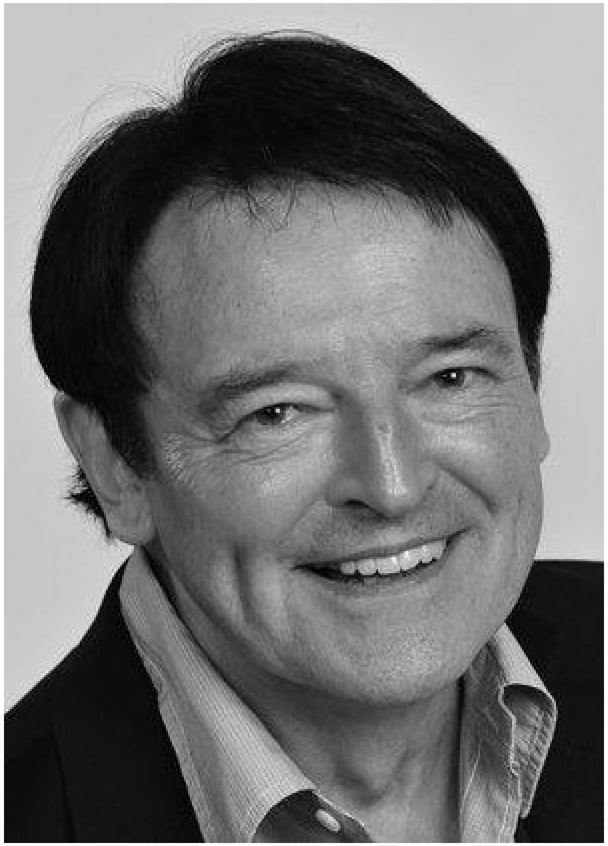
Making the Montecito Mudslides:

Unpacking the (relevant) physics of debris flows


MIKE ELIASON/SBC FIRE DEPARTMENT/NEWSCOM/ZUMA PRESS/NEWSCOM



Douglas Jerolmack[1,2], ***Thomas Dunne***[3]

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3. Bren School, UC Santa Barbara

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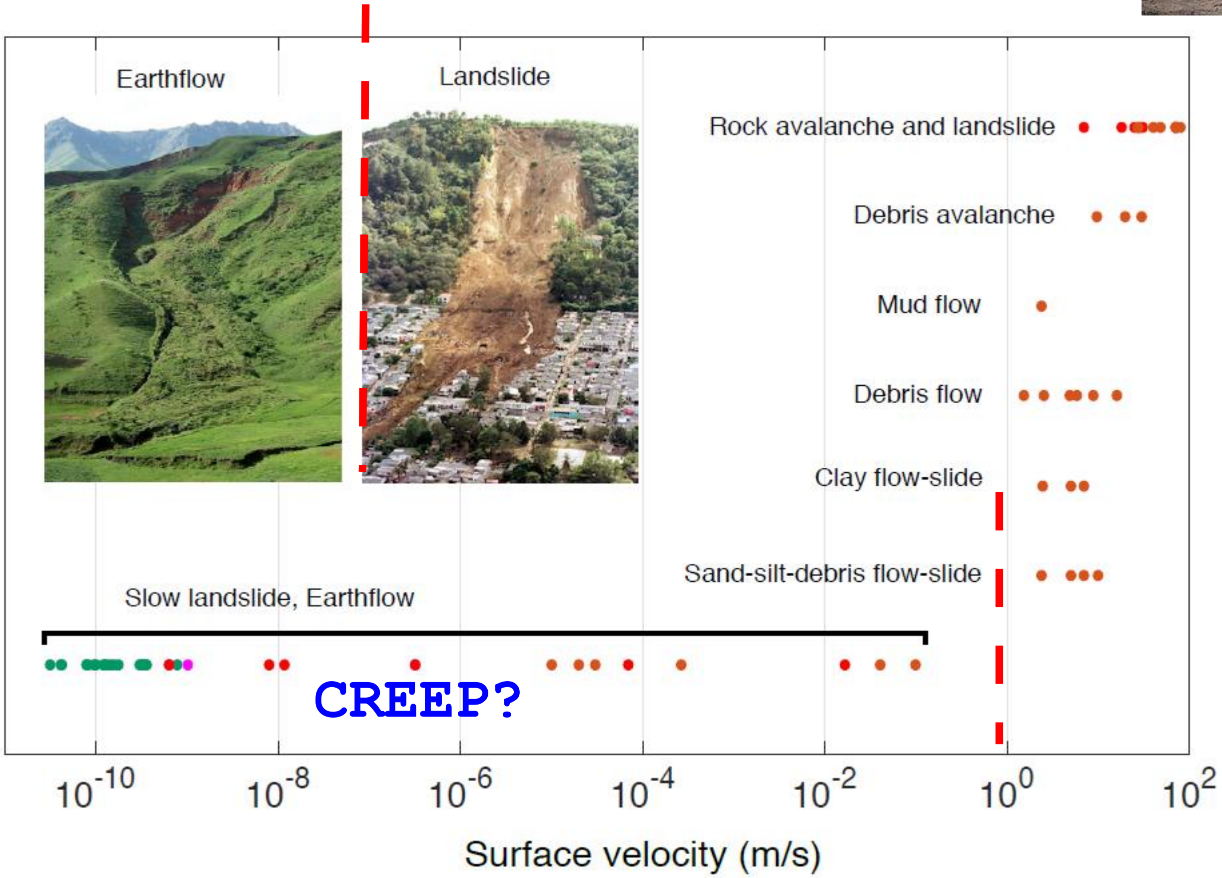
Landscapes:: creeping ↔ flowing



Montecito – 3x vertical exaggeration

A landscape built by debris flows

Flow struck early morning: limited direct observation

https://youtu.be/JNl2wUIynvY

0 – 0:40.
3:10 – end

Boulder-mud debris flow.

"The patrol vehicle was elevated off the road by the mudflow and was spinning without traction. The car was spun 180 degrees after fifteen seconds and was able to gain traction."

https://youtu.be/dDSAwM1nf_c

0:21 – 0:30.
2:07 – 2:21

Viscous suspension
High concentration silt/clay

Surges continued for hours

(cf. Nico Gray's talk)

https://youtu.be/HALHkKcFbg8

~1m deep, mud-rich flow pushing ~1m boulders.
Speed is ~5 m/s.

"2 phases": boulder-rich front → dense granular flow, makes a "dam".
Mud-rich flow behind: a visco-plastic (non-Newtonian) fluid(?)

Debris flow - Ilgraben

https://youtu.be/Fsh5E9m3PrM?list=PLrBn8y0HF3J0XjJt4l2N3BFQdDtjhAGr3

Boulder-rich “dam” front, up to car-sized.

Dense, viscous mud ponded behind

Headwaters – burned hills

Looking upstream at trib. entry to San Ysidro Creek. 12 February, 2018

Source material – mud → gravel

Dry ravel moving into channel.

Cold Spring Creek, 6 February 2018.

Rills cut into ash and mud.

Trib to San Ysidro Creek, 12 Feb.

Source material - boulders

Boulders tumble down valley walls, accumulate in channels.

Looking upstream, bedrock headwater trib. to San Ysidro Creek.
12 February, 2018

The aftermath - canyon

Looking downstream in Cold Spring Creek canyon.

Flow in picture is result of ruptured water line.

Note blown out channel, with boulders and debris.
Many trees were cleared out.

The aftermath – top of fan

A new “boulder field” left behind by the debris flow.

Glen Oaks neighborhood, Montecito.

2 February, 2018.

The aftermath – top of fan

Glen Oaks neighborhood,
Montecito.

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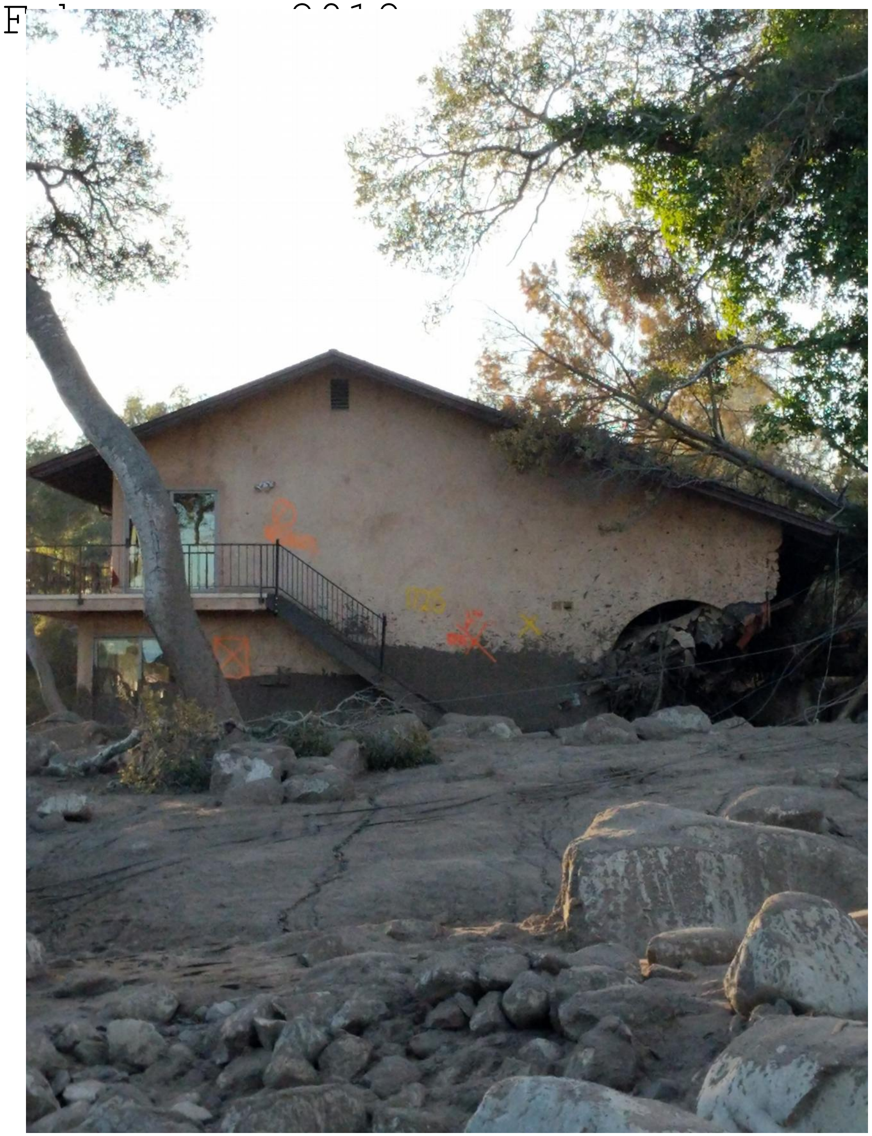


The aftermath - down fan

An avocado grove on San Leandro Drive.
San Ysidro Creek.

2 February, 2018.

~20 cm mud drape, still wet 3 weeks after deposition.

Estimating flow depth

Mudline on trees.

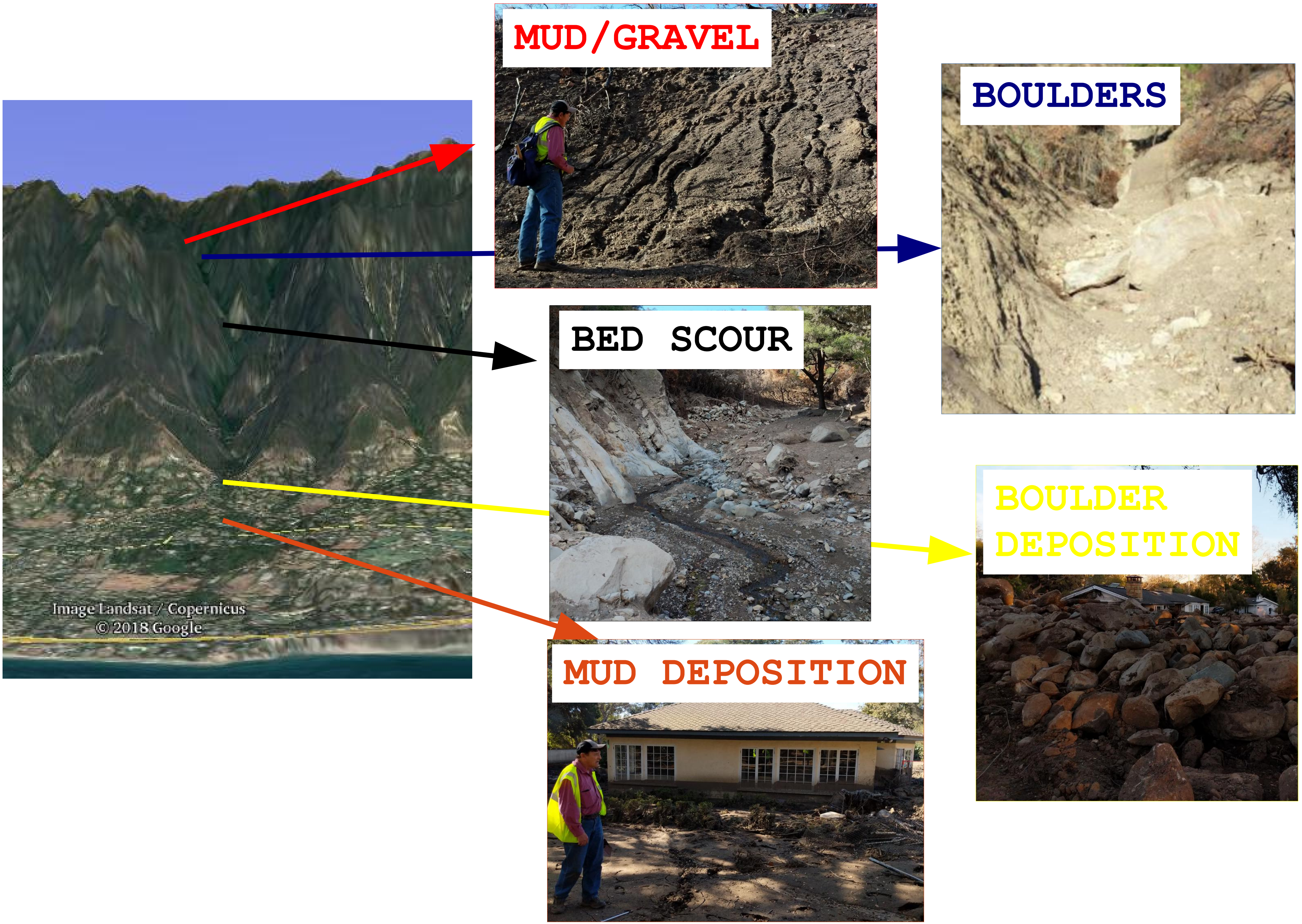
San Ysidro Creek,2 February 2018

Damage on bridge bottom.

