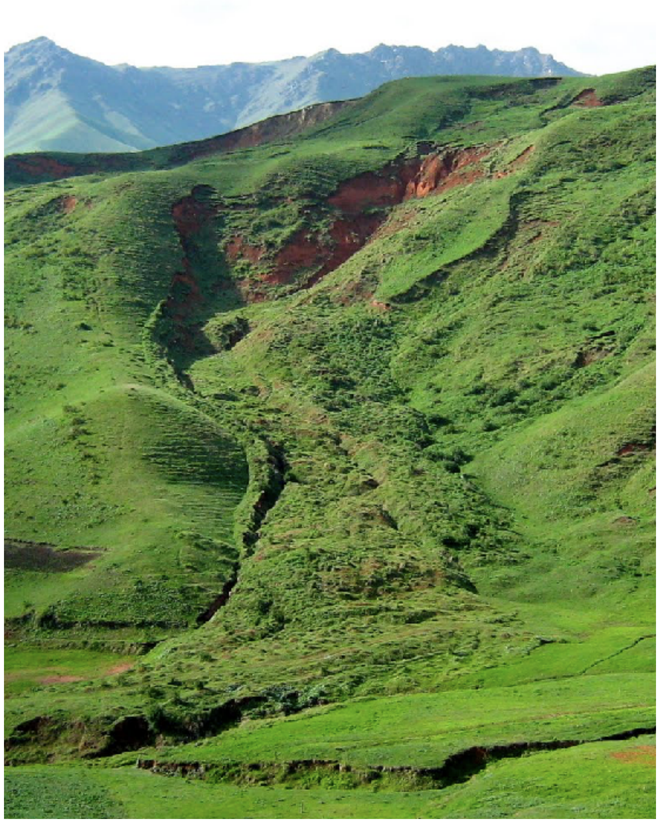
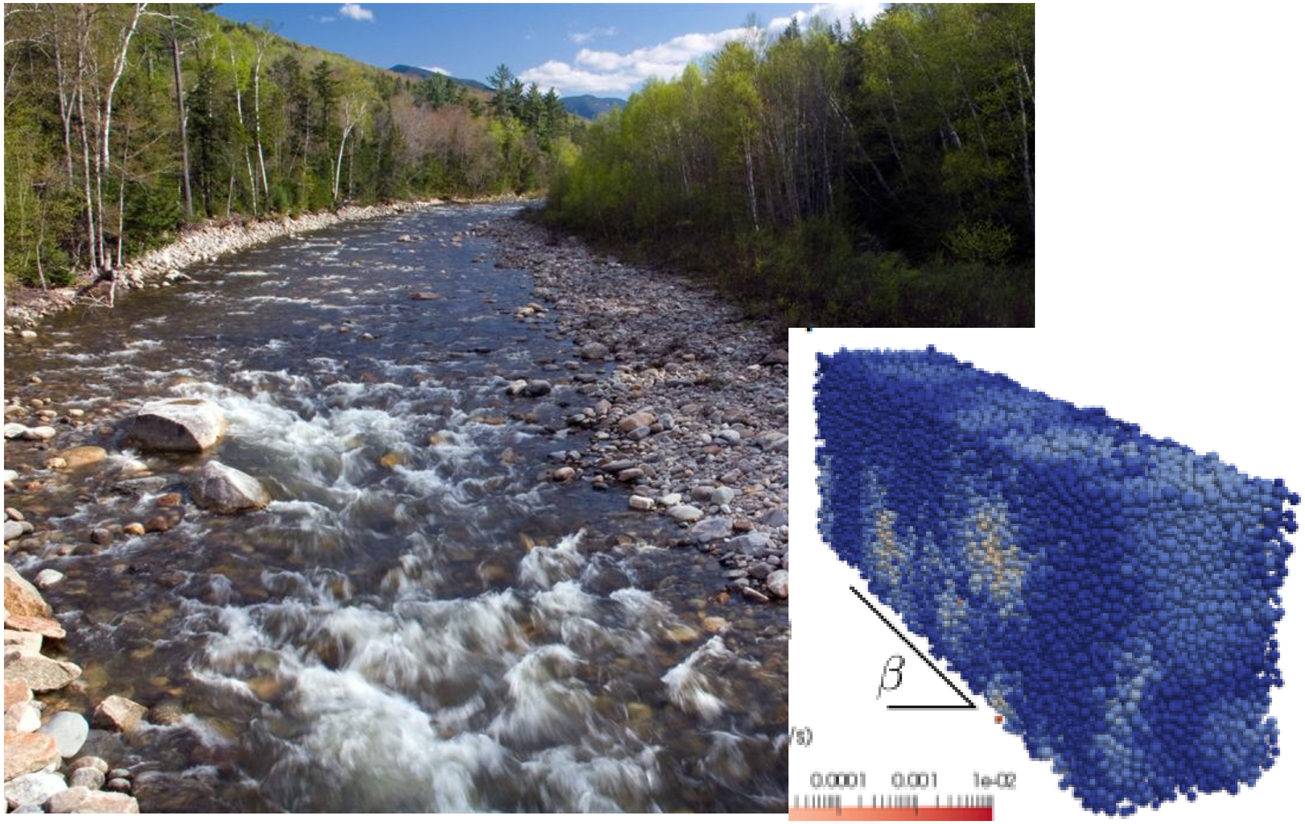
Glassy dynamics of landscapes

KITP, 2 March 2018





Douglas Jerolmack[1,2], **Behrooz Ferdowsi**[3], **Carlos Ortiz**[4], **Morgane Houssais**[5], **Colin Phillips**[6] **and Douglas Durian**[7]

1. PennSeD, Earth & Environmental Science, Univ. Pennsylvania
2. Mechanical Engineering & Applied Mechanics, Univ. Pennsylvania
3. Geosciences, Princeton Univ.
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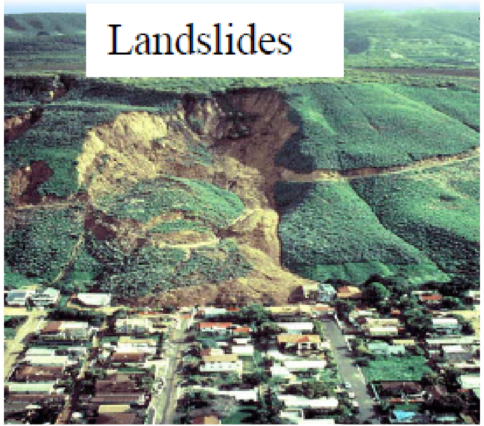
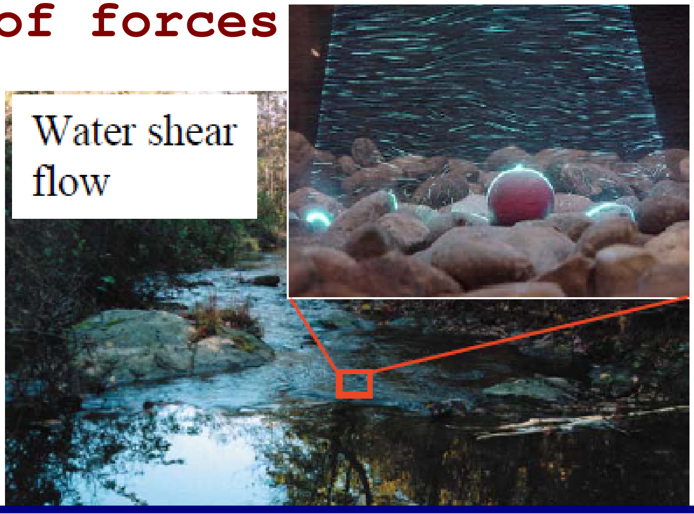
6. Civil & Environmental Engineering, Northwestern Univ.
7. Physics & Astronomy, Univ. Pennsylvania

Earth's surface is a granular-fluid interface

Shape of landscapes → balance of forces


Landslides


Soil creep

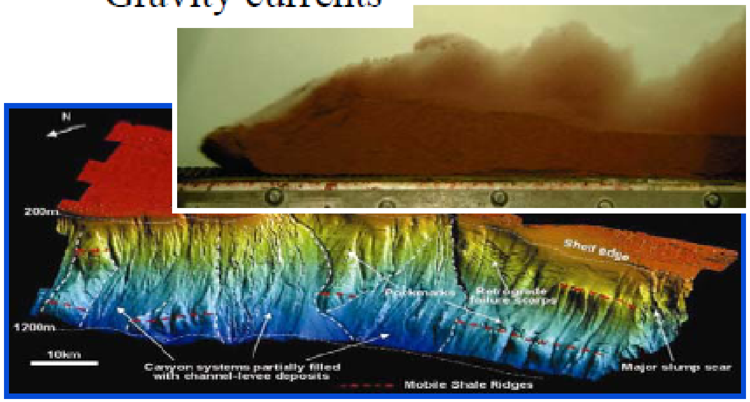

Water shear flow

"Hillslope" processes

"Fluvial" processes

Wind shear flow

Gravity currents



Density contrast (buoyancy effect) drives fluid motion

Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear

By R. A. Bagnold, F.R.S.

(*Received* 20 *February* 1954)

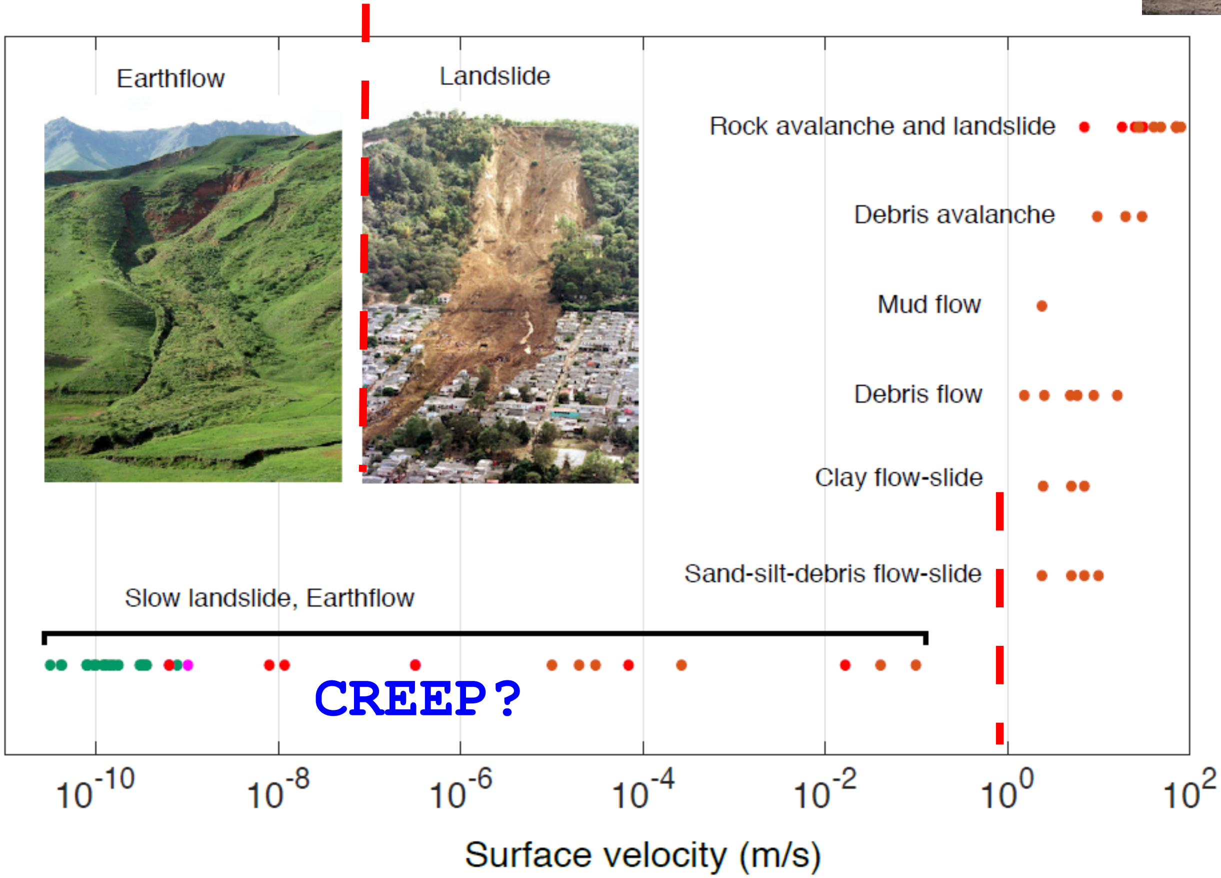
THE FLOW OF COHESIONLESS GRAINS IN FLUIDS

By R. A. BAGNOLD, F.R.S.

