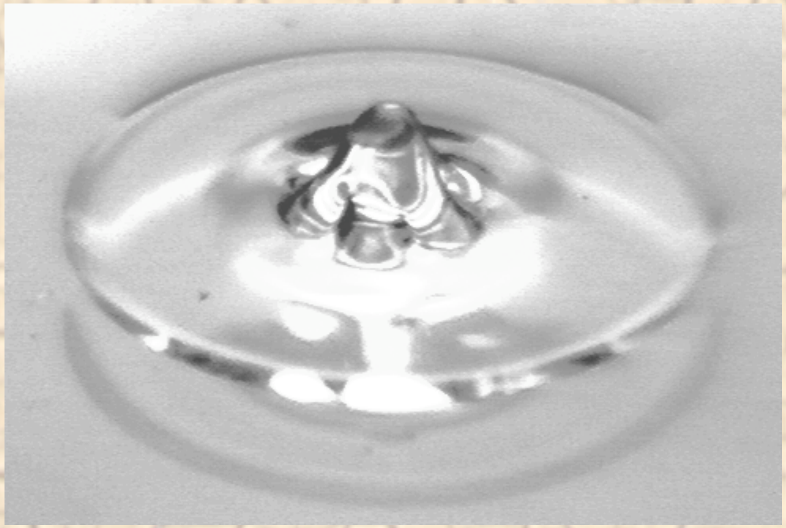
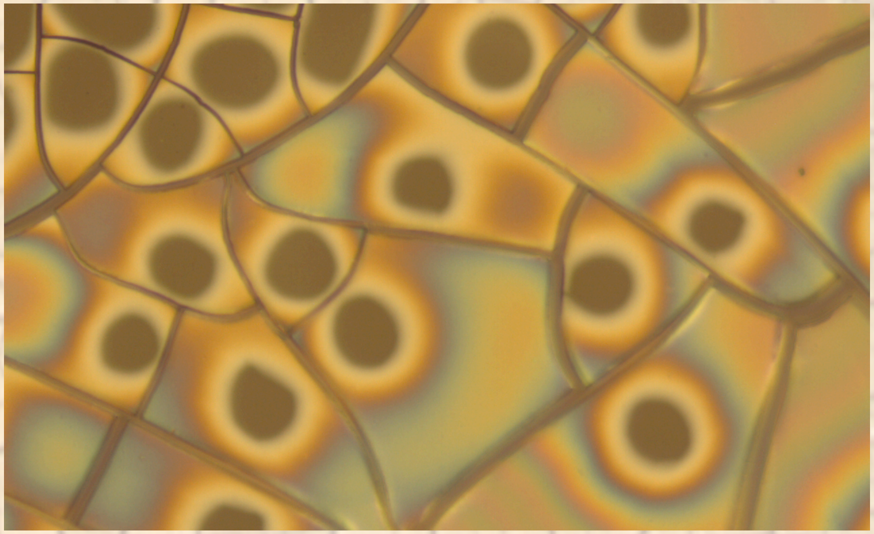
Drying of complex fluids: Deformations and fractures

L. Pauchard
FAST

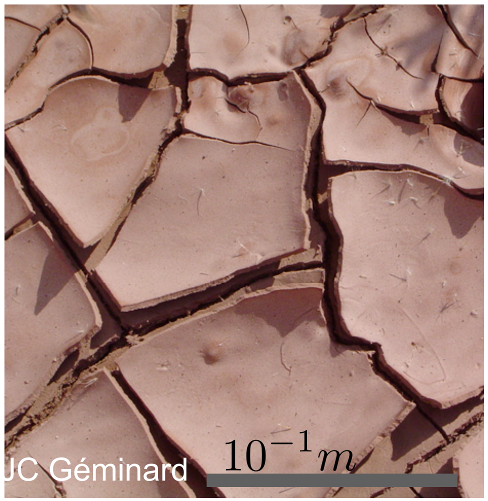


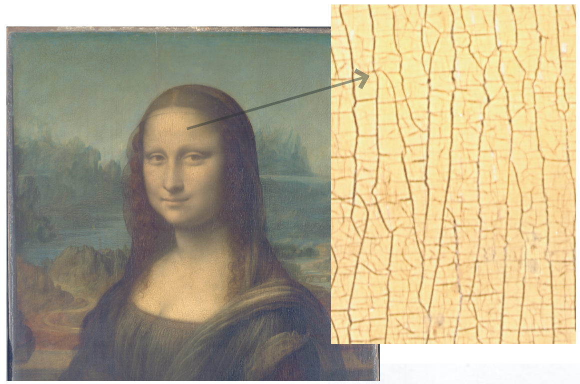


Singularities

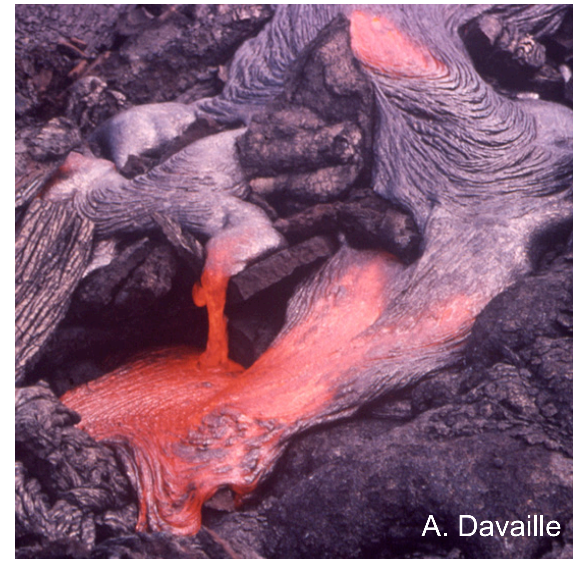
crack patterns

inversion of curvature in shells

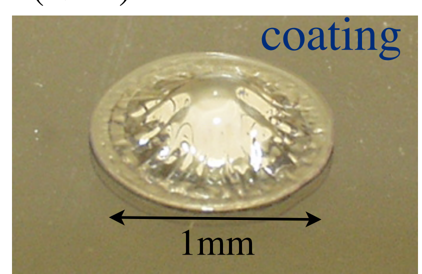


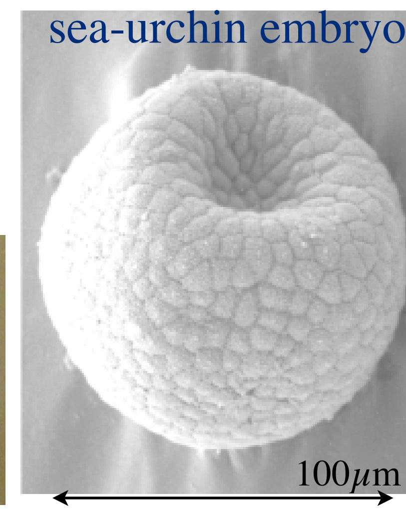


Carlson (1967)