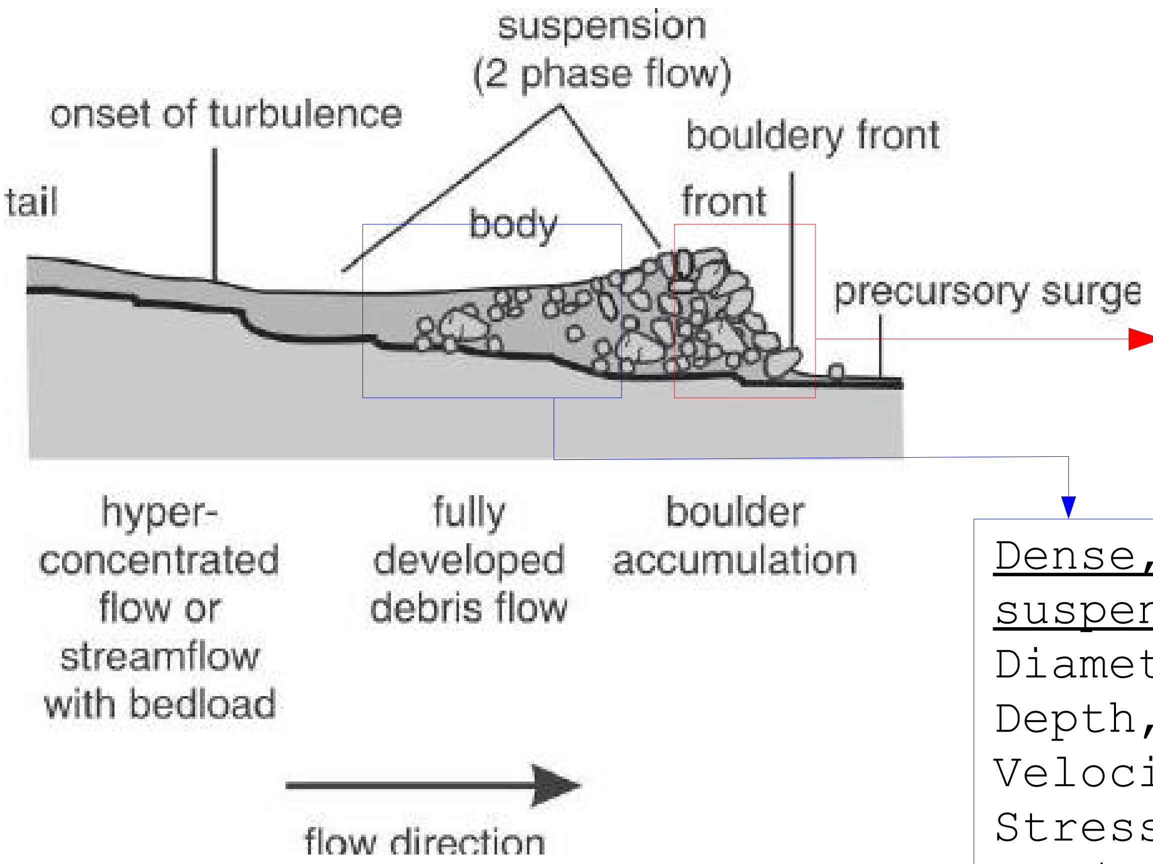
~4 m flow depth

Mud/gravel mix on
~1.5m boulder
~3m above channel

Montecito debris flow zones



Debris flow – conceptual model

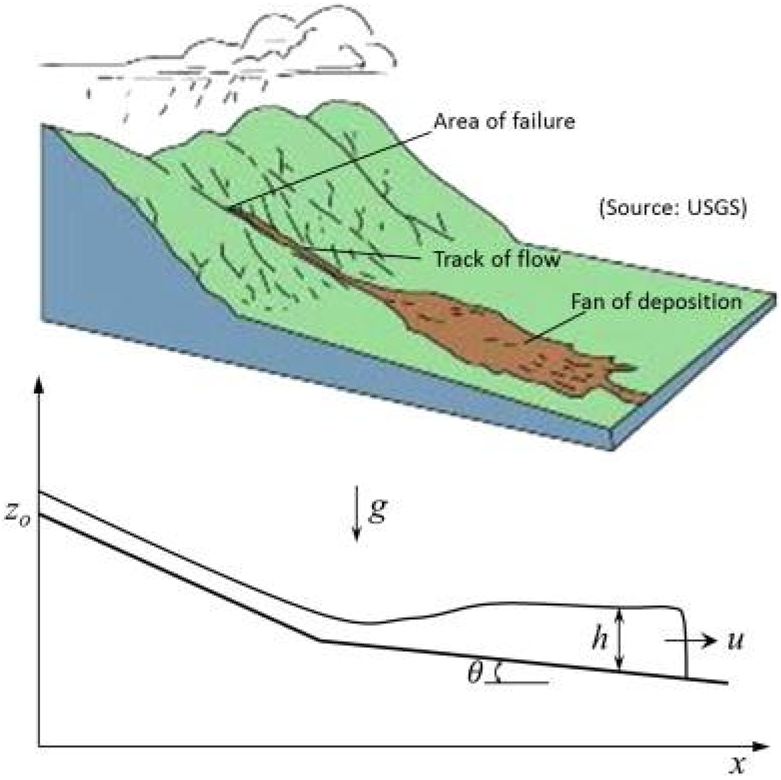


Dense granular flow:
Diameter, $D \sim 1$ m
Depth, $h \sim 1\text{-}4$ m
Velocity, $u \sim 5\text{-}10$ m/s
Stress carried by grains

Dense, sedimenting suspension (mudflow):
Diameter, $D < 10^{-3}$ m
Depth, $h \sim 1\text{-}4$ m
Velocity, $u \sim 5\text{-}10$ m/s
Stress carried by fluid
Mud/sand
High concentration → laminar

How do we create this flow?

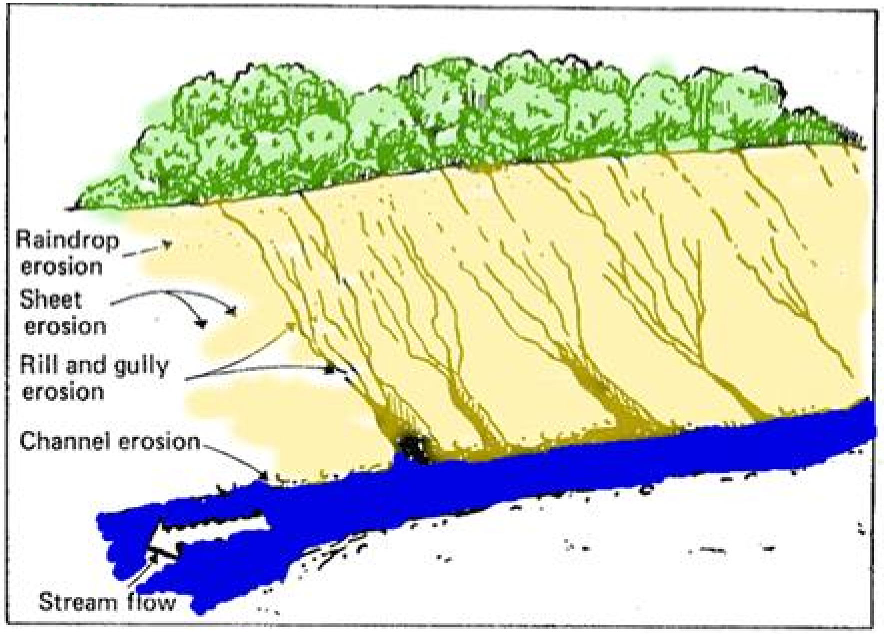
Montecito debris flow - NOT a landslide



[Paik, *J. Hydro-env. Res.* 2015]

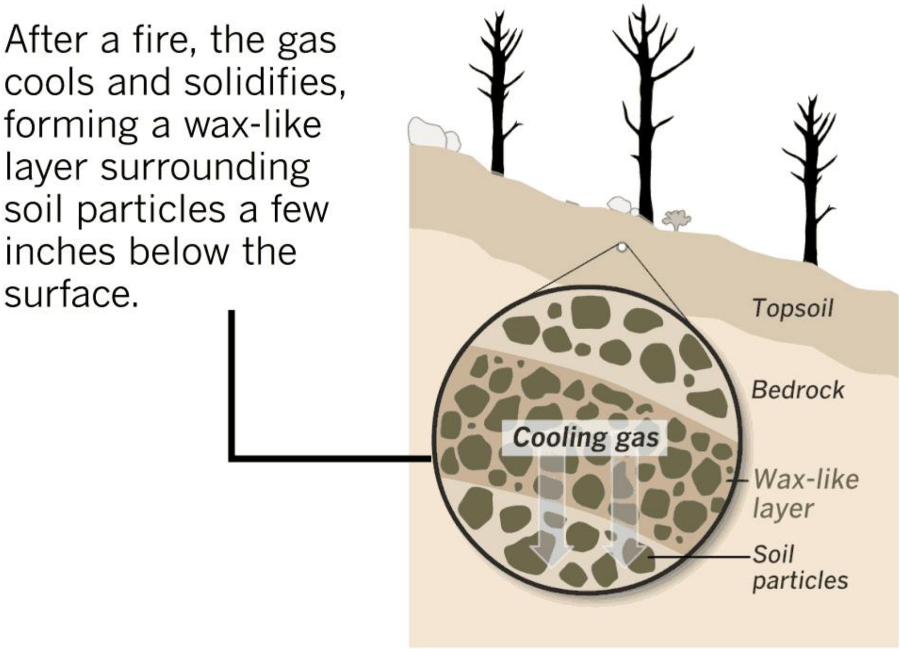
[science-art.com]

Mud-sand-gravel suspension formed from hillslope runoff.



[http://www.civil.ryerson.ca/Stormwater/menu_5/index.htm]

Mudflow setup: Thomas fire



After a fire, the gas cools and solidifies, forming a wax-like layer surrounding soil particles a few inches below the surface.

[Noozhawk.com]

[latimes.com]

[Cerda, *Fire effects on soils and restoration strategies* 2009]

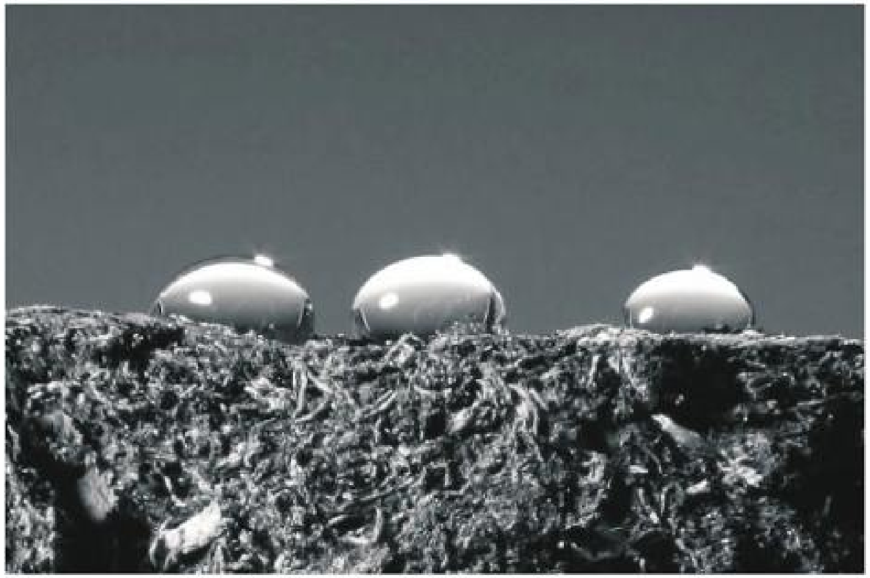


Fig. 1 Water drops resting on a highly repellent organic-rich soil (photo by Erik van den Elsen).

