

Grain-scale numerical modeling of granular mechanics and fluid dynamics

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Granular materials are all around us

Definition

Conglomeration of discrete solid and macroscopic particles characterized by inelastic interaction
(loss of energy)

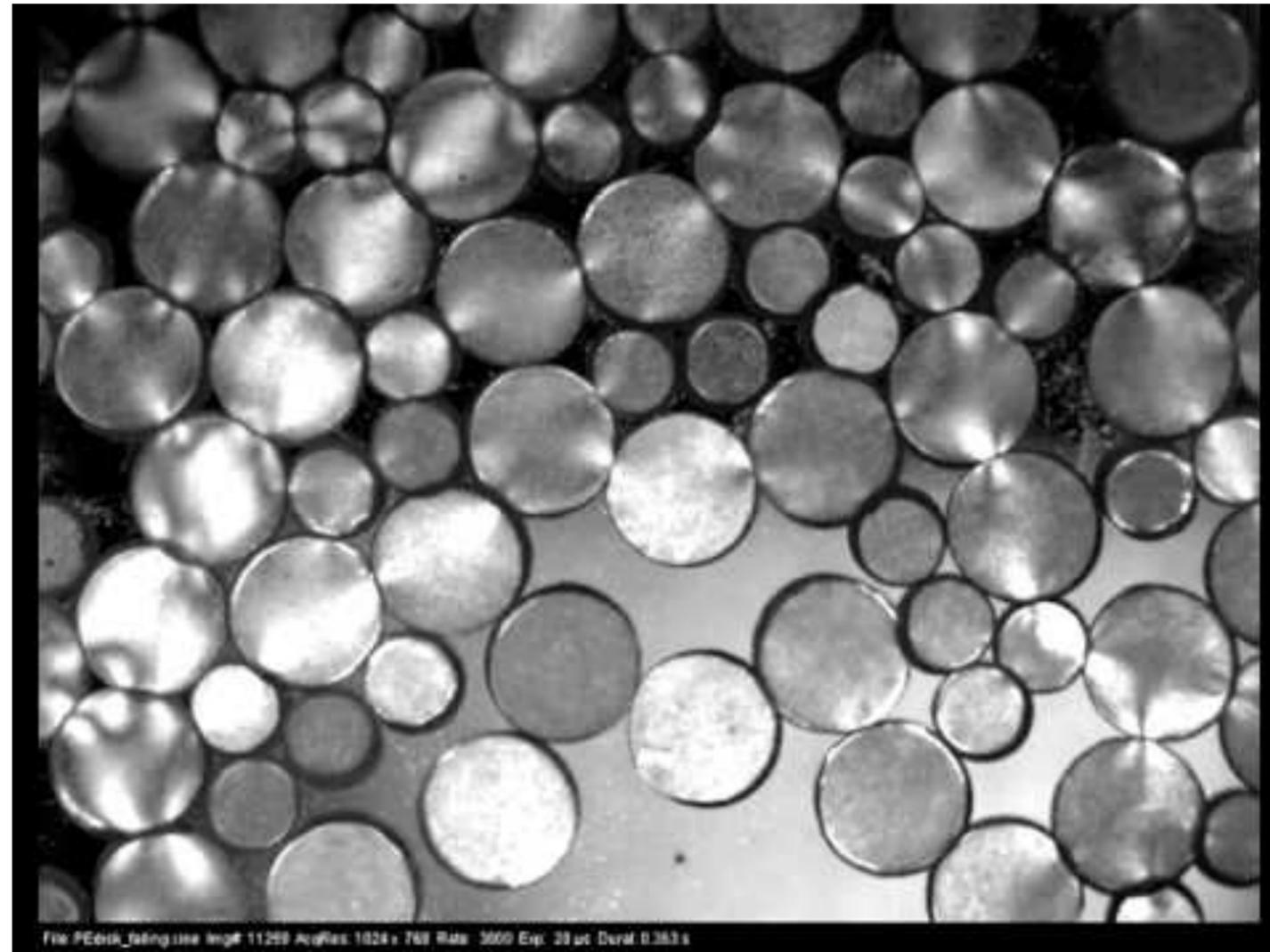
Sand takes many forms



Increasing kinetic energy   Increasing density

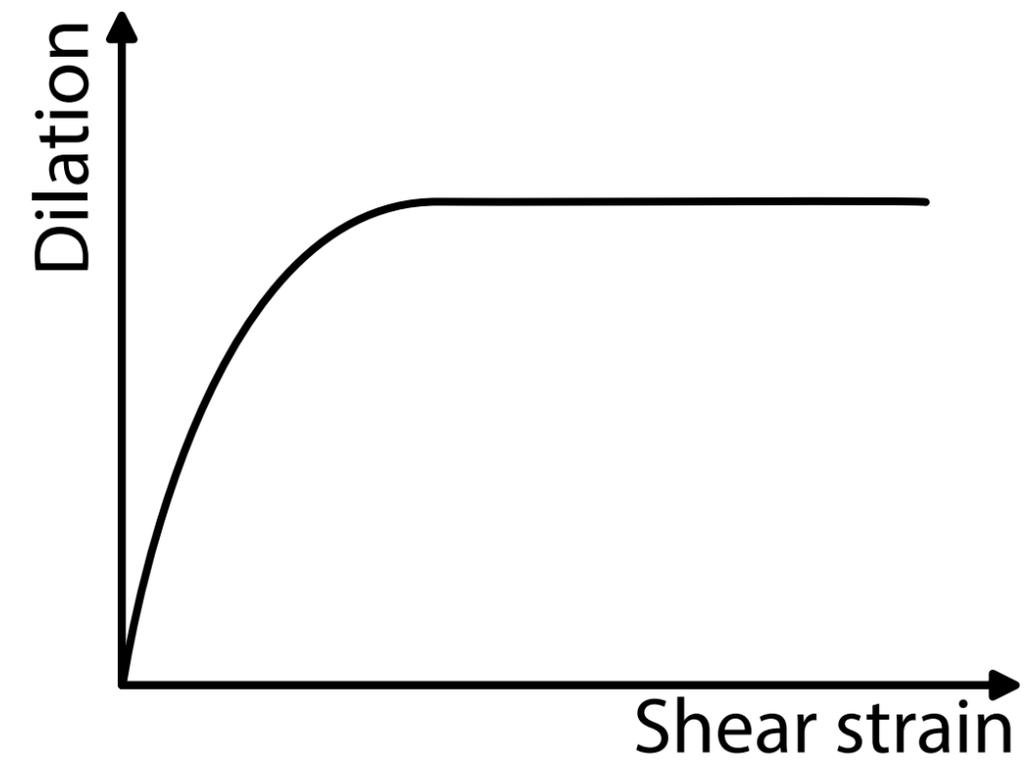
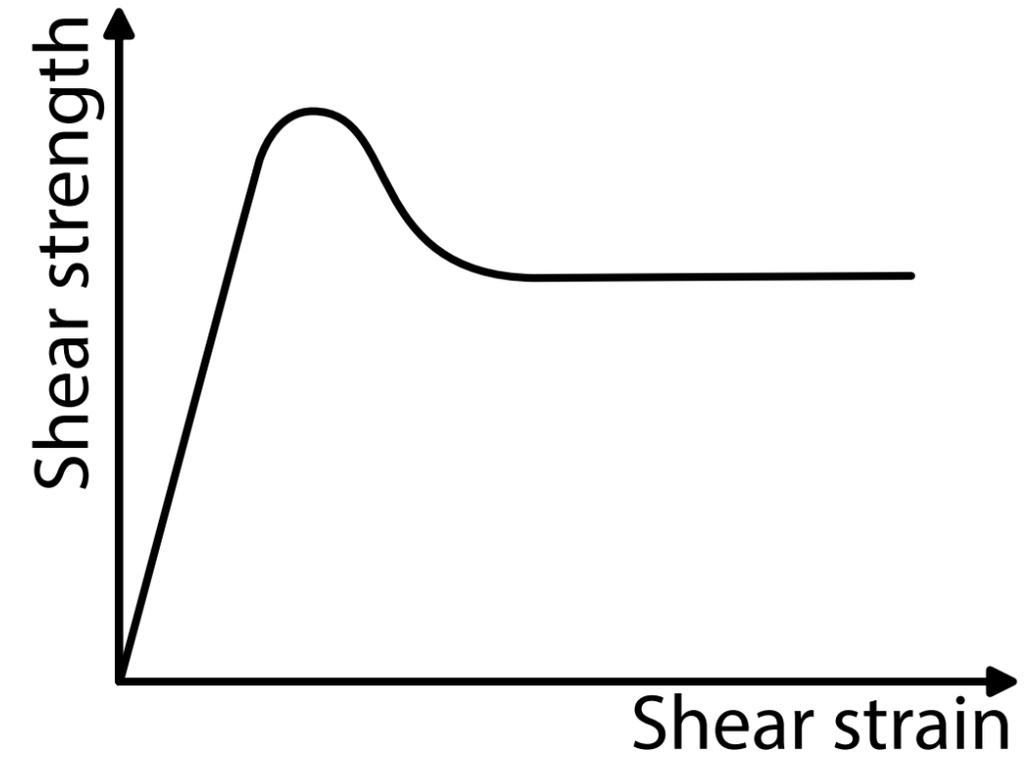
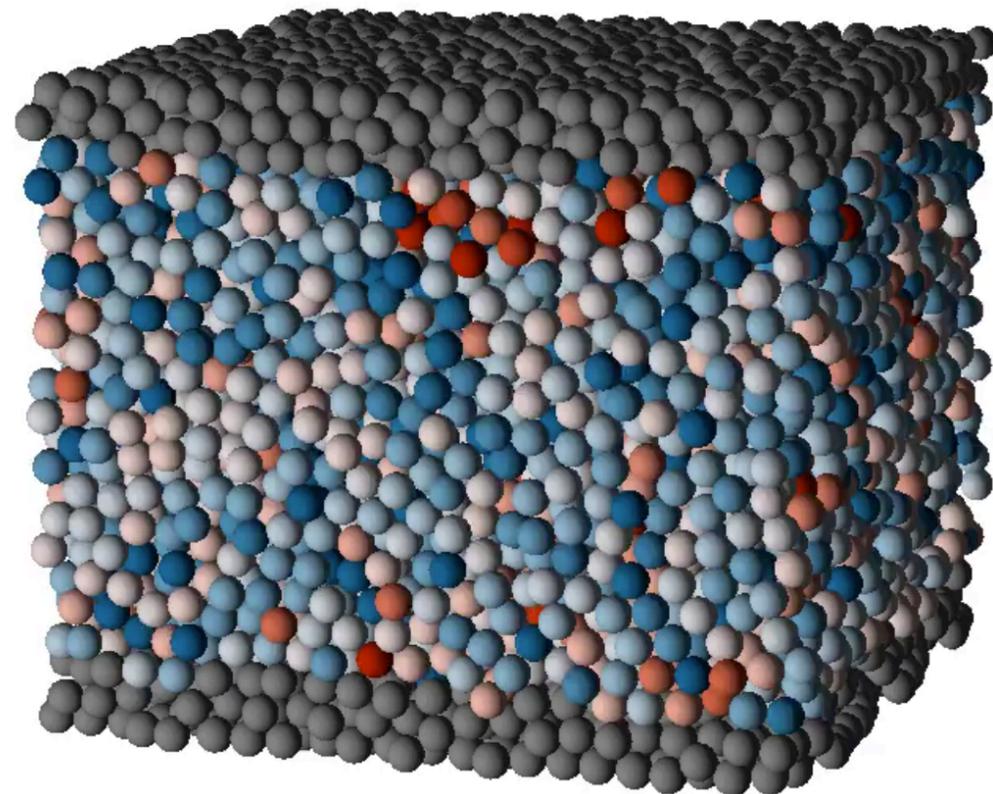
Force chains

