Shear-banding in complex fluids

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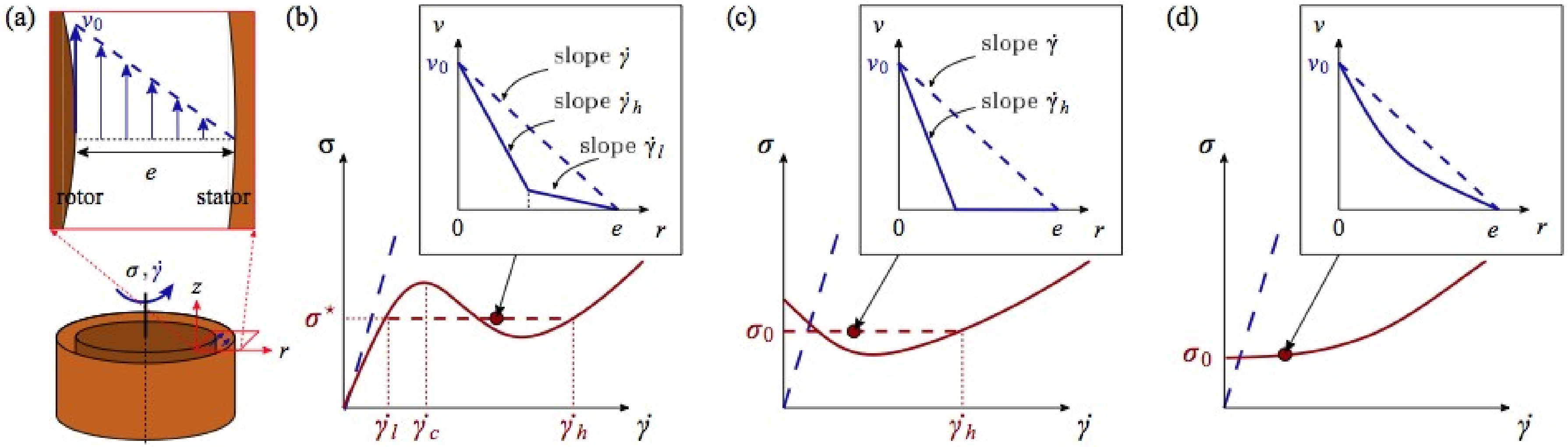
GDR Phenix – Driven Disordered Systems
Grenoble, June 5-6th, 2014

Shear-banding in complex fluids

Are the mechanisms underplay behind the “shear-banding instability” the same in complex fluids with or without yield stress?
Can similar theoretical and numerical approaches be used to rationalize it?
Or are there important differences?
What do recent experiments tell us about this problem?



