

Glassy dynamics of landscape evolution

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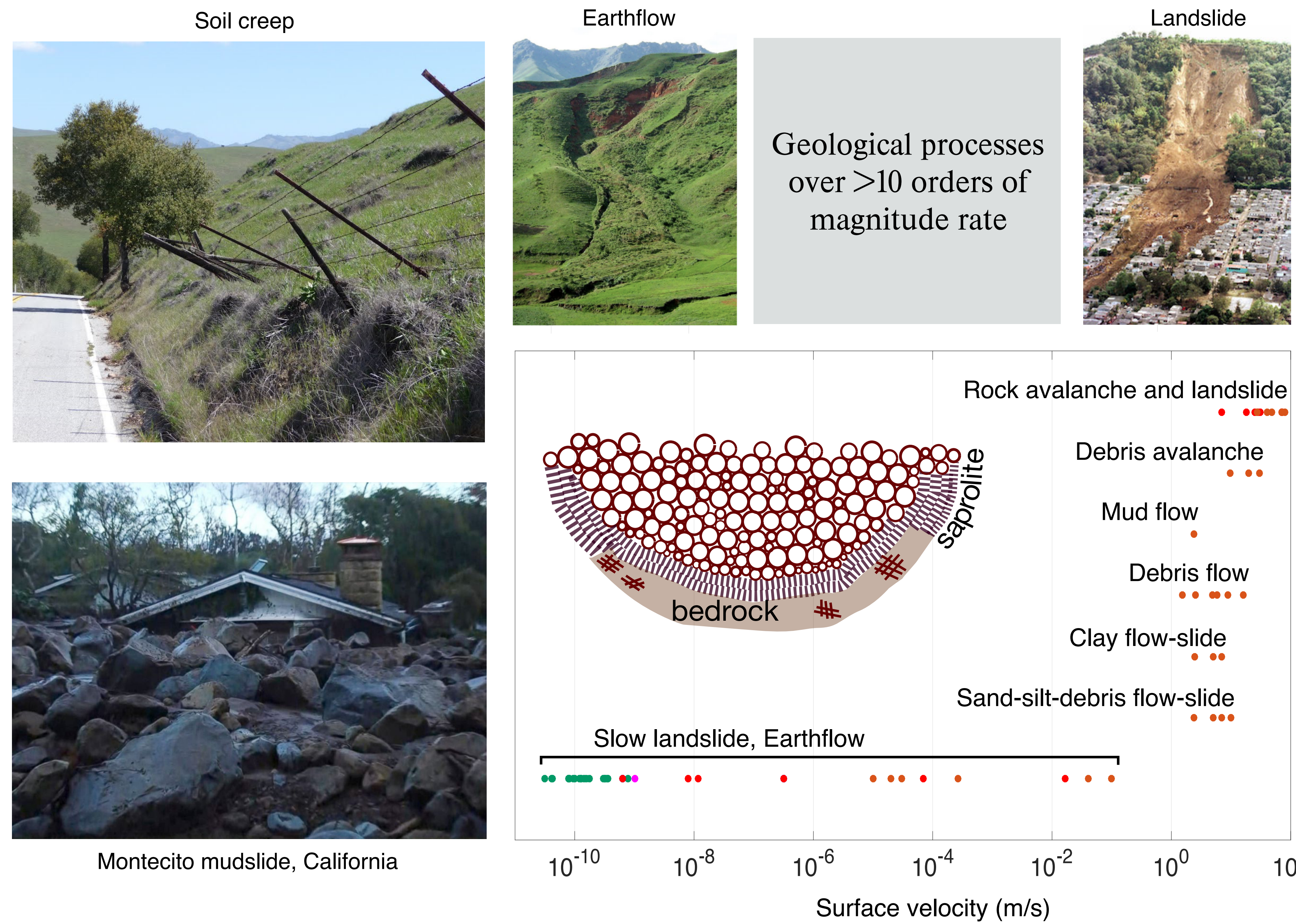


