot \nabla \omega_3 = -\rho \boldsymbol{R}_{\pi/2} : \boldsymbol{\sigma}. \tag{4.66k}$$

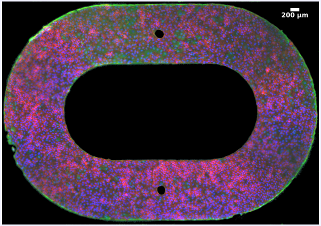
Simulations

Beatrici



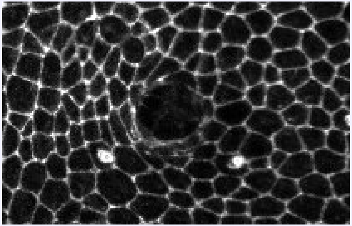
Boundaries

Durande



In vivo

Villedieu



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