Drying of complex fluids: fractures

L. Pauchard
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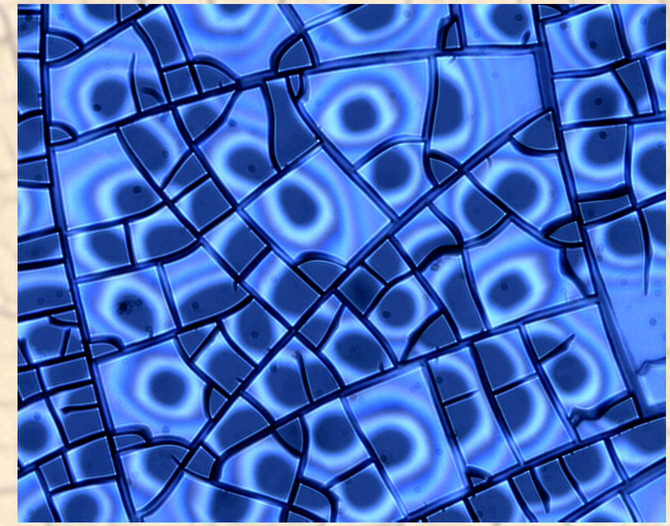


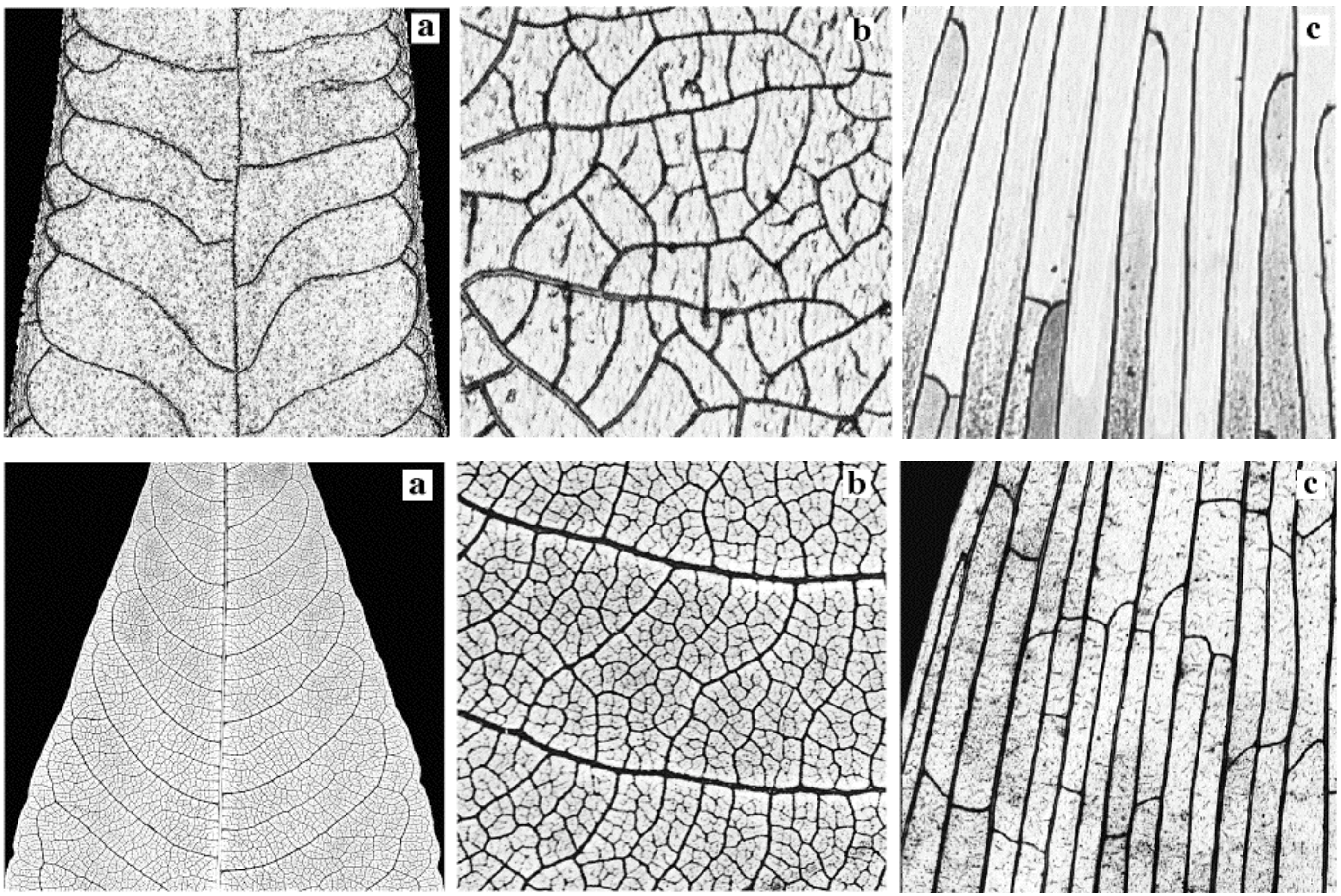
Cargèse, Corsica, 28/07-08/08 2008

Some motivations...

- growth patterns

cracks

venation



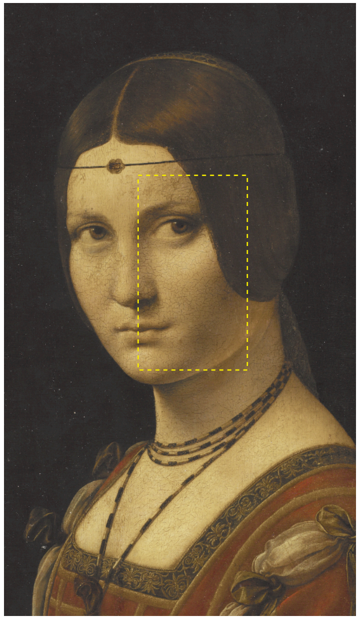
Couder, Pauchard, Allain, Douady *EPJB* (2002)

Interests to study crack patterns...

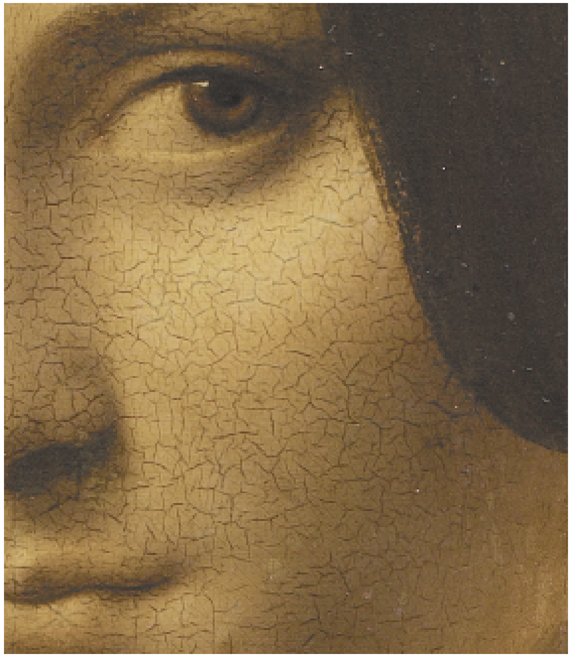
- restoration, judging authenticity and knowledge of techniques in Paintings

ANR « Morphologies » L. Pauchard, B. Abou, V. Lazarus, K. Sekimoto

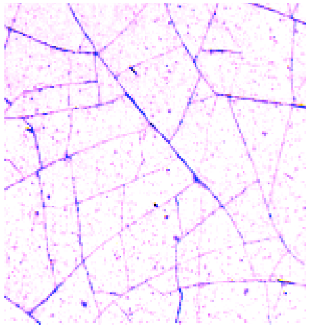
C. Lahanier, G. Aitken (Centre de Recherche et de Restauration des Musées de France - Musée du Louvre)

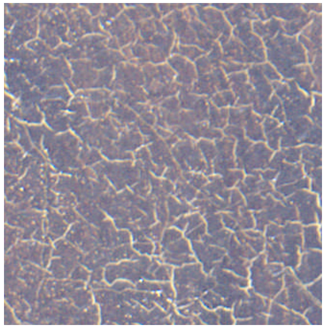


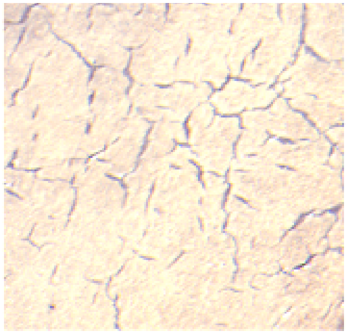
"*la Belle Ferronnière*"
De Vinci



large variety of craquelures



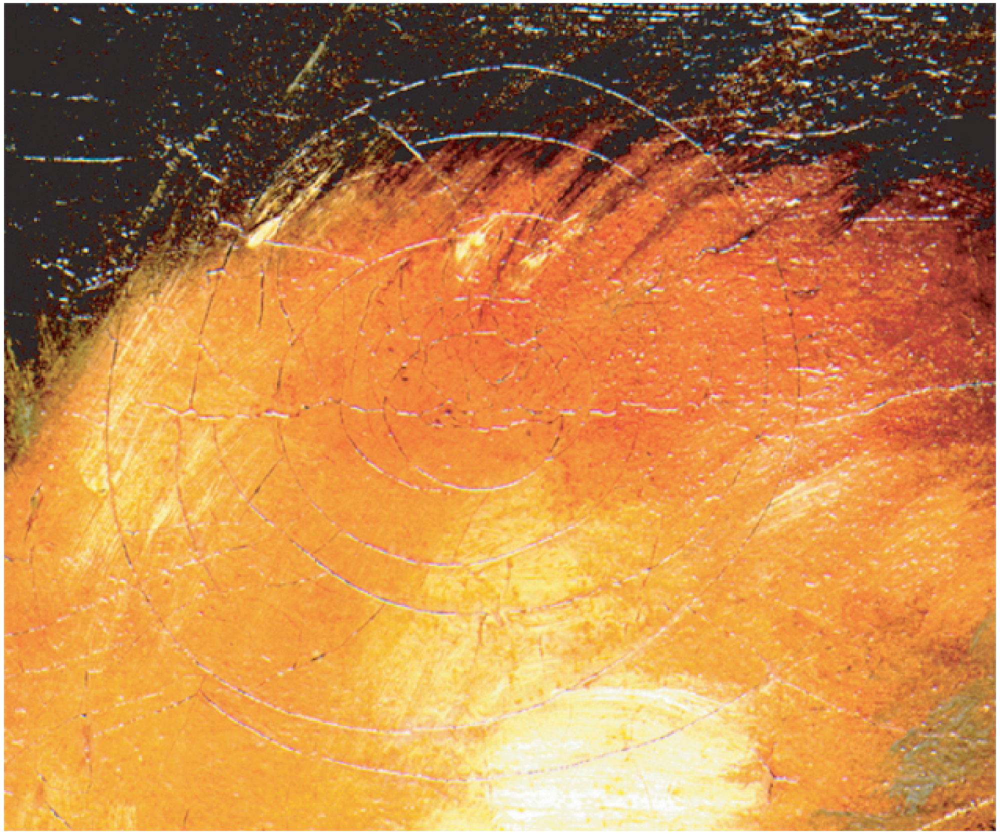




Interests to study crack patterns...

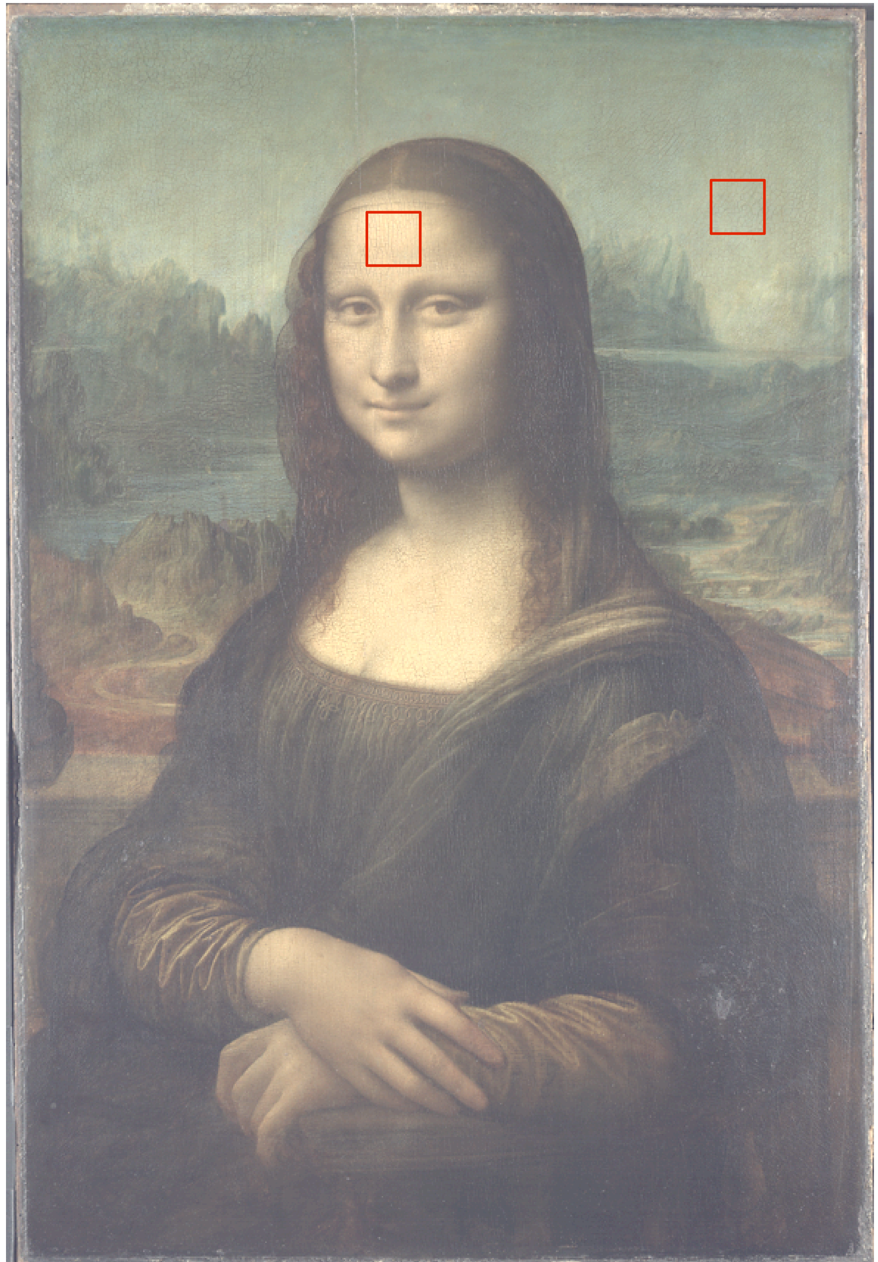
cracking due to a physical impact

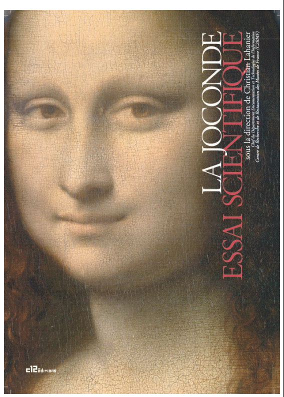
"*Saint Matthias*"
Georges de La Tour



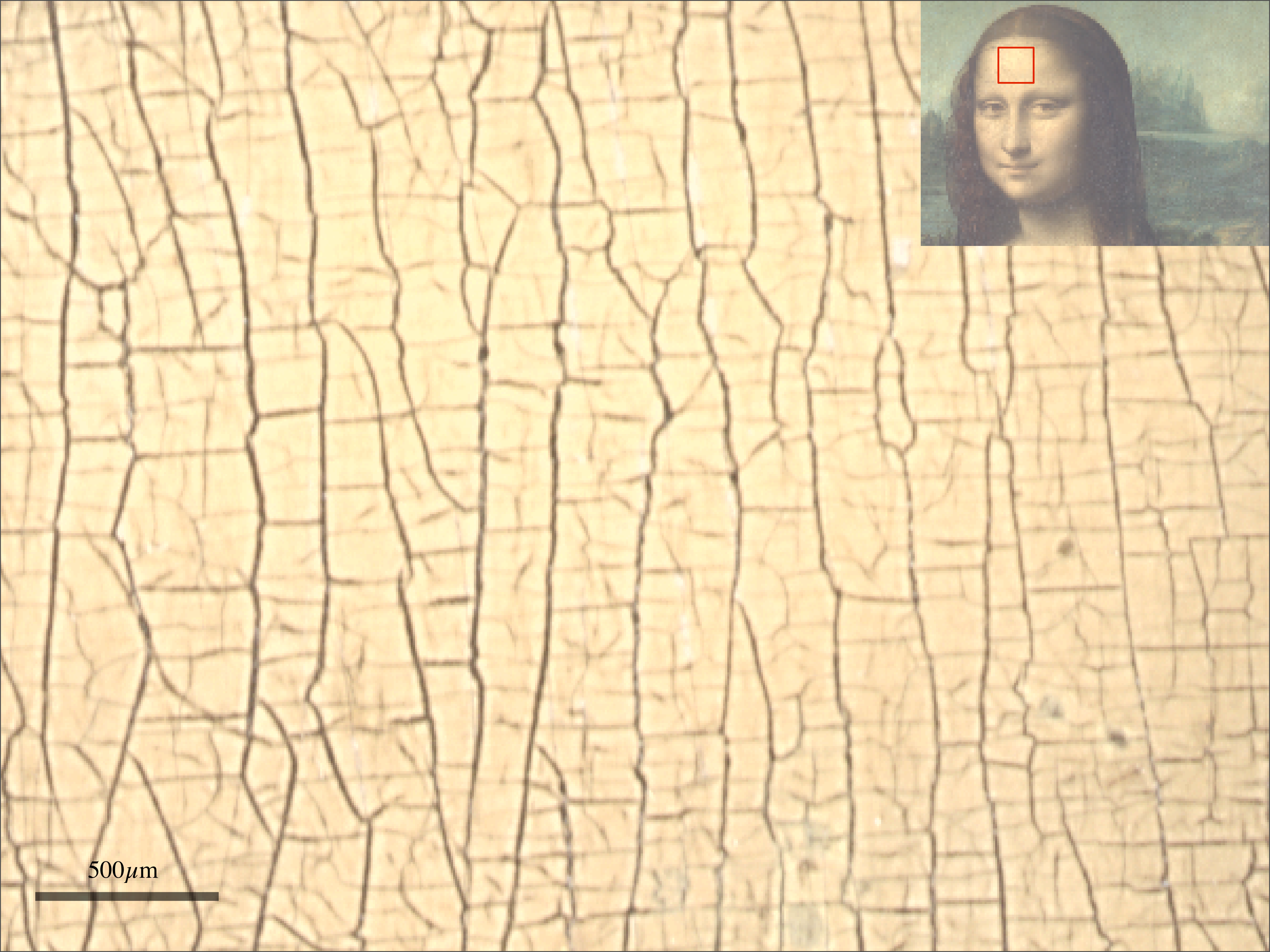
Exemple of craquelures linked to the support