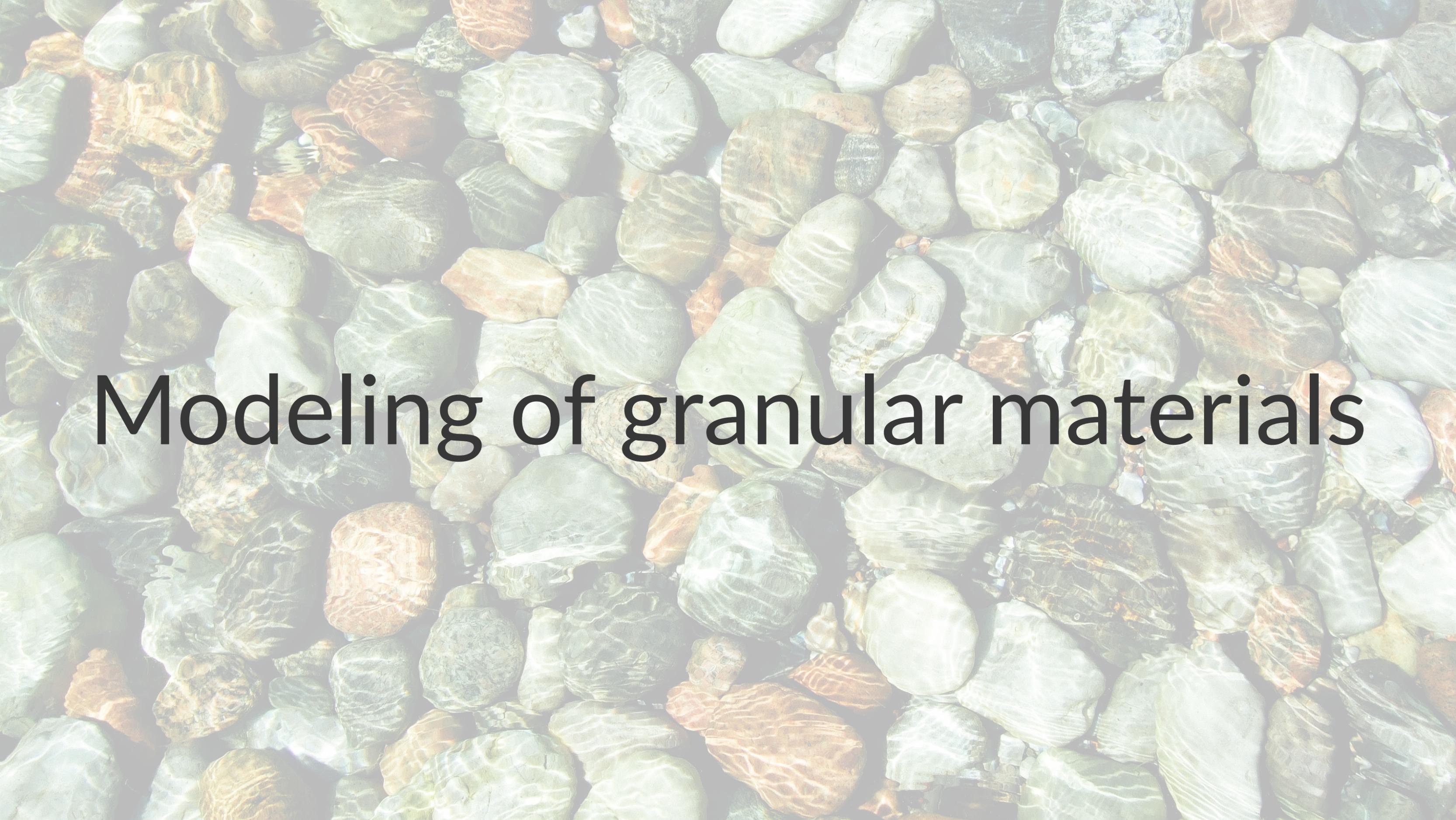
<https://youtu.be/da8763Km0h8>



Granular materials during shear

Damsgaard et al. 2013 *J. Geophys. Res.-Earth* **118**



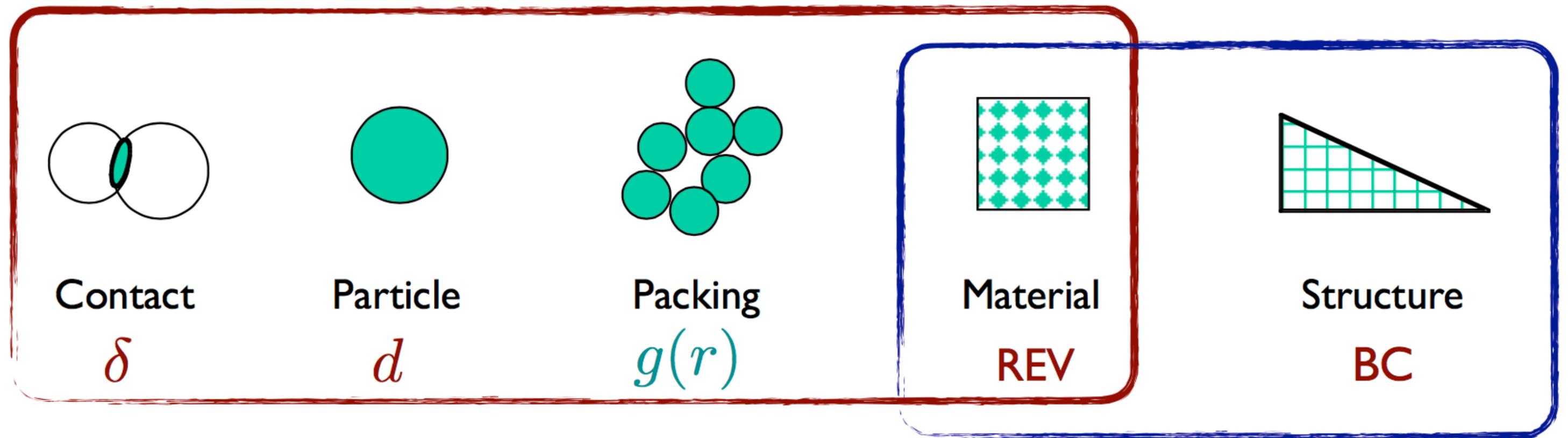


Modeling of granular materials

Multi-scale problem

J-Y. Delenne, from slides for STAiR PhD course 2011

Discrete mechanics...



...Continuum mechanics

sphere

<https://github.com/anders-dc/sphere>

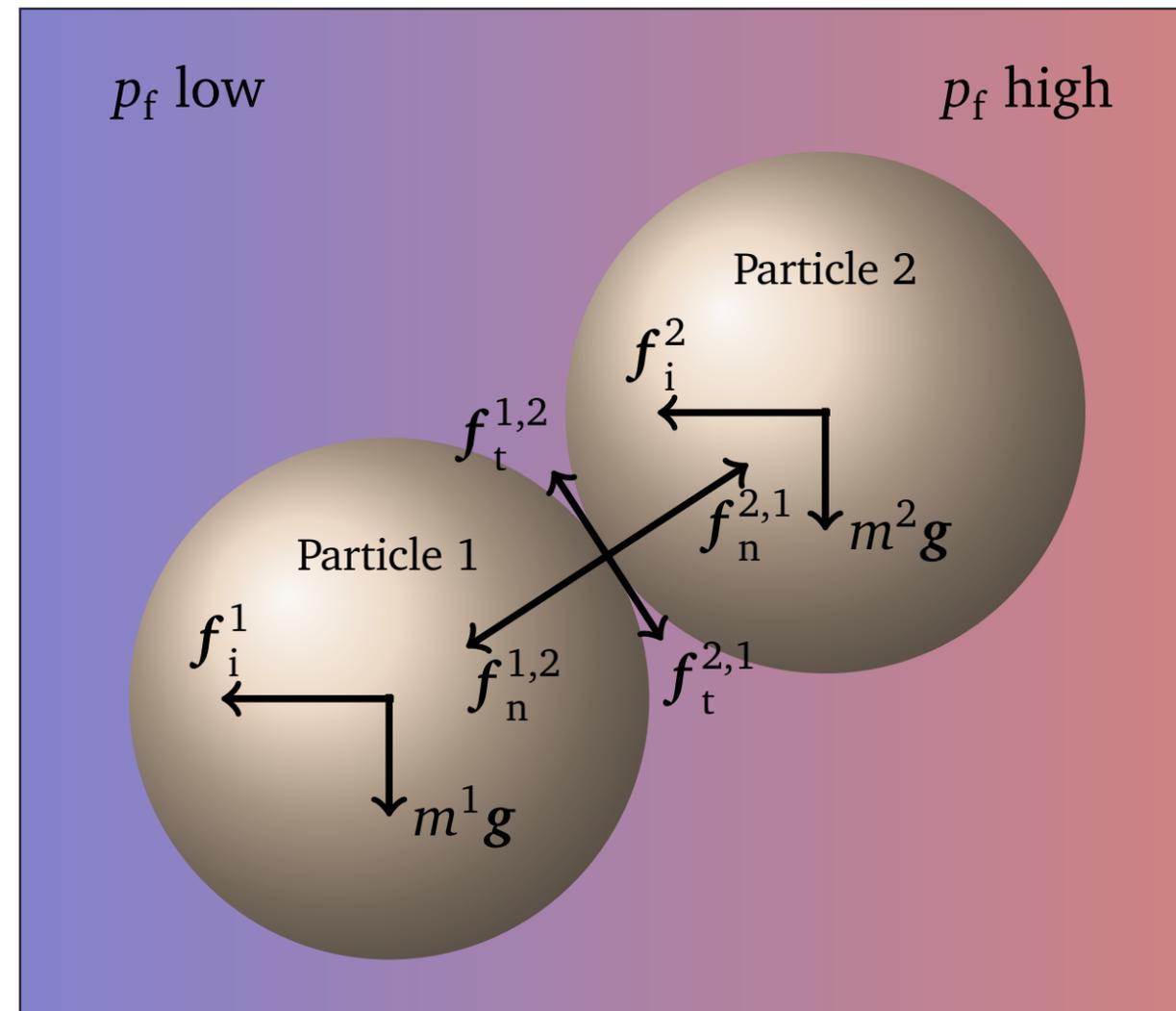
- 3D soft-body Discrete Element Method
- Optional fluid coupling:
Saturated: Navier-Stokes or Darcian flow
Unsaturated: capillary cohesion
- ~30k LOC in CUDA C, C++, Python
- Free software and open source, GPL v3 license
- Visualization with Matplotlib, Paraview or ray tracer

Advantages of choosing free software licenses

- Reproducible results (share *all* source code)
- Research products (publications, software) should be available to the general public
- Give others the opportunity to learn, build on, and improve your tools

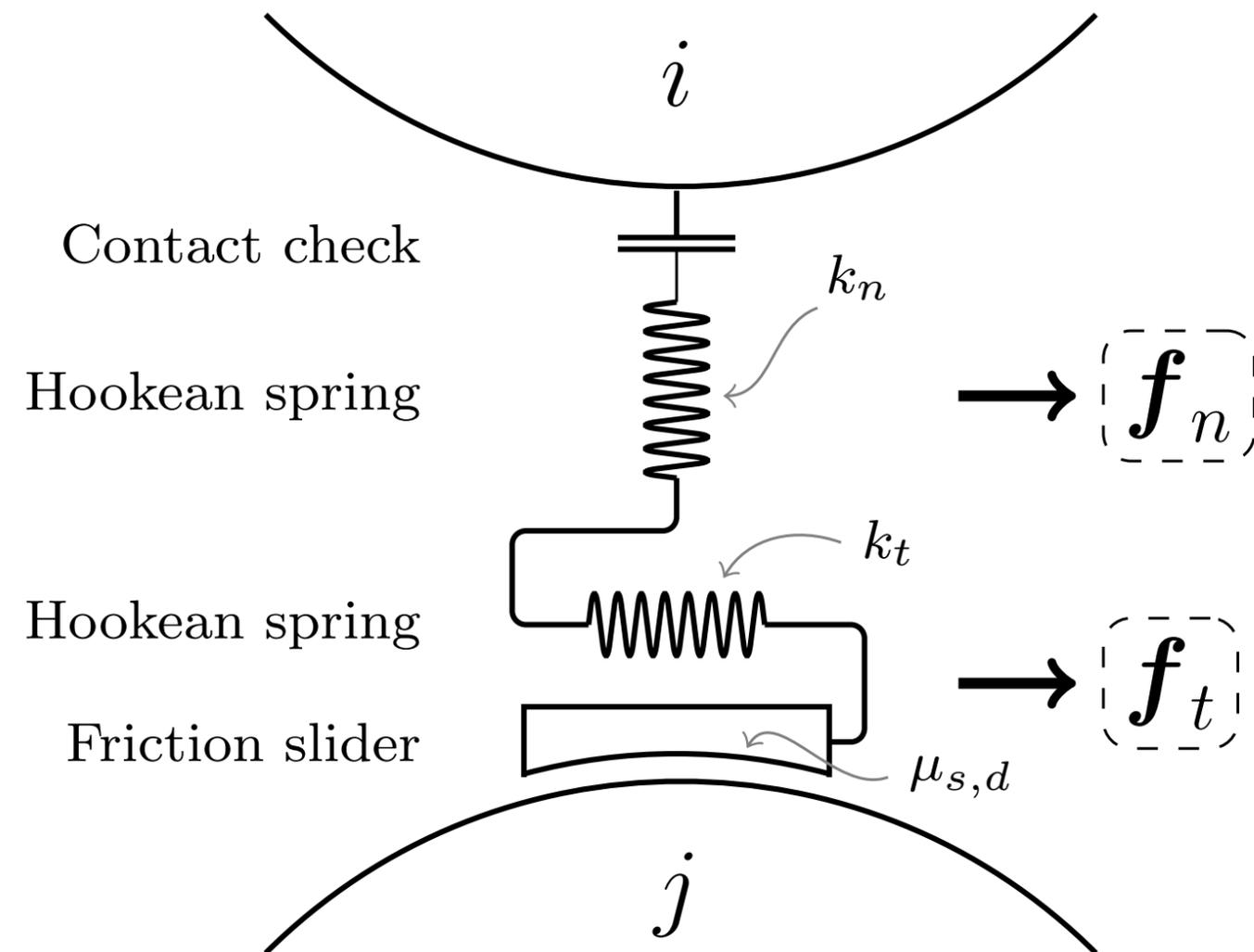
Discrete Element Method

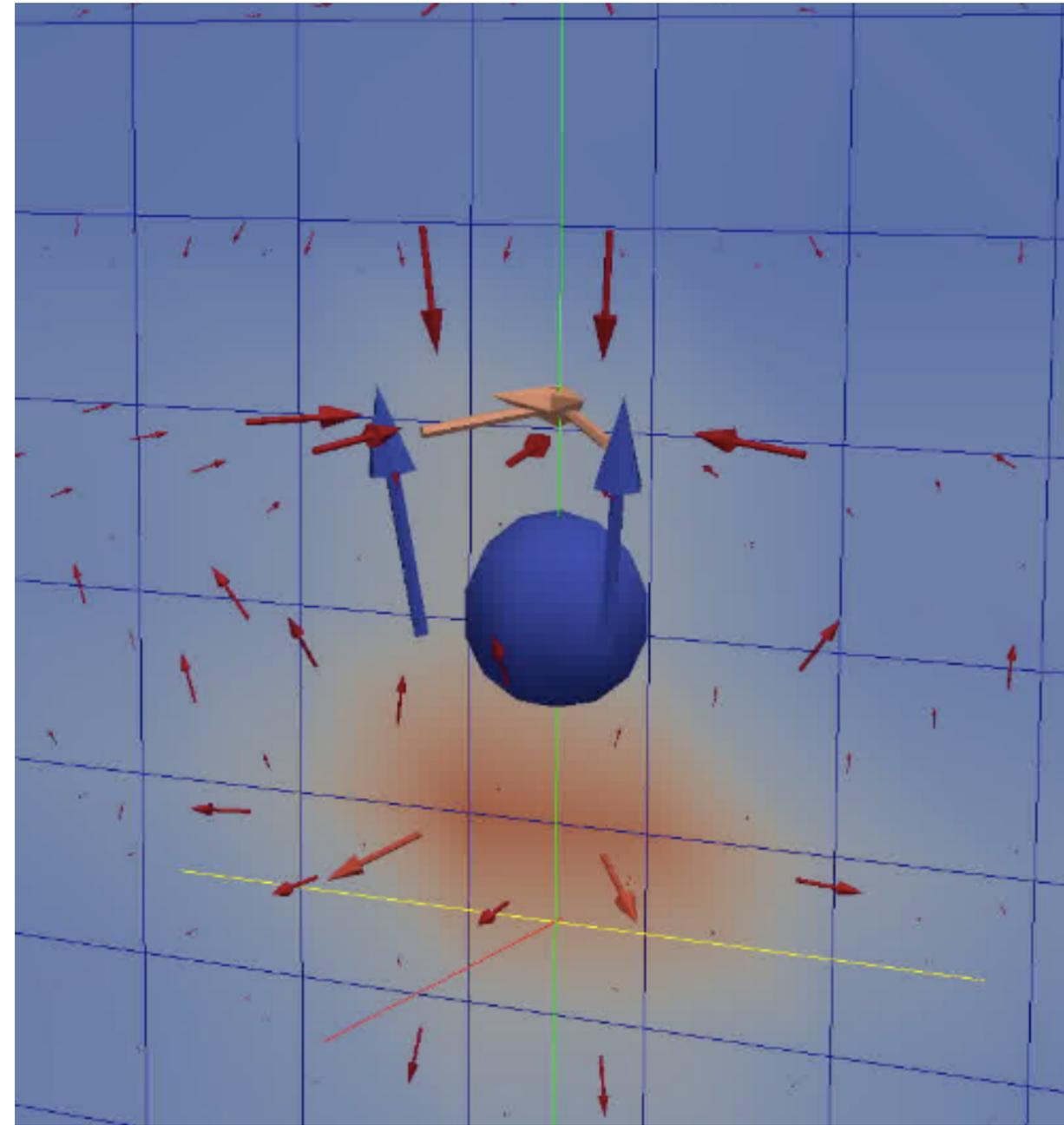
Damsgaard et al. 2015 *The Cryosphere* 9, 2183-2200.