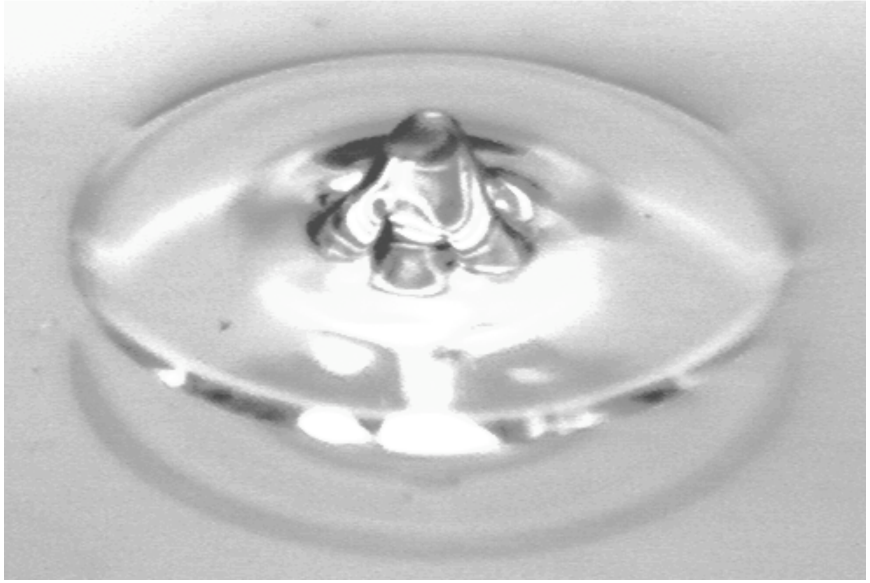
directional cracks propagation





I

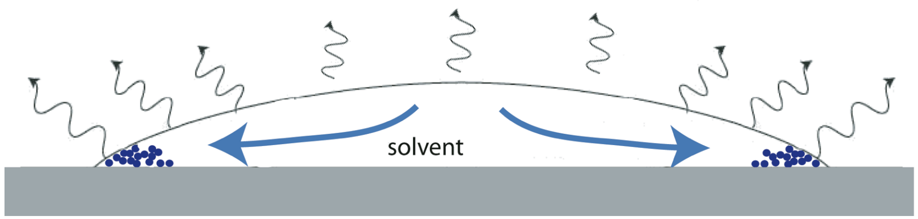
Drying of drops of complex fluids



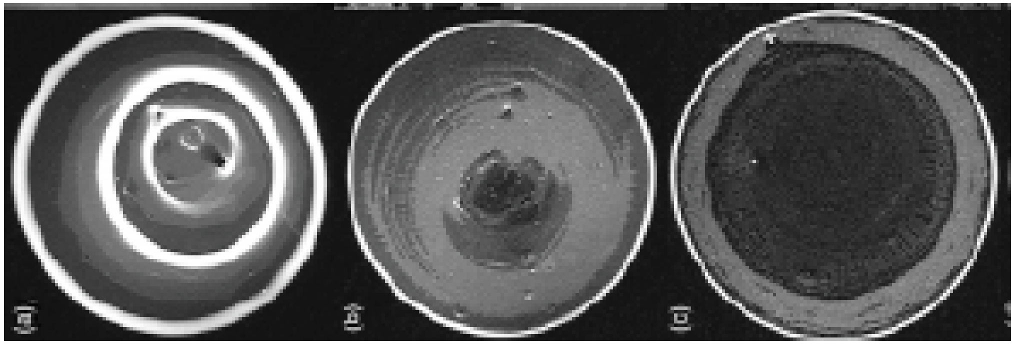
Drying a sessile drop of complex liquids
dilute solutions

3-phase line

side view



deposition patterns left by a drop of a dilute colloidal suspension



top view

Deegan, thesis (1998)

evaporation-induced flow → deposition of layers (Berteloot et al., Eur. Phys. Lett. (2008))

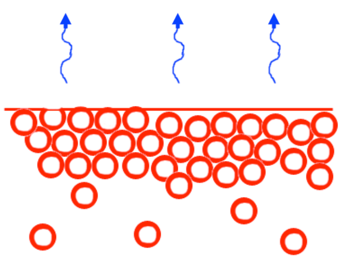
Drying a sessile drop of complex liquids
concentrated solutions

complex drop shapes due to different process

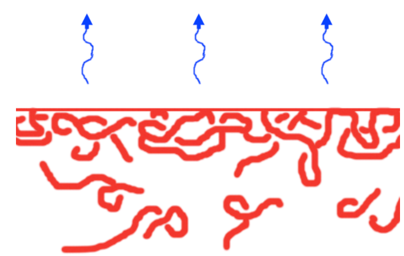
- pinning of the three-phase line

- large concentration gradients

colloidal suspensions

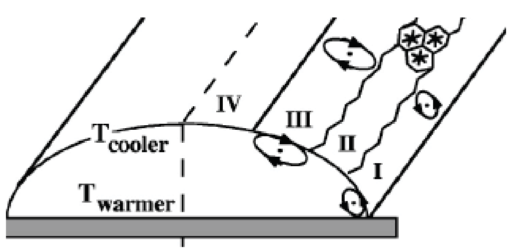


polymer solutions



- hydrodynamic

Rayleigh-Bénard or
Bénard-Marangoni effects



or mechanical instabilities

Drying a sessile drop of complex liquids concentrated solutions

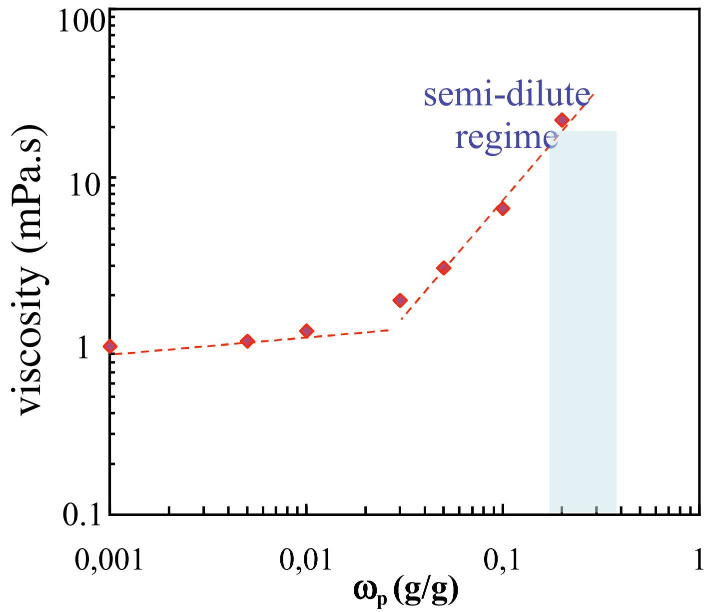
importance of :

- drying conditions,
- geometry,
- physico-chemical properties of the system.

Drying a drop of polymer solution: glass transition during desiccation

polymer = dextran (hydrosoluble polysaccharide)

concentration in mass : from 20 to 40% (ω_p)



