A microphysical model of rate- and state-friction controlled by dislocation glide and backstress (internal stress) evolution

One sentence summary: Internal stress and its temperature dependence controls fault stability and the transition from frictional sliding to bulk deformation.

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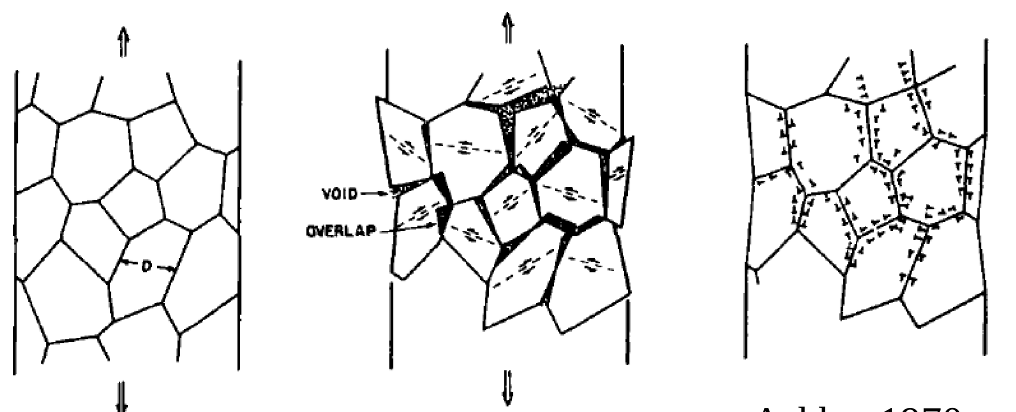
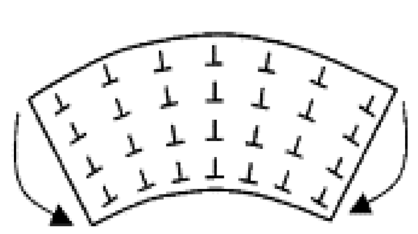
1. What is backstress and what causes it?

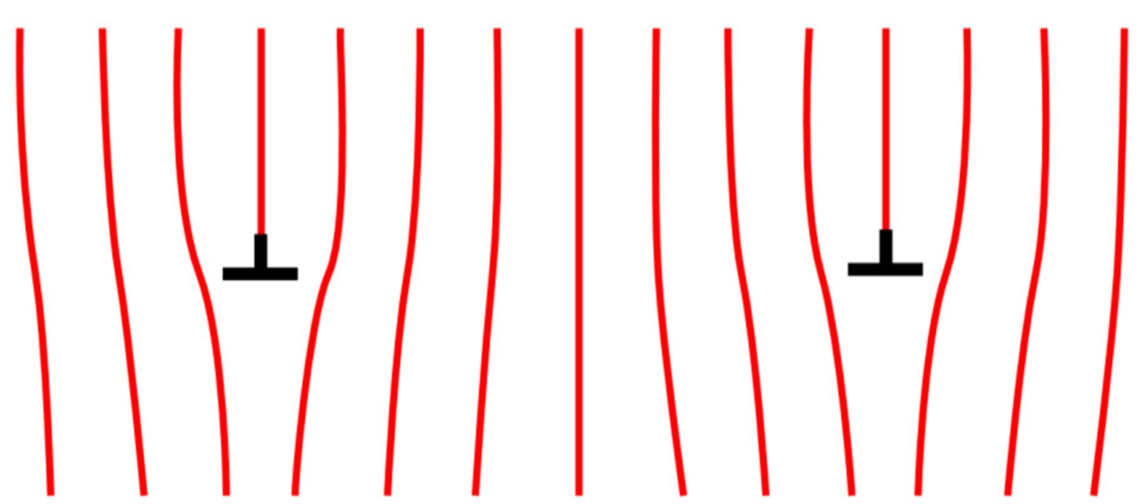


Ashby, 1970



When a polycrystalline aggregate or single crystal deforms inhomogeneously, **geometrically necessary dislocations (GNDs)** must be created to 1) maintain compatibility at grain boundaries (above) or 2) **allow for curvature of the crystal lattice** (right).

