→ nonequilibirum thermodynamics

Glassy dynamics of landscape evolution

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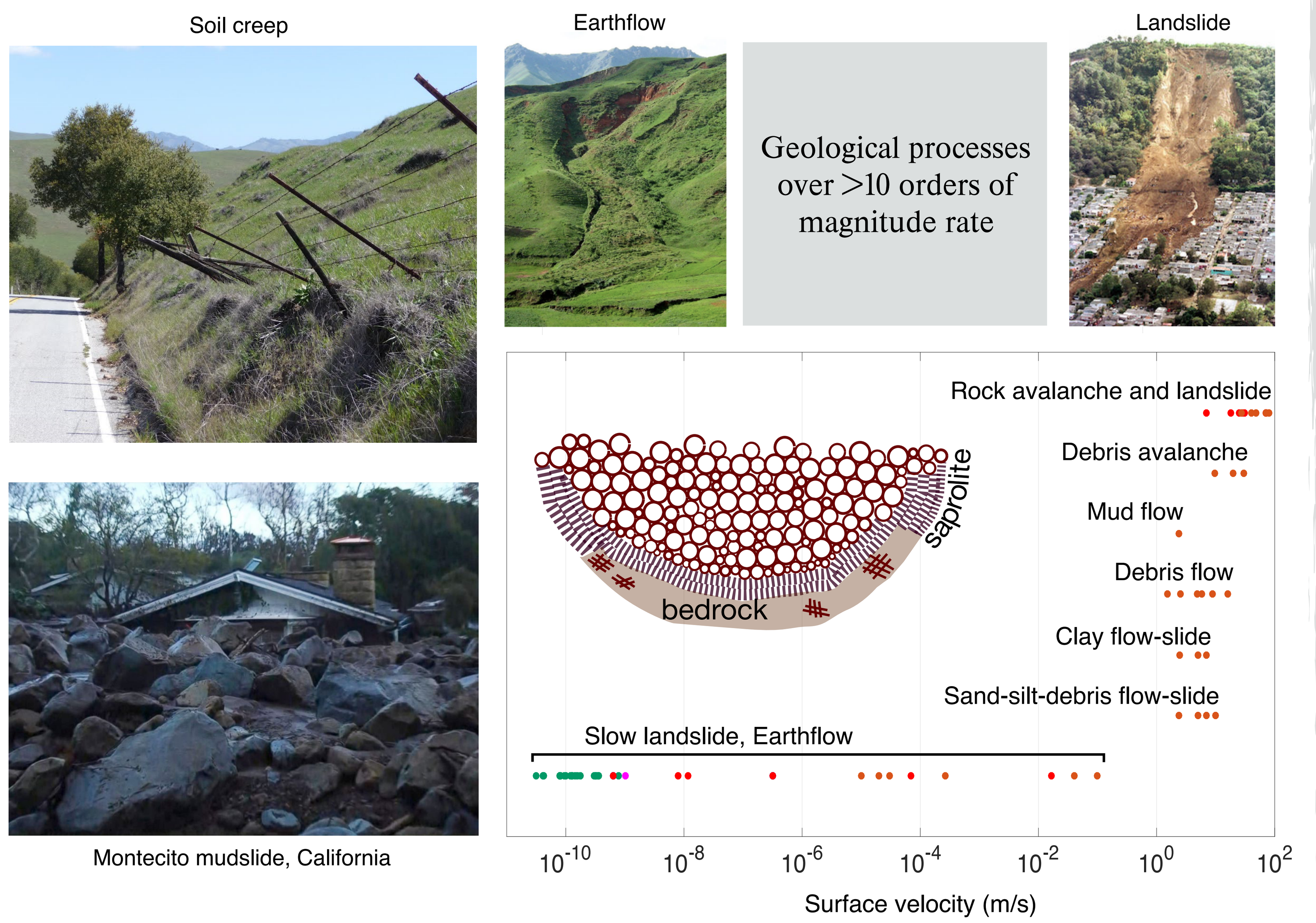
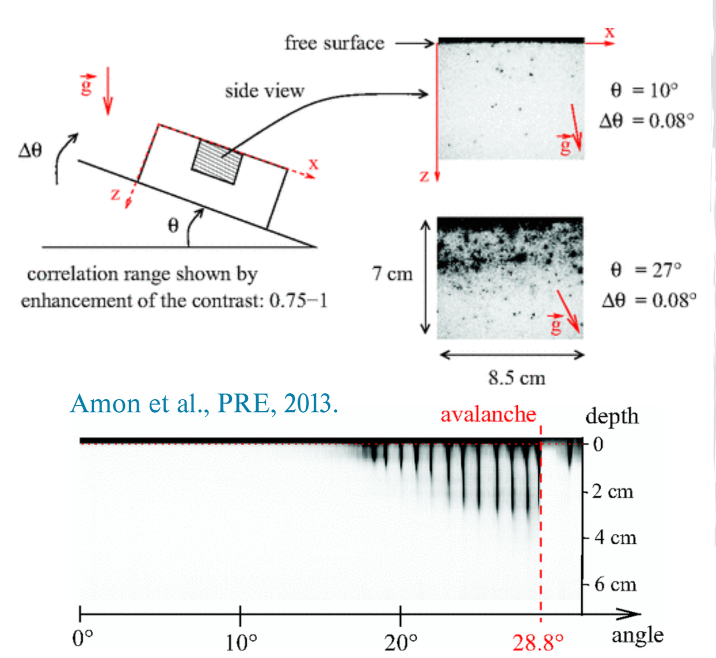
Creep in soil-mantled hillslopes takes place due to slow rearrangements of grains that can be reasonably approximated as a viscous flow. At critical slopes or under certain perturbations like rain events, however, soil may fail catastrophically to create landslides. These processes control the erosion and form of hillslopes and the delivery of sediment to rivers. Despite widely varying materials and environments, hillslope soil motion falls into two distinct categories: slowly creeping "earthflows" that cover 10 orders of magnitude up to ~10^{-1} m/s and rapid landslides (including debris flows, mudflows, etc.) that are faster than 1 m/s (Fig. below). Much progress has been made in mechanistic models for the latter; in particular, continuum models based on mass and momentum conservation for the granular and fluid phases are able to reproduce important aspects of soil failure and mass-movement runout. Models for hillslope soil creep, however, lack a mechanistic underpinning. For over 50 y, a heuristic "diffusive-like law"—in which sediment flux q_s [L^2/T] is proportional to topographic gradient $S = \partial z/\partial x$—has been used to model landscape erosion. For soil to creep at subcritical gradients, it is supposed that dilation occurs as a result of (bio)physical perturbations such as freeze/thaw/swell, rain splash, tree throw, and burrowing animals.