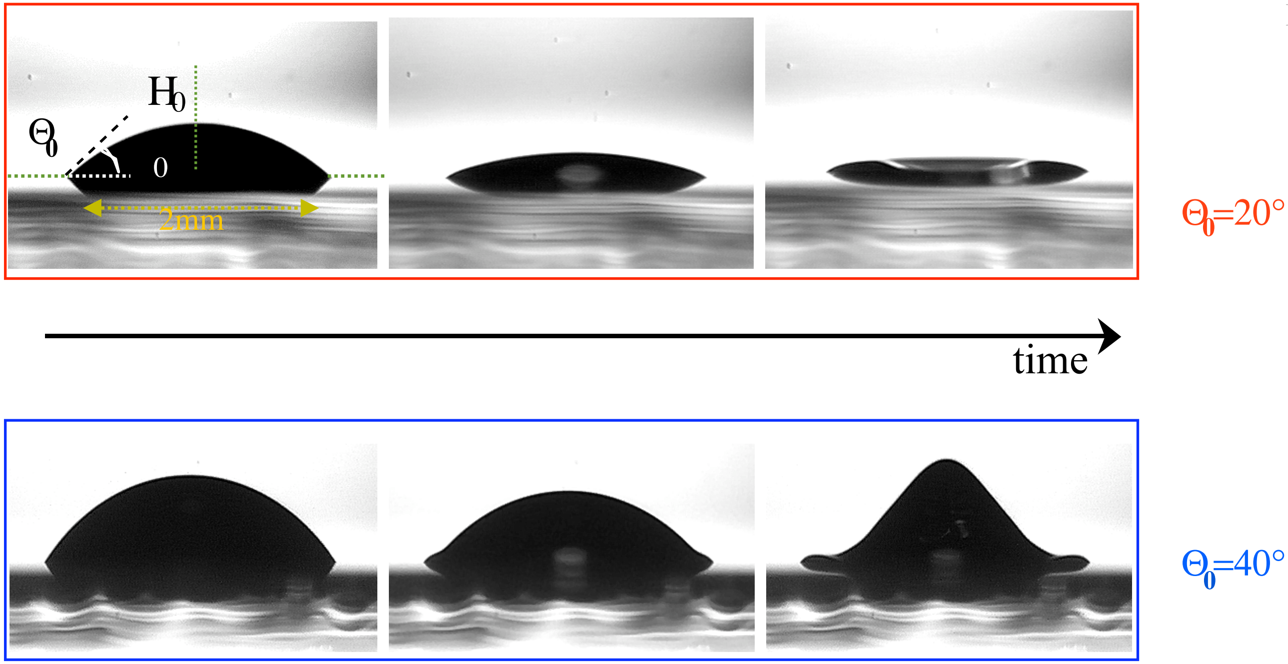
Tg~220°C (glass transition temperature)

solvent loss

⇒ polymer concentration increases

⇒ medium becomes glassy

ω_p ,RH,T : constants



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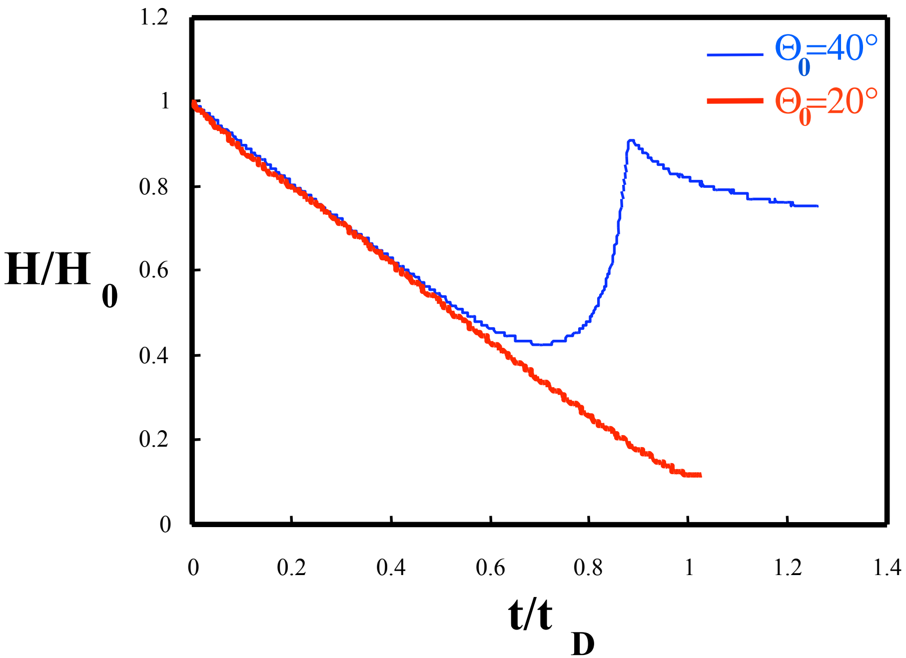
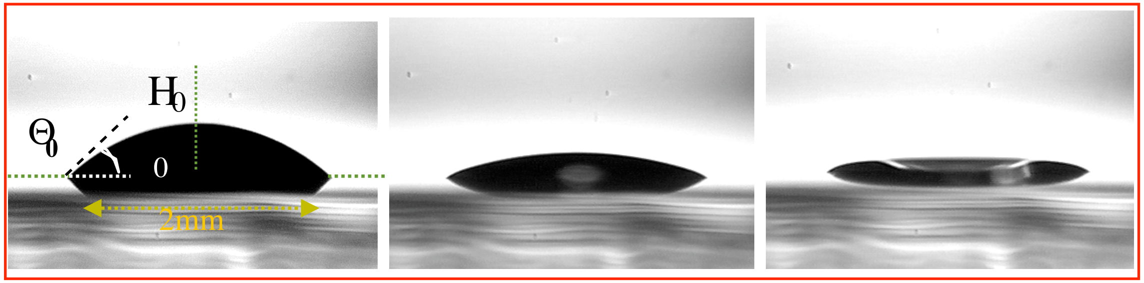
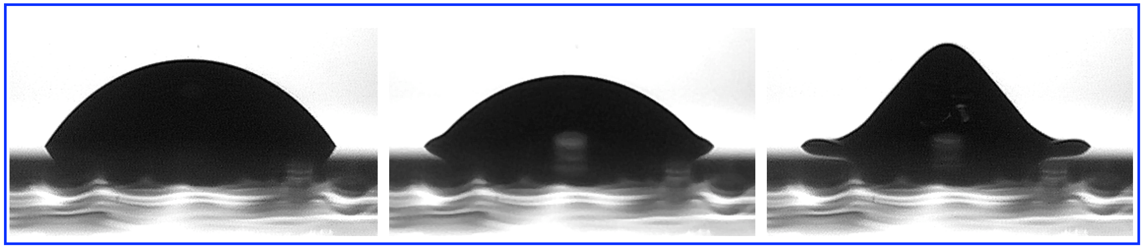