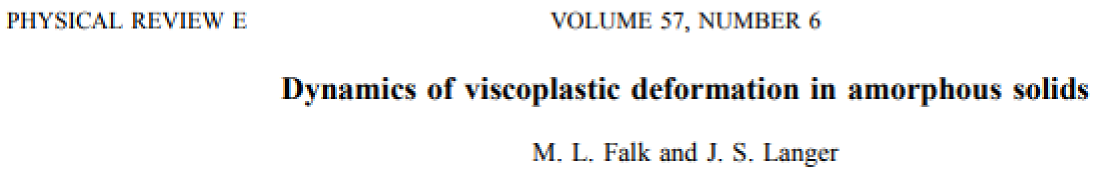
(*Received* 31 *January* 1955—*Revised* 14 *April* 1956)

Landscapes are near critical: creeping ↔ flowing

Santa Barbara, 9 January 2018



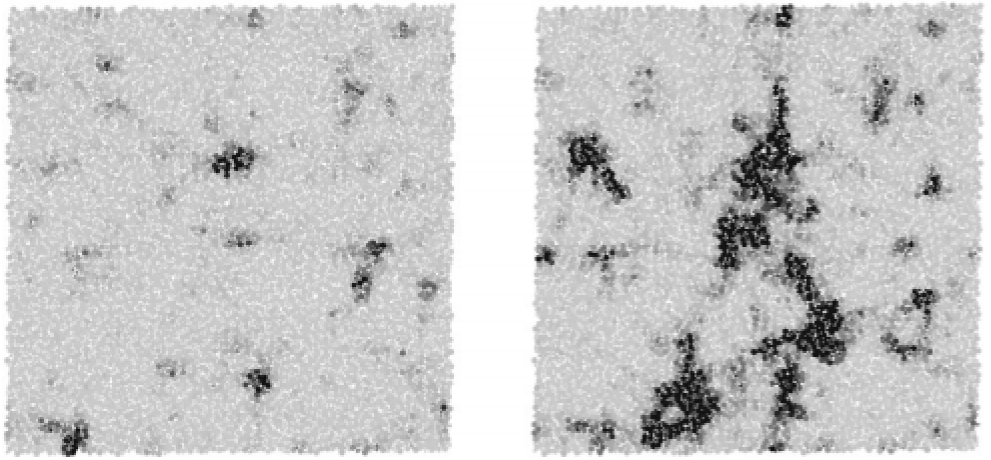
Creep in amorphous solids → DISORDER

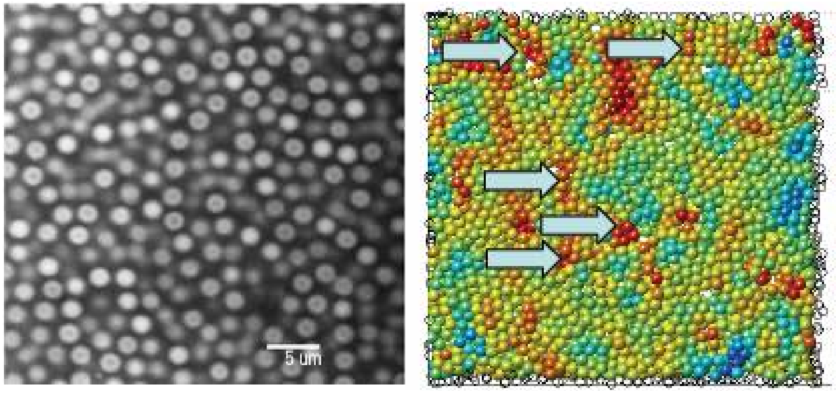

PHYSICAL REVIEW E VOLUME 57, NUMBER 6

Dynamics of viscoplastic deformation in amorphous solids

M. L. Falk and J. S. Langer

Shear transformation zones
in metallic glass simulations



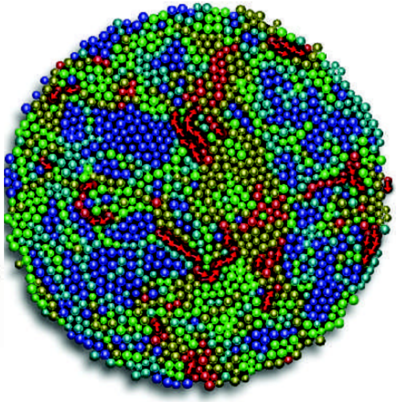


[Weitz group, Harvard]

Confirmed in:

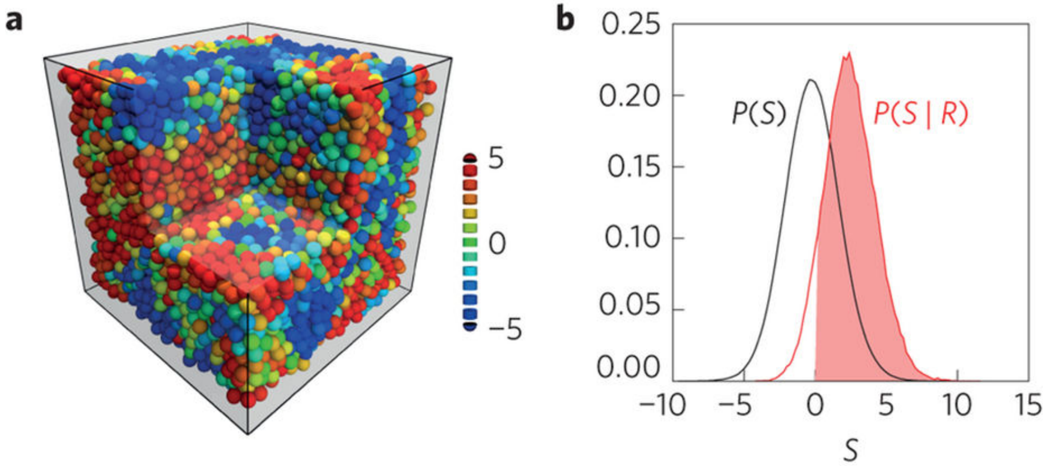
-Suspensions

-Granular materials



[Keys et al., *Nature Physics 2007*]

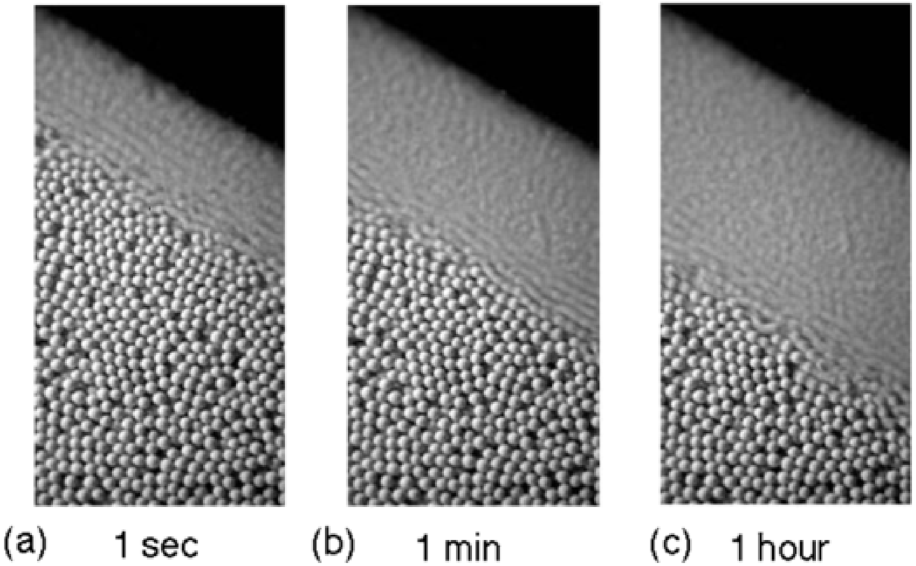
Structural defects
(disorder) → “soft spots” →
dislocation/flow



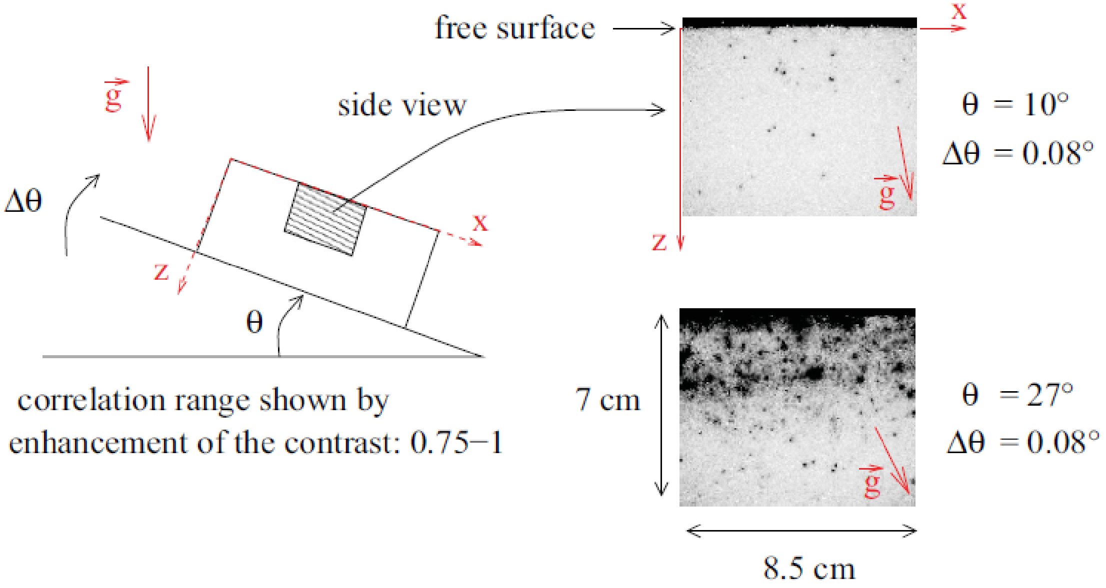
[Liu group, University of Pennsylvania]

Creep to flowing transition: glassy dynamics

[Komatsu et al., *PRL 2001*]


(a) 1 sec (b) 1 min (c) 1 hour

[Amos et al., *Phys. Rev.E 2013*]

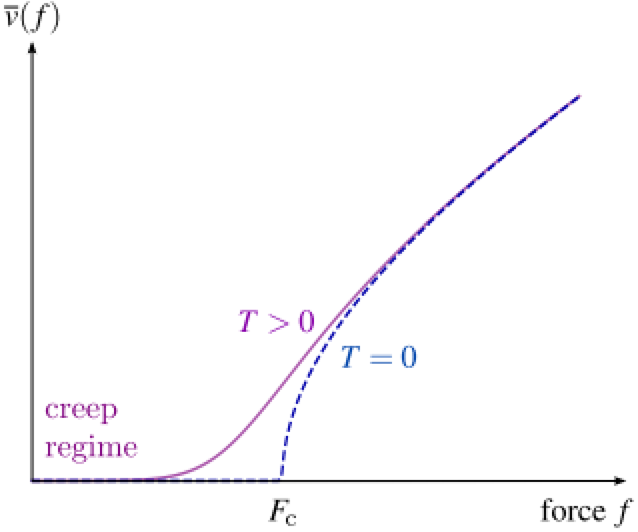


correlation range shown by enhancement of the contrast: 0.75–1

[Agoritsas et al., *J. Stat. Phys. 2017*]

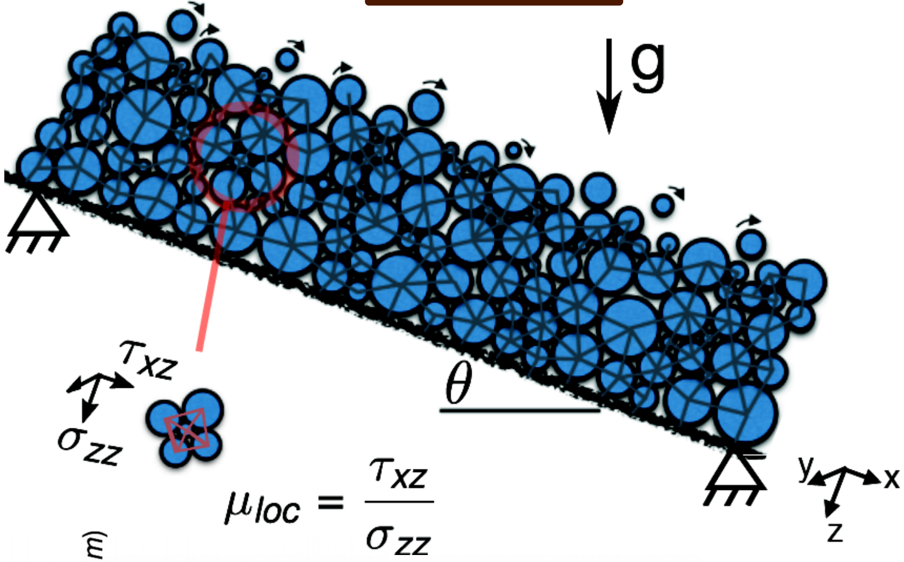
Glassy failure model

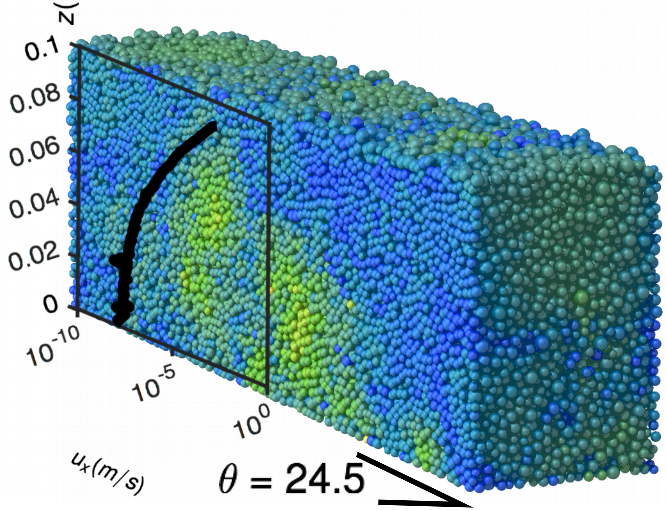
- Avalanches of plasticity.
- At yield: avalanches merge across sample.
- Exponential (CREEP) to power-law (FLOW).
- Temperature - enhances creep.