e.g. wormlike micelles

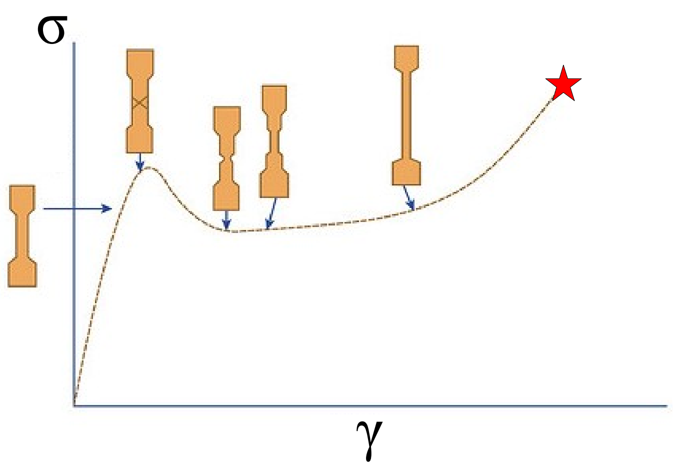
e.g. “thixotropic” yield stress fluids

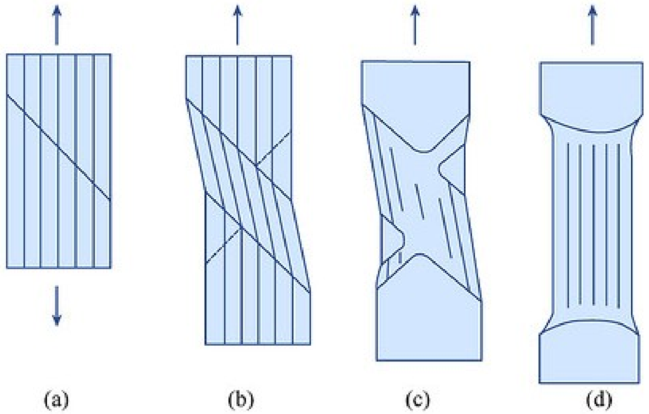
e.g. “simple” yield stress fluids

C. Perge, M.A. Fardin, S. Manneville, *EPJE* (2014)

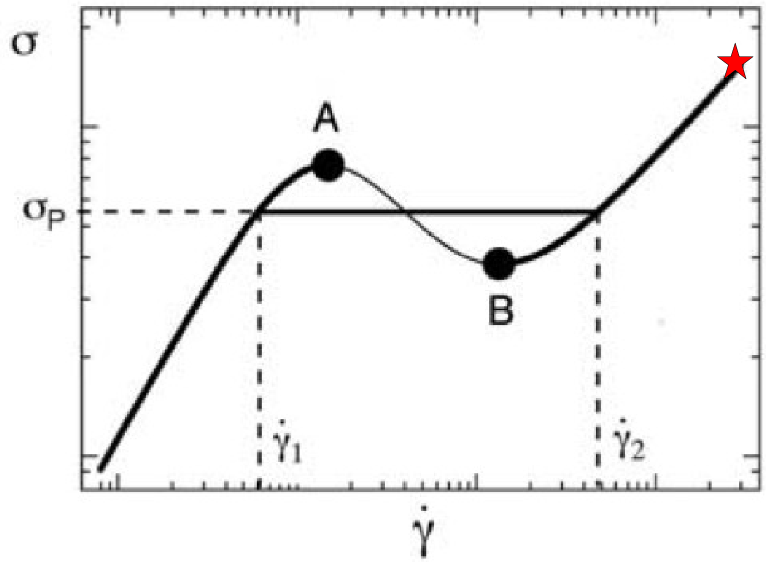
Shear-banding in complex fluids/solids

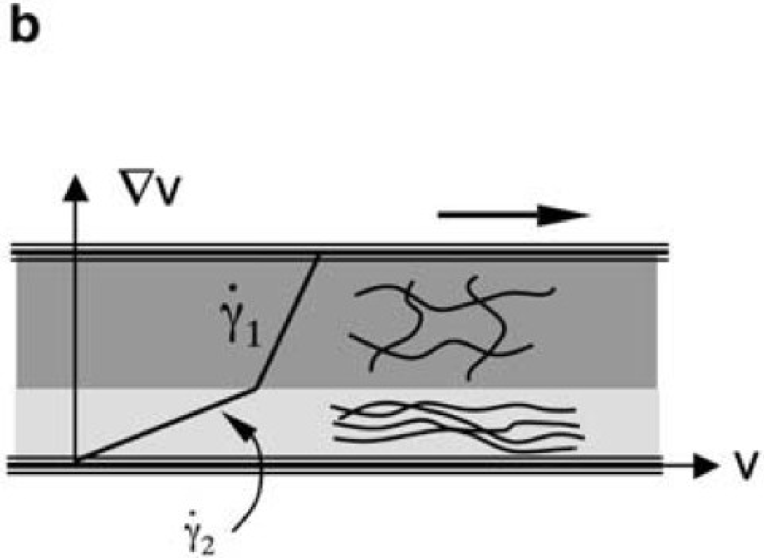
Solid



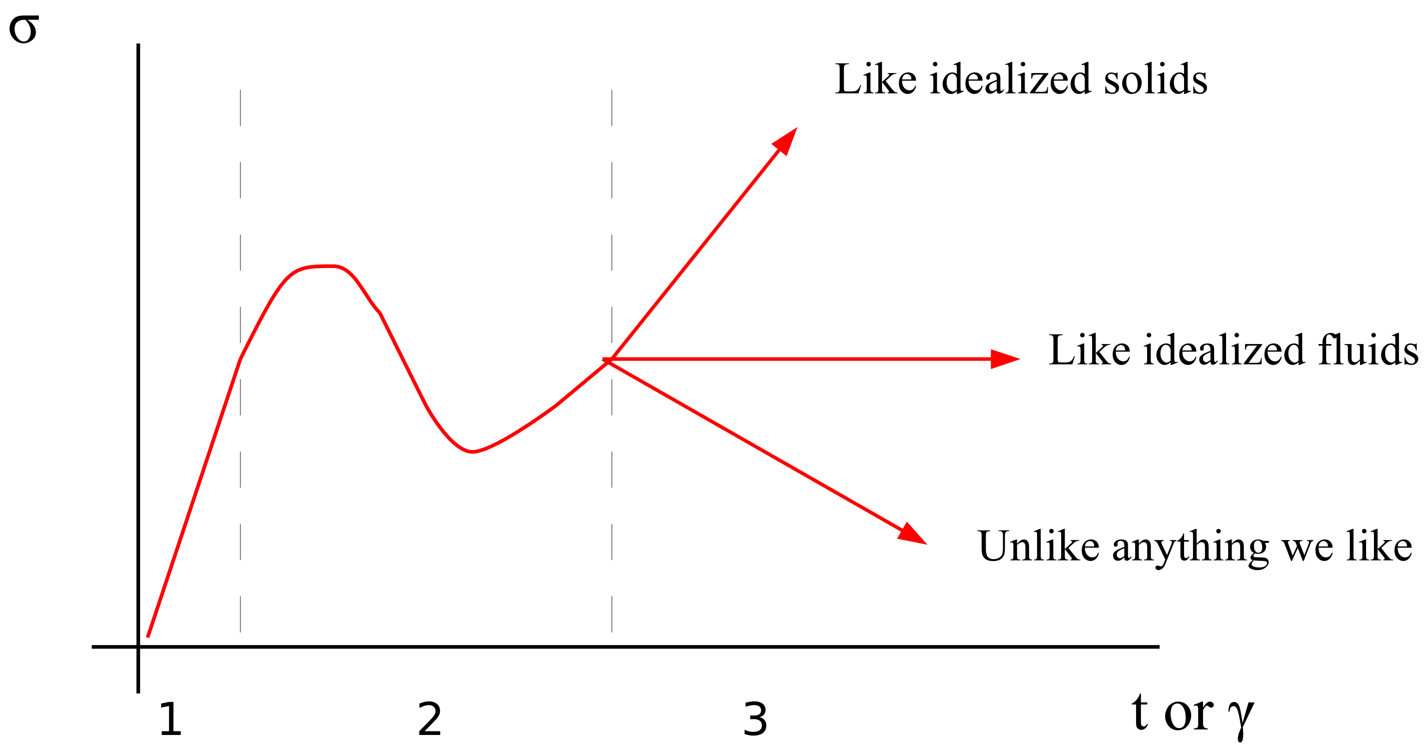


Fluid



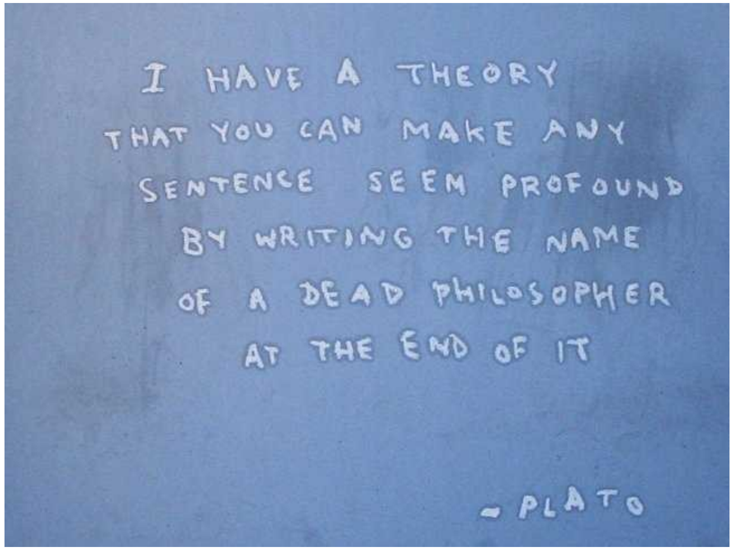


Shear-banding and yielding in fluids?



R.L. Moorcroft and S.M. Fielding, *PRL* (2013) and following papers.

Shear-banding in complex fluids



GDR Phenix – Driven Disordered Systems
Grenoble, June 5-6th, 2014

S. Lerouge
G.H. McKinley
S. Manneville
T. Divoux

O. Cardoso
J.L. Counord
C. Gay
G. Grégoire
C. Perge
N. Taberlet

S. Asnacios
J.F. Berret
S. M. Fielding
A. Lindner
A. N. Morozov
S. J. Muller
C. Wagner

Shear-banding in complex fluids

Shear band, shear-band, shear banding, shear-banding, etc…

WIKIPEDIA
The Free Encyclopedia

Shear band

A shear band (or, more generally, a 'strain localization') is a narrow zone of intense shearing strain, usually of plastic nature, developing during severe deformation of ductile materials. As an example, a soil (overconsolidated silty-clay) specimen is shown in Fig. 1, after an axialsymmetric compression test. Initially the sample was cylindrical in shape and, since symmetry was tried to be preserved during the test, the cylindrical shape was maintained for a while during the test and the deformation was homogeneous, but at extreme loading two X-shaped shear bands had formed and the subsequent deformation was strongly localized (see also the sketch on the right of Fig. 1).