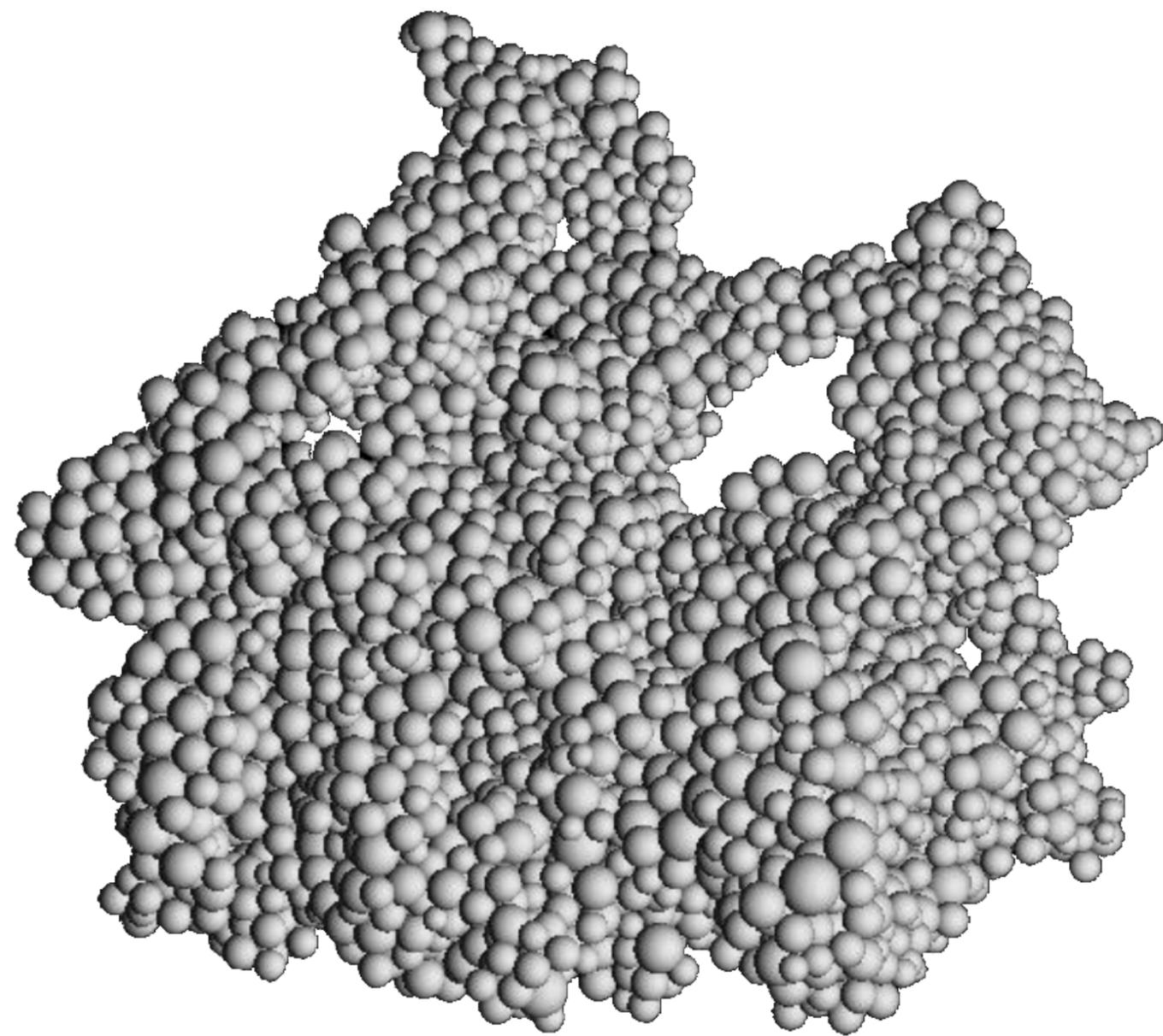
Grain contact mechanics

Damsgaard et al. 2013 *J. Geophys. Res.-Earth* **118**, 2230-2242.