ω_p ,*RH,T : constants*



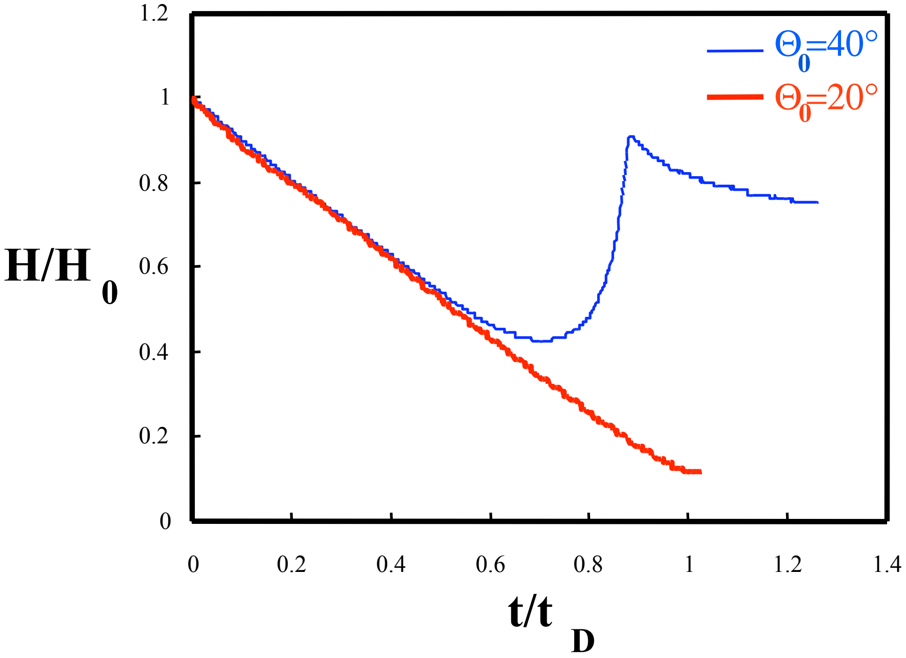
Θ_0=20°

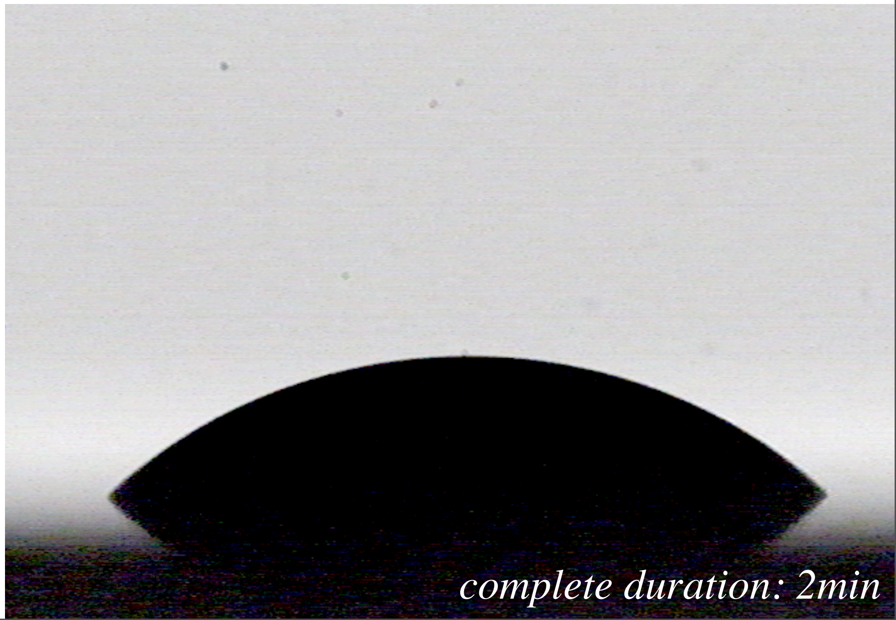
time

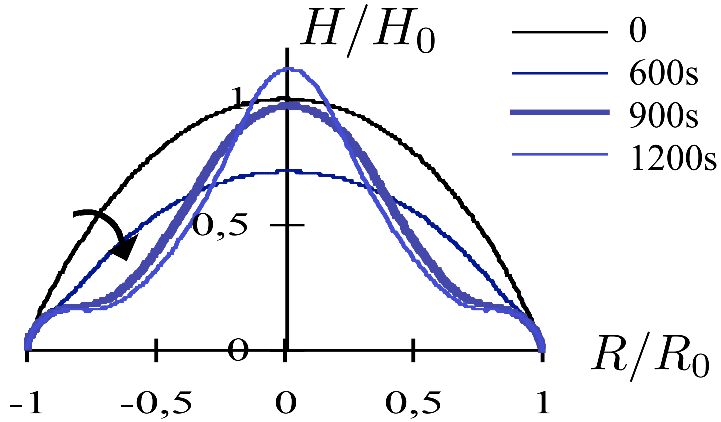


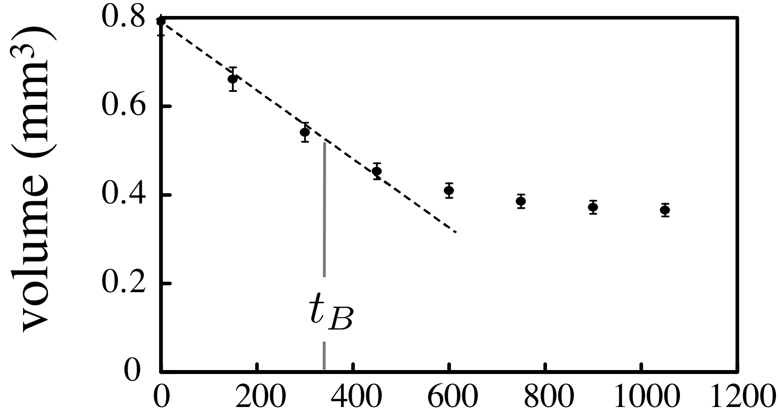
Θ_0=40°

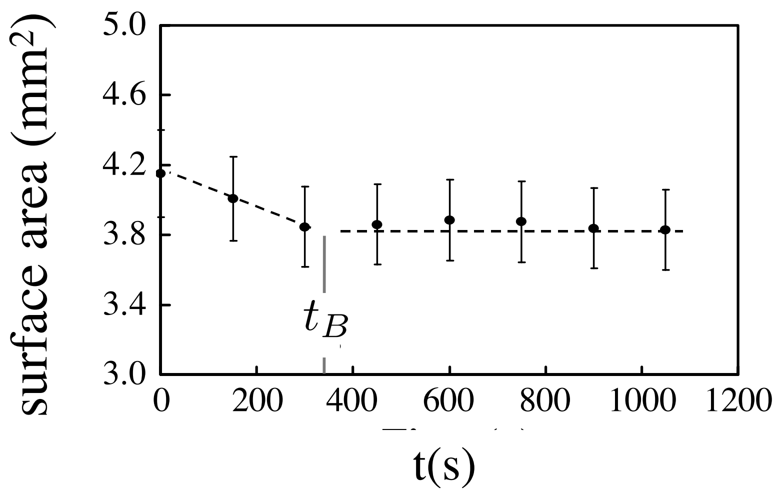
?

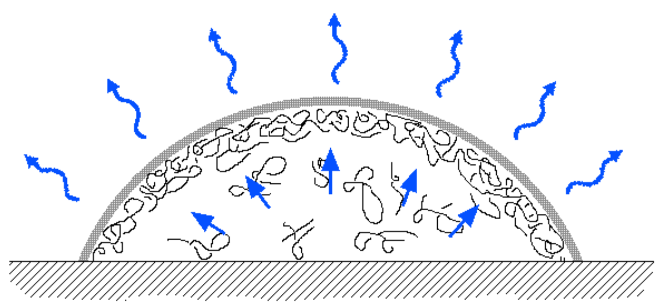












formation of a glassy skin at the evaporation surface

deformation: buckling process

Drop shape characterization

Evaporation rate: $$\dot{V}_E = A(\theta_0) D_a \frac{n_{ws}(1-RH)}{R_0}$$

Transfer of solvent in air limited by diffusion $$\Rightarrow t_D = \frac{R_0}{\dot{V}_E} \cdot \frac{V_0}{R_0 S_0}$$