Other disconnected page: “Adiabatic shear band”

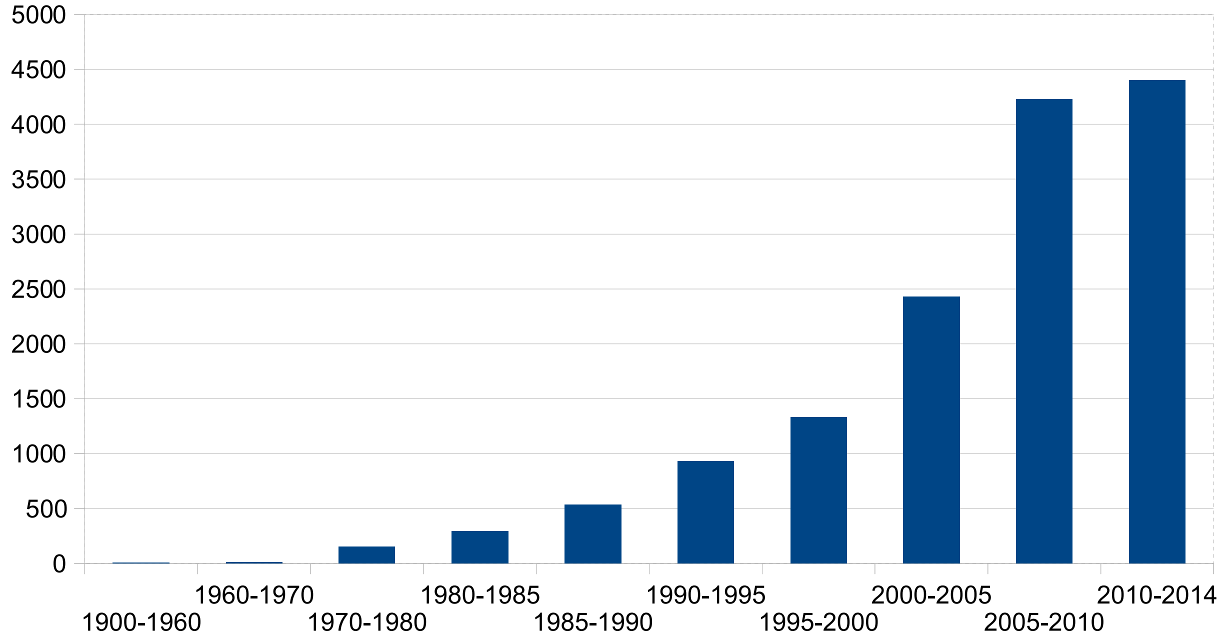
Shear-banding in complex fluids

Shear-banding
12000 papers
using Google Scholar

Shear-banding + solid = 8500
Shear-banding + fluid = 6000

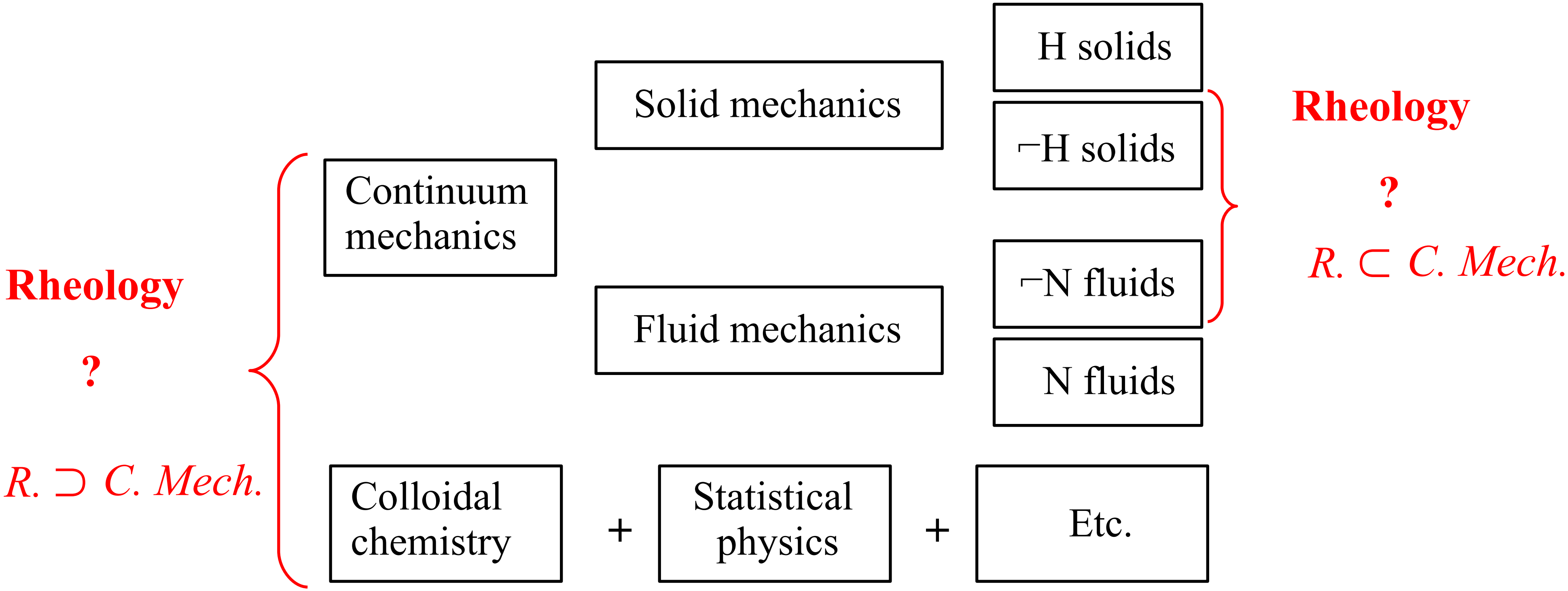
SB+ solid + fluid = 4000

# of papers



Consistency and completeness...

Shear-banding in complex fluids



"rheology is the study of deformations and flows of matter."

<u>Bingham</u>: "Were you, a civil engineer, and I, a chemist, are working together at joint problems. With the development of colloid chemistry, such a situation will be more and more common. We therefore must establish a branch of physics where such problems will be dealt with."