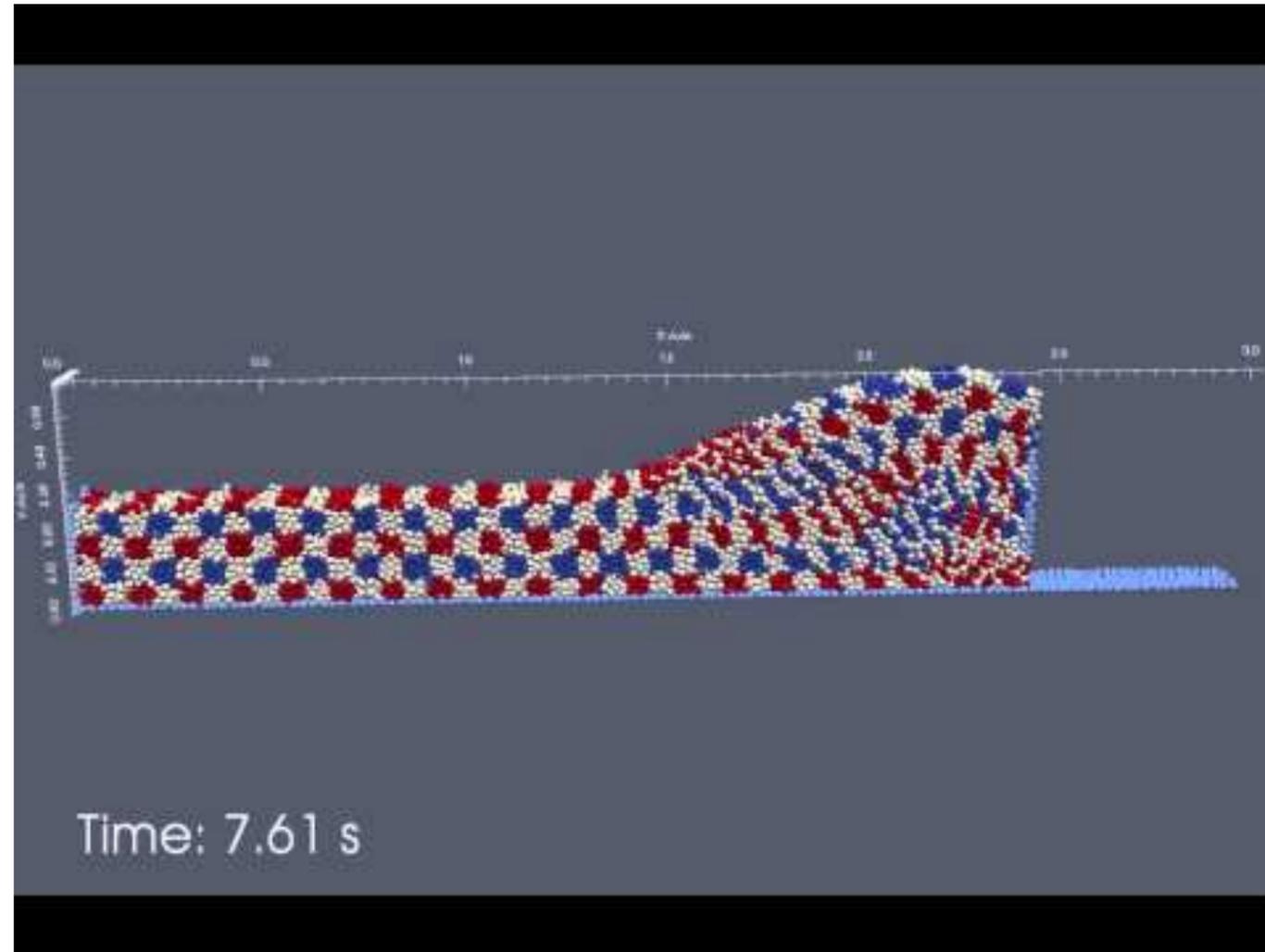


cfid_tests.py



capillary-cohesion.py

<https://youtu.be/jihHa58oWK4>

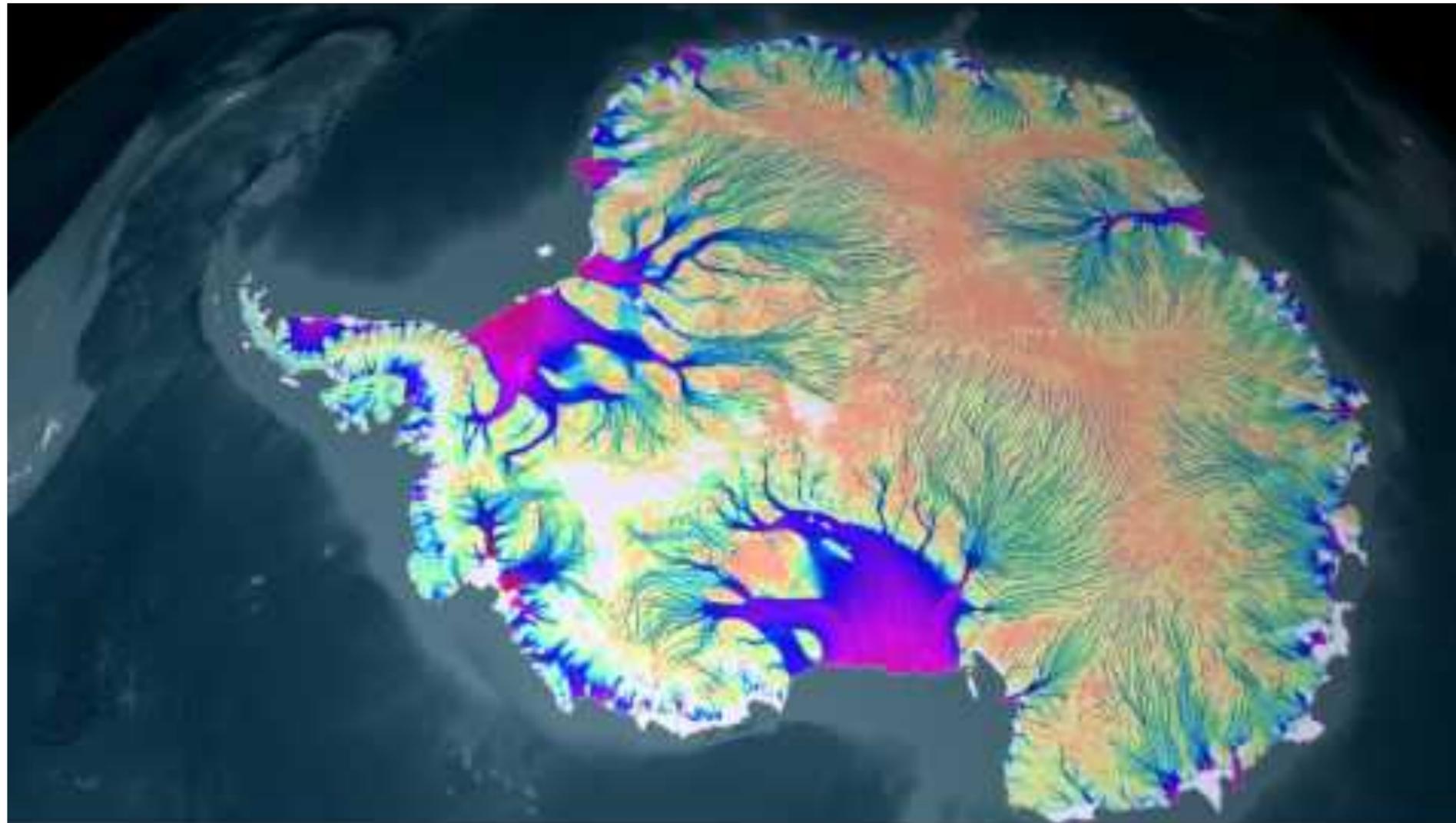


`shortening.py`

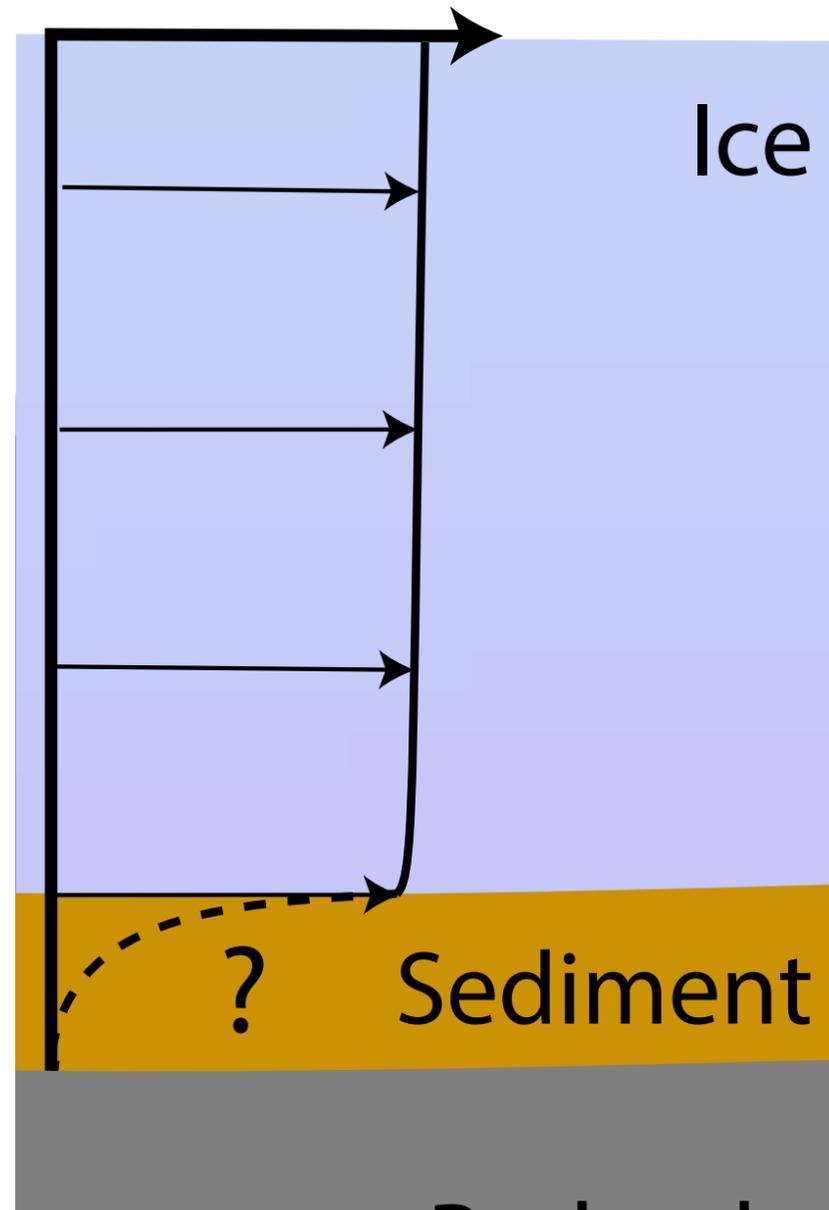
Granular dynamics influencing ice flow

NASA/Goddard Visualization Studio & Rignot et al. 2011 *Science*

https://youtu.be/1S7Gkbd_Hxc

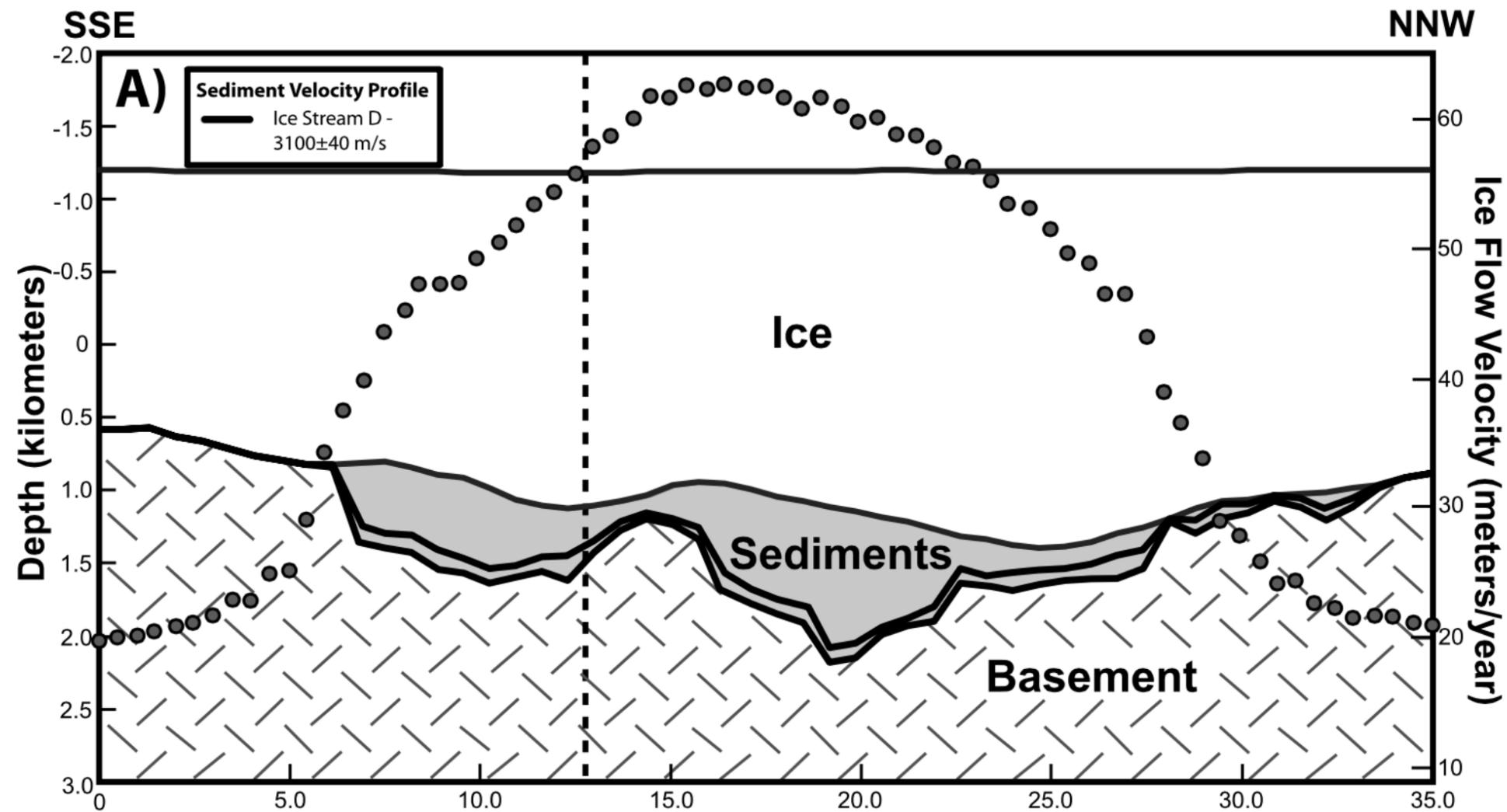


Ice streams moving as *plug flows*



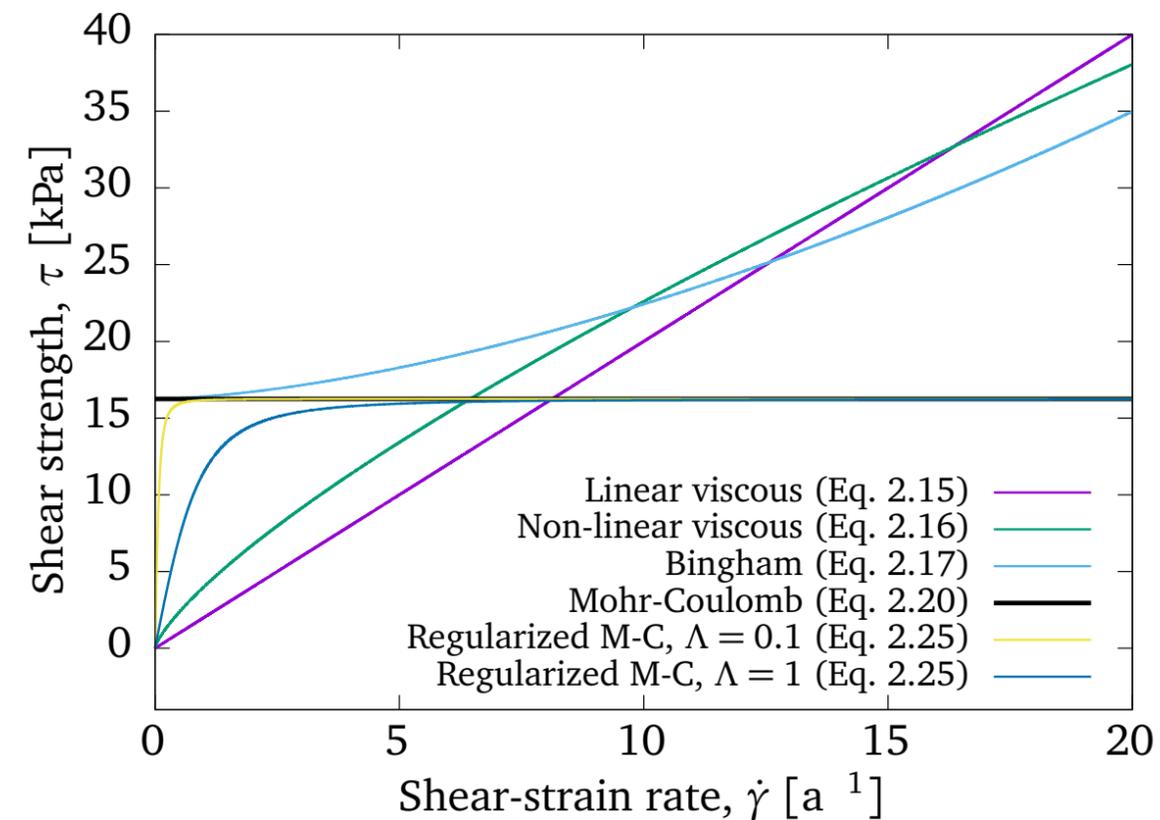
Weak sediments facilitate fast flow

Peters et al. (2006) *J. Geophys. Res.* **111** B01302.