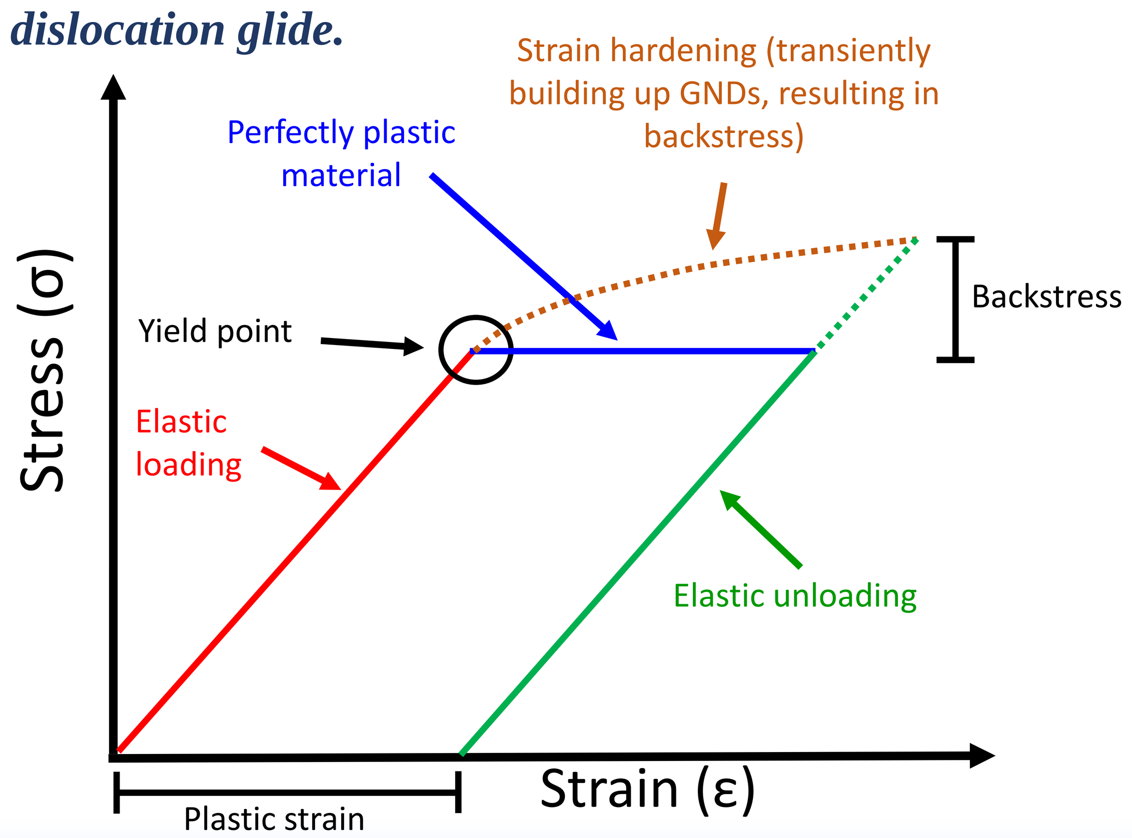
Because GNDs are dislocations of the same sign, they experience repulsive forces. The **local distortion** of the crystal lattice around GNDs **results in long-range stress fields proportional to GND average spacing** (i.e., dislocation density, see Taylor equation below). In the schematic below, red lines represent lattice planes. If the 2 GNDs were forced closer together, their repulsive stress field would increase.