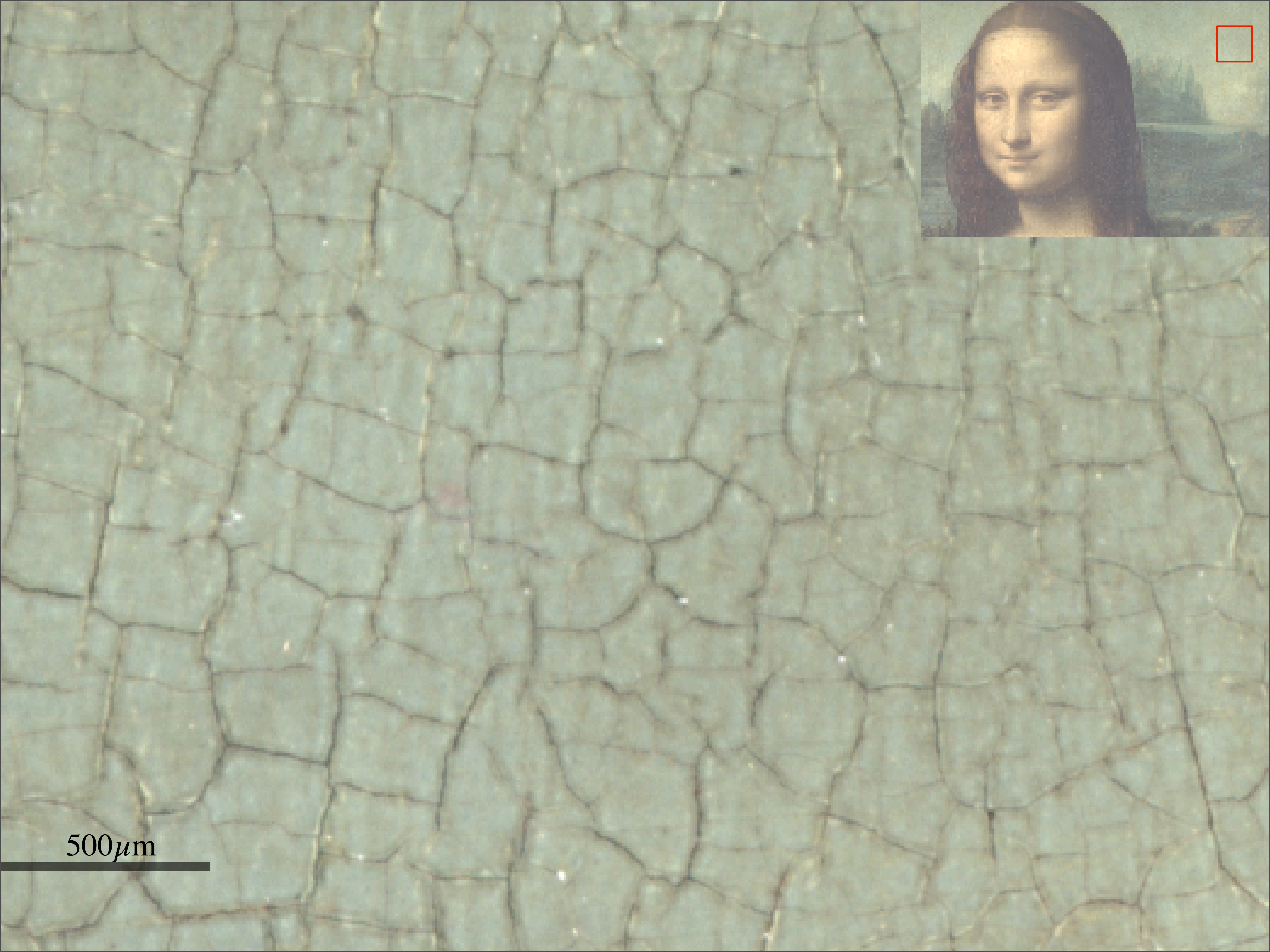
la Joconde: Painting on a poplar panel





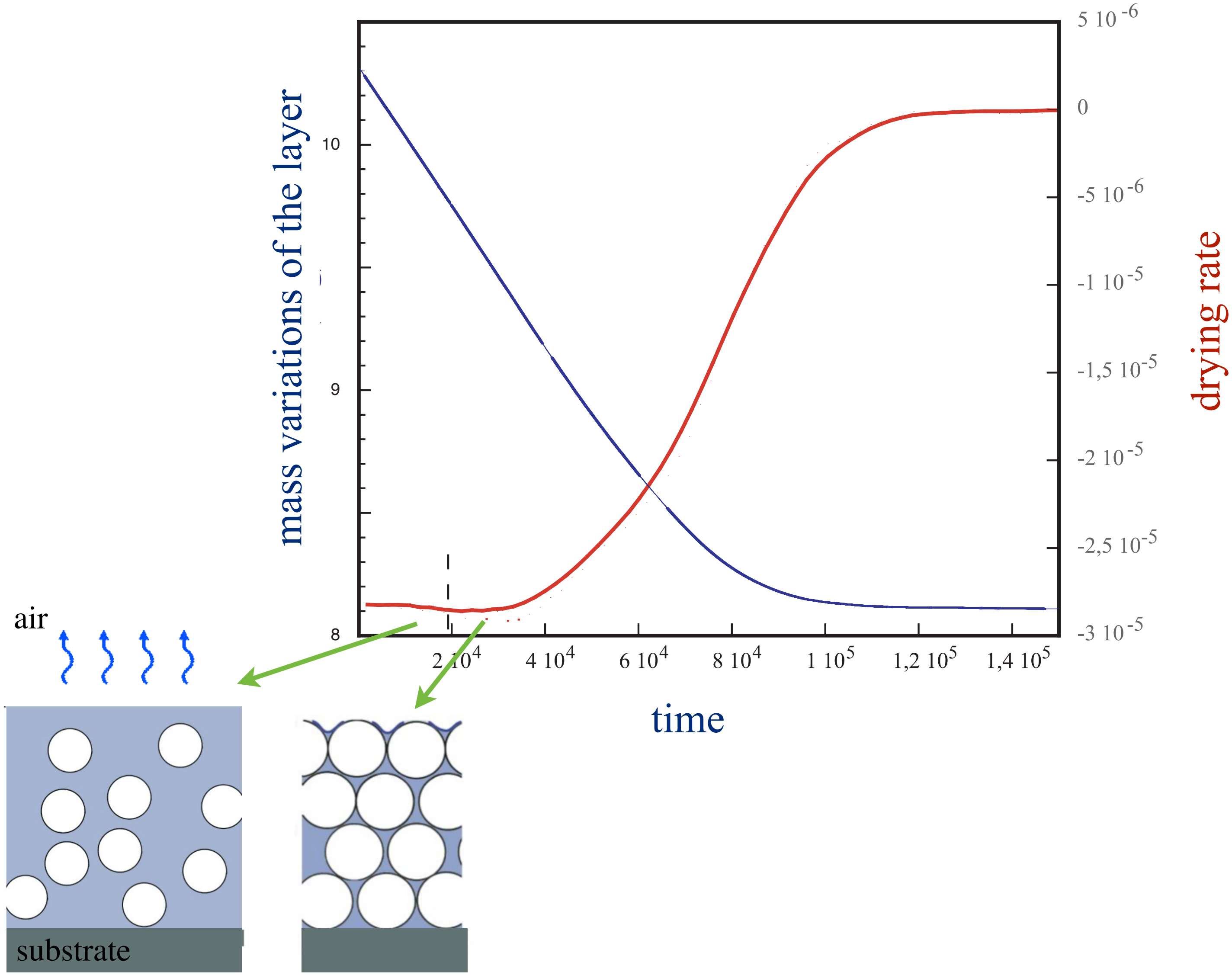
« la Joconde: essai scientfique»
ouvrage collectif (2007)


500μm


500μm

Model: drying colloidal suspensions

concentrated suspensions of colloidal particles (nanolatex ∅~*15nm*, $\phi_{V0} \sim 30\%$)



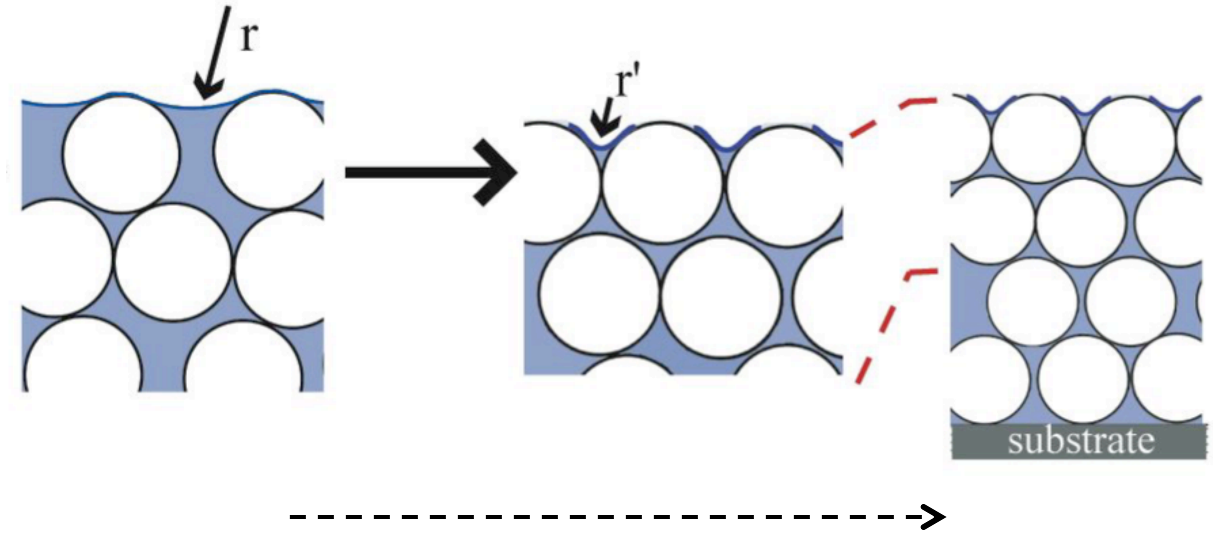
Constant Rate Period

$\phi \sim 60\%$

Drying colloidal suspensions
Mechanical stress induced by desiccation

evaporation ⇨ high capillary pressure

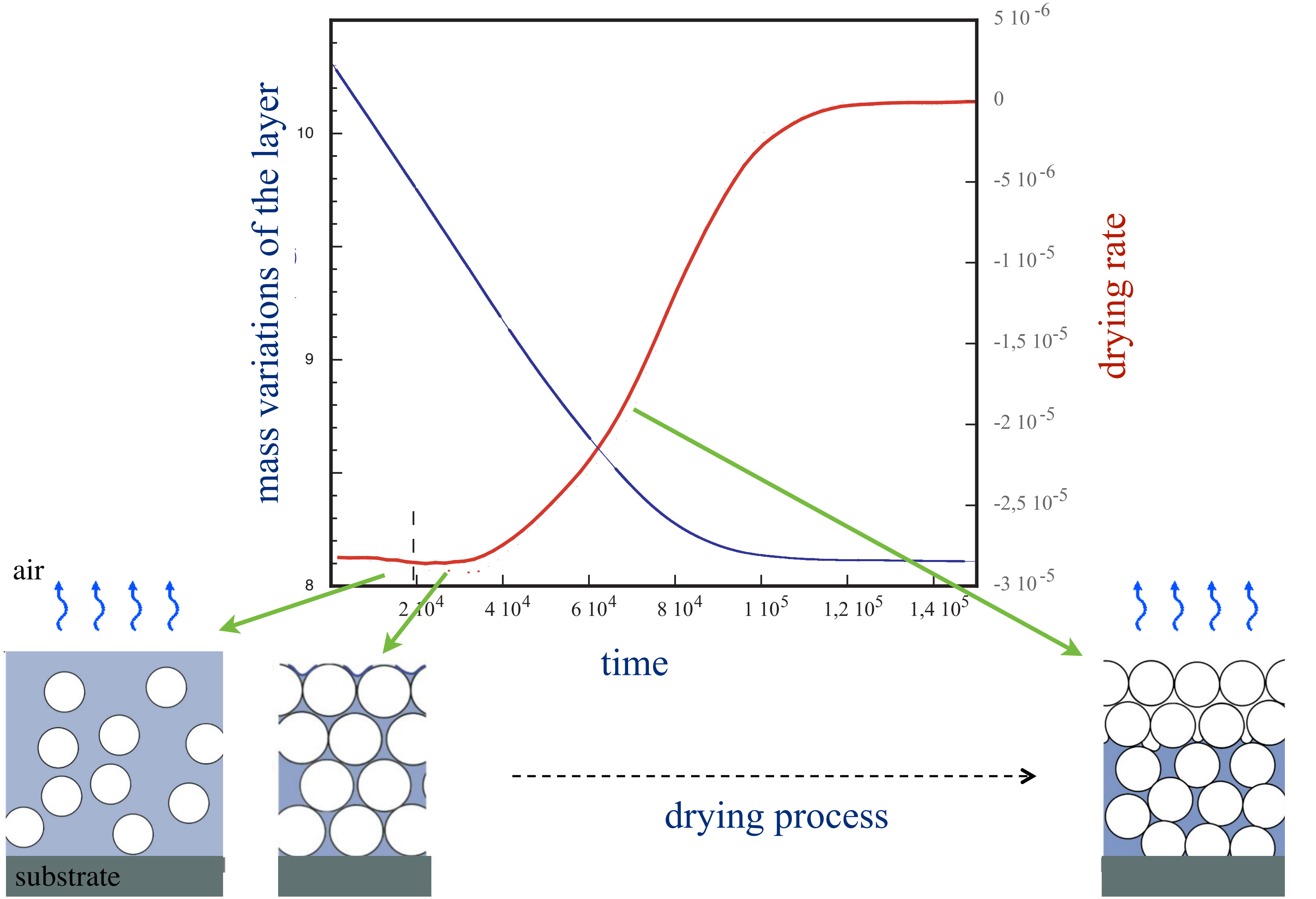
$$P = -2\frac{\gamma_{solvent/air}.cos\theta}{r_{pore}} \sim -10^7 Pa$$



shrinkage limited by adhesion

Model: drying colloidal suspensions

concentrated suspensions of colloidal particles ($\phi_{V0} \sim 30\%$)



Constant Rate Period

$\phi \sim 60\%$

Falling Rate Period

Drying colloidal suspensions
Mechanical stress induced by desiccation

Drying stress due to:

* shrinkage induced by capillary pressure limited by adhesion

* shrinkage-resistance by the compressibility modulus of the gel

mechanical stress → elastic energy stored in the consolidating layer

Drying colloidal suspensions
Mechanical stress induced by desiccation

flux balance at the drying surface: $\dot{V}_E = \frac{D}{\eta} \nabla P \mid_{surface}$ Darcy'law

$$D \propto (porosity) \times (pore\ radius)^2$$

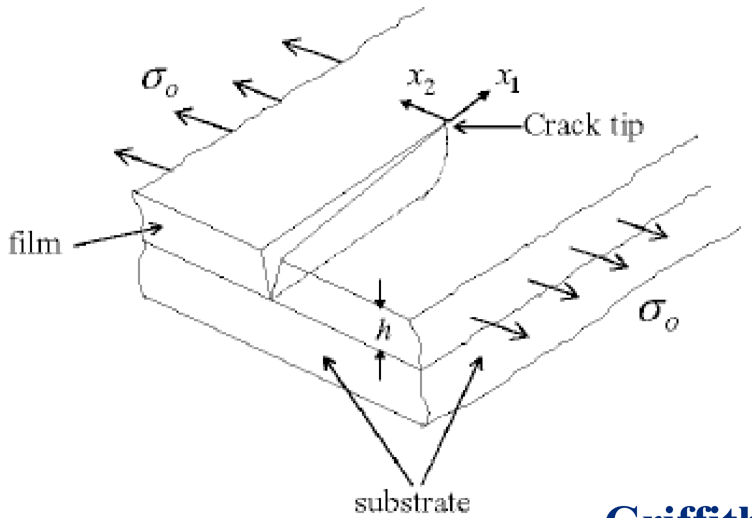
drying stress depends on transport parameters: $\sigma \sim \frac{\eta h \dot{V}_E}{D}$

mechanical stress depend on:

