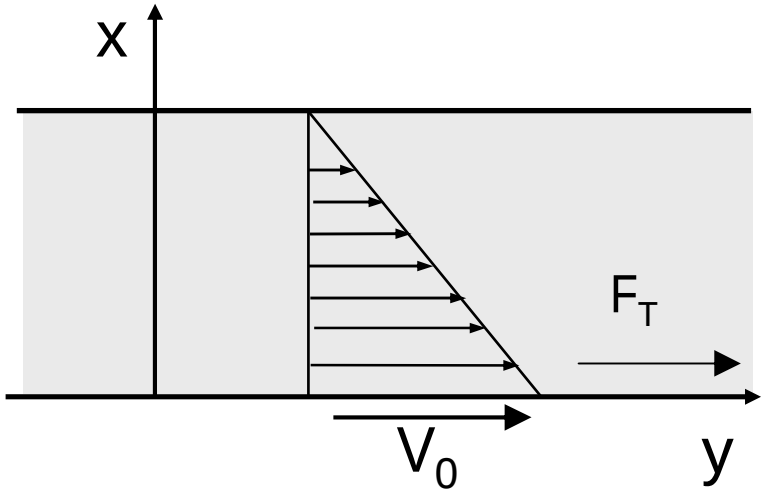
Fluid avalanches: from hairgel to quicksand and landslides

Daniel Bonn
(LPS de l'ENS-Paris and WZI-Amsterdam)

with:
N . Huang, J. Meunier (ENS)
E. Khaldoun, S. Jabbari, E. Eiser, G. Wegdam (WZI-Amsterdam)
P. Coussot, G. Ovarlez, F. Bertrand (LCPC, Paris)

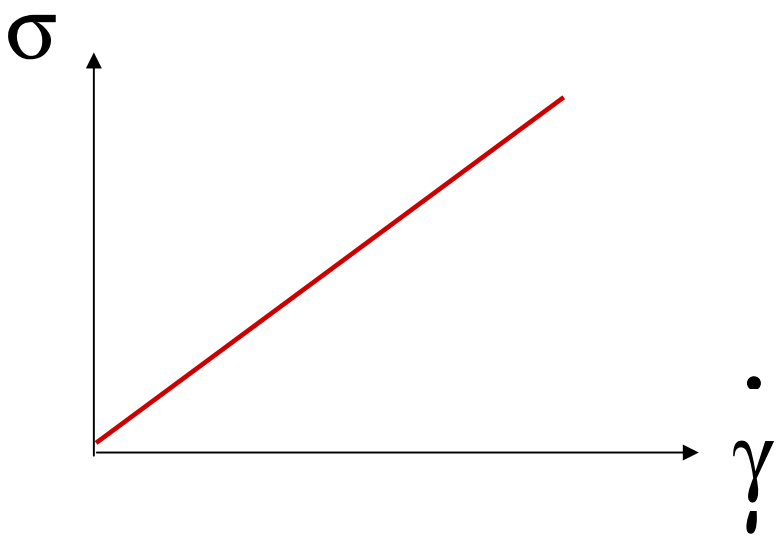
Viscosity



- Stress : $\sigma_{xy} = \frac{F_T}{A}$
- shear rate : $\dot{\gamma} = \frac{\partial v_y}{\partial x}$
- Viscosity : $\eta = \frac{\sigma}{\dot{\gamma}}$

viscosity

$$\eta = \frac{\sigma}{\dot{\gamma}}$$



“Yield stress fluids”

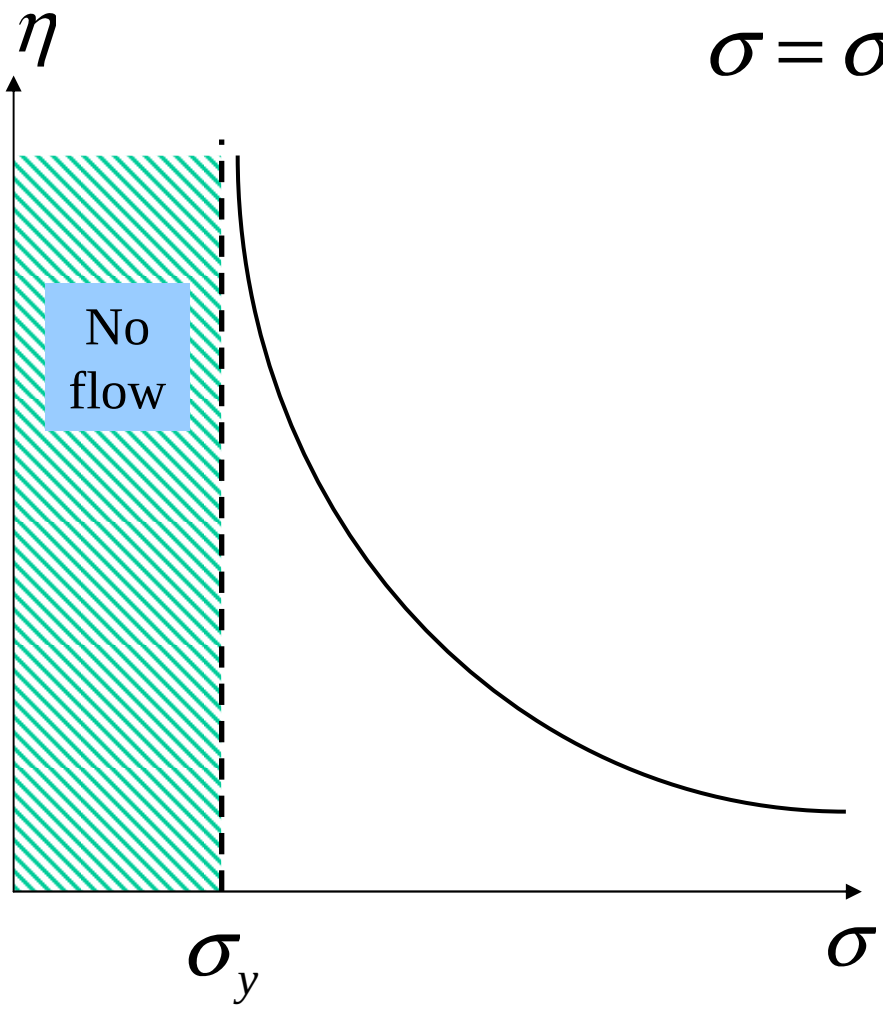
-in your refrigerator: mayonnaise, ketchup, yoghurt, whipped cream…
-in your bathroom: beauty creams, hairgel, shaving foam…
-in civil engineering: (wet) sand, concrete, cement….
-in geophysisics: sand, quicksand, quick clay…

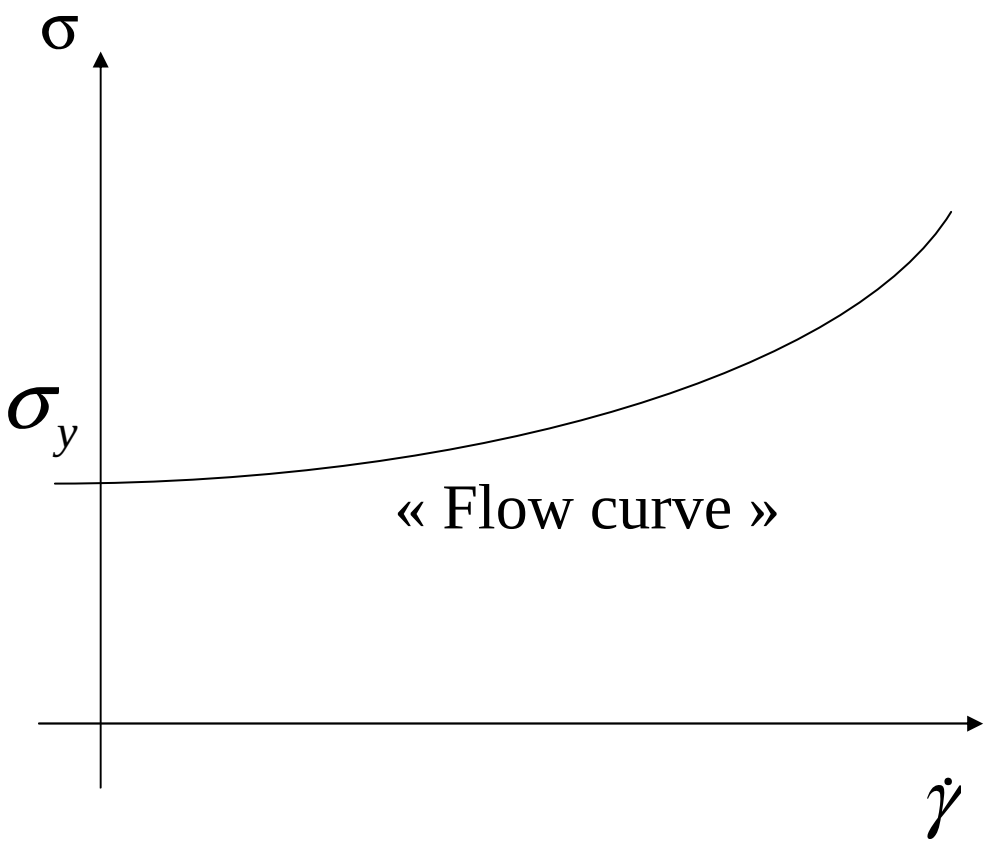
Liquid and solid at the same time!

Yield stress fluids

Simple yield stress fluids: Herschel-Bulkley model

$$\sigma = \sigma_y + k\dot{\gamma}^n$$





Yield stress, thixotropy and aging

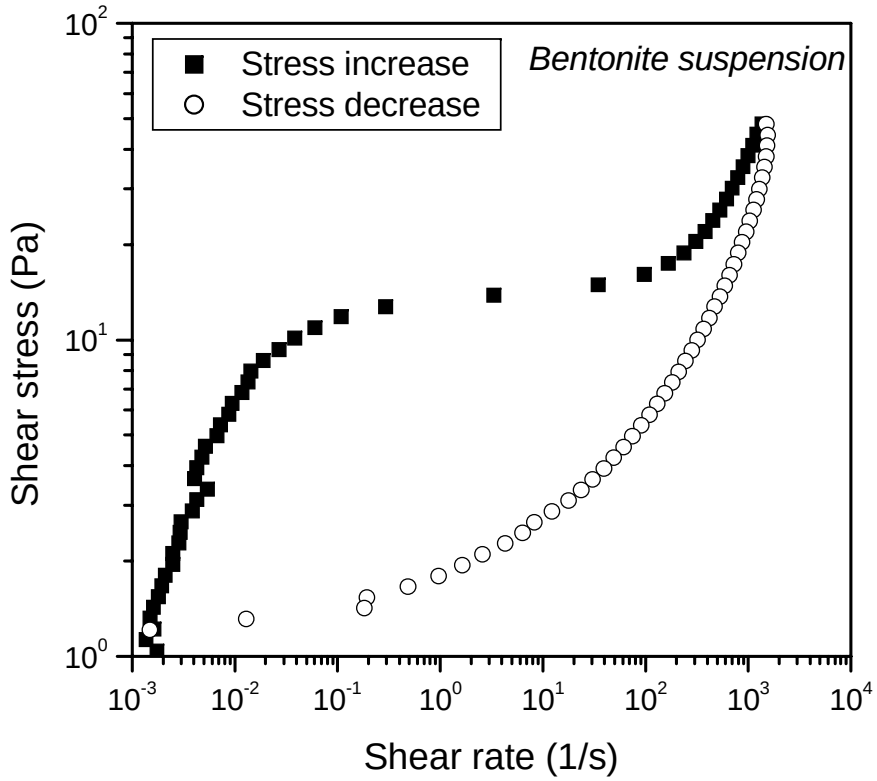
Two **HUGE** problems:

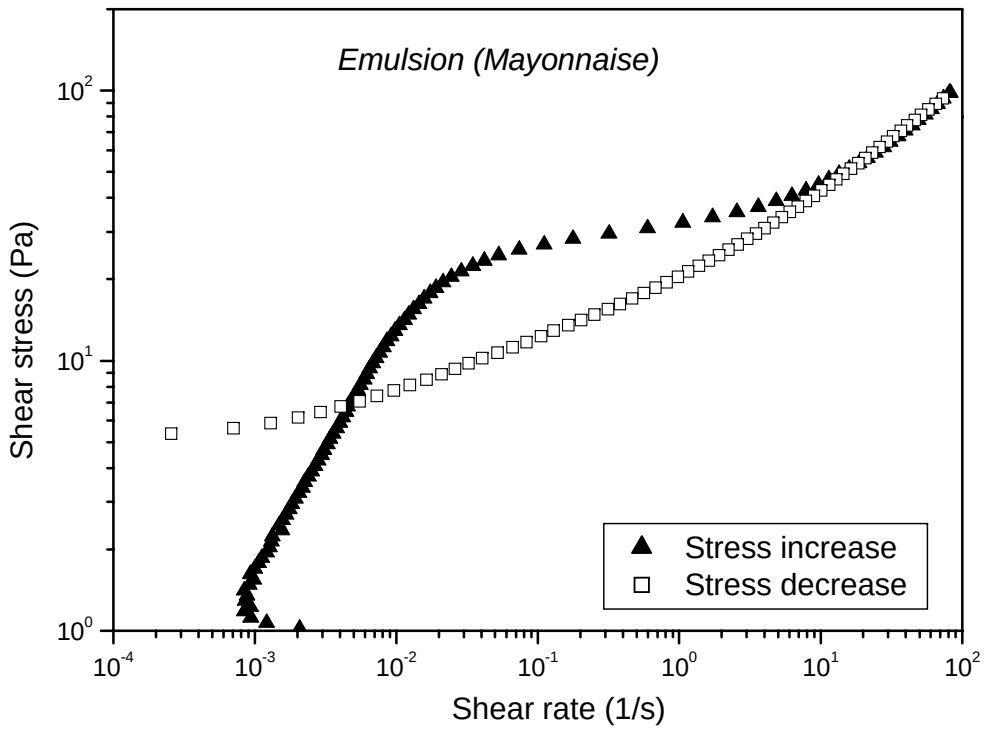
1. Yield stress is difficult, if not impossible to measure experimentally (‘παντα ρει’)
2. Herschel-Bulkley model does NOT account for shear localization (shear banding)

1. Measurement of the yield stress

Bentonite suspension: a typical colloidal clay gel
Mayonnaise: a stable emulsion

Stress loop: increase then decrease
(time on the order of 2 min.) for
different pasty or granular materials



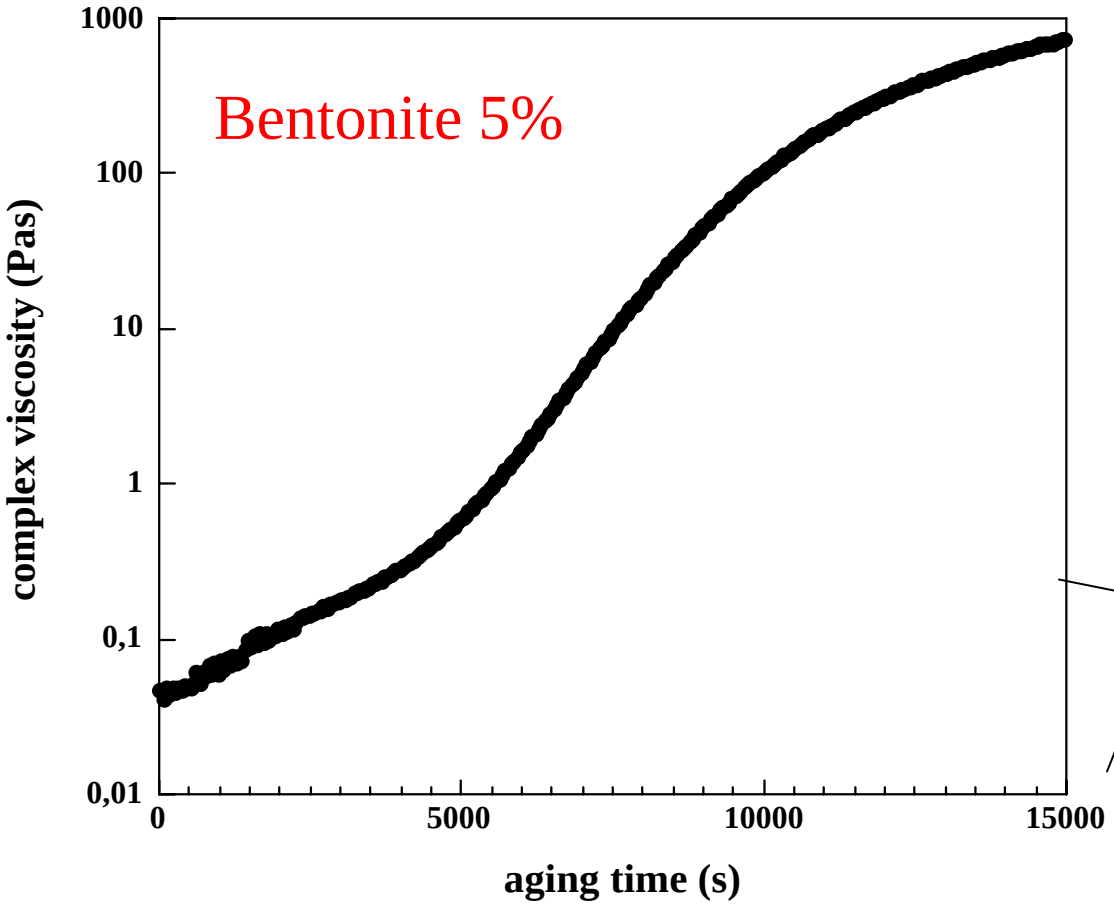


2. Shear localization (banding)

QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.

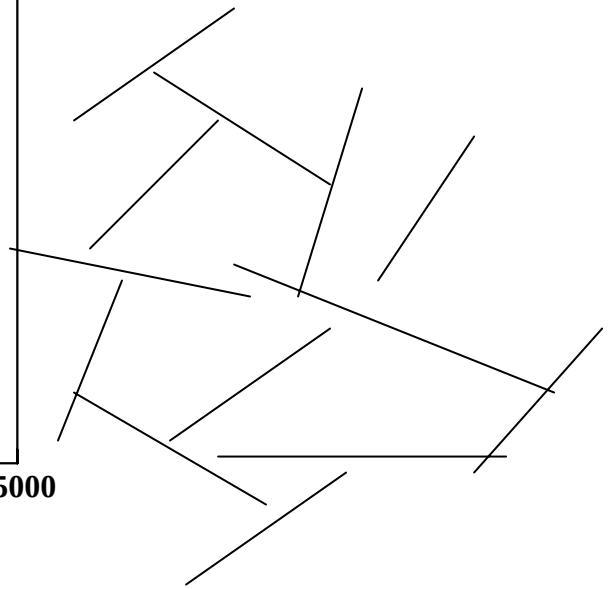
A first important clue: aging

Aging: increase of the viscosity at rest, and at zero (or very low) shear



clay gel

“house of cards” structure

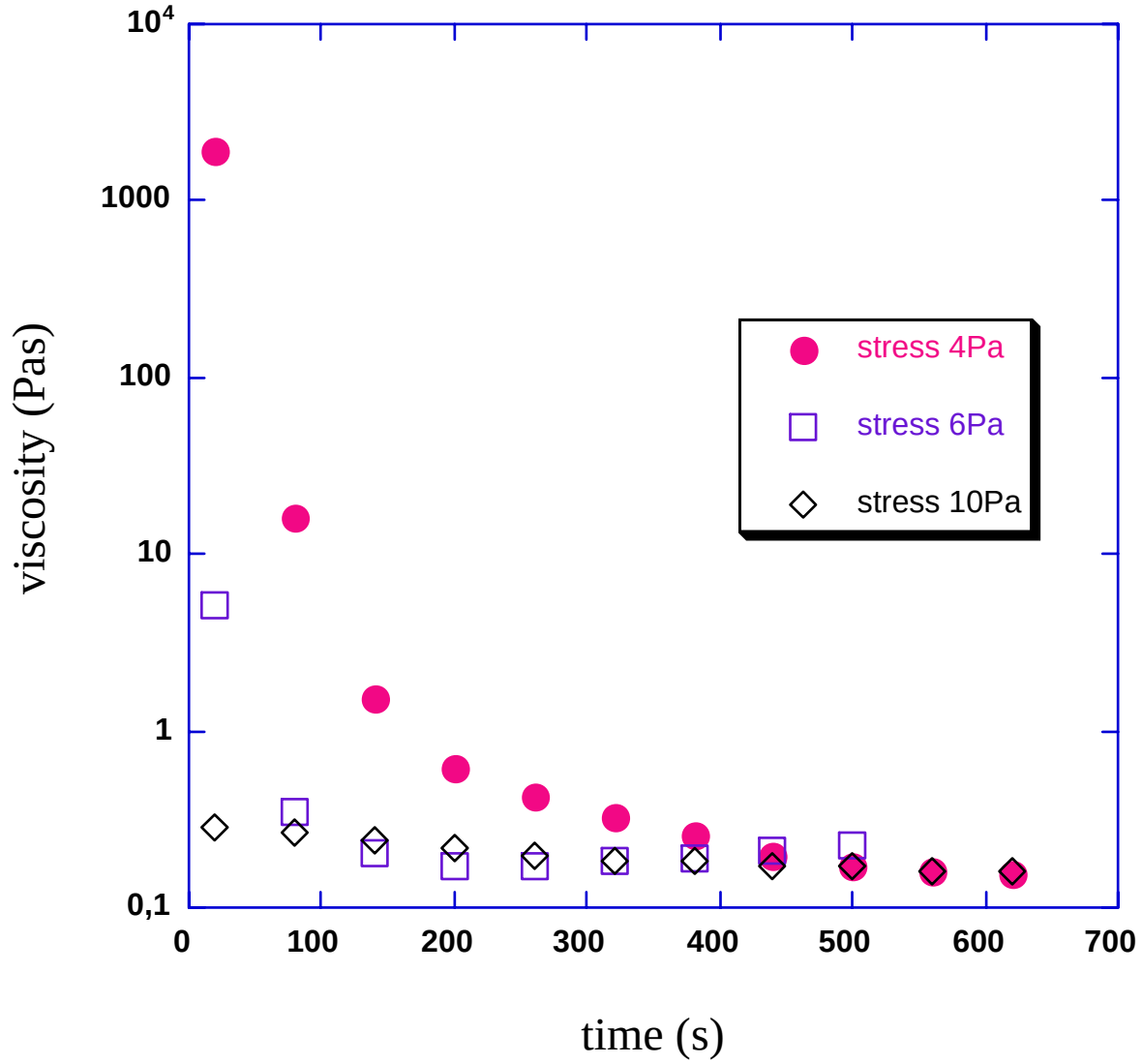


Can aging be reversed by shear?

aging

rejuvenation

Second important clue: « shear rejuvenation » («French yoghurt effect)



Abou et al. J. Rheol. 2003

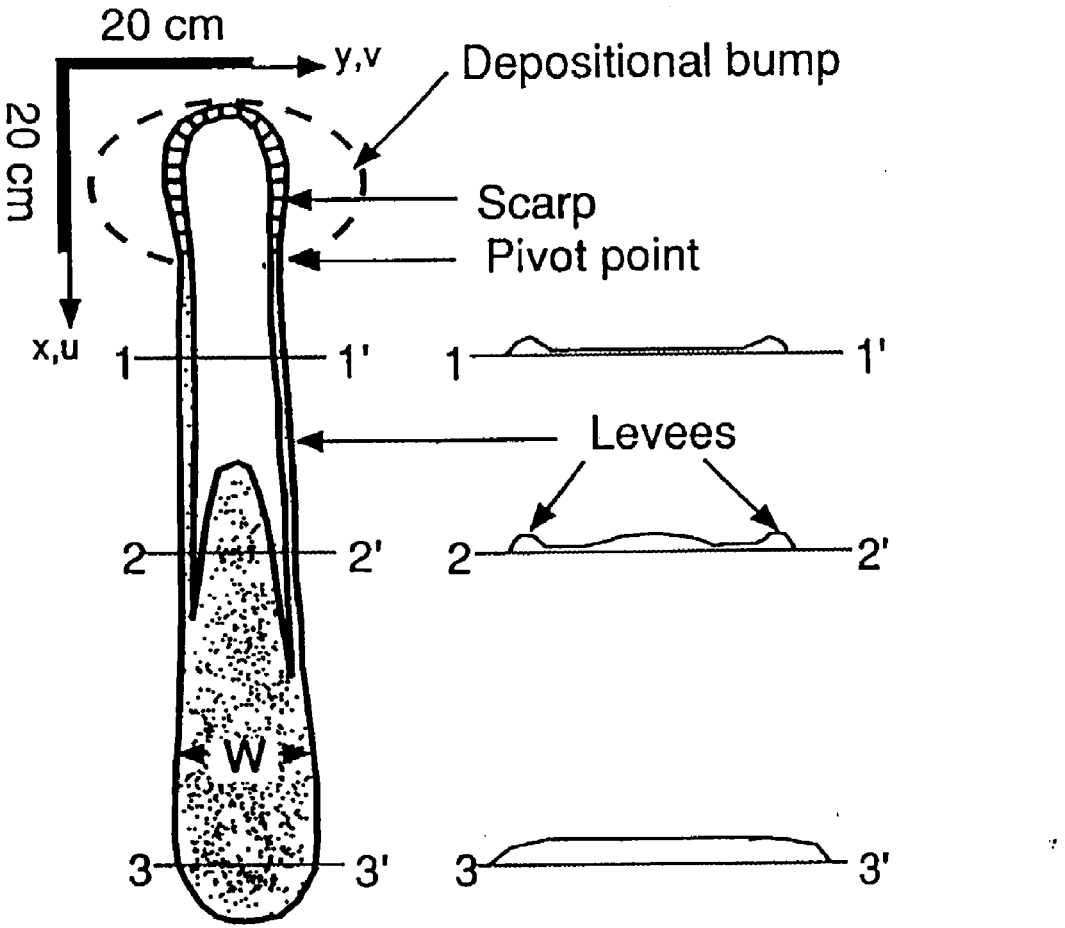
Yield stress, aging and shear rejuvenation

