

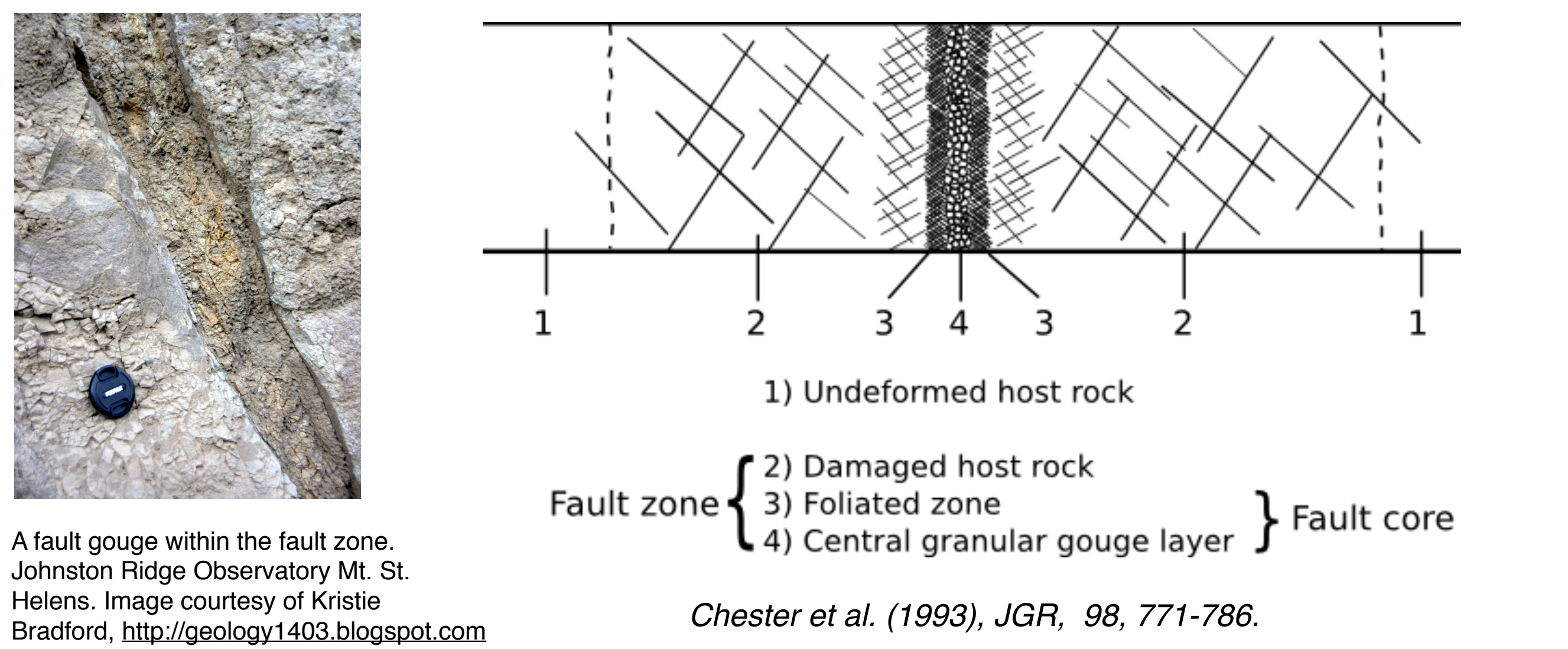
# Granular origins of rate and state friction behavior of fault gouge

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## Introduction: Granular fault gouge

Most mature faults contain a **granular layer** at their core, termed "**fault gouge**". Gouge is accumulated through wear and fragmentation of the fault interface and most often is the weakest zone of the fault. The dynamical behavior of gouge thus plays a fundamental role in the stability of the fault system.