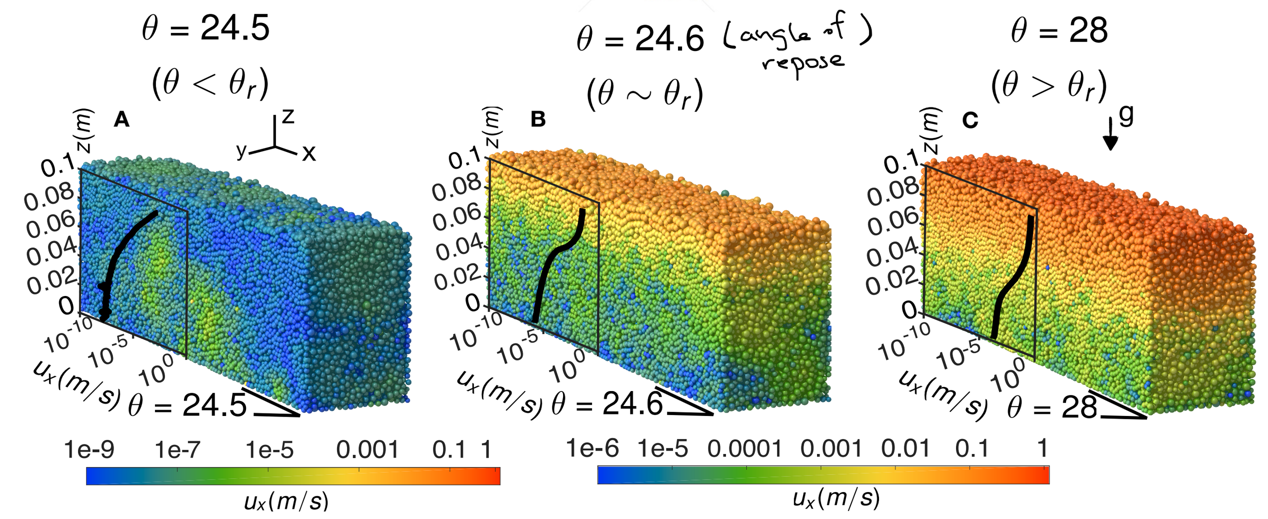
Hillslope soil creep has not been connected to the creep phenomenon observed in diverse amorphous and granular systems with a wide range of materials and particle shapes, including dry and fluid-driven granular flows. These materials belong to a large class of systems—including glasses, pastes, foams, gels, and suspensions—that are known to exhibit interesting rheological properties termed "**glassy dynamics**" that include slow dynamics such as compaction, hysteresis and history dependence of the static configurations, and intermittency and spatially heterogeneous dynamics. These behaviors are thought to be a natural consequence of two properties shared by all glassy materials: structural disorder and metastability. In such materials, thermal motion alone is not enough to achieve complete structural relaxation, and consequently relaxation times are extremely large compared with the timescale of a typical experiment. As a result and for practical purposes, glassy materials are non-equilibrium systems with long memory. For the evolution of soil-mantled landscapes over geologic time, such glassy dynamics should be relevant.