Competition between aging and shear rejuvenation is general for soft materials, and leads to AVALANCHES

Bentonite avalanche on an inclined plane

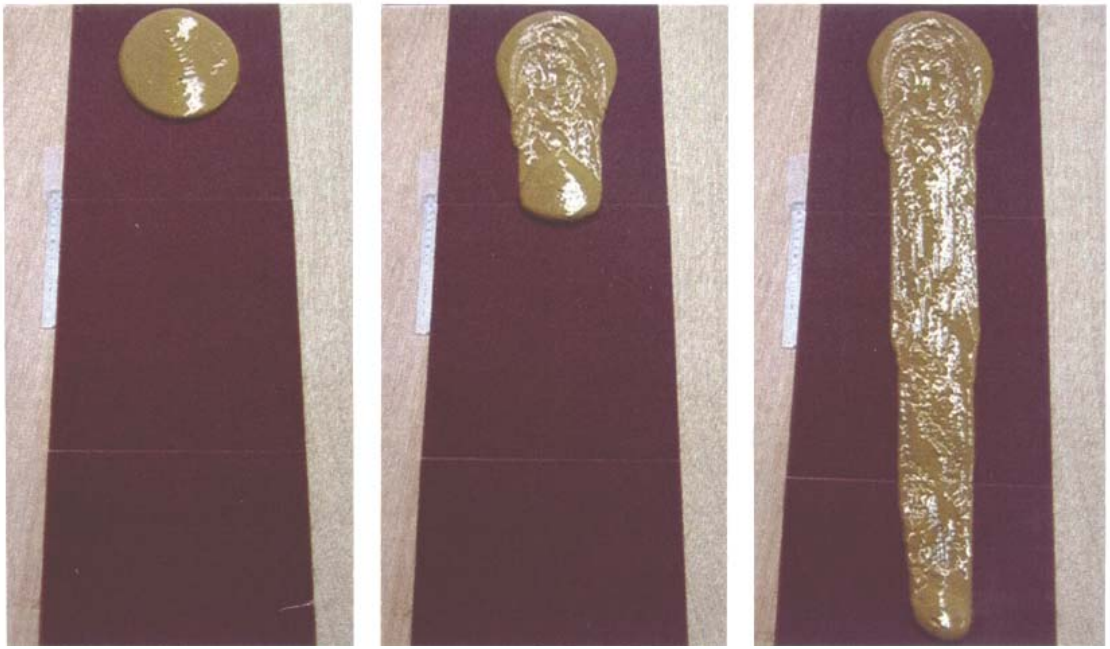
$$\sigma_y = \rho g h \sin(\alpha)$$

Sand avalanches

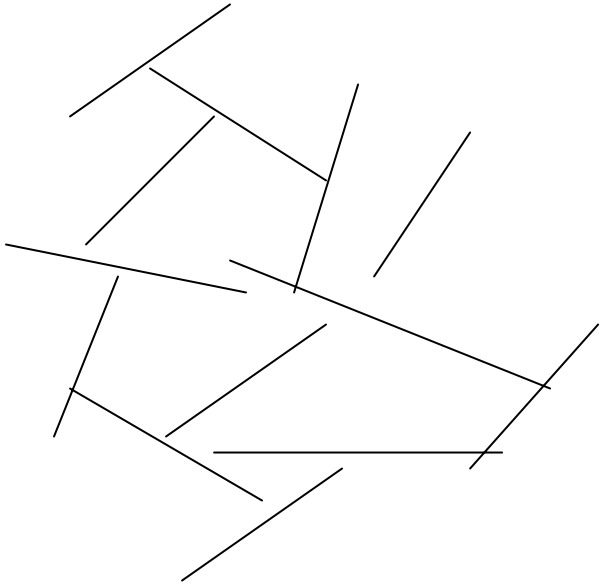


McDonald and Anderson, 1988

Aging/shear rejuvenation of a clay gel

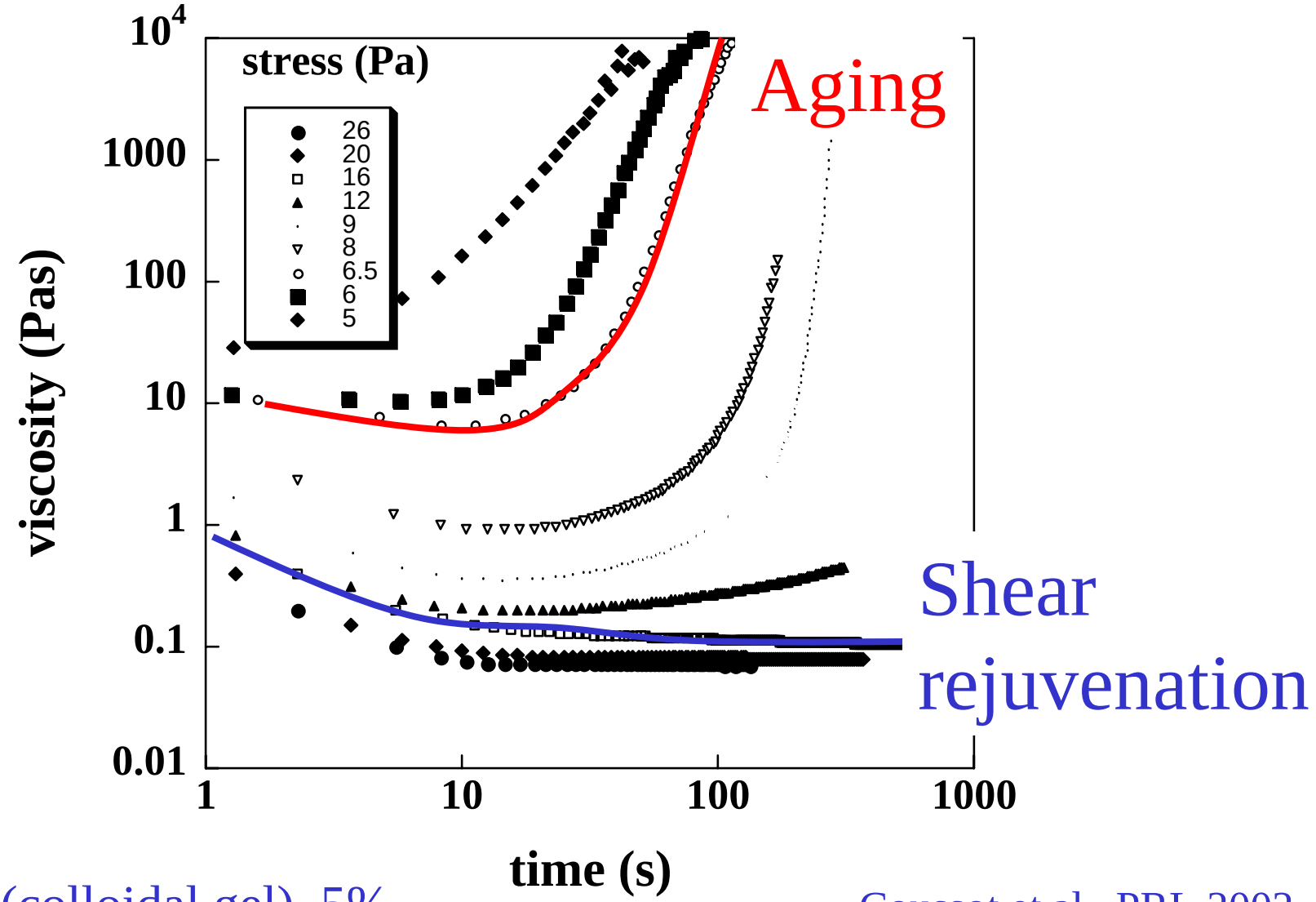


“house of cards” structure



$$E \propto \frac{\text{number of connections}}{\text{volume}} \propto \sigma_c$$

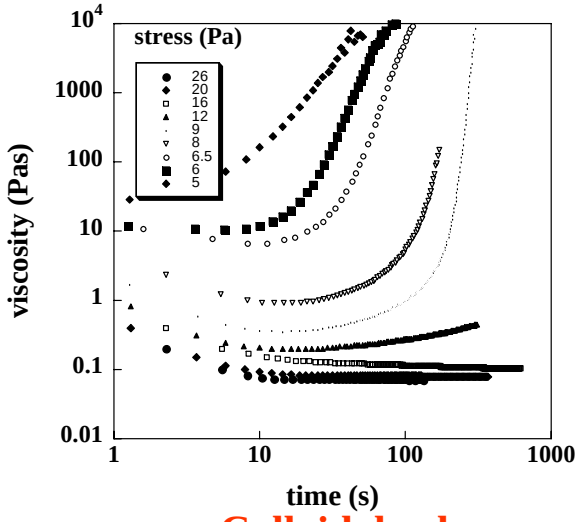
RHEOLOGY: VISCOSITY BIFURCATION



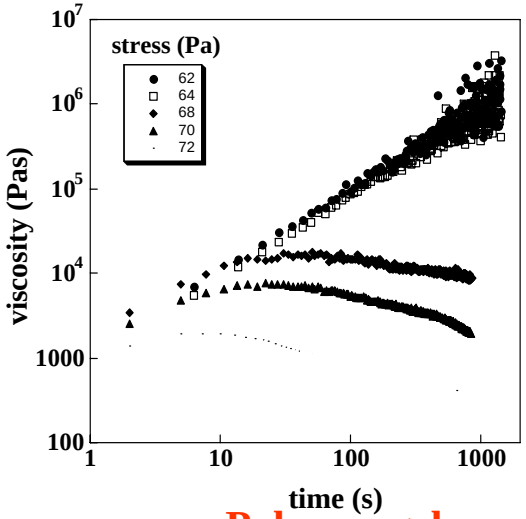
Bentonite (colloidal gel), 5%

Coussot et al., PRL 2002

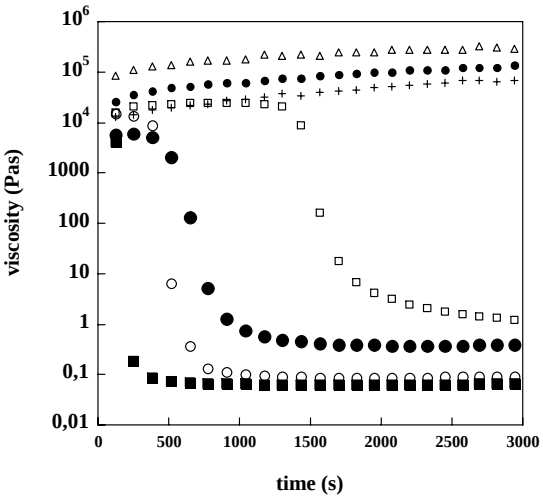
The phenomenon is general!