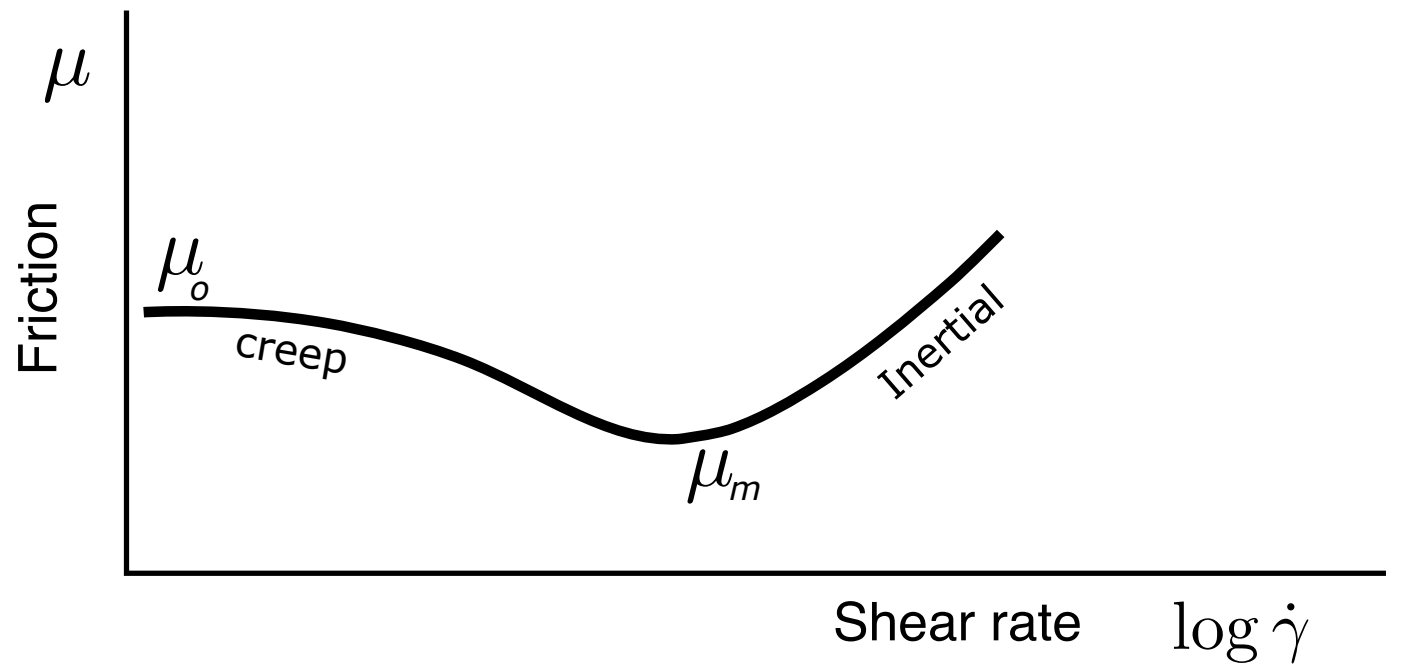


## Physics of sheared granular layers

Granular layers exhibit a variety of dynamical behavior from **steady-sliding** to **stick-slip** and **creep** when subjected to shearing at increasing confining pressures and decreasing shearing velocities in laboratory experiments and simulations.

Sick-slip instabilities have been associated with a non-monotonic shear stress vs. shear rate response in disordered granular layers with frictional dissipation [1,2].

The non-monotonic response [1-4] is suggestive of inherent instabilities and has been argued to be a source of rate and state dependent frictional behavior [3].