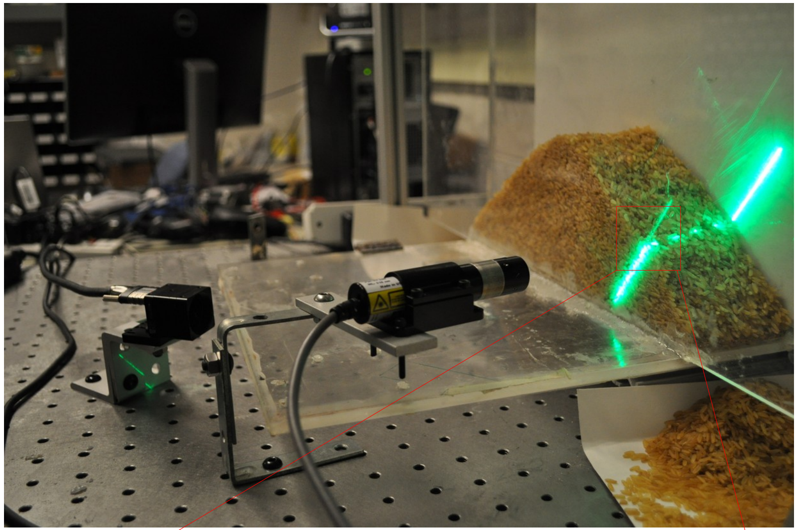
Creep on hillslopes without disturbance

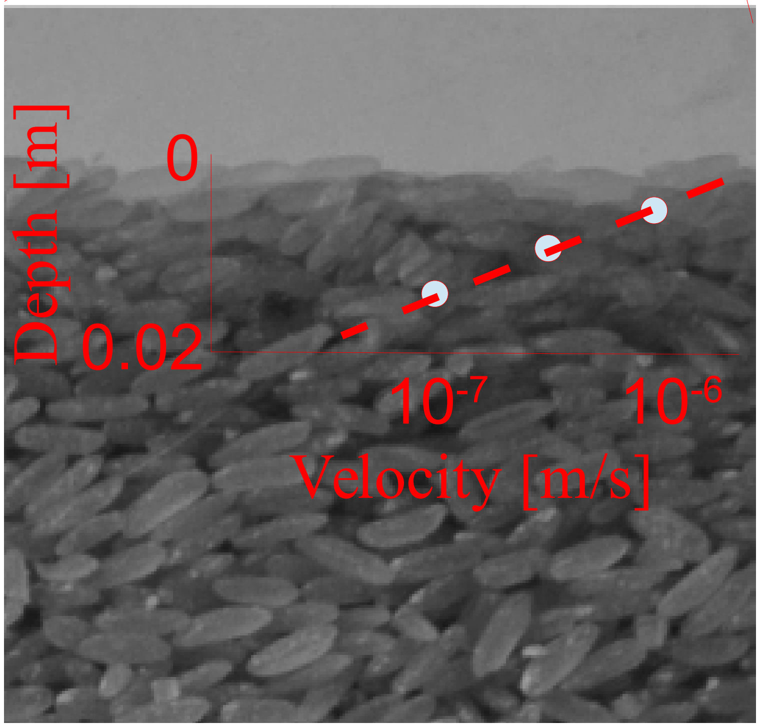
Creep: DEM simulations.





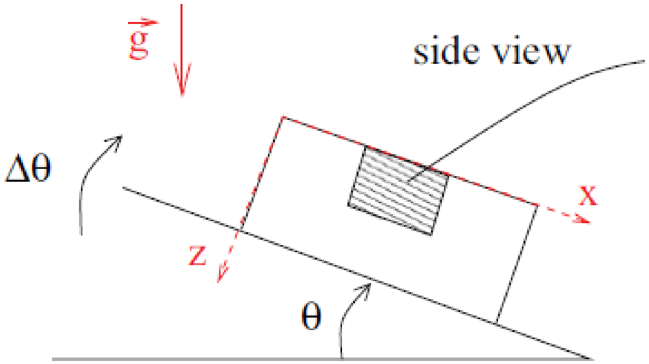
Creep: rice pile experiments.

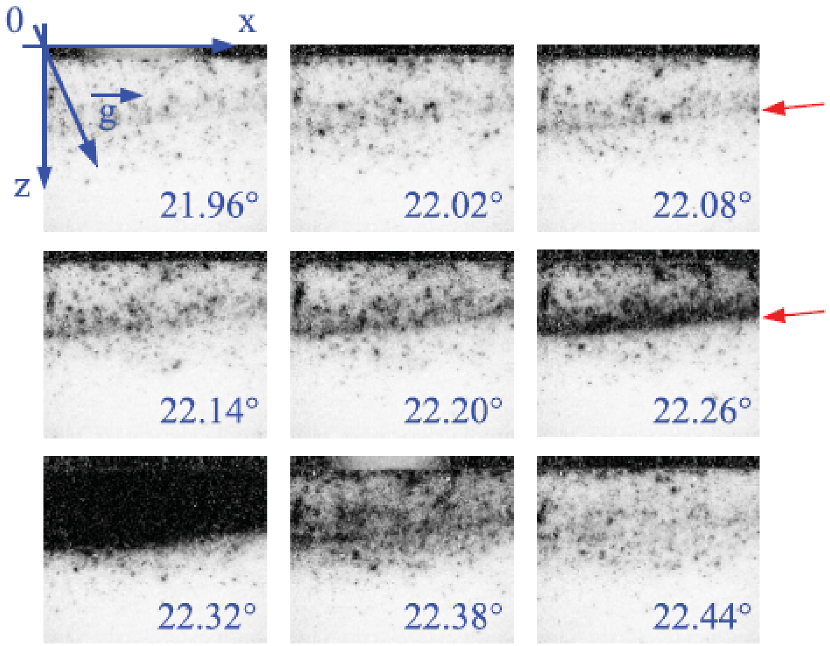




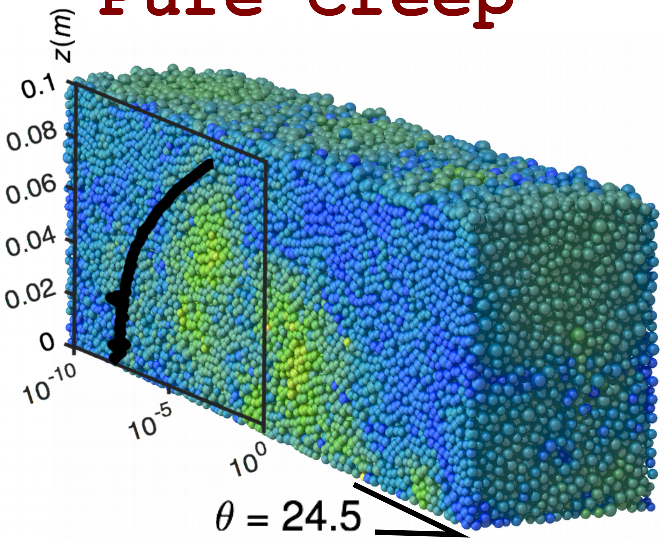
Glassy dynamics in granular hillslopes

[Amos et al., *Phys. Rev.E 2013*]



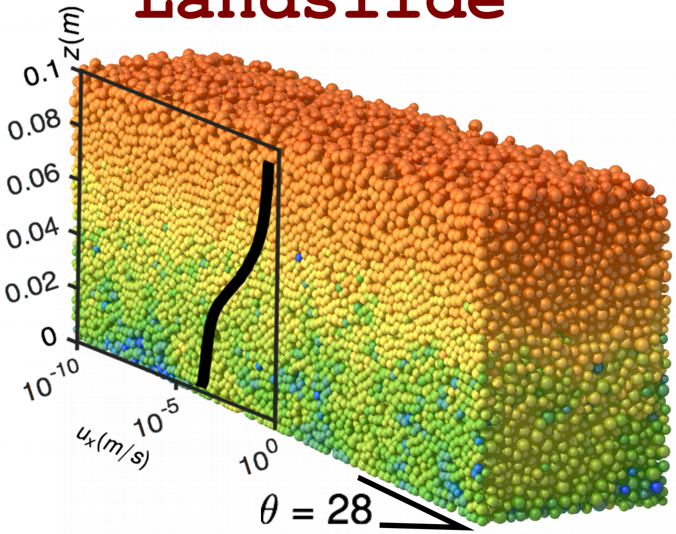


Pure Creep



Creep occurs at sub-critical slopes.

"Landslide"



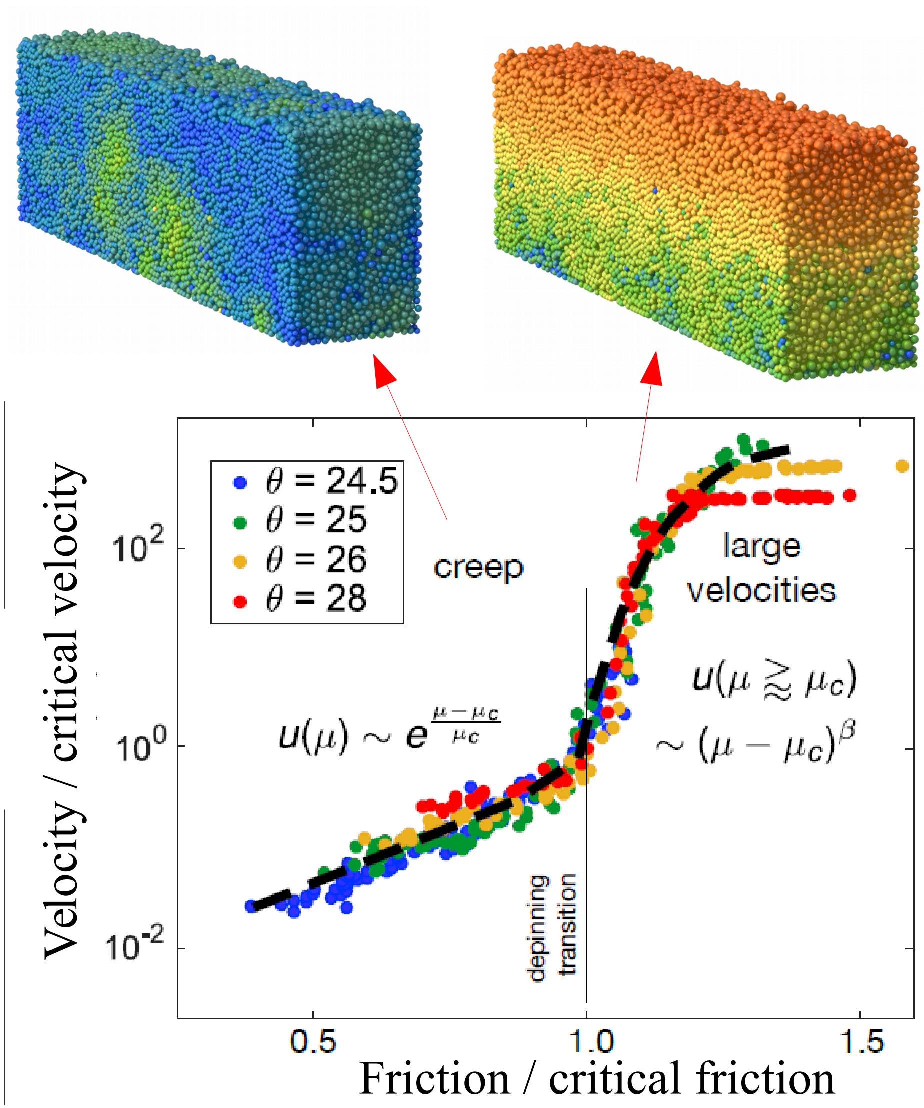
Creep → Landslide is glassy

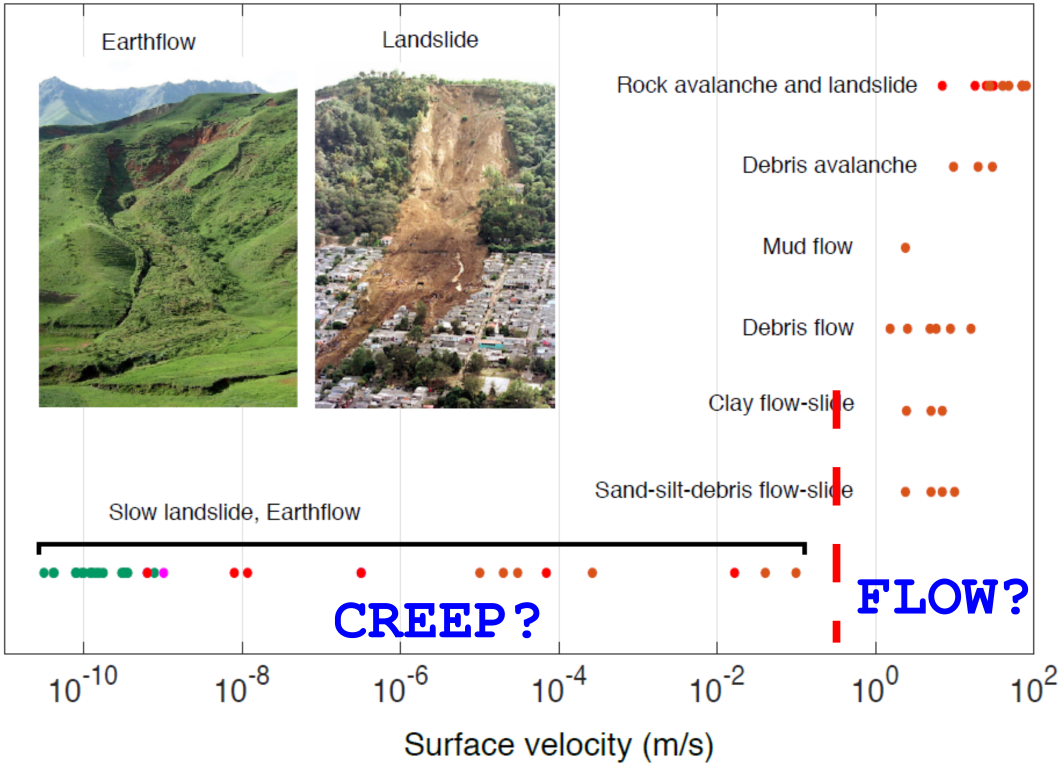
[Ferdowsi, Ortiz and Jerolmack, *REJECTED 2017*]