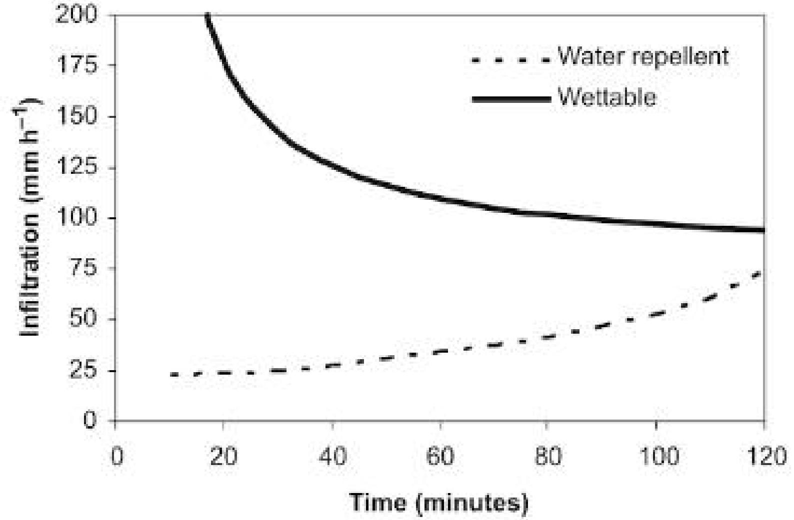
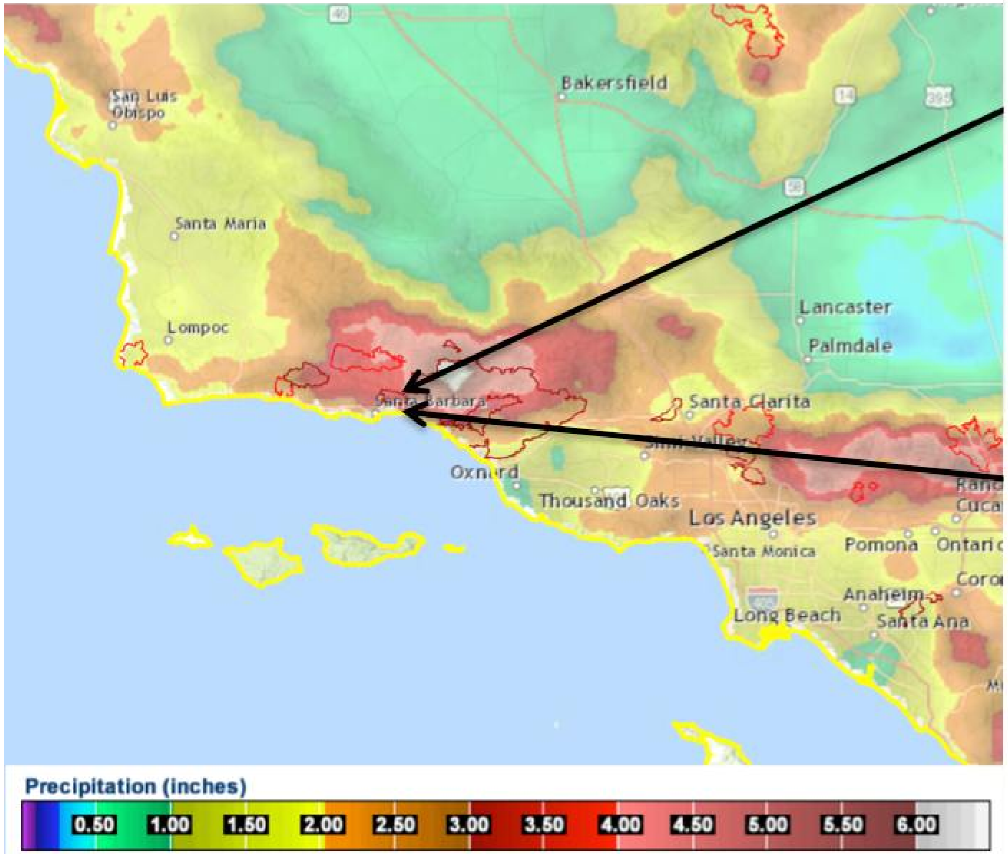
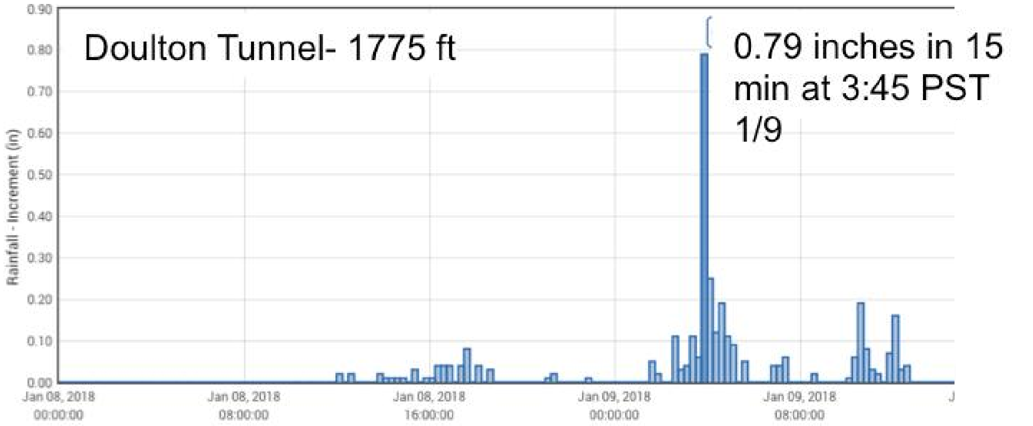


Fig. 2 Infiltration rates into water repellent and wettable soil (modified from Letey et al. 1962).

Mudflow trigger: intense rain

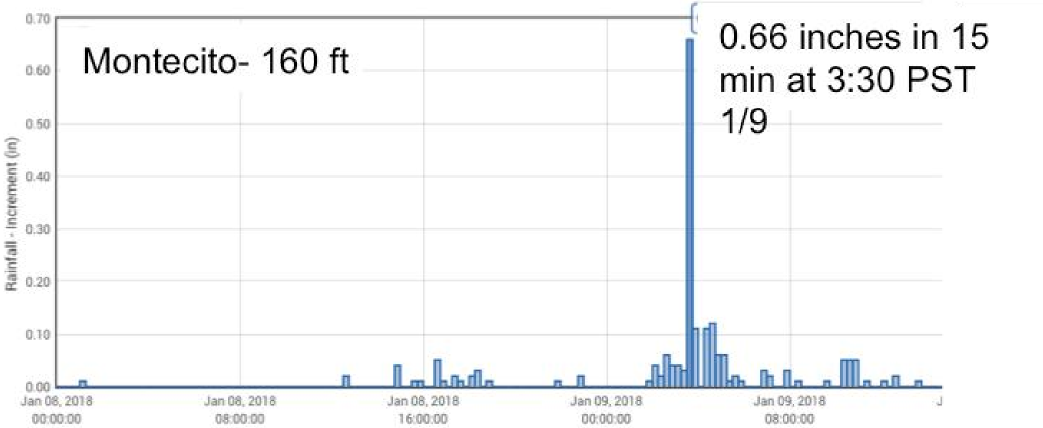


[http://cw3e.ucsd.edu/category/precipitation-event/]



Doulton Tunnel- 1775 ft

0.79 inches in 15 min at 3:45 PST 1/9



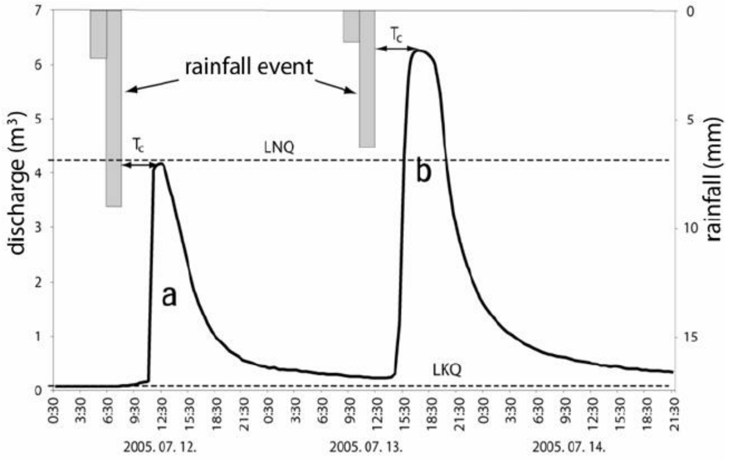
Montecito- 160 ft

0.66 inches in 15 min at 3:30 PST 1/9

Rainfall: almost delta function

Flash flood: shallow wave

To do: determine hydrograph (Tom Dunne), IC for mudlow



[Loczy et al., *Flash flood hazards* 2012]

Making mudflows on hillsides

Rills cut *all the way to ridge*

→ *no water accumulation*

Some lobate and mild levee features

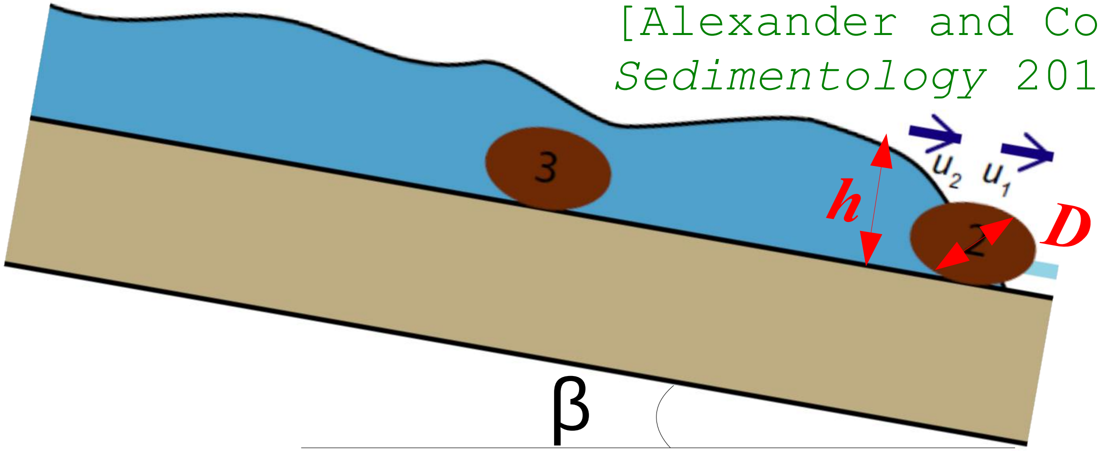
→ *viscous flow deposits*

Laboratory experiments:

→ *sediment concentration = f(slope)*

[Aksoy et al *Hydro Sci J* 2013; Chen et al *PLoS ONE* 2014]

Boulder entrainment



[Alexander and Cooker, *Sedimentology* 2016]

Force balance on a boulder at initiation of motion:

$$\frac{1}{2}C_D\rho_f A_s u^2 + F_g^{'} sin(\beta) + ku\boxed{\frac{\partial u}{\partial x}}V_s\rho_f - F_g^{'} cos(\beta)\mu_f = 0 \longrightarrow a \sim gh/D$$

Drag **Downslope-*g*** **Impulse** **Friction**

$$F_g^{'} = (\rho_s - \rho_f)gD$$

(Neglect lift force since *h* ~ *D*:)

Front moves as wave: $Fr \approx 1$ $\boxed{\rightarrow h_{crit} \approx \left(\frac{\rho_s}{\rho_f} - 1\right)\frac{\mu_f D}{0.5C_D + k}}$

Mud reduces h_{crit} 3x compared to water, due to density.

Lubrication reduces μ_f 2x or more.

h

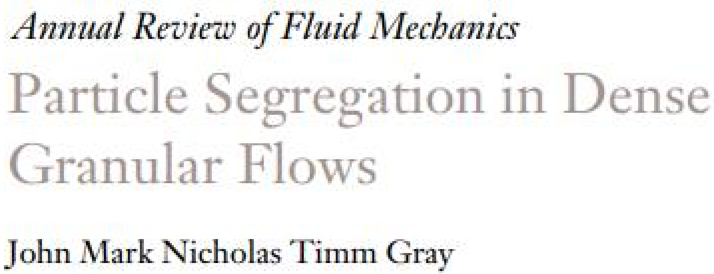
h_{crit} as small as *D*/10!

Condition for lift: $(u_t^2 - u_b^2) \approx \frac{2gD}{C_L}\left(\frac{\rho_s}{\rho_f} - 1\right)$

Mud reduces u_{crit} 2x compared to water.

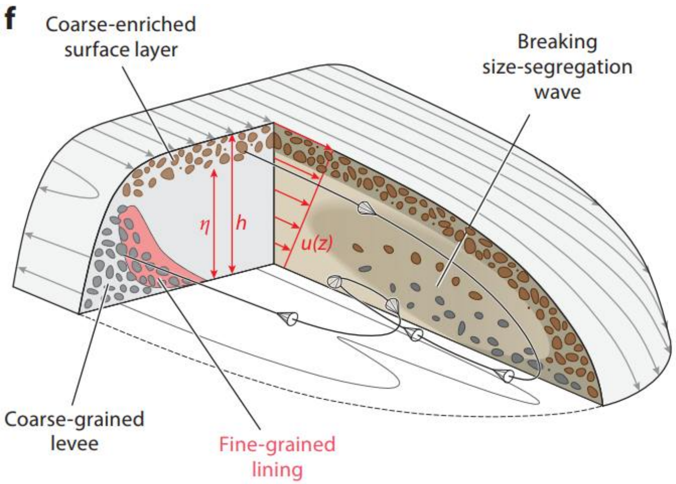
Creating a boulder dam: Granular segregation(?)