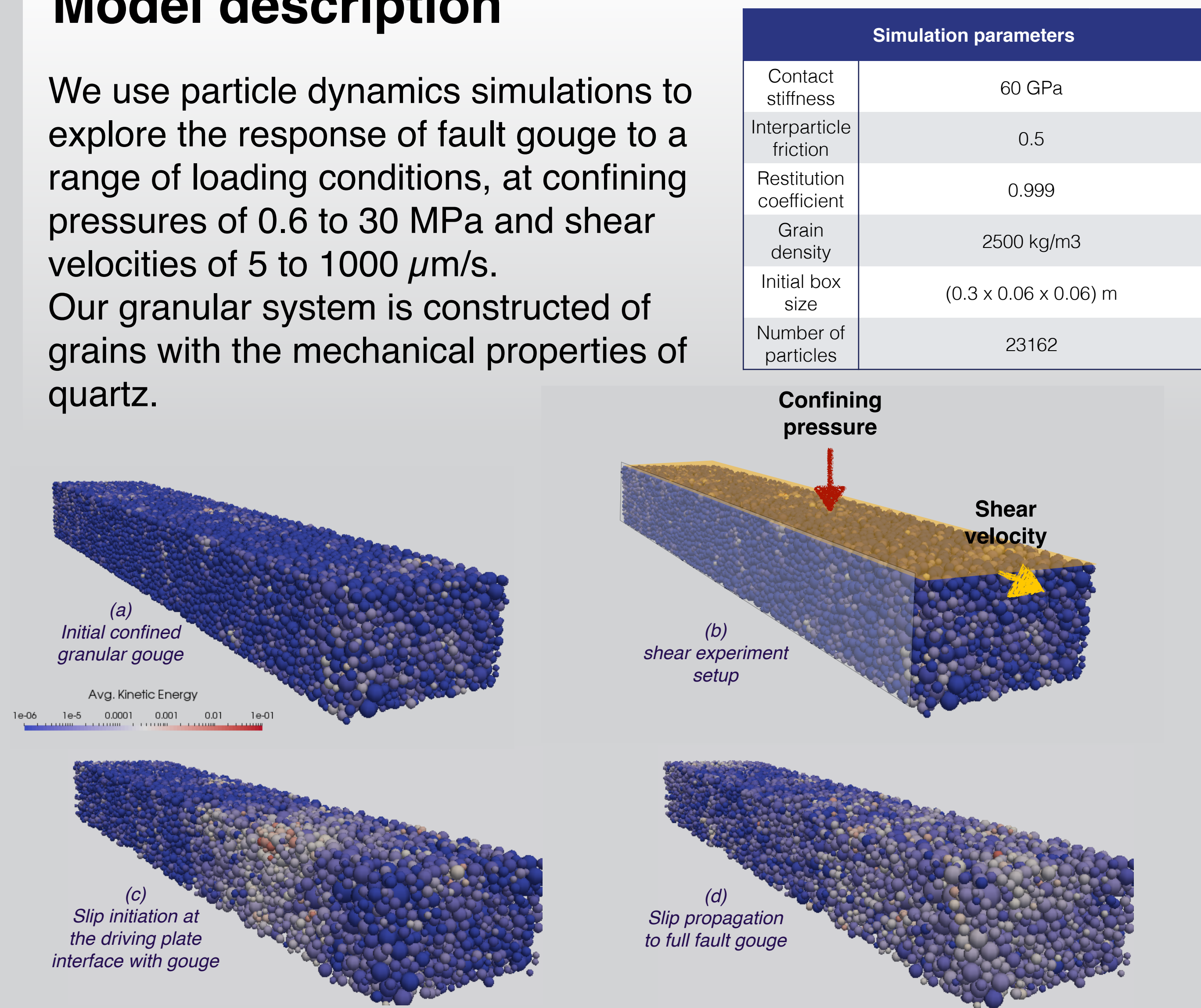
## Objectives and approach

We seek to understand the physics of rate and state friction behavior of simulated fault gouge using theory and methods from the field of granular physics.