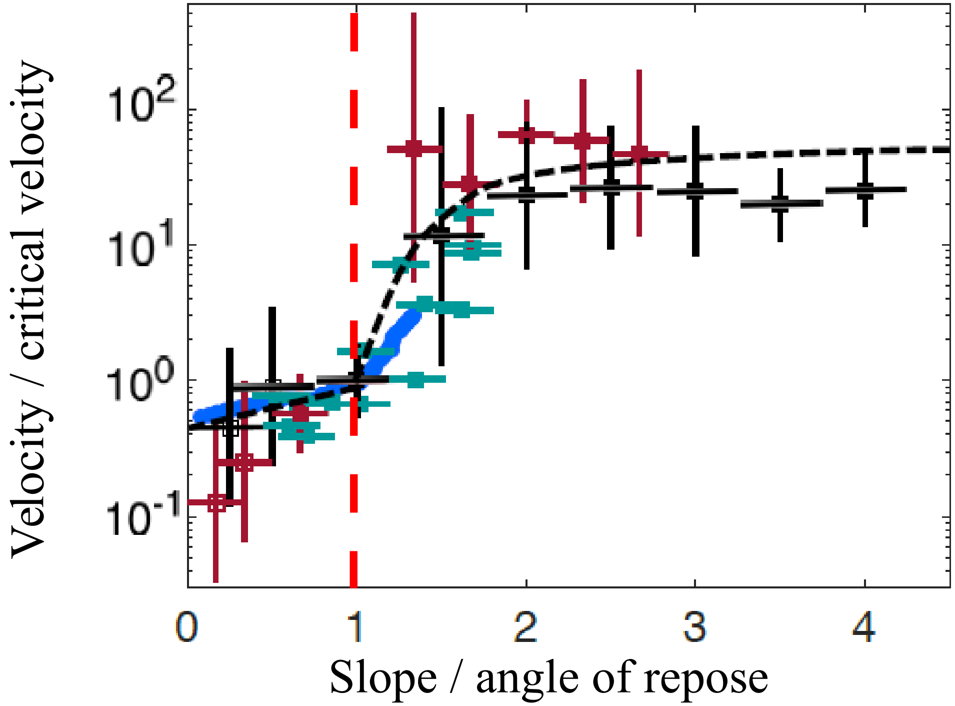
Creep to landslide transition is glassy!

[Ferdowsi, Ortiz and Jerolmack, *REJECTED 2017*]

Exponential (CREEP) to power-law (LANDSLIDE)







Are mountains glassy? Oregon Coast Range test

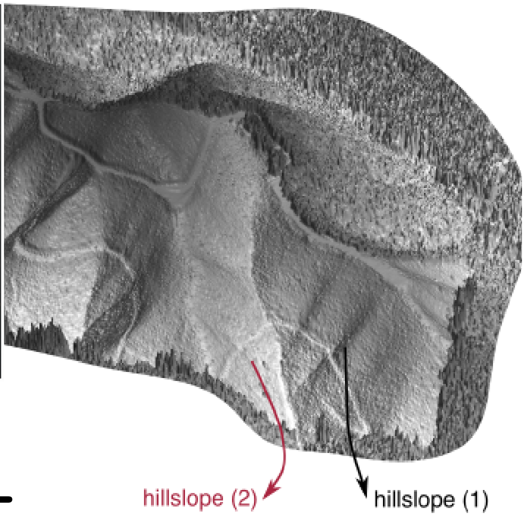
Mass conservation:

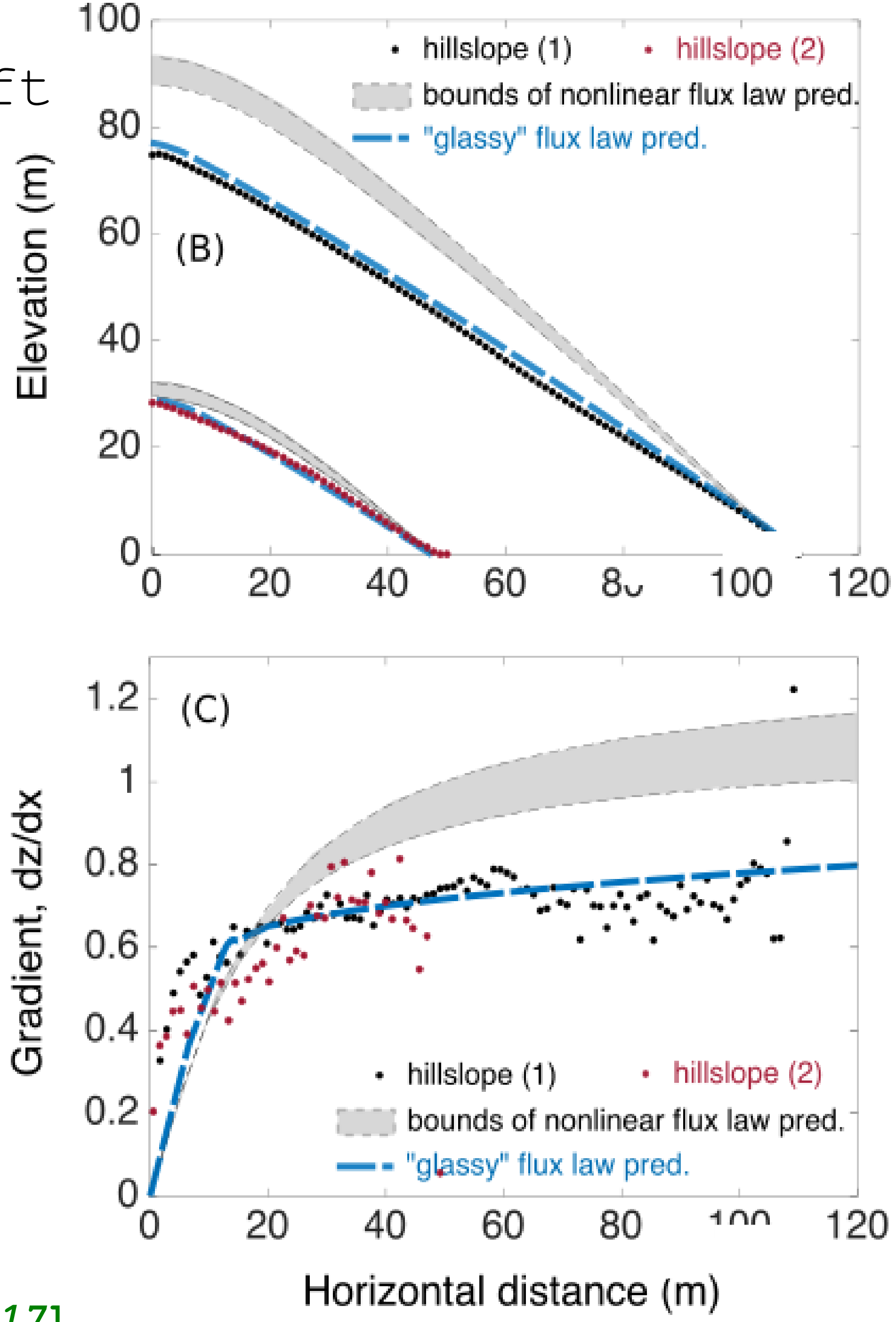
Steady state: Erosion = uplift

$$-\rho_s \cancelto{0}{\frac{\partial z}{\partial t}} = \rho_s \nabla \cdot q_s + \rho_r C_o$$

Glassy flux model:

$$\frac{q_s}{q_{sc}} = \begin{cases} e^{\frac{S-S_c}{S_c}} \, \big|_{S<S_c} \\ A(S-S_c)^{\beta} \, \big|_{S>S_c} \end{cases}$$





Constant uplift.

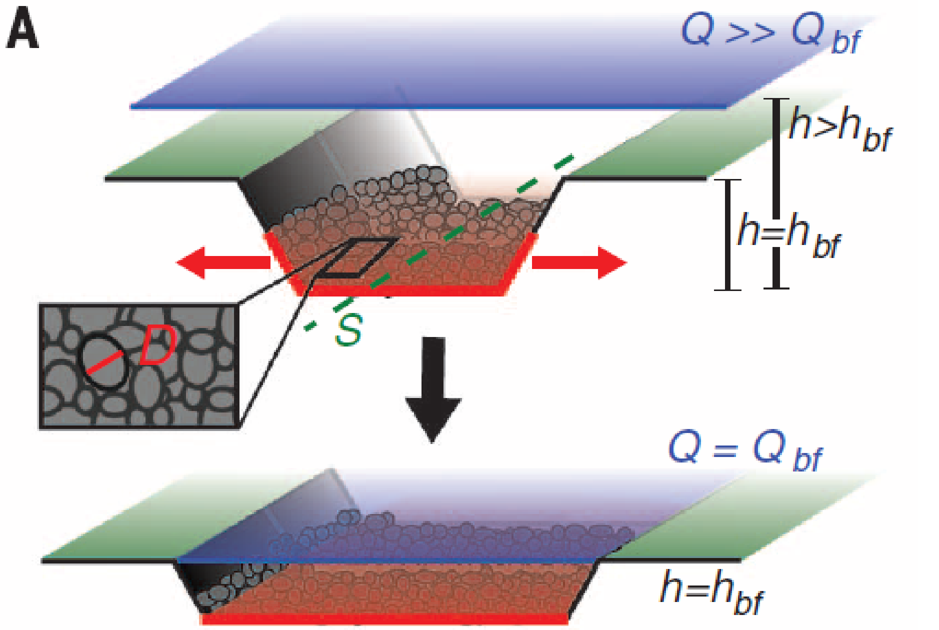
Best-fit determination of S_c.

[Ferdowsi, Ortiz and Jerolmack, *REJECTED 2017*]

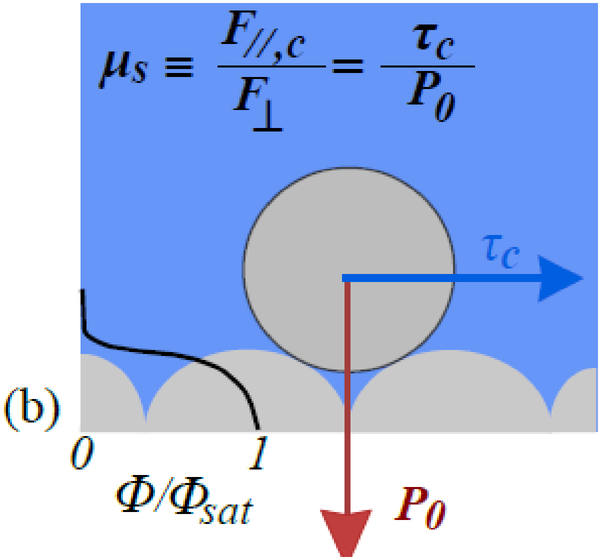
Rivers are near also near critical

$$(1+\epsilon)\tau_{*c} = \tau_{*bf} \approx 1.2\,\tau_{*c}$$

[Parker, *J. Fluid Mech.* 1978]