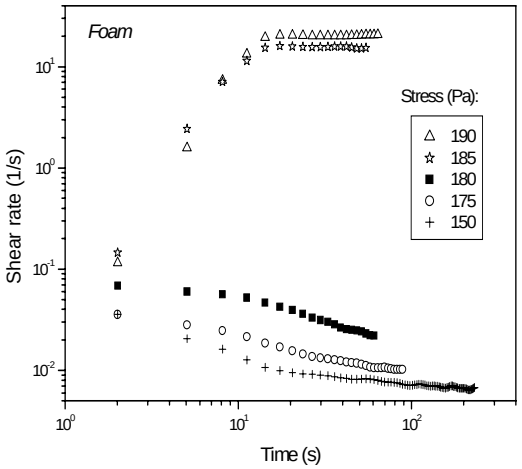
Colloidal gel (Bentonite)



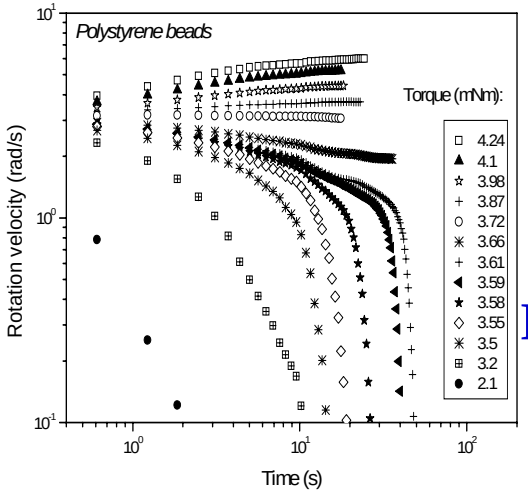
Polymer gel (hairgel)



Colloidal glass (Laponite)



Foam (shaving foam)



Granular matter (polystyrene beads)

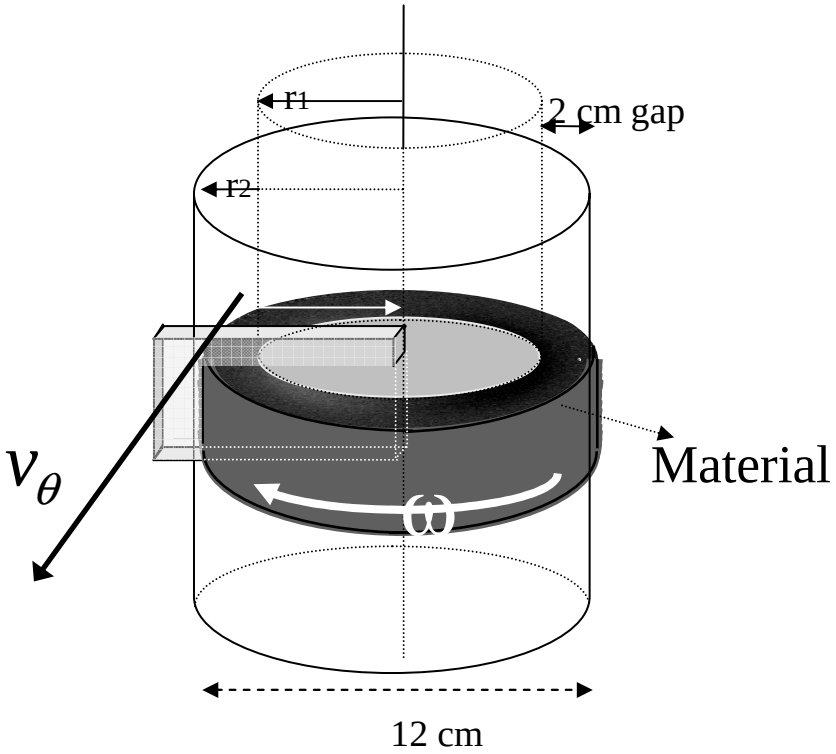
QUESTION: WHAT HAPPENS IF A SHEAR RATE IS IMPOSED THAT IS NOT ACCESSIBLE WHEN FIXING THE STRESS?

Coussot et al., PRL 2002
Da Cruz et al PRE 2003

Vertical MRI, 40cm borehole, 0.5-2.4T

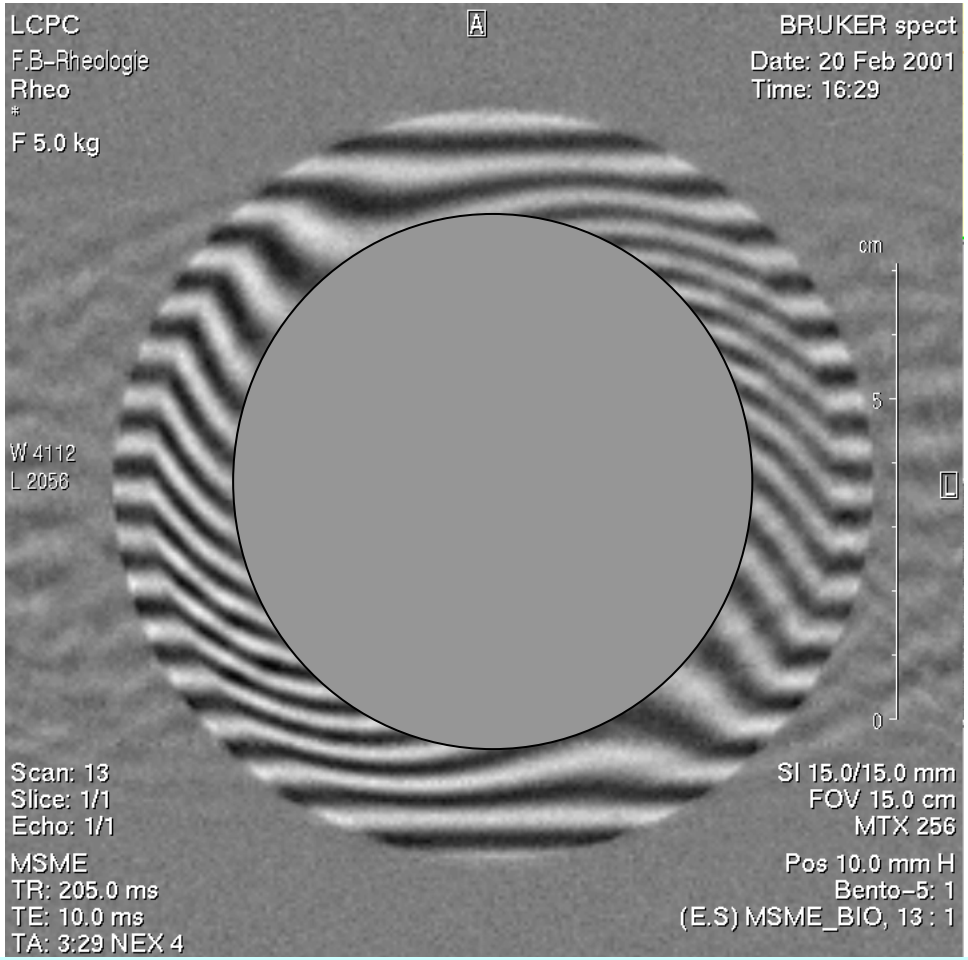
Inserted rheometer

Controlled rotation velocity



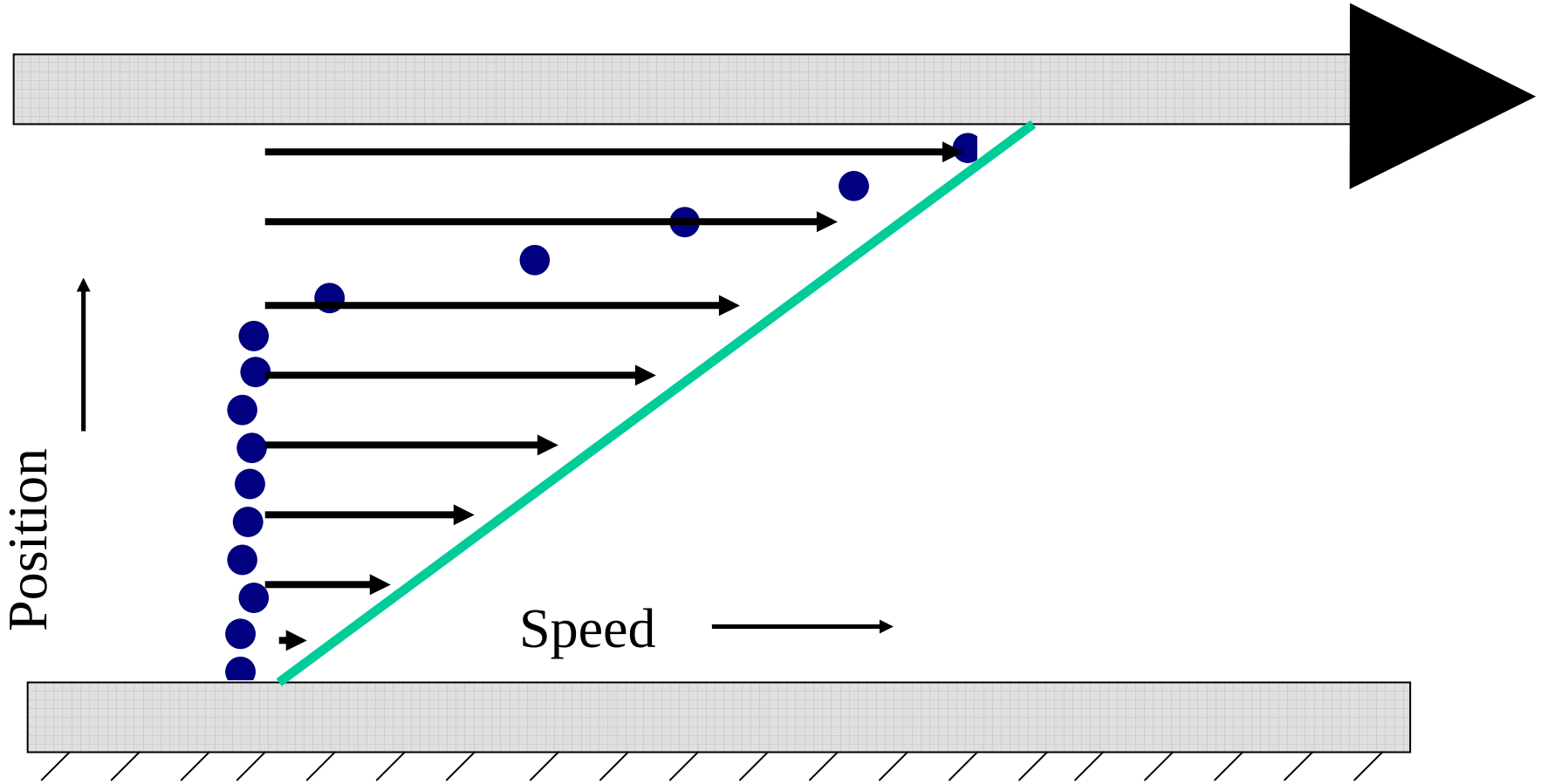
Tangential velocity measured
in a central fluid portion

MRI velocity profile measurement in a Couette cell



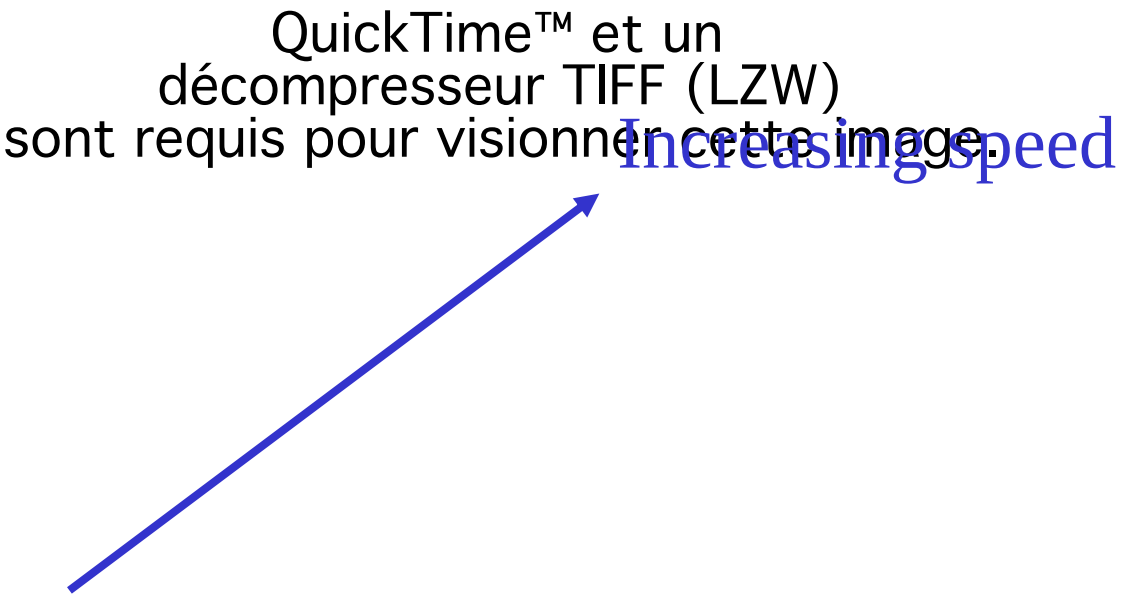
Deformation of fictive lines within the material in a Couette geometry

MRI measurements of the velocity profile
Under imposed shear rate (unstable region)



Competition between aging and shear rejuvenation
naturally leads to the viscosity bifurcation, which
in turn implies SHEAR BANDING!