(*cf. Nico Gray's talk*)

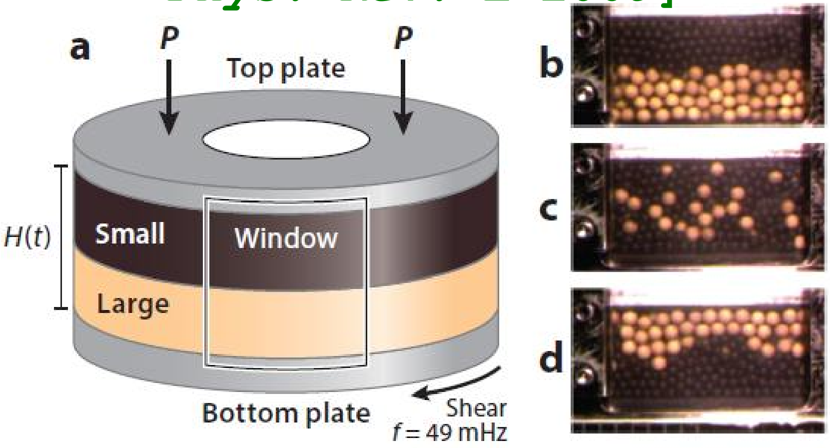

Annual Review of Fluid Mechanics

Particle Segregation in Dense Granular Flows

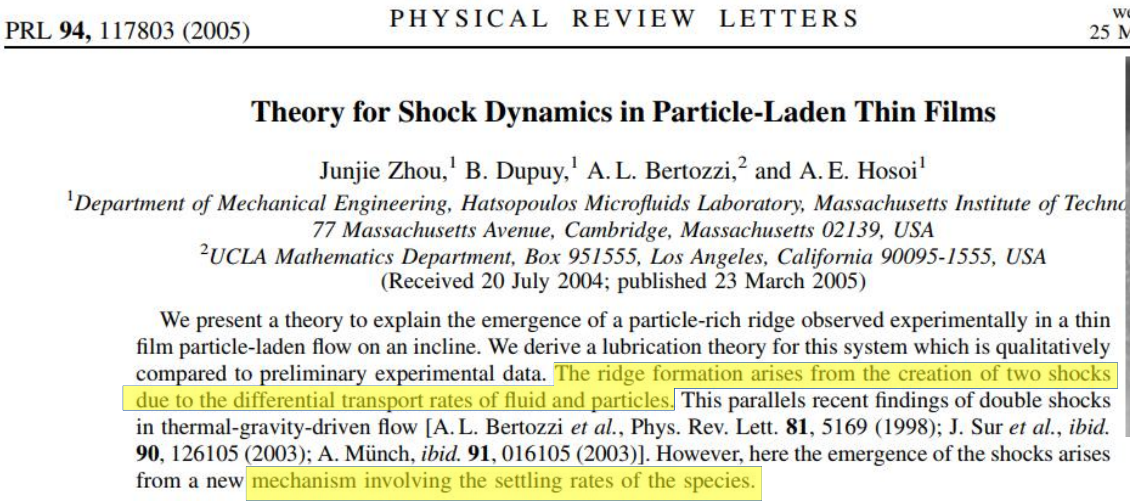
John Mark Nicholas Timm Gray



[Golick & Daniels, *Phys. Rev. E* 2009]



But granular fronts form in fluids too...



PRL **94,** 117803 (2005) PHYSICAL REVIEW LETTERS week ending 25 MARCH 2005

Theory for Shock Dynamics in Particle-Laden Thin Films

Junjie Zhou,[1] B. Dupuy,[1] A. L. Bertozzi,[2] and A. E. Hosoi[1]

[1]*Department of Mechanical Engineering, Hatsopoulos Microfluids Laboratory, Massachusetts Institute of Techn*
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA
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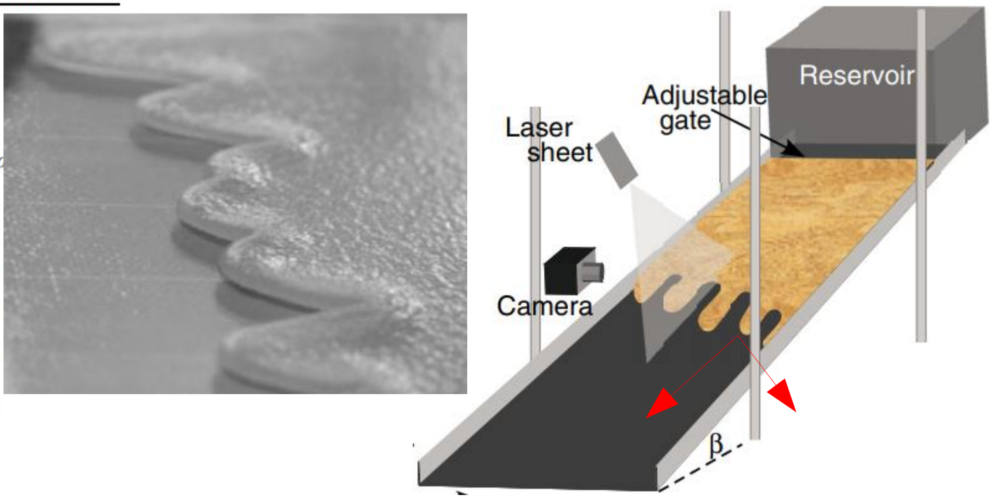
(Received 20 July 2004; published 23 March 2005)

We present a theory to explain the emergence of a particle-rich ridge observed experimentally in a thin film particle-laden flow on an incline. We derive a lubrication theory for this system which is qualitatively compared to preliminary experimental data. The ridge formation arises from the creation of two shocks due to the differential transport rates of fluid and particles. This parallels recent findings of double shocks in thermal-gravity-driven flow [A. L. Bertozzi *et al.*, Phys. Rev. Lett. **81**, 5169 (1998); J. Sur *et al.*, *ibid.* **90**, 126105 (2003); A. Münch, *ibid.* **91**, 016105 (2003)]. However, here the emergence of the shocks arises from a new mechanism involving the settling rates of the species.



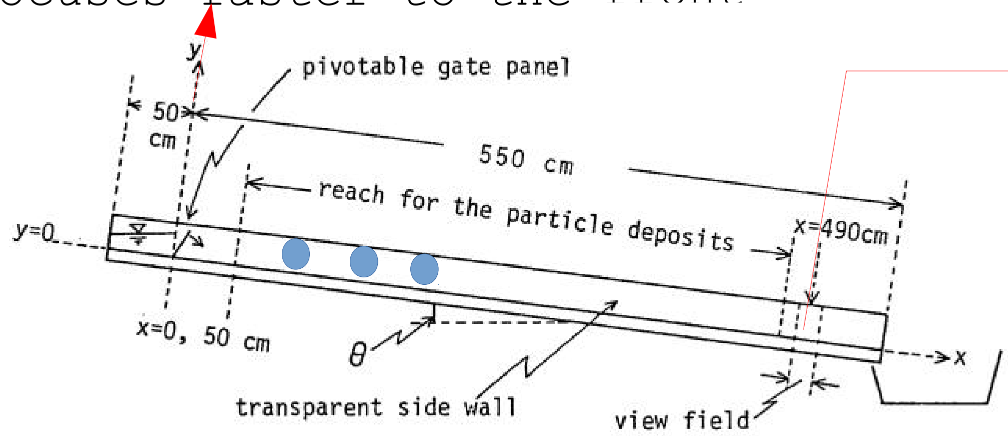
"Intuitively, we expect the large ridge to arise if the particle settling velocity along the plate exceeds that of the front."

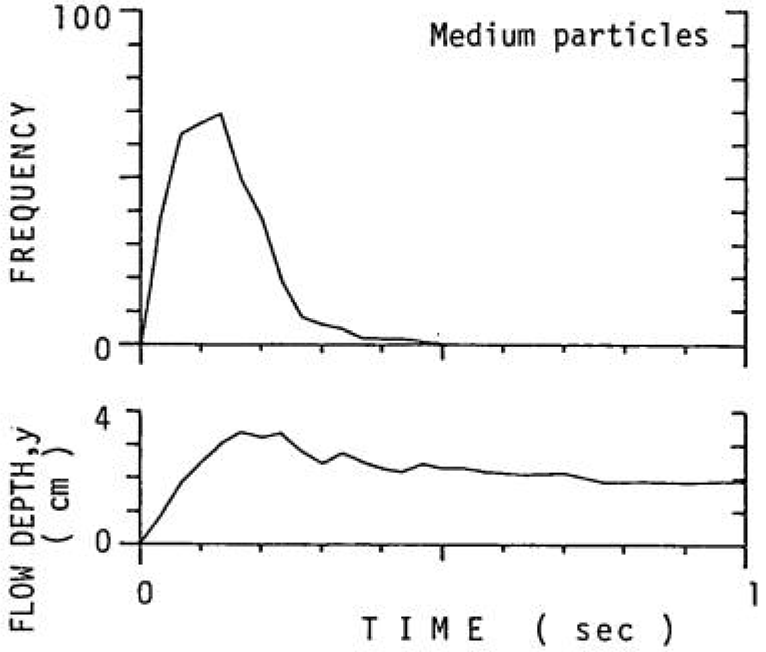
→ **Invokes hindered settling in high concentrations**

[Suwa, *Dissertation, Kyoto University* 1988]

Clear-water flood waves over gravel

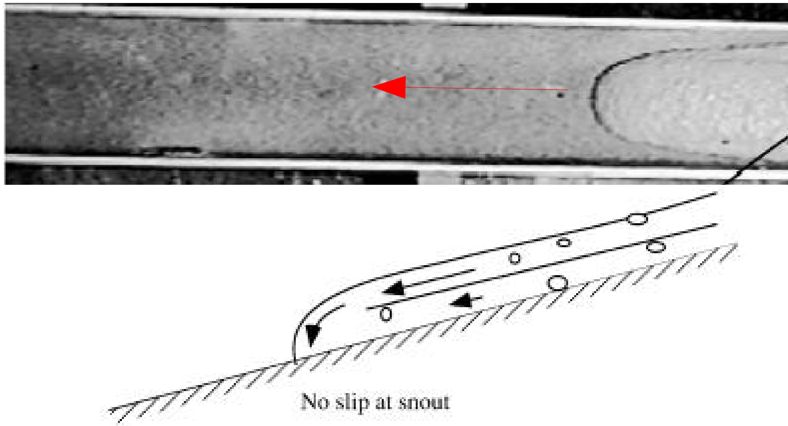
"[A] larger boulder attains a higher terminal velocity on a steep slope and focuses faster to the front"



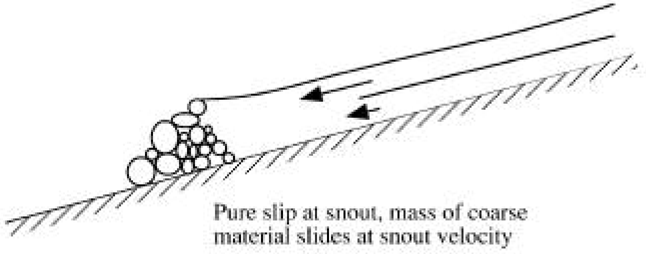


Granular fronts in mud

Sedimentation + shear...

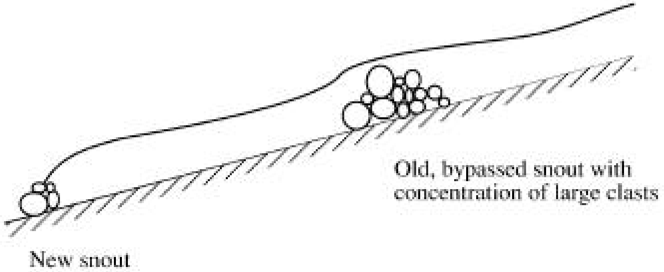


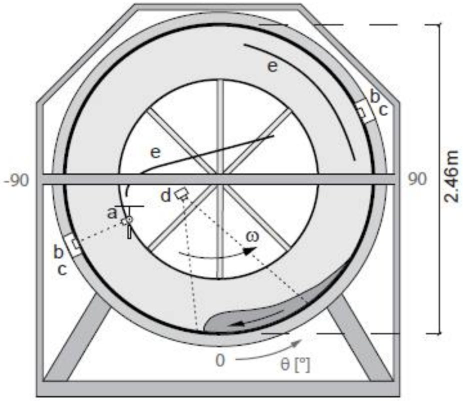
Debris flow without or prior to snout effect. Conveyor belt driven by body motion constantly and consistently lays down a new front from behind.