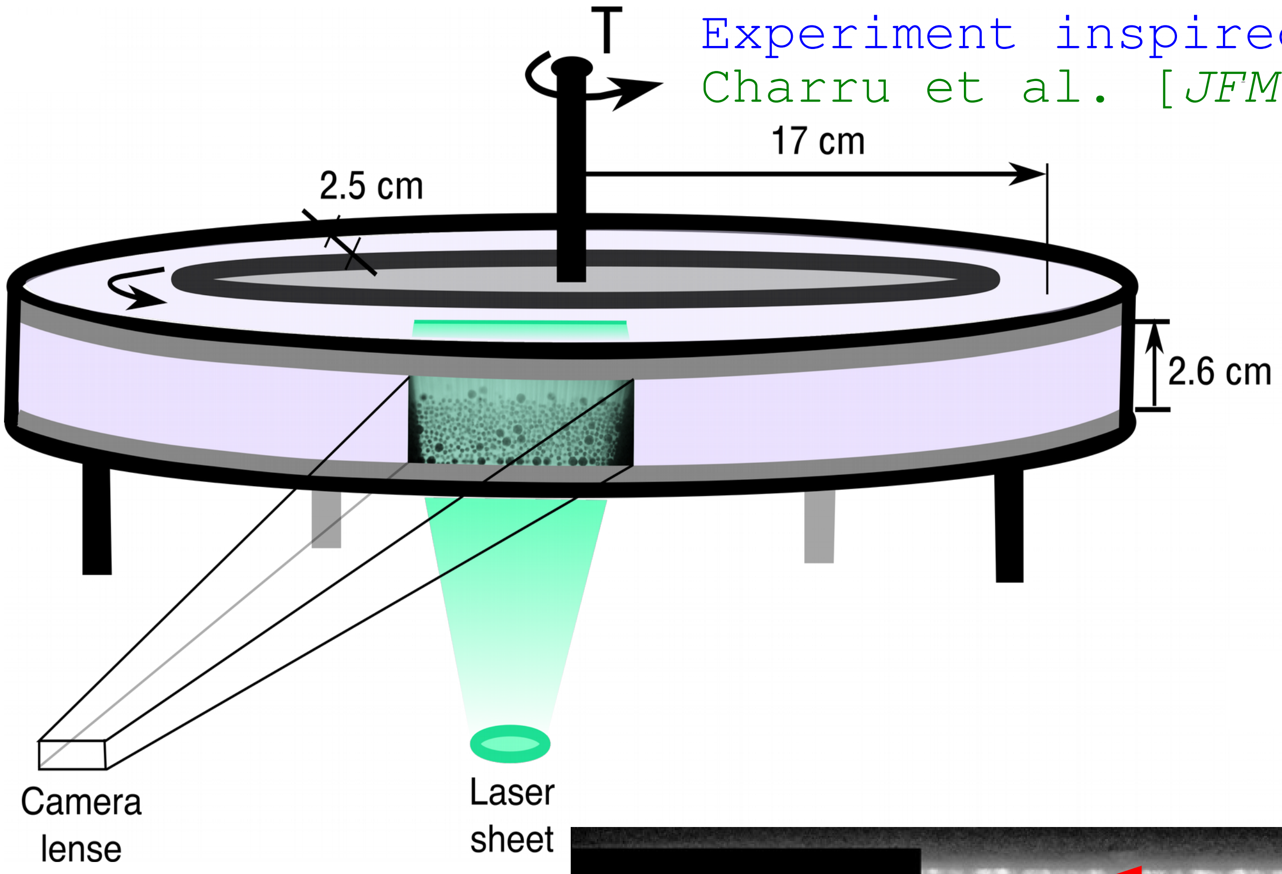
[Phillips & Jerolmack, Science 2016]



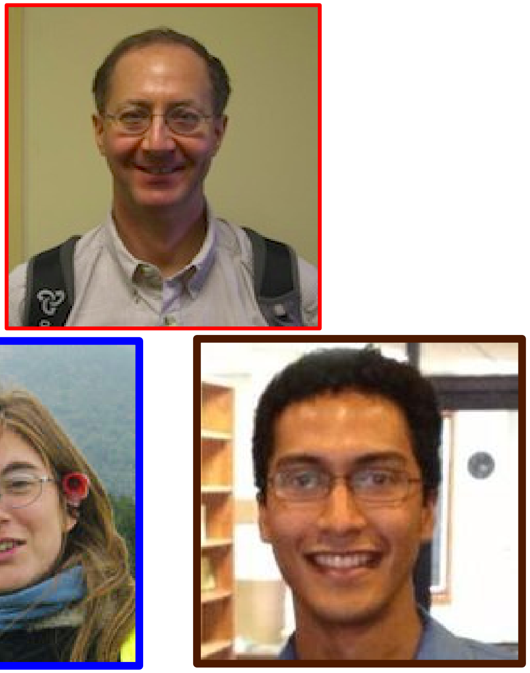
$$\tau^* = \frac{\tau}{(\rho_p - \rho)gd}$$

Ethan Mora:
https://vimeo.com/22140684

The onset of erosion: glassy dynamics?



Experiment inspired by
Charru et al. [*JFM 2004*]

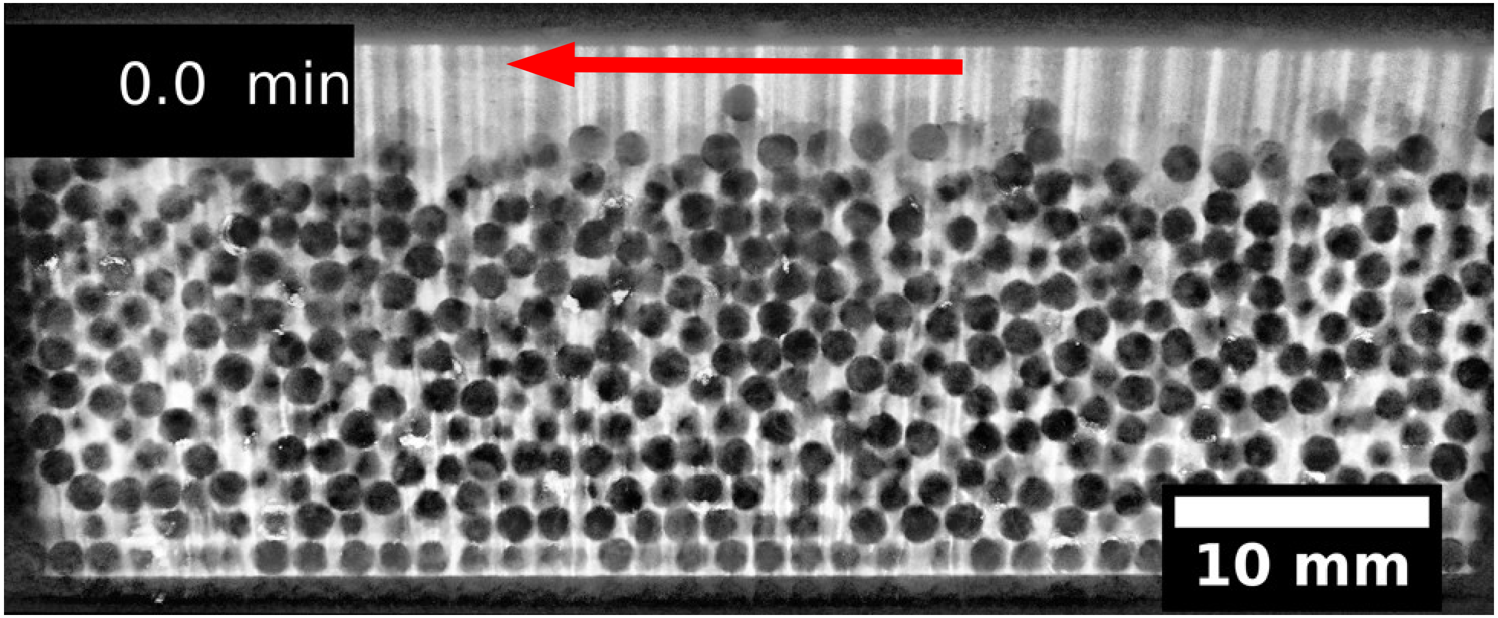


[Houssais, Ortiz, Durian and Jerolmack, Nature Comm. 2015]

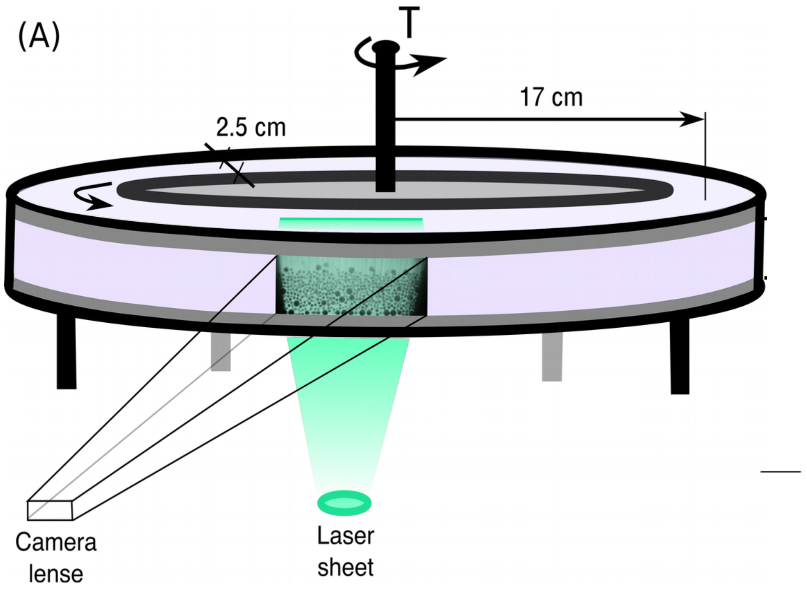
1.5 mm spheres

***Re* < 5 :**
Laminar flow

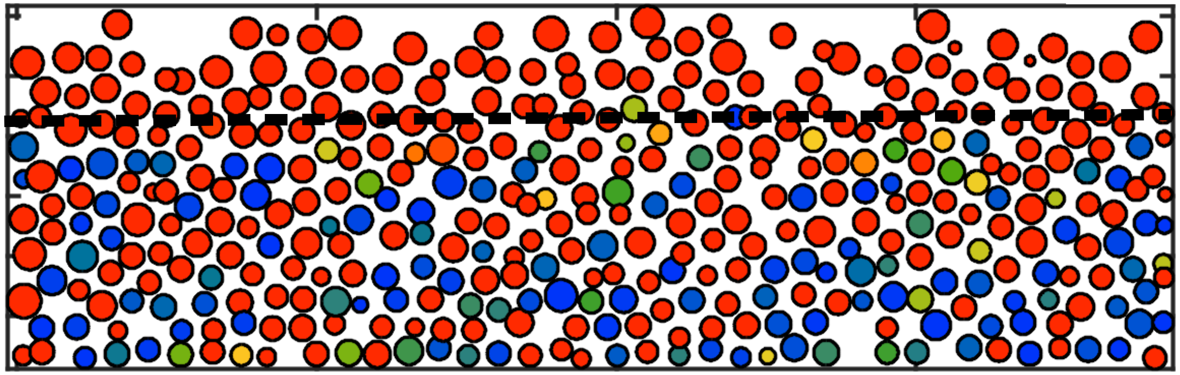
Refractive-Index Matched Scanning



"Glassy" dynamics near threshold

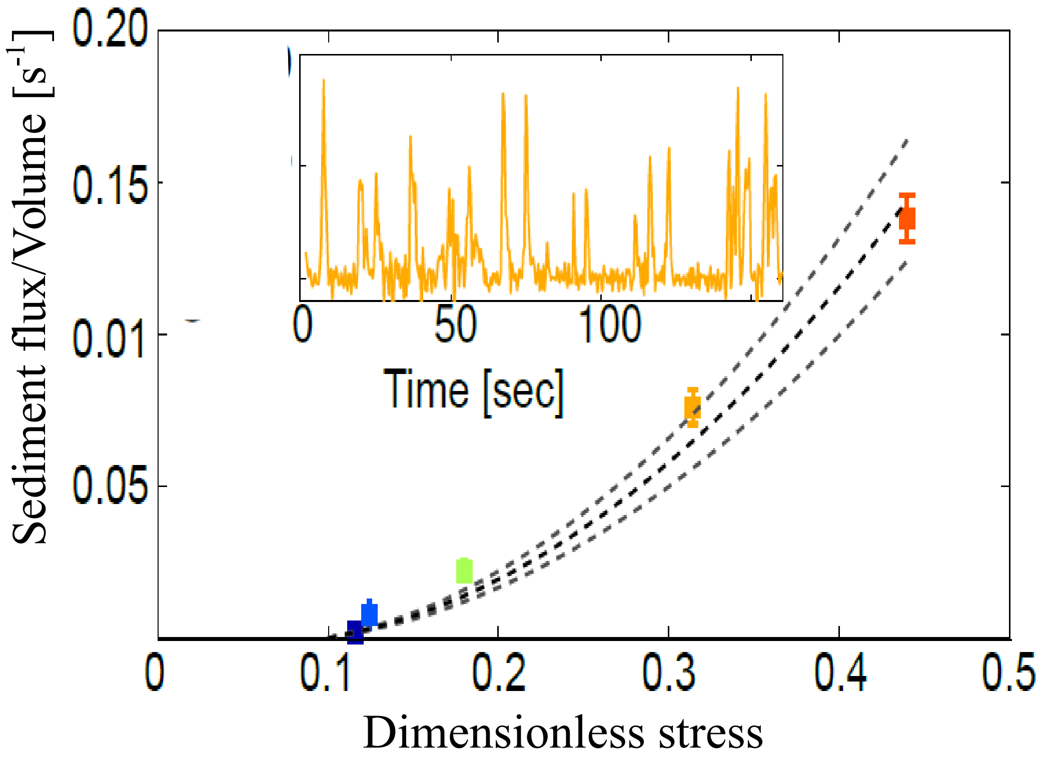


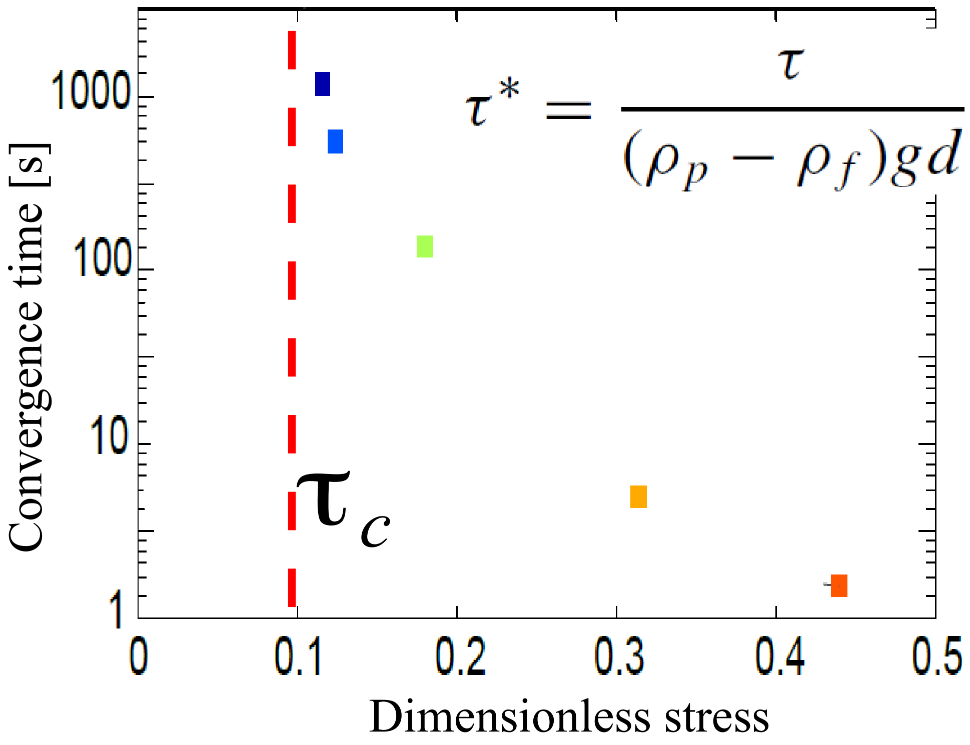
Particle motion relative to neighbors



"Spatially heterogeneous dynamics": Collective particle rearrangements.