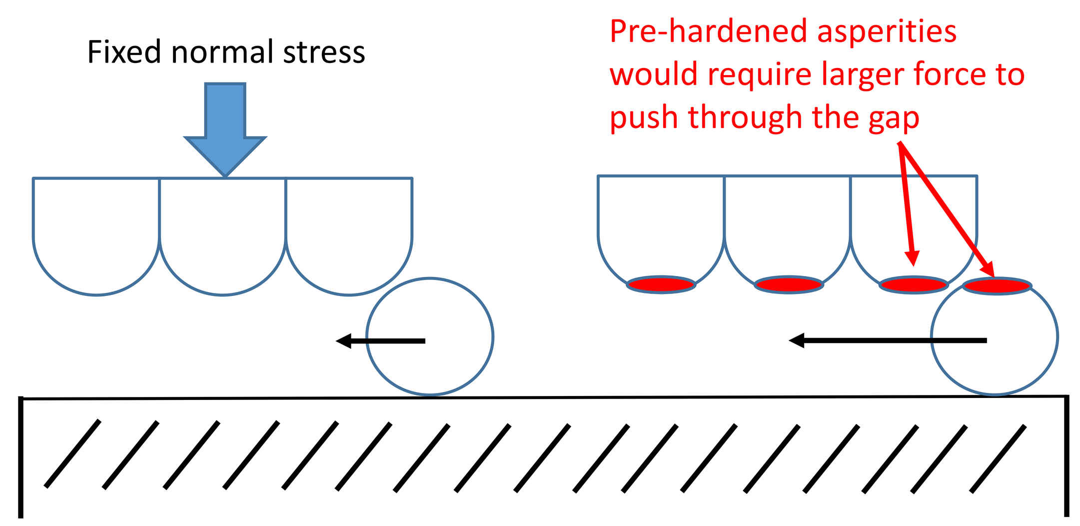
$$\sigma_b = \alpha G b \sqrt{\rho_{GND}}$$

Backstress — Constant — Shear (elastic) modulus — Burgers vector — Dislocation density

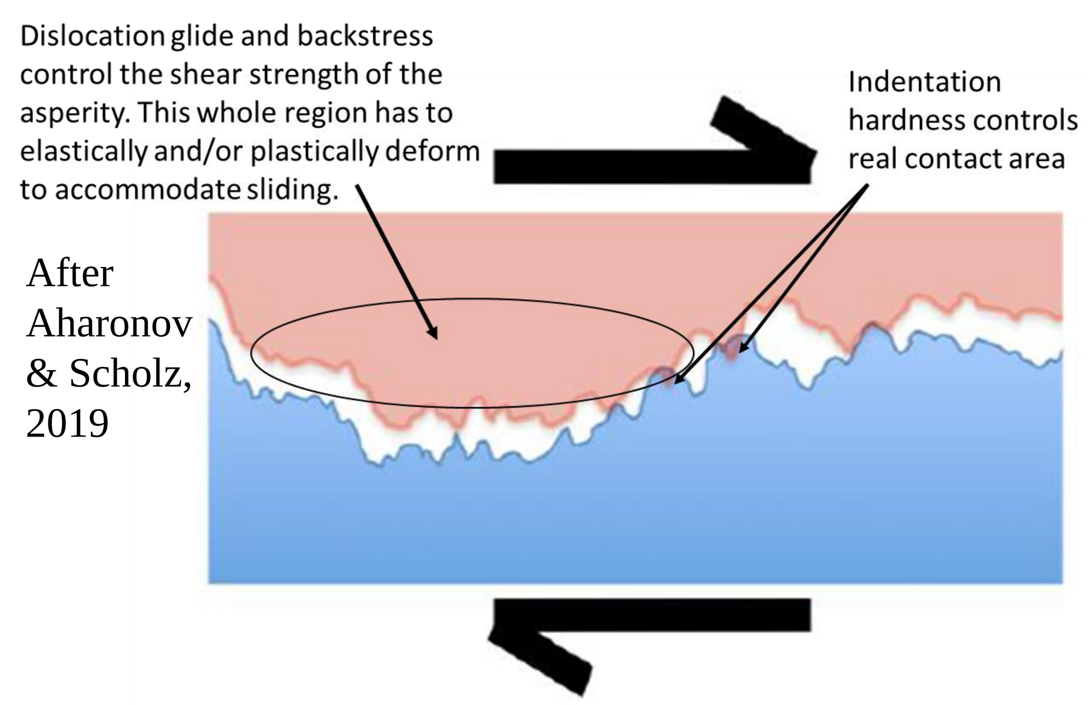
Macroscopically, the accumulation of GNDs during plastic deformation is what causes strain hardening to occur (see schematic below). The total applied stress (at a fixed strain rate) can be written as the sum of two terms (Hansen et al., 2019): 1) the yield stress and 2) the backstress. Thus, ***backstress is a stress caused by long-range elastic interactions among lattice dislocations that opposes further deformation by dislocation glide.***



2. How does backstress influence friction?



In the schematic above on the left, a spherical particle is forced through a gap that is bounded by a rigid frictionless plane and a periodic array of 'asperities' with a fixed normal stress. **Some deformation of the particle and the asperity tips must occur** for the particle to slide through the gap. Now consider the same geometry on the right, but with **significant backstresses (internal stresses) locked into the particle and asperities** from previous deformation (shown in red). A **larger force would be required** to move the particle through the gap (i.e., a larger coefficient of friction).



