Granular controls of hillslope creep and deformation

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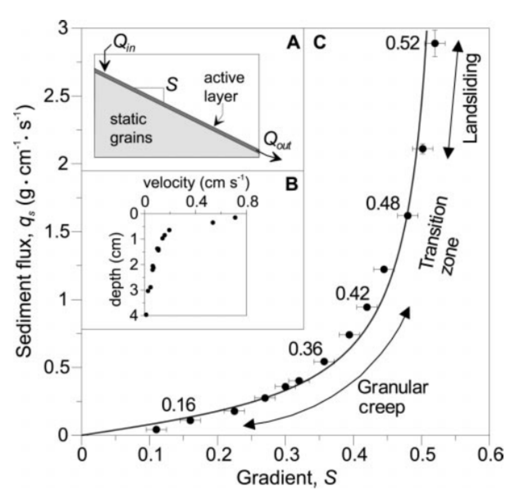
Introduction

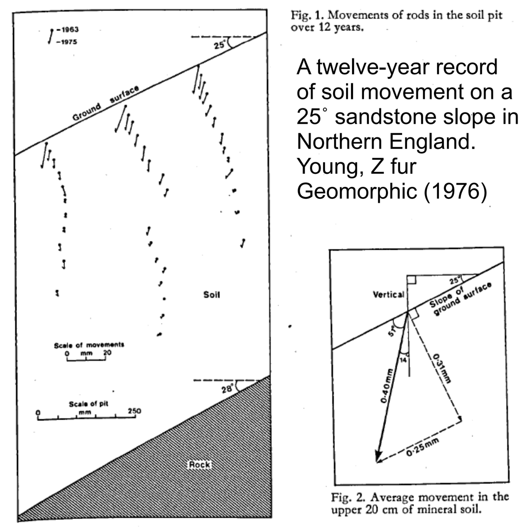
Sediment transport on hillslopes has been described as "creep", and has been modeled as a "diffusive" process by invoking random disturbance of soil in the presence of a gradient. In this framework, physical and biological agents are envisioned to cause dilation of the soil that is greatest at the surface and decays with depth (1). Thus, there is a kind of internal energy of the sediment that allows flow, even below the angle of repose. This transport has not yet been connected, however, to the more general phenomenon of creep in disordered, particulate systems. Work in such "soft matter" materials has shown that disordered solids are fragile, and may deform slowly by localized particle rearrangement under static loads much smaller than the yield stress at which fluid-like flow occurs. The transition from creep to granular flow has not been thoroughly examined.



A. Schematic of steady-state sediment transport experiments by Roering et al, Geology (2001). B: Typical grain velocity profile for sandpile with gradient equal to 0.4. C: Relationship between sediment flux and slope gradient in Roering et al. observations.

A laboratory hillslope of granular material has been used by Roering et al. (2001) to experimentally test how creep and landsliding contribute to hillslope erosion. In their experimental hillslope, disturbance-driven sediment transport rates increase nonlinearly with slope due to dilation-driven granular creep, and become increasingly episodic at steep slope angles as creep gives way to periodic landsliding.

Here, we use a similarly designed numerical setup to explore the transition from creep to landsliding, first in absence of external disturbances and only due to disordered nature of the system and then in the presence of external disturbances.



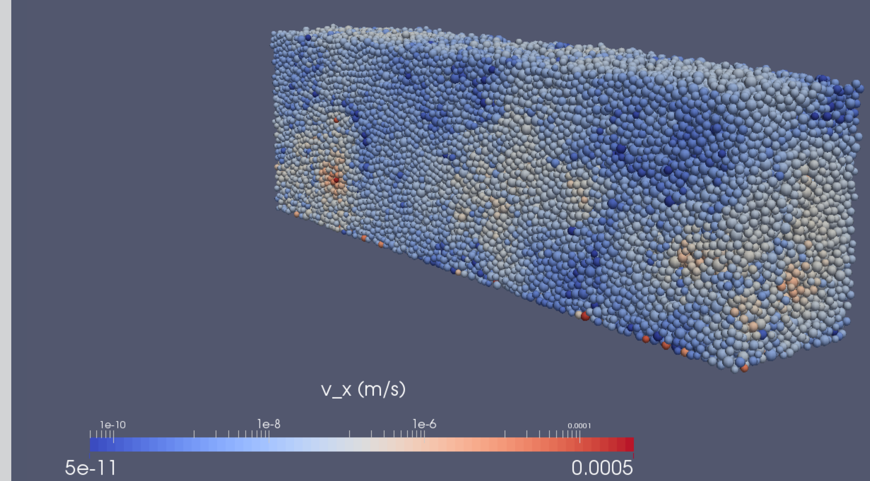
A twelve-year record of soil movement on a 25° sandstone slope in Northern England. Young, Z fur Geomorphic (1976)