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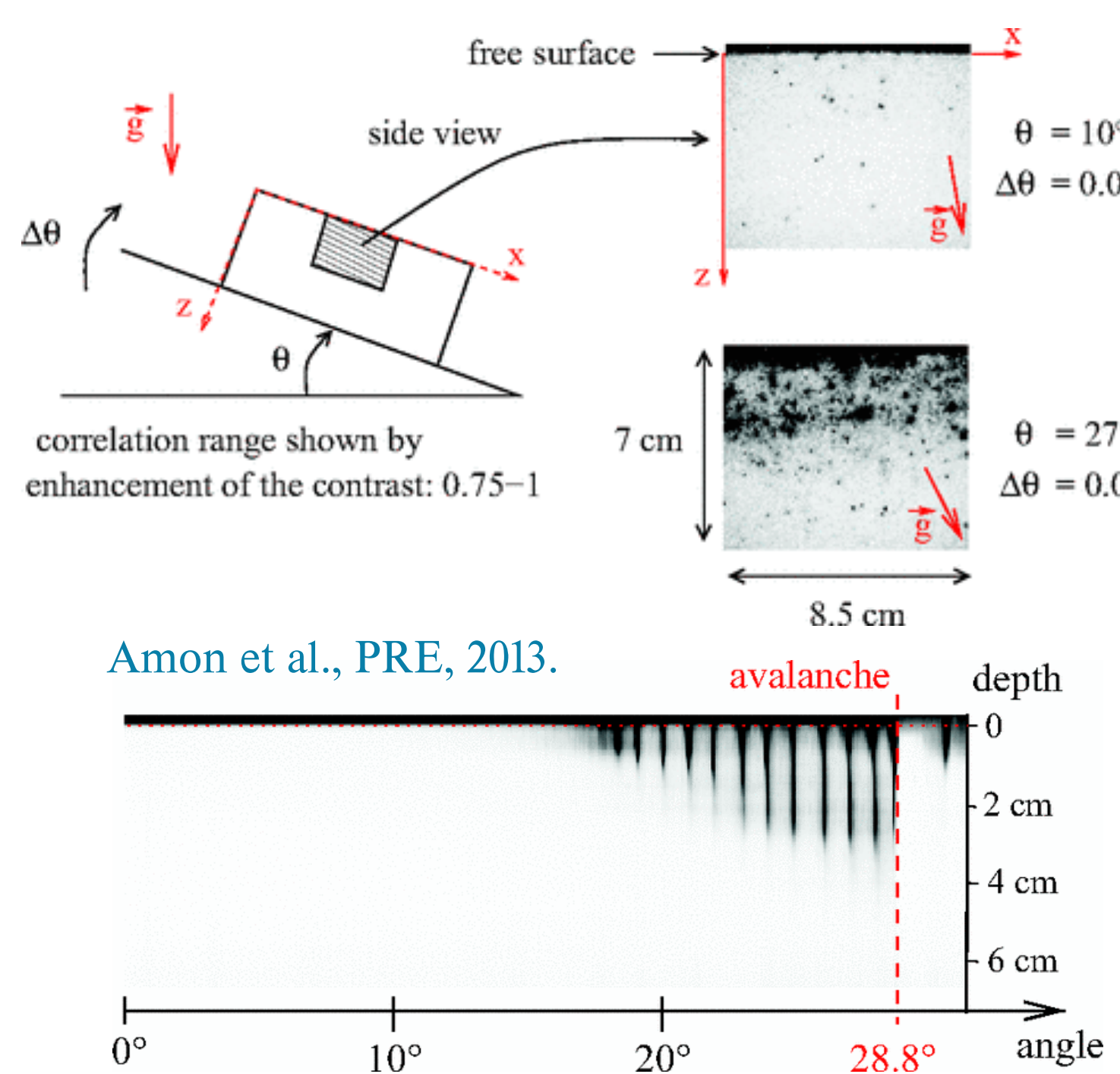
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Creep in soil-mantled hillslopes takes place due to slow rearrangements of grains that can be reasonably approximated as a viscous flow. At critical slopes or under certain perturbations like rain events, however, soil may fail catastrophically to 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” associated with surface velocities that cover 10 orders of magnitude up to $\sim 10^{-1}$ 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 runoff. 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 [L²/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.

