FRICTION OF POLYMER GELS

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Gels = soft elastic solid with high content of fluid = poroelastic solid
⇒ specific frictionnal properties

- e.g. : gels in biological systems : very low friction (e.g. articular cartilage)
- Network / solvent contributions to friction ?

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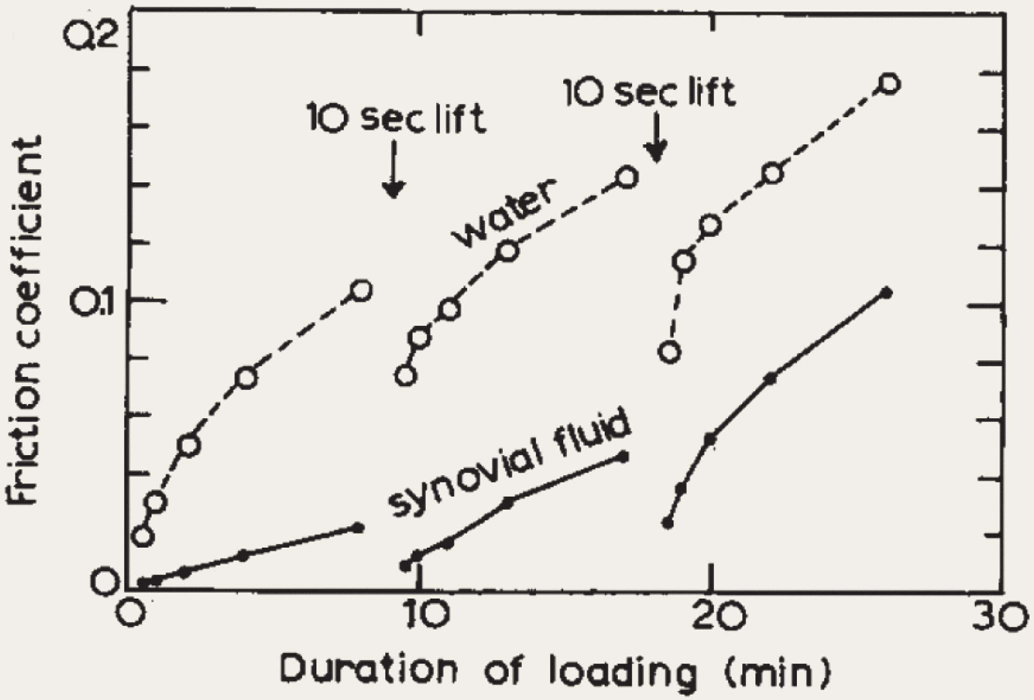
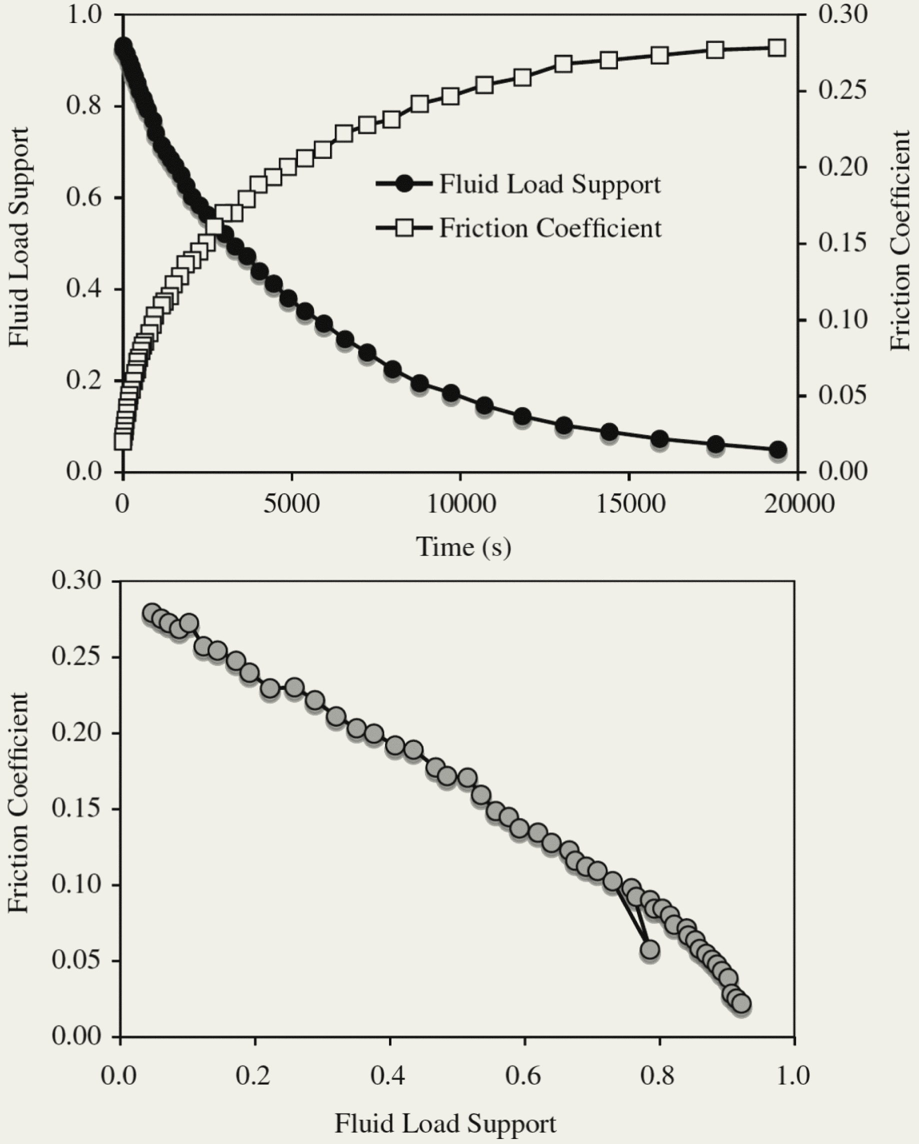
POROELASTIC EFFECTS : ARTICULAR CARTILAGE (COLLAGEN GEL)





Poroelastic transfer of fluid across cartilage

→ load supported by fluid at short times
low friction : fluid lubrication

→ increasing contribution of matrix as $t \nearrow$
higher friction : solid friction

$$\mu = \mu_\infty \left(1 - (1-\phi)\frac{W_{\text{fluid}}}{W_{\text{total}}}\right)$$

C. W. McCutchen, *Wear* **5**, 1 (1959).

G. A. Ateshian, *Journal of Biomechanics* **42**, 1163 (2009).

POLYMER GELS

- network = chains + cross-links ★ (physical or chemical), distance ξ
- solvent (90–99%), viscosity η