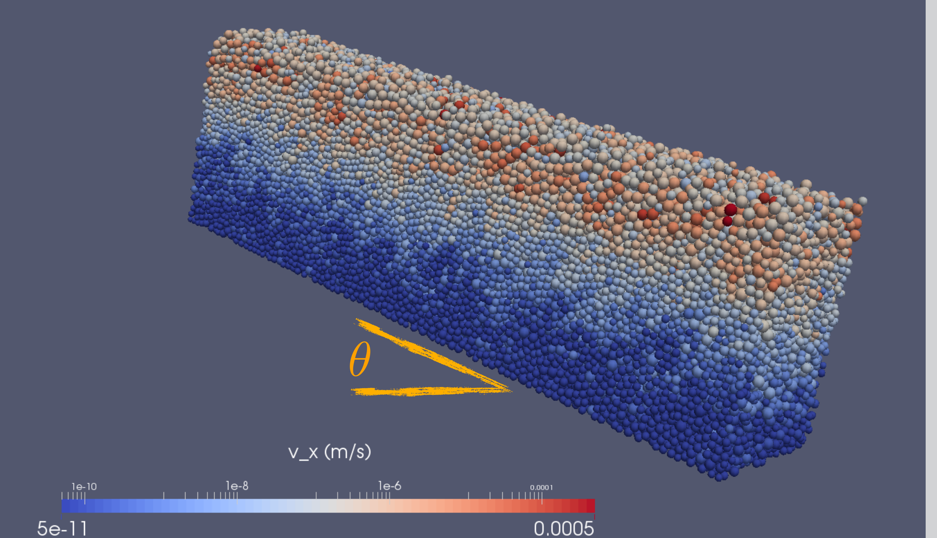
Gabilan Mesa near San Ardo, California. Image courtesy of James W. Kirchner

Granular model of hillslope deformation

Initial state of the system

Inclined system at θ degree

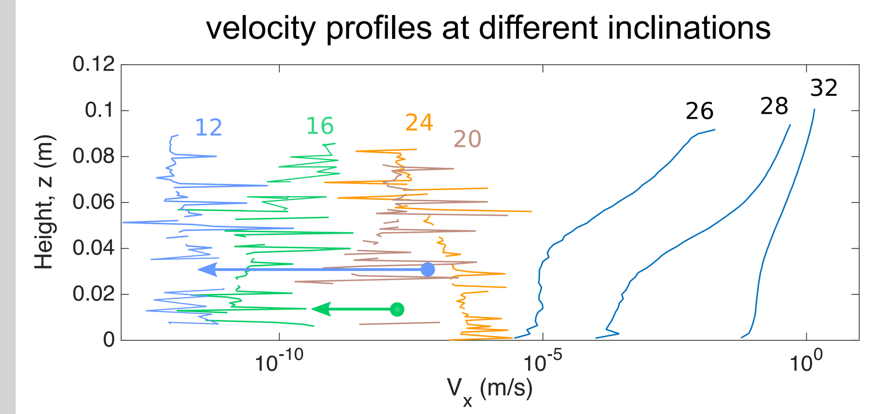




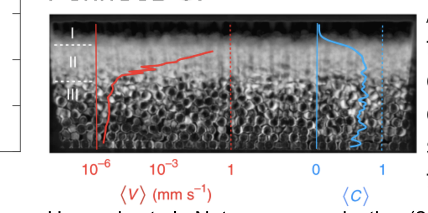
We use particle dynamics simulations to examine creep and granular flow dynamics and the transition between them, and to test the ability of a granular physics model to describe observations of hillslope soil creep. We employ a well-developed discrete element model, with frictional and over-damped interactions among grains to approximate the conditions of earth hillslopes. Transient and equilibrium particle dynamics are described for a range of inclination angles that transit the angle of repose. We verify that sub-threshold creep occurs, even in the absence of internal energy, and describe its dynamic signature.