* permeability of porous matrix
* elasticity of porous matrix
* drying kinetics
* presence of surfactants (diminishing capillary pressure)

Drying colloidal suspensions
Mechanical stress induced by desiccation

mechanical stress σ_{ij} → elastic energy stored in the consolidating layer



Griffith criterion

recovery of elastic energy

$$\Delta E = h \iint \left\{ \sigma_{33} d\varepsilon'_{33} + \sigma_{22} d\varepsilon'_{22} + 2\sigma_{23} d\varepsilon'_{23} \right\} dx_2$$

||

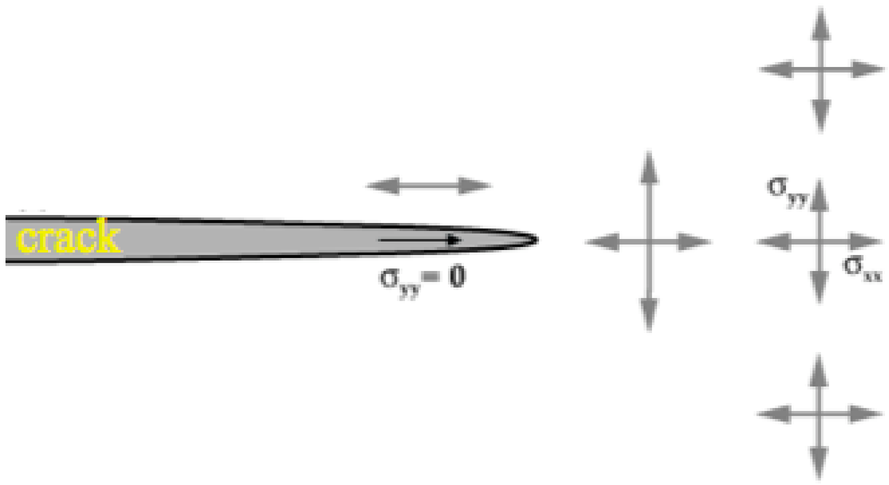
$$\|$$

cost of surface energy

$$2h\gamma$$

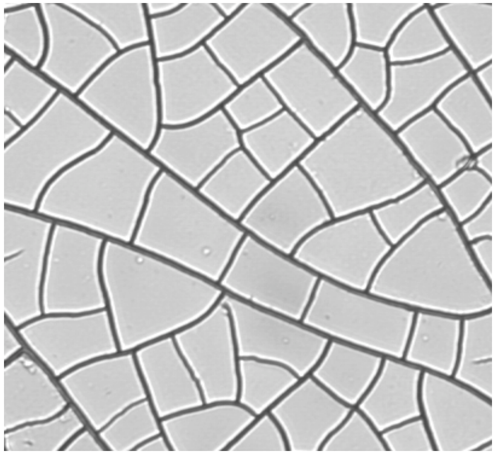
Griffith *Trans. R. Soc. London* (1920)
Xia, Hutchinson *J. Mech. Phys. Solids* (2000)

Drying colloidal suspensions
Mechanical stress induced by desiccation



QUIZ #1
What is the angles distribution in a cracks pattern ?

in the plane ?

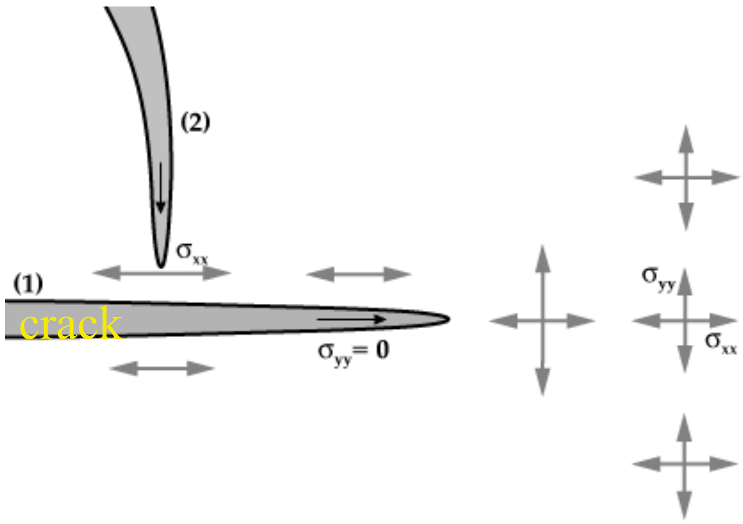


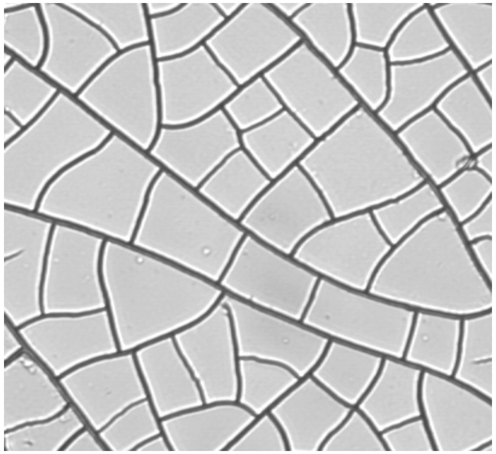
in 3D ?

QUIZ #1
What is the angles distribution in a cracks pattern ?

in the plane ?

- 90° due to connection between cracks





- 120° due to nucleation process in certain conditions

in 3D ?

QUIZ #1
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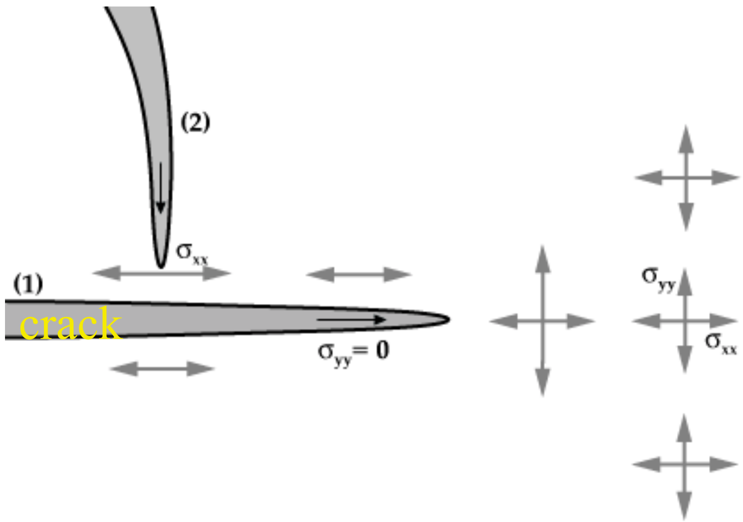
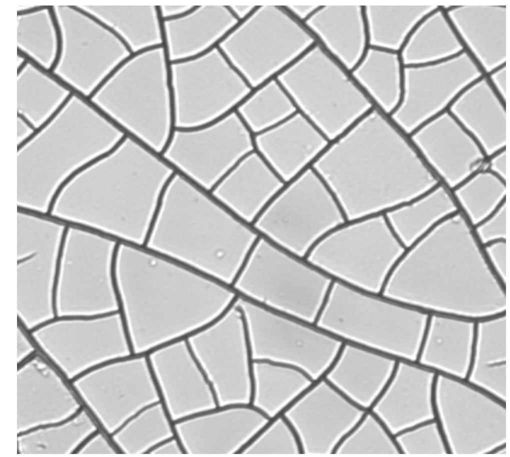




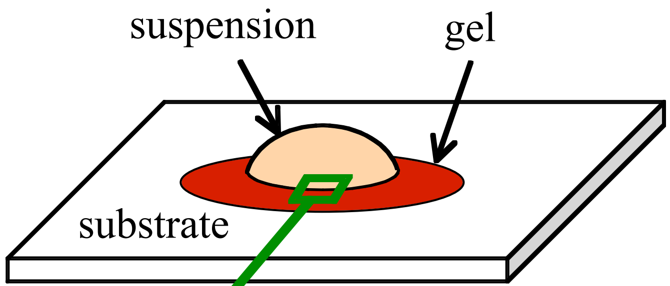
- 120° due to nucleation process in certain conditions

in 3D ?

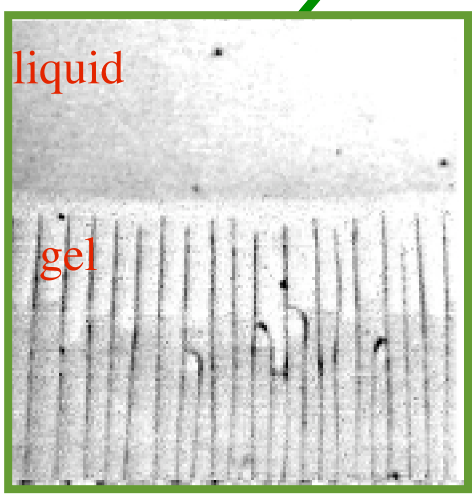
more complex: depends on the growth kinetics

Directional propagation of cracks

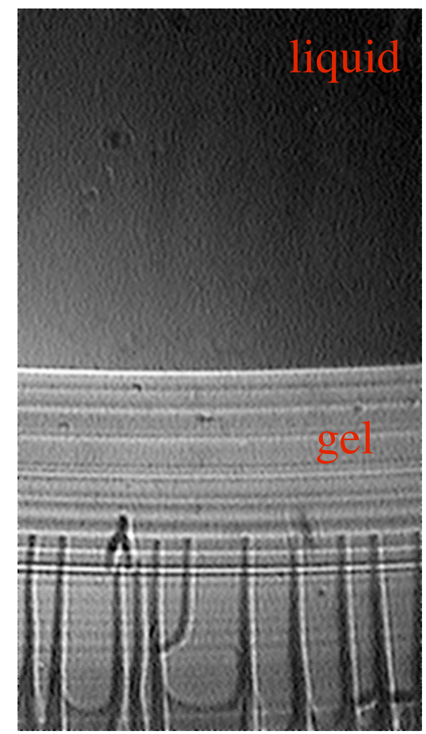
opened geometries



silica sols or latex particles



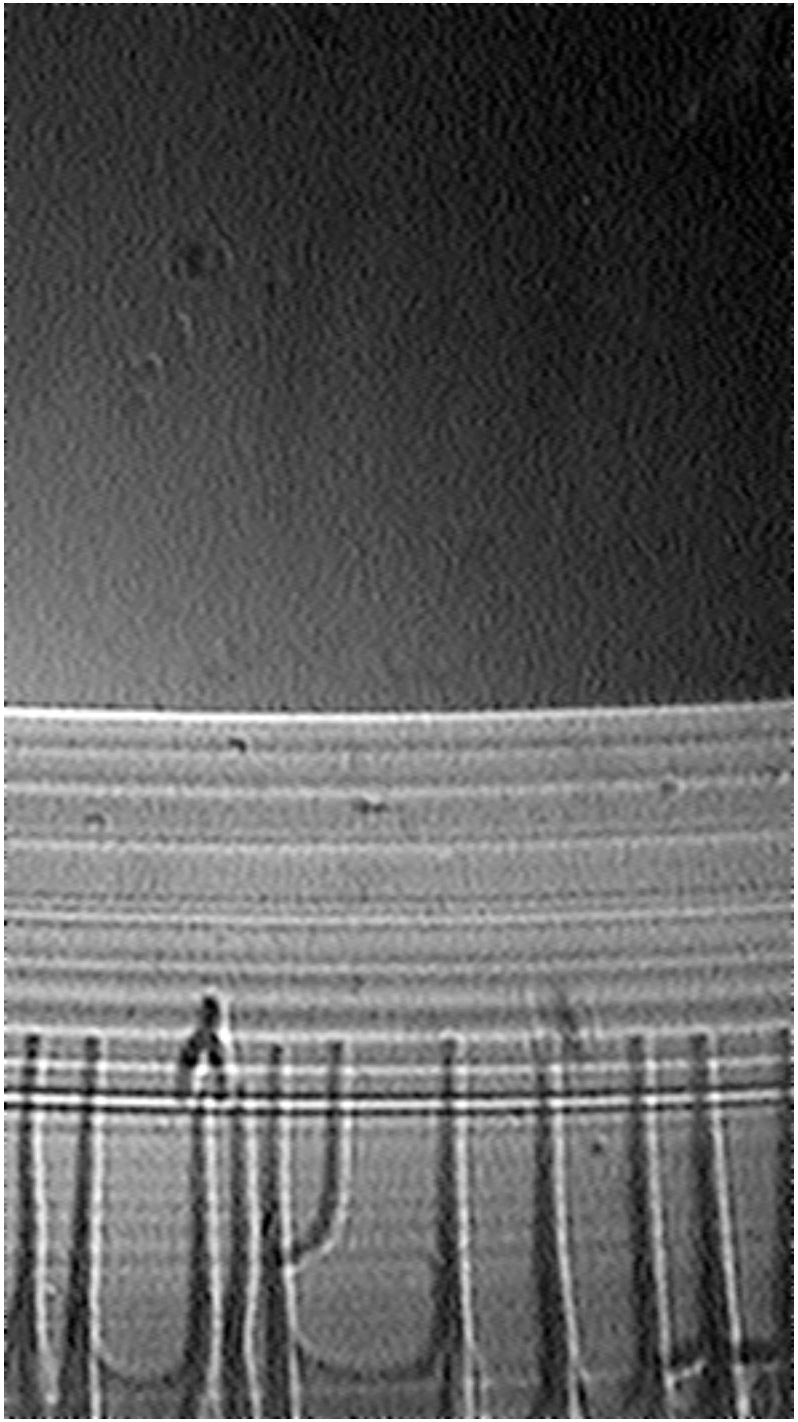
ferrofluid



Pauchard, Adda-Bedia, Allain, Couder *Phys. Rev. E* (2002)

Pauchard, Elias, Boltenhagen, Bacri *Phys. Rev. E* (2008)