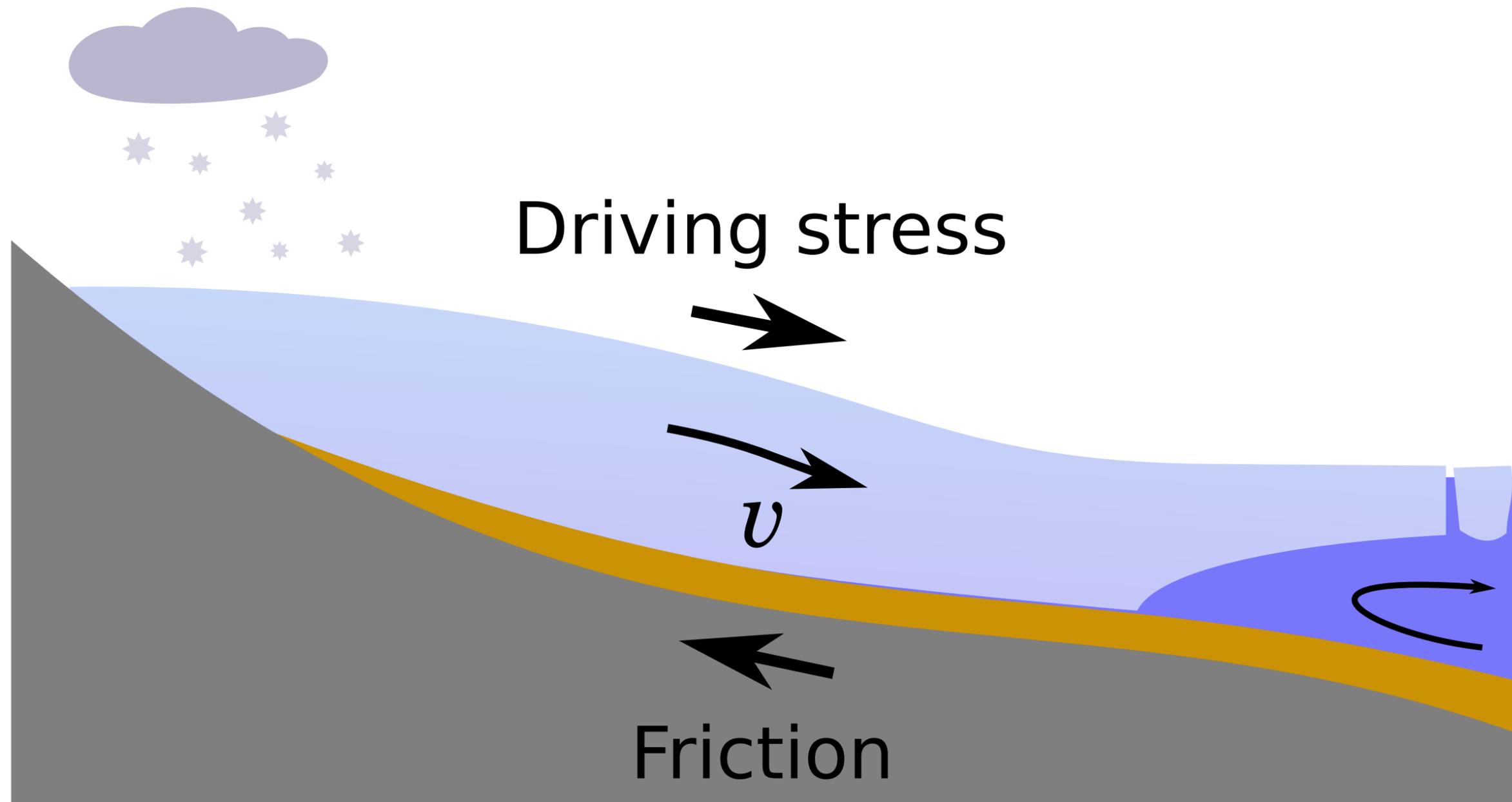
Proposed sediment rheologies

Damsgaard 2015 *Ph.D. thesis*

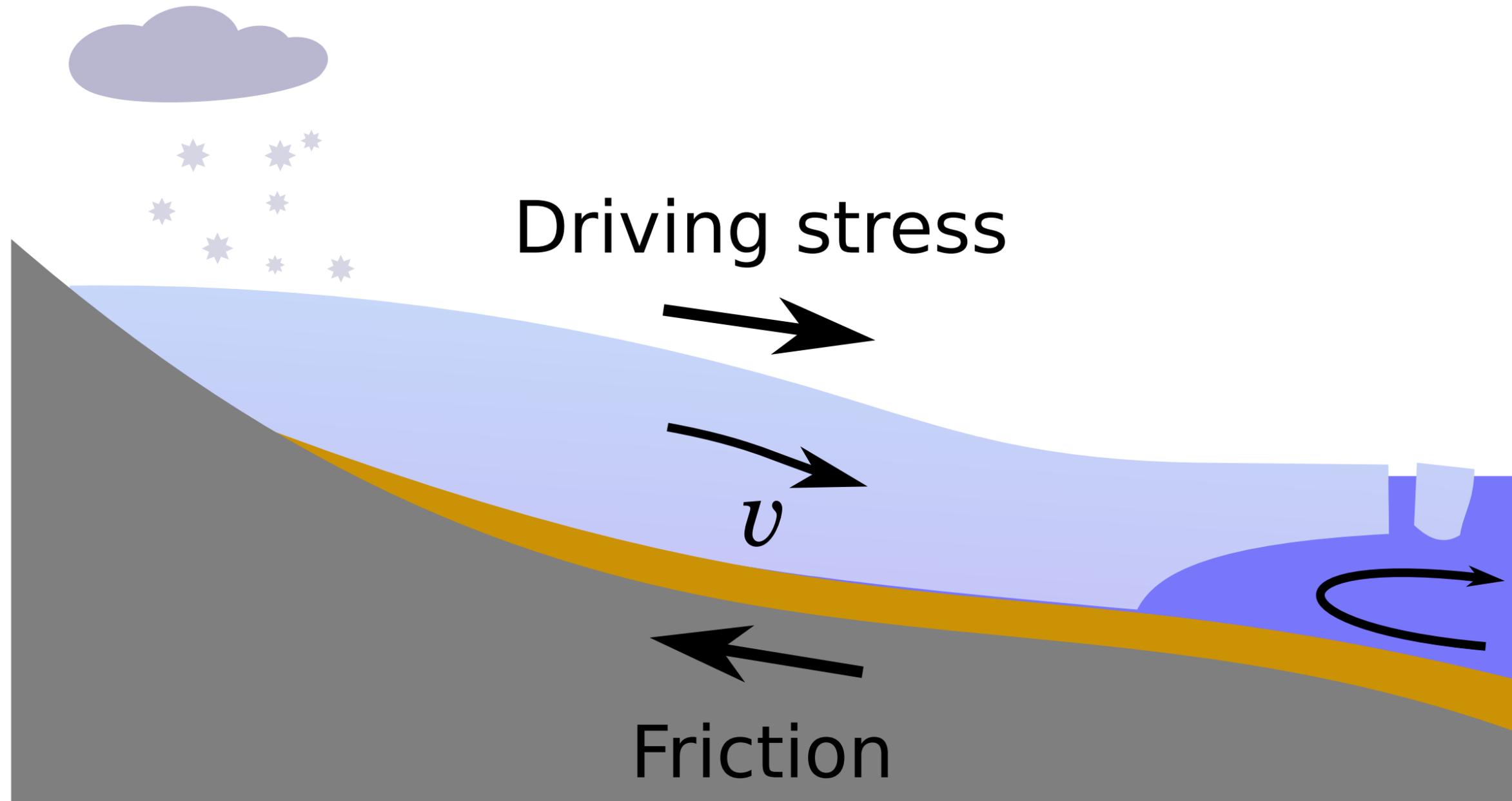


Viscous: damping, **Plastic:** instabilities/oscillations

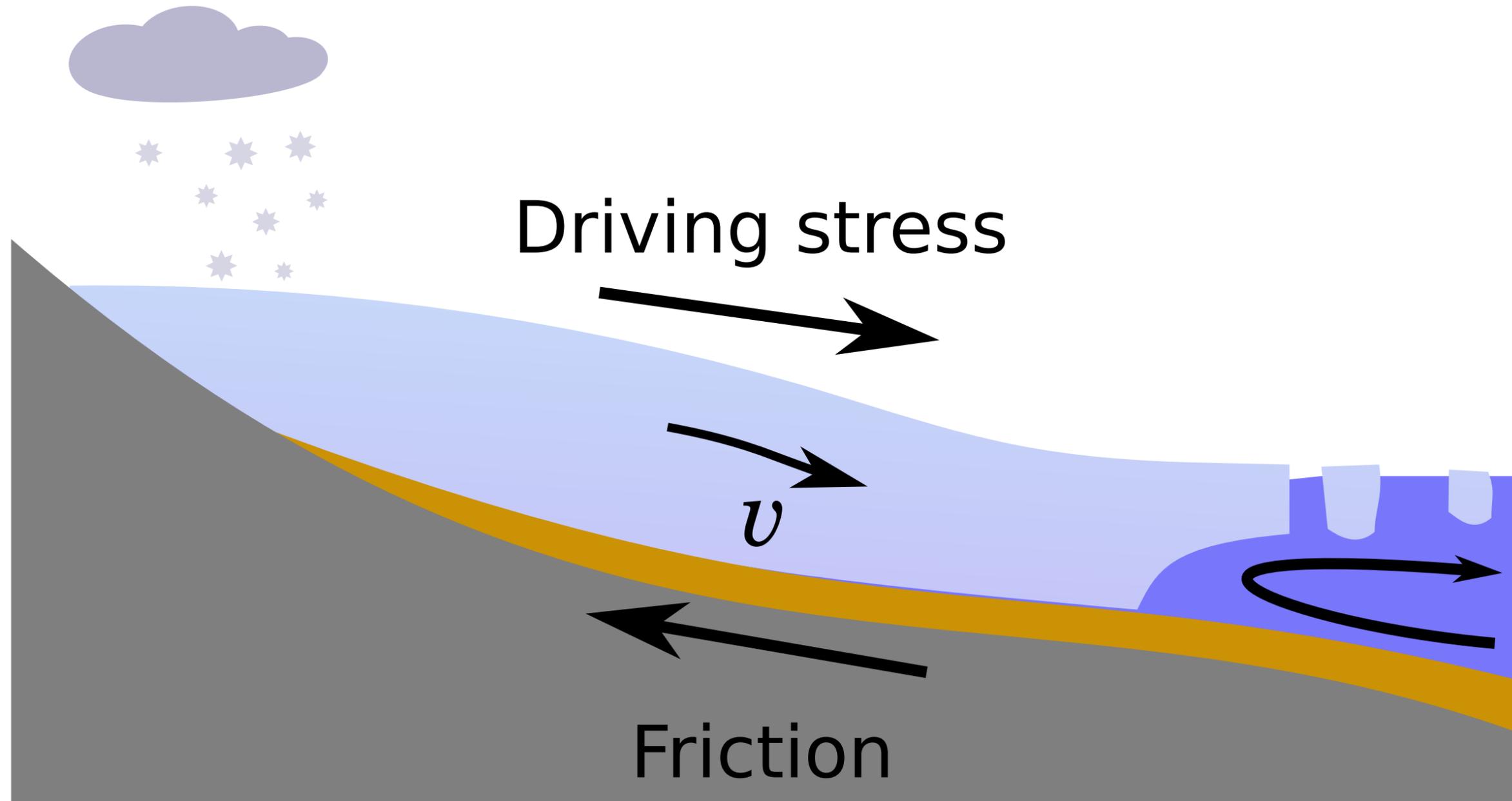
Viscous sediment rheology



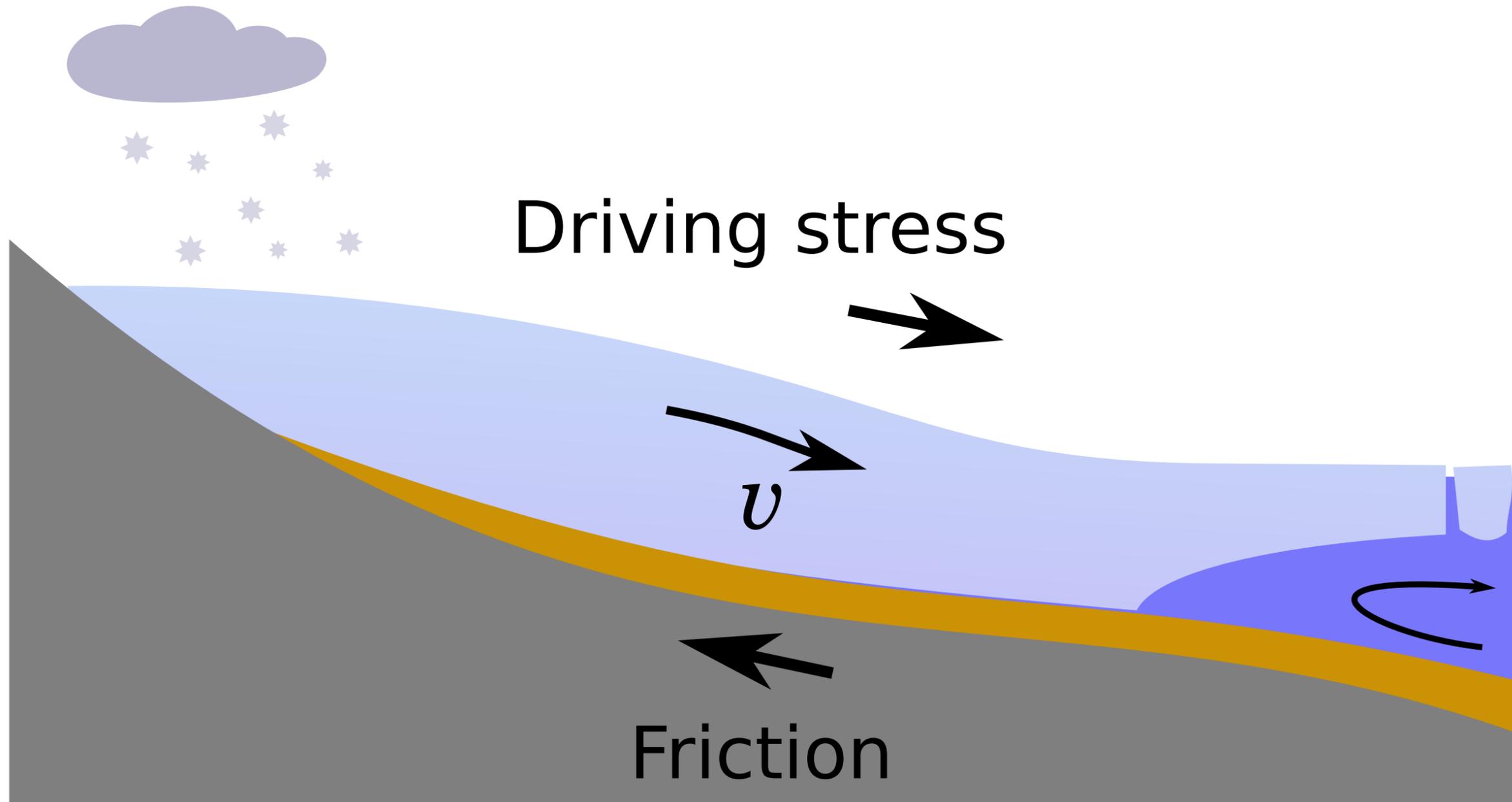
Viscous sediment rheology



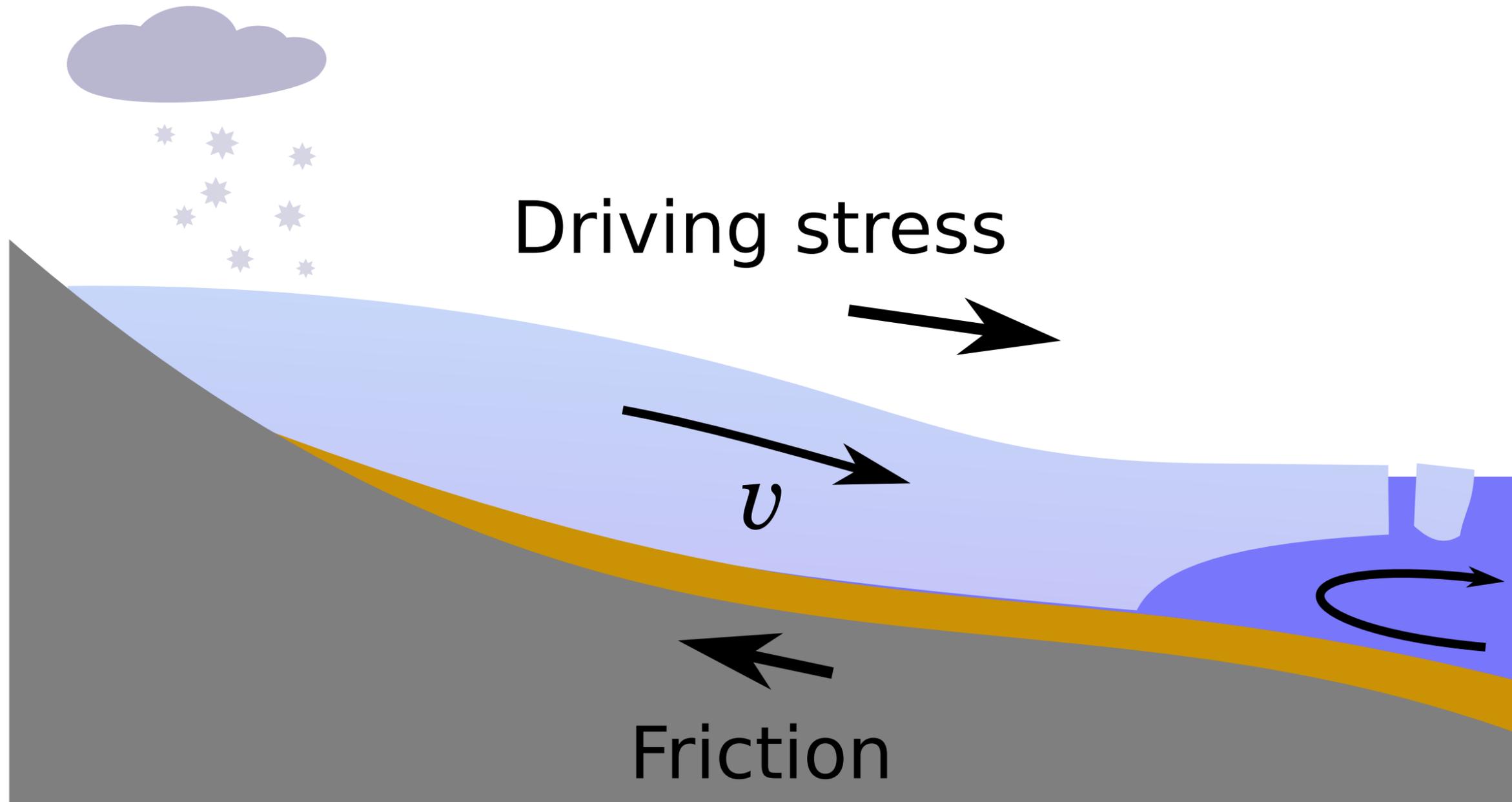