<u>Reiner</u>: "This branch of physics already exists; it is called mechanics of continuous media, or mechanics of continua."
<u>Bingham</u>: "No, this will not do, such a designation will frighten away the chemists."

Reiner, M. (1964), *Physics Today* **17**, 62.

Shear-banding in complex fluids

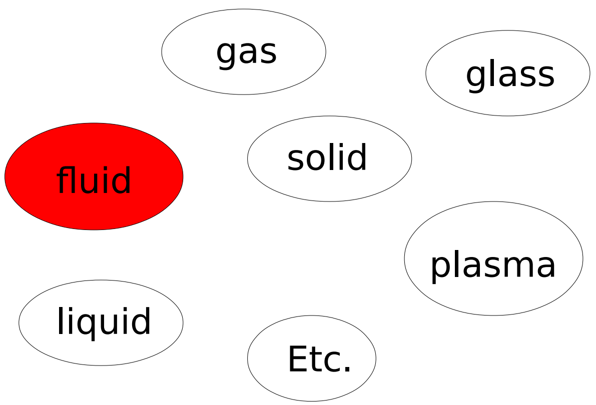
- The Deborah number De = time of relaxation / time of observation

$$De = \tau/t$$

παντα ρει!
Everything flows!

"**Solid** is the state in which matter *maintains* a fixed volume and shape;
liquid is the state in which matter *maintains* a fixed volume but *adapts* to the shape of its container;
and **gas** is the state in which matter *expands* to occupy whatever volume is available"

[From wikipedia: "state of matter"]



$$De = \tau/t \longrightarrow 0,\ \text{more fluid}$$

$$De = \tau/t \longrightarrow \infty,\ \text{more solid}$$

"Everything flows and nothing abides;
everything gives way and nothing stays fixed."

Reiner, M. (1964), *Physics Today* **17**, 62.

Shear-banding in complex fluids

- The Deborah number   De = time of relaxation / time of observation

$$De = \tau/t$$

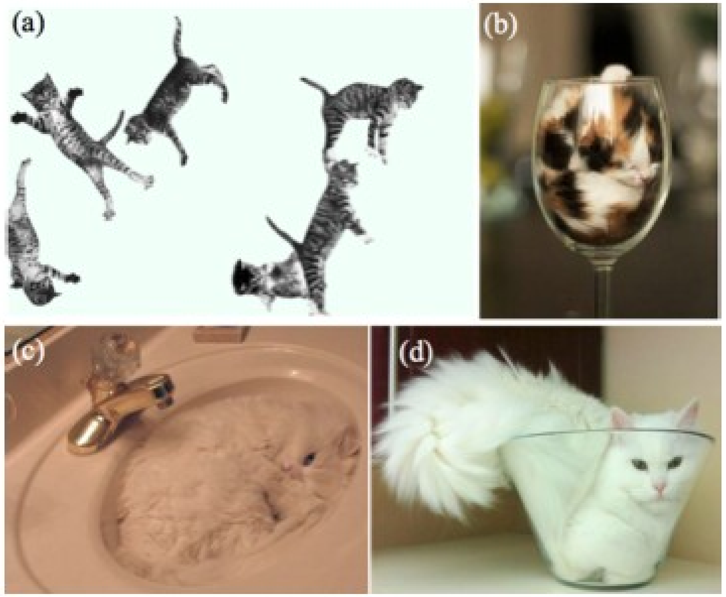
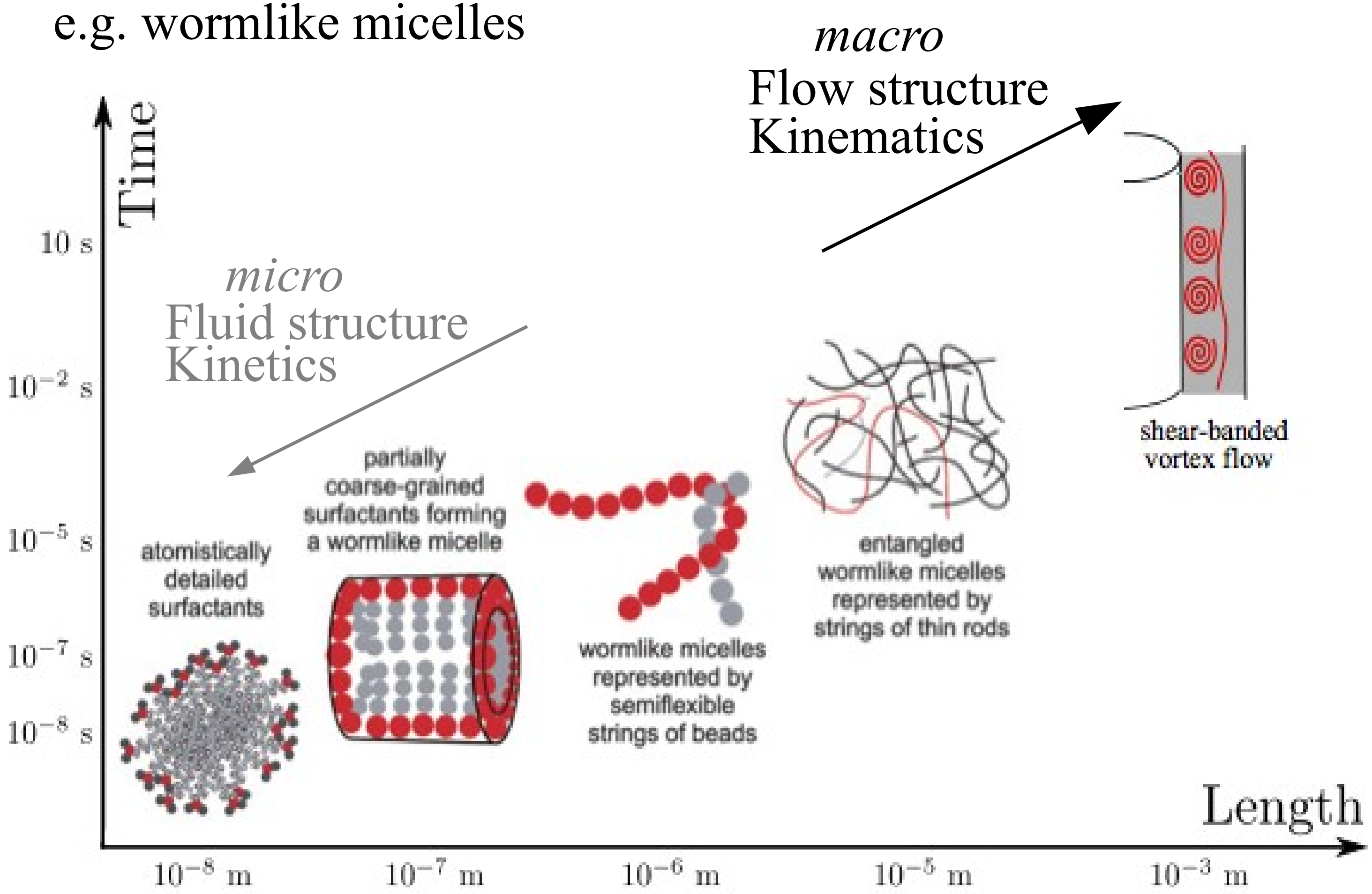