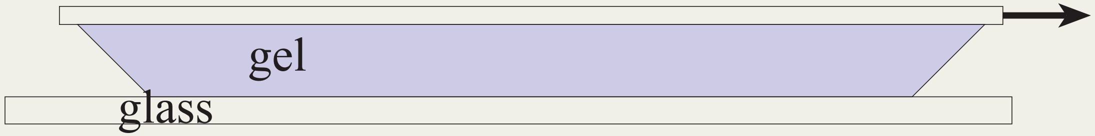
⇒ "poro-elastic" material

- elasticity of entropic origin (rubber) $G \simeq \dfrac{k_B T}{\xi^3} \simeq 10^2 - 10^5$ Pa, $\xi \simeq 3 - 30$ nm.
- solvent/network relative motion ⇒ diffusive mode $D_{\text{coll.}} \simeq 10^{-9} - 10^{-11}$ m^2.s^{-1} for aqueous gels (10^{-7}m^2.s^{-1} for cartilage) ⇒ $10^5 - -10^7$ s for 1 cm thick sample ⇒ get rid of time dependence of fluid loaded part.

HYDRODYNAMIC FRICTION OF GELATIN GELS

Model system : gelatin gel on clean flat glass in plane/plane contact.

→ control almost independently solvent viscosity $\eta_S \simeq 1-4$ Pa.s (water + glycerol) and network mesh size $\xi \simeq 6-12$ nm (gelatin contentration c)



impose

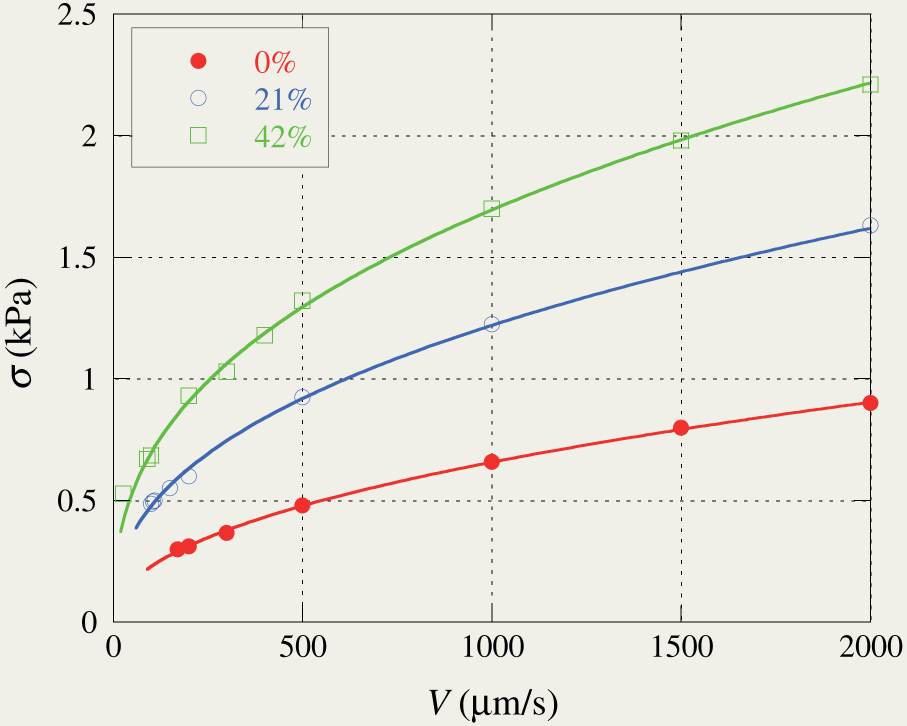
- sliding velocity V (1 – 2000 μm/s)
- normal pressure p (0 – 2 kPa)

measure

- stationnary frictionnal shear stress $\sigma(V)$.
- interfacial slip.

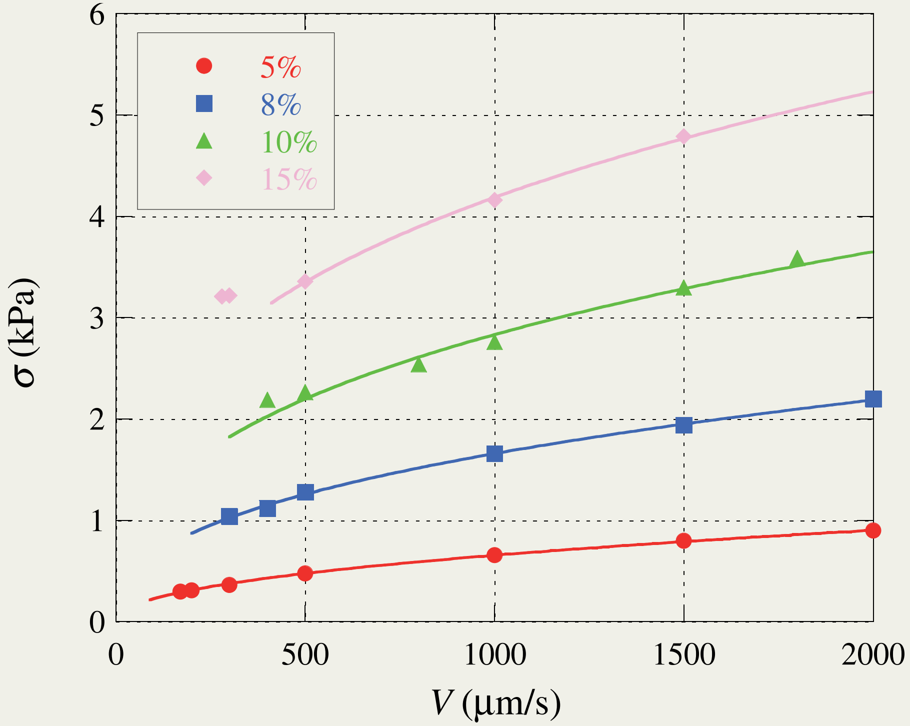
HYDRODYNAMIC FRICTION OF GELATIN GELS

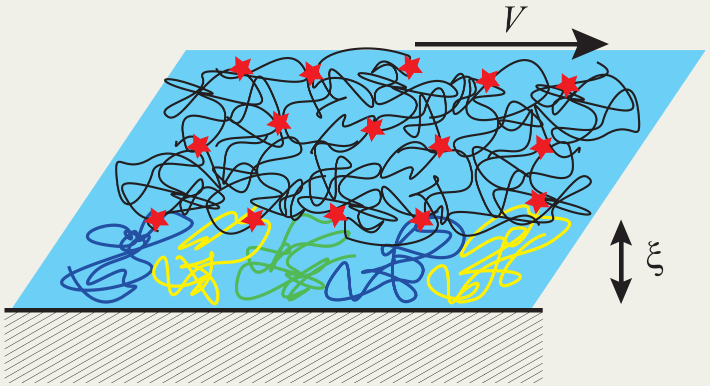
Changing solvent viscosity η_S



Changing gelatin concentration

$c \nearrow \Rightarrow G \nearrow \Rightarrow \xi \searrow$





$\Rightarrow$ Response of a confined layer of thickness $\simeq \xi$?