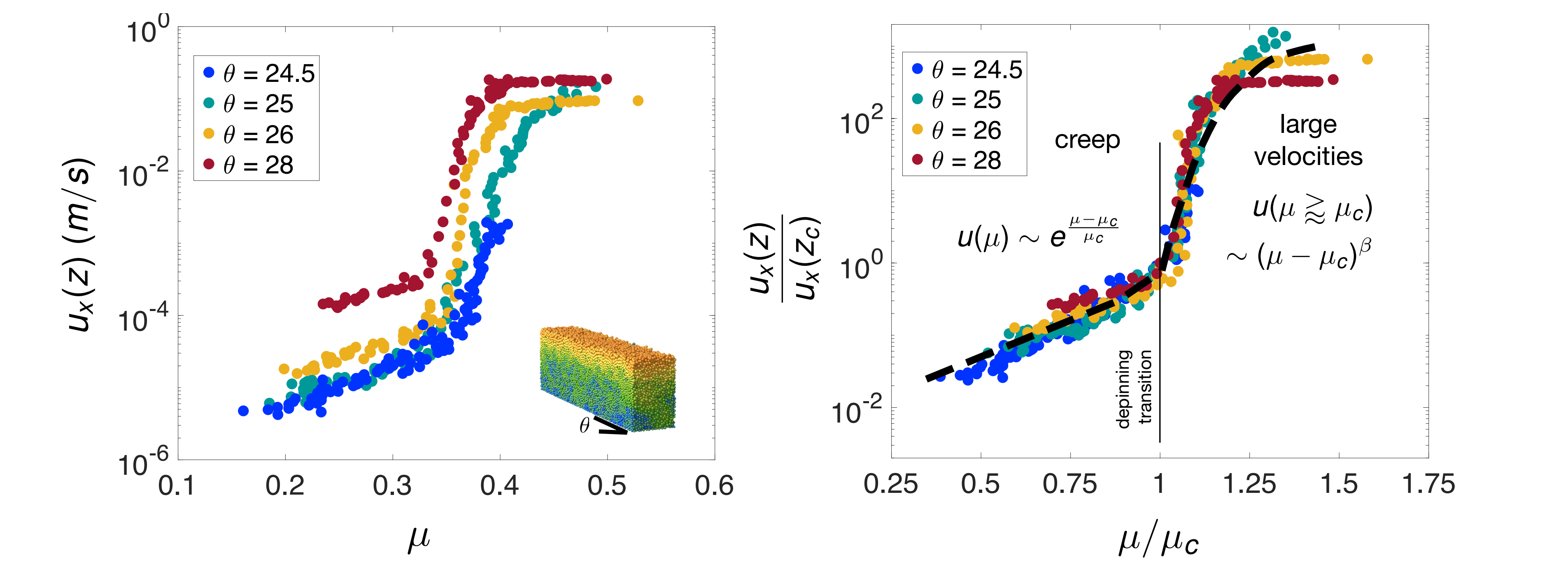
Dense granular flows on inclined planes are a reasonable idealized model for hillslope soil transport, and the rheology of such flows has been thoroughly examined in simulations and experiments. Creep involves grain-scale rearrangement—due to structural and mechanical disorder in the pack—that induces 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).