- Number of grains: 54760
- Coefficient of restitution: 0.001
- Coefficient of granular friction: 0.5
- Hertz normal contact implemented
- Coulomb tangential contact implemented
- Polydisperse system: [0.0012:0.0021]m
- When external disturbances are on, they are applied to grains in all directions and as a randomly distributed displacement within [-a,a] amplitude range. A maximum disturbance amplitudes of $a=10^{-3}$ x average grain diameter is used.

Further properties of hillslope deformation



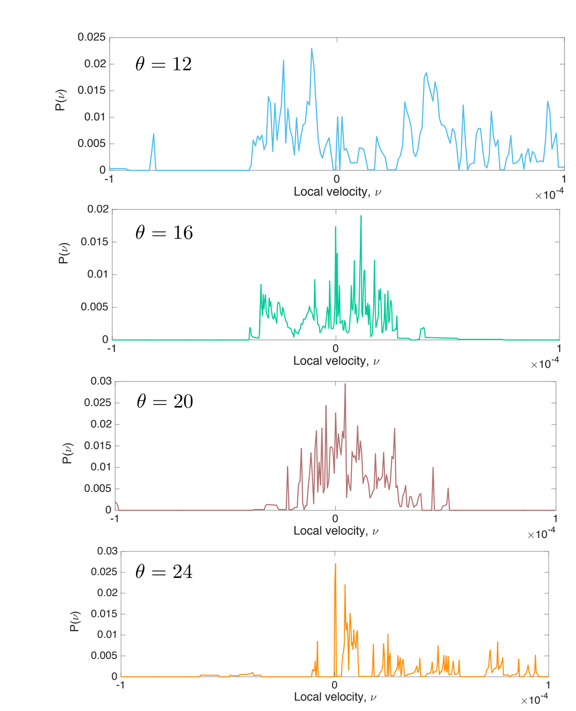
The velocity profiles at inclinations ≥ 26° suggest a transition from dense granular flow to subsurface creep at a given depth of the system, depending on the applied stress. A similar observation has been made in the sediment transport experiments in the annular flume setup at PennSeD ↓.



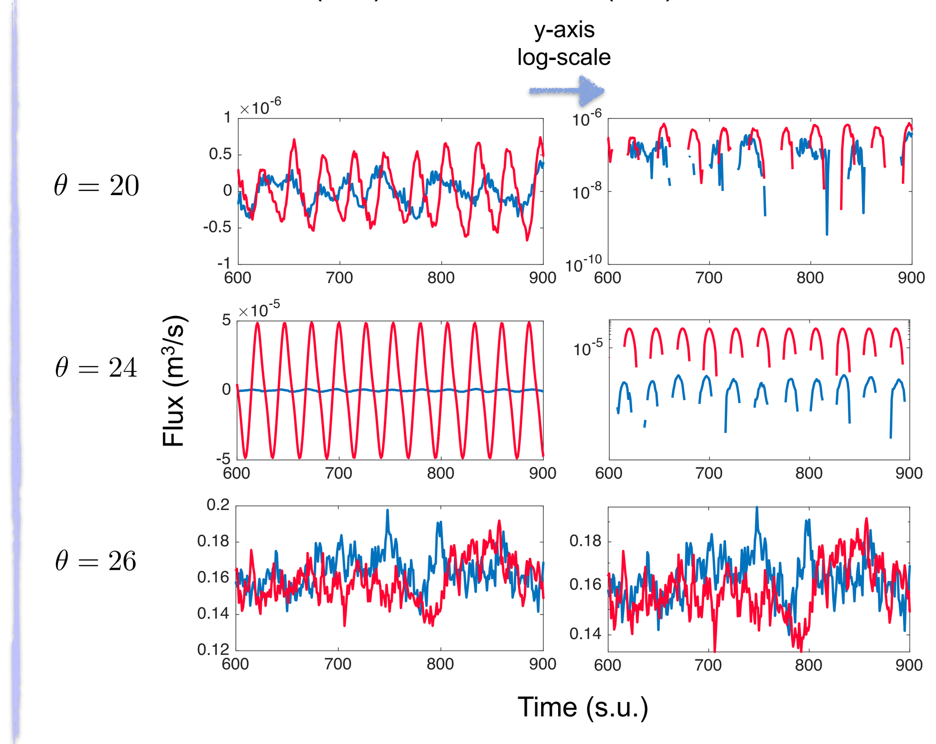
Houssais et al., Nature communication (2015)