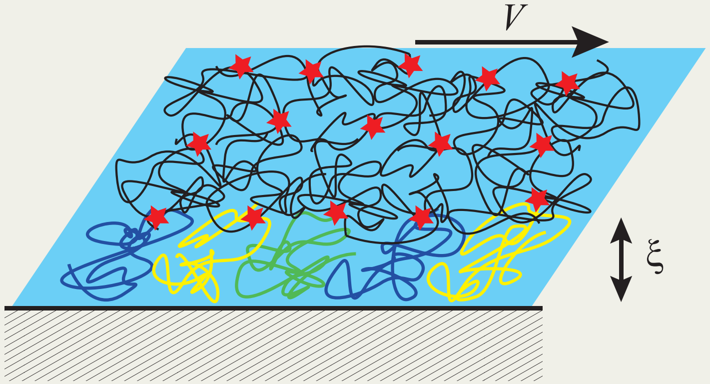
T. Baumberger, C. Caroli and O. Ronsin, *Eur. Phys. J. E* **11**, 85 (2003).

HYDRODYNAMIC FRICTION OF GELATIN GELS

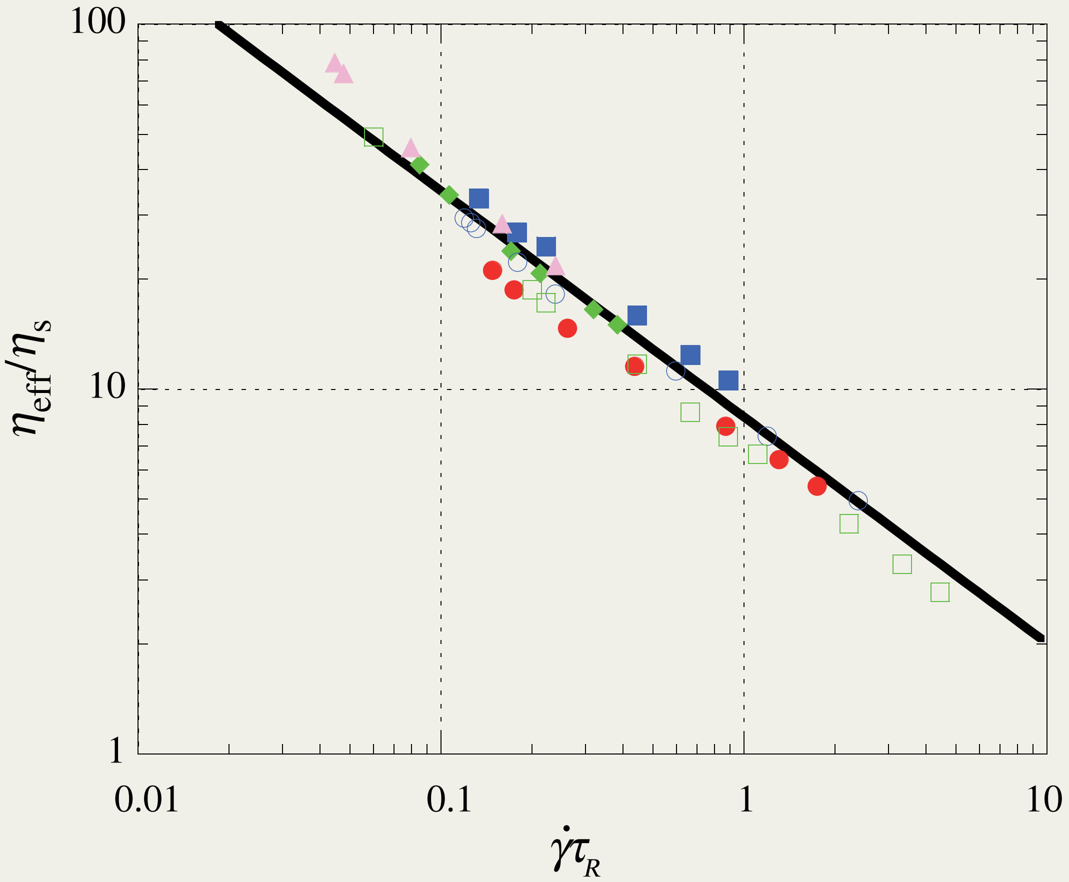
layer sheared at a rate $\dot{\gamma} = V/\xi$

measured effective visosity $\eta_{\text{eff}} = \dfrac{\sigma\xi}{V}$

relaxation time τ_R of a chain of size ξ (Rouse)



$\dfrac{\eta_{\text{eff}}}{\eta_s} \sim \left(\dot{\gamma}\tau_R\right)^{-\alpha}$, $\alpha = 0.6$ compatible with macroscopic rheology of solutions.



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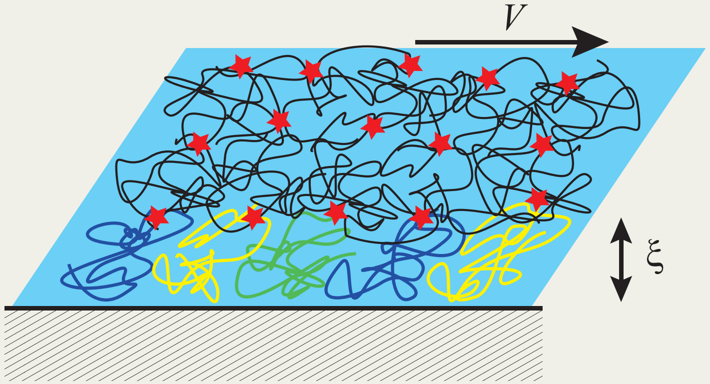