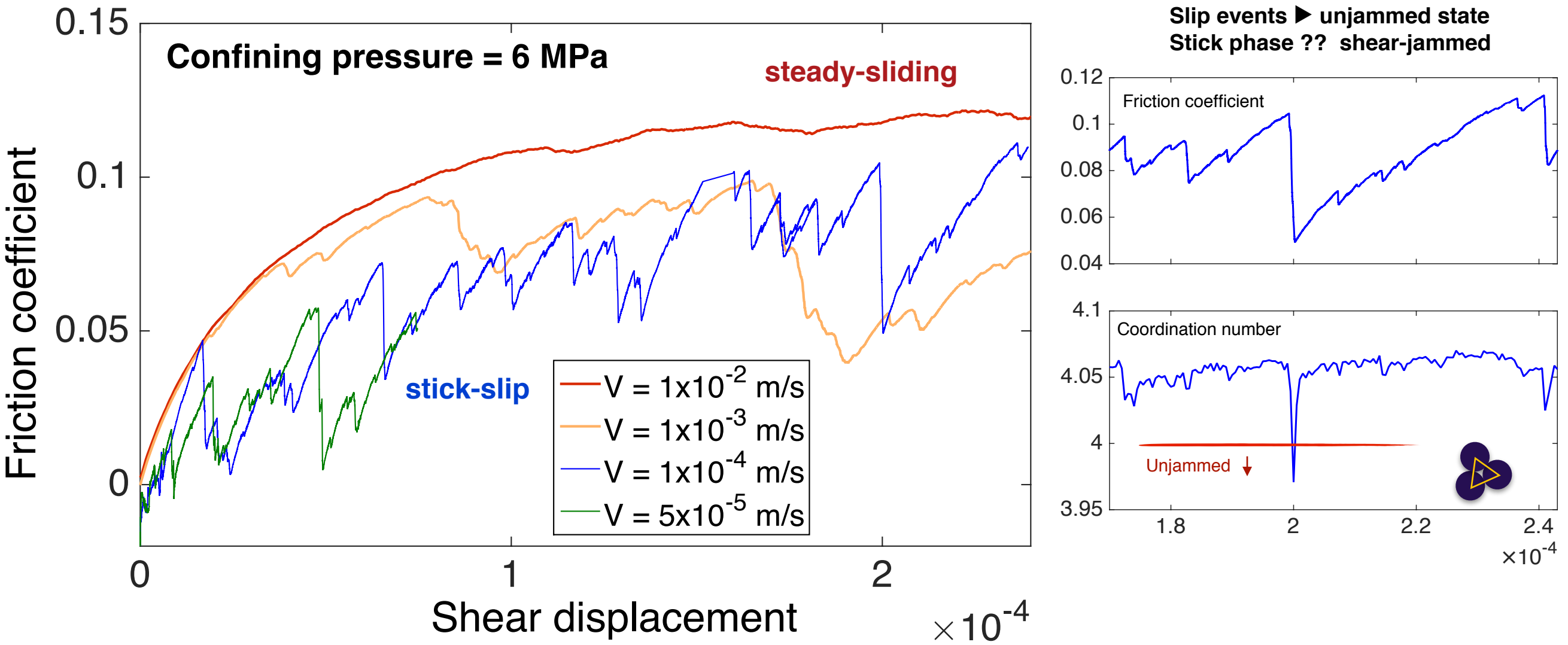
We examine the response of the system to a change in shear rate (in simulated velocity-stepping tests), providing insight into granular processes at the core of observed velocity-weakening and velocity-strengthening behaviors.

