**GEOLGY**

**Toward a universal glacier slip law**

A new friction rule may describe ice flow over rigid or deformable surfaces

By Brent Minchew and Ian Joughin

Glaciers and ice sheets shape Earth’s surface and are important components of the climate system. Among the notable effects of glacier flow are erosion and sedimentation of Earth’s surface and variations in sea level as glaciers lose or gain mass. These effects depend on the slip of glaciers along their beds, which is accompanied by drag at ice-bed interfaces. Parameterizations of drag with slip rate are called sliding or slip laws. Recent acceleration in glacier flow and rates of mass loss in Greenland and Antarctica highlight the need to better understand and parameterize glacier sliding (1–4). On page 76 of this issue, Zoet and Iverson (5) present a slip law for deformable sediment that is similar to laws derived for rigid beds, thereby supporting a universal slip law that could improve projections of ice sheet contributions to sea level.

Given that myriad processes act at the ice-bed interface, it is not immediately obvious that a universal slip law should exist. Glaciers slide over beds that vary from rigid bedrock to deformable sediment, with slip defined as the combination of sliding along the ice-bed interface and deformation of the bed itself (6). Irrespective of composition, glacier beds have roughness features that influence drag but are difficult to characterize from observations (7, 8). Water at the bed acts as a lubricant. When this water is pressurized to nearly the overburden pressure (weight of ice column per unit area) of the glacier, cavities can form downstream of bumps in the bed, decoupling the ice from the bed (8, 9). Thus, basal water pressure influences slip while introducing complexities as it varies spatially and temporally in response to changes in basal and surface melt rates and evolution of hydrological systems above, below, and within the glacier (6, 10).

The potential for a universal form of the slip law is underpinned by the fact that total drag is the sum of skin friction and form drag. Skin friction describes the resistance to sliding along an interface, whereas form drag results from the pressure gradient associated with flow around an object. In the context of a slip law, the important distinctions between these two mechanisms are their dependencies on water pressure and the rate of slip at the bed.

Form drag strongly depends on flow speed but does not directly depend on water pressure. Conversely, skin friction strongly depends on water pressure but is essentially independent of the slip rate. Thus, a slip law that represents only skin friction may be considered perfectly plastic (rate-independent), similar to Coulomb friction, in which drag equals the product of a friction coefficient and effective normal stress (pressure), the difference between overburden and water pressure (11, 12). By contrast, a slip law representing only form drag with no cavity formation is rate-strengthening (drag increases with slip rate) and can take the form of a power-law relation between drag and slip rate (7). Allowing for cavity formation admits rate-strengthening, rate-weakening, and perfectly plastic behavior, depending on the bed properties and slip rate (9).

Zoet and Iverson derive a simple slip law for sediment-covered glacier beds, wherein the total drag is governed by form drag at slow slip rates and skin friction at faster rates. Form drag dominates when the bed is rigid and ice flows around rocks (clasts) at the ice-bed interface. Skin friction dominates when the bed is deformating and friction acts on sediment grain boundaries. Thus, the transition between the two drag mechanisms is controlled by the shear stress (or yield stress) of the sediment, defined as the product of the effective pressure and the tangent of the internal friction angle (11, 12) (see the figure). Zoet and Iverson benchmark their model with several laboratory experiments that examine glacier slip over glacial sediment. These experiments were conducted under constant water pressure...
Universal glacier slip law

New evidence suggests that a single glacier slip law can describe slip over the full spectrum of glacier bed types, from rough, rigid beds to deformable, sediment-covered beds. Such a universal slip law should improve projections of glacier and ice sheet mass loss.

with and without centimeter-scale clasts embedded in the sediment, and at slip rates ranging from zero to moderately fast by glacier standards (~500 m/year). Overall, they found good agreement between their model and experiments.

Zoet and Iverson focus on glaciers with deformable beds, but their slip law has the same form as the so-called regularized Coulomb sliding law originally proposed for glaciers sliding over rough, rigid beds (9). At slow slip rates, the two laws represent form drag due to flow of ice around roughness features. The transition to plasticity at faster slip rates in the rigid-bed model, however, arises from cavity formation that reduces the ice-bed contact area and, thereby, form drag. The limit on drag at rapid sliding rates is governed by the product of effective pressure and the tangent of the maximum bed slope, known as Iken's bound (13), which is a different physical mechanism with the same functional form as skin friction in the Zoet and Iverson model. Despite the differences in physical mechanisms, the deformable-bed and rigid-bed models yield the same parameterization, suggesting that the form of the regularized Coulomb sliding law is universally applicable to glaciers irrespective of bed type (1). A major benefit of this similarity is that observationally constrained models can be used to infer the slip law parameters without prior knowledge of whether the bed is rigid or deforming.

The potential for a universal form of the slip law is encouraging but remains to be thoroughly tested with observations. The increasing availability of remote sensing datasets has enabled a few relevant studies by providing measurements of spatiotemporal variations in glacier flow velocity and surface elevation. Most of these studies support the use of the regularized Coulomb sliding law (1, 14, 15), although more work is needed to test the robustness of this slip law and to constrain the parameters. Zoet and Iverson's laboratory experiments have provided strong evidence suggesting that the regularized Coulomb sliding law works similarly well for deformable beds as theory and observation suggest for rigid beds (1, 9, 15). This is an encouraging development that should help reduce uncertainties in sea level projections.

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10.1126/science.abb3566

Tuning drug binding
Understanding anticancer drug binding to its target could improve drug discovery and efficacy

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Inhibitors of poly(ADP-ribose) polymerase 1 (PARP-1) are used to treat ovarian and breast cancer (1). PARP-1 is activated on binding single-stranded DNA breaks (SSBs) and released from DNA by automodification (auto-PARYlation) (2, 3). By preventing auto-PARYlation, PARP inhibitors induce PARP-1 trapping on DNA (4). PARP inhibitors have similar in vitro potency in reducing PARP-1 activity, but their ability to induce cell killing differs substantially, most likely owing to differential potency in trapping PARP-1 on DNA (5, 6). In addition to catalytic inhibition, PARP-1 trapping was proposed to rely on reverse allosteric changes within PARP-1 from the catalytic domain to the DNA binding domain (5–7). On page 46 of this issue, Zandarashvili et al. (8) dissect the allosteric effects of different PARP inhibitors and show how these can be harnessed for targeted design of new pro-trapping or pro-release PARP inhibitors, which may have greater efficacy and versatile application potential.

A particularly enigmatic form of allosteric regulation lies at the heart of PARP-1 activation (2). A cascade of structural changes is triggered when a single PARP-1 molecule encounters an SSB: The flexibly connected PARP-1 domains no longer behave like beads on a string but instead engage each other in communicating the DNA damage signal from the amino-terminal zinc fingers toward the Trp-Gly-Arg (WGR) domain and the carboxyl-terminal domain, which consists of the helical domain (HD) and the catalytic adenosine diphosphate (ADP)–riboseyltransferase domain. Partial unfolding of the HD relieves its autoinhibitory effects and allows the NAD⁺ (oxidized form of nicotinamide adenine dinucleotide) cofactor to access the

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