Velocity profiles: shear localization



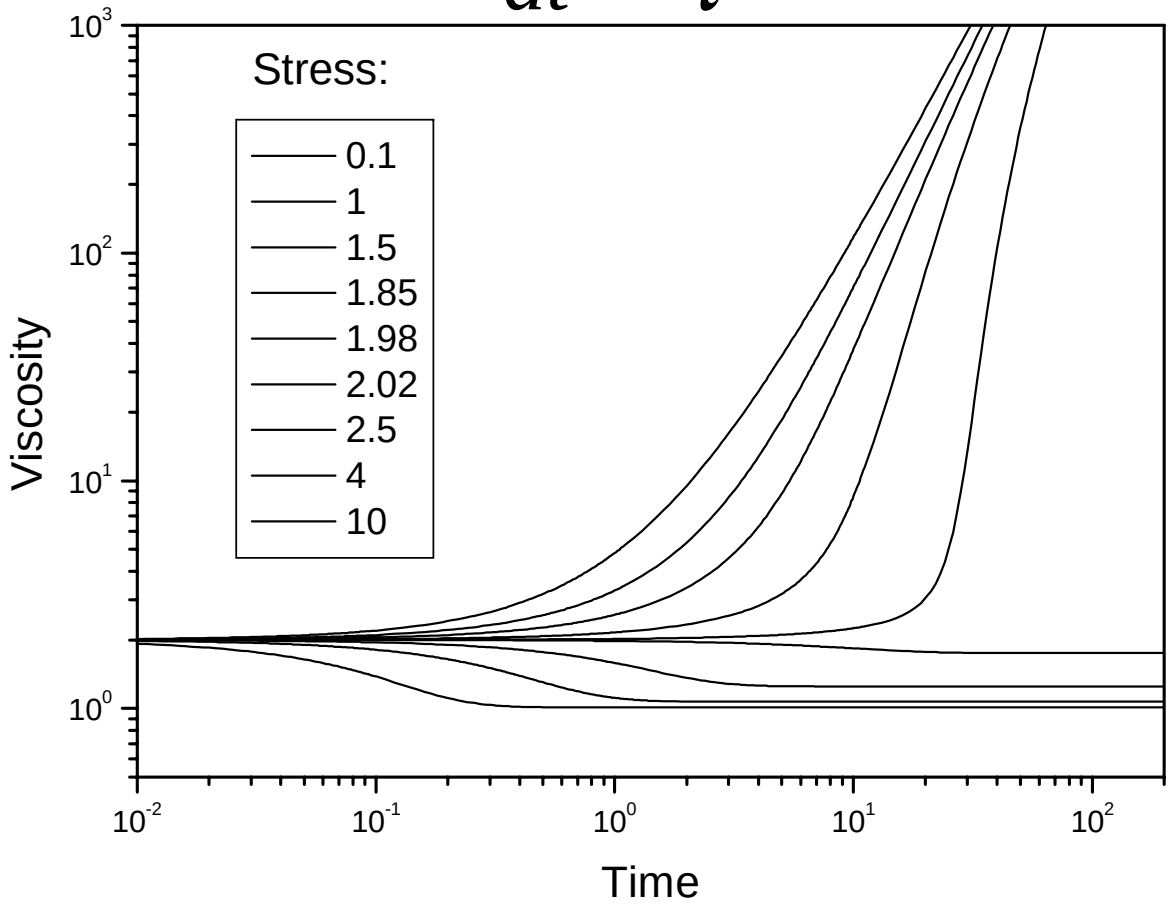
Simplest possible model

Instantaneous state of structure (degree of jamming)

λ e.g. $\eta(\lambda) = \eta_0(1+\lambda^n)$

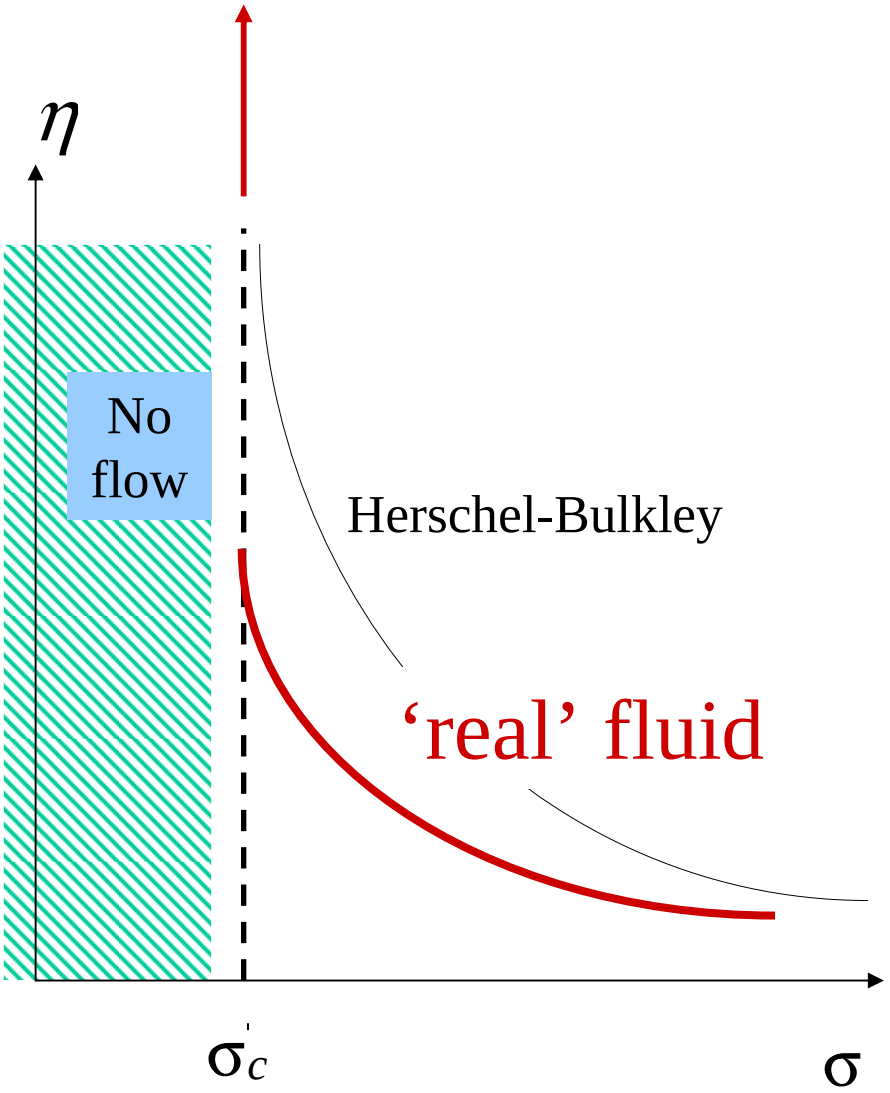
$E \propto \lambda$

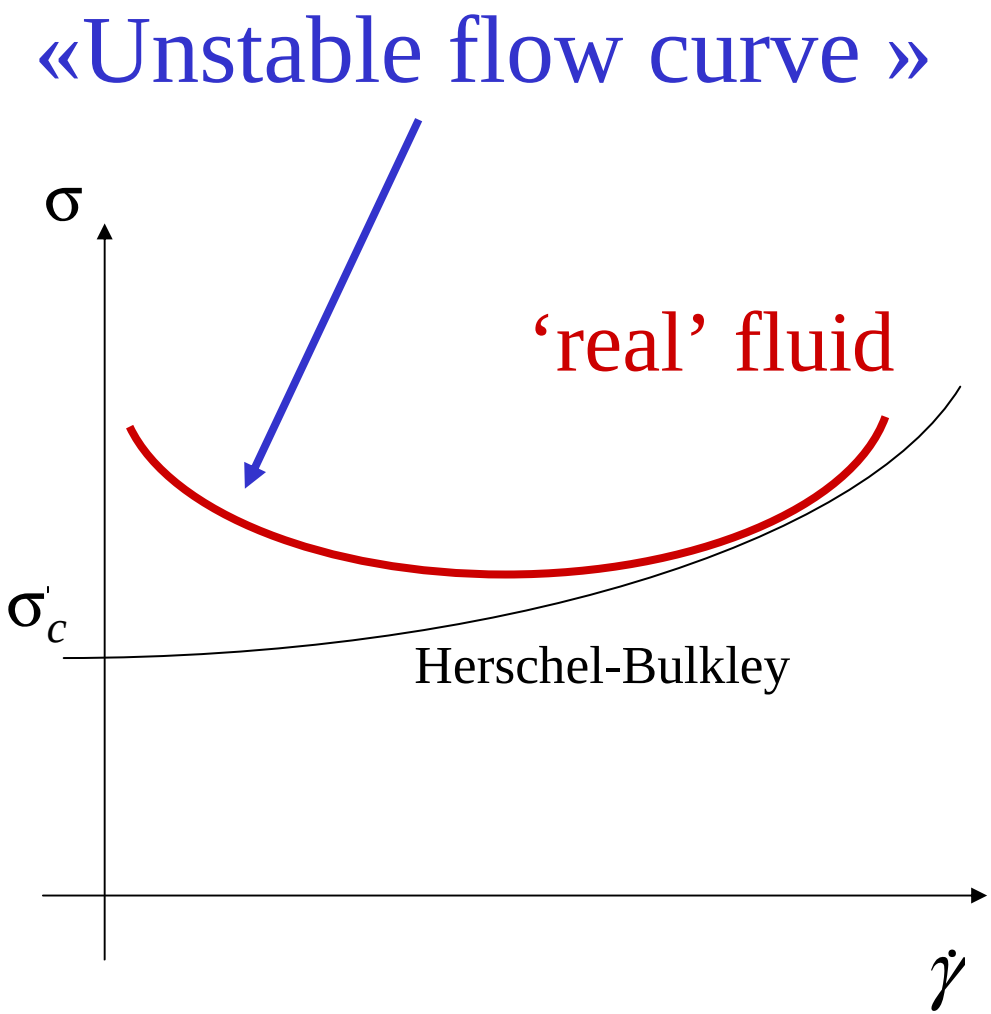
$$\frac{d\lambda}{dt} = \frac{1}{\tau} - \alpha\dot{\gamma}\lambda$$



Coussot et al., PRL 2002
J. Rheol. 2002

Yield stress, shear rejuvenation & aging





Coussot et al., PRL 2002,
J. Rheol. 2002

Applications in geophysics: Quicksand and Quickclay

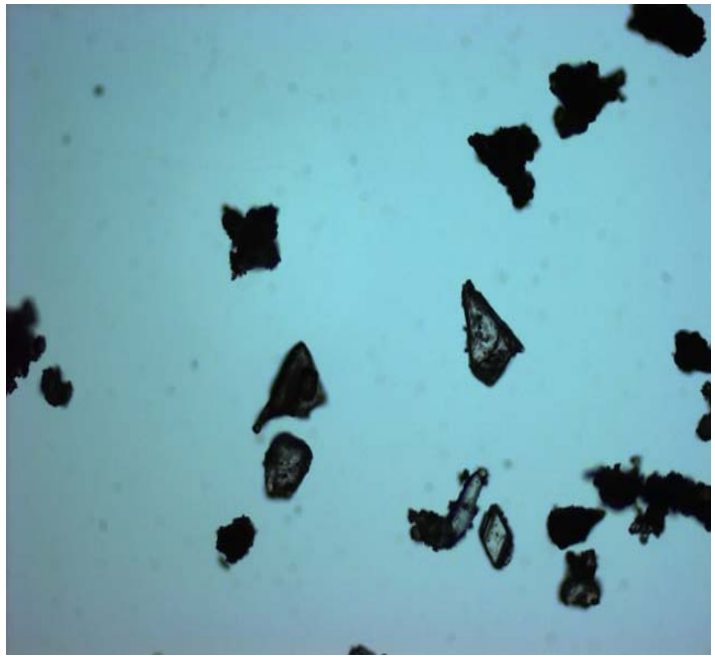
Three Quicksand Myths:

1) once in, don't move
2) once in, hard to get out
3) once in, one drowns

A. Khaldoun, E. Eiser, G. Wegdam, Daniel Bonn
(van der Waals-Zeeman Insitute, University of Amsterdam and LPS, ENS-Paris)

What is quicksand?