Dense granular flows on inclined planes are a reasonable idealized model for hillslope soil transport, and the rheology of such flows has been thoroughly examined in simulations and experiments. Creep involves grain-scale rearrangement—due to structural and mechanical disorder in the pack—that induces exponentially small but finite particle velocities below threshold. Experiments performed with an inclined granular layer show localized and isolated events—microfailures—in the bulk at inclinations below the bulk angle of repose. As the inclination increases, microfailures occur more frequently until they coalesce to form an avalanche (1).

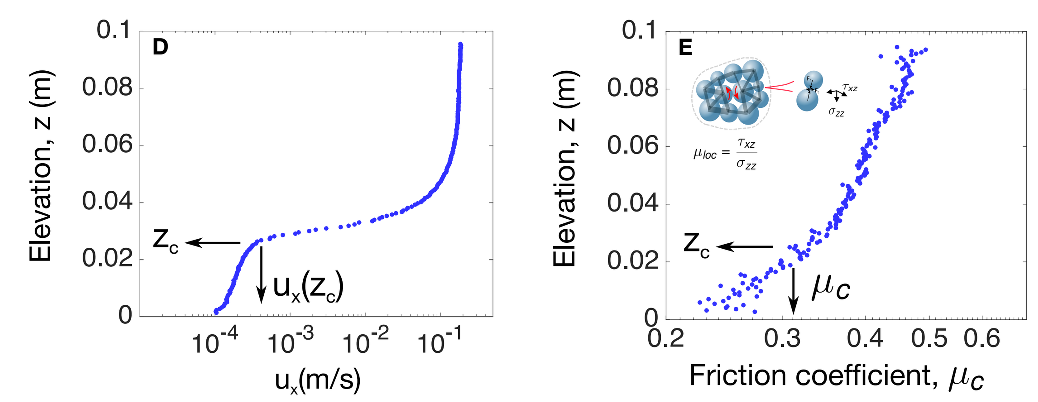


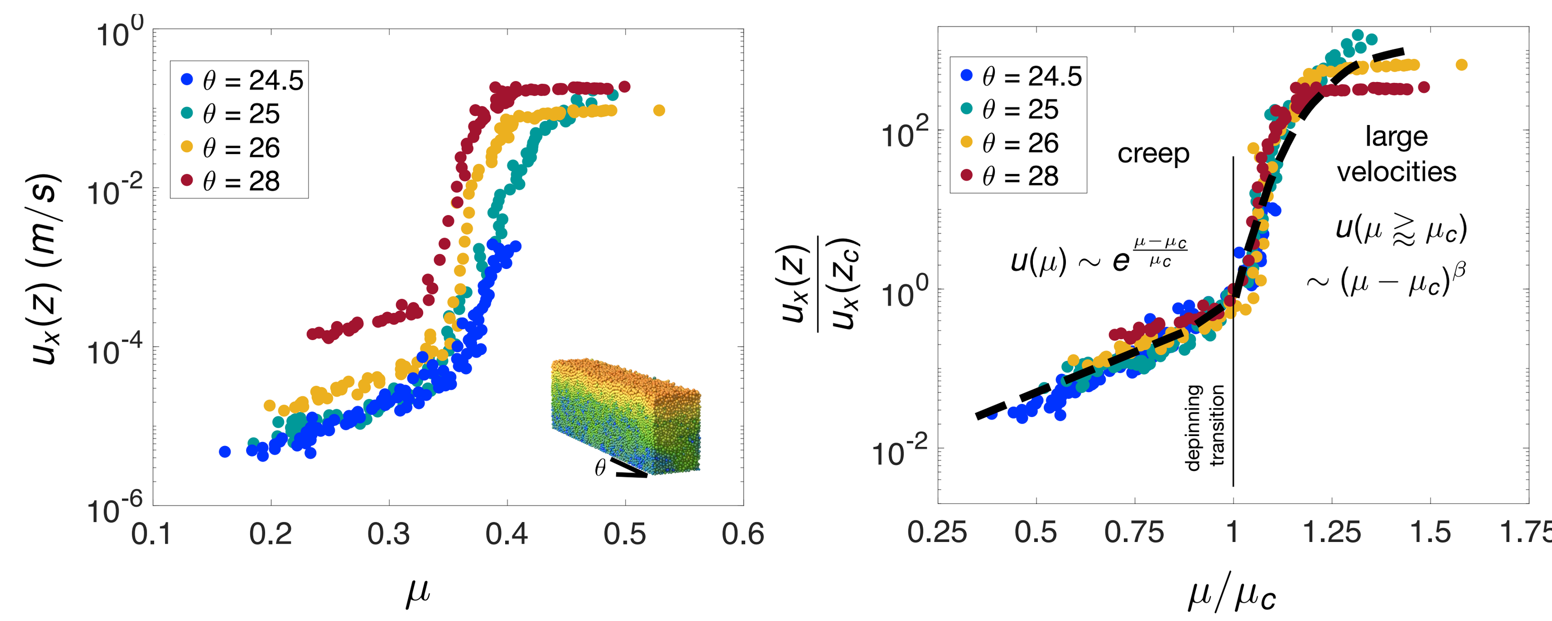
Granular Hillslope Model

Here, we first conduct 3D numerical experiments of granular heap flows to first document sub-threshold creep and then demonstrate that the creep to landslide transition is continuous and is quantitatively consistent with a plastic depinning transition.