FIG. 1: (a) A cat appears as a solid material with a consistent shape rotating and bouncing, like Silly Putty on short time scales. We have $De \gg 1$ because the time of observation is under a second. (b) At longer time scales, a cat flows and fills an empty wine glass. In this case we have $De \ll 1$. In both cases, even if the samples are different, we can estimate the relaxation time to be in the range $\tau = 1$ s to 1 min. (c-d) For older cats, we can also introduce a characteristic time of expansion and distinguish between liquid (c) and gaseous (d) feline states.

M.A. Fardin, *On the Rheology of Cats* (2014?)

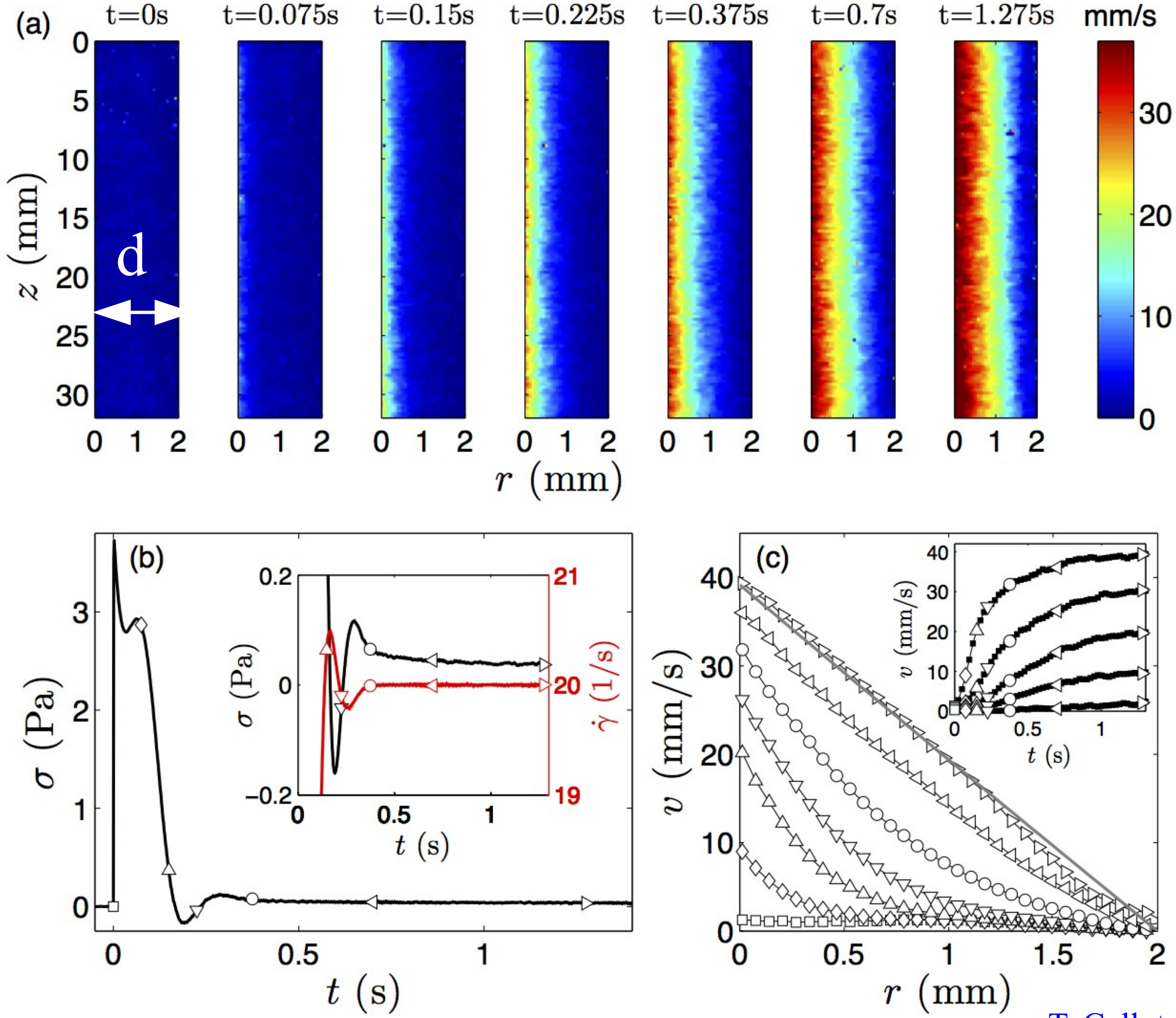
Shear-banding in complex fluids

e.g. wormlike micelles



M.A.. Fardin and S. Lerouge, Highlight for *Soft Matter* (to be published – 2014)
M.A. Fardin and S. Lerouge, *EPJE* 2012
S. Lerouge and J.F. Berret, *Adv. Polym. Sci.* **230**, 1 (2010)
J. T. Padding et al., *Soft Matter* **5**, 4367–4375 (2009)

What it is not (?) : shear start-up in liquid water [$\dot{\gamma} = 20\ \mathrm{s}^{-1}$]