At inclinations<26°, the system transitions to full creep. The distribution of velocities across depth of the systems reveals some properties of this transition.

Distribution of horizontal velocities across depth at different inclinations



Reference (—) and disturbed (—) flux time series



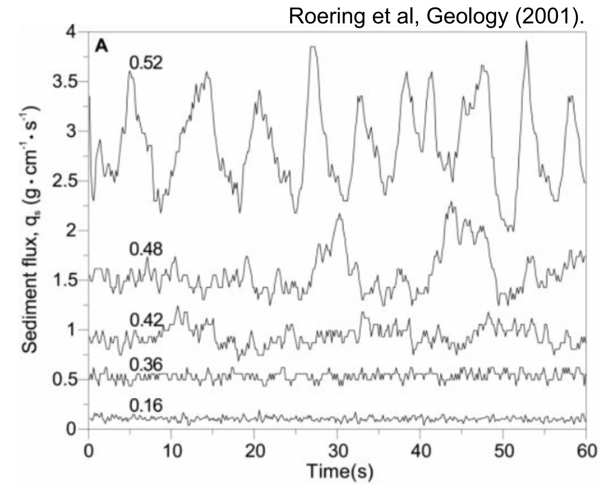
Flux time series at different inclinations

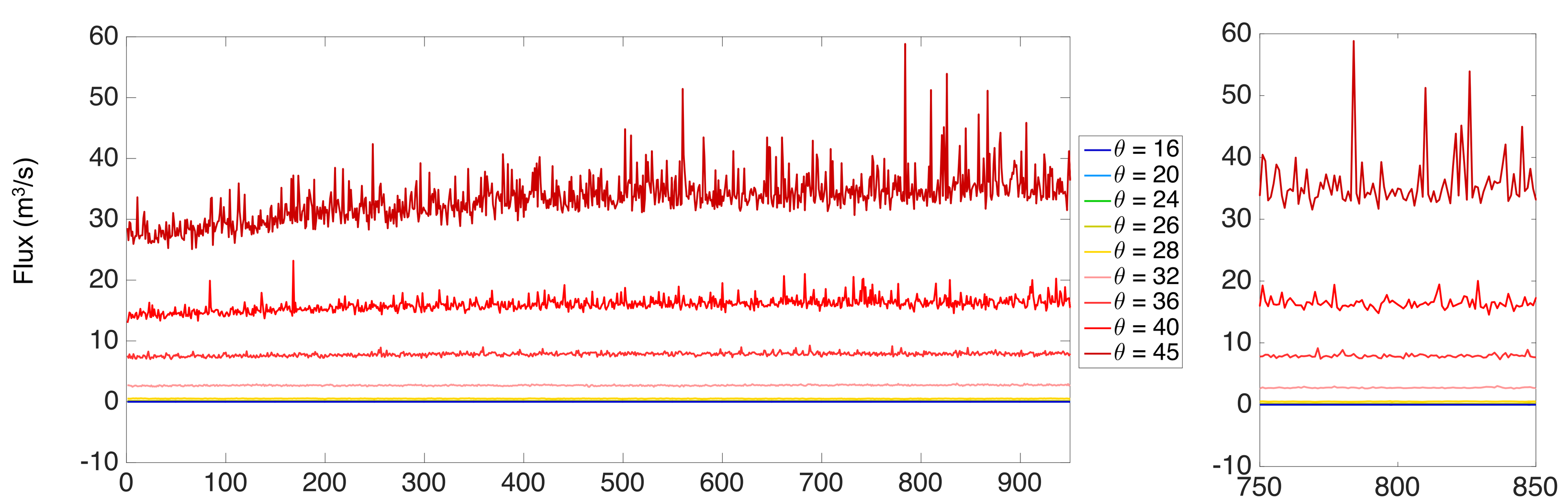
The experimental observation by Roering et al. (2001) shows that there is a continuous flux vs. gradient/inclination curve in presence of boundary vibration. The boundary vibration in their experimental setup meant to reproduce the disturbance-driven transport in hillslopes. A transition zone, in their work, separates creep from landsliding and dense granular flow.