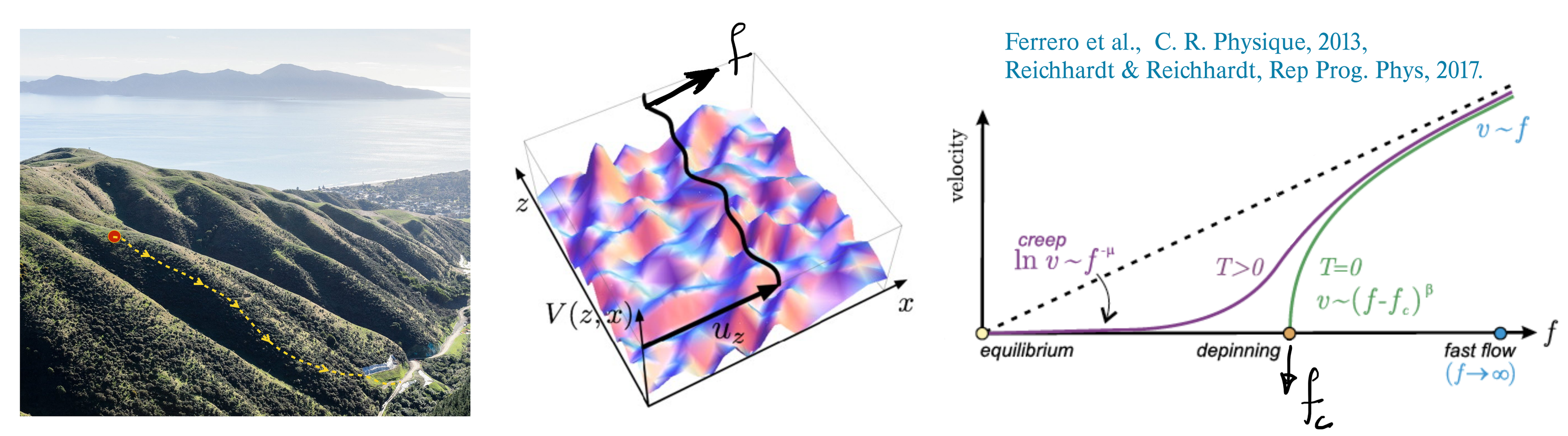


- Granular simulation in LAMMPS
- Number of grains: 54780
- Coefficient of restitution: 0.001
- Coefficient of granular friction: 0.5
- Hertz normal contact implemented
- Coulomb tangential contact implemented
- Polydisperse system: [0.0012:0.0021]