magnetic
colloidal particles



magnetic
colloidal particles

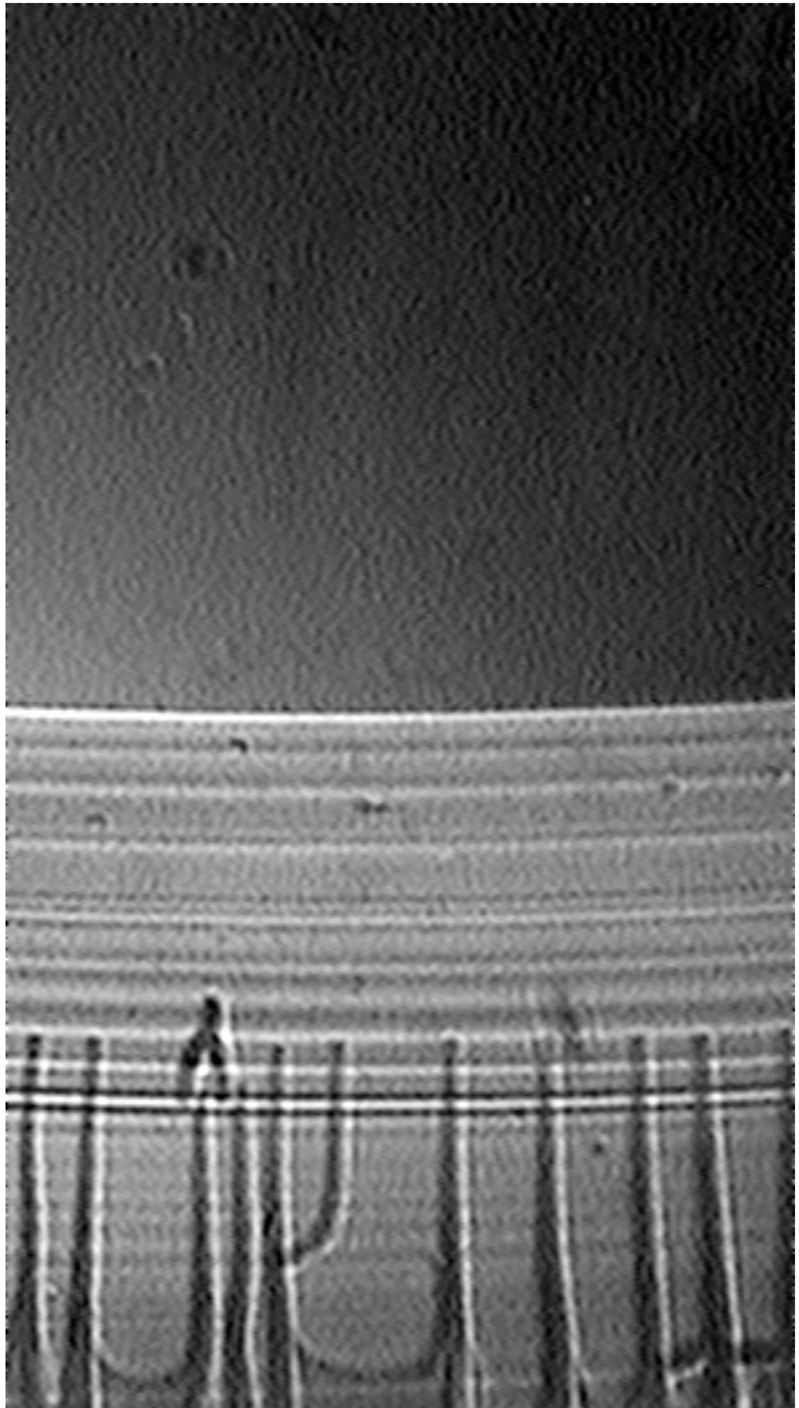
$\overrightarrow{B}$ →

$\overrightarrow{B}$ →

$\overrightarrow{B}$ →

$\overrightarrow{B}$ →

$\overrightarrow{B}$ →



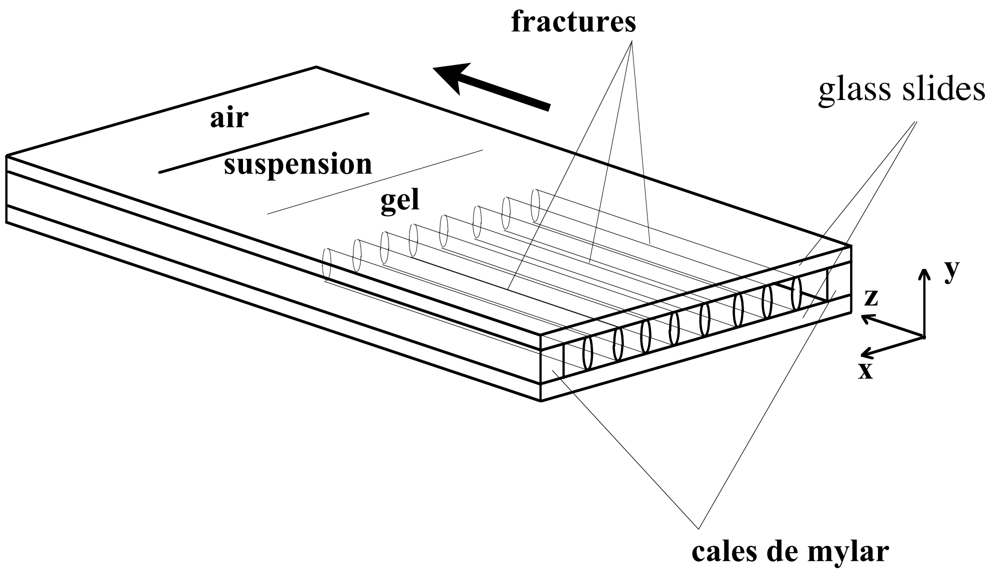
liquid

gel

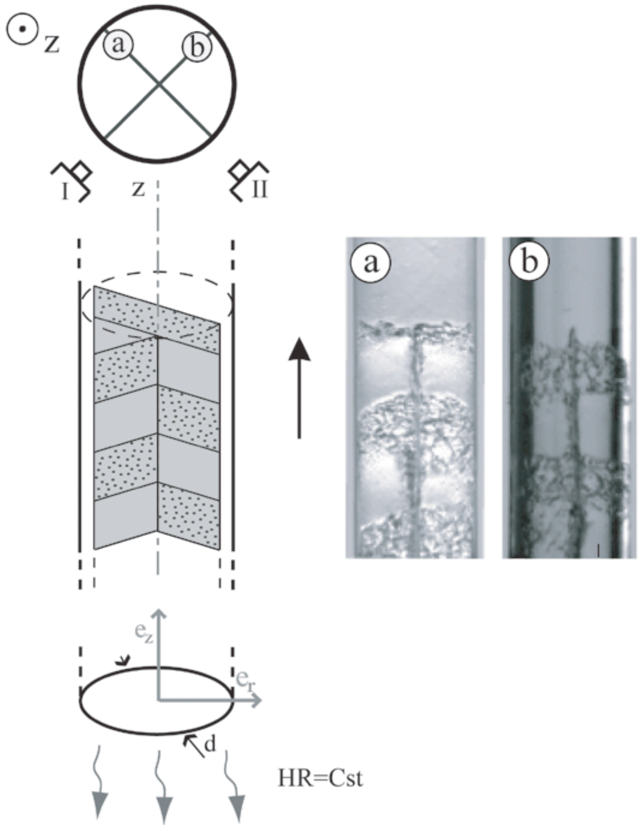
Directional propagation of cracks

confined geometries

Hele Shaw cell



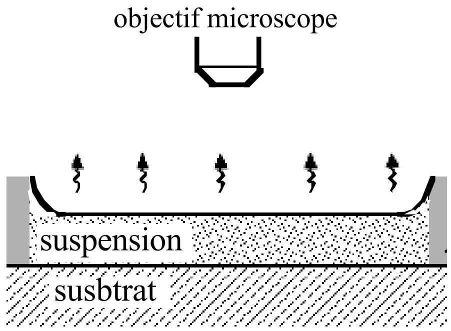
capillary tube



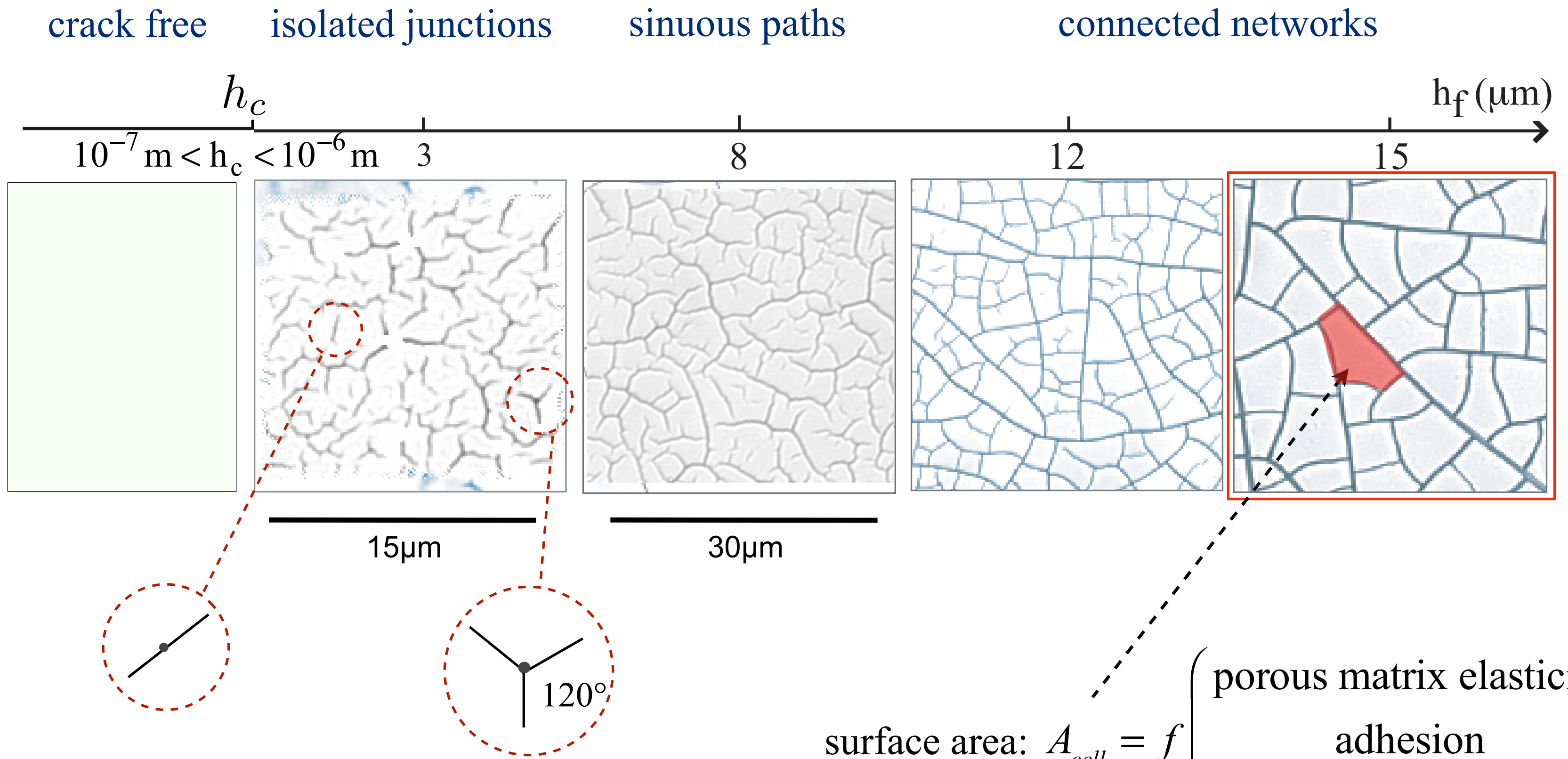
Allain, Limat *Phys. Rev. Lett.* (1995)
Dufresne et al. *Phys. Rev. Lett.* (2003)

Gauthier et al. *Langmuir* (2007)

Isotropic crack patterns



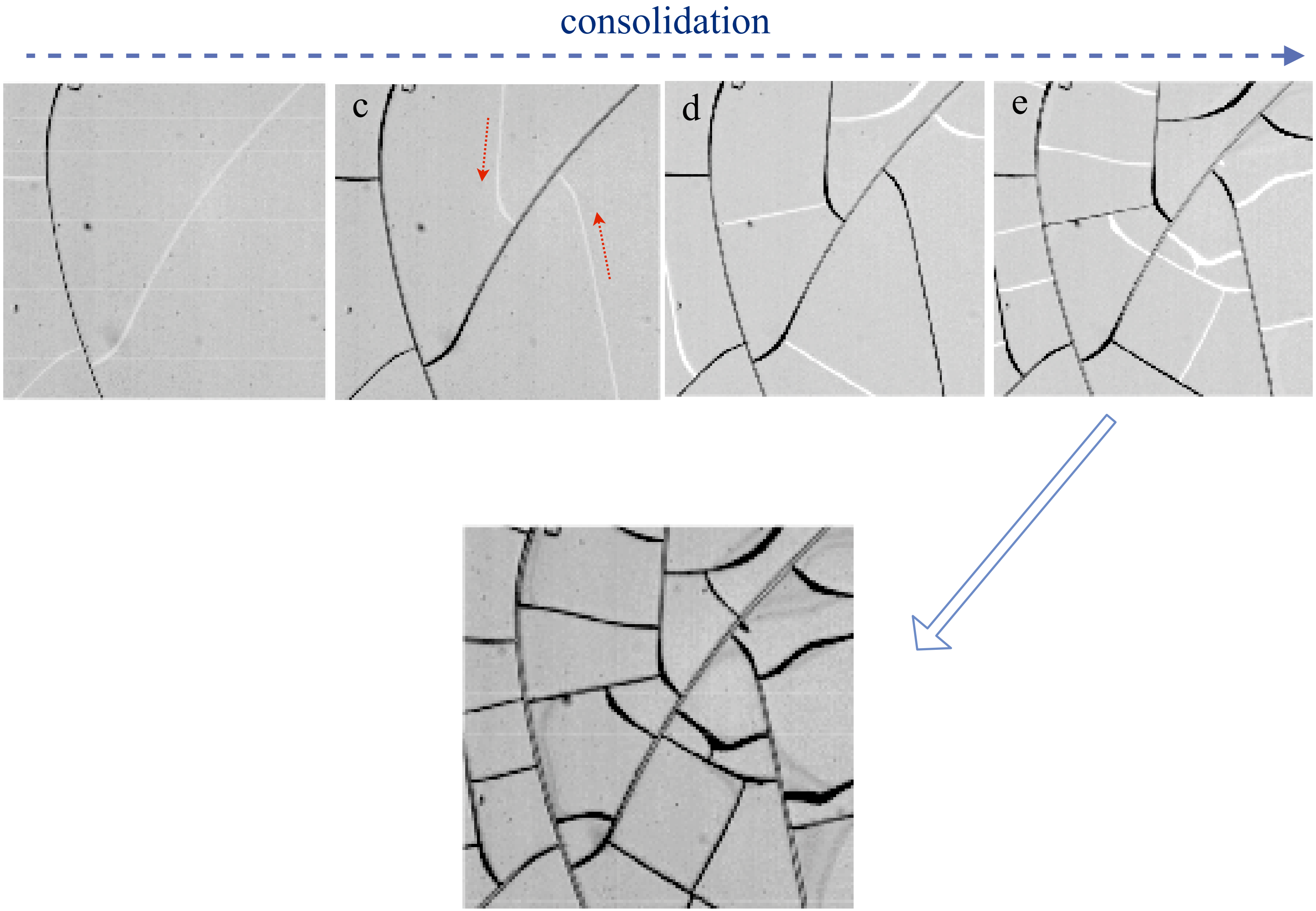
final patterns for layers of different thicknesses



$$\text{surface area: } A_{cell} = f\begin{pmatrix}\text{porous matrix elasticity}\\ \text{adhesion}\\ \text{drying rate}\end{pmatrix}.h_f^2$$

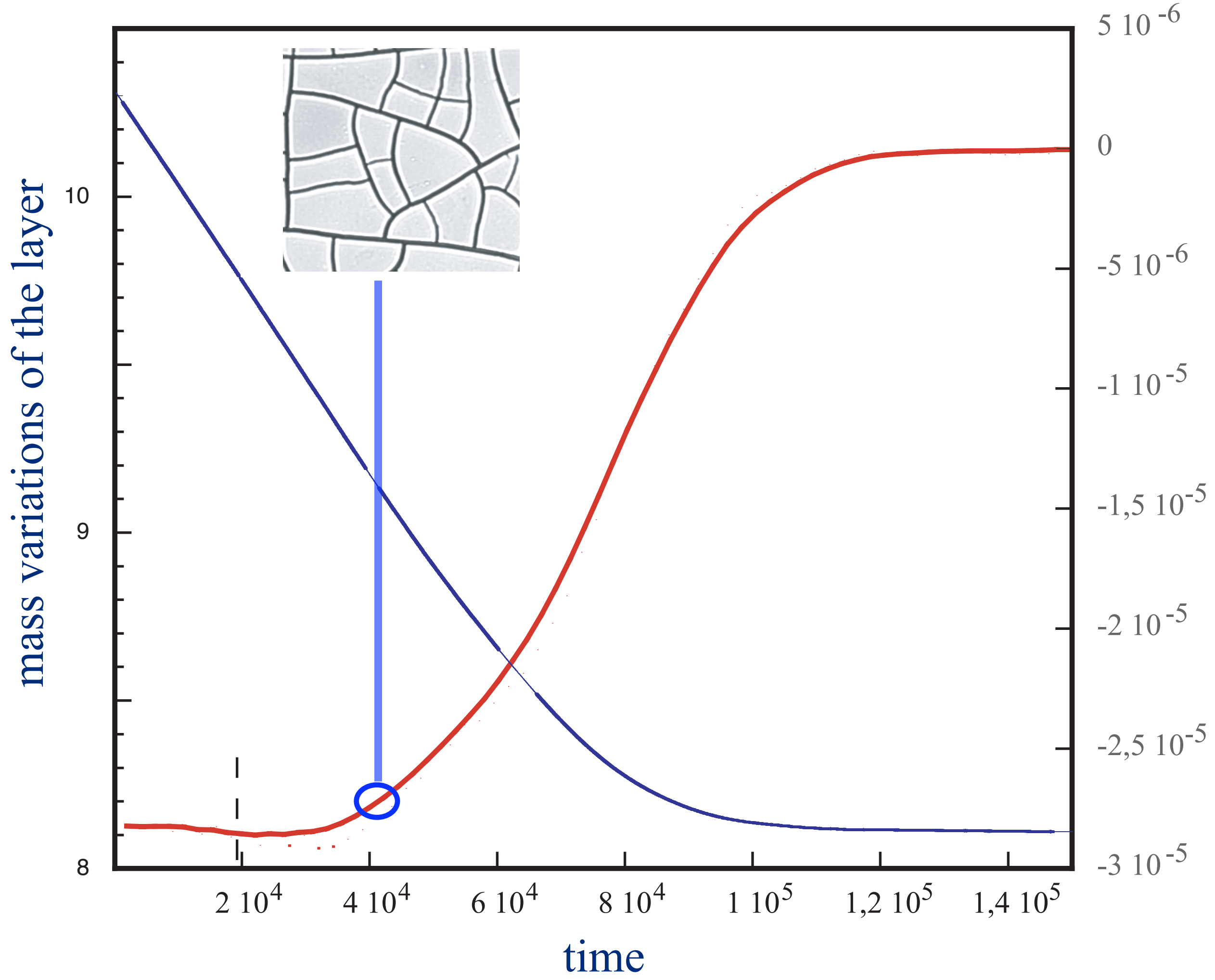
Atkinson et al *J. Mat. Sc.* (1991)
Hutchinson et al *Advances in Applied Mechanics* (1992)

Hierarchical formation of cracks network



Bohn, Pauchard, Couder *Phys Rev E* (2005)