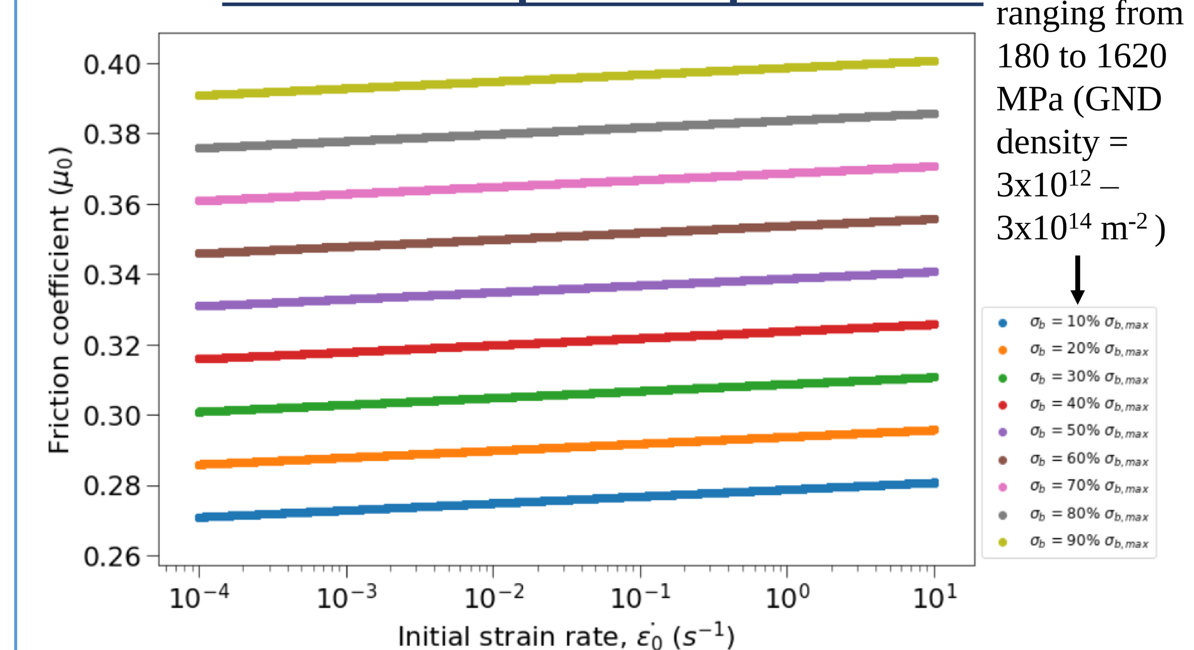
We assume a Bowden & Tabor (1950) description of friction, where the frictional resistance is the average shear stress supported by asperities (from Hansen et al. 2019; 2021 transient plasticity flow law) multiplied by the real contact area of the rough surface (inversely proportional to indentation hardness, H, Thom et al. 2017). Below, **we provide rate- and state-friction parameters based on transient creep equations assuming an instantaneous change in the strain rate (*a* parameter) and the subsequent anelastic response of asperities due to backstress (*b* parameter).** The value of D_c is determined using the Taylor equation (boxed in left panel) and the radius of curvature required to accommodate the density of GNDs (backstress) in the asperities.

$$\mu_0 = \frac{\left(\frac{RT\Sigma}{E}\sinh^{-1}\left[\frac{\dot{\epsilon}_0}{A}\exp\left(\frac{E}{RT}\right)\right] + \sigma_{b,0}\right)}{H} \qquad D_c = \frac{2\alpha^2 G^2 b_v}{\sigma_b^2}$$

$$a \approx \frac{\frac{RT\Sigma}{E}}{\frac{RT\Sigma}{E}\ln\left(\frac{2\dot{\epsilon}_0}{A}\right) + \Sigma + \sigma_{b,0}} \qquad b \approx \frac{(\sigma_{b,max} - \sigma_{b,0})\gamma\beta}{\frac{RT\Sigma}{E}\ln\left(\frac{2\dot{\epsilon}_0}{A}\right) + \Sigma + \sigma_{b,0}}$$