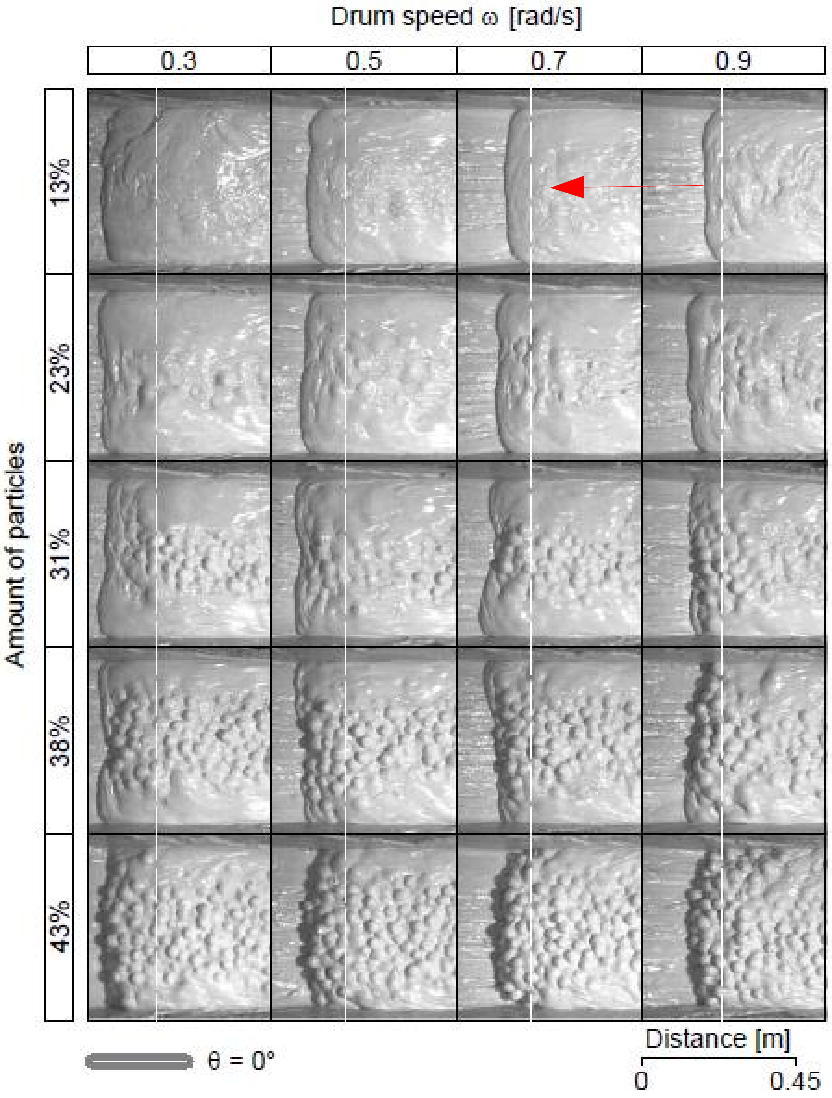
Snout effect. Larger clasts collect at front, shutting off the conveyor. Freezing of body occurs from front backward. Backwater also forms.

[Parsons et al., *J. Geology* 2001]

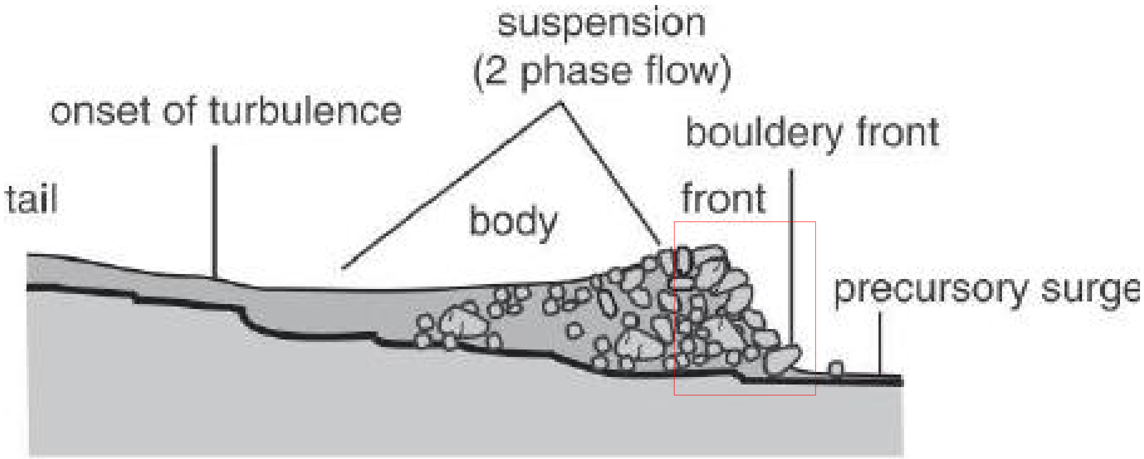




[Leonari et al., *Phys. Rev. E* 2015]



Boulder front: relevant scales



Front moves as wave:

$$Fr = \frac{u}{\sqrt{gh}} \approx 1$$

$$h = 1\text{-}4 \text{ m}$$
$$U = 5\text{-}10 \text{ m/s}$$

Collisions >> viscosity ***if fluid is clear water...***

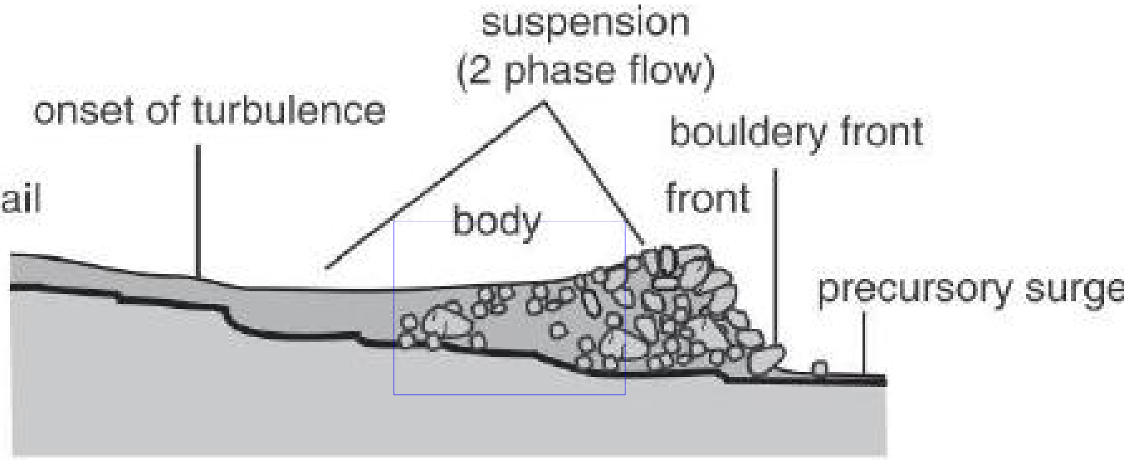
$$St = \frac{(\rho_s - \rho_f)Du}{\eta_f} \sim 10^6 \qquad N_b = \frac{\phi_s(\rho_s - \rho_f)D^2\frac{\partial u}{\partial h}}{(1-\phi_s)\eta_f} \sim 10^6$$

...but collisions ~ viscosity for concentrated muds.

Inertial ~ Confining/normal stress

$$N_s = \frac{\rho_s D^2(\frac{\partial u}{\partial h})^2}{(\rho_s - \rho_f)gh} \sim 1 \qquad I = D(\partial u/\partial h)\sqrt{(\rho_s - \rho_f)/P^p} \sim 1$$

Mud phase: scales

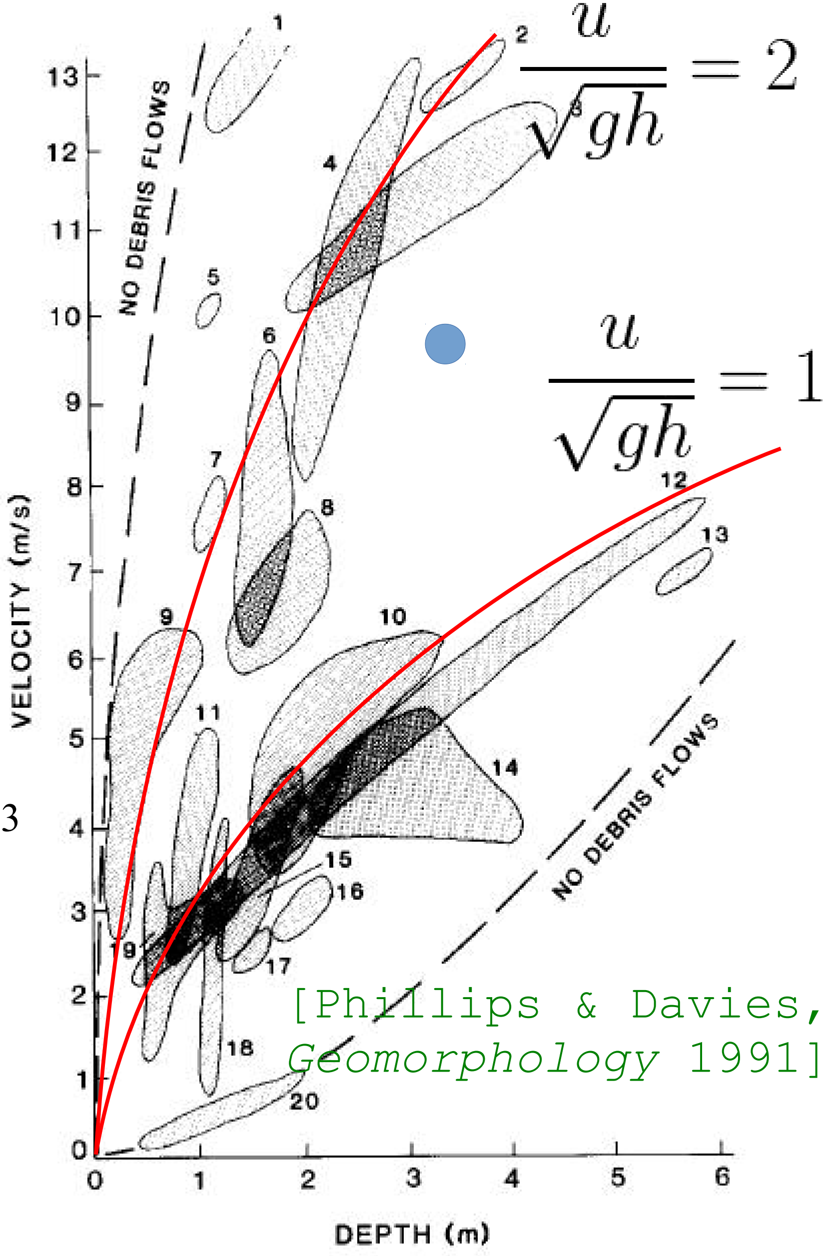


Boundary shear stress:
assume mud-rich flow

$$\tau_b = \rho_f g h S$$

$$S \sim 0.1$$

$$\rho_f \approx 2000\ \mathrm{kg/m^3}$$

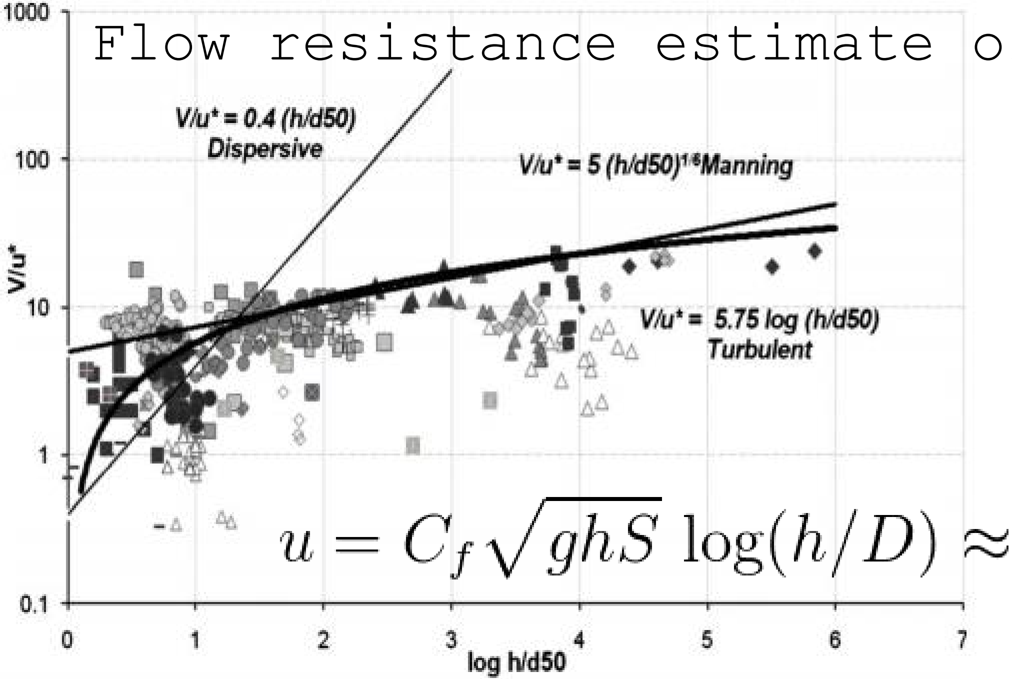


$$\frac{u}{\sqrt[3]{gh}} = 2$$

$$\frac{u}{\sqrt{gh}} = 1$$

[Phillips & Davies, *Geomorphology* 1991]