Viscous sediment rheology



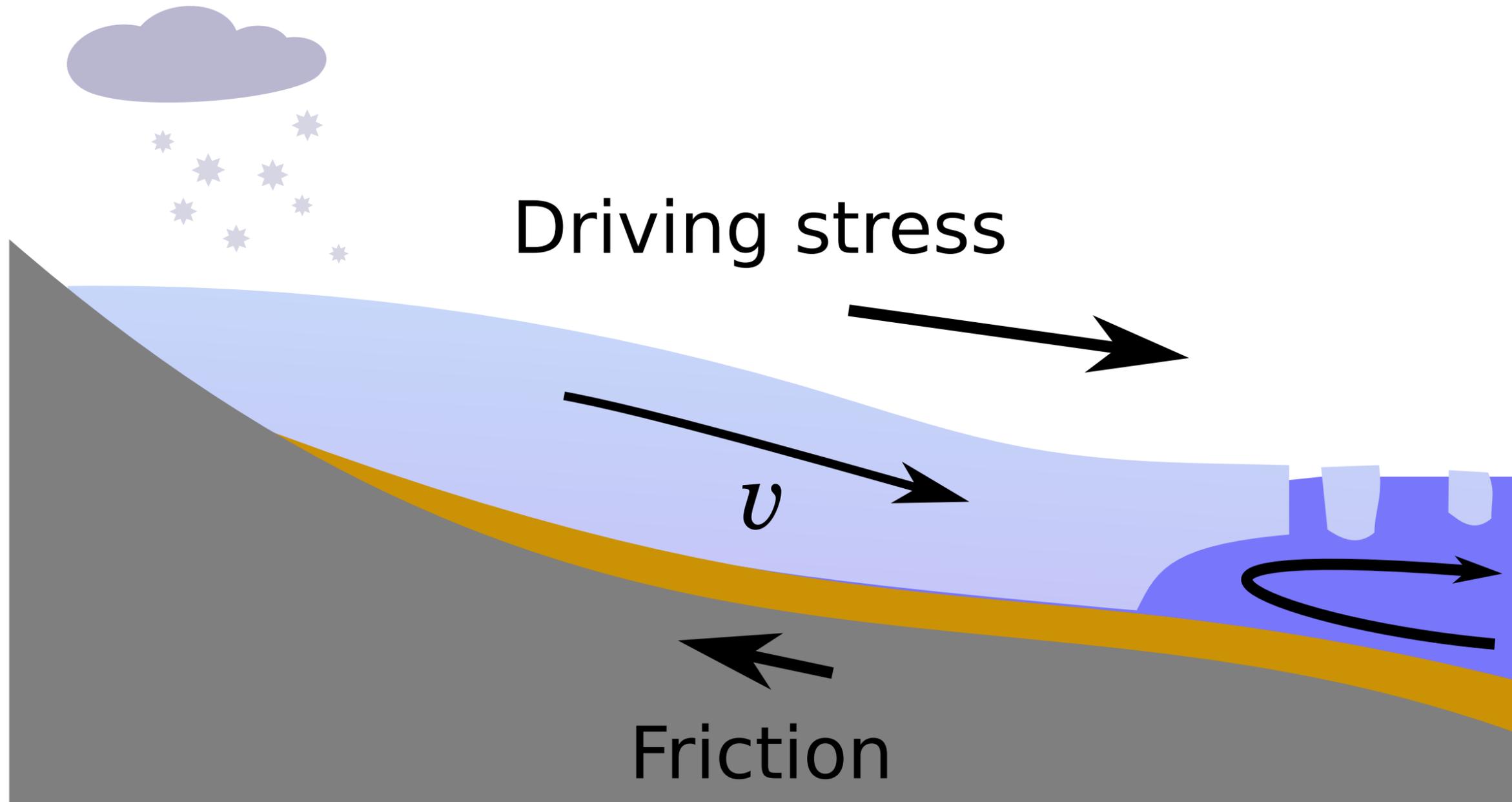
Plastic sediment rheology



Plastic sediment rheology

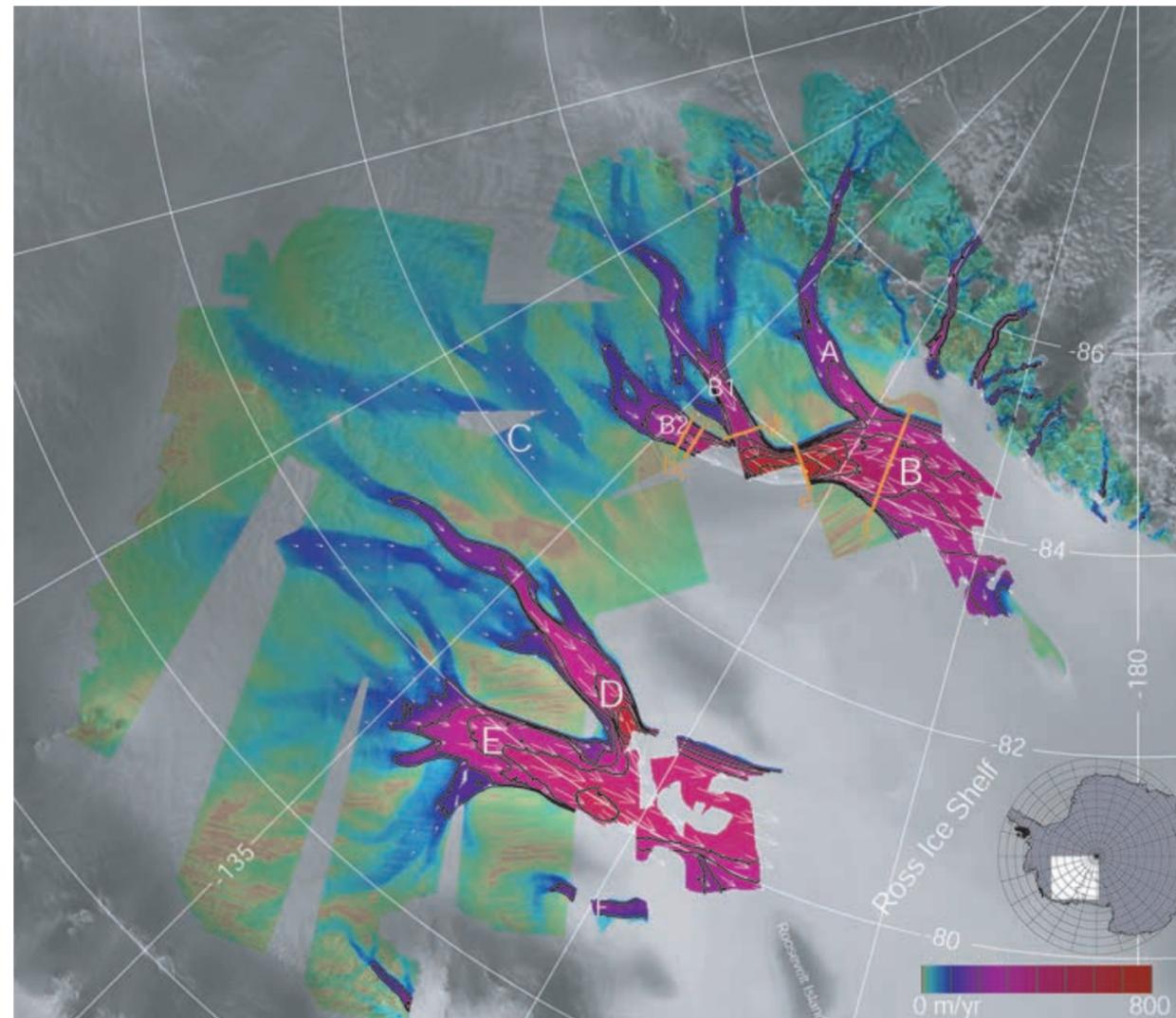


Plastic sediment rheology



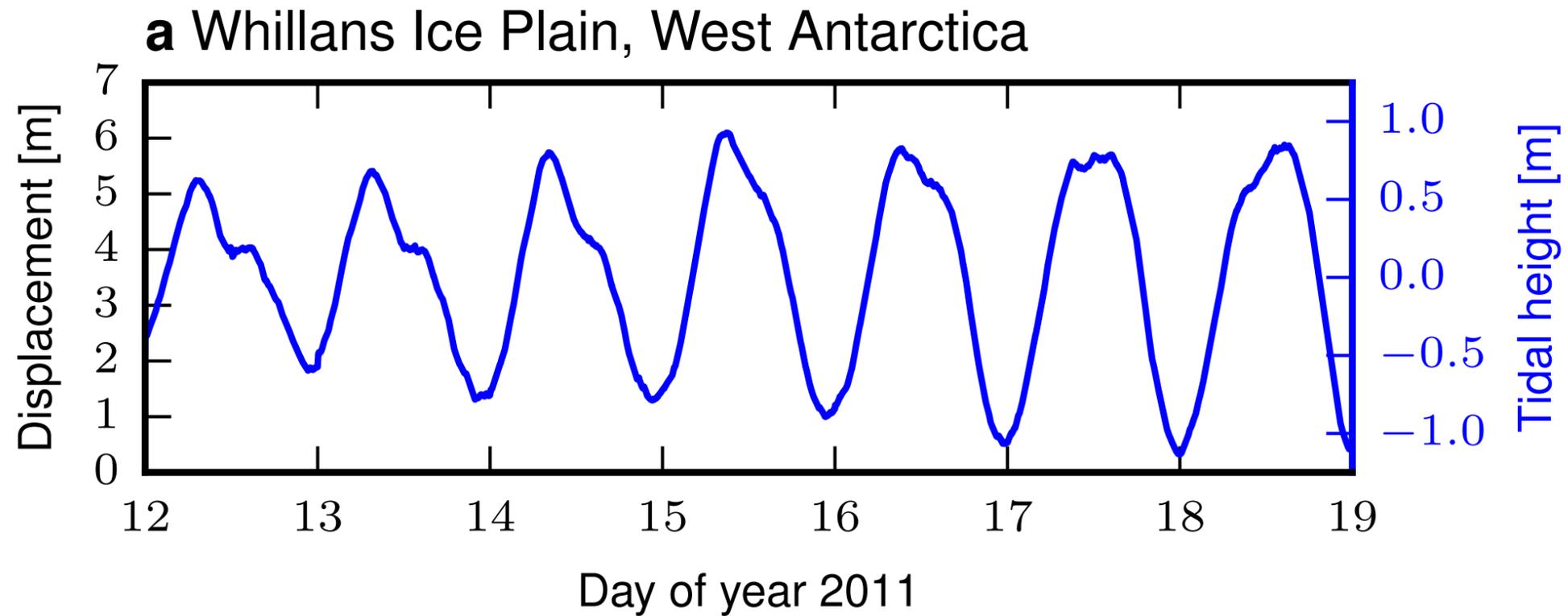
Ross sea ice streams

Joughin et al. 2004 *J. Geophys. Res.-Solid* **109**, B09405.



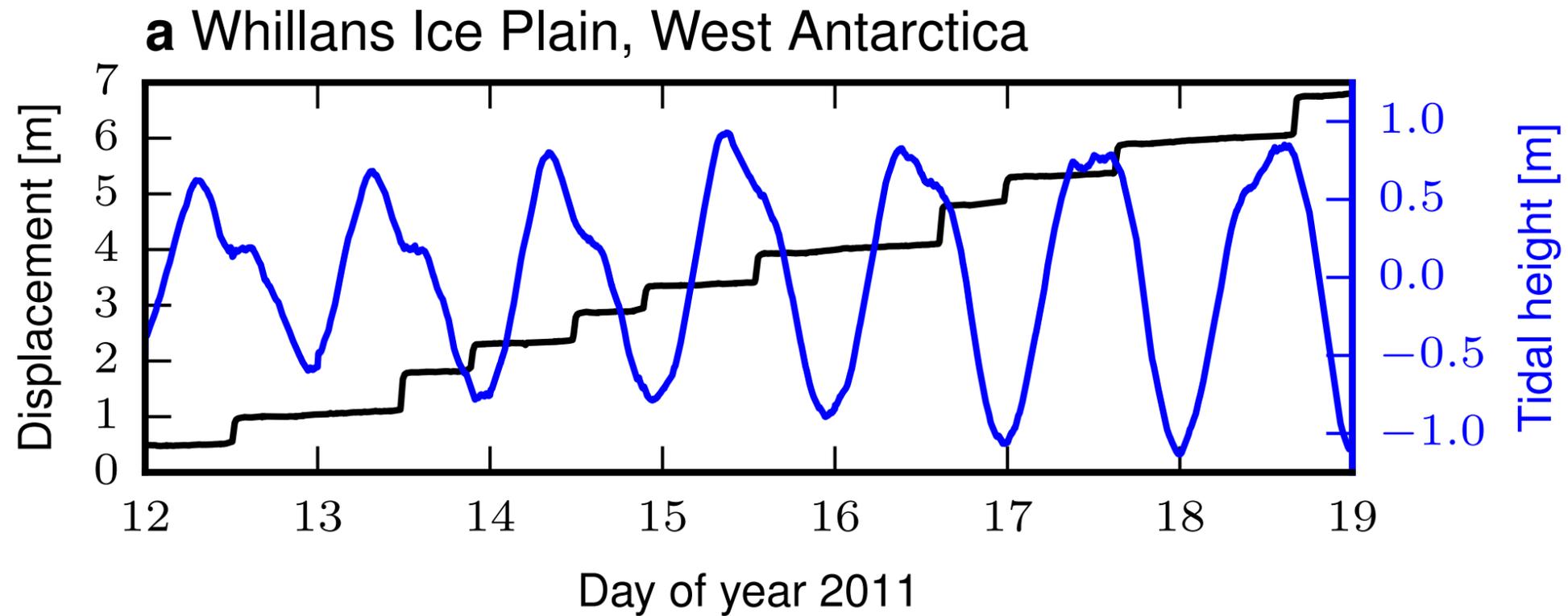
GPS measurements from Whillans ice plain