Natural quicksand
From Qom-Iran (salt lake)
And Tarfaya-Maroc (close to the sea)
Sand+water + CLAY +SALT

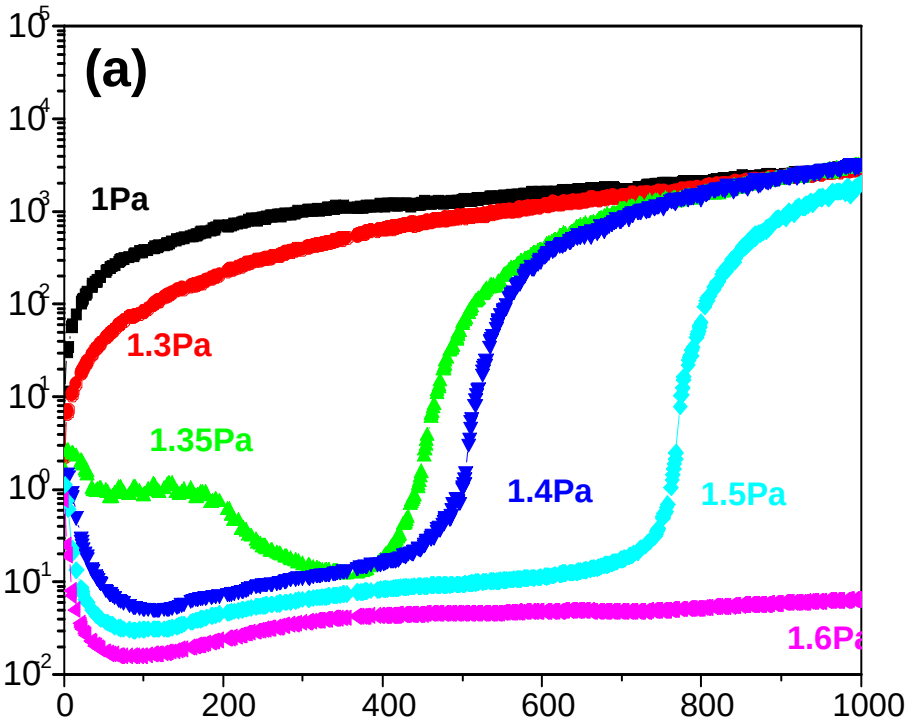


Size of the sand particles 20-50µm

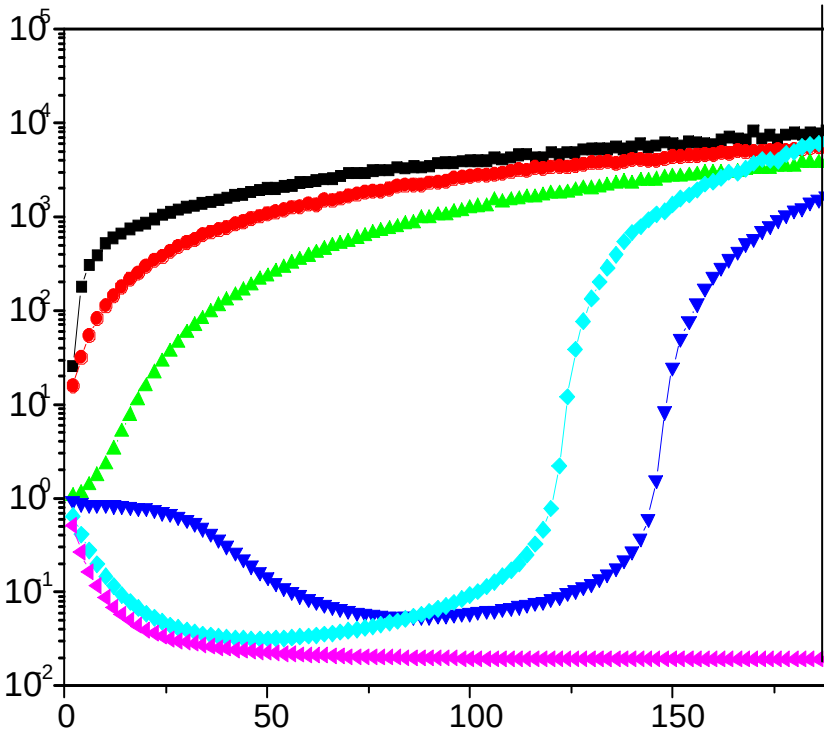
Gypsum	Quartz	Cristobalite	Hematite	Swelling Clays
50%	25%	15%	3%	7 %

Results of X-ray analysis

Rheology of quicksand



salinity 10^{-1} mole/l

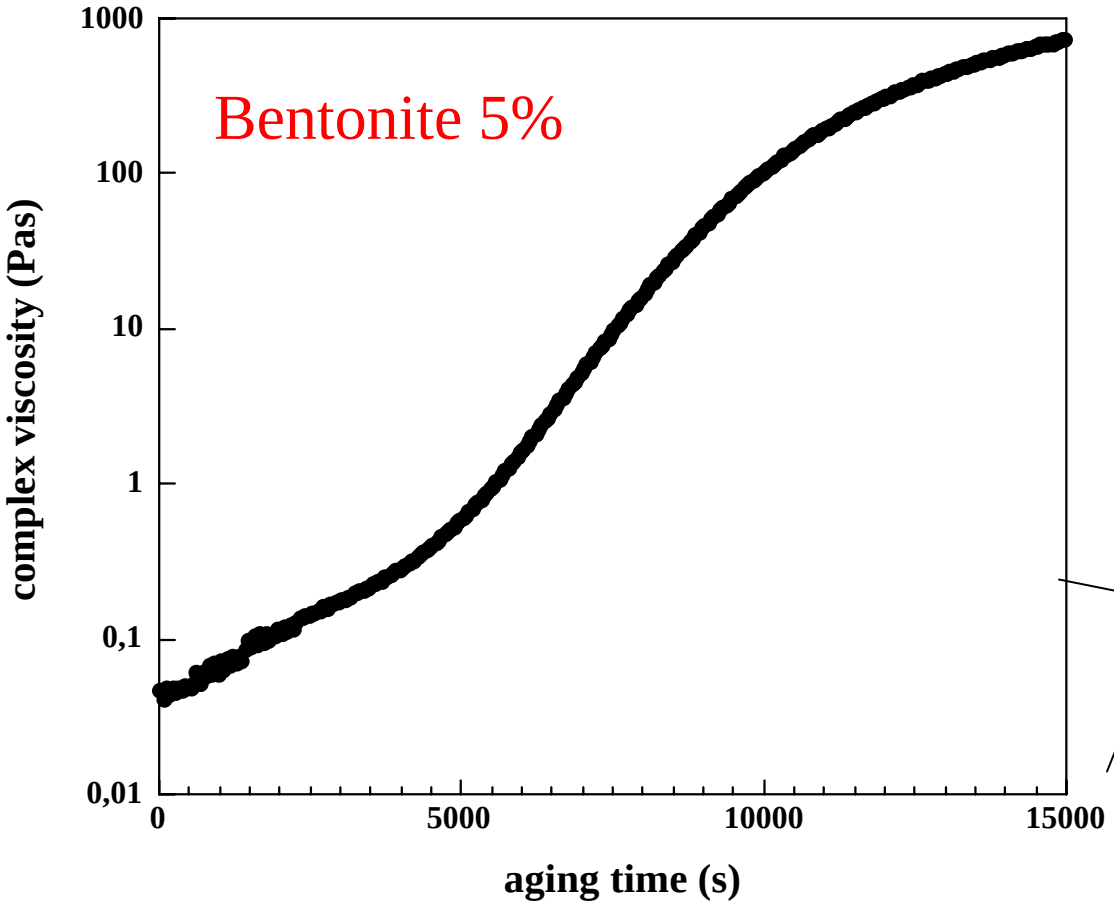


salinity $>2.10^{-2}$ mole/l

By mixing sand and clay (bentonite) in salt water, “laboratory quicksand” can be created.

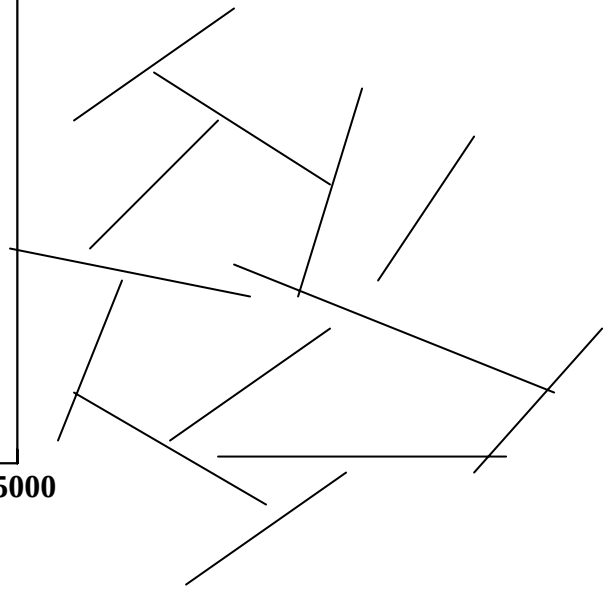
Viscosity increase: aging

Aging: increase of the viscosity at rest, and at zero (or very low) shear: characteristic of clays

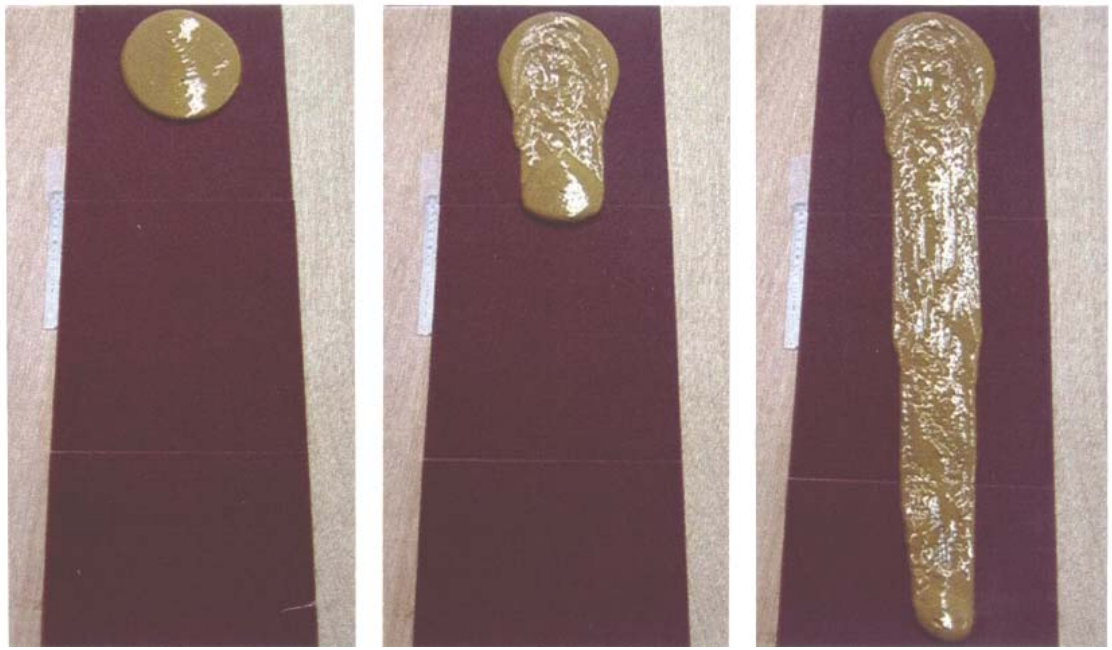


clay gel

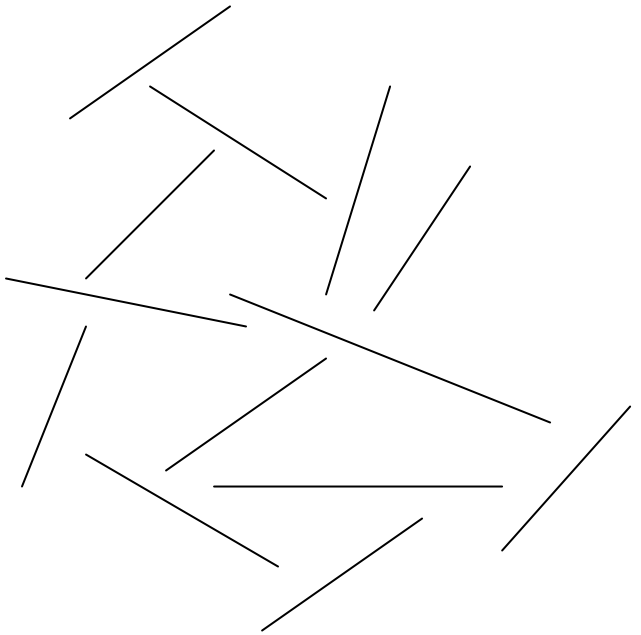
“house of cards” structure



..combined with liquefaction under shear

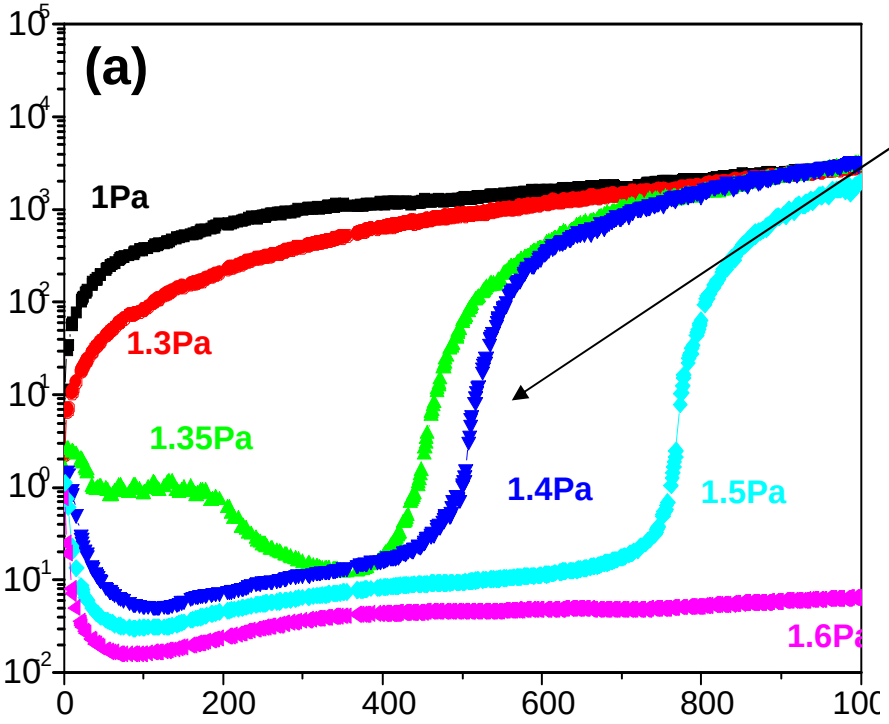


“house of cards”
Structure is destroyed

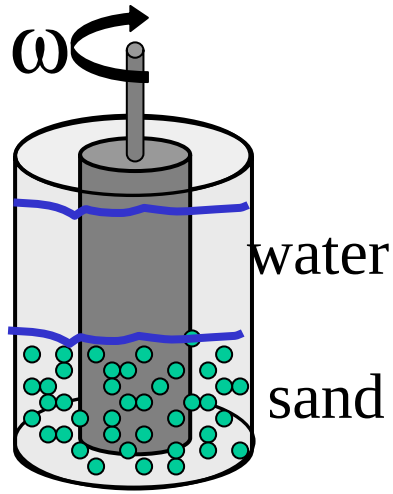


$$E \propto \frac{\text{number of connections}}{\text{volume}} \propto \sigma_c$$

....and phase separation



Phase separation: sedimented sand with a very high viscosity: $\phi \approx 0.8$
You're stuck!