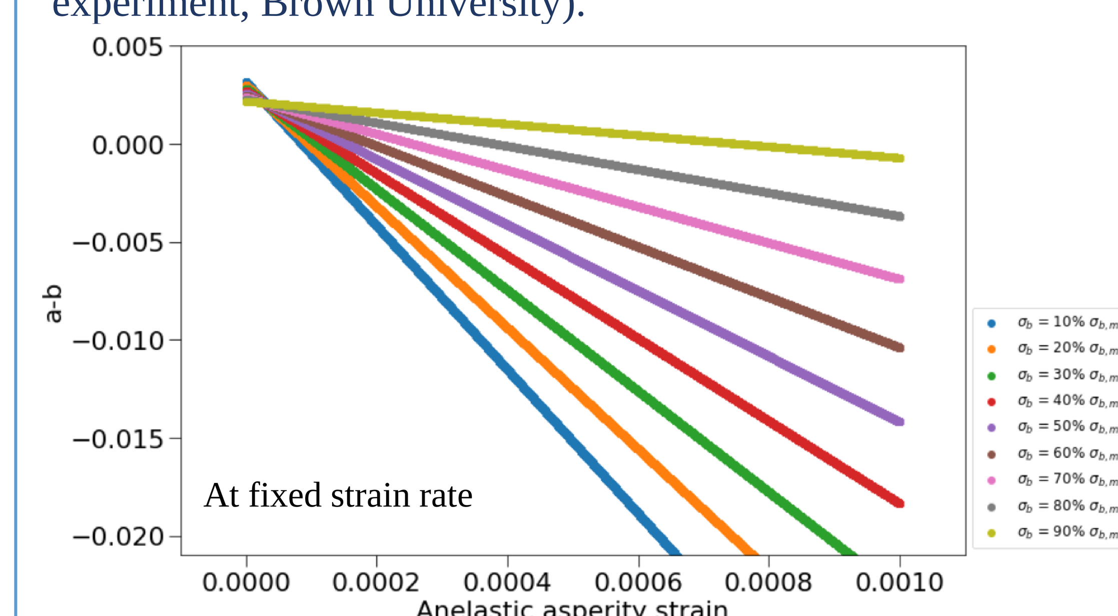
μ_0 friction coefficient	A material constant	b 'state' parameter
R gas constant	H indentation hardness	γ hardening parameter
T absolute temperature	D_c critical slip distance	β asperity strain
Σ Peierls stress	α constant	***NOTE* Backstress evolution equation can be found in Hansen et al. (2021)**
E activation energy	G shear modulus	
$\dot{\epsilon}_0$ strain rate	b_v Burgers vector (lattice spacing)	
σ_b backstress	a 'rate' parameter	