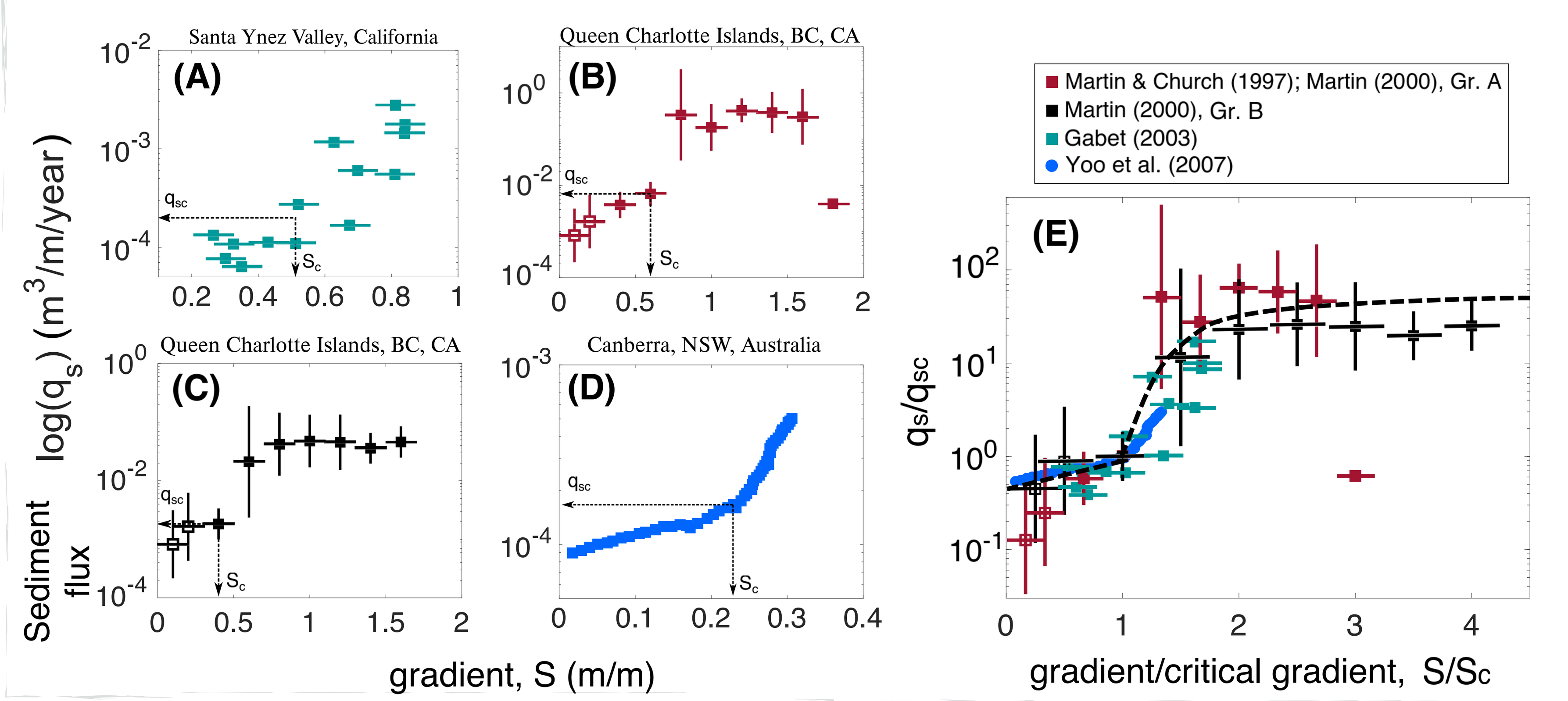




Depinning Transition in Disordered Solids/Interfaces



Hillslope Evolution as a Depinning Transition: Field Evidence



Modeling Landscape Evolution with a Glassy Flux Model

Sediment flux law

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

ρ_s : soil mass density

ρ_r : rock density

C_o : tectonic uplift rate $\quad S = \frac{dz}{dx}$ (gradient)