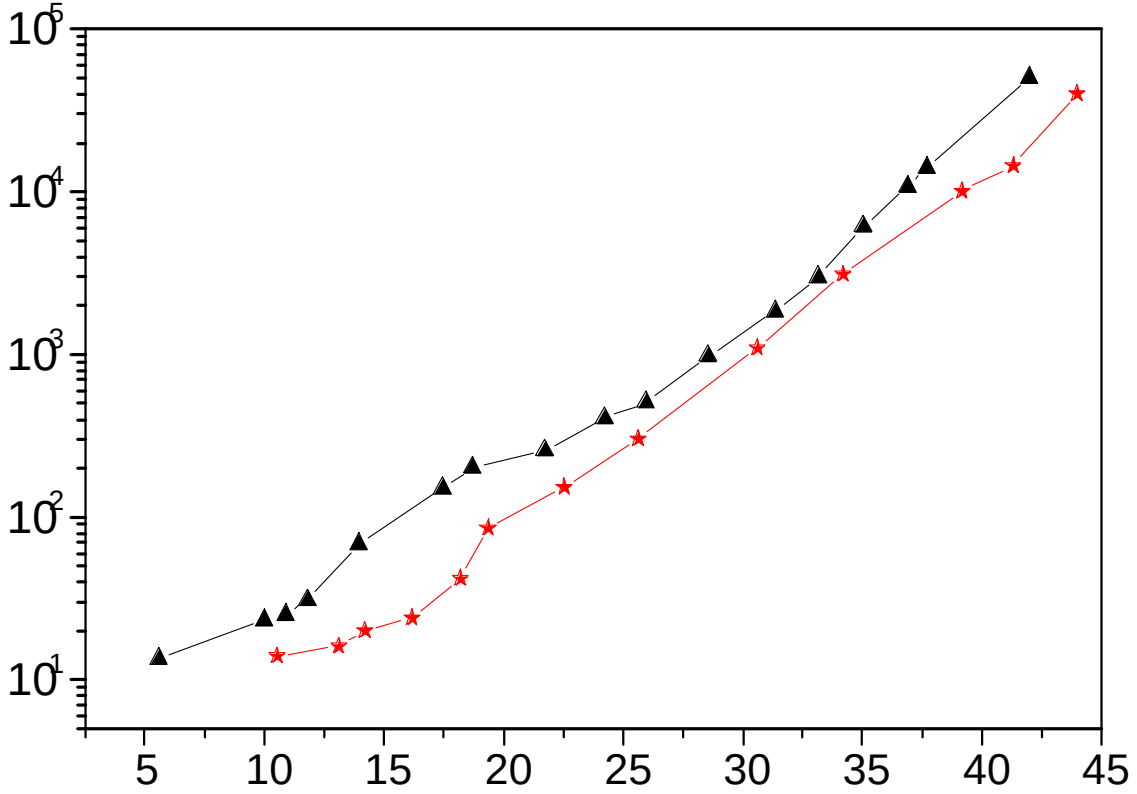


To get your foot out you have to introduce water in the sand packing:
at 1 cm/s : $F=10^4$ N!

From salt lake: salinity 10^{-1} mole/l

Salt is essential for the collapse: salinity needs to be $>2.10^{-2}$ mole/l for the laboratory quicksand

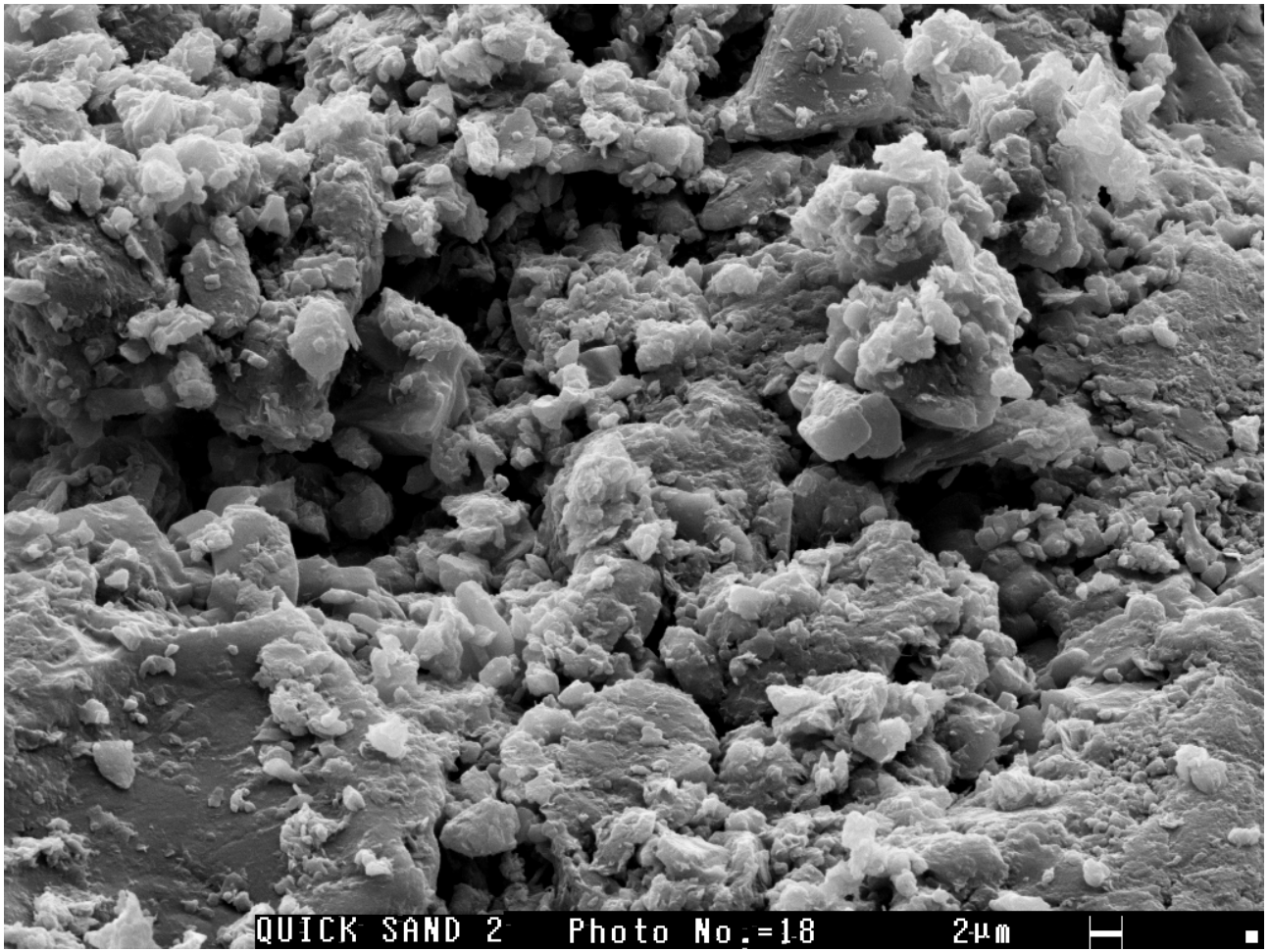
Elastic modulus from rheology



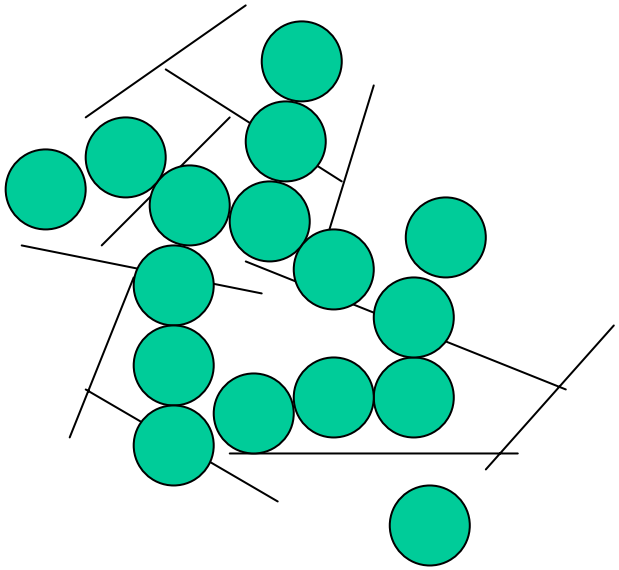
Quicksand can support the weight of an adult person at ϕ=0.4!

$$\frac{F}{A} = \frac{50kg * 10m/s^2}{10^{-2}m^2} = 5 \cdot 10^4 Pa \approx E$$ (supposing normal and shear forces to be similar)

Electron microscopy of quicksand



quicksand



« house of cards structure »
in which a dilute (ϕ=0.40) sand packing
is stable against sedimentation
because of the yield
stress of the clay suspension.

Both the packing and the house of cards structure are unstable against mechnical perturbation.

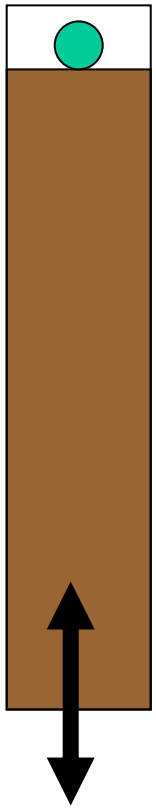
The high salt concentration makes the colloids flocculate, making the liquefaction even more spectacular.

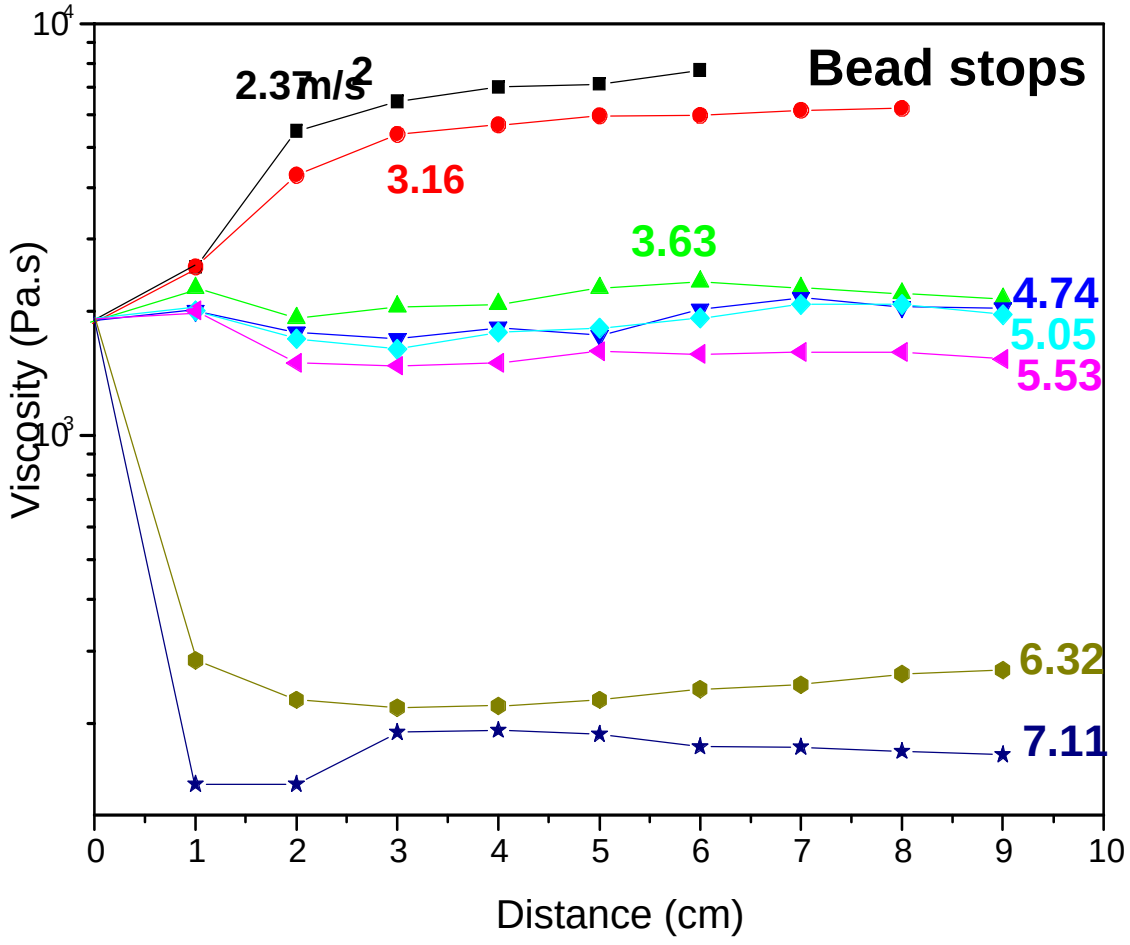
Next questions: -buoyancy?
-normal/viscous stresses

Sinking test....