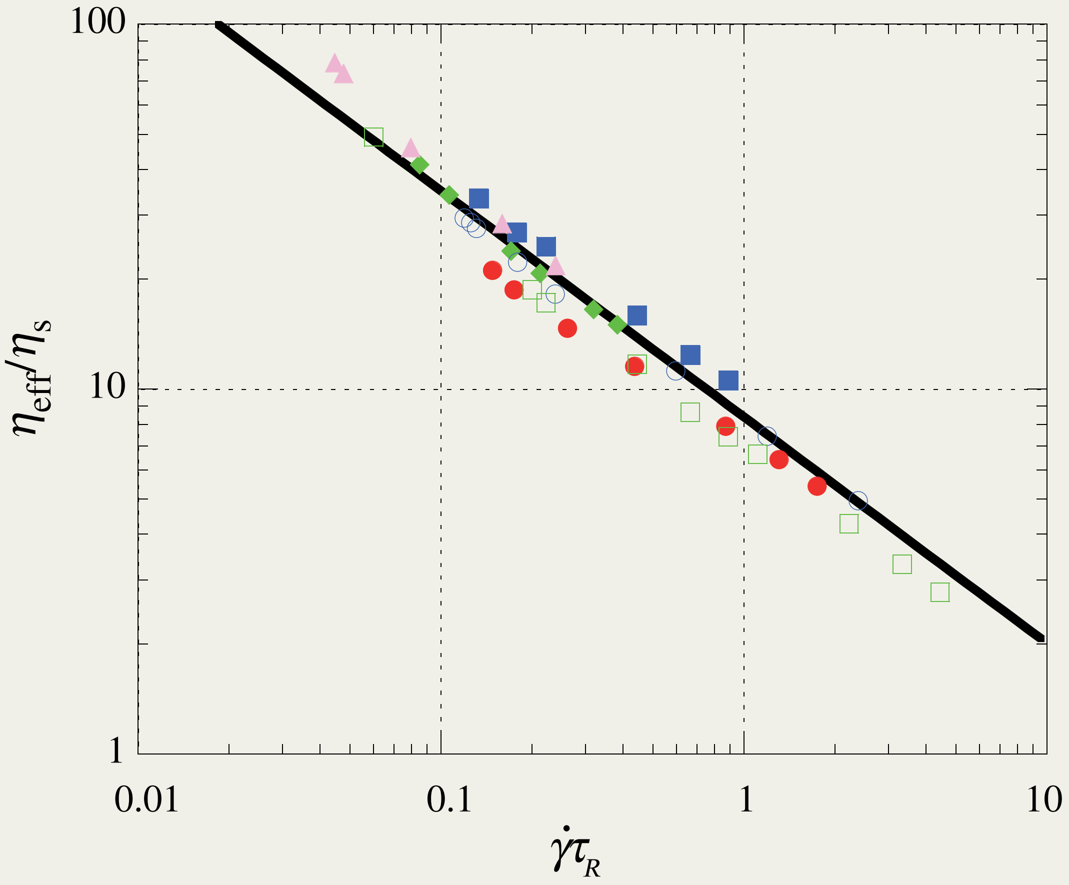

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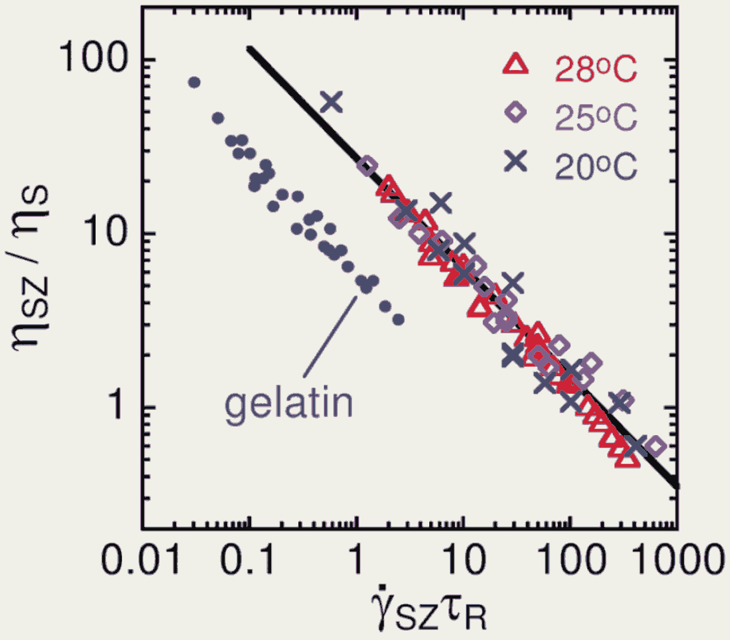
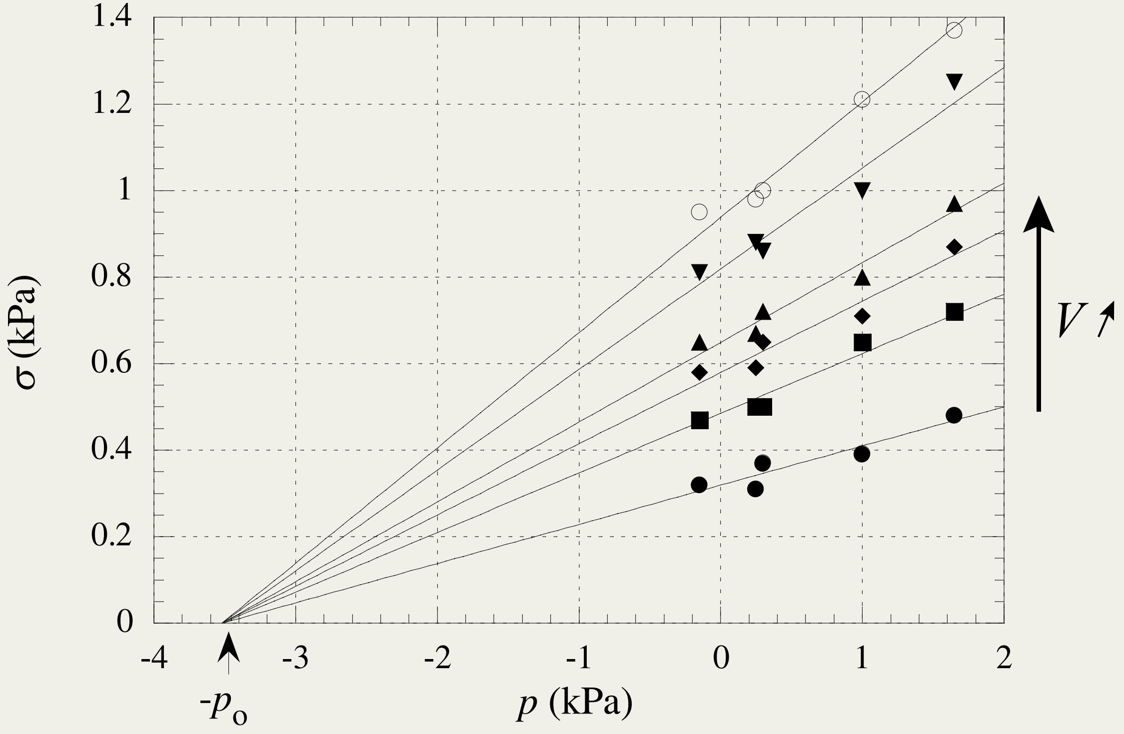
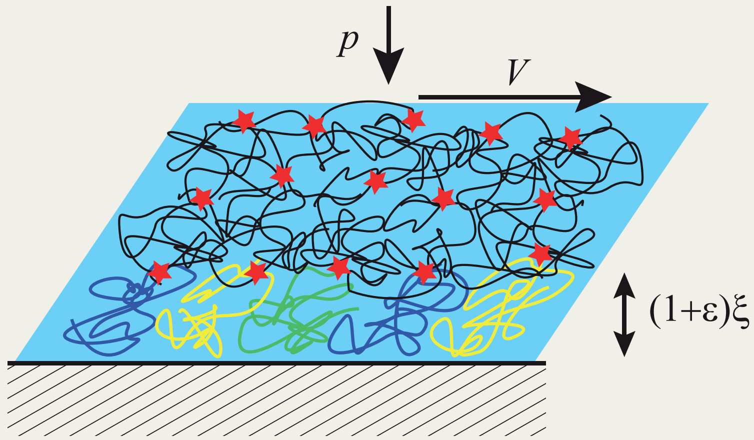
Also observed with block copolymer gels