Drying kinectics

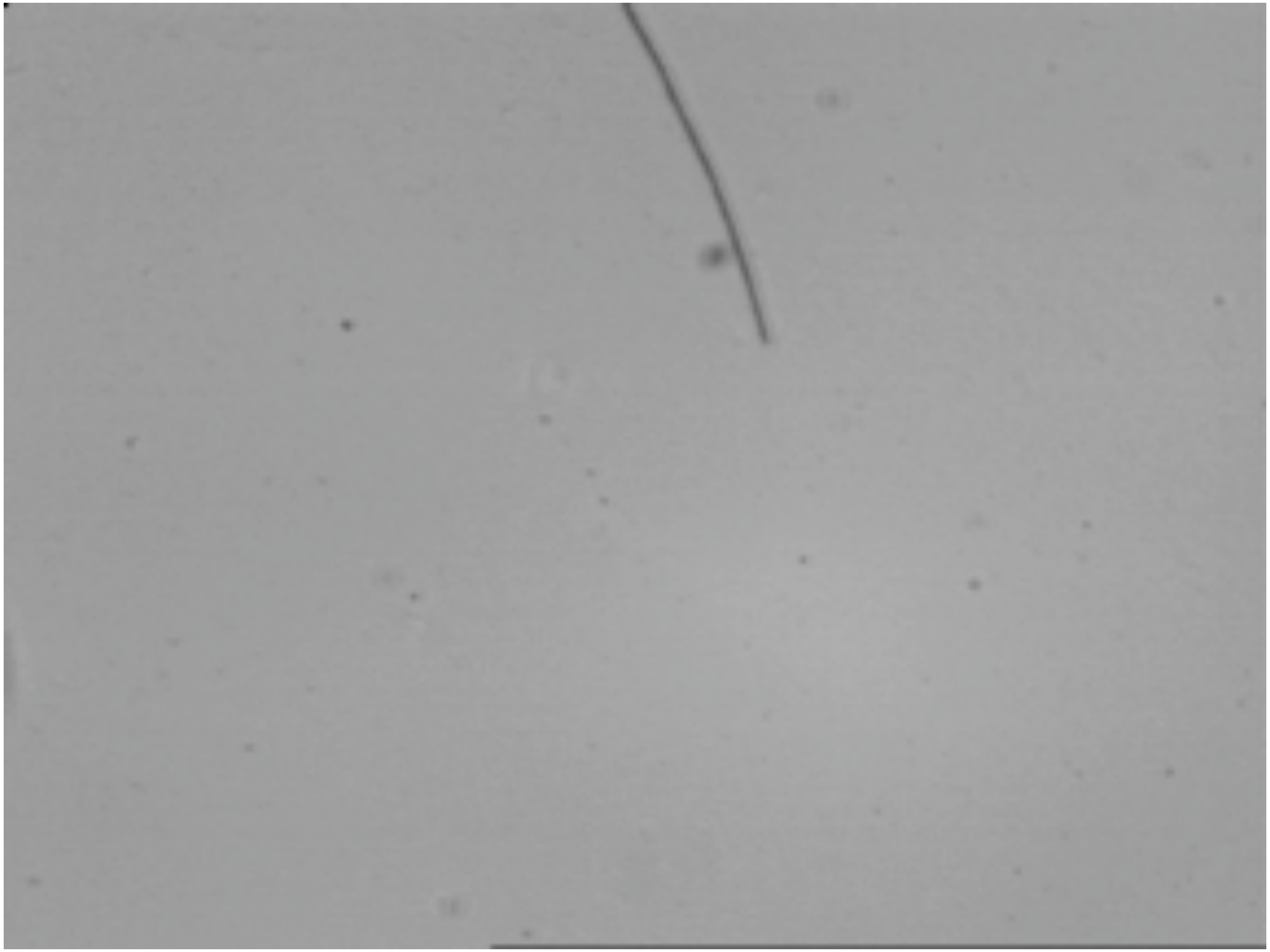


Delamination process

50µm

rate ×5

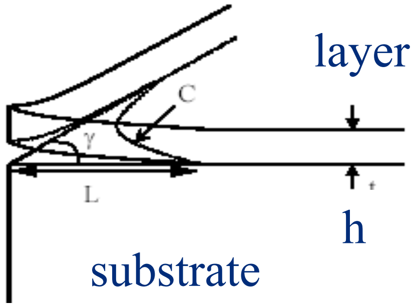
Delamination process



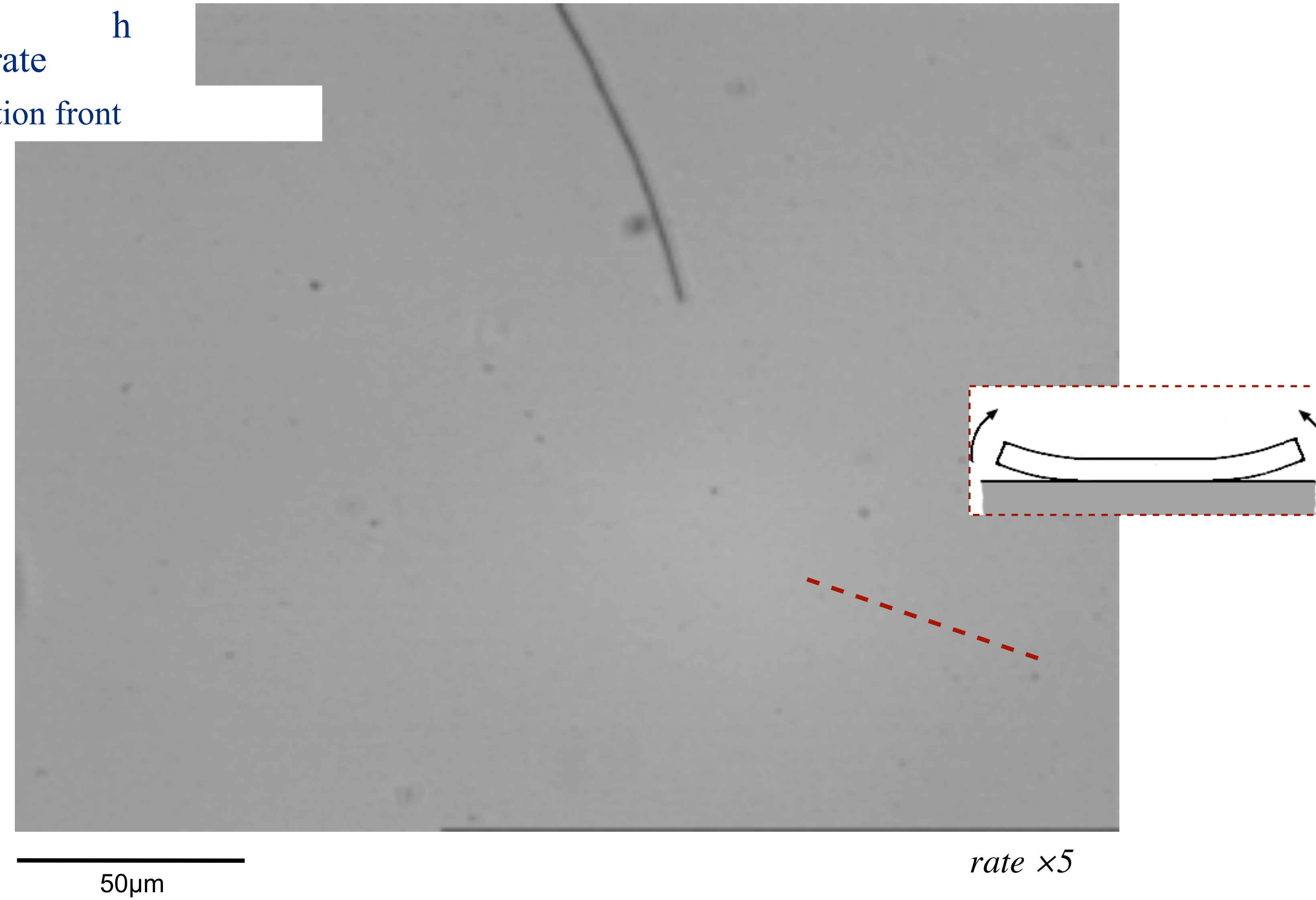
50μm

rate ×5

Delamination process

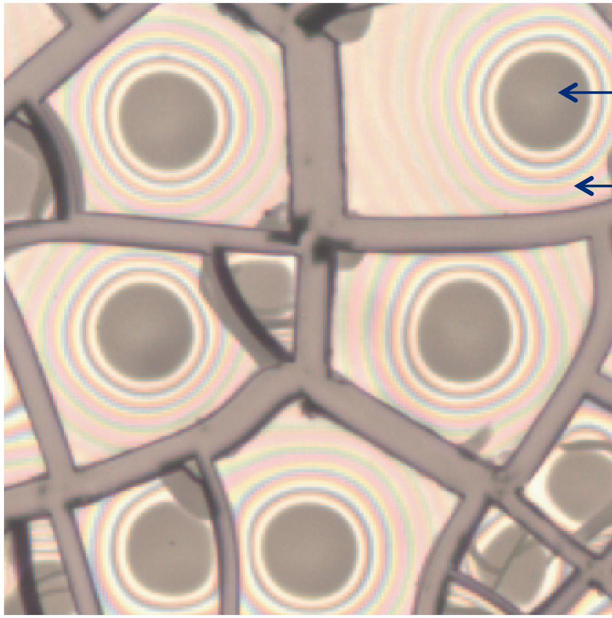


C : delamination front



rate ×5

Delamination process



A_{adh}

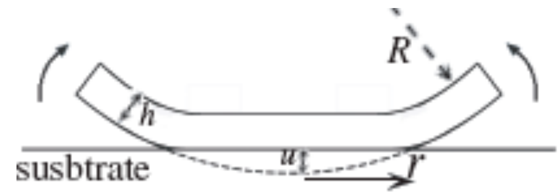
A_{cell}

measuring A_{adh}/A_{cell}

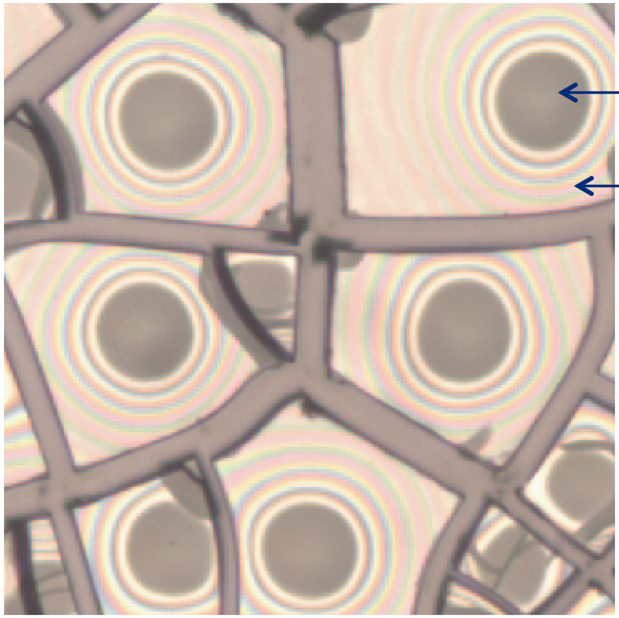
⇩

adhesion energy gel/substrate

?



Delamination process



A_{adh}

A_{cell}

measuring A_{adh}/A_{cell}

⇩

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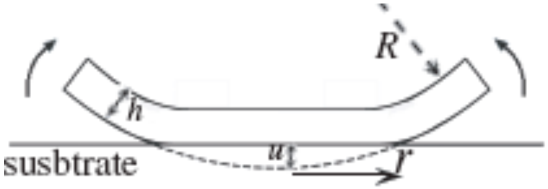
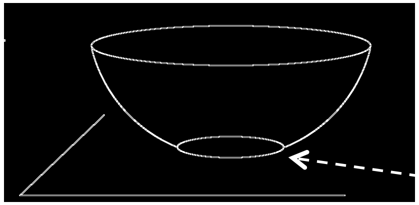


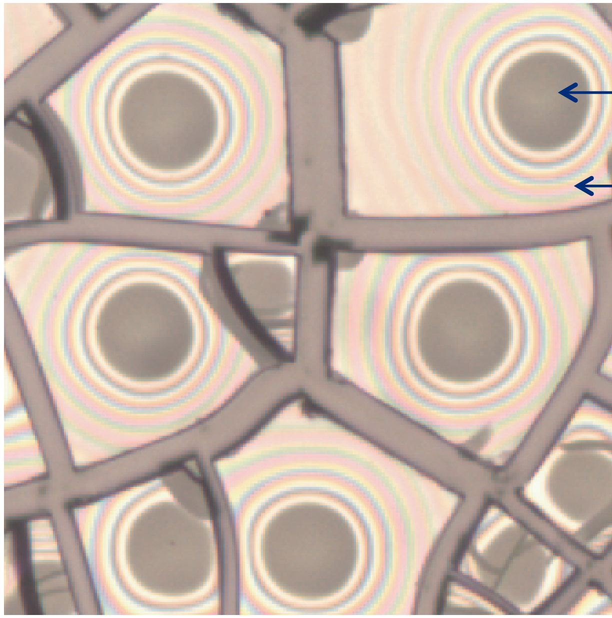
Competition between elastic energy : $\frac{h_f}{R} \ll 1$

$$U_{buckl} = \frac{2C}{3\left[12(1-\nu^2)\right]^{3/4}} Y \left(\frac{h_f}{R}\right)^{5/2} r^3$$



pli

Delamination process

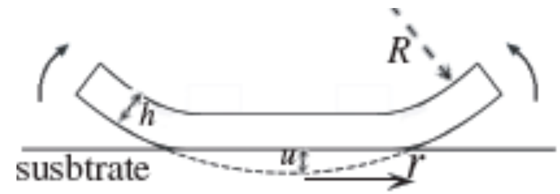


measuring A_{adh}/A_{cell}

⇩

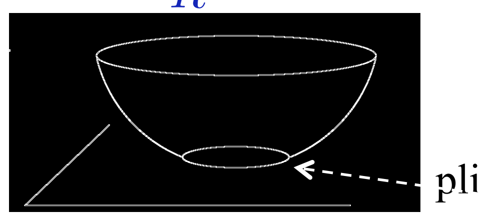
adhesion energy gel/substrate

?



Competition between elastic energy : $\frac{h_f}{R} \ll 1$

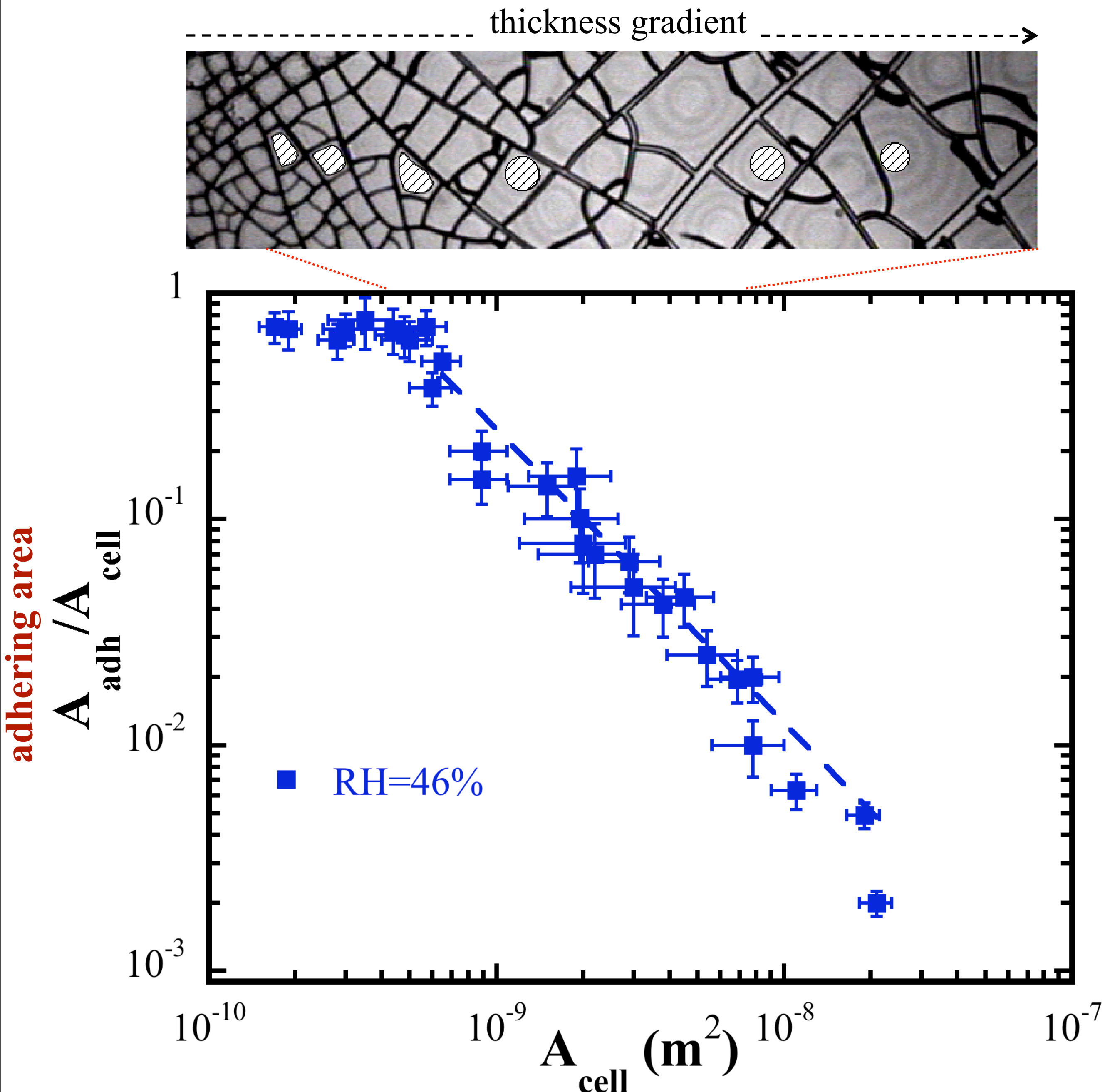
$$U_{buckl} = \frac{2C}{3\left[12(1-\nu^2)\right]^{3/4}} Y \left(\frac{h_f}{R}\right)^{5/2} r^3$$



and interfacial crack energy :

$$U_{crack} = 2\Gamma_{gel/substrat}\left(A_{cell} - A_{adh}\right)$$

$$\Rightarrow \quad \Gamma_{gel/substrat} \propto Y A_{adh}^{1/2} \left(\frac{h_f}{R}\right)^{5/2}$$