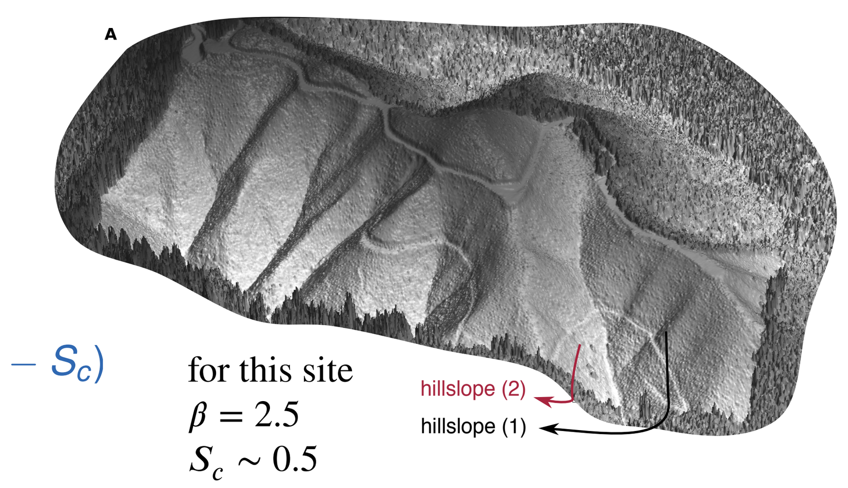
Glassy flux law (Slow creep regime; Fast regime)

$$q_s/q_{sc} = e^{\frac{S-S_c}{S_c}} \mathcal{H}(S_c - S) + [A(S-S_c)^{\beta} + 1]\mathcal{H}(S - S_c)$$

$\mathcal{H}$: Heaviside function $\quad A$: is the only one free parameter

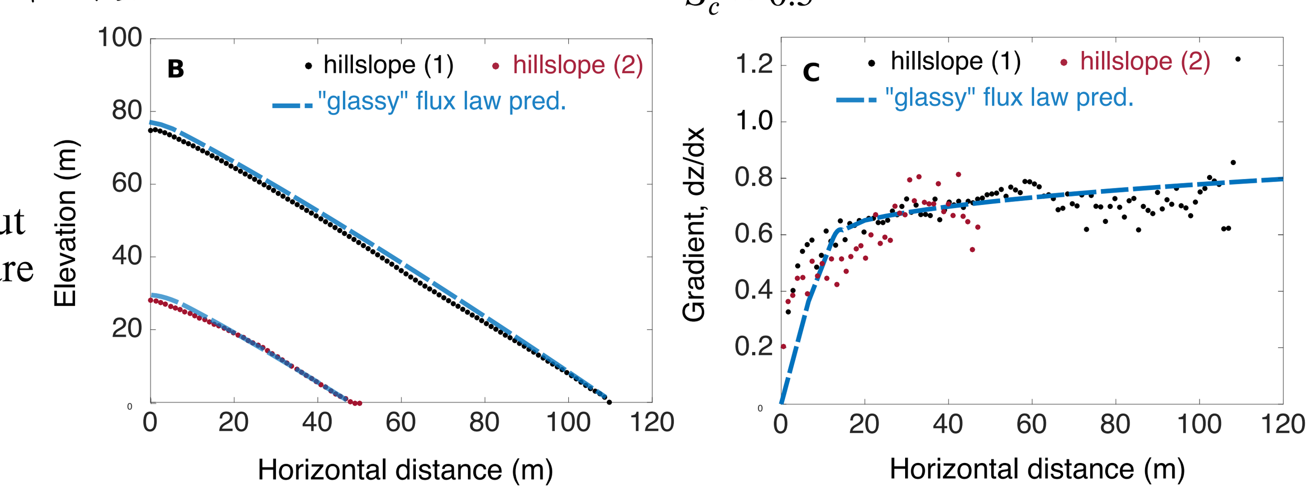
$S_c = (dz/dx)_c \simeq 0.5 \quad \beta = 5/2$