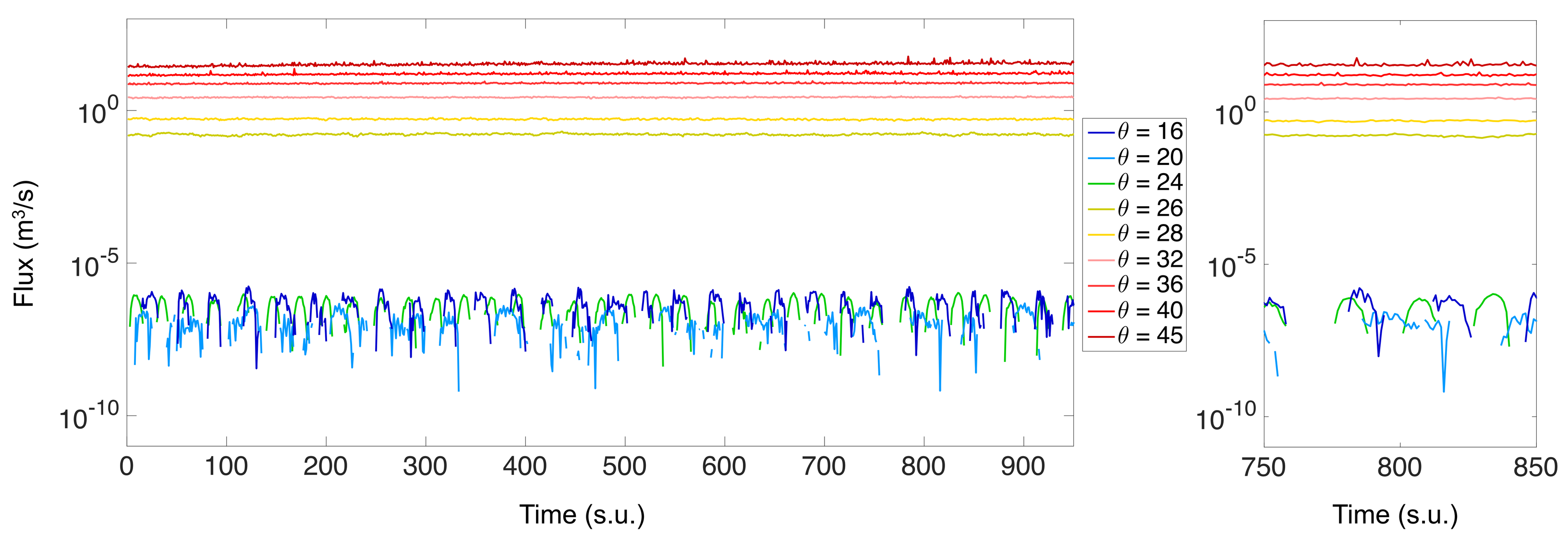
In our DEM simulations, we observe that starting from a disordered granular system, creep emerges as an intermittent slow deformation regime below the critical angle of repose. There are indications of a discontinuous transition to dense/avalanche/landsliding flow at inclinations above the angle of repose.