Sinking away in quicksand

Sinking ball (aluminum) on a shaker





Clay: ball sinks immediately; sand: ball doesn't move

Ball of density 1 floats! You cannot drown in quicksand !

Density 1 g/cm^3

Density of quicksand: approximately 2g/cm^3

Quicksand

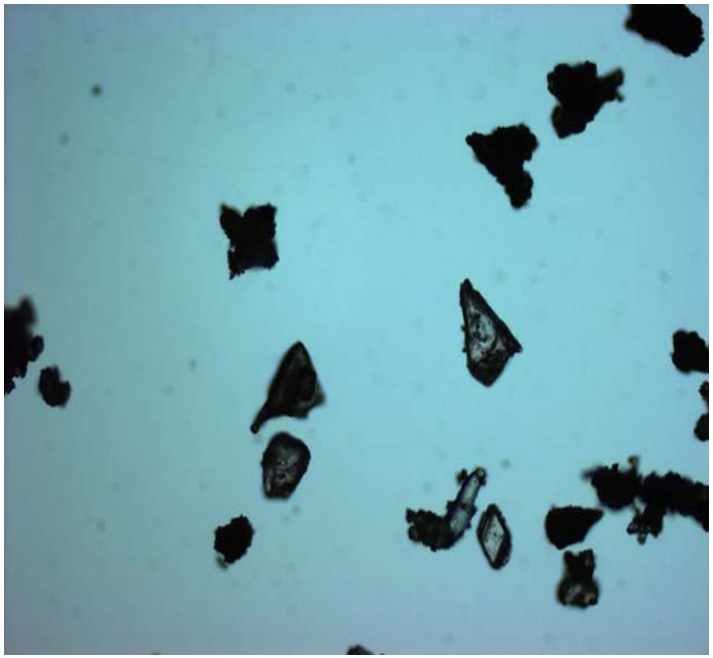
Three Quicksand Myths:

1) once in, don't move: TRUE
2) once in, hard to get out: TRUE
3) once in, one drowns: FALSE

…but what is the difference with Quick clay????

What is quickclay?

Natural quickclay
From Trondheim-Norway
)
water + non-swelling CLAY+sand
NO SALT!



Size of the sand particles 5-30µm

Illite	Chlorite	sand
50%	50%	A few %

Results of X-ray analysis

Quick clay landslides

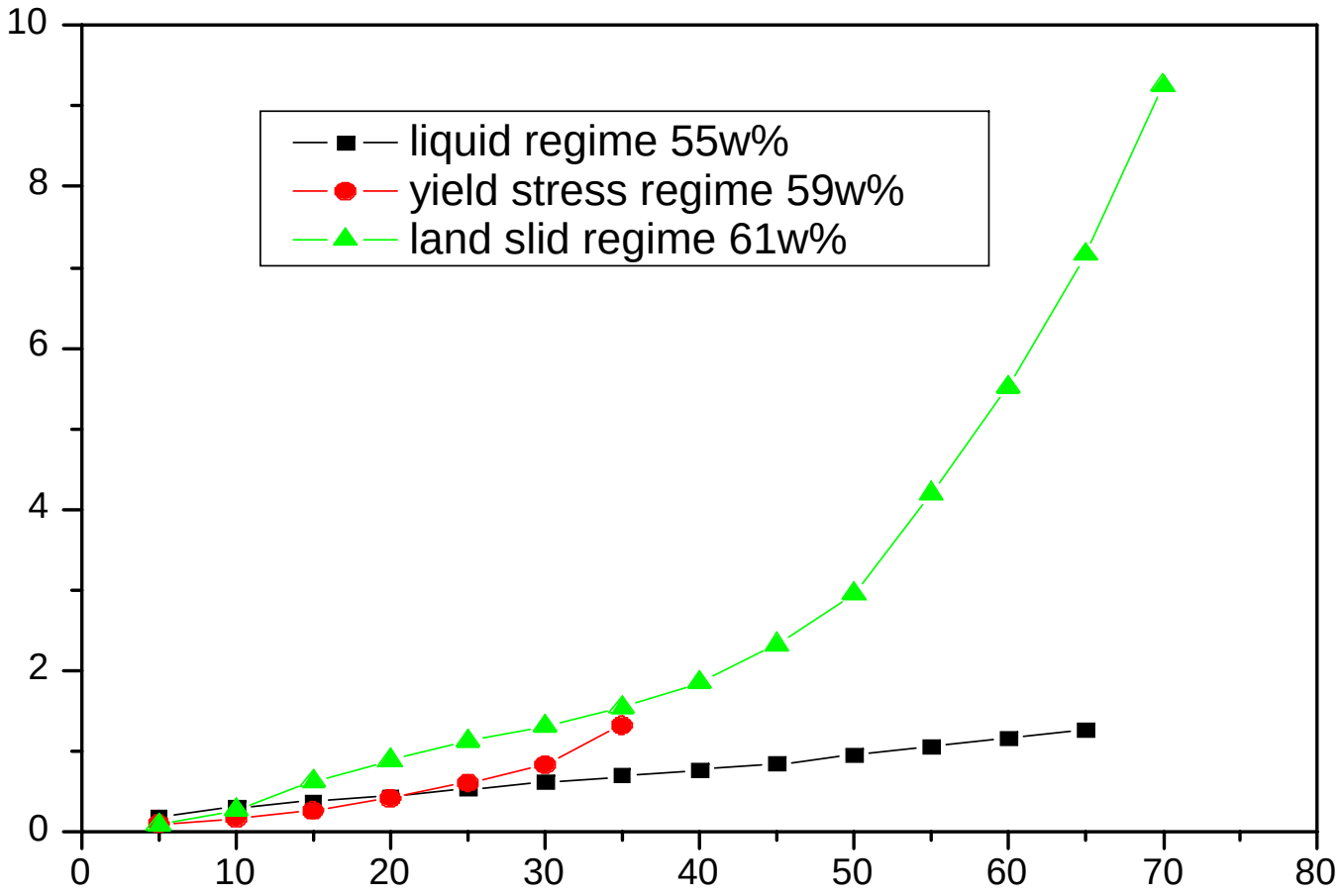
QuickTime™ et un
décompresseur Cinepak-kodek fra Radius
sont requis pour visionner cette image.

Quick clay landslides (the Rissa raset)

QuickTime™ et un
décompresseur Cinepak-kodek fra Radius
sont requis pour visionner cette image.

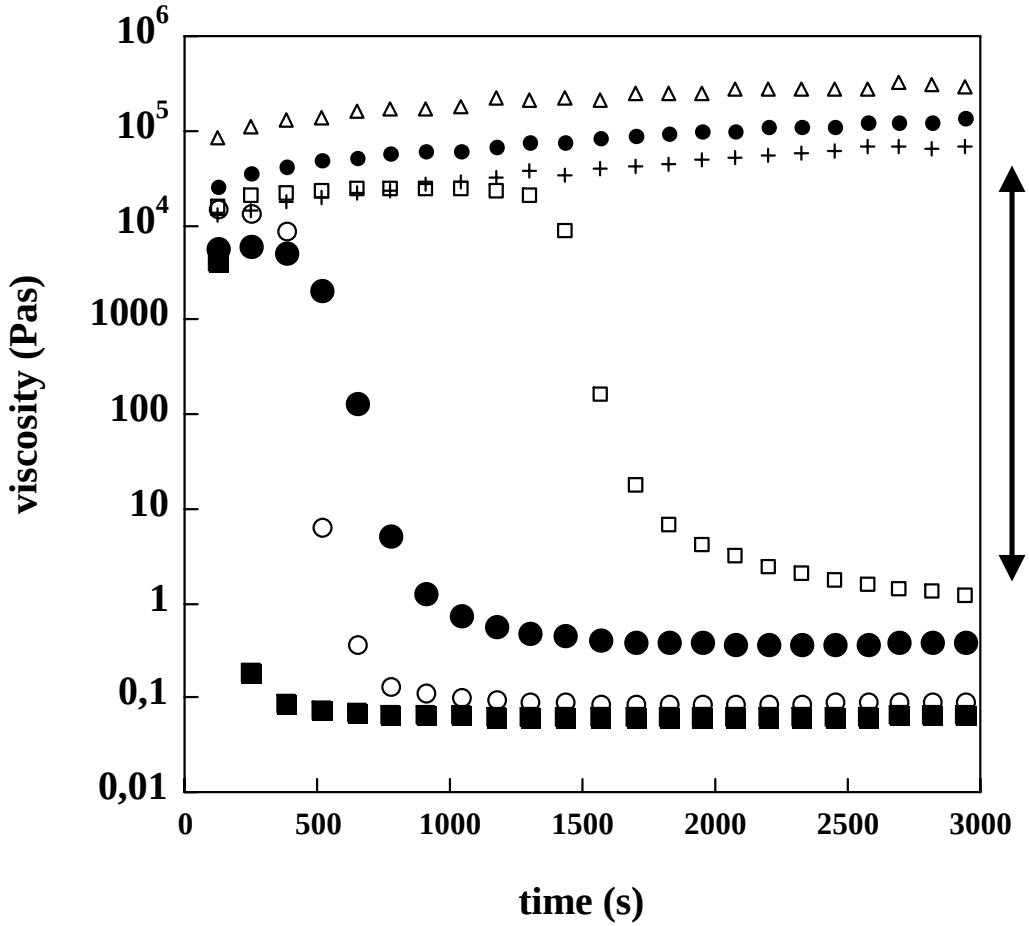
Laboratory landslides

Laboratory landslides



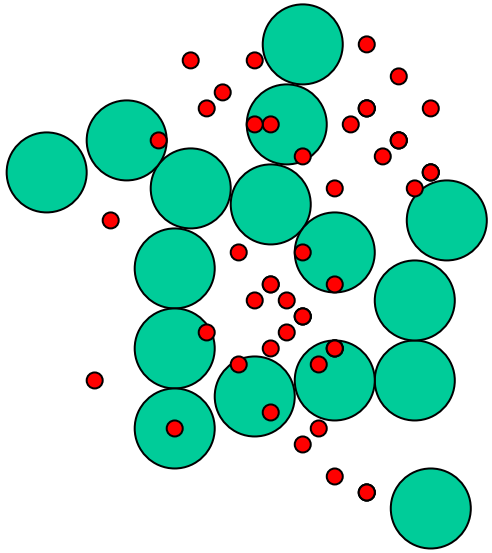
Quick clay: viscosity bifurcation

Natural quick clay
Trondheim, norway
Sand+water + clay (Illite/Clorite),
NO SALT



1% difference
In water
content

Quick clay



Particle (sand+clay) suspension
NO house of cards
Too much water:
Yield stress disappears

Sand particles (10-100 mm) and clay (Illite and Chlorite)
Illite and Chlorite are non-swelling clays: no electroststatic interactions and thus no house-of-cards structure.

General conclusion

Aging and shear rejuvenation (thixotropy) are GENERAL for structured complex fluids and lead naturally to
-a viscosity bifurcation
-shear localization

Providing a common framework (the rheological properties)
To describe glasses, gels, granular matter, emulsions, clayey soils…..

Applications in geophysics: landslides, quicksand

Coussot et al., Phys.Rev.Lett 2002, Huang et al., Phys.Rev.Lett 2005,
Quicksand: Khaldoun et al, Nature, september 2005

Questions/remarks: bonn@lps.ens.fr