RH = 46%

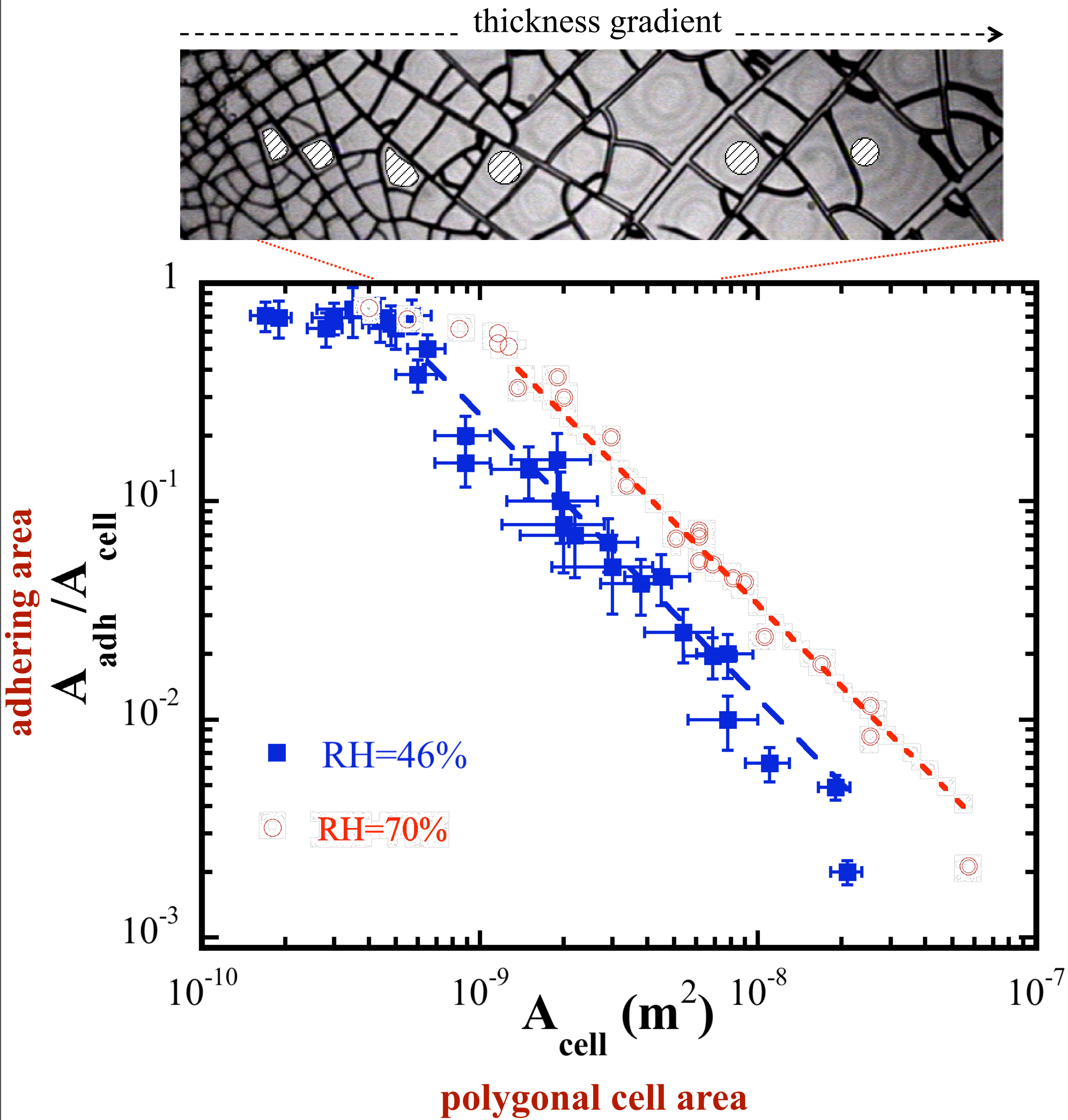
$Y = 5\pm1\times10^{7}\ N.m^{-2}$

$R \approx 85.A_{cell}^{0.44}$

$A_{cell} \approx 1.8\ h^2$

$\Gamma_{gel/sub} = 70\pm23 N.m^{-1}$

Pauchard *Europhys. Lett.* (2006)



RH = 70%

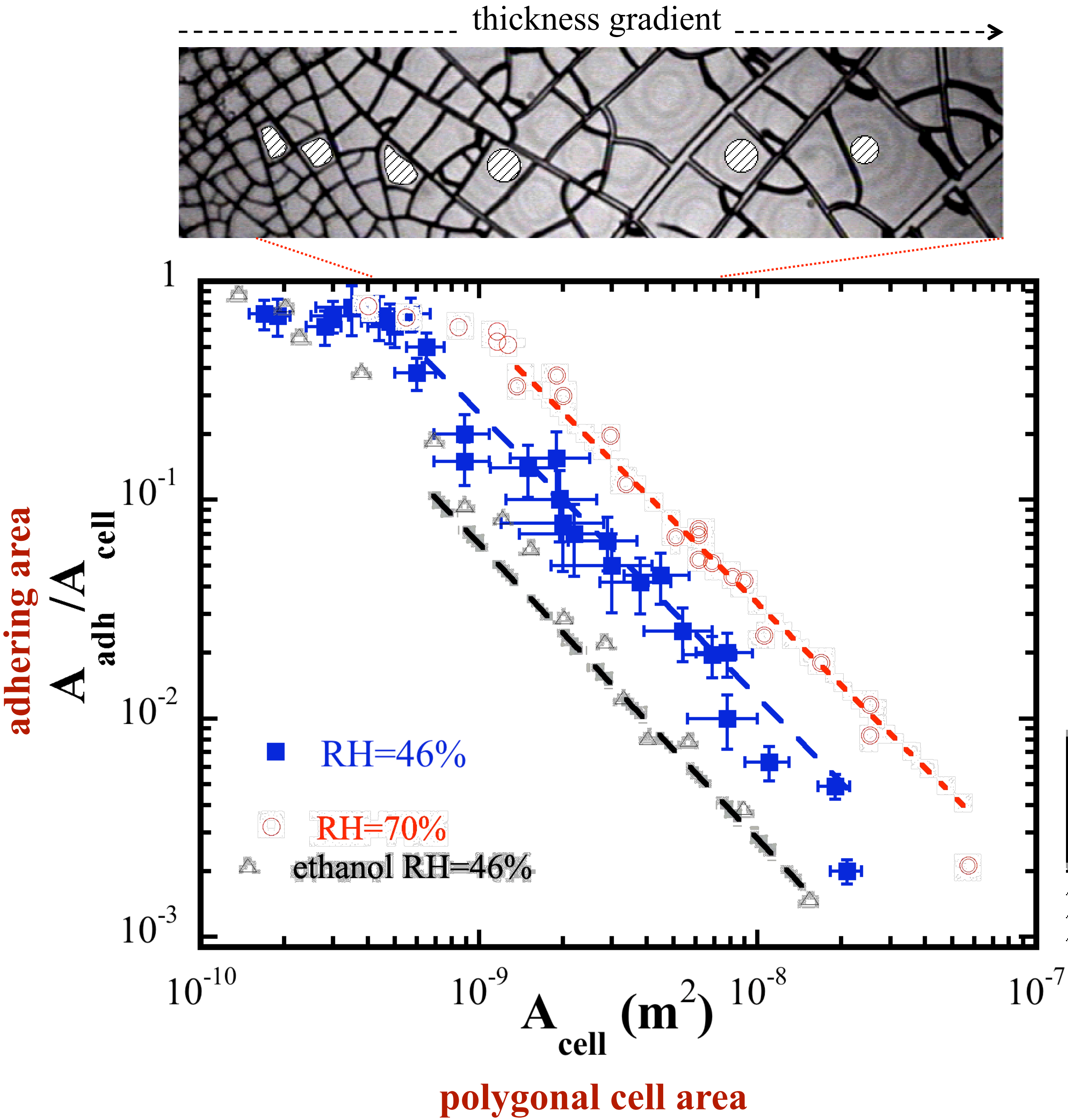
$Y = 8 \pm 2 \times 10^{7}\ N.m^{-2}$

$R \approx 100.A_{cell}^{0.44}$

$A_{cell} \approx 2.6\ h^{2}$

$\Gamma_{gel/sub} = 62 \pm 28 N.m^{-1}$

Pauchard *Europhys. Lett.* (2006)



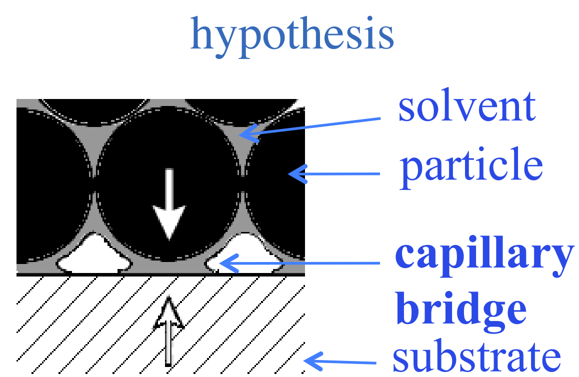
RH = 46%

$Y = 30 \pm 2 \times 10^7$ N.m^{-2}

$R \approx 202.A_{cell}^{0.44}$

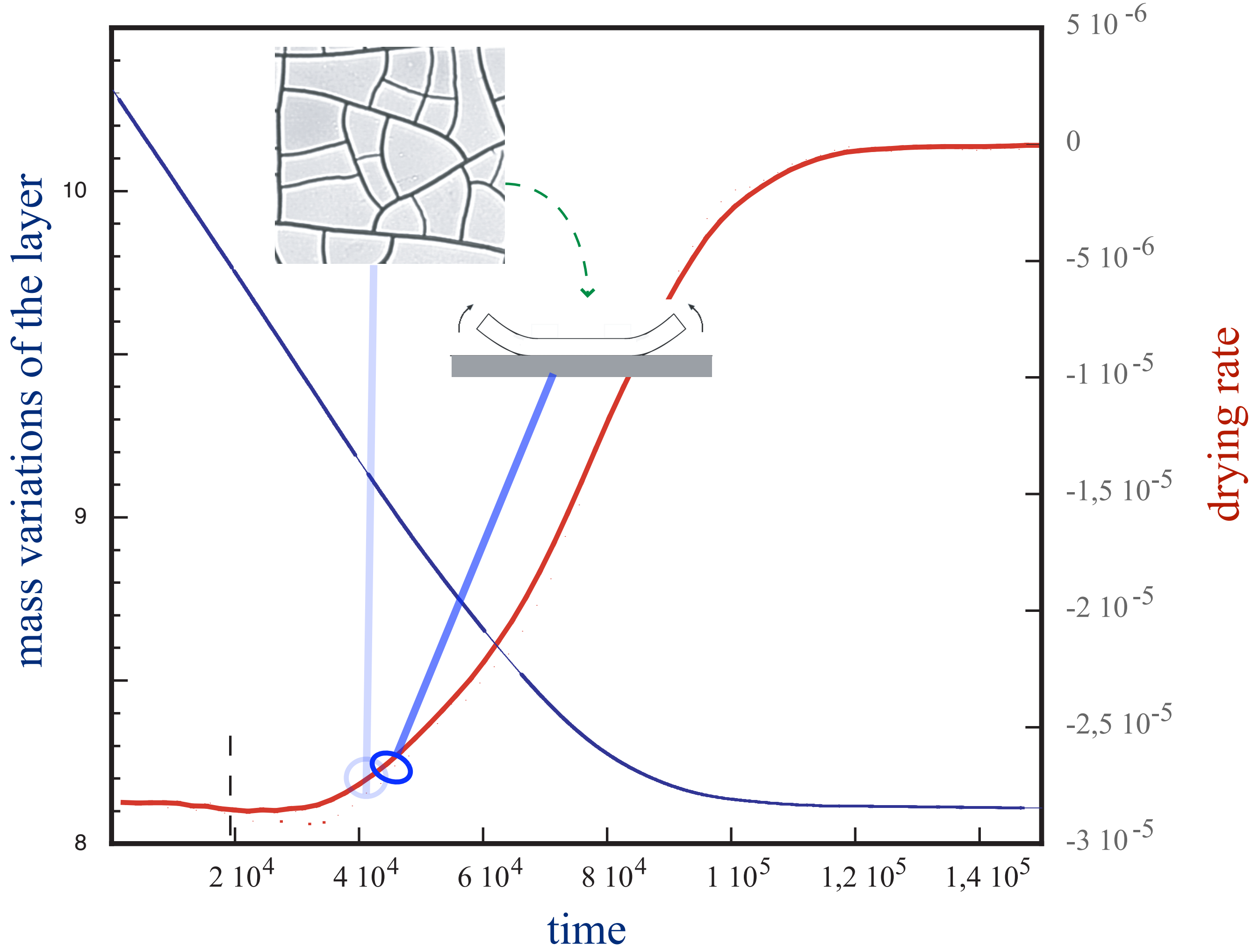
$A_{cell} \approx 1.2\ h^2$

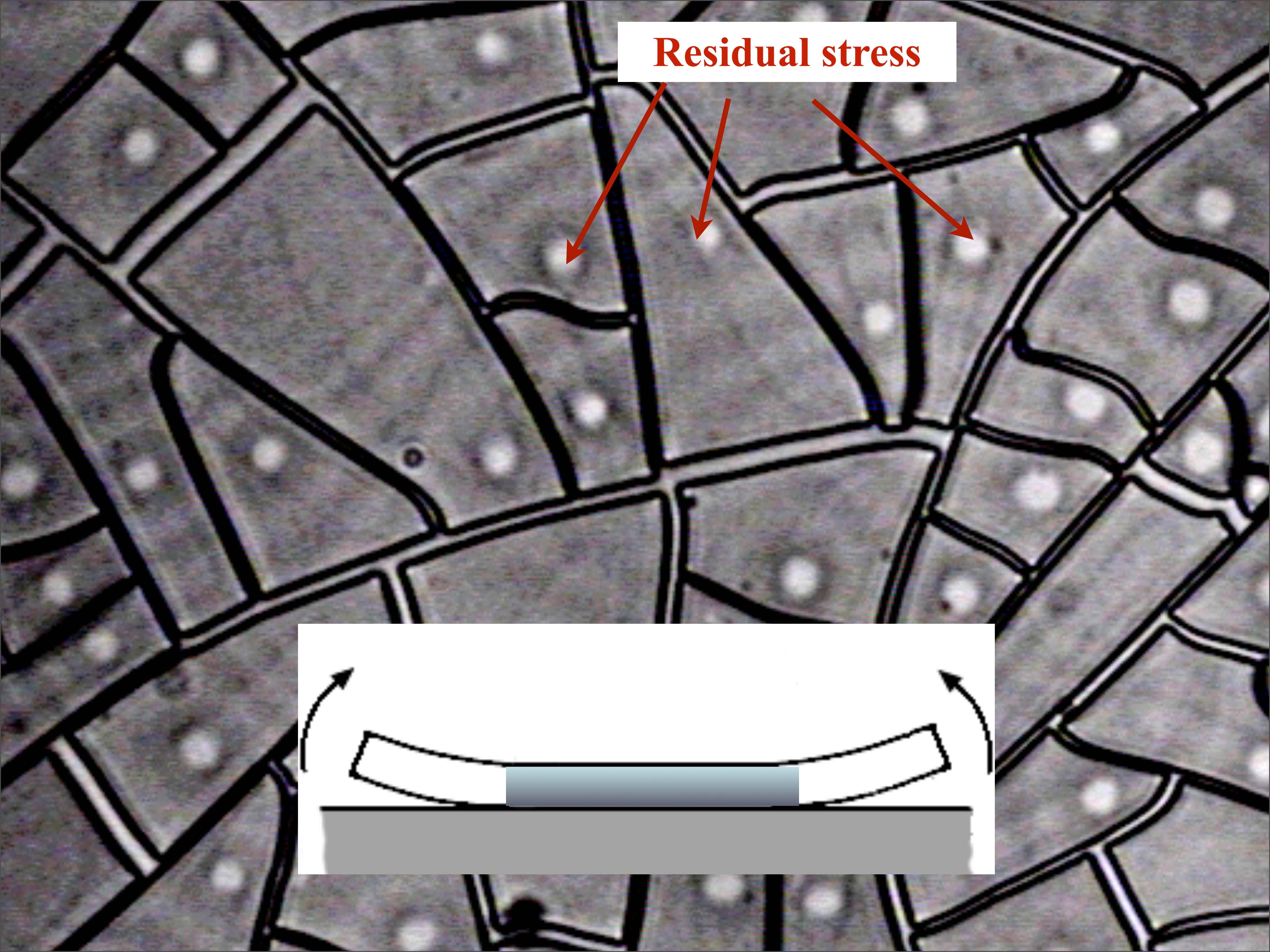
$\Gamma_{gel/sub} = 30 \pm 25$ N.m^{-1}



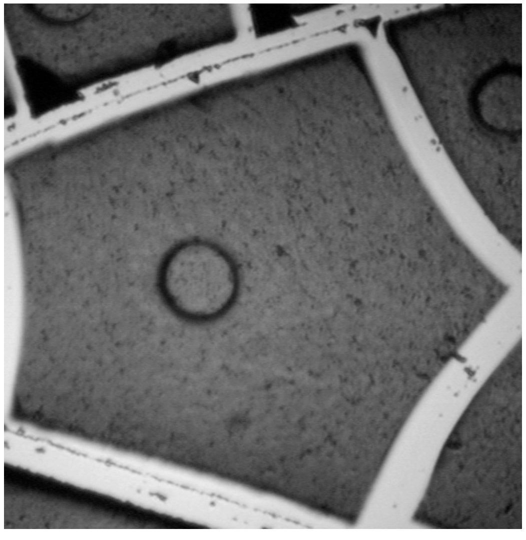
Pauchard *Europhys. Lett.* (2006)