We next explore the influences of applying a random displacement disturbance to the grains on the discontinuous nature of the flow curve.

Roering et al, Geology (2001).





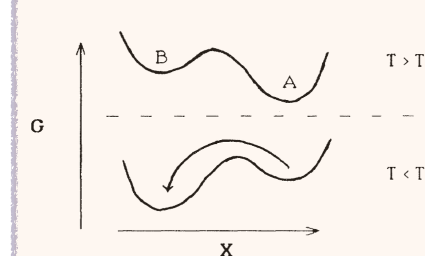


Average flux for reference and perturbed hillslopes

Simulations suggest that the transition from creeping to a sustained granular flow is discontinuous as the angle of repose is crossed and that is reminiscent of a first order phase transition. A two parameter nonlinear transport model proposed by Roering et al. (1999) and Andrew & Buckram (1987) cannot describe the variation of flux versus inclination in two different regimes.

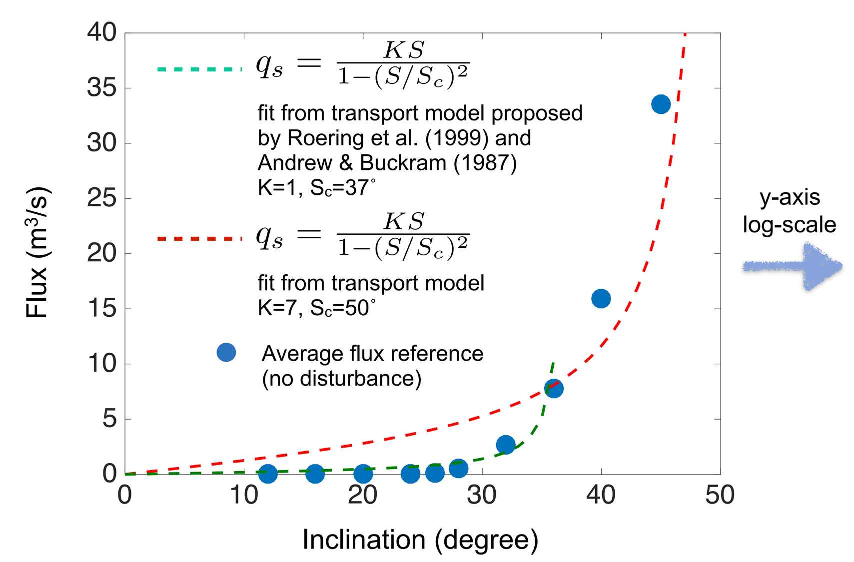
We perturb the granular system with random displacement applied to grains, to directly compare the model with previously-reported laboratory experiments of acoustically-driven hillslope transport. Random disturbances with a max. amplitude 0.001xd elevates creep flux, while it does not change the dense flow flux. The discontinuous transition persists with the perturbation amplitude used here.

