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Spontaneous Formation of Internal Shear Zone in Ice Flowing over a Topographically Variable Bed

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The transition from slow flow to rapid sliding is a noticeable feature of both ice sheets and outlet glaciers. Most existing models attempting to understand the complex physical transition processes assume an idealized model geometry with a flat bed. These models have shown that the onset of sliding entails basal refreezing, which in turn suppresses sliding. The theoretical difficulties in understanding sliding commencement in these process-based models contrast with the apparent ubiquity of the transition in the field. Here, we hypothesize that the presence of basal topography could resolve the inconsistency between model predictions and field observations.

We test our hypothesis by investigating the flow-to-sliding transition in a process-based model of ice flowing over bedrock with significant roughness. We assume that the bed is rigid and that the boundary condition at the bed is no-slip. We incorporate variations in basal topography into an iterative nonlinear Stokes solver for thermo-mechanically coupled ice deformation using the Immersed Boundary Method. This approach permits us to address the basal ice to bedrock transition with high accuracy and to study the impact of the shape of this transition zone.

Our results suggest that shear heating in the vicinity of pronounced roughness extends well into the bulk of the ice, leading to a spatially variable viscosity. These spatial variations in topography can therefore significantly impact the overall viscosity distribution in the ice. High shear strain rates localize at the tops of the bedrock topography. Thermo-mechanical feedback lead to the spontaneous formation of internal shear band over time, by connecting the topographic heights. The internal shear zone accommodates the majority of shear deformation, inducing a sliding motion of the upper part of the domain. Our results provide a process-based explanation of recently measured ice deformation data at the West margin of Greenland Ice Sheet (Maier et al. 2019). It is also consistent with the proposed existence of a radio-echo free zone located in the lowest hundreds of meters above bedrock (Drews et al. 2009, Fujita et al. 1999).

Maier, Nathan, et al. "Sliding dominates slow-flowing margin regions, Greenland Ice Sheet." Science advances 5.7 (2019): eaaw5406.

Drews, Reinhard, et al. "Layer disturbances and the radio-echo free zone in ice sheets." The Cryosphere 3 (2009): 195-203.

Fujita, Shuji, et al. "Nature of radio echo layering in the Antarctic ice sheet detected by a two‐frequency experiment." Journal of Geophysical Research: Solid Earth 104.B6 (1999): 13013-13024.