$$\tau = d^2/\nu = \rho d^2/\eta$$

$\tau \approx 1$ s

De ≤ 1 : unsteady
De ≥ 1 : steady

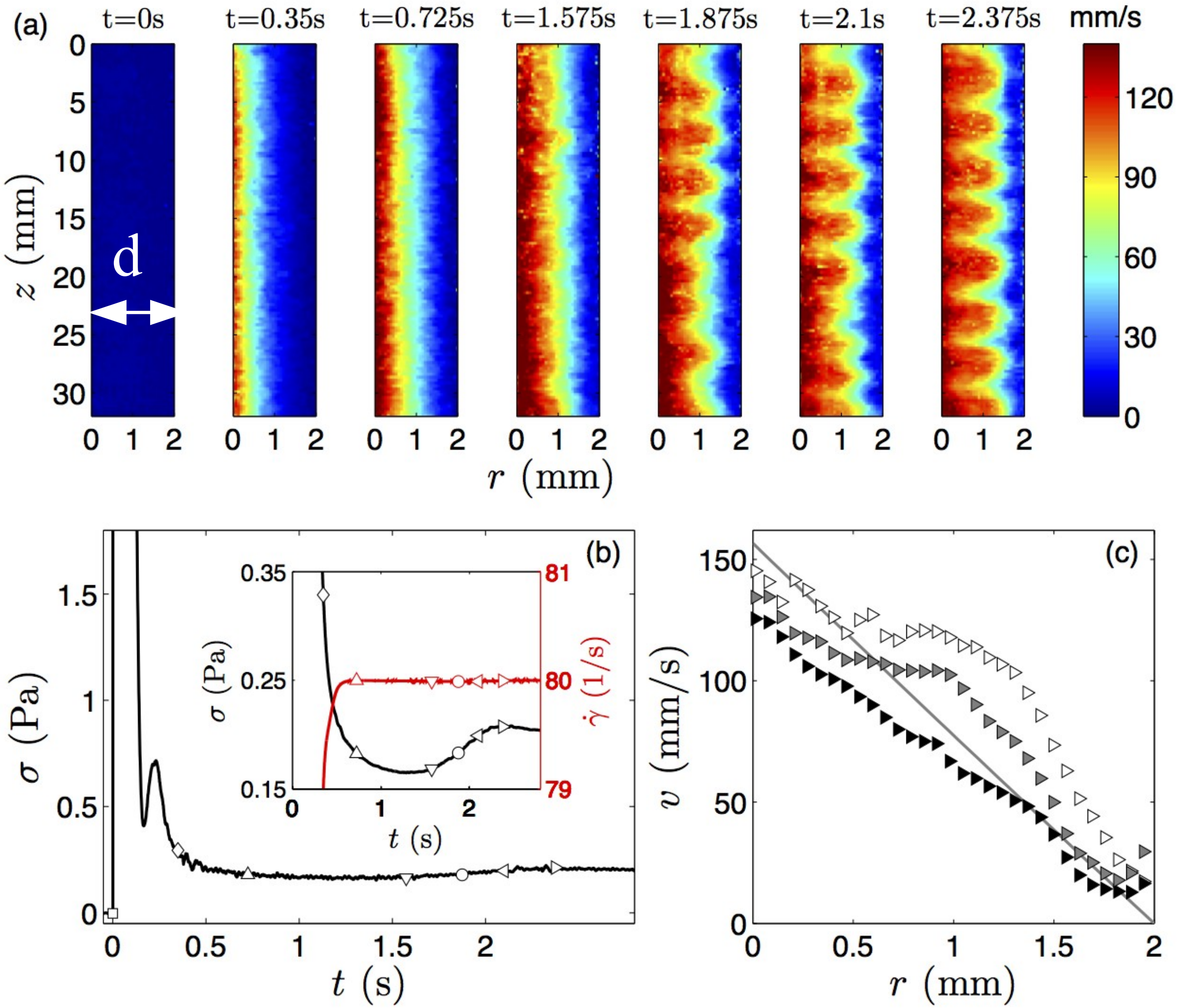
Transient gradient banding?

~~Moorcroft & Fielding, *PRL* (2013)~~

T. Gallot *et al.*, *Rev. Sci. Instrum.* **84**, 045107 (2013)

Shear-banding in complex fluids

What it is not (?) : shear start-up in liquid water [$\dot{\gamma} = 80\ s^{-1}$]



$\tau = d^2/\nu = \rho d^2/\eta$

$\tau \approx 1$ s ?

De does not tell us anything about stability!

Steady vorticity banding??

T. Gallot *et al.*, *Rev. Sci. Instrum.* (2013)

Shear-banding in complex fluids

Deborah number

$$De_i \equiv \tau_i / T$$

Reynolds number

$$Re \equiv \tau_i \dot{\gamma}$$

$$De_i \frac{\partial \vec{v}}{\partial t} + \bar{R}e\,(\vec{v}\nabla)\,\vec{v} = \nabla \cdot \mathbf{\Sigma}$$

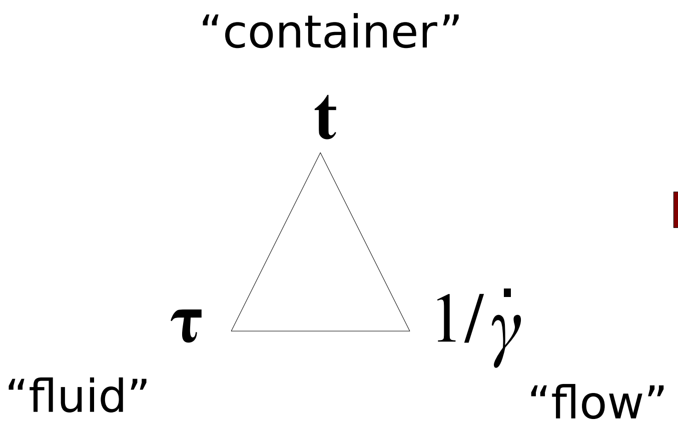
"inertial nonlinearity"

For a simple incompressible fluid, $\tau_i \equiv \dfrac{\rho d^2}{\eta_0}$

We assume that the stress is proportional to the shear-rate.
Shear-thickening is only apparent and is due to *flow instabilities*.
De_i gives us information about the *unsteady/steady* nature of the flow.
Re gives us information about the *stable/unstable* nature of the flow.
We do not speak of shear-banding but of *boundary layer dynamics* etc.

Shear-localization in matter

Simple fluids	*Soft matter*
Shear localization "due to" - Boundary layers dynamics - Hydrodynamic instabilities - No mesoscopic picture	Shear localization "due to" - Shear-banding "instability" - No flow instabilities because Re ~ 0... - Some mesoscopic pictures



If no yield stress

Steadiness number

$$S_1 \equiv \tau/t$$

Stability number

$$S_2 \equiv \tau\,\dot{\gamma}$$

If yield stress

Rather use:

Deformation

$$S_2/S_1 \equiv \gamma$$

+ S_1 w S_2

Reynolds number

$$Re \equiv \tau_i \, \dot{\gamma}$$

$$\tau_i \equiv \frac{\rho d^2}{2\eta_0}$$

If no yield stress

Weissenberg number

$$Wi \equiv \tau_e \, \dot{\gamma}$$

$$De_i \, \frac{\partial \vec{v}}{\partial t} + \bar{Re} \, \underbrace{(\vec{v}\nabla)\vec{v}}_{\text{“inertial nonlinearity”}} = \nabla \cdot \mathbf{\Sigma}$$

$$De \frac{\partial \mathbf{\Sigma}}{\partial t} + \bar{Wi}\left(\underbrace{\vec{v}\cdot\nabla\mathbf{\Sigma} - (\nabla\vec{v})^t\cdot\mathbf{\Sigma} - \mathbf{\Sigma}\cdot\nabla\vec{v}}_{\text{“viscoelastic nonlinearities”}}\right) = \nabla\vec{v} + (\nabla\vec{v})^t - \mathbf{\Sigma}$$

laminar flow — ~1-10 — non-trivial coherent flow — turbulent flow → $S_2 = f(Re, Wi)$