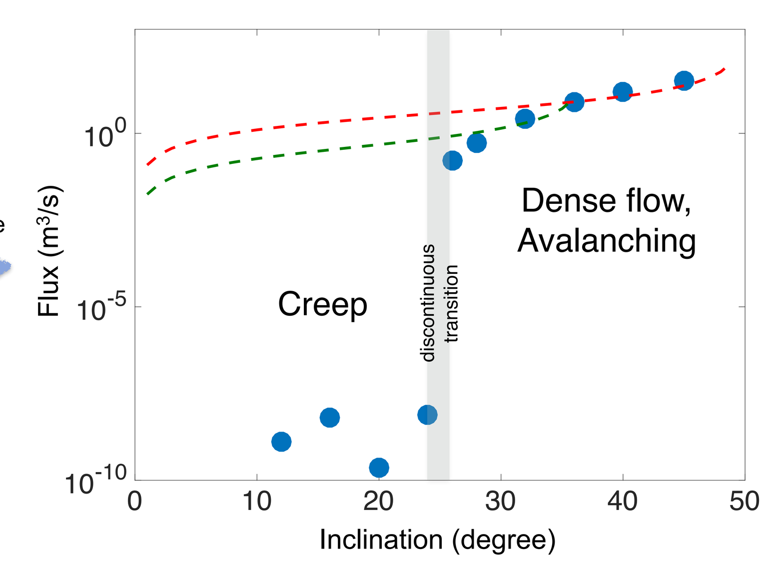
Nagel, Review of Modern Physics, 1992

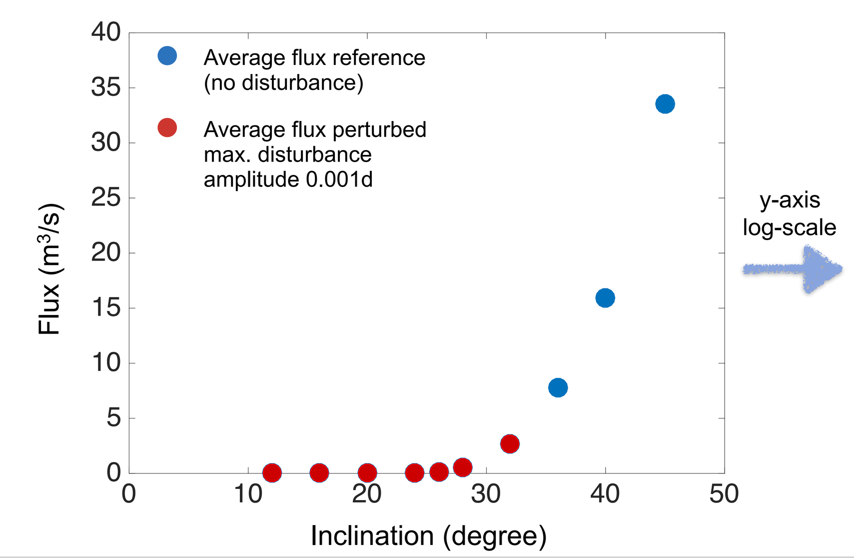


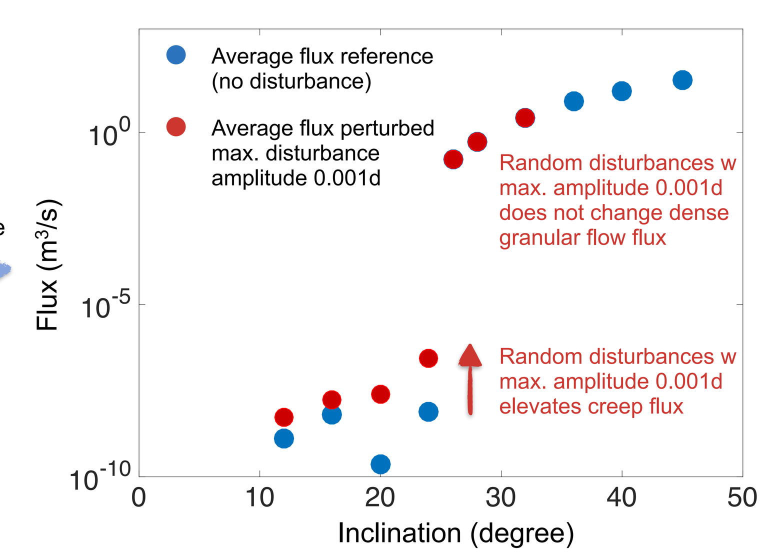
Schematic illustration of the free-energy surface at a first-order phase transition. **G** represents the free energy and **X** represents a coordinate of the system such as the density. At high temperature, above the phase-transition "temperature" T, the lowest free-energy minimum occurs at **A**, whereas at low "temperature" it occurs at **B**.

As the "temperature" is lowered, the system remains in the minimum at **A** until a nucleation event occurs. Nucleation is caused by a fluctuation that takes a small part of the sample over the energy barrier from the metastable minimum at **A** to the stable minimum at **B**. If the nucleus is sufficiently large, it will grow to envelop the entire sample.