3. Room temperature predictions

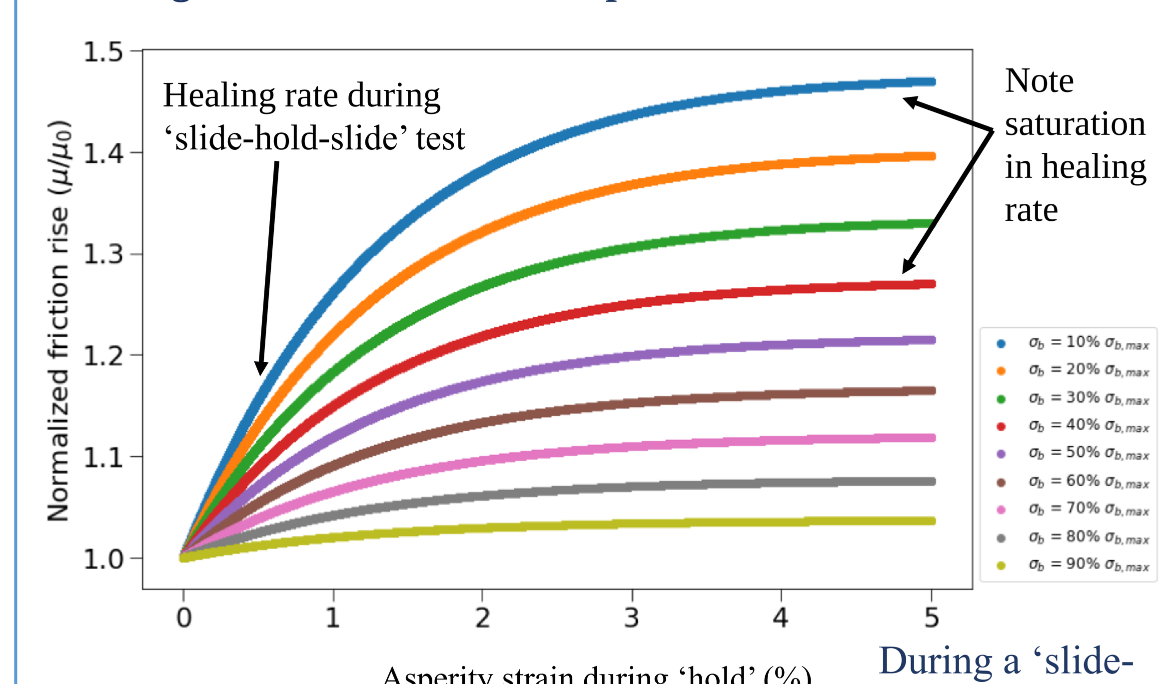


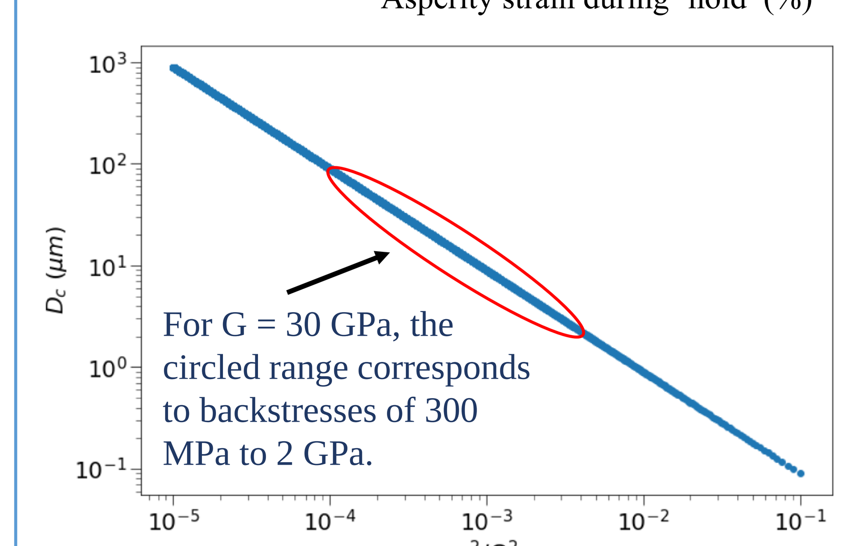
Backstresses ranging from 180 to 1620 MPa (GND density = 3x10[12] – 3x10[14] m[-2])

NOTE These predictions at varying levels of backstress (dislocation density) are for olivine (the only mineral with a well-calibrated transient creep flow law), which has a friction coefficient at room temperature of 0.31-0.35 (unpublished experiment, Brown University).