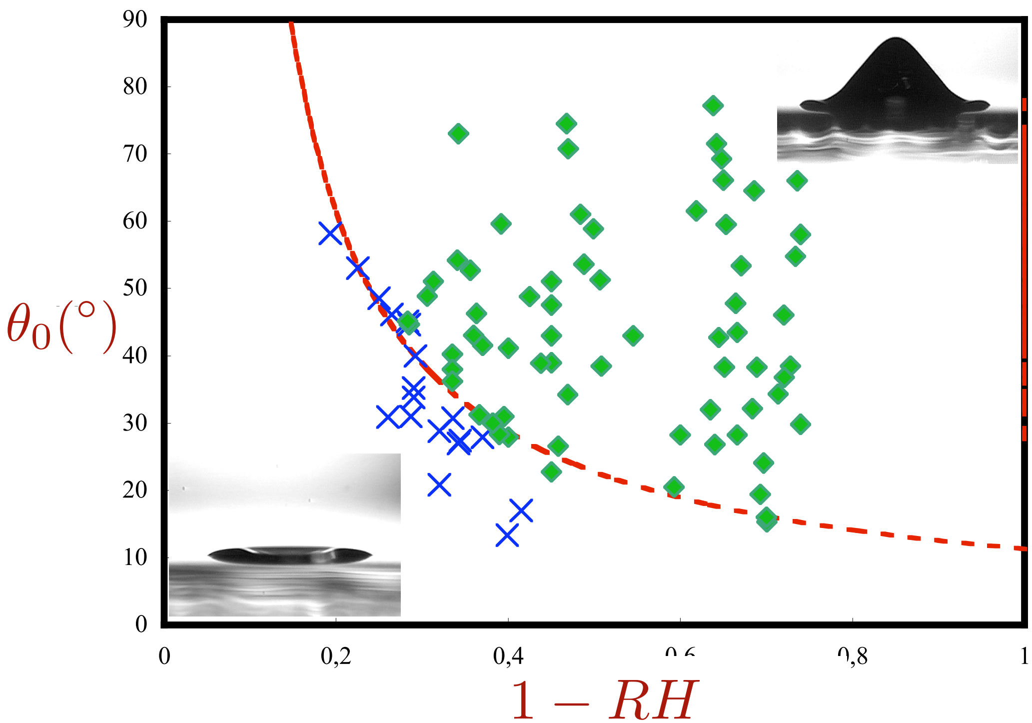
Solvent flux conservation at interface $$\dot{V}_E = D_m . \nabla \phi_p$$

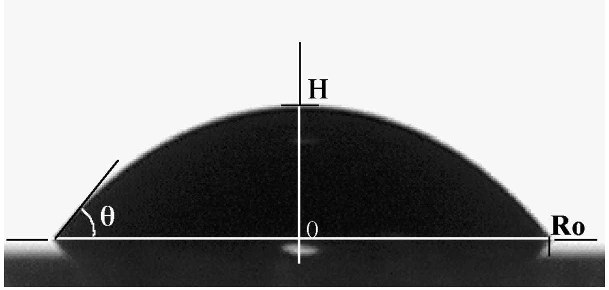
Deformation criterion $$\phi_{p|surface} = \phi_g$$ (glassy state)

$$\Rightarrow t_B = f(\theta_0, RH) \frac{R_0^2}{D_m}$$

$t_B > t_D$: no buckling

$t_B < t_D$: buckling

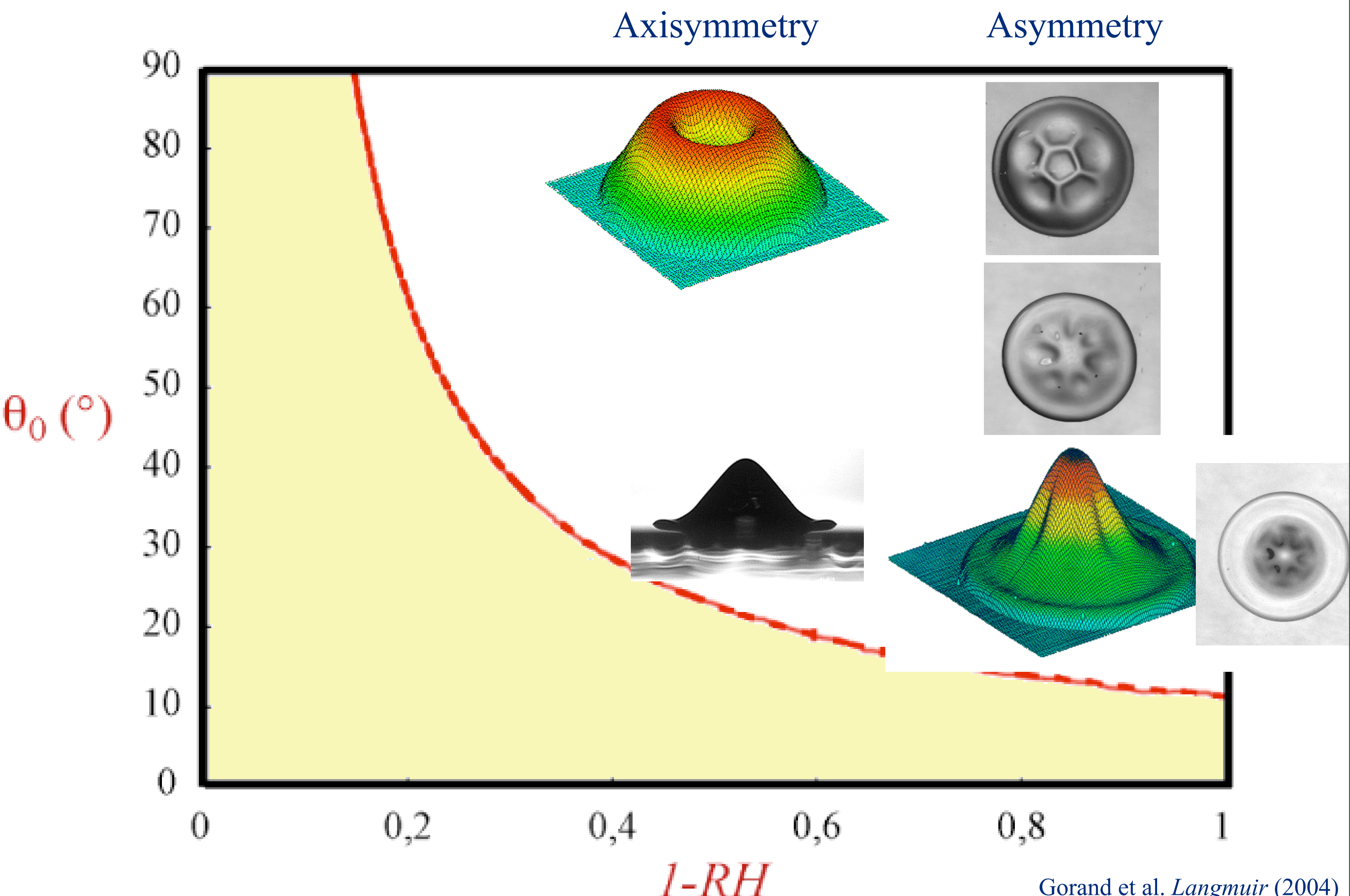




Pauchard, Allain *Europhys. Lett.* (2003)

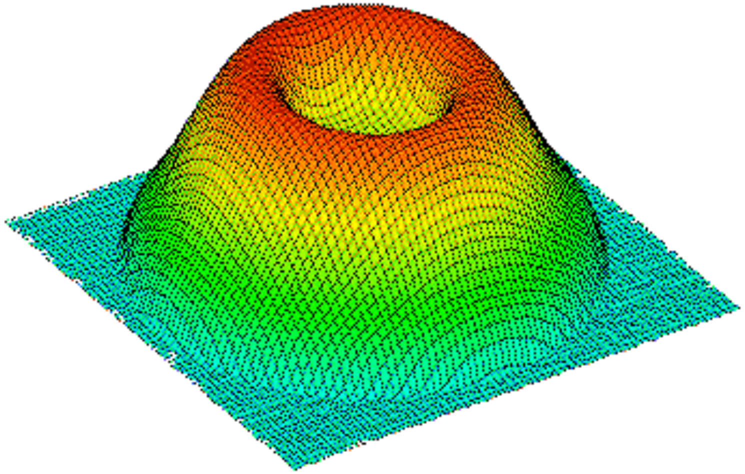
Pauchard, Allain *Phys. Rev. E* (2003)