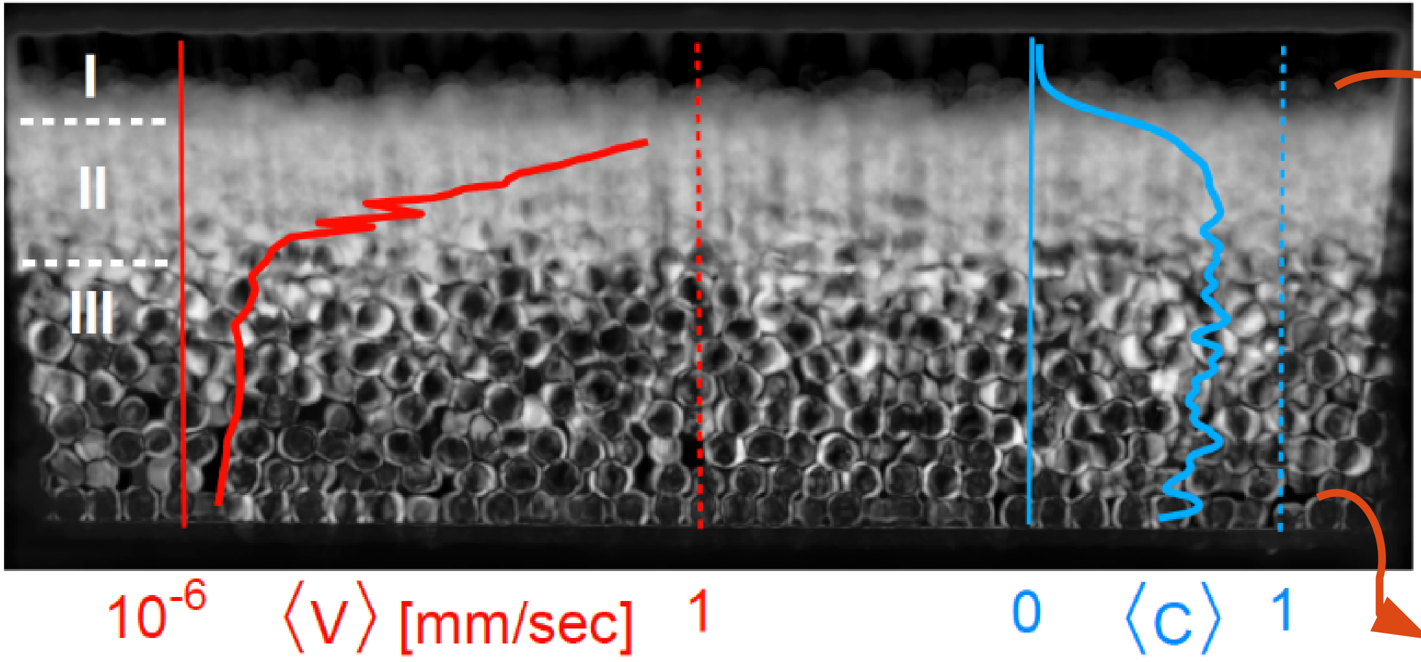
[Houssais, Ortiz, Durian and Jerolmack, Nature Comm. 2015]

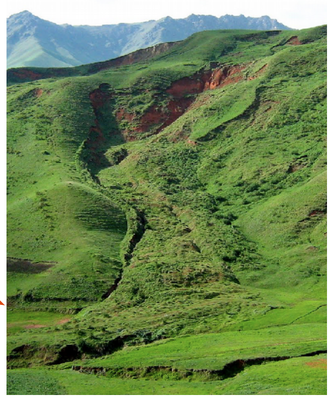


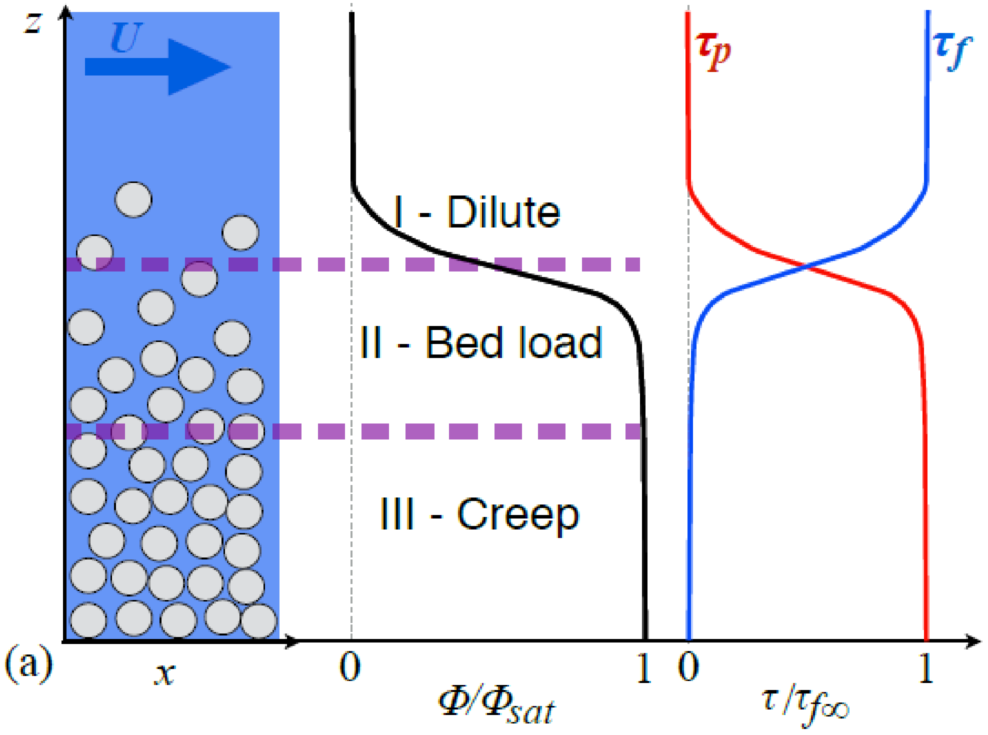


$$\tau^* = \frac{\tau}{(\rho_p - \rho_f)gd}$$

Averaged vertical profiles

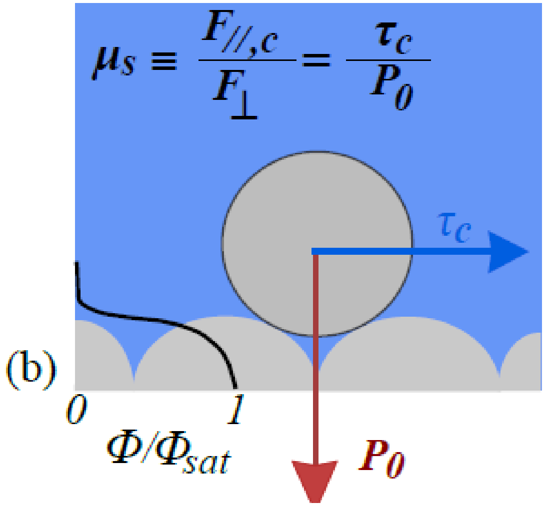




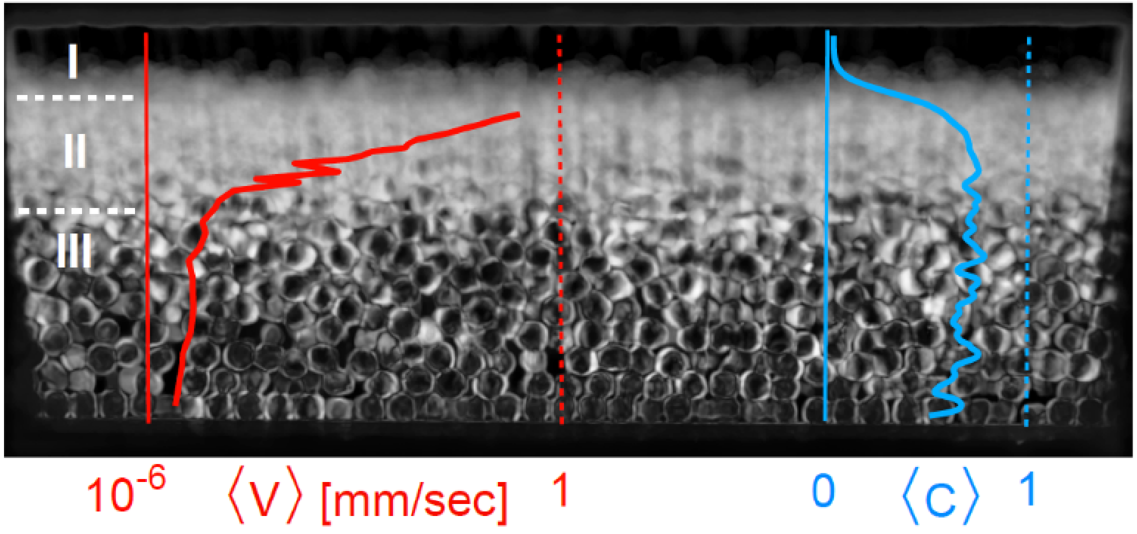


Three transport regimes.

What is the(ir) rheology?



Averaged vertical profiles



Viscous # f(depth):

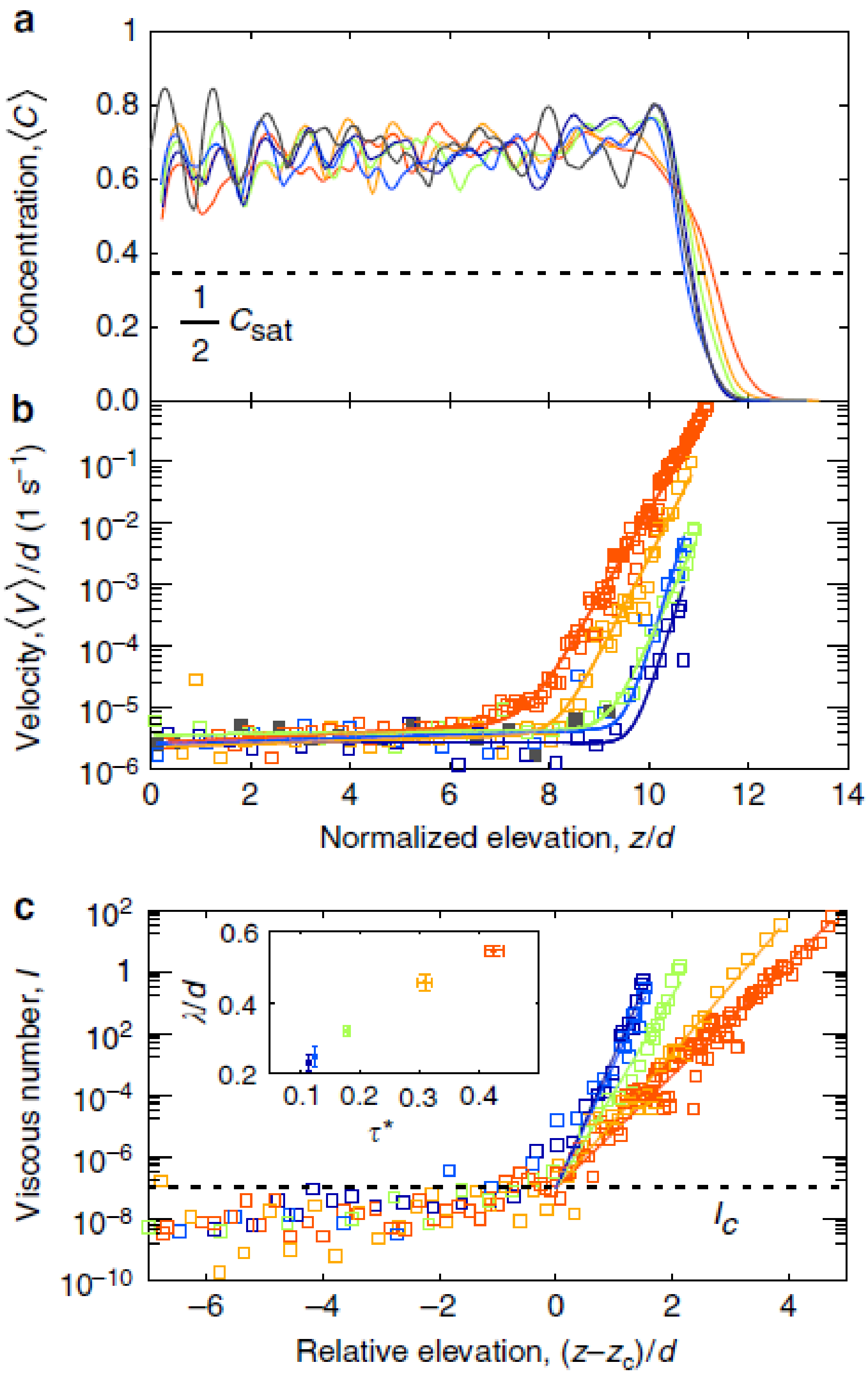
$$I_v = \frac{\eta_f |\dot{\gamma}|}{P_p}$$