Drying kinectics




Residual stress

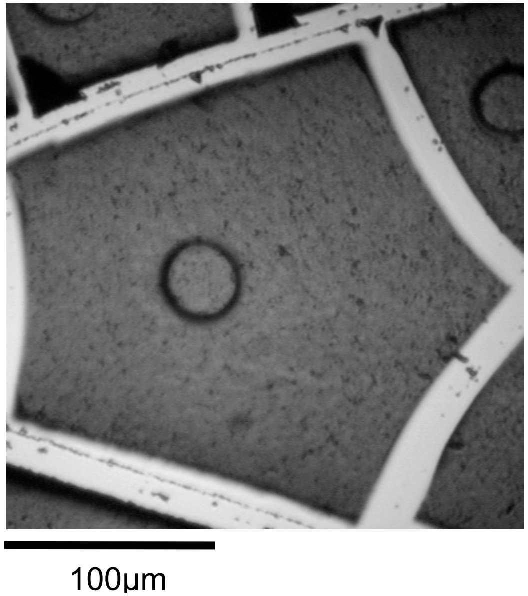
A new generation of cracks inside the adhering region of gel



100µm

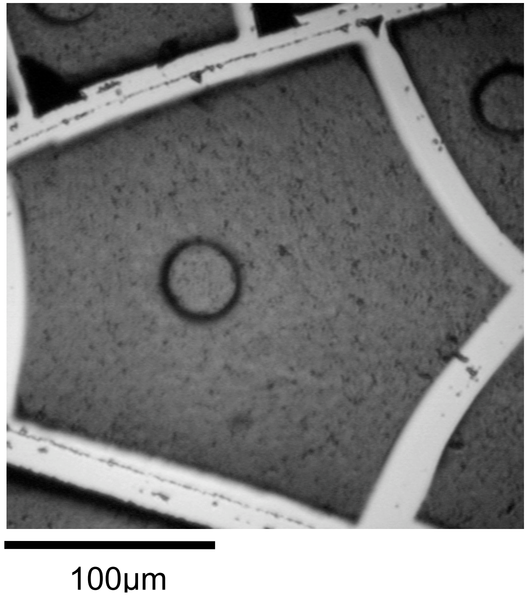
rate ×5

A new generation of cracks inside the adhering region of gel



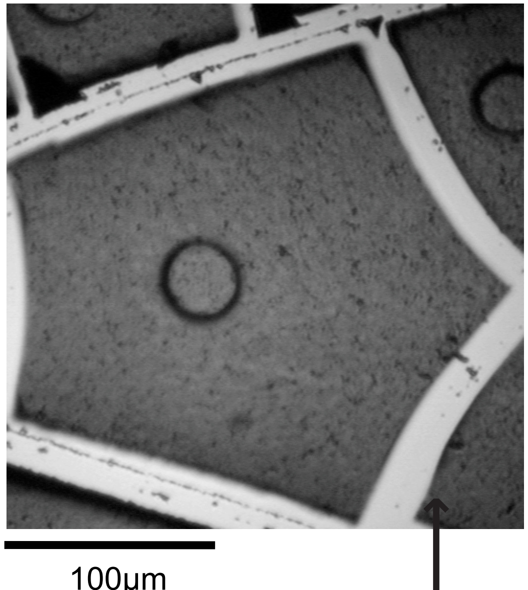
rate ×5

A new generation of cracks inside the adhering region of gel



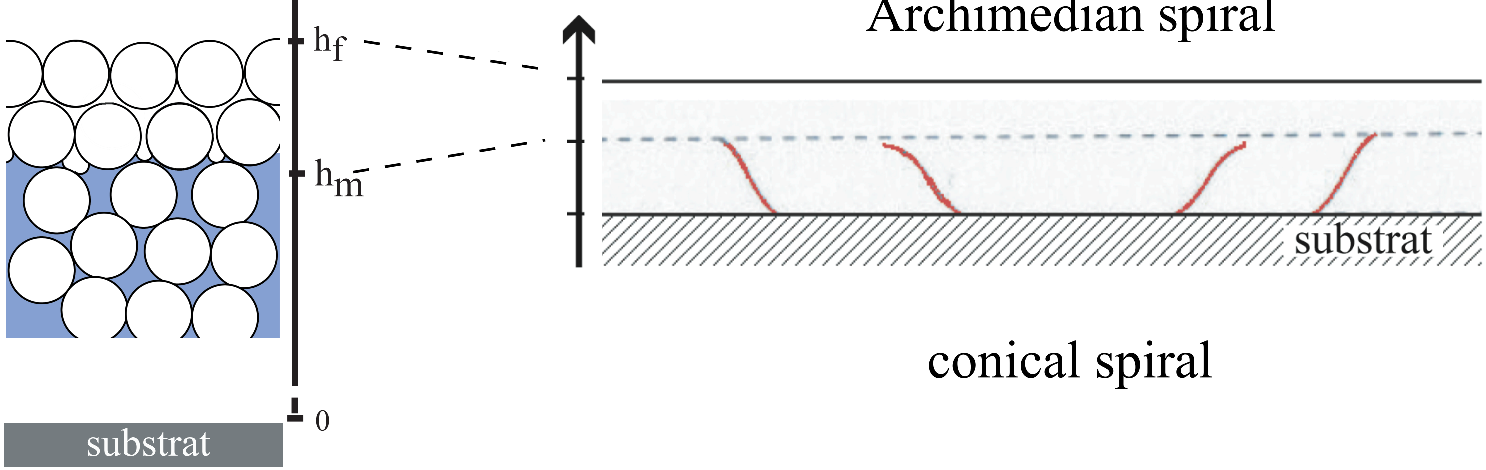
rate ×5

A new generation of cracks inside the adhering region of gel



rate ×5

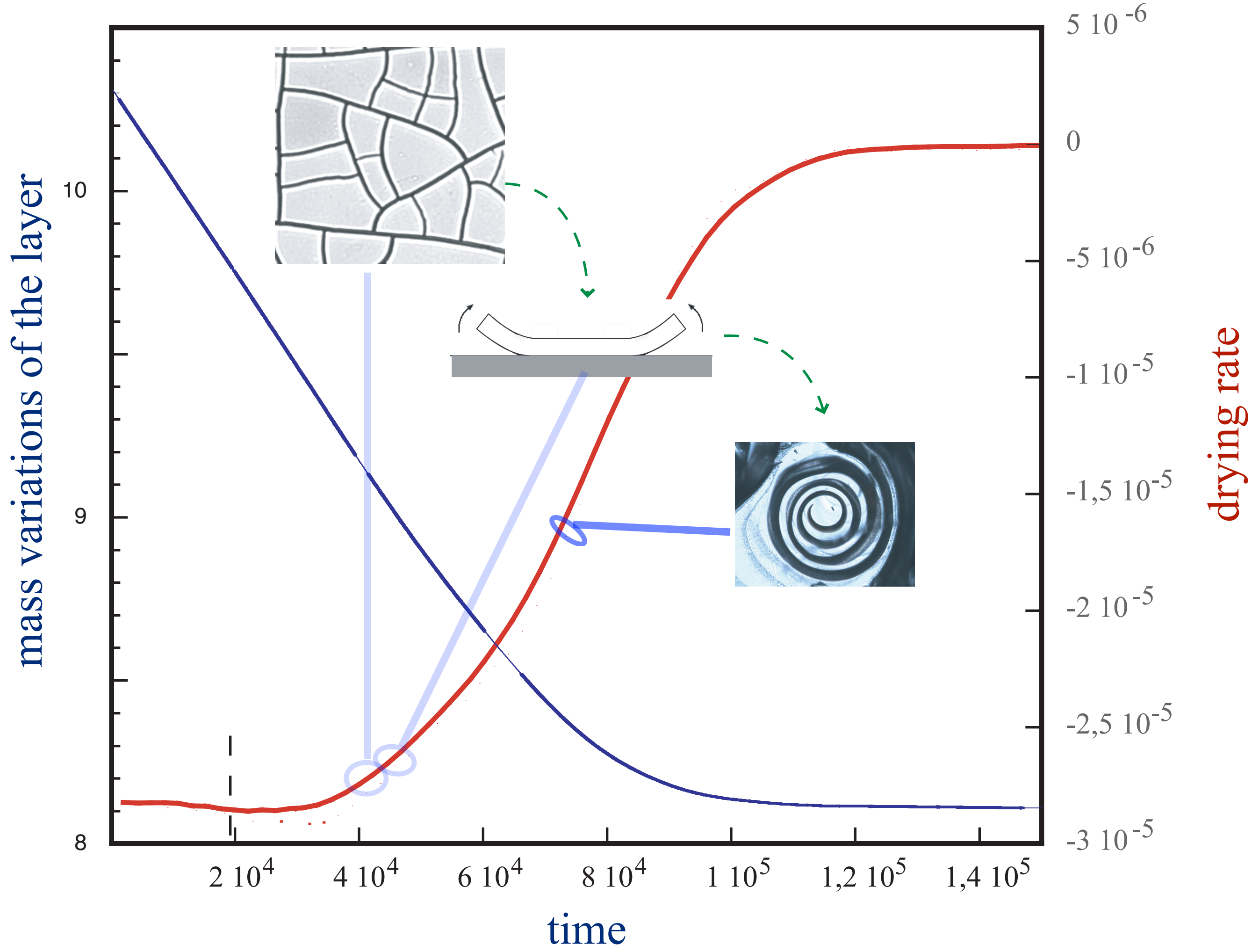
Archimedian spiral



side view

conical spiral

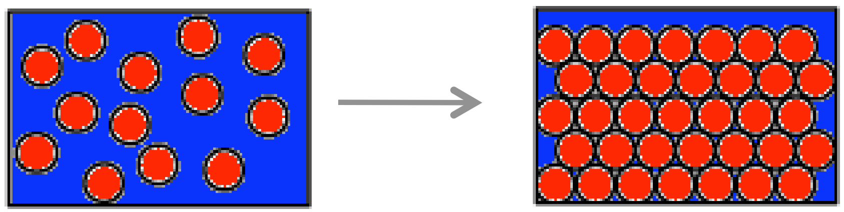
Drying kinectics



Influence of the porous matrix stiffness on the crack patterns

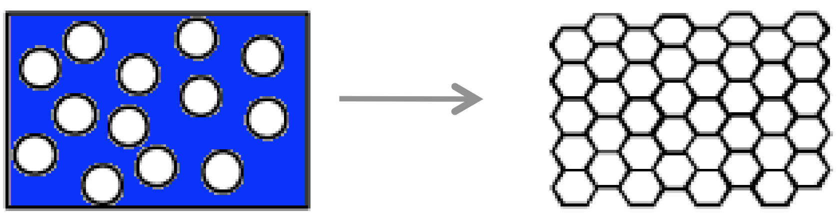
Latex particles

suspension of hard particles



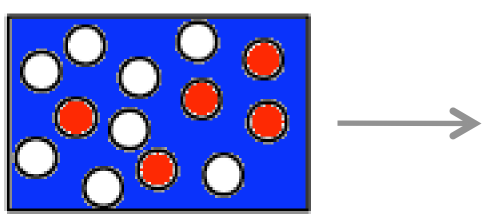
high Tg particles
$T_{amb} < T_g$

suspension of soft particle



low Tg particles
$T_g < T_{amb}$

binary mixtures



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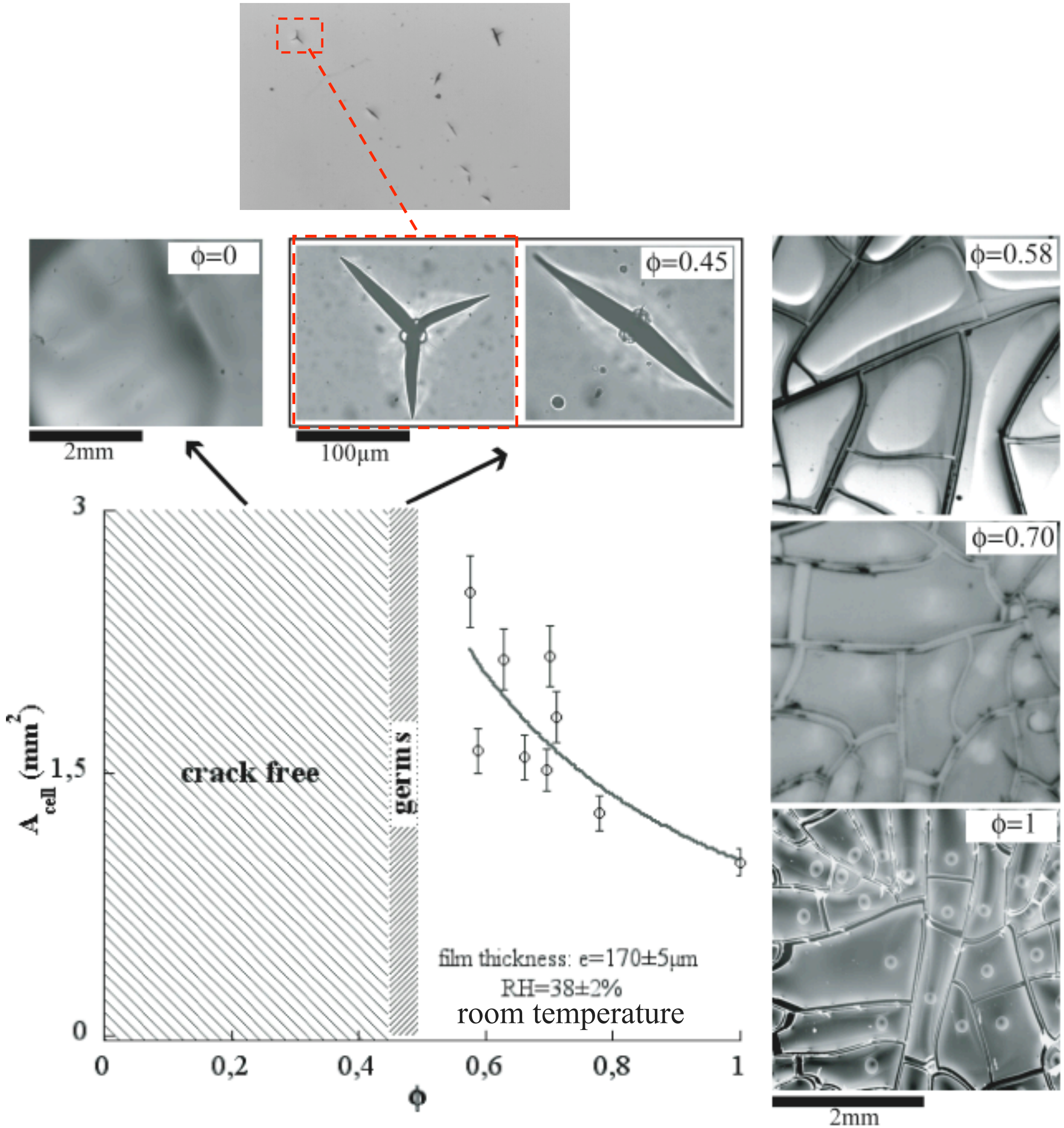
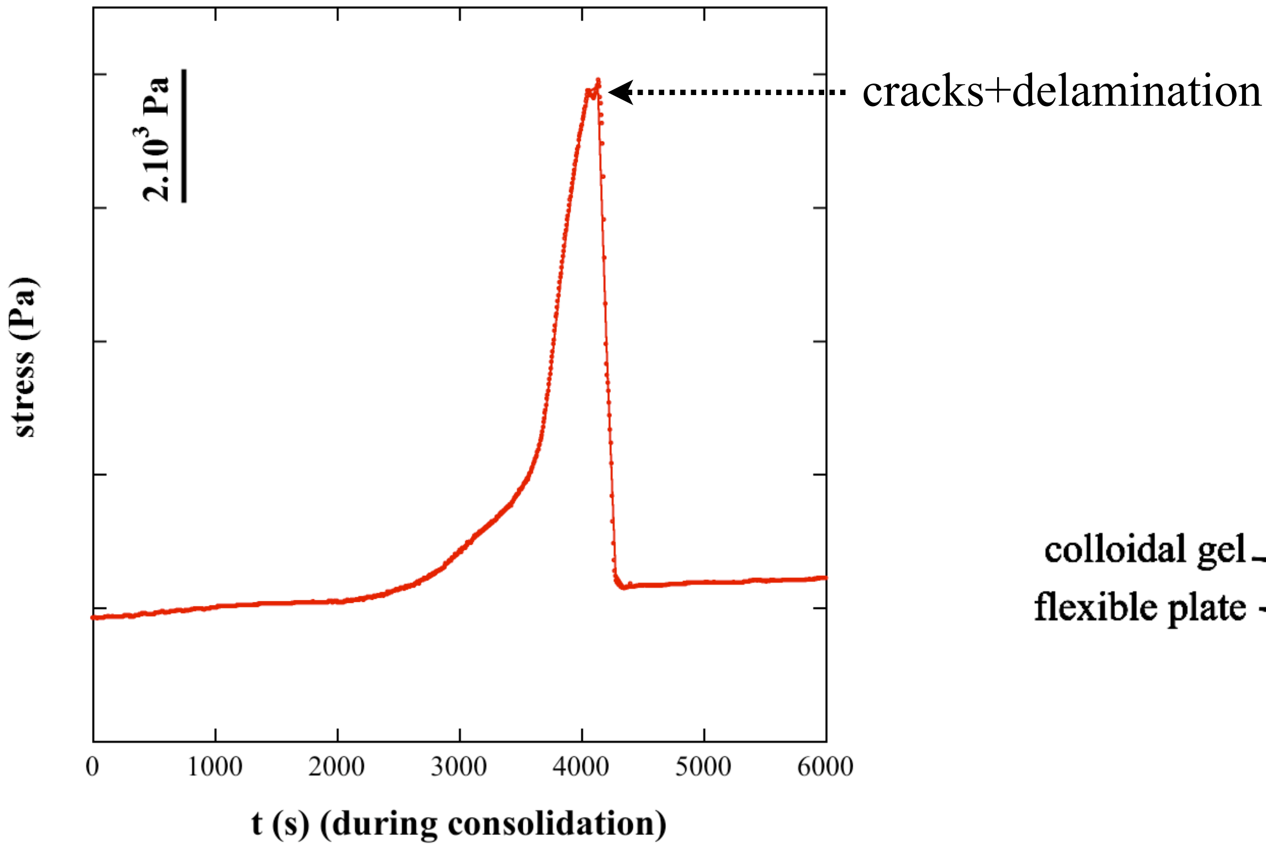
Influence of the porous matrix stiffness on the crack patterns