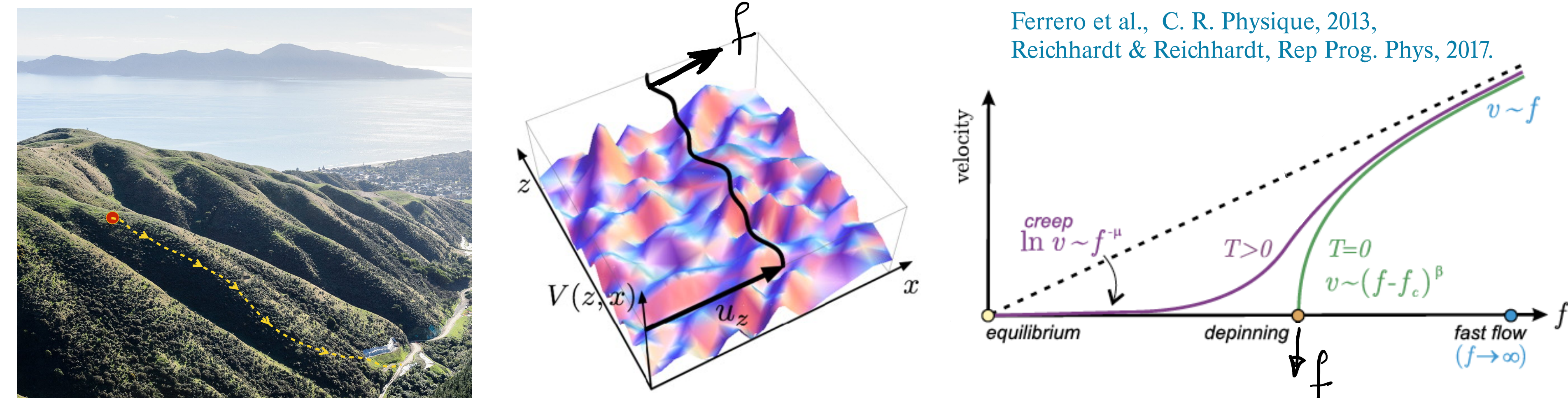
Granular Hillslope Model

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.

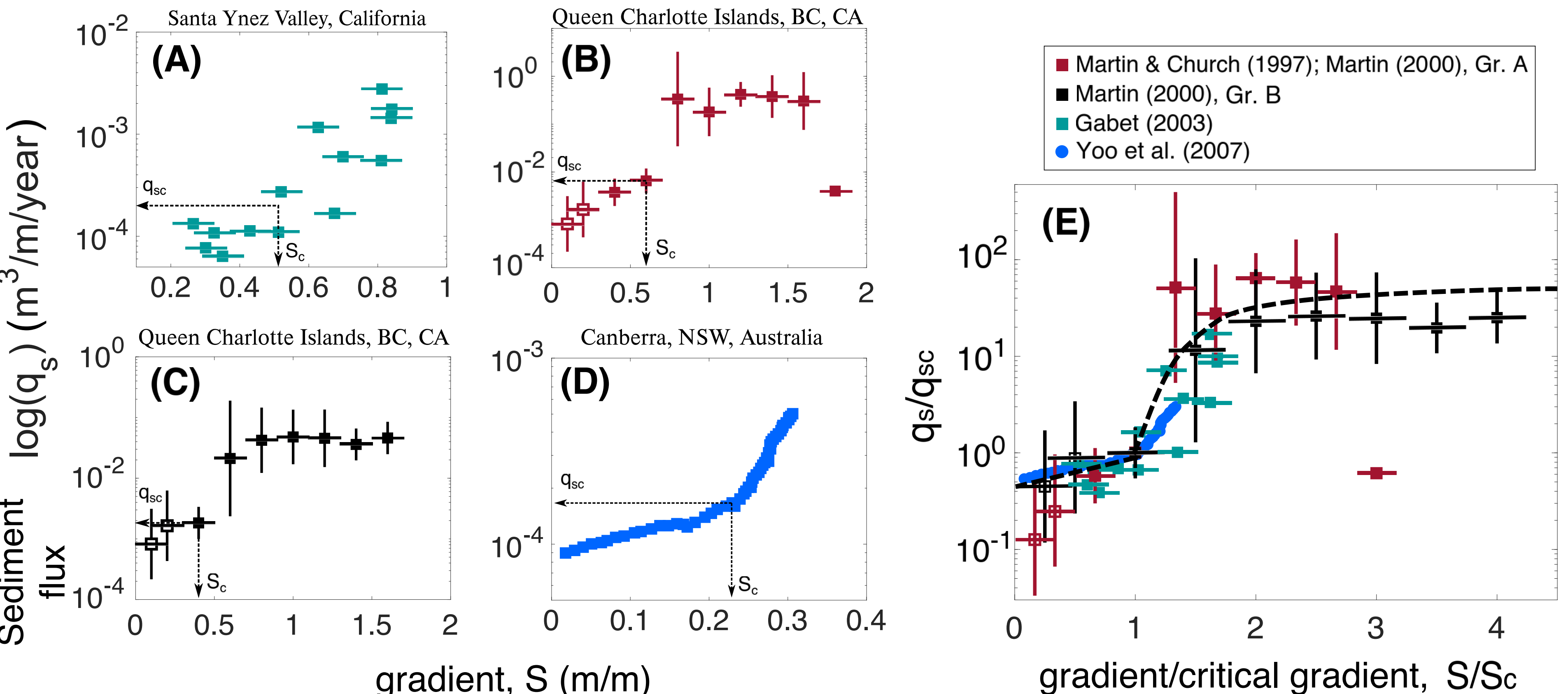
- Granular simulation in LAMMPS
- Number of grains: 54780
- Coefficient of restitution: 0.001
- Coefficient of granular friction: 0.5
- Hertz normal contact implemented
- Coulomb tangential contact implemented
- Polydisperse system: [0.0012:0.0021]