Effective friction & viscosity:

$$\tau = \mu \, P_p = \eta_{\text{eff}} \, \dot{\gamma}$$

Confining pressure f(depth)

$$P_p(z) = P_0 + (\rho_p - \rho_f) g \int_z^{+\infty} \langle \phi \rangle dz$$

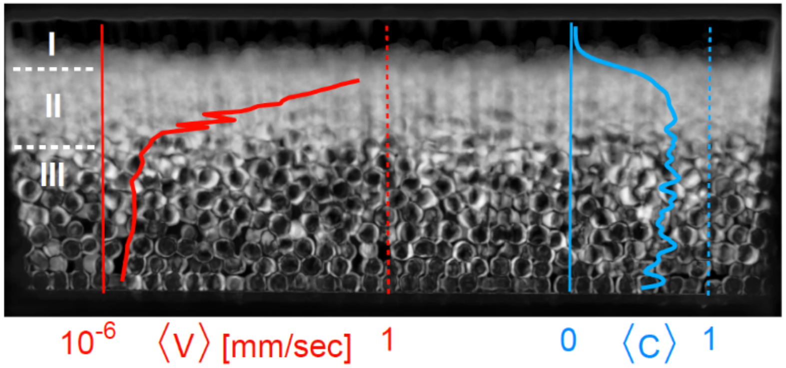


[Houssais, Ortiz, Durian & Jerolmack, *Nature Comm.* 2015; *PRE* 2017]

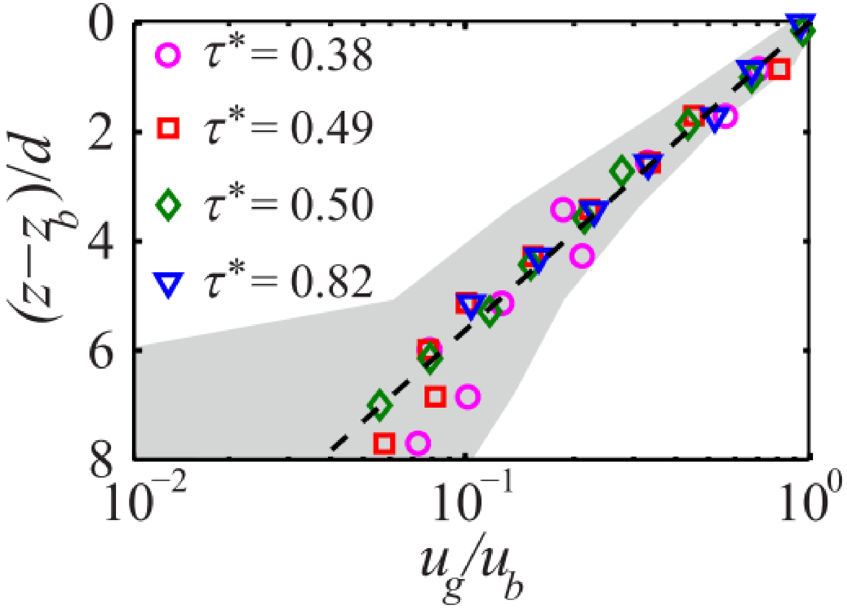
Testing μ(I) rheology of Boyer et al. [*PRL 2011*]

Remarkable agreement for $10^{-5} < I_v < 1$

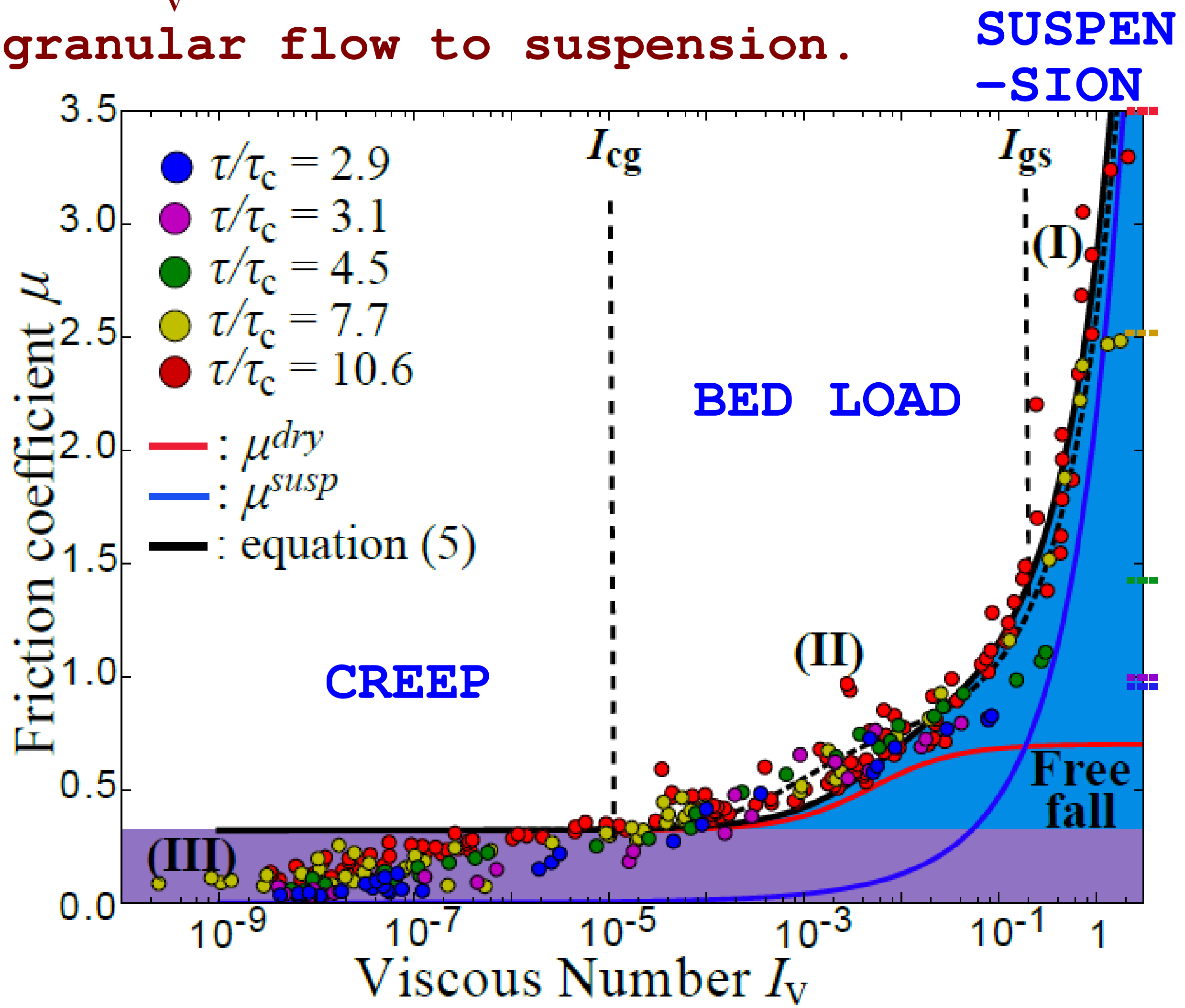
Sediment transport: Dense granular flow to suspension.



[Houssais, Ortiz, Durian & Jerolmack, *Phys. Rev. E 2017*]



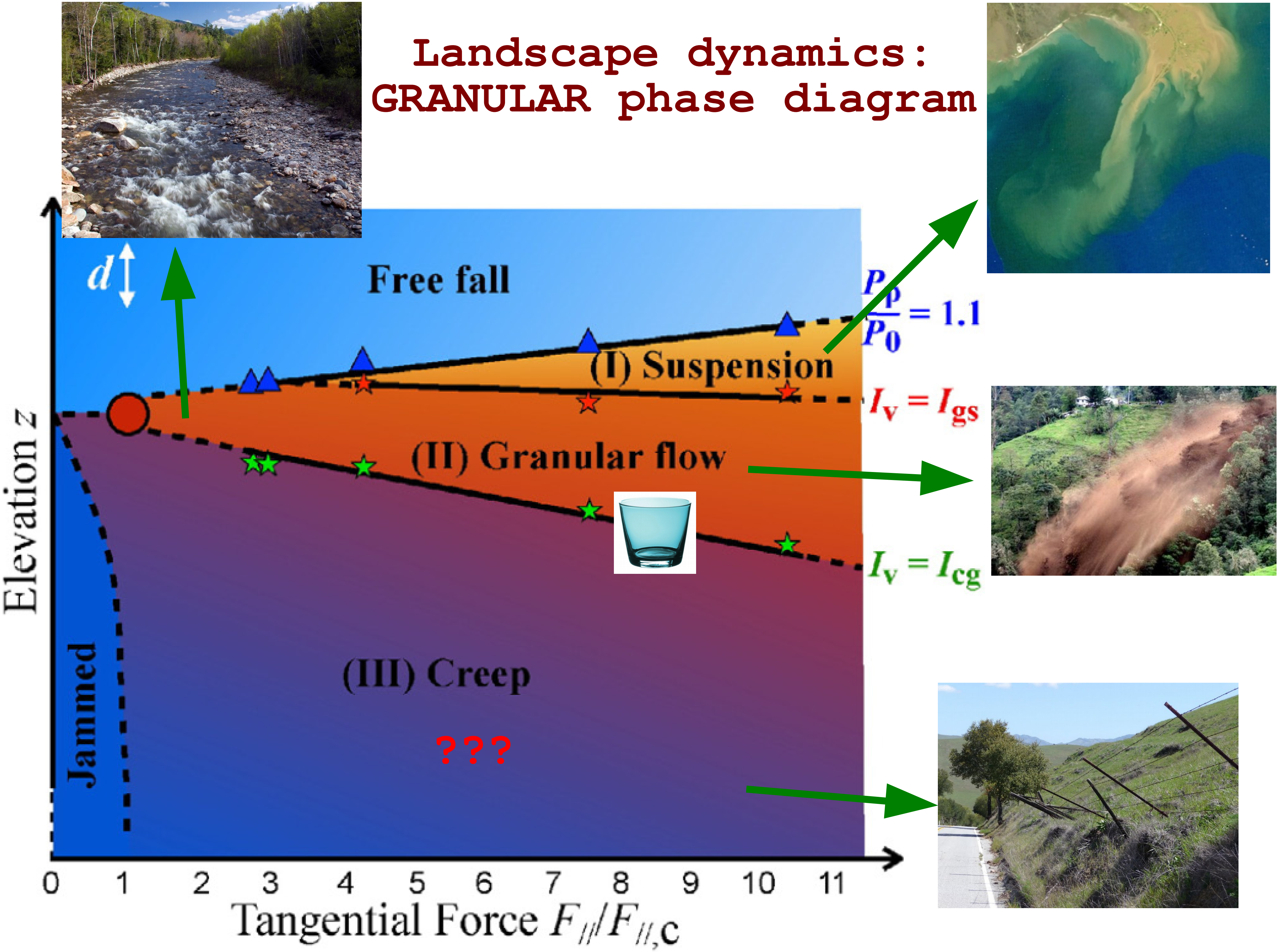
[Allen & Kudrolli, *Phys. Rev. Fluids* 2017]



Creep breaks local rheology!