Damsgaard et al. *In prep.*



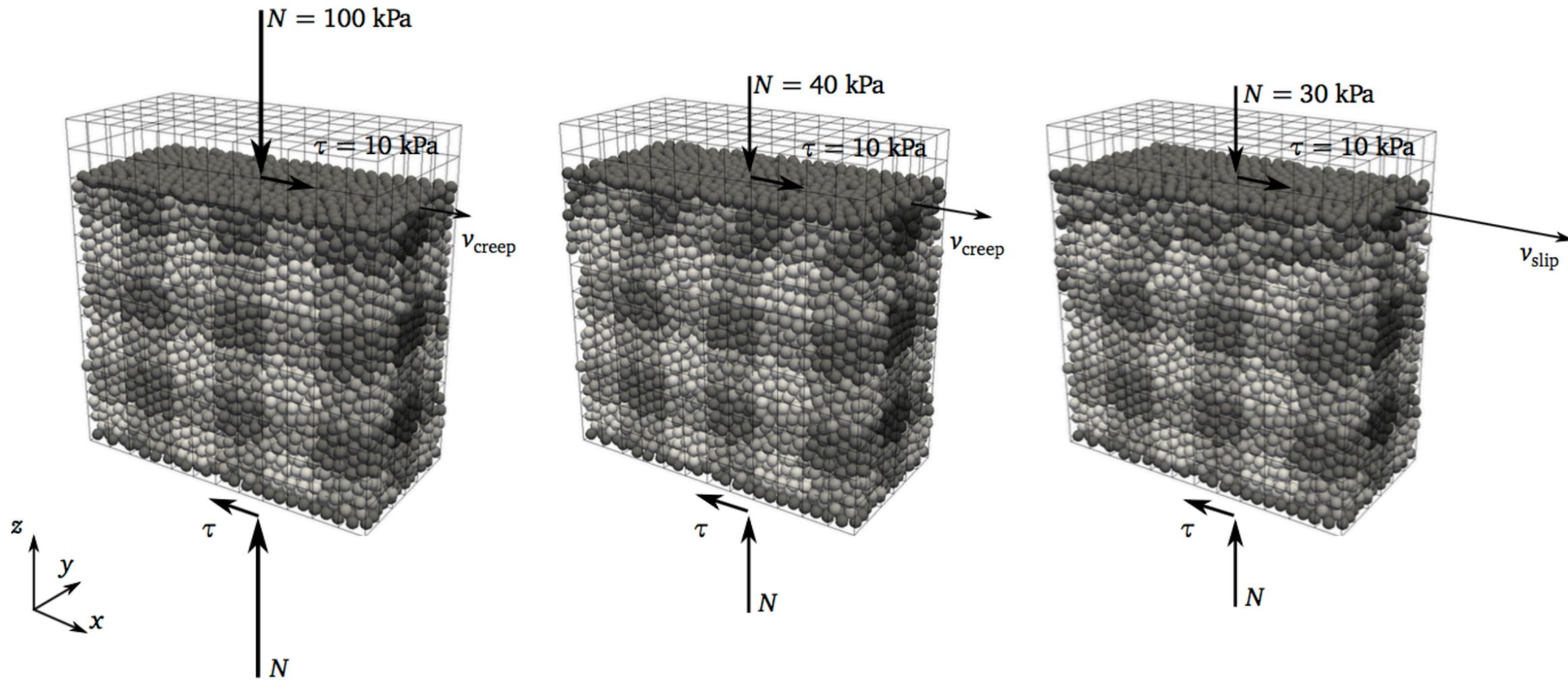
GPS measurements from Whillans ice plain