Different patterns



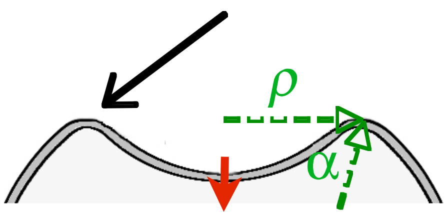
Gorand et al. *Langmuir* (2004)

Inversion of curvature



in-plane deformation

out-of-plane deformation



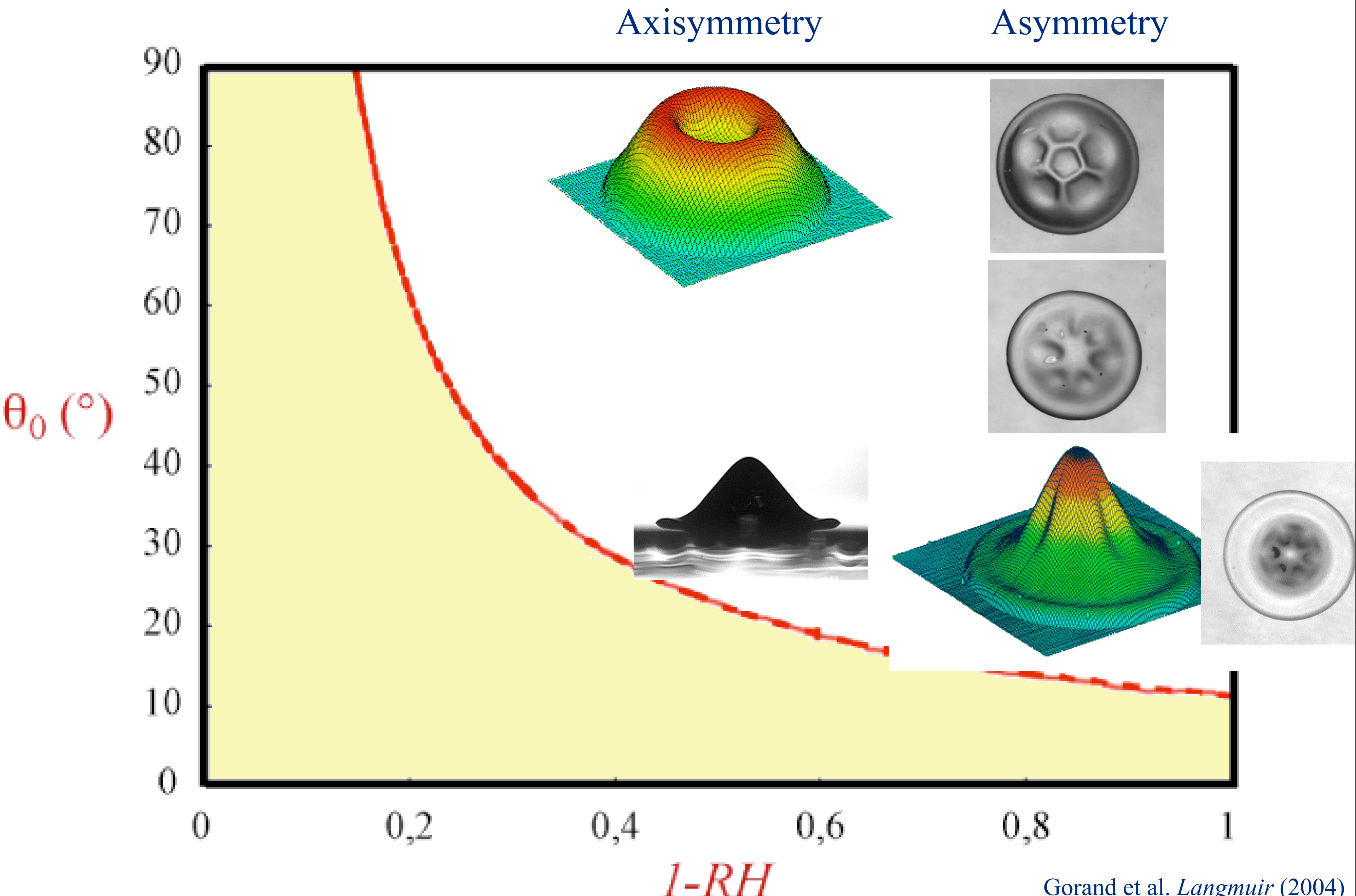
$$h \sim \frac{\alpha^2}{\rho} \sim \frac{\left(400.10^{-6}\right)^2}{2.10^{-3}} = 100\,\mu m$$

$$U_{compression} = C_2 \frac{Eh}{R} \delta^3$$

$$U_{\text{fold}} = C_1 \frac{Eh^{5/2}}{R} \delta^{3/2}$$

elastic energy $U = Eh \int [\frac{h^2}{24(1-\nu^2)} H^2 + 1/8(\Delta^{-1} K)^2] ds$ Föppl (1907)

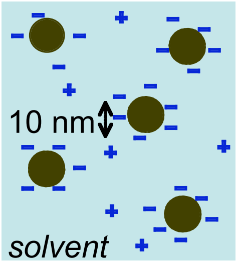
Different patterns



Gorand et al. *Langmuir* (2004)

Drying a drop of colloidal suspension

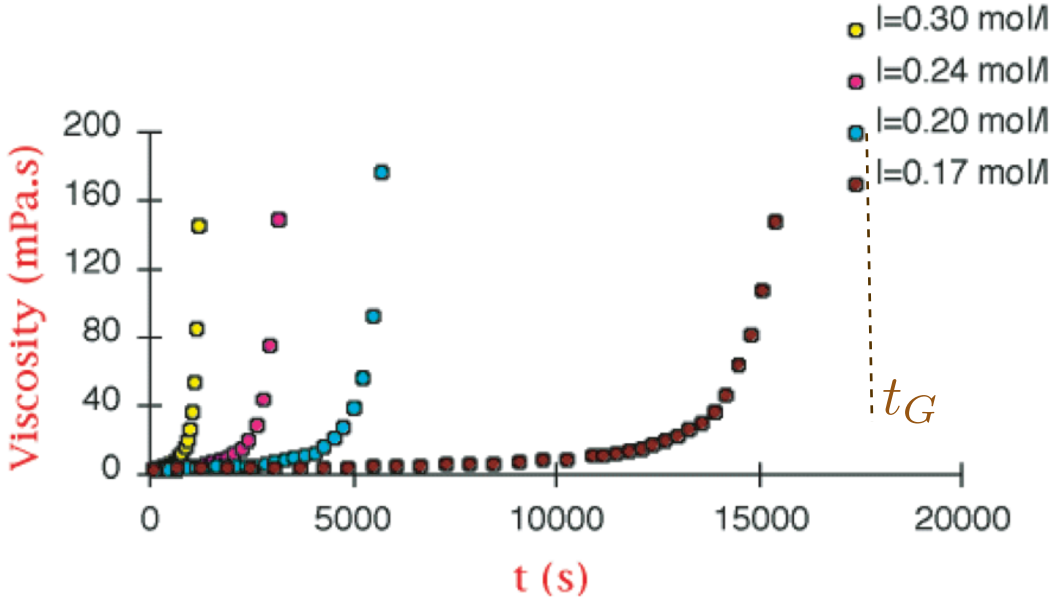
2 coupled effects in the sol-gel transformation (case of a silica dispersion)