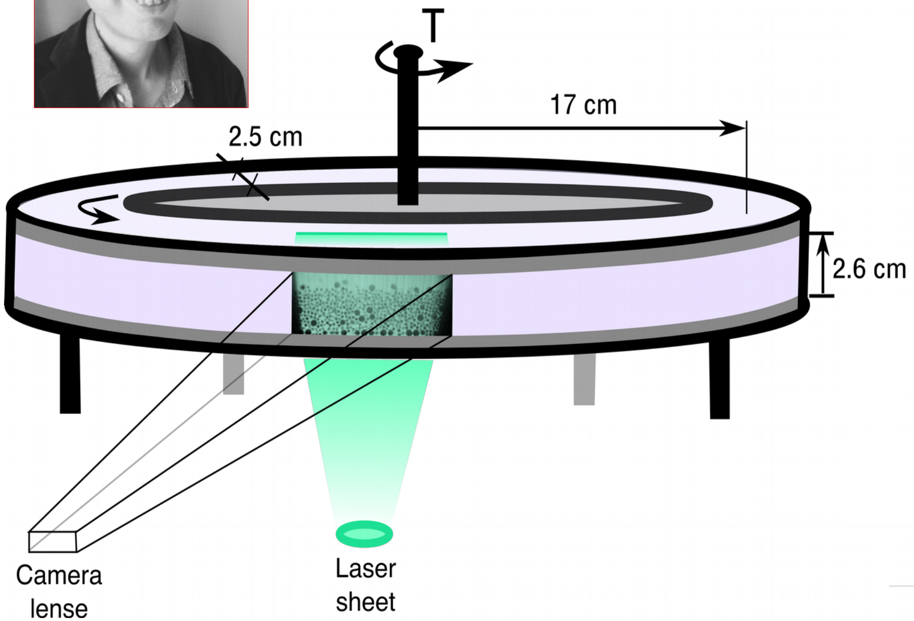
Nonlocal rheology models (e.g., Kamrin) appear to work.

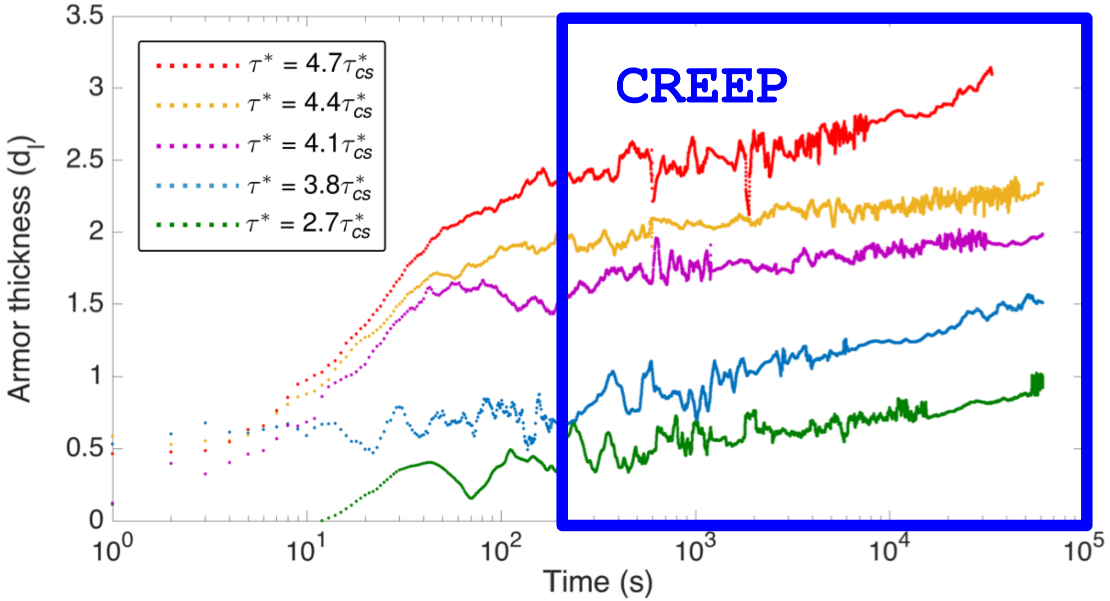
Landscape dynamics:
GRANULAR phase diagram

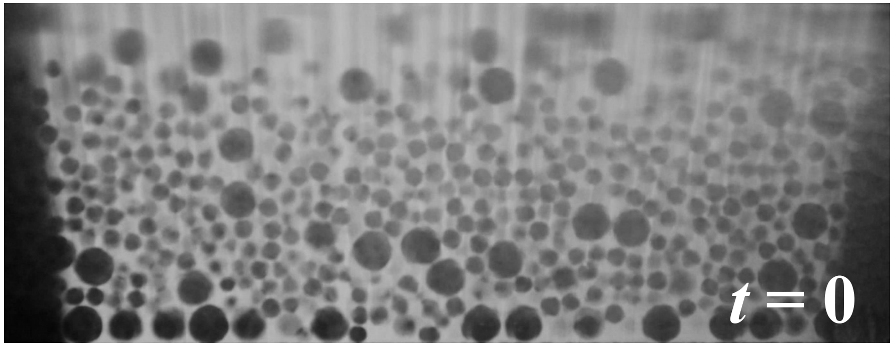


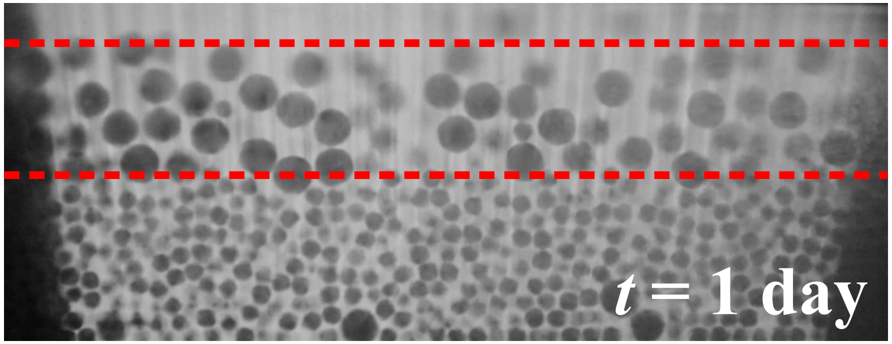
Contribution of creep to segregation

[Ferdowsi, Ortiz, Houssais & Jerolmack, *Nature Comm. 2017*]





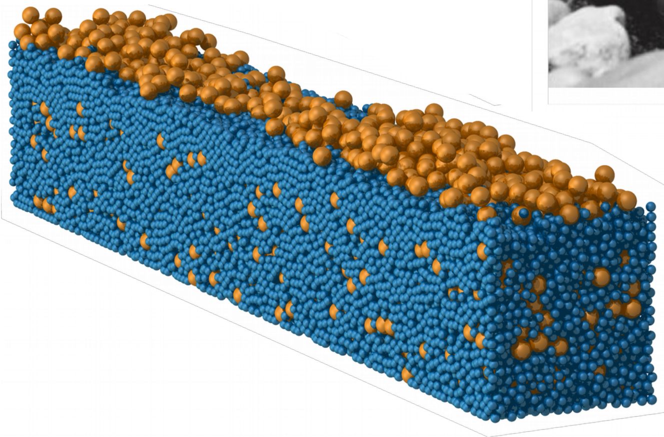




Segregation modes

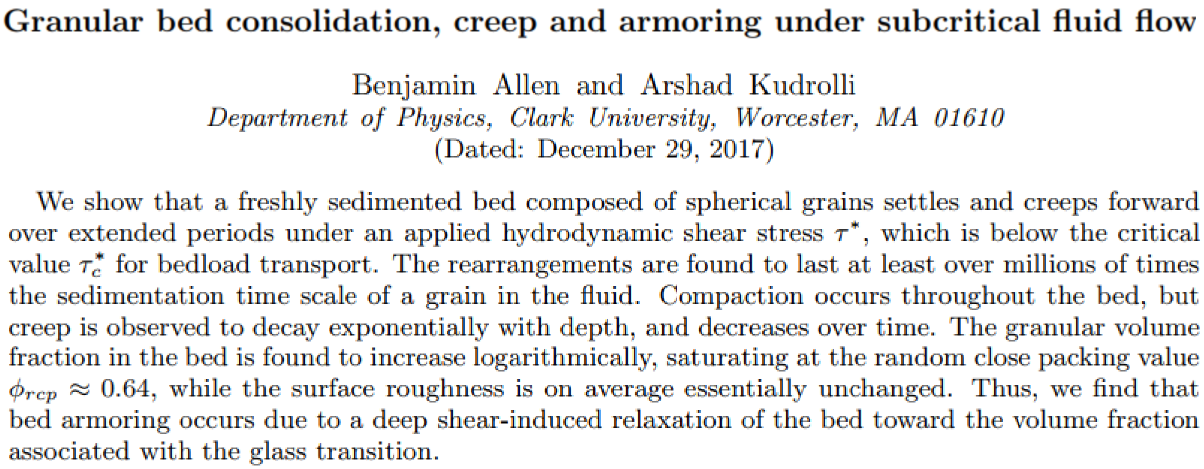
Bed-load → advection
Creep → diffusion.

River-bed armoring:
granular phenomenon



DEM simulations reproduce experiments, WITHOUT FLUID.

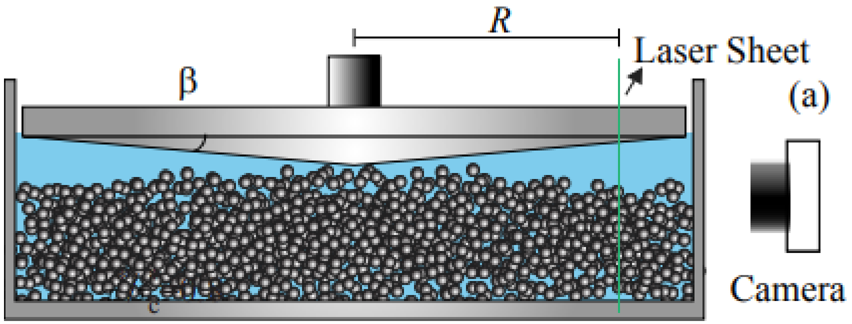
What does creep do? → "armoring"

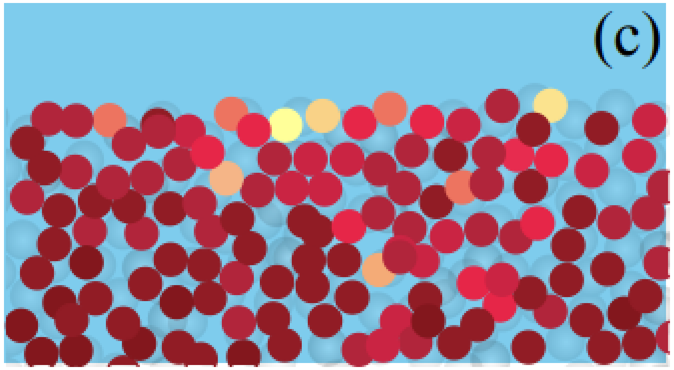


Granular bed consolidation, creep and armoring under subcritical fluid flow

Benjamin Allen and Arshad Kudrolli
Department of Physics, Clark University, Worcester, MA 01610
(Dated: December 29, 2017)

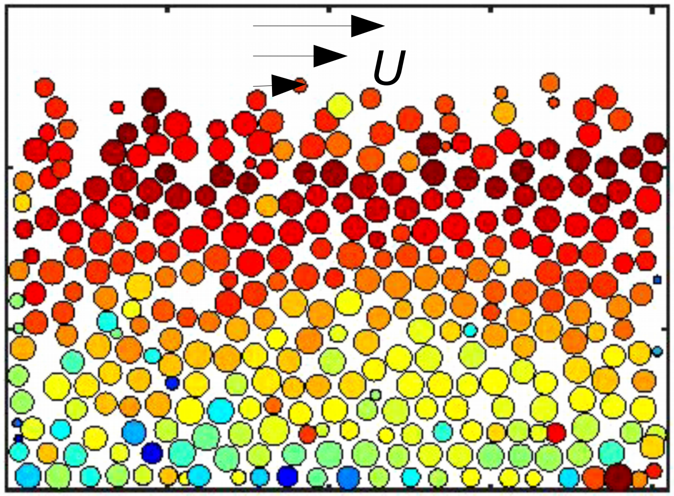
We show that a freshly sedimented bed composed of spherical grains settles and creeps forward over extended periods under an applied hydrodynamic shear stress τ^*, which is below the critical value τ_c^* for bedload transport. The rearrangements are found to last at least over millions of times the sedimentation time scale of a grain in the fluid. Compaction occurs throughout the bed, but creep is observed to decay exponentially with depth, and decreases over time. The granular volume fraction in the bed is found to increase logarithmically, saturating at the random close packing value $\phi_{rcp} \approx 0.64$, while the surface roughness is on average essentially unchanged. Thus, we find that bed armoring occurs due to a deep shear-induced relaxation of the bed toward the volume fraction associated with the glass transition.



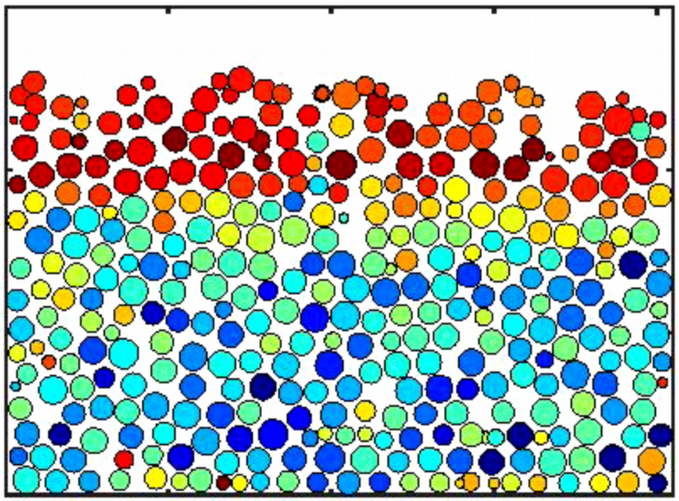


Sub-yield creep in the absence of "flow".

Grain velocity – start
→ Loose bed



Grain velocity – 10 min
→ More rigid



→ Creep drives subsurface development of structure.