Purely inertial limit: $Wi = 0$, so $S_2 = Re$

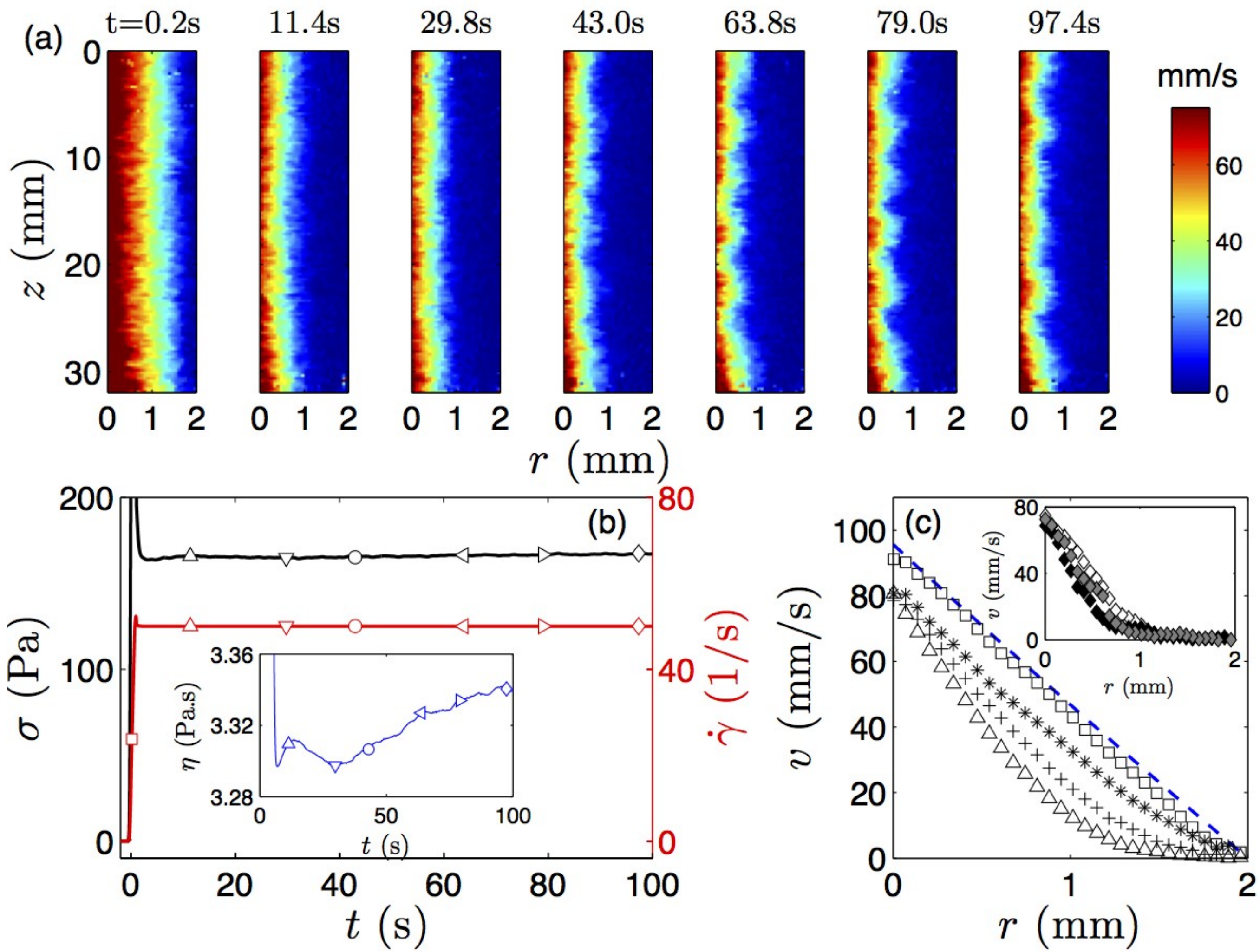
Purely elastic limit: $Re = 0$, so $S_2 = Wi$

with $S_1 \rightarrow 0$

For a review see A.N. Morozov and W.van Saarloos, *Physics Reports* (2007)

Shear-localization and flow instabilities

Polymers and living polymers; e.g. entangled micelles.



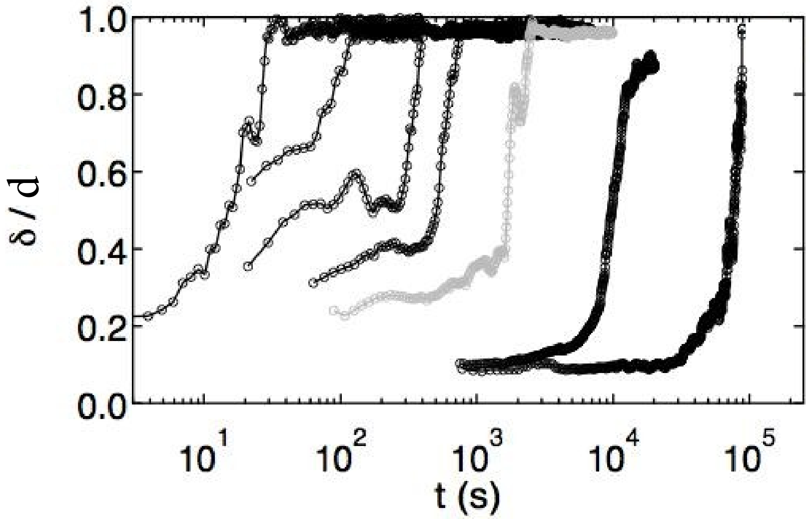
Now well understood if:

$$S_2 = Wi \quad (\text{if } Re \to 0)$$
$$S_1 \to 0$$

Perspectives...

Search papers by M.A. Fardin *et al*....