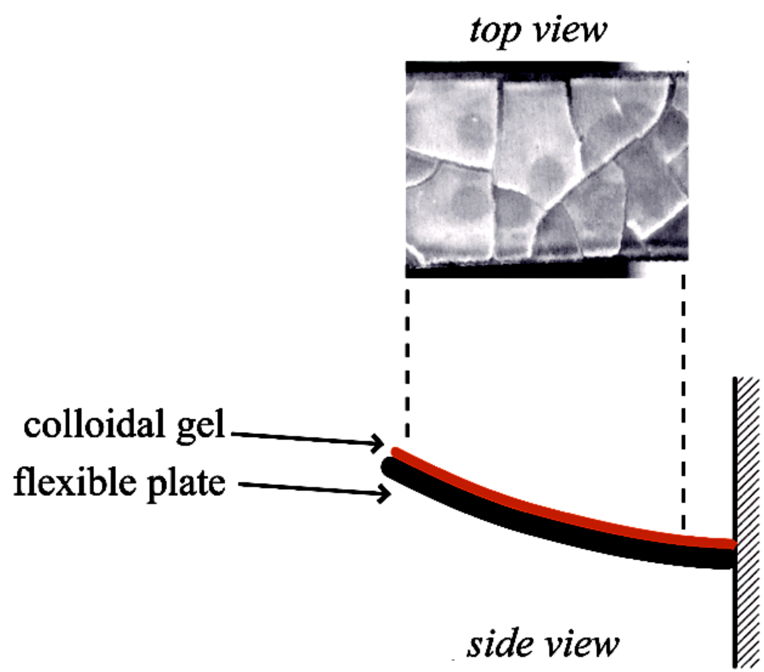


Influence of the porous matrix stiffness on the crack patterns

Mechanical characterization of gels made of binary mixtures:

1. mean stress measurements during bending of desiccating gelled layer/flexible plate

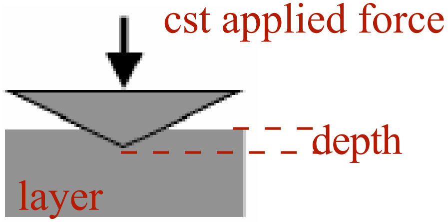


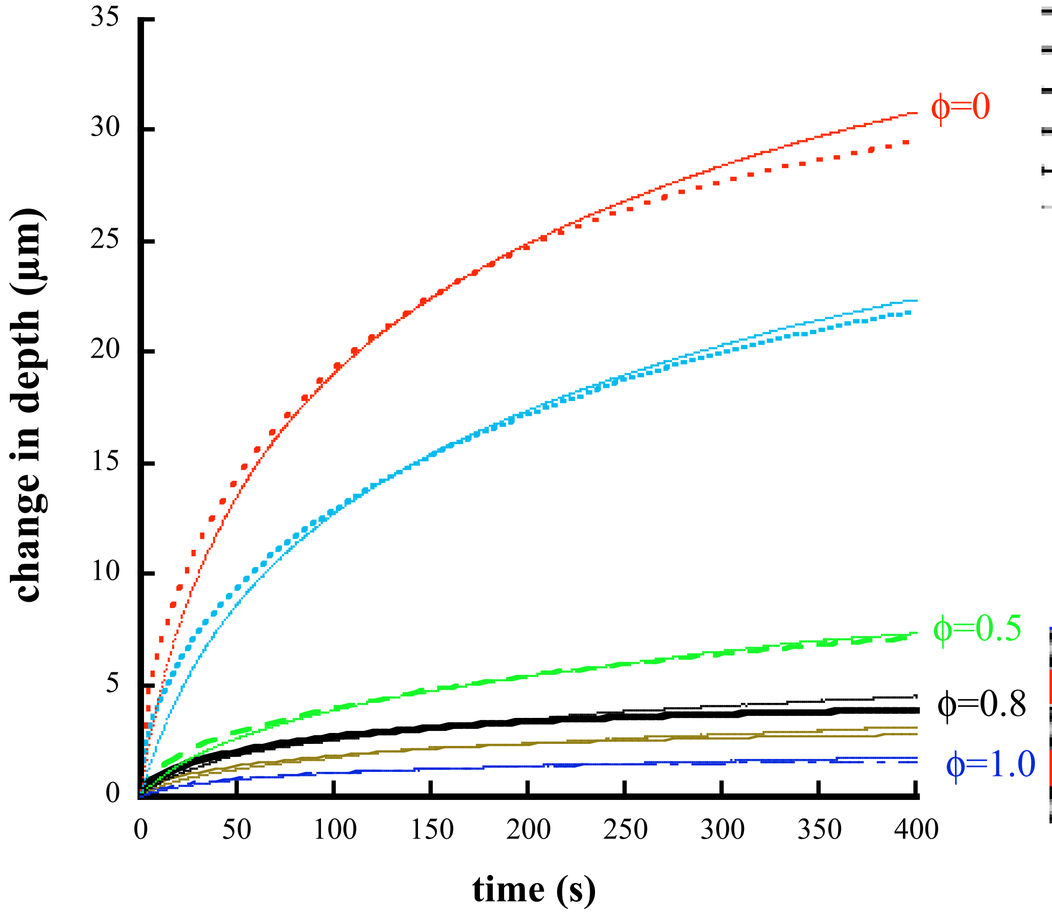


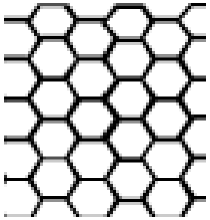
Influence of the porous matrix stiffness on the crack patterns

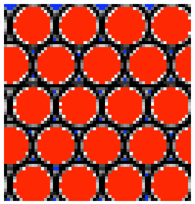
Mechanical characterization of gels made of binary mixtures:

2. creep measurements by micro-indention process









Influence of the porous matrix stiffness on the crack patterns

Model for 1D-film formation:

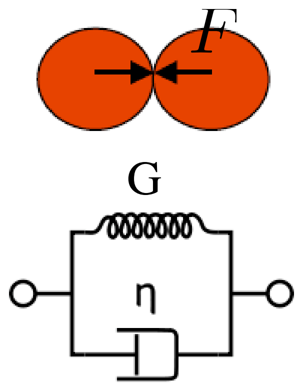
viscoelastic behaviour

$$F \sim -a^2 \left(\frac{G}{2(1-\nu)} + \eta \frac{d}{dt} \right) \epsilon^{3/2}$$

Matthews (1980)

Man, Russel *Phys. Rev. Lett.* (2008)

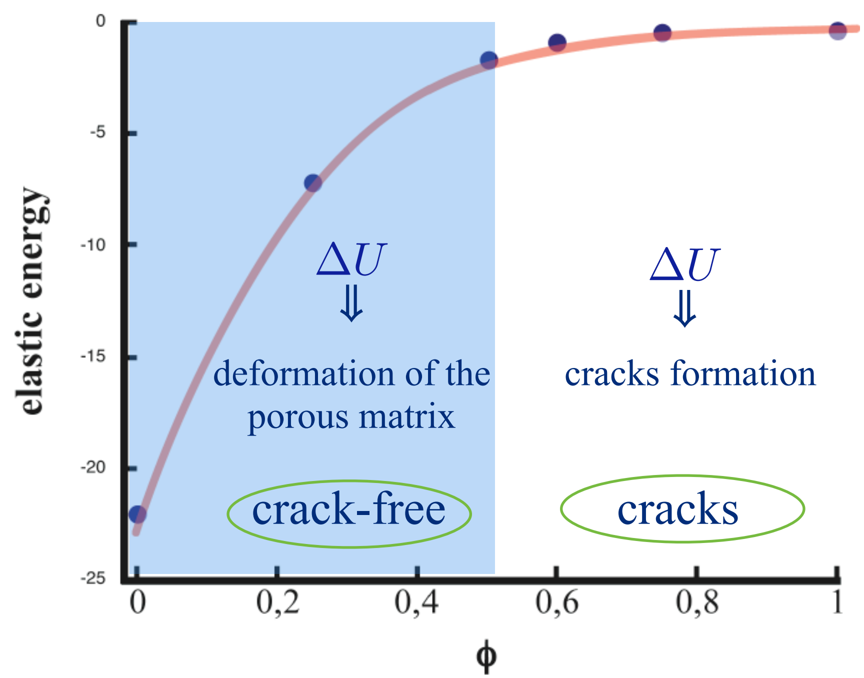
Kelvin-Voigt model



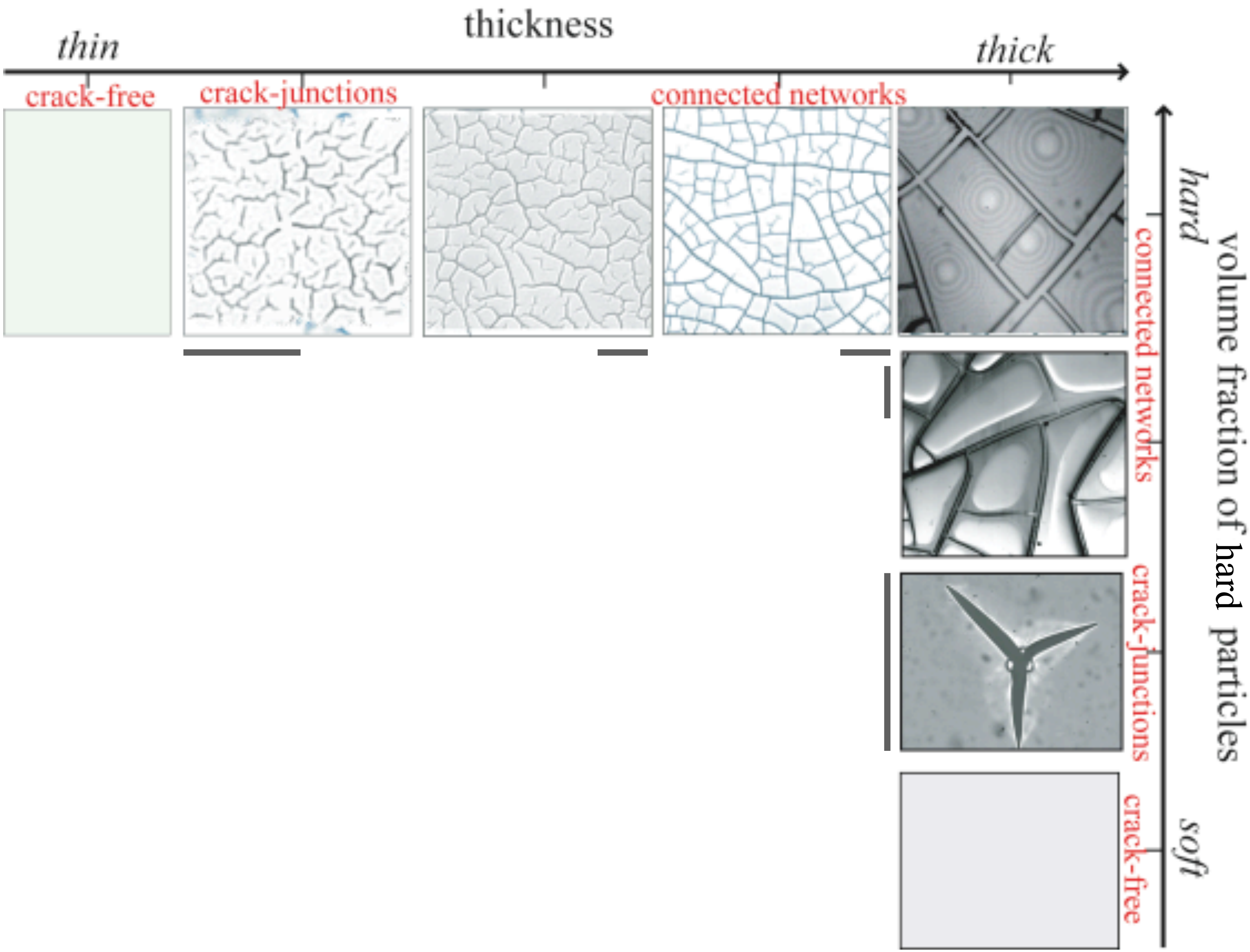
micro-indentation measurements $\Rightarrow (G, \eta)$

Recovery of elastic energy in the film:

$$\Delta U = \sum_{i,j} \sigma_{ij} \epsilon_{ij}$$



Influence of the layer thickness and porous matrix stiffness on crack patterns

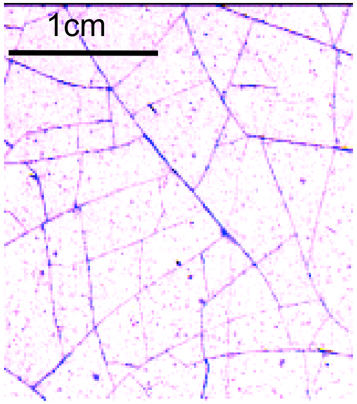


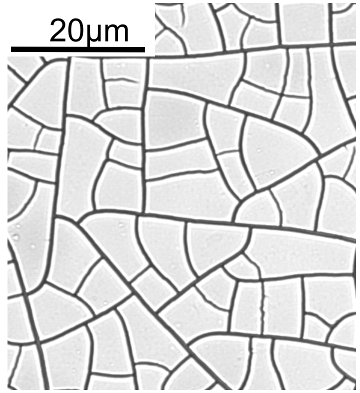
Craquelures related to the composition of the painting layer

series of « les Apôtres » Georges de La Tour

experiments

equivalent thicknesses

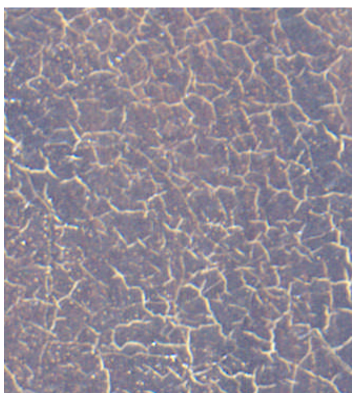




network of connected cracks

layer thickness~100µm

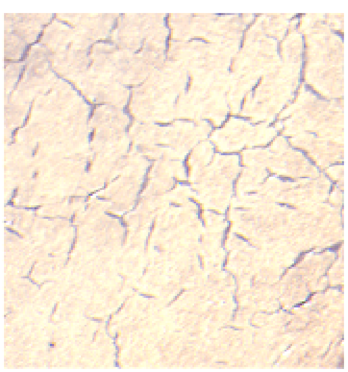
"rigid" particles

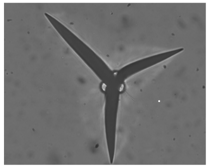


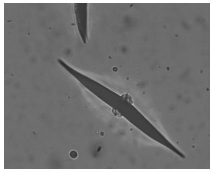
dense network of isolated cracks

layer thickness~10µm

"rigid" particles







low density of isolated cracks

layer thickness~100µm

"soft" particles