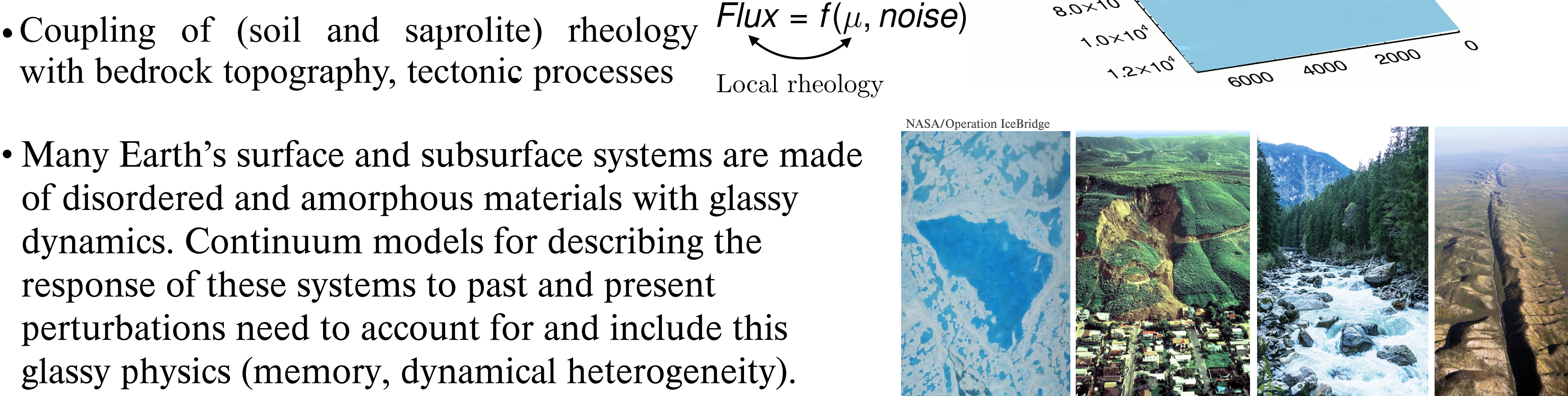
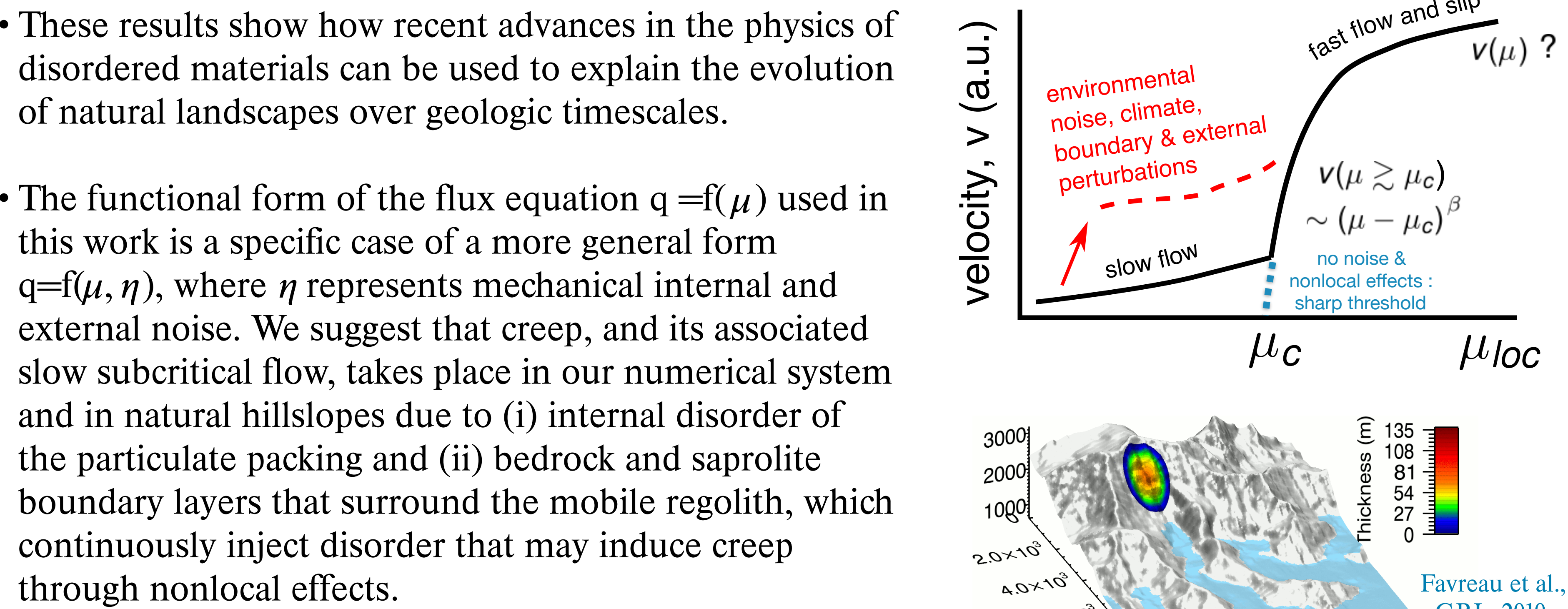
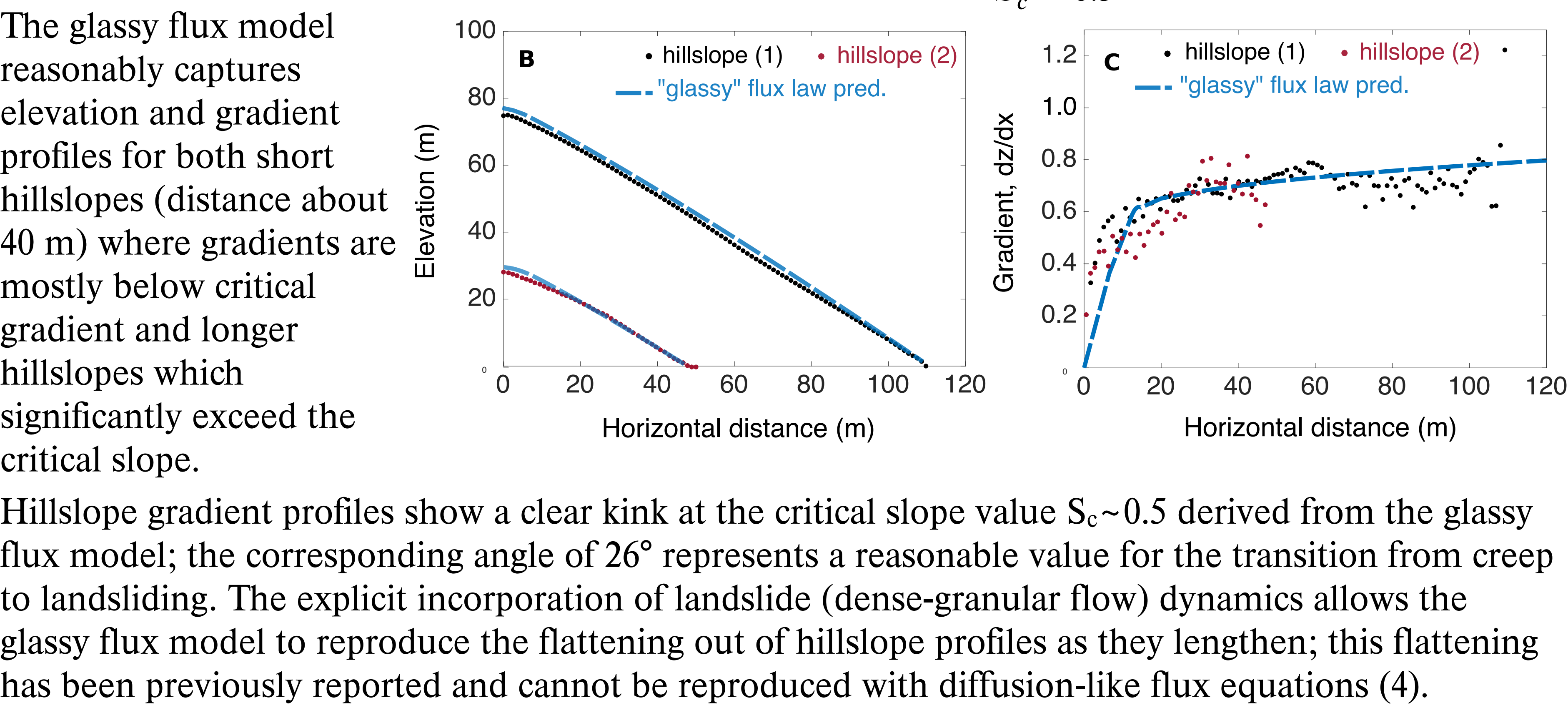
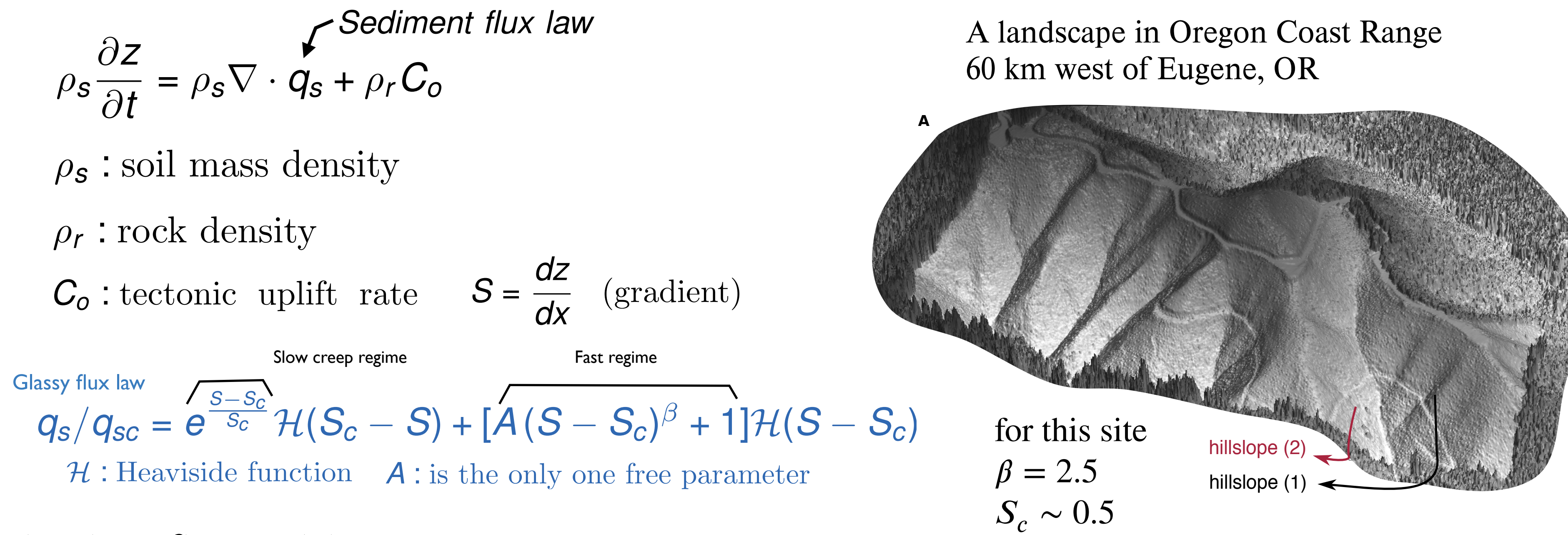
Depinning Transition in Disordered Solids/Interfaces



Hillslope Evolution as a Depinning Transition: Field Evidence



Modeling Landscape Evolution with a Glassy Flux Model



References

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Acknowledgments

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