Damsgaard et al. *In prep.*



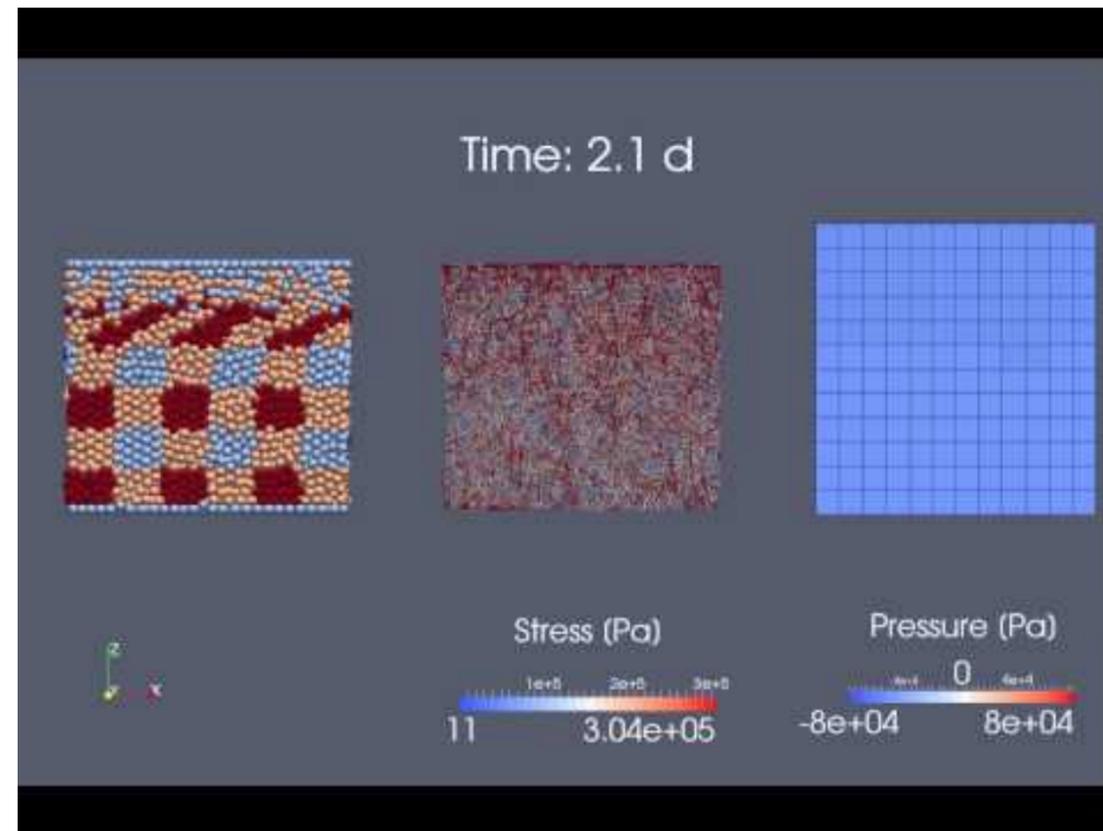
Discrete-element experiments

Damsgaard et al. *In prep.*



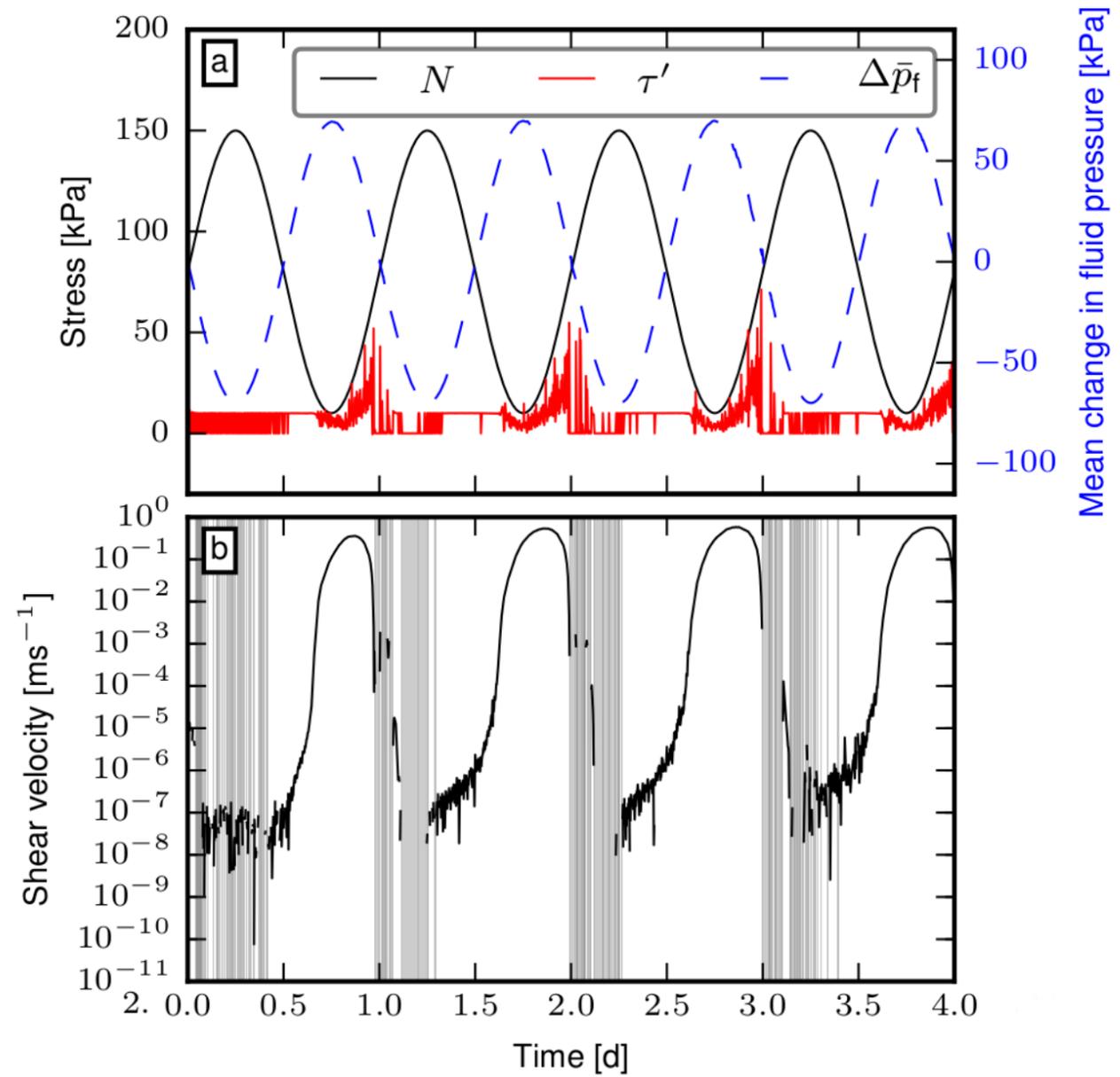
Damsgaard et al. *In prep.*

<https://youtu.be/e2SR5woJgVU>

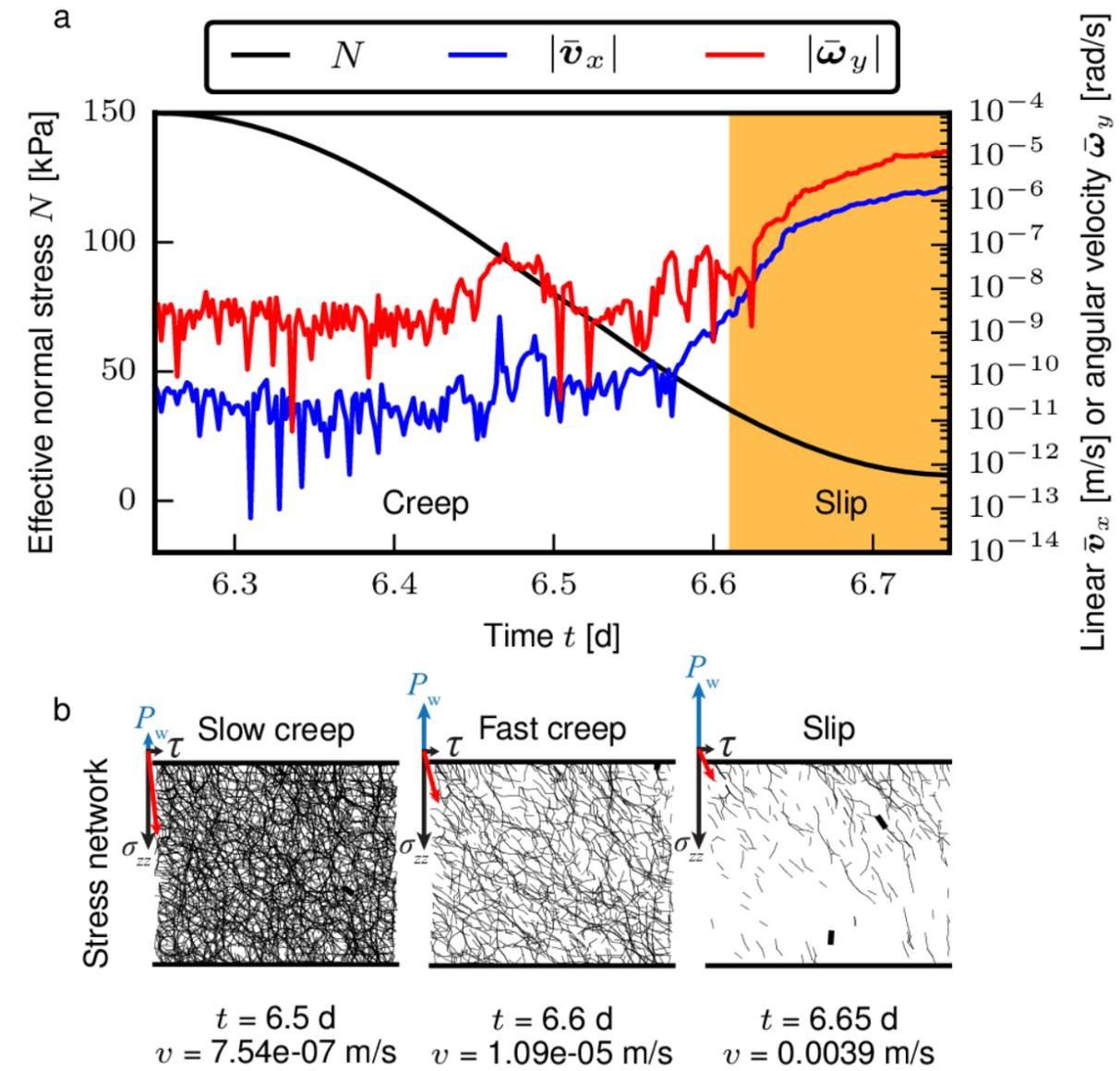


halfshear-darcy-stress-mod-starter.py

Damsgaard et al. *In prep.*

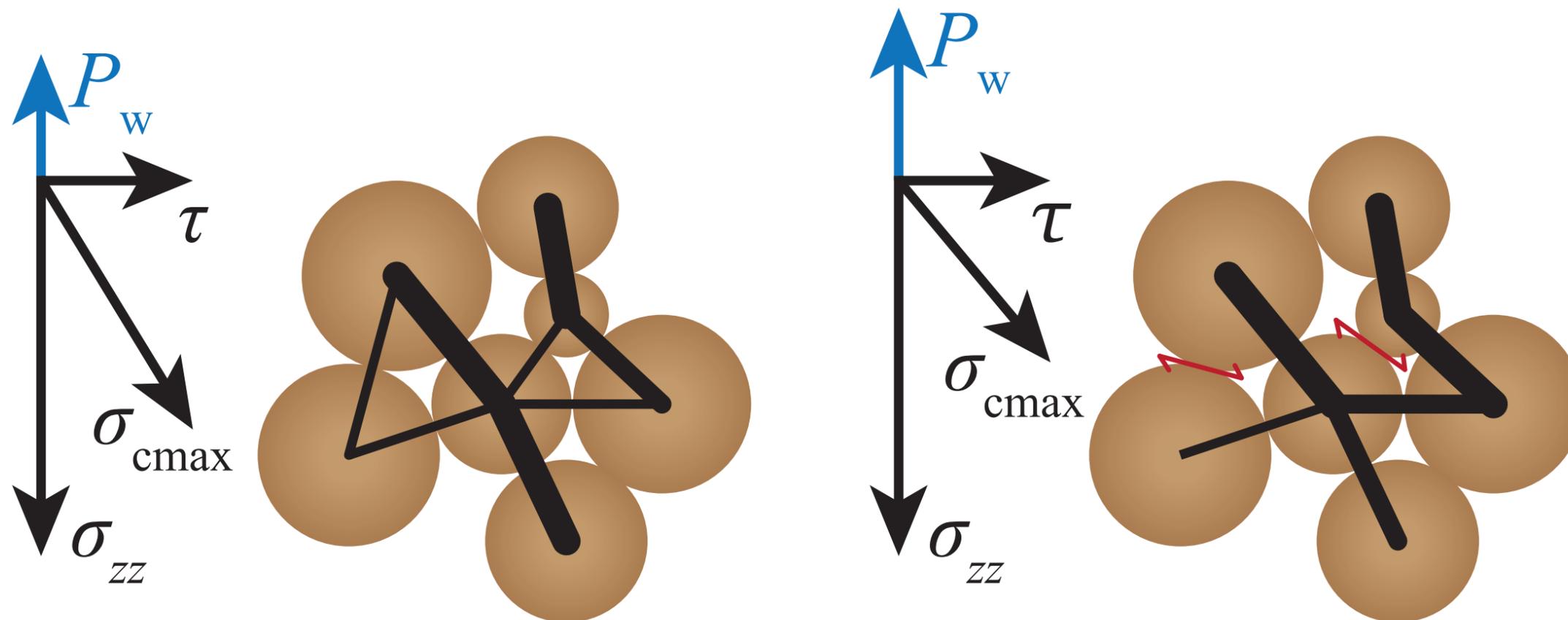


Damsgaard et al. *In prep.*

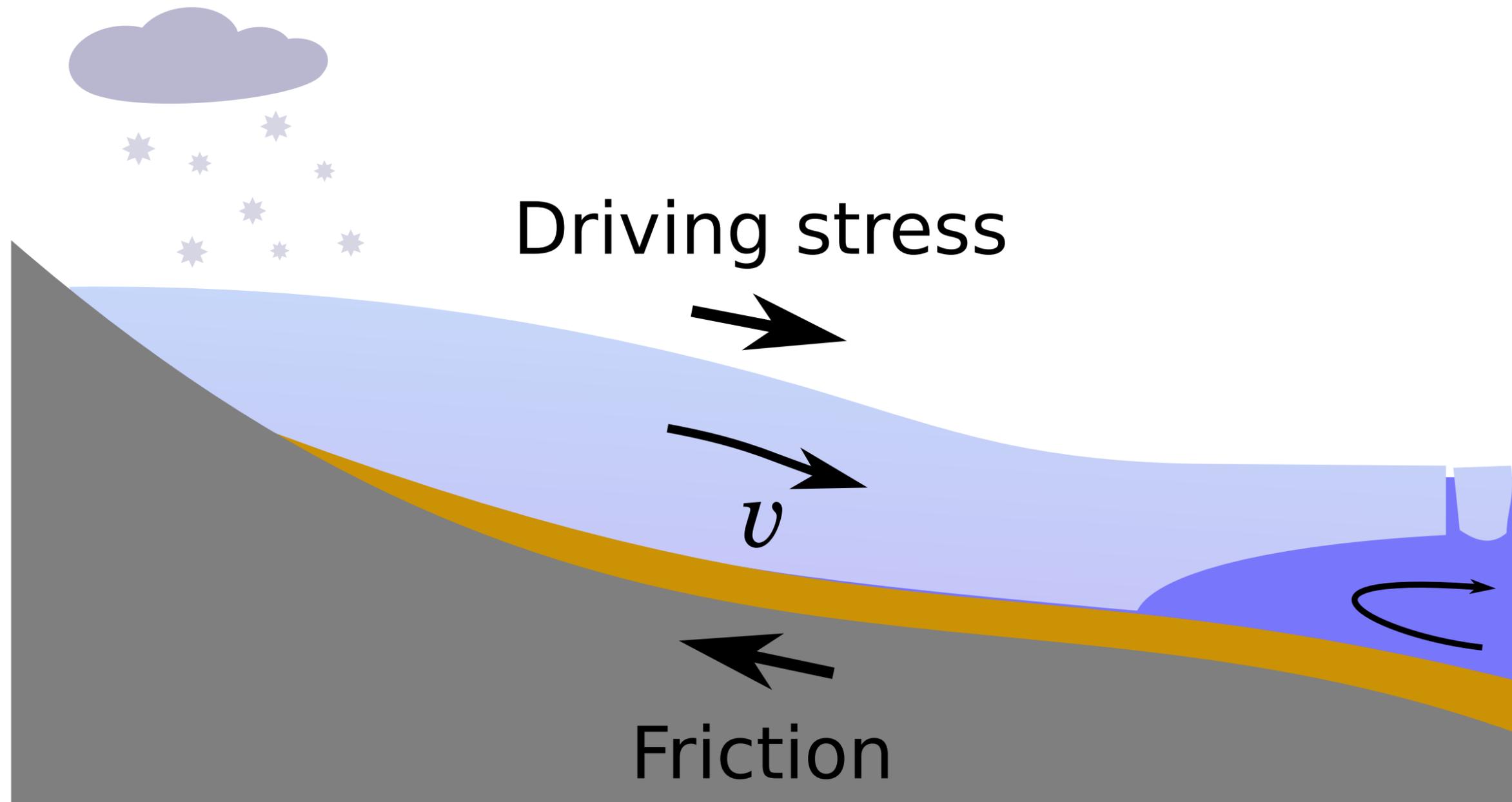


Creep by micro-deformation of the granular skeleton

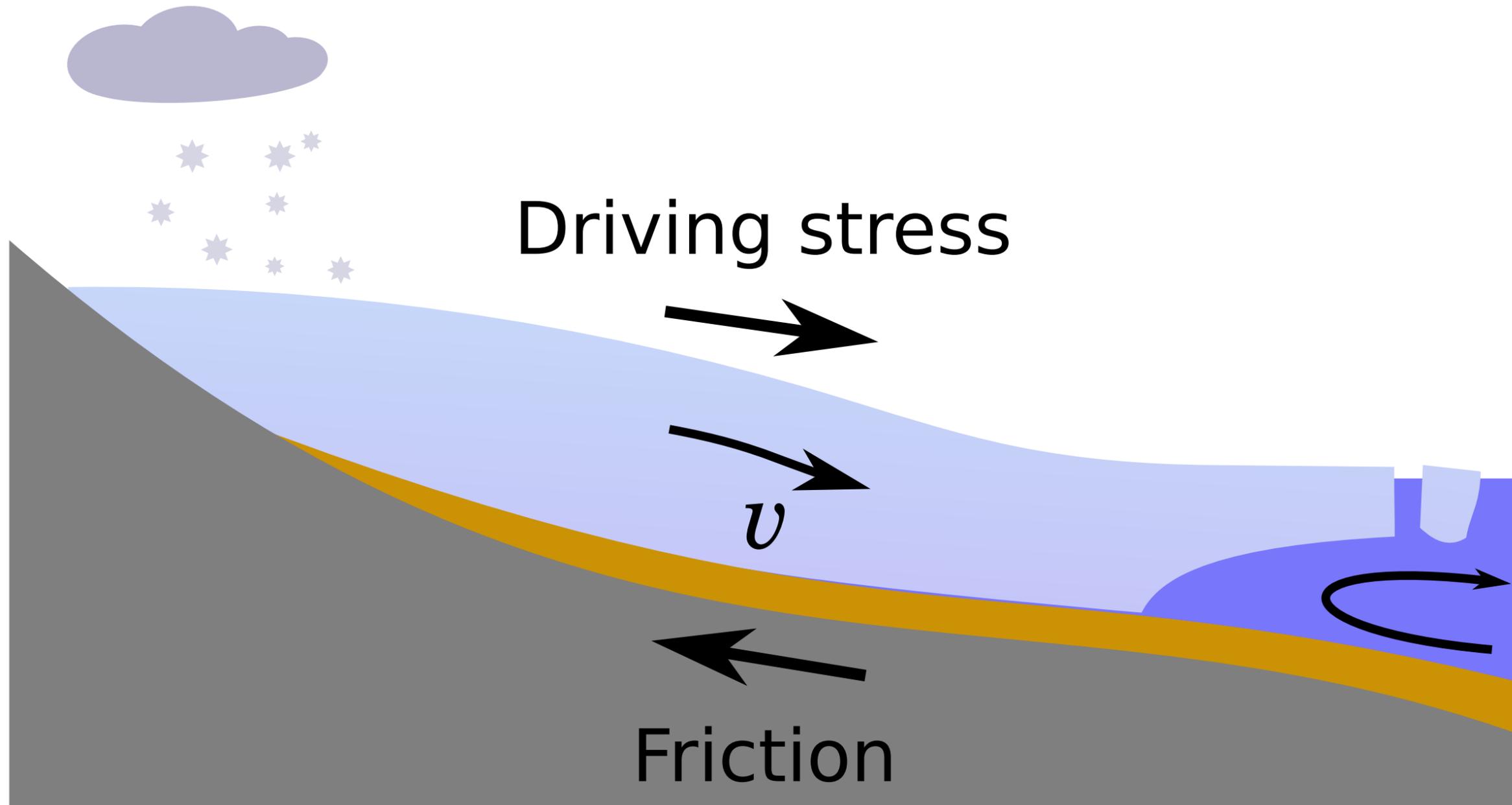
Damsgaard et al. *In prep.*



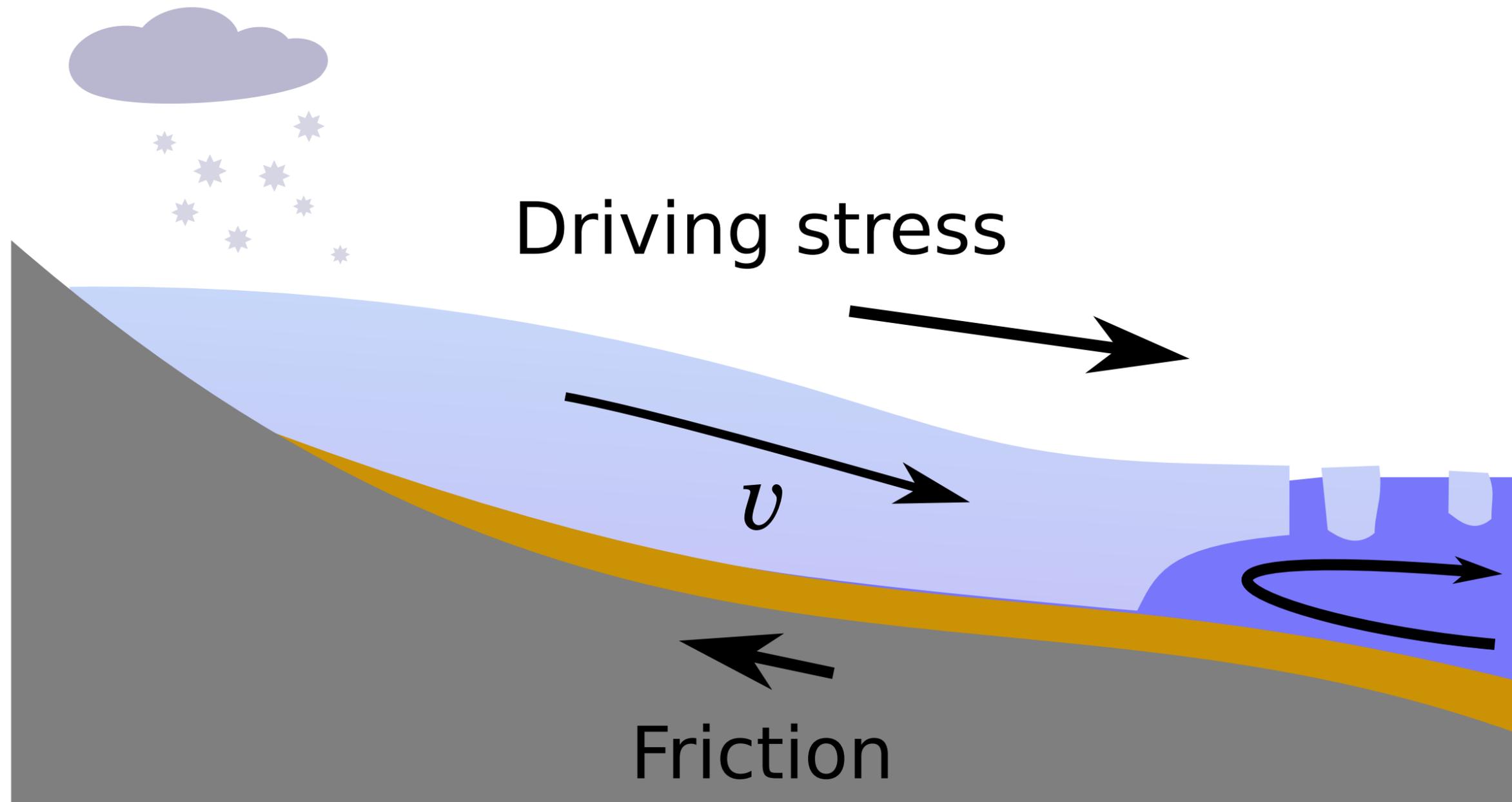
Creeping sediment



Creeping sediment



Plastic sediment failure



Summary

- Discrete element method inherently captures granular dynamics but is computationally expensive
- Granular materials neither a perfect plastic material or a viscous fluid
- Plastic slip above yield stress, creep below when driving stresses change
 - > Glacier beds
 - > Tremor and fault creep
 - > Hillslope movement

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Key References

Granular materials

Jaeger, H.M. and Nagel, S.R. 1996
Granular solids, liquids and gases
Rev. Mod. Phys. **68**, 1259-1273.

Discrete Element Method

Radjai, F. and Dubois, F. 2011
Discrete-element Modeling of Granular Materials. Wiley.

Glaciology

Cuffey, K. and Paterson, W.S.B. 2010