K.A. Erk *et al.*, Langmuir, **28**, 4472 (2012).

EFFECT OF NORMAL STRESS





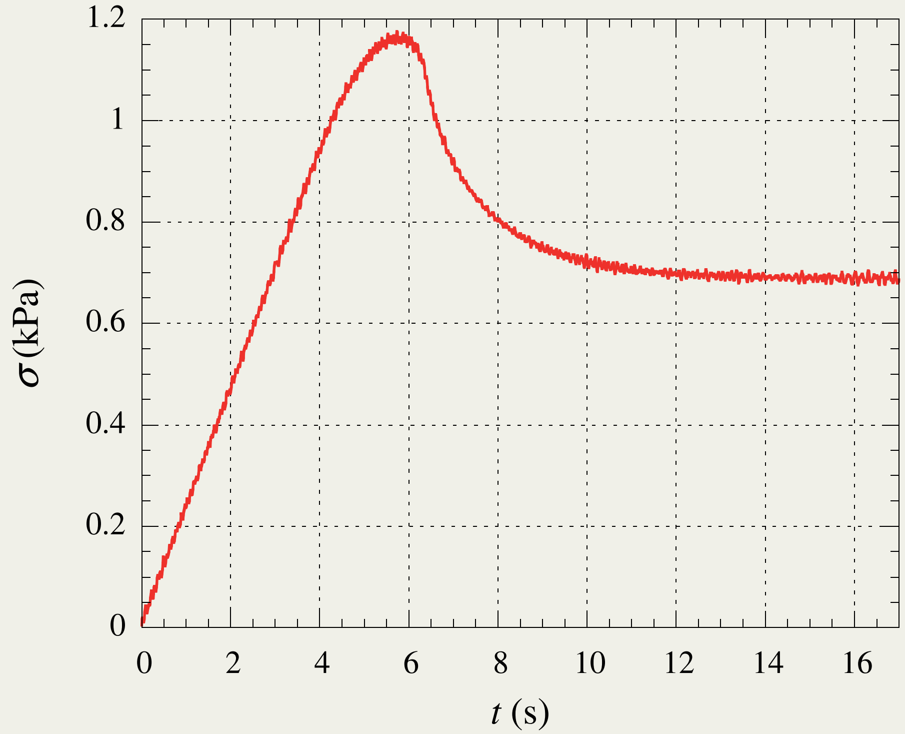
deformation under compression $\epsilon = -\dfrac{p}{E} = -\dfrac{p}{3G}$

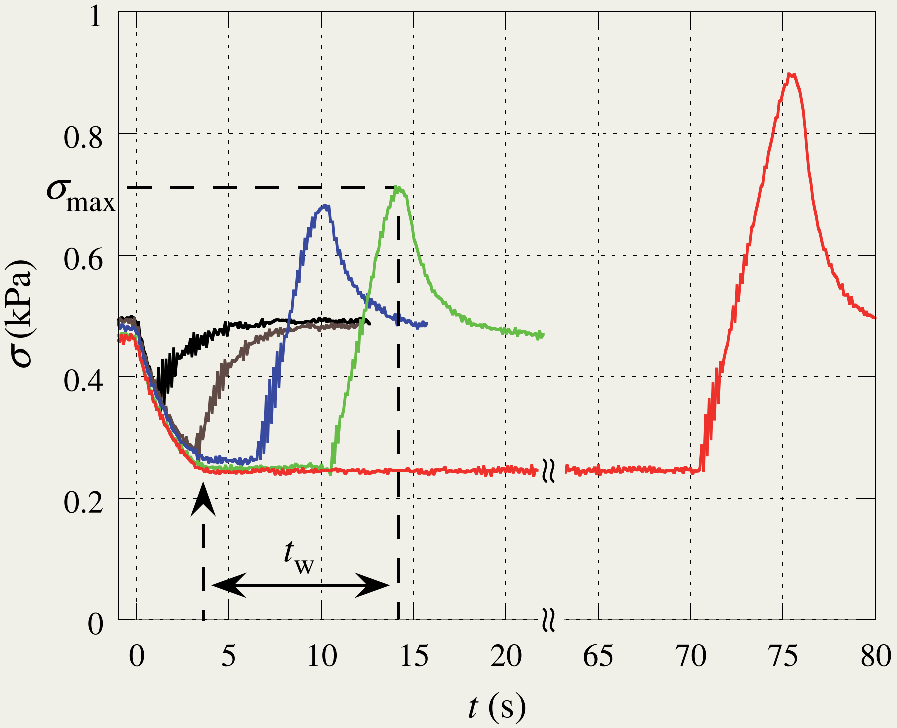
$\Rightarrow$ layer thickness $(1+\epsilon)\xi$

$$\Rightarrow \quad \sigma(V,p) = \sigma(V,p=0)\left[1+(1+3\alpha)\frac{p}{3G}\right]$$