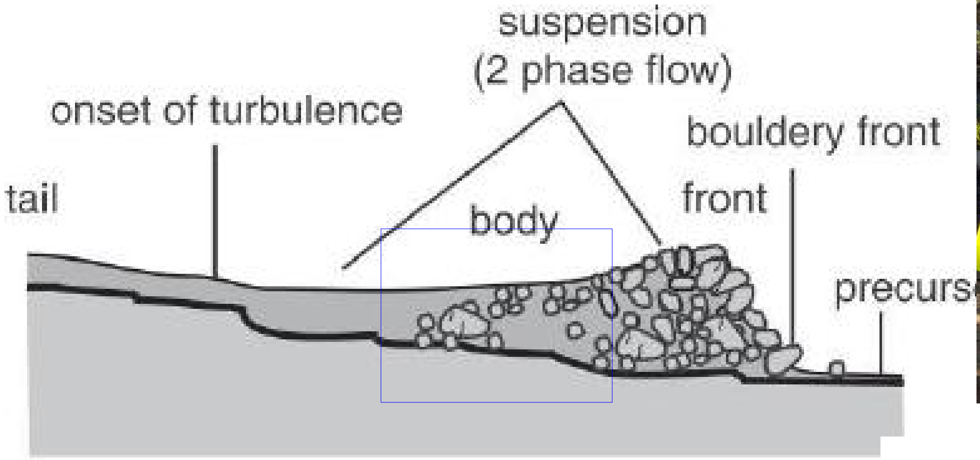
Flow resistance estimate of *u*:



$$u = C_f \sqrt{ghS}\,\log(h/D) \approx 10\sqrt{ghS} \sim 10\mathrm{m/s}$$

[Julien & Paris, *Am. Soc. Civil Eng. 2010*]

Mud phase: viscous, frictional flow



"Mud": $D < 1$ mm

Viscous

$$N_b = \frac{\phi_s(\rho_s - \rho_f)D^2\frac{\partial u}{\partial h}}{(1-\phi_s)\eta_f} \sim 1$$

Frictional

$$N_s = \frac{\rho_s D^2(\frac{\partial u}{\partial h})^2}{(\rho_s - \rho_f)gh} \sim 10^{-6}$$

Herschel-Buckley rheology:

$$\tau = \tau_0 + k\dot{\gamma}^n$$

Yield stress **Viscosity (if $n = 1$)**

$h \sim 0.2$ m mud
'frozen' on $S \sim 0.04$

$$\tau_0 = \rho_f ghS$$

Yield stress:

$$\boxed{\tau_0 \sim 200 \text{ Pa}}$$

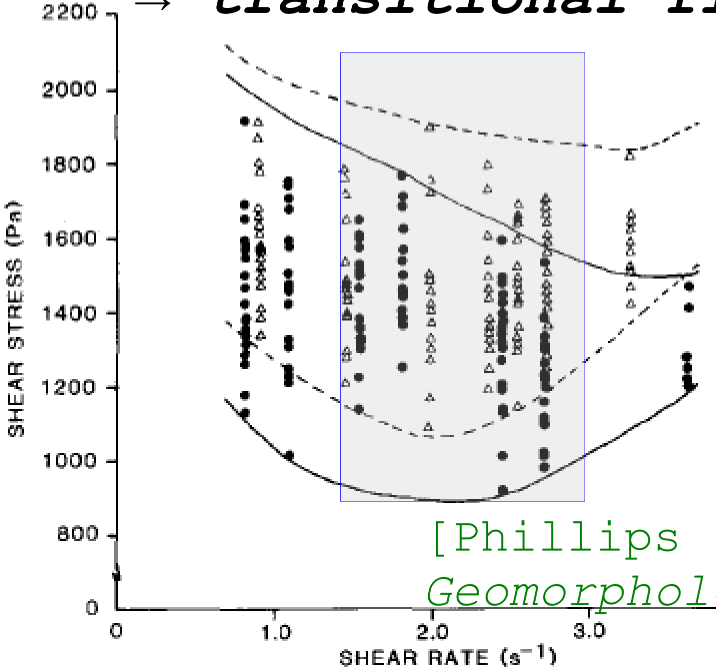
VISCOSITY: Bingham: $n = 1$ for high shear rates (??)

$$(\tau_b - \tau_o)/\dot{\gamma} = \eta_{eff} \approx 300 \text{ Pa} \cdot \text{s}$$

→ ***viscosity > 10^5 water***

$$Re = \rho_f hu/\eta_{eff} \sim 10^2$$

→ ***transitional flow***



[Phillips & Davies, *Geomorphology* 1991]

Mud phase comparison: your sink

Froude number

$$Fr = \frac{u}{\sqrt{gh}} \quad \geq 1$$

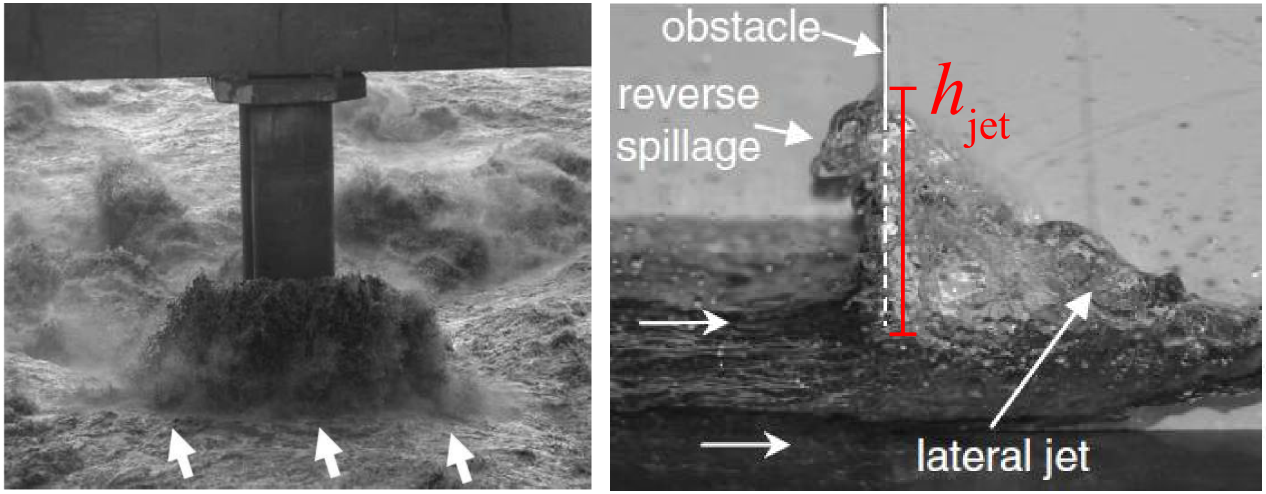
$h \sim 0.001$ m

$\rightarrow u \sim 0.1$ m/s

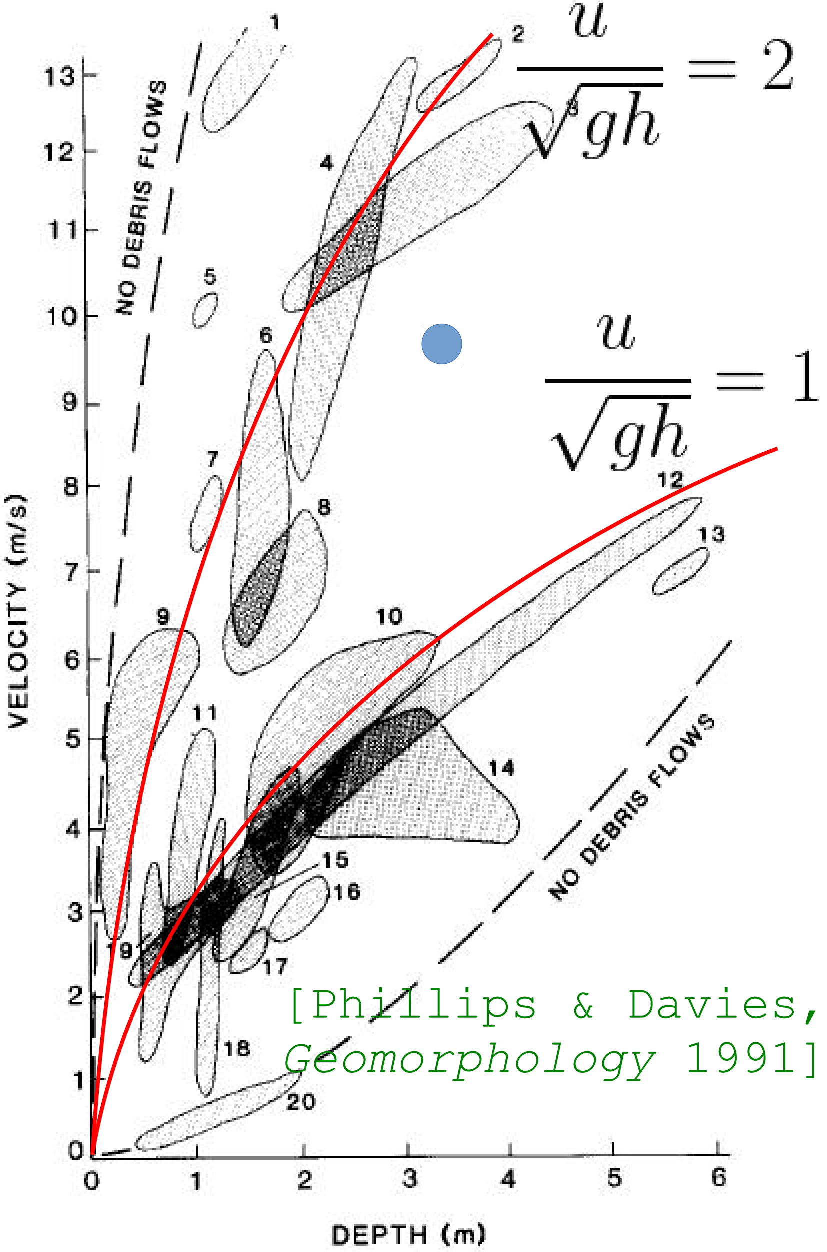
Reynolds number

$$Re = \rho_f hu/\eta_{eff} \sim 10^2$$

Mud phase: scales



[Riviere et al., *J. Hydraulic Eng.* 2017]



$$\frac{u}{\sqrt{gh}} = 2$$

$$\frac{u}{\sqrt{gh}} = 1$$

[Phillips & Davies, *Geomorphology* 1991]

$$Fr \geq 1$$

Energy balance argument for wall jet height (no backwater):

$$h_{jet} \approx \frac{u^2}{2g}$$

Mudlines indicate h_{jet} up to ~4 m(!!)

$$\rightarrow u = 9 \text{ m/s}$$

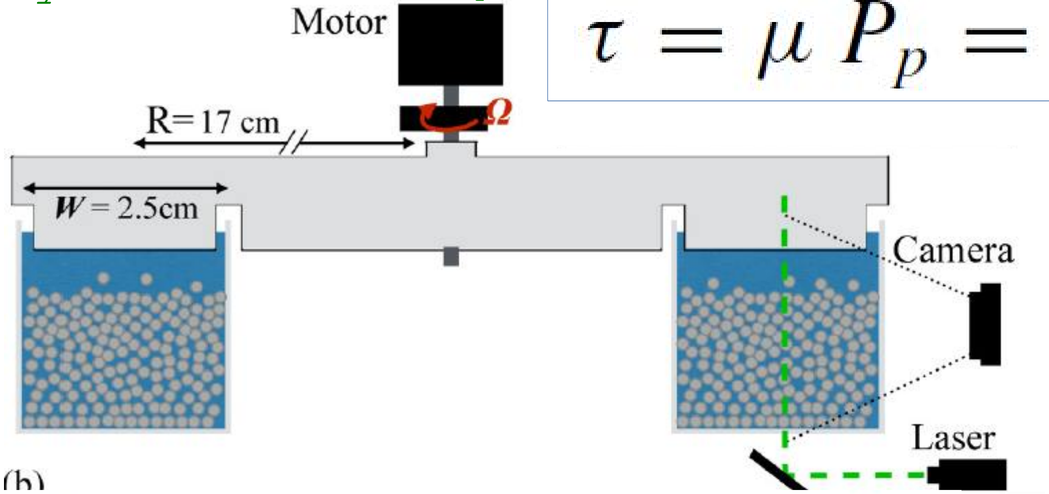
Mud phase: rheology and solids content

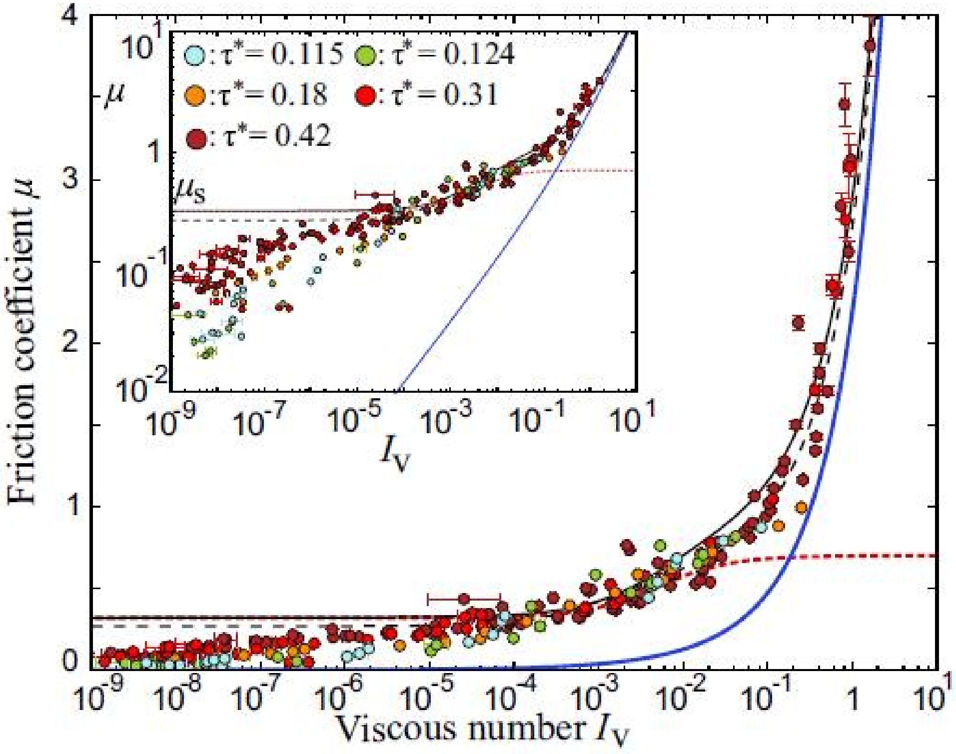
[Boyer et al, *Phys. Rev. Lett.* 2011]
[Houssais et al, *Phys. Rev. E* 2017]