Gelation kinetics

influence of the ionic strength I:
screening charges borne by particles

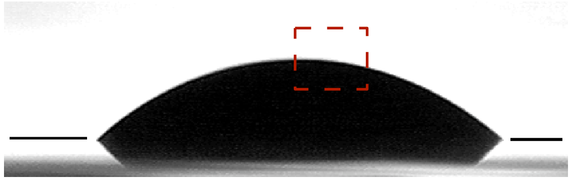
suspension viscosity increases as aggregates form
⇒ colloidal gel = solid porous matrix saturated by solvent

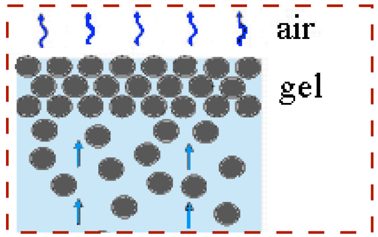


gelation time t_G

Drying kinetics

evaporation of solvent



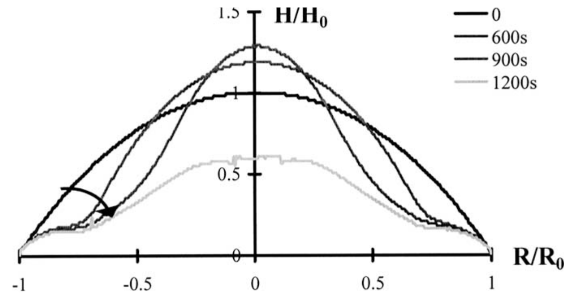


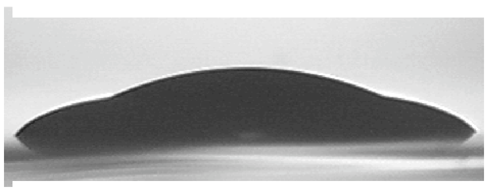
drying time $t_D = \frac{R_0}{\dot{V}_E} \cdot \frac{V_0}{R_0 S_0}$

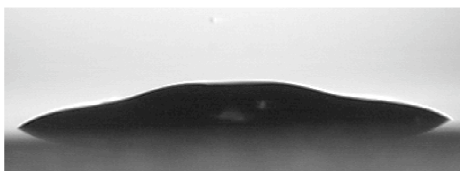
$t_G/t_D > 10^2$
drying

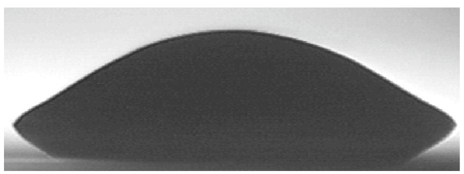
$10^{-1} < t_G/t_D < 10$
drying + gelation

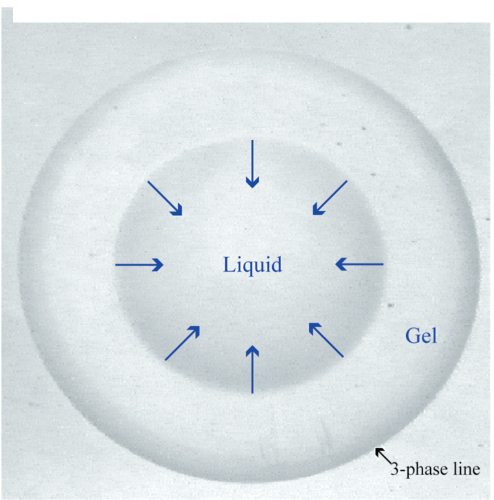
$t_G/t_D < 10^{-2}$
gelation

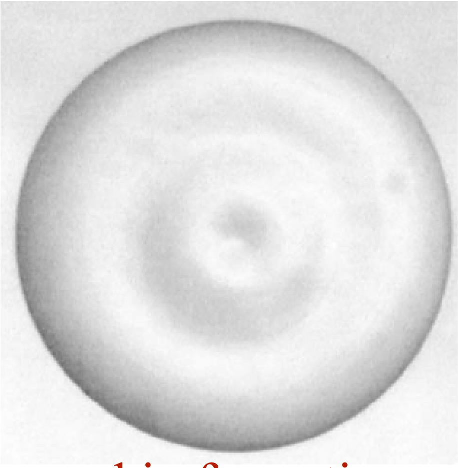


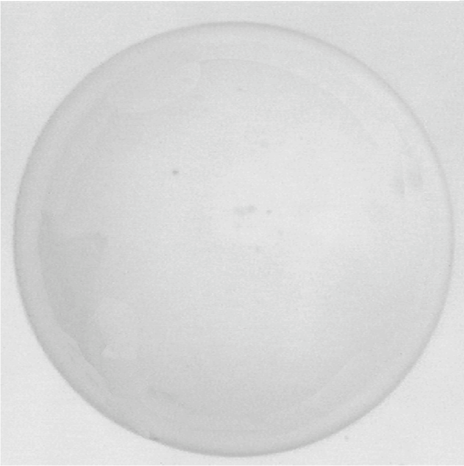








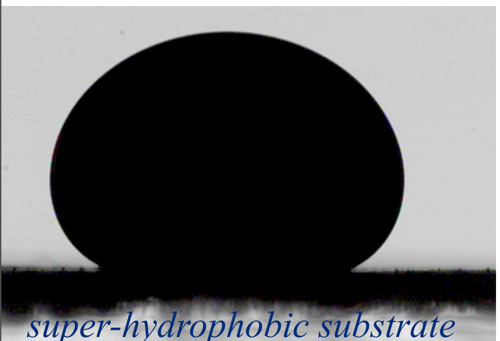




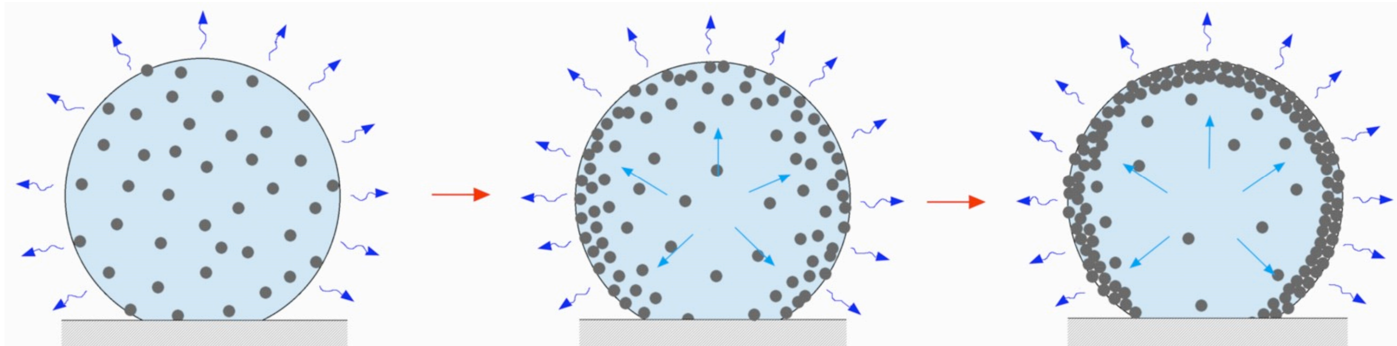
skin formation
buckling process

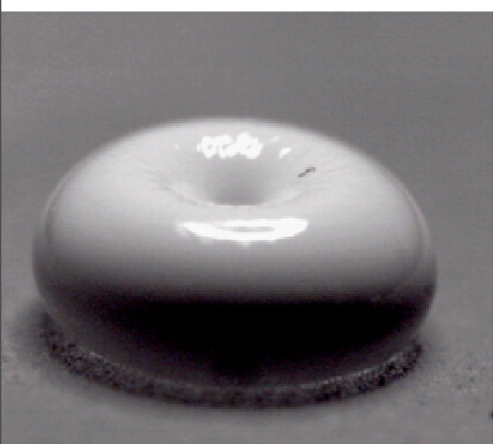
Pauchard, Parisse, Allain *Phys. Rev. E* (1999)