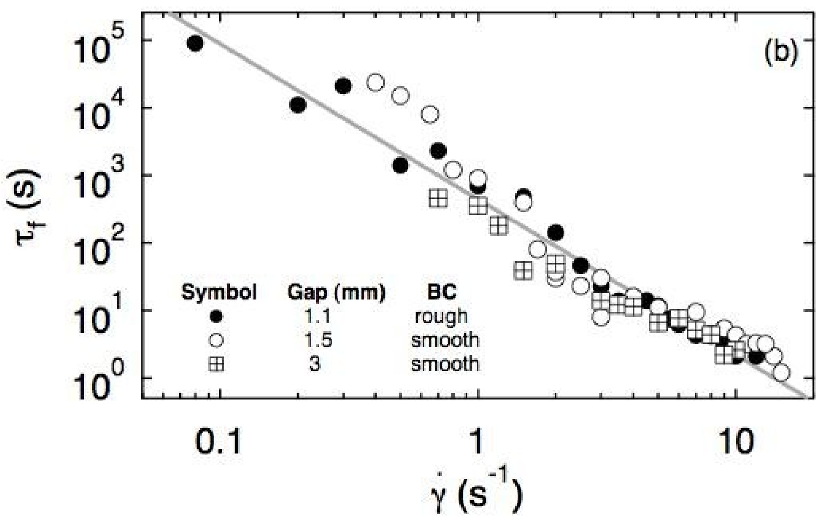
Transient shear-localization and yielding

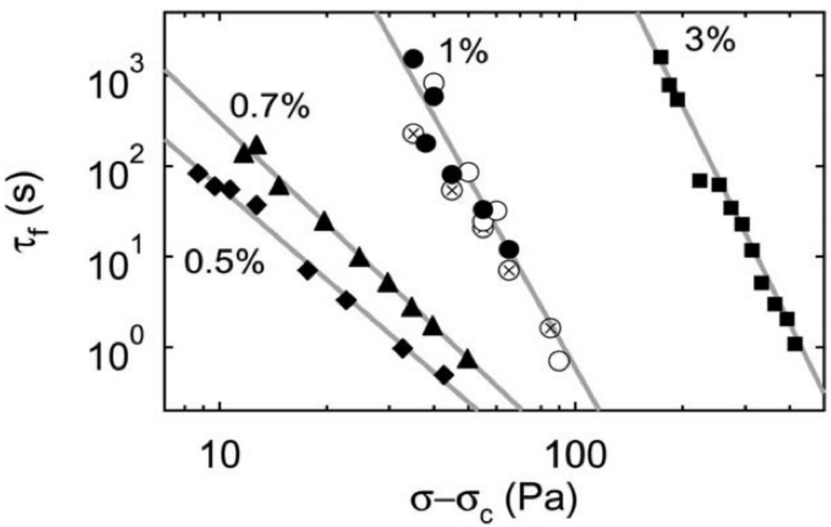


$S_2/S_1 = \gamma$

$S_1 = f(\sigma,\dot{\gamma})$

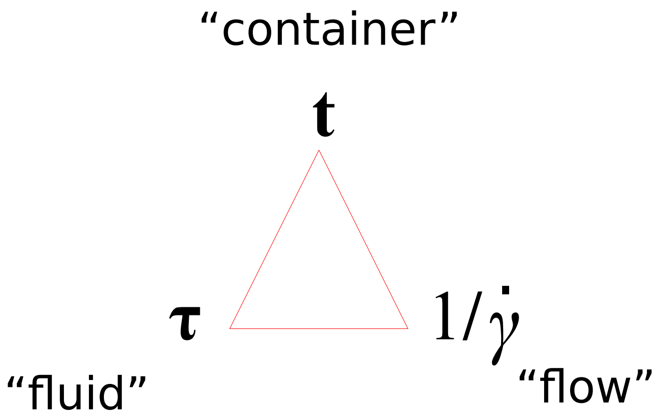
Perspectives...





Search papers by T. Divoux *et al.*...

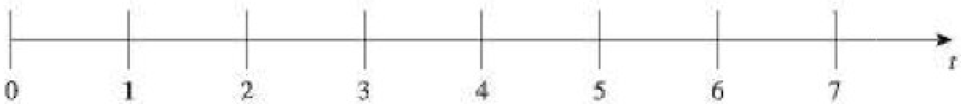
If yield stress



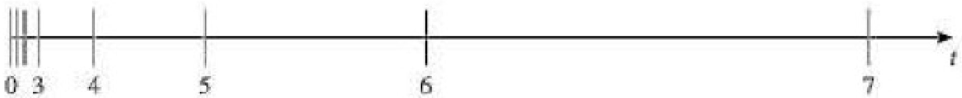
$$\tau = f(\dot{\gamma})$$

Or non-Newtonian **t** measure ?

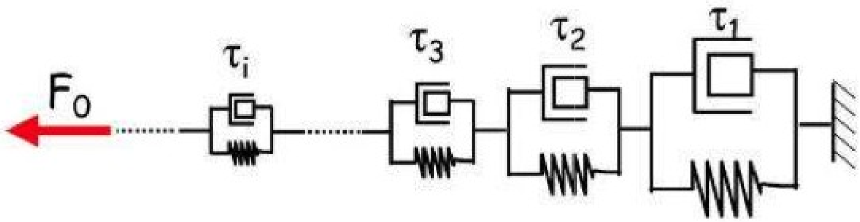
<u>Fractional Calculus</u>



$\xrightarrow{\text{CG}}$ regular continuum $\mathbf{T}^{\mathbb{Z}}$



$\xrightarrow{\text{CG}}$ fractional continuum $\mathbf{T}^{\mathbb{R}}$



- Anomalous diffusion
- Stretched exponential relaxation
- Power law modulus
- Spectrum of relaxation times
- Yielding? (ongoing)

For an introduction see A. Jaishankar, *Fractional Constitutive Equations and the Rheology of Multiscale Materials* (2014)
And McKinley Group webpage: summer readings 2010.

Reviews

How the discovery of flow instabilities in micelles rationalized “rheochaos”:
S. Lerouge and J.F. Berret, *Adv. Polym. Sci.* **230**, 1 (2010)

How to adapt the phenomenology of viscoelastic instability to shear-banded flows of micelles:
M.A. Fardin and S. Lerouge, *EPJE* **35**, 91 (2012)

Why the “purely mechanical” vs “thermodynamical” debate on shear-banding is outdated:
M.A. Fardin *et al.*, *Soft Matter* **8**, 910 (2012)

Flow instabilities and shear-localization in dilute, entangled and maybe ordered micelles:
C. Perge, M.A. Fardin and S. Manneville, *EPJE* **37**, *23* (2014)

How results in Taylor-Couette flow tell us about many other types of flows:
M.A. Fardin, C. Perge and N. Taberlet, *Soft Matter* **10**, *3523* (2014)

The hydrodynamic vs structural perspectives on micellar flows:
M.A. Fardin and S. Lerouge, *Soft Matter* – under review (2014)

In 2015 → 2x Rev. Mod. Phys.
- One on flow instabilities in complex fluids (Fardin, McKinley, Lerouge)
- One on yield stress fluids (Divoux, Manneville, Berthier, Bonn, Denn)