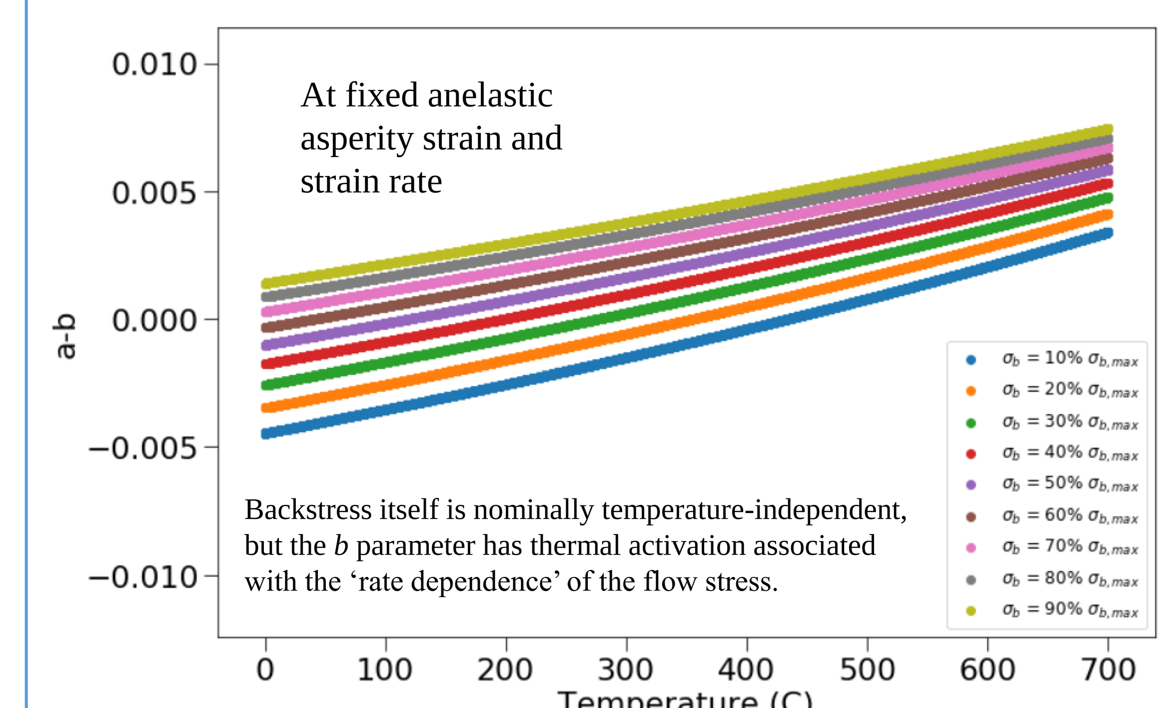
In this framework, the '*a*' value of rate- and state-friction captures the instantaneous 'rate dependence' of friction, as many previous authors have described. However, the '*b*' value is controlled by the evolution of backstress (i.e., dislocation density) within asperities. ***a-b* < 0 can only occur when anelastic relaxation of asperities is more significant than the rate dependence.**