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

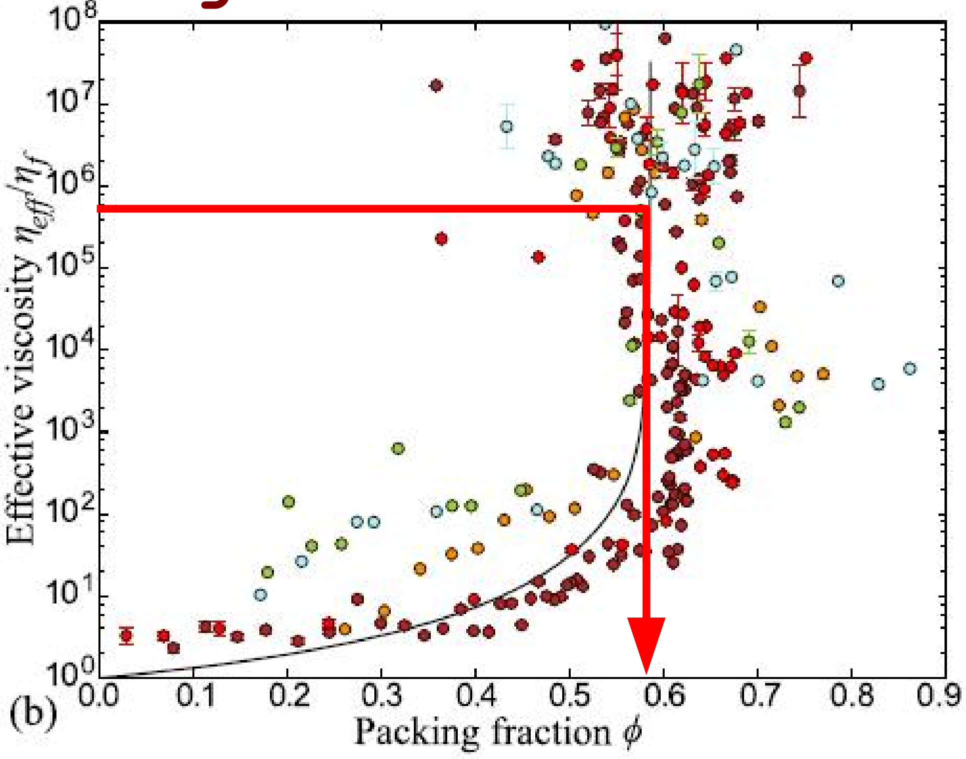
$$I_v = \frac{\eta_f \, |\dot{\gamma}|}{P_p} \sim 10^{-6}$$

$$\phi = \frac{\phi_c}{1 + I_v^{1/2}}$$





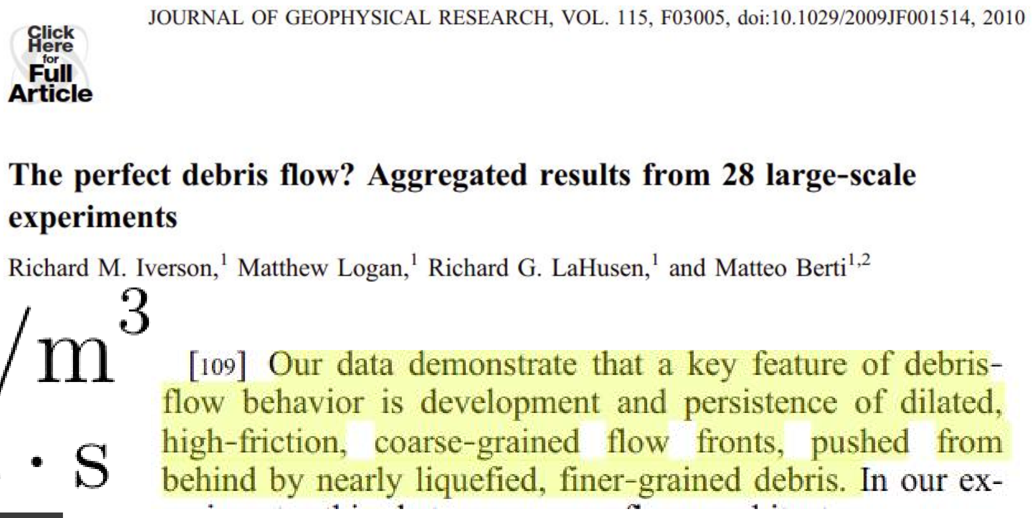
High solids content



Inferred debris flow properties similar to Iverson experiments/theory:

$$\phi \approx 0.6 \rightarrow \rho_f \approx 2000 \text{ kg/m}^3$$

$$u = 10 \text{ m/s} \qquad \tau_y \approx 100 \text{Pa} \cdot \text{s}$$

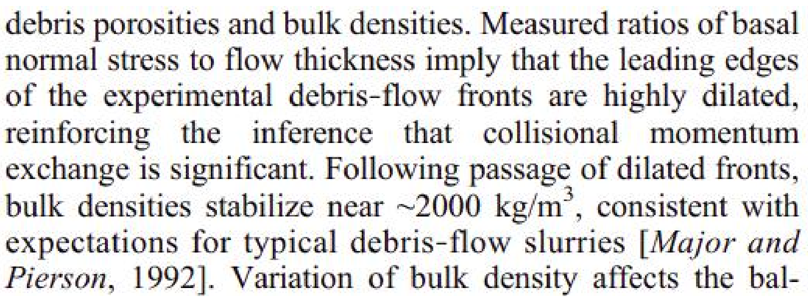


JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 115, F03005, doi:10.1029/2009JF001514, 2010

The perfect debris flow? Aggregated results from 28 large-scale experiments

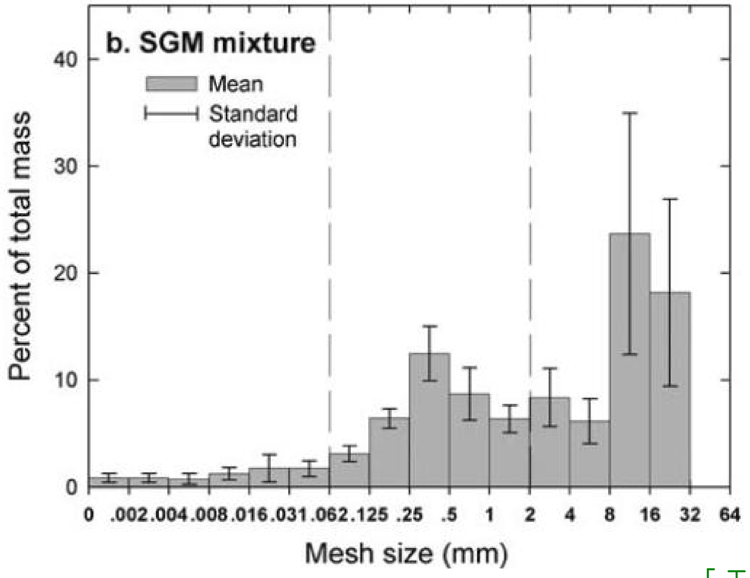
Richard M. Iverson,[1] Matthew Logan,[1] Richard G. LaHusen,[1] and Matteo Berti[1,2]

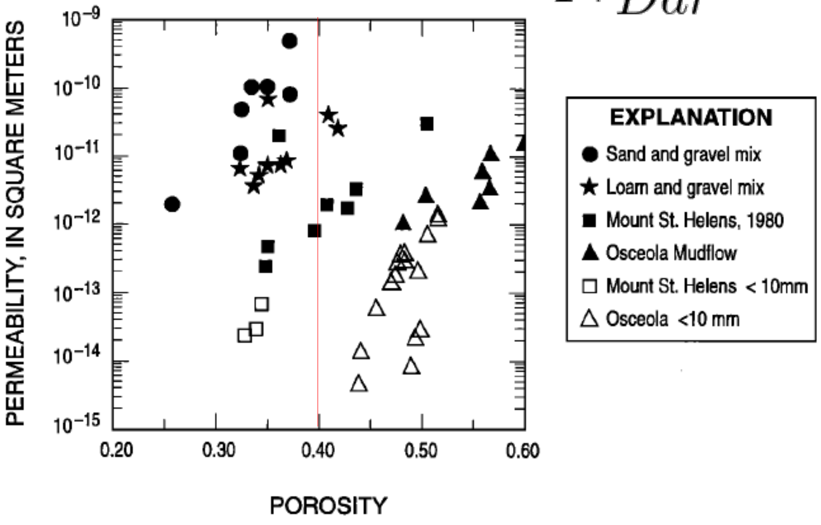
[109] Our data demonstrate that a key feature of debris-flow behavior is development and persistence of dilated, high-friction, coarse-grained flow fronts, pushed from behind by nearly liquefied, finer-grained debris. In our ex-



debris porosities and bulk densities. Measured ratios of basal normal stress to flow thickness imply that the leading edges of the experimental debris-flow fronts are highly dilated, reinforcing the inference that collisional momentum exchange is significant. Following passage of dilated fronts, bulk densities stabilize near ~2000 kg/m^3, consistent with expectations for typical debris-flow slurries [*Major and Pierson*, 1992]. Variation of bulk density affects the bal-

$$N_{Dar} = \frac{\eta_f}{\phi \rho_s \dot{\gamma} k} \sim 10^5$$





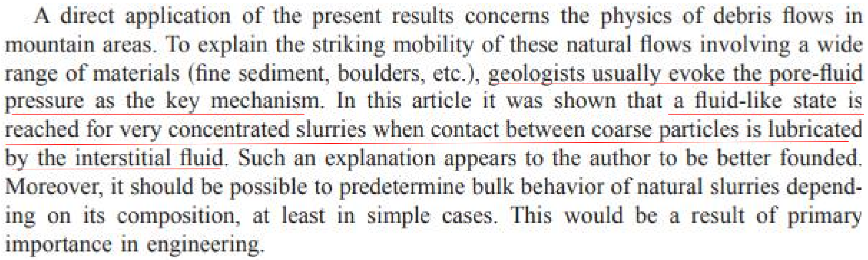
Darcy #: Significant fluid pressures

[Iverson, *Rev. Geophys.* 1997]

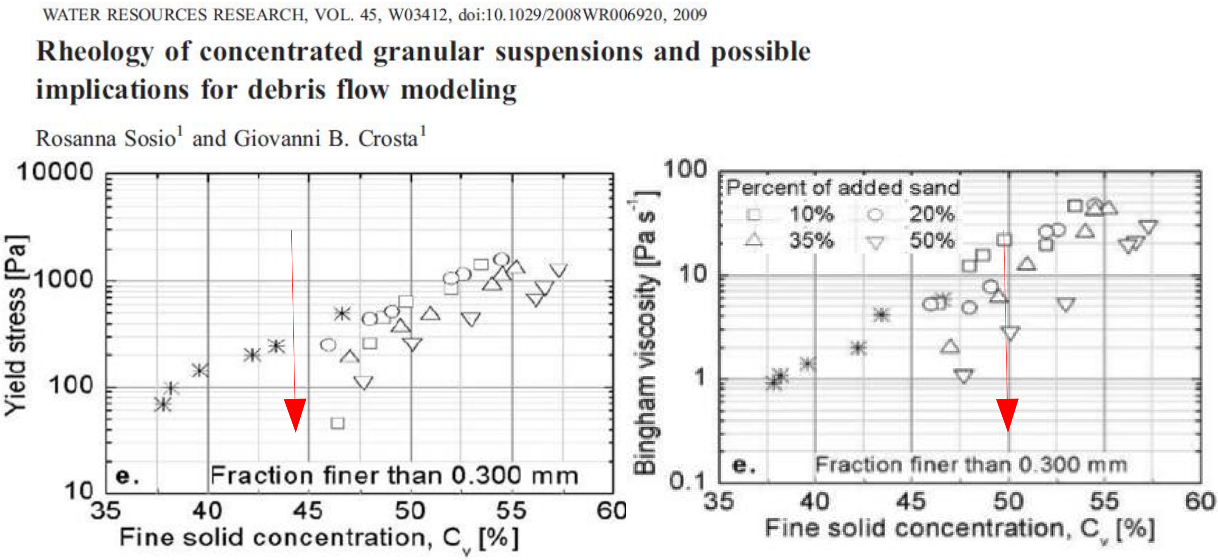
Outstanding problems 1: rheology/tribology of polydisperse suspensions

Sand breaks contact networks of clay/silt?
Clay/silt lubricates sand?

[Ancey, *J. Rheology* 2001]



A direct application of the present results concerns the physics of debris flows in mountain areas. To explain the striking mobility of these natural flows involving a wide range of materials (fine sediment, boulders, etc.), geologists usually evoke the pore-fluid pressure as the key mechanism. In this article it was shown that a fluid-like state is reached for very concentrated slurries when contact between coarse particles is lubricated by the interstitial fluid. Such an explanation appears to the author to be better founded. Moreover, it should be possible to predetermine bulk behavior of natural slurries depending on its composition, at least in simple cases. This would be a result of primary importance in engineering.