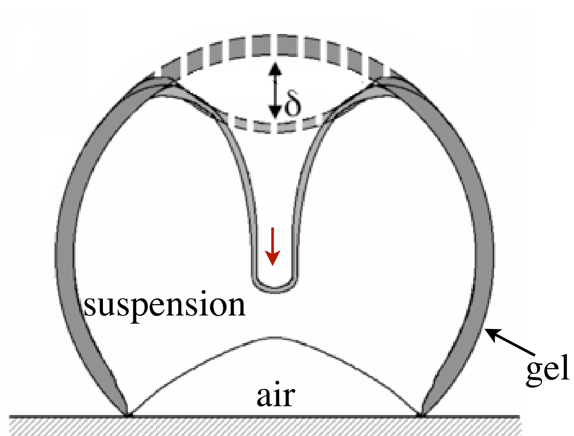
Invagination during the collapse of an inhomogeneous spheroidal shell



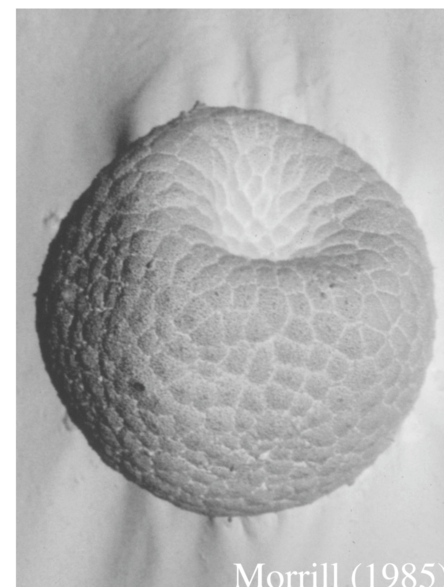
2mm

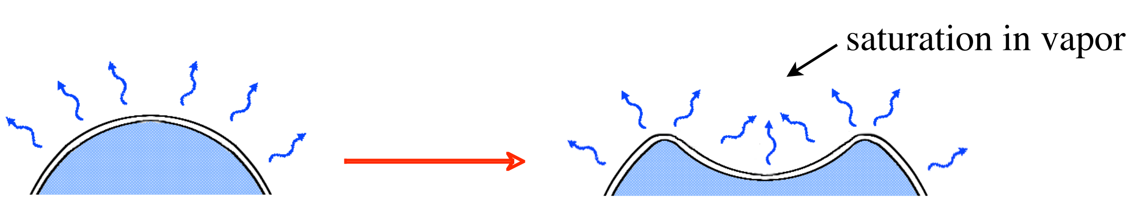






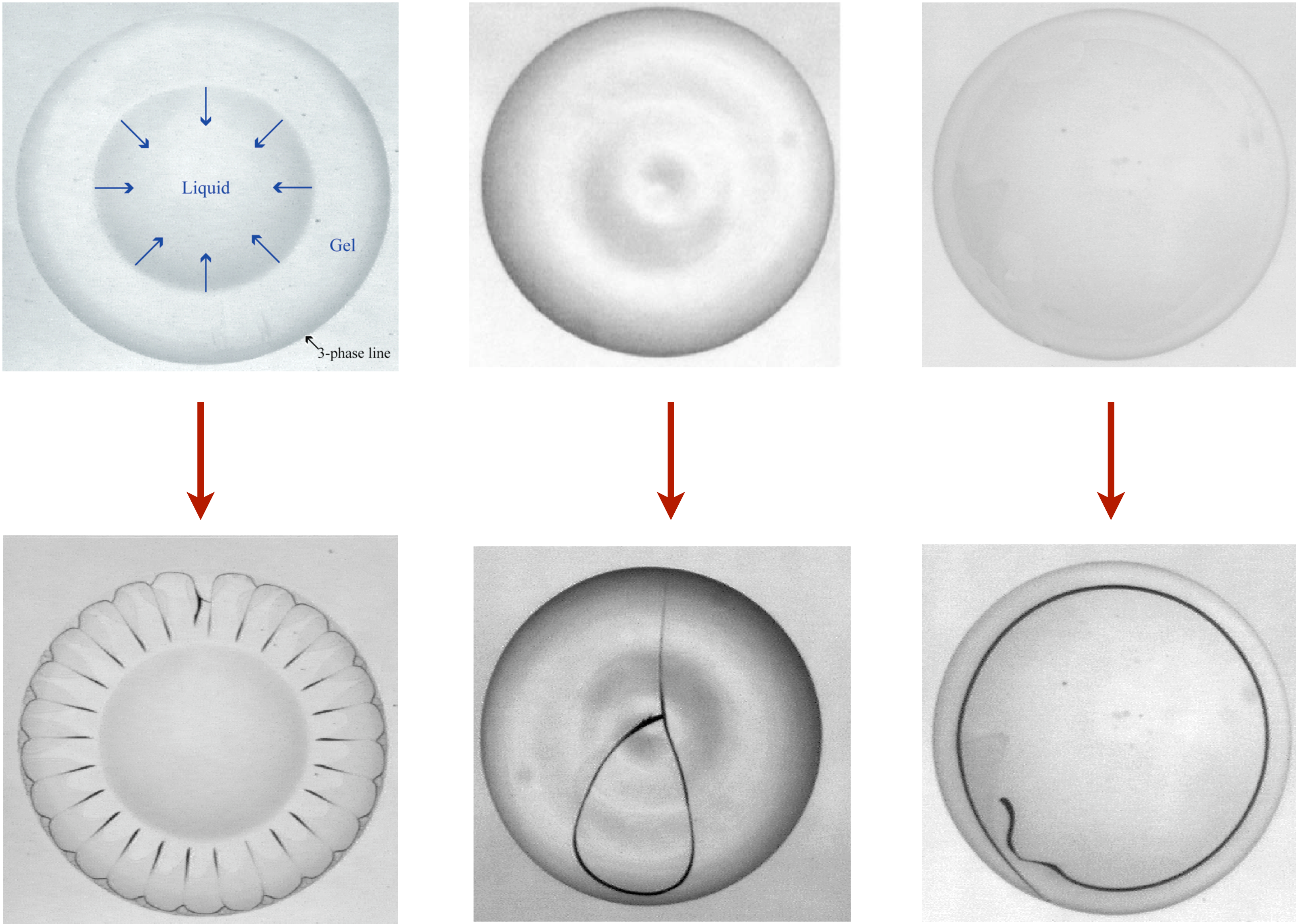
invagination in sea-urchin embryo



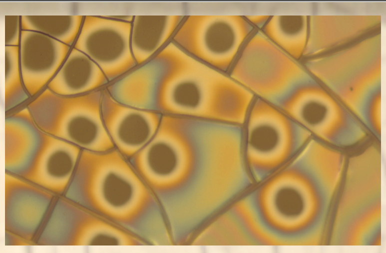


Pauchard, Couder *Europhys. Lett.* (2004)
Goriely, Ben Amar *Phys. Rev. Lett.* (2005)

Crack patterns induced by desiccation



Conclusion



exemples of problems coupling physico-chemical properties and mechanical properties

large domain of elasticity — brittle domain

stress relaxation ⇒ modifications internal structures

⇒ deformations (wrinkles, fractures)

successsive generations of cracks induced by residual stresses

FAST
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