## Model description

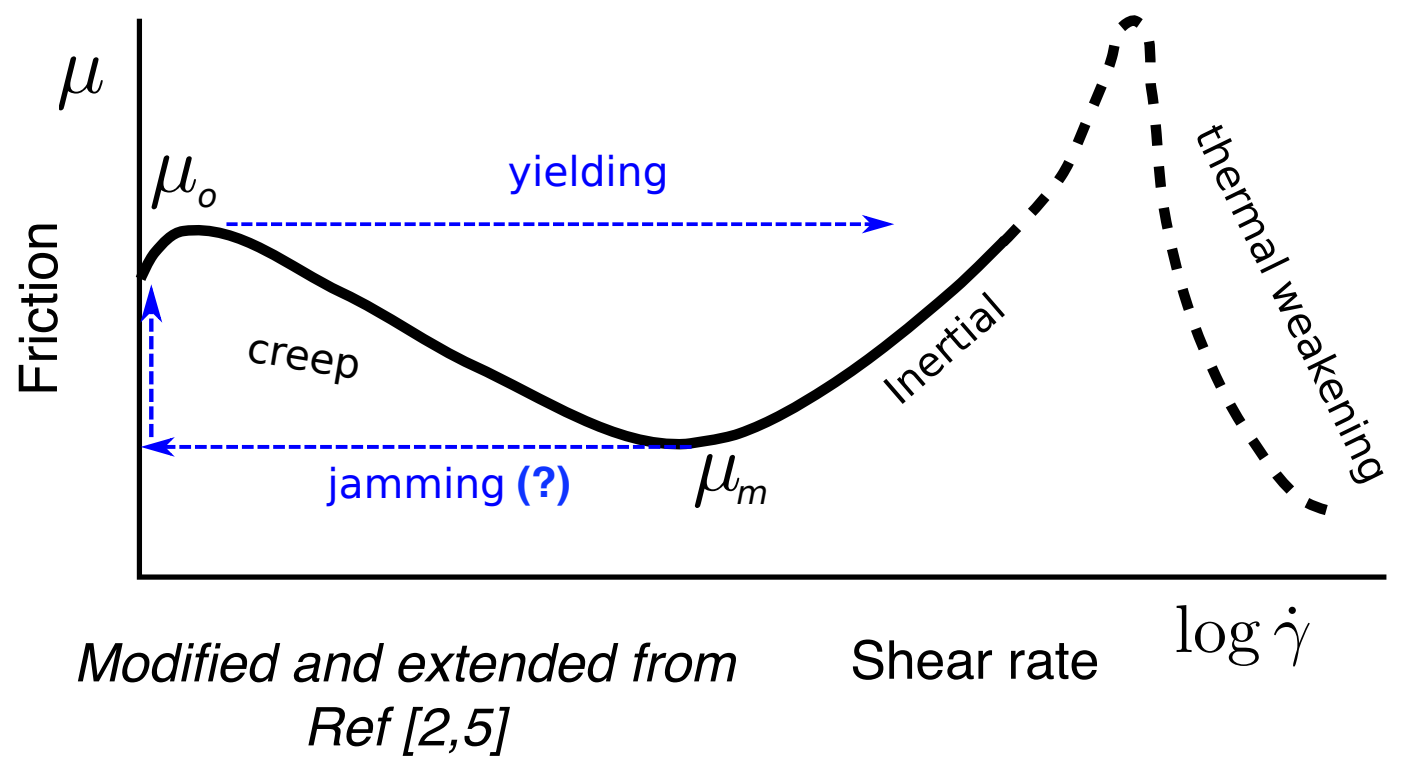
We use particle dynamics simulations to explore the response of fault gouge to a range of loading conditions, at confining pressures of 0.6 to 30 MPa and shear velocities of 5 to 1000  $\mu\text{m/s}$ . Our granular system is constructed of grains with the mechanical properties of quartz.



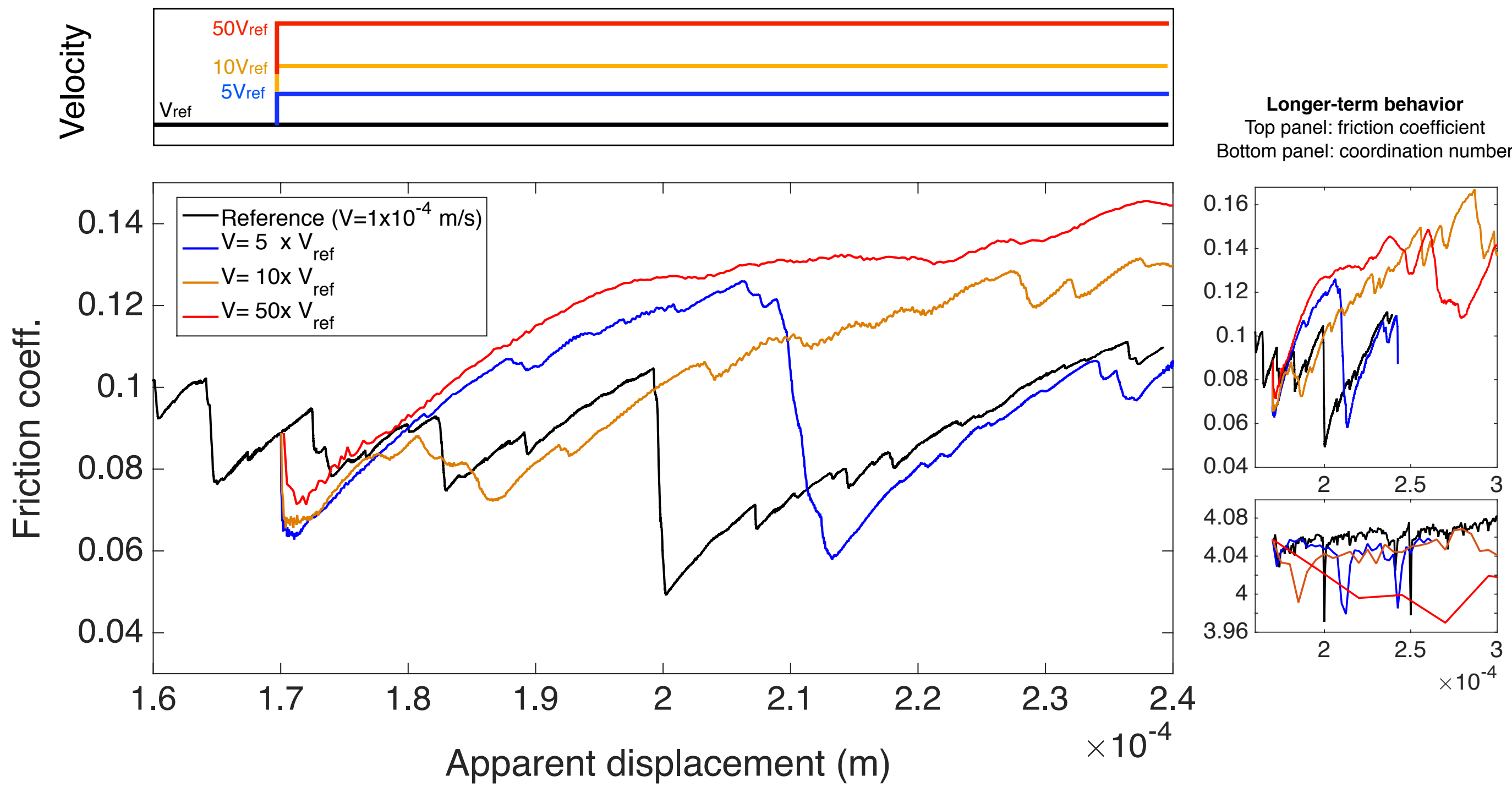
## Frictional behavior of granular gouge