WATER RESOURCES RESEARCH, VOL. 45, W03412, doi:10.1029/2008WR006920, 2009

Rheology of concentrated granular suspensions and possible implications for debris flow modeling

Rosanna Sosio[1] and Giovanni B. Crosta[1]

(*cf.* Sarah Hormozi talk)

J. Fluid Mech. (2015), vol. 776, R2, doi:10.1017/jfm.2015.329

JFM RAPIDS
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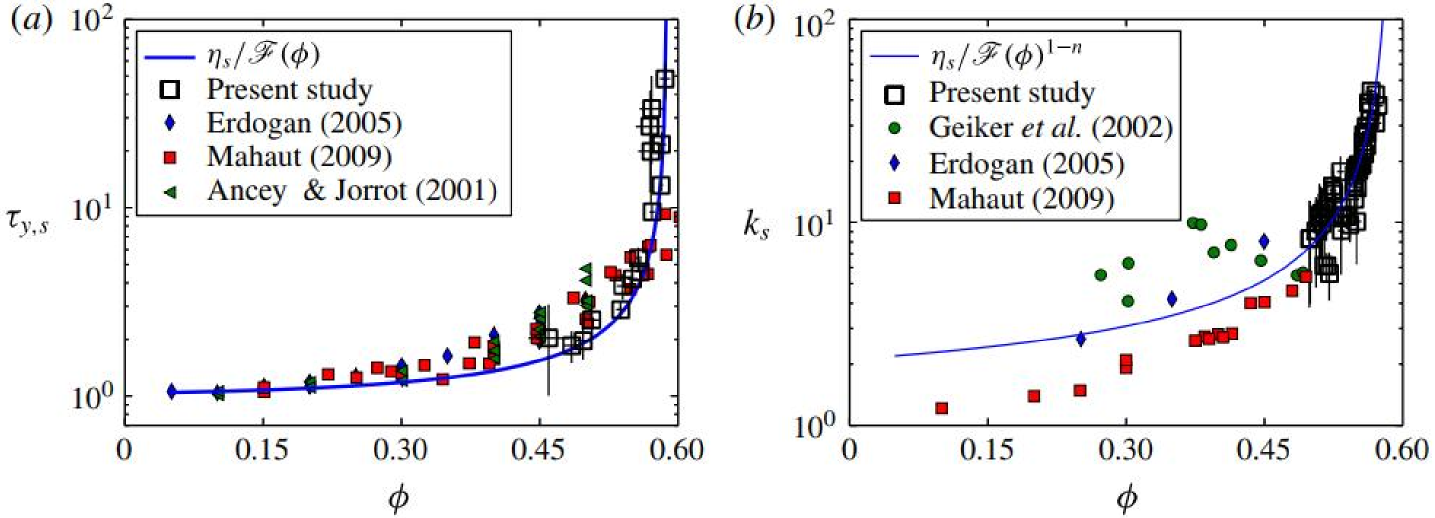
Rheology of dense suspensions of non-colloidal spheres in yield-stress fluids

Simon Dagois-Bohy[1,†], Sarah Hormozi[2], Élisabeth Guazzelli[1] and Olivier Pouliquen[1]

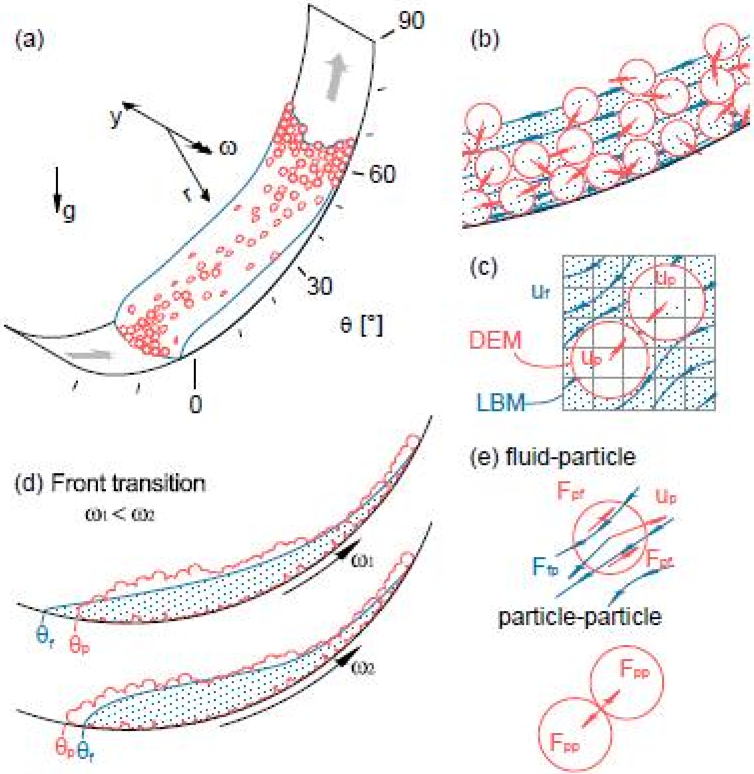
$$\tau = \tau_{y,s}(\phi)\tau_y + k_s(\phi)k\dot{\gamma}^n$$



Debris flow: dense non-colloidal suspension in yield stress fluid? → Grain polydispersity is challenging!

Outstanding problems 2: phase separation/segregation of particles and fluids

[Leonardi et al, *Phys. Rev. E* 2015]



Unsaturated boulder front:
→ Very destructive
→ Enhances flood levels behind

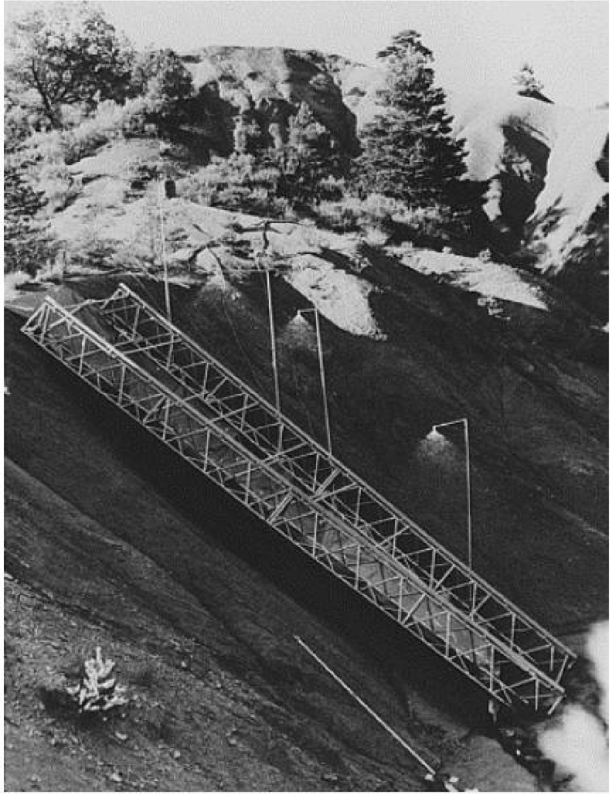
Formation depends on:
→ Shear rate
→ Fluid viscosity(?)
→ Fines content(?)

[Kaitna et al., *Int. Conference*, 2011]

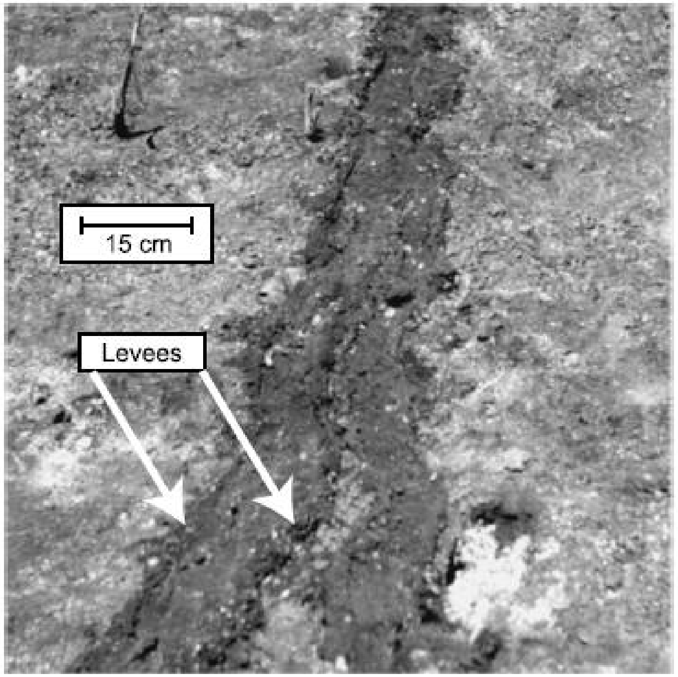
[Zhou et al, *Phys. Rev. Lett.* 2005]

Outstanding problems 3: gradual liquefaction and continuous failure by wetting

https://youtu.be/Rd6W2aP2dkA



[Wijdenes & Ergenzinger, *Catena* 1998]



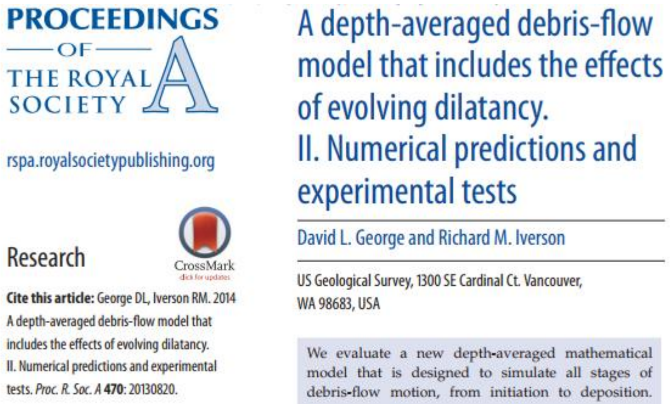
[Gabet, *Earth Surf. Proc. Landforms* 1998]

Shear-induced liquefaction is reasonably well studied.

Rainfall-induced landslides commonly reported.

Gradual, viscous failure: physics are un(der)studied
→ Pore pressure vs. lubrication, material controls

Conclusions: how do we make this flow?



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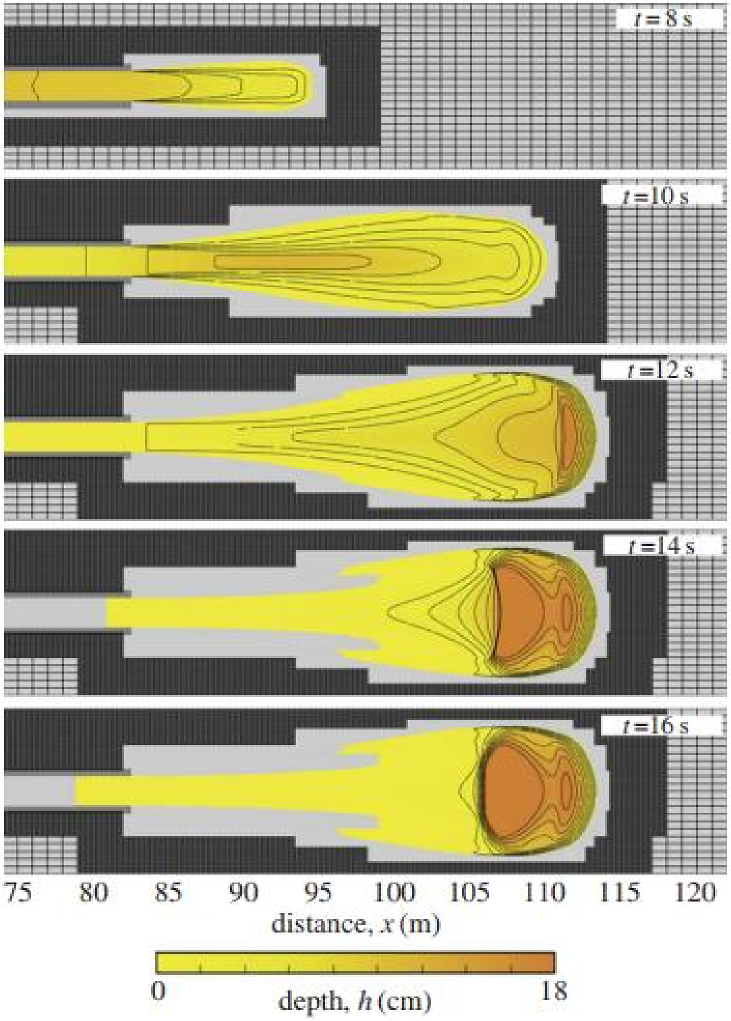
A depth-averaged debris-flow model that includes the effects of evolving dilatancy.
II. Numerical predictions and experimental tests

David L. George and Richard M. Iverson

US Geological Survey, 1300 SE Cardinal Ct. Vancouver, WA 98683, USA

We evaluate a new depth-averaged mathematical model that is designed to simulate all stages of debris-flow motion, from initiation to deposition.



Current models that include **pore pressure, compressibility** and **granular rheology** reproduce important features of debris flows.

Limitations:

1. Do not include grain-size/phase segregation → no boulder front.

2. Sensitivity to initial conditions:
"...a fundamental bifurcation of behaviour (runaway acceleration versus slow, regulated motion) can result from rather minor differences in the initial state."

Our objectives:

1. Determine how initially-dry hillslopes "liquified" → rills, mud.

2. Understand entrainment of boulders and front formation.

How?
Materials characterization.