A landscape in Oregon Coast Range
60 km west of Eugene, OR



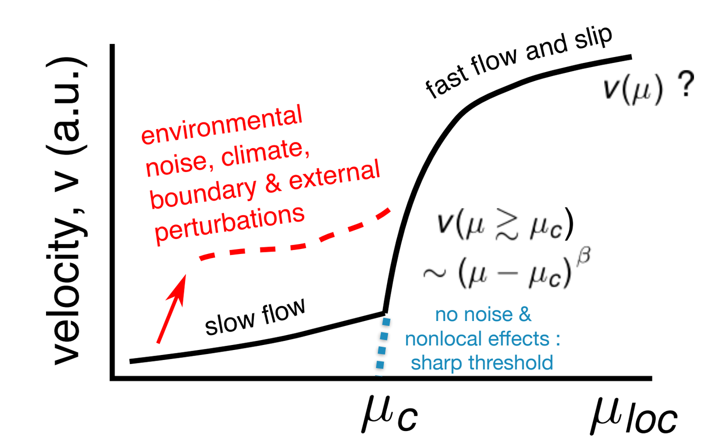
for this site
$\beta = 2.5$
$S_c \sim 0.5$

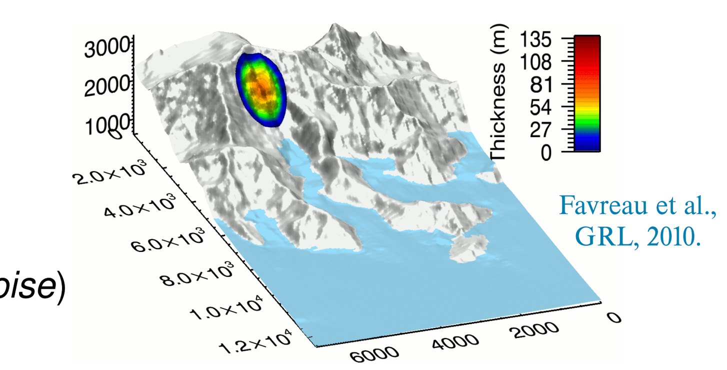
The glassy flux model reasonably captures elevation and gradient profiles for both short hillslopes (distance about 40 m) where gradients are mostly below critical gradient and longer hillslopes which significantly exceed the critical slope.



Hillslope gradient profiles show a clear kink at the critical slope value S_c~0.5 derived from the glassy flux model; the corresponding angle of 26° represents a reasonable value for the transition from creep to landsliding. The explicit incorporation of landslide (dense-granular flow) dynamics allows the glassy flux model to reproduce the flattening out of hillslope profiles as they lengthen; this flattening has been previously reported and cannot be reproduced with diffusion-like flux equations (4).

- These results show how recent advances in the physics of disordered materials can be used to explain the evolution of natural landscapes over geologic timescales.
- The functional form of the flux equation $q = f(\mu)$ used in this work is a specific case of a more general form $q = f(\mu, \eta)$, where η represents mechanical internal and external noise. We suggest that creep, and its associated slow subcritical flow, takes place in our numerical system and in natural hillslopes due to (i) internal disorder of the particulate packing and (ii) bedrock and saprolite boundary layers that surround the mobile regolith, which continuously inject disorder that may induce creep through nonlocal effects.





- Coupling of (soil and saprolite) rheology with Bedrock topography, tectonics processes $\quad Flux = f(\mu, noise)$ Local rheology
- Many Earth's surface and subsurface systems are made of disordered and amorphous materials with glassy dynamics. Continuum models for describing the response of these systems to past and present perturbations need to account for and include this glassy physics (memory, dynamical heterogeneity).

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Acknowledgments

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