- The granular gouge shows a range of behavior from steady-sliding to stick-slip and creep as the shearing velocity is decreased.
- Our simulations confirm the hypothesis by van Hecke (2015) that slip (local minima) can in fact be an unjammed state. However, whether (and how) it is followed by another approach to jamming is not yet sufficiently explored.



## Velocity step (increase) tests



- Increasing drive velocity initially causes an instability and is then followed by velocity-strengthening response.
- The velocity-strengthening response can be interpreted as a continuous evolution of dynamical behavior of the granular gouge. This can be seen as a continuous change of coordination number to lower levels with increasing drive velocity (right figure-bottom panel).

## Conclusions and future work

- A disordered granular gouge layer has an inherent instability that results in a range of dynamical behavior from steady-sliding to stick-slip and creep at varying shear rates.
- Investigating the rheology of confined gouge can be a key step toward physically-based friction laws applicable to fault gouge.
- It is important to know if the jamming-unjamming paradigm-a widely explored source of instability in granular systems- has implications for fault friction. Slip is an unjammed state, but what is the nature of the transition from stick to slip states?
- After understanding and quantifying the contribution of disordered granular structure to the rate and state frictional response, the next steps will be exploring the role of humidity, fluid and plastic deformation at the contact scale.

### References

- Lieou, C. K., Elbanna, A. E., Langer, J. S., & Carlson, J. M. (2015). Stick-slip instabilities in sheared granular flow: The role of friction and acoustic vibrations. *PRE*, 92(2), 022209.
- van Hecke, M. (2015). Slow granular flows: The dominant role of tiny fluctuations. *Comptes Rendus Physique*, 16(1), 37-44.
- Heslot, F., Baumberger, T., Perrin, B., Caroli, B., & Caroli, C. (1994). Creep, stick-slip, and dry-friction dynamics: Experiments and a heuristic model. *PRE*, 49(6), 4973
- Elst, N. J., Brodsky, E. E., Le Bas, P. Y., & Johnson, P. A. (2012). Auto-acoustic compaction in steady shear flows: Experimental evidence for suppression of shear dilatancy by internal acoustic vibration. *JGR*, 117(B9).
- Bar-Sinai, Y., Spatschek, R., Brener, E. A., & Bouchbinder, E. (2014). On the velocity-strengthening behavior of dry friction. *JGR*, 119(3), 1738-1748.