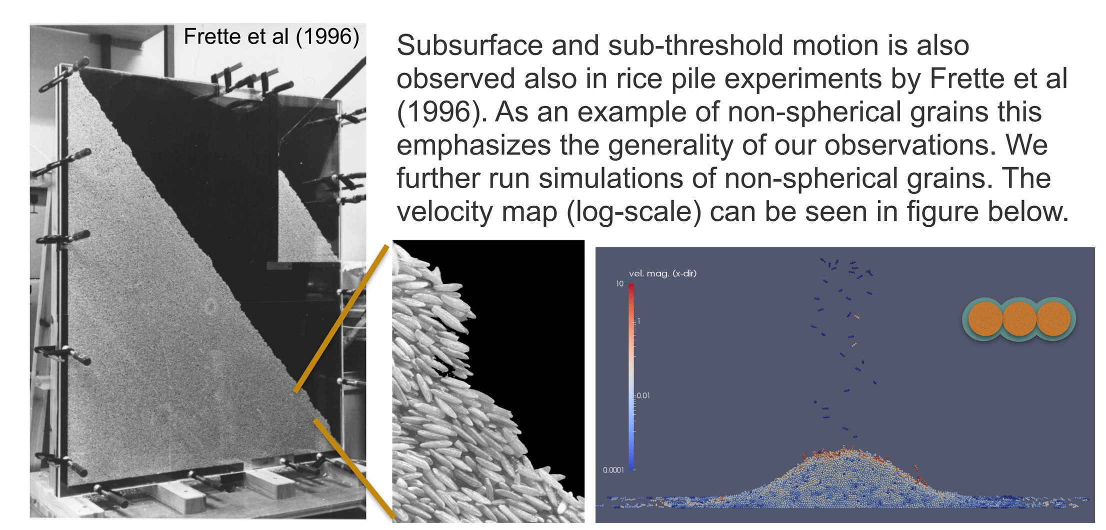




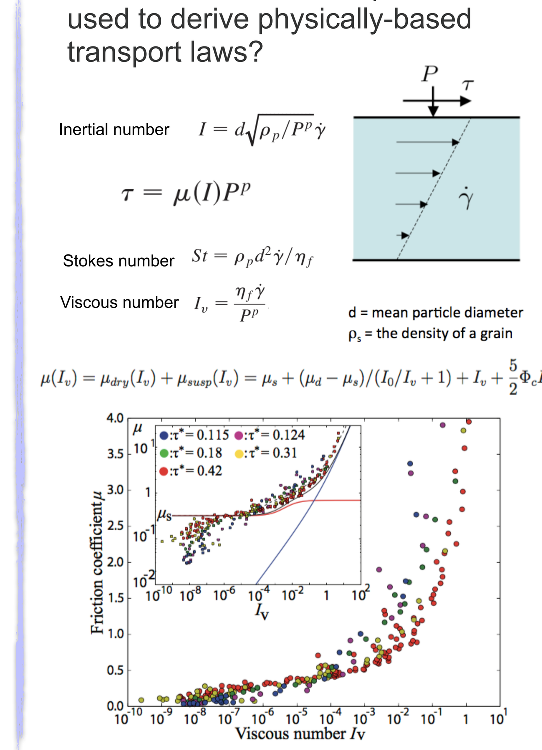
Conclusions and outlook

- Simulations suggest that the transition from creeping to a sustained granular flow is discontinuous as the angle of repose is crossed.
- Results reveal that the bulk movement of hillslope sediment over long timescales may be accomplished by intermittent and localized particle motion - i.e., creeping of a disordered solid - for sub-critical slopes.
- Applying random disturbances of order of 10^{-3}x average grain sizes, facilitates and elevates the creep deformation. It however does not affect the dense granular flow significantly.

Subsurface and sub-threshold motion is also observed also in rice pile experiments by Frette et al (1996). As an example of non-spherical grains this emphasizes the generality of our observations. We further run simulations of non-spherical grains. The velocity map (log-scale) can be seen in figure below.



- Can granular rheology explain different modes of transport and be used to derive physically-based transport laws?



Houssais, M., et al. "Rheology of sediment transported by a laminar flow." *arXiv preprint arXiv:1509.08395* (2015).

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