$$p_0 = \frac{3G}{1+3\alpha} \simeq G$$

STATIC FRICTION



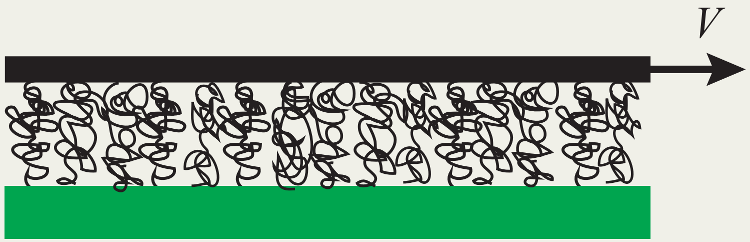


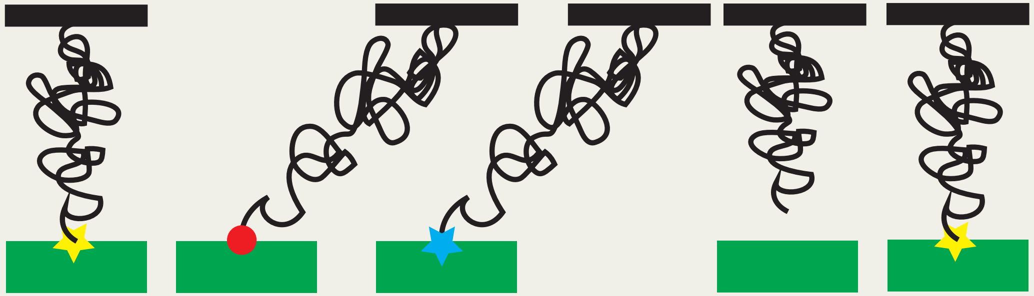
Increase of the number of pinned chains with time.

⇒ Decrease of the number of pinned chains with velocity.

ELASTIC CONTRIBUTION TO GEL FRICTION

Schallamach model of rubber friction : dynamics of chain pinning/depinning

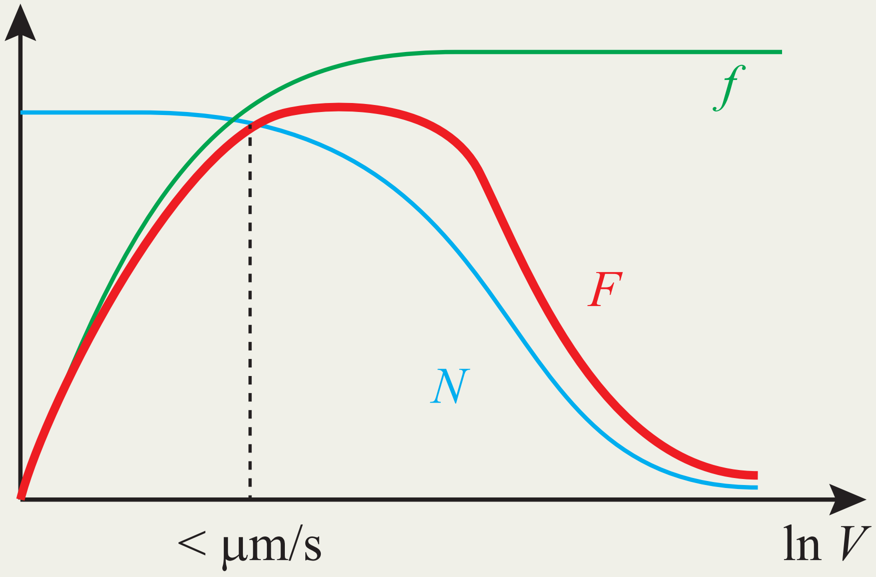




thermally activated depinning
+ advection at velocity V

⇒ number of pinned chains ↘ with V

⇒ force per chain ↗ with V

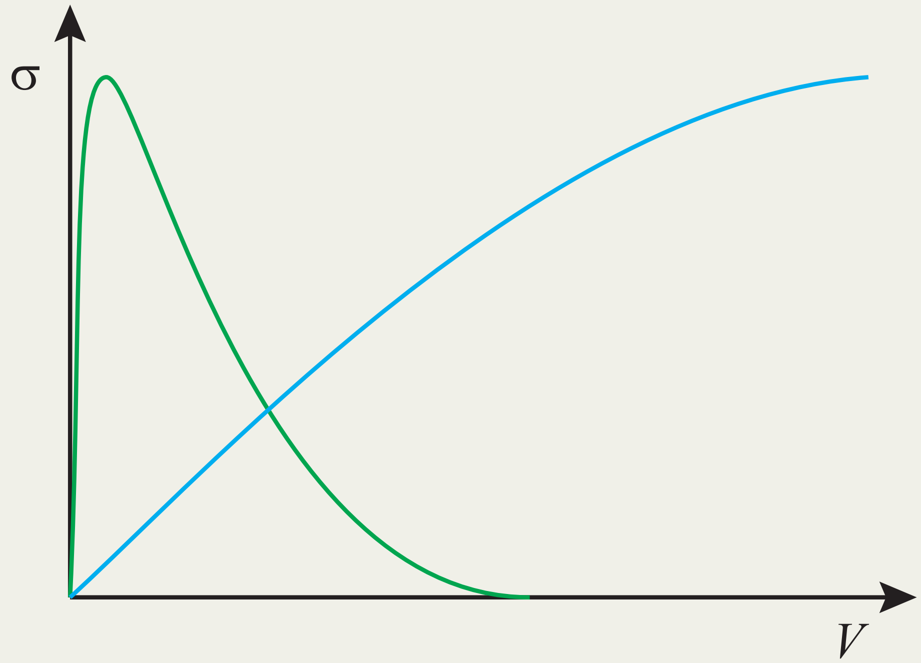


A. Schallamach, *Wear*, vol. 6, p. 375 (1963)

POLYMER GELS FRICTION

two contributions:

- chain pinning
- viscosity of interfacial layer

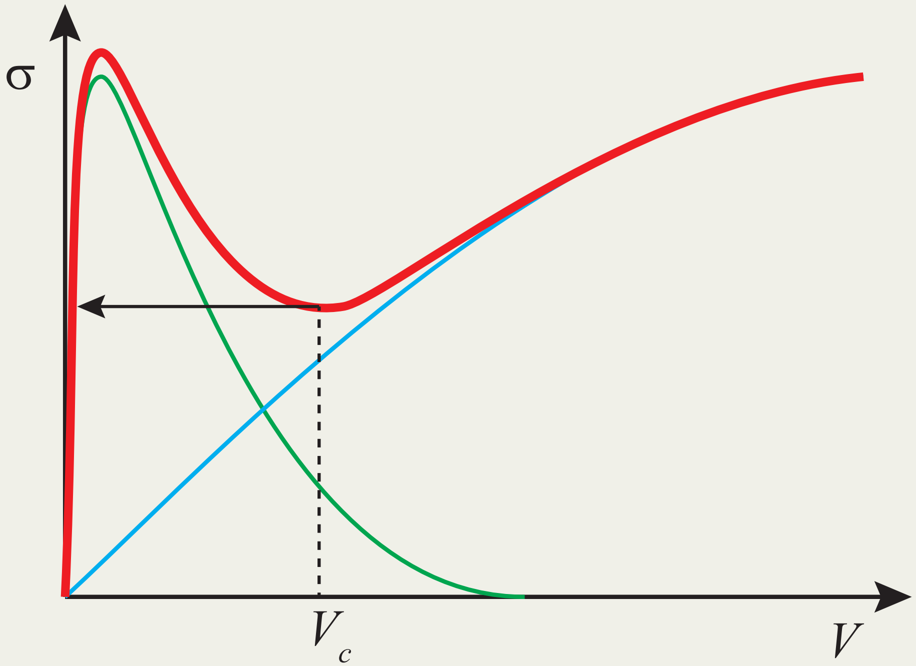


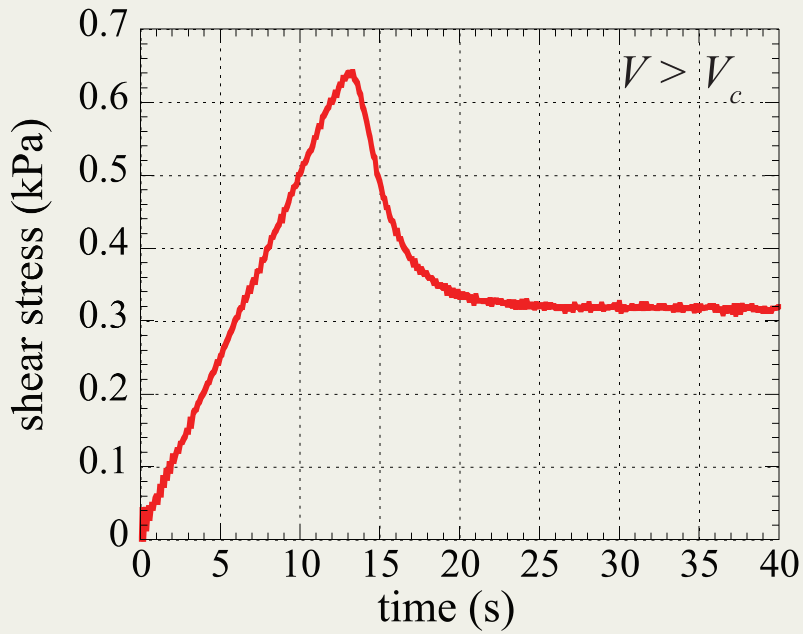
POLYMER GELS FRICTION

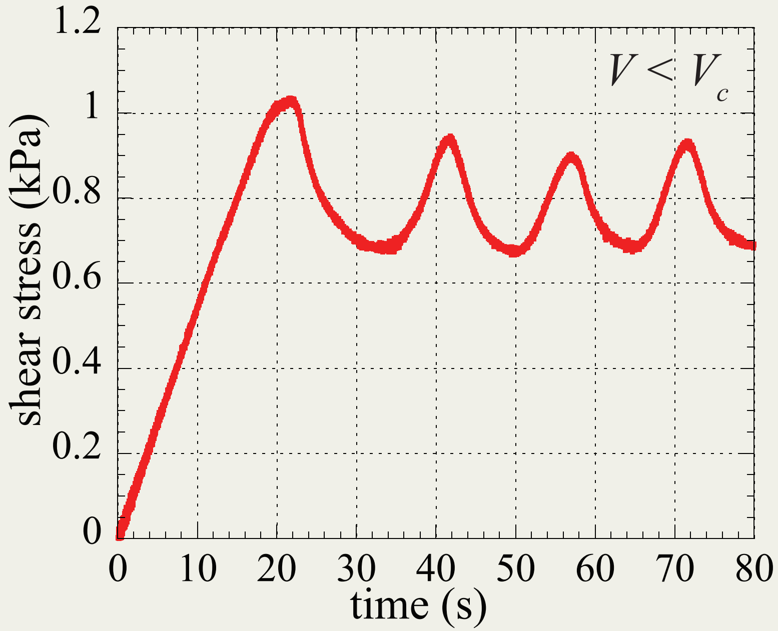
two contributions:

- chain pinning
- viscosity of interfacial layer

$\Rightarrow$ instability at V_c (compliant system $\simeq$ imposed stress)