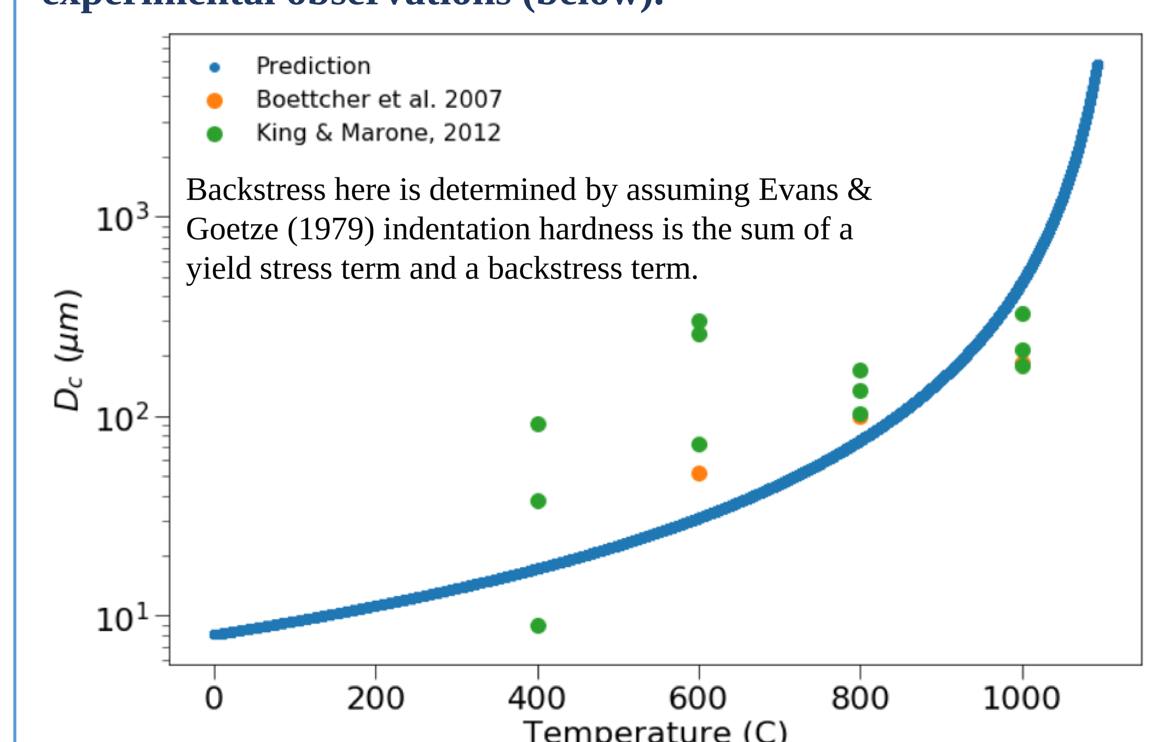


During a 'slide-hold-slide' test, backstress is accrued by creep of asperities during the hold, and the **rate of healing depends on the initial backstress** (dislocation density), as shown above.

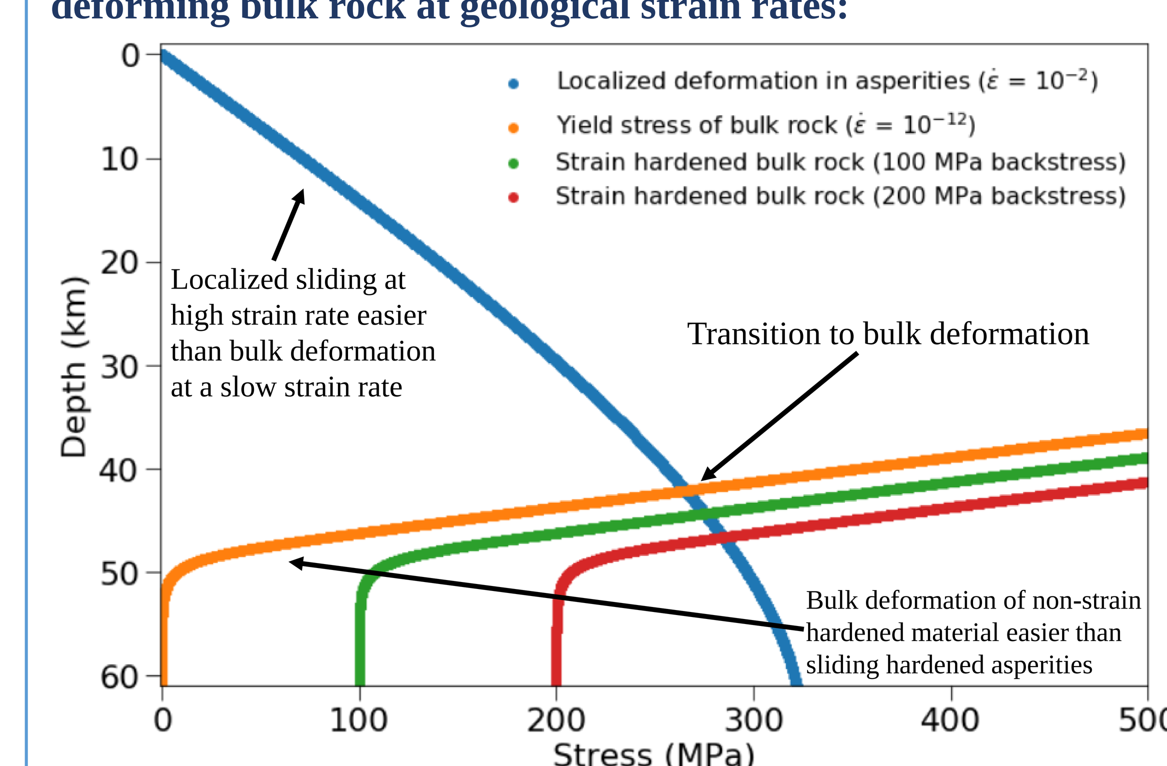
4. Extrapolation to high temperature



Fault stability (*a-b*) is a function of both temperature and backstress (above), and predictions of D_c agree with experimental observations (below).



We predict a major rheological change to occur when highly localized frictional deformation becomes more difficult than deforming bulk rock at geological strain rates:



TAKE HOME MESSAGES

1. **We recover rate- and state-frictional behavior using a transient plasticity flow law that accounts for long-range elastic interactions between lattice dislocations.**
2. **The 'state' dependence is caused by the anelastic response of asperities to large local backstresses (internal stresses).**
3. **Fault stability (*a-b* value) exhibits a dependence on both backstress and temperature.**