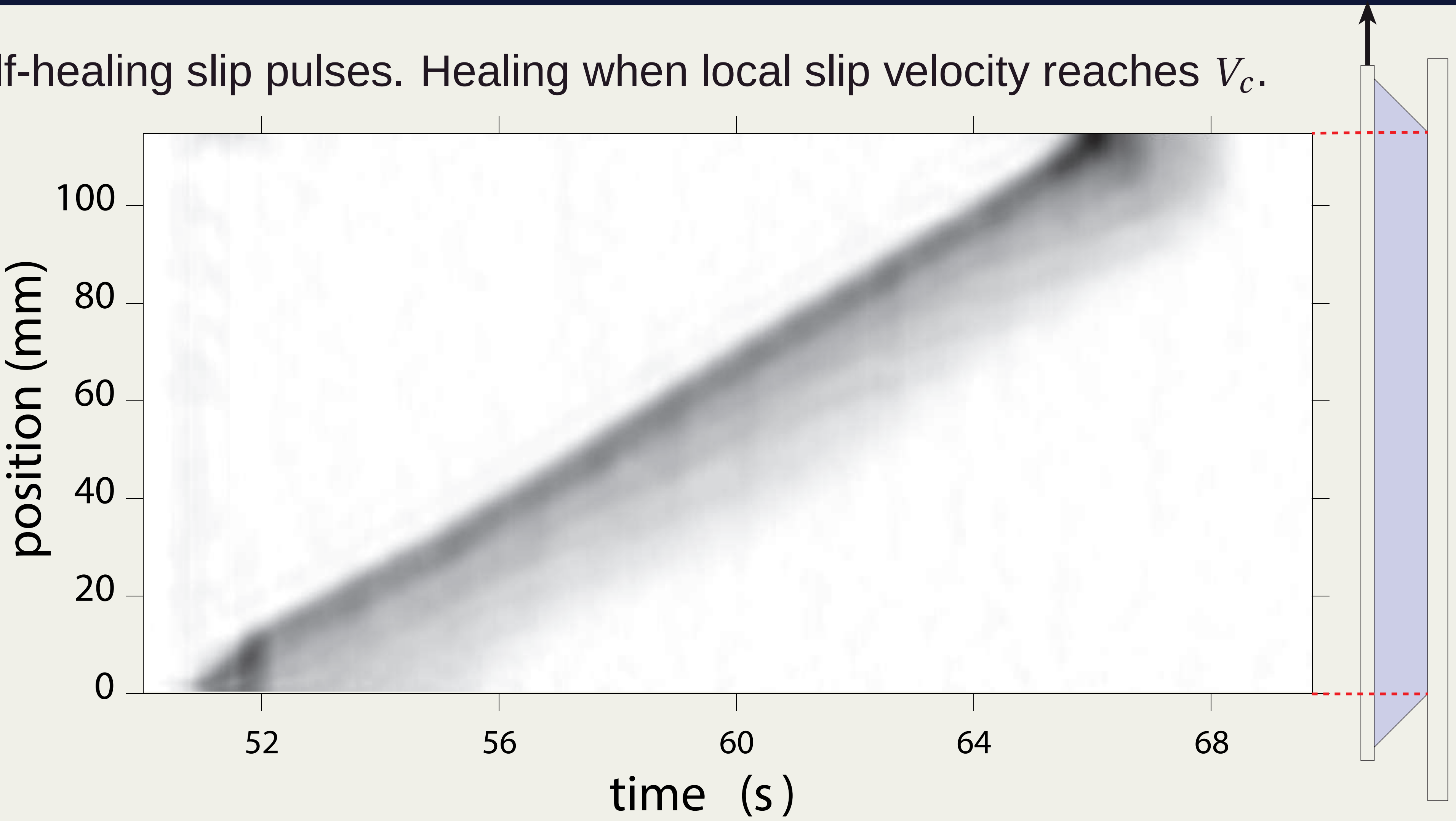






SLEF-HEALING SLIP PULSES IN GELATIN

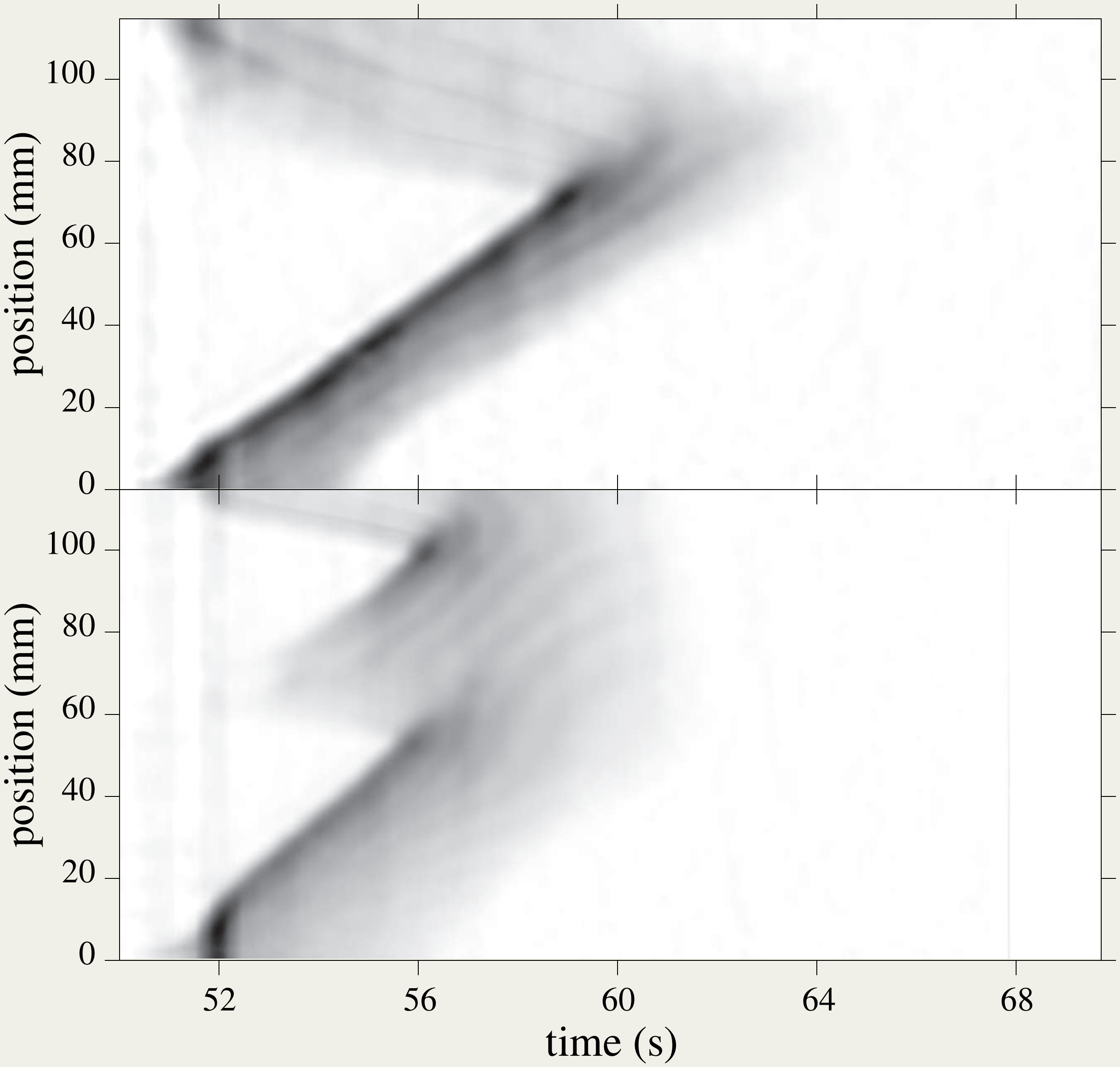
self-healing slip pulses. Healing when local slip velocity reaches V_c.



O. Ronsin, T. Baumberger and C.Y. Hui, *J. Adhesion*, vol. 87, p. 504 (2011)

SLEF-HEALING SLIP PULSES IN GELATIN

nucleation favored at the edge(s) of the contact, but also within the contact.



CONCLUSION

biphasic nature of gels ⇒ 2 contributions to friction

- elastic : (rate-dependent) stretching of adsorbed polymer chains
- hydrodynamic : viscous flow of fluid interfacial layer

relative contributions influenced by many parameters (velocity, pressure, charges, surface chemistry, roughness...)

- Tuning these parameters to achieve very low friction → artificial cartilage : need for tougher gels ⇒ double network gels (J.P. Gong *et al.*).
- their competition can lead to instabilities ⇒ model system for earth crust (F. Corbi *et al.*, *J.G.R. Solid Earth*, vol. 118, p. 1483 (2013)).