ter changes have been observed to precede symptom onset (*13*). Other neuropsychiatric conditions also implicate white matter, including schizophrenia, depression, attention deficit hyperactivity disorder, autism, amyotrophic lateral sclerosis, glioma, and stroke. Relevant to both stroke and AD, white matter hyperintensities often seen on magnetic resonance imaging scans of older people (*5*) have been associated with a locus on chromosome 17 (*14*).

Zhao *et al.* found that many commonly used centrally-active medications exert effects on genes associated with white matter microstructure—an observation that may lead to improvements in the treatment of many brain diseases. The pharmacology of drugs used for neuropsychiatric disorders is not well understood, and knowledge of the interactions of these drugs with white matter neurobiology may substantially bolster the clinician's armamentarium.

The emerging recognition of white matter and its contribution to human behavior will advance medicine as well as neuroscience. Considering both environmental and genetic factors clarifies the structure and function of normal and abnormal tracts, and this knowledge promises in turn to improve the diagnosis and treatment of people in whom white matter dysfunction may be disturbing neurobehavioral capacity. Moreover, the understanding of AD and many disabling neuropsychiatric disorders may be transformed by a focus on microstructural pathology in myelinated tracts. Broadly, a more detailed understanding of the relationships between white matter and behavior will surely expand knowledge of the brain. A complete portrait of the structural basis of cognition and emotion cannot neglect the white matter because it interacts so intimately with its gray matter counterpart. ■

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A new model helps explain ice cliff collapse, such as the ice calving from the Perito Moreno Glacier, Argentina, in 2010.

GLACIOLOGY

Is the marine ice cliff hypothesis collapsing?

An improved rheologic model shows that glacier retreat may not always be quite so quick

By **Nicholas R. Golledge**[1] *and* **Daniel P. Lowry**[2]

Marine margins, where ice sheets flow from land into the ocean, become exposed to environmental conditions and internally generated forces markedly different from those governing the flow of ice further inland. Prior research has suggested that if the retreat of such margins formed tall ice cliffs, they may become structurally unstable and collapse, leading to further retreat (*1*). Although the veracity and importance of the "marine ice-cliff instability" are still uncertain (*2*), increasing the accuracy of simulated ice cliff processes is a key challenge because the Greenland and Antarctic ice sheets could raise global sea level by 65 m. On page 1342 of this issue, Bassis *et al.* (*3*) developed a model that reliably captures the complex behavior of ice cliffs as they deform and fracture. In doing so, they find that marine-terminating parts of Antarctica may be less vulnerable than previously suggested to rapid and irreversible collapse (*4, 5*).

Ice sheets terminating in the ocean lose mass through melting either at the surface or on the underside of floating ice, and through calving of icebergs. For the calving fronts of thick glaciers to remain stable, they need to be grounded in deep water (*6*). Thicker ice or shallower water increases the height of the ice cliff exposed above water, and where this exceeds the threshold for structural stability (~100 m), the cliff may collapse through slumping (*7*) (see the fig-

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ure). The rate at which such calving proceeds is governed by the yield strength of ice (*8*), as well as the geometric configuration of the glacier front and the environmental forcing.

Experimentation has also revealed that the critical height required for collapse of a marine ice cliff depends on how rapidly it becomes exposed (*9*). The sudden break-up of buttressing ice shelves, such as witnessed in the Antarctic Peninsula over recent decades, could expose a new ice cliff within days or weeks. This "preconditioning" means that cliffs could fail at lower heights than if ice shelf collapse proceeded more slowly. A "speed limit" for how quickly an ice shelf can collapse has been recently computed (*10*), but one of the key difficulties in accurately modeling or predicting any ice cliff failure that then follows is that the calving process itself comprises two distinct modes of failure. Thick and undamaged ice has a high tensile strength and tends to fail through shearing (deformation) (*11*), whereas rapidly sliding glaciers are prone to tensile failure (fracturing) because of their extensional flow regime and the intersection of crevasses that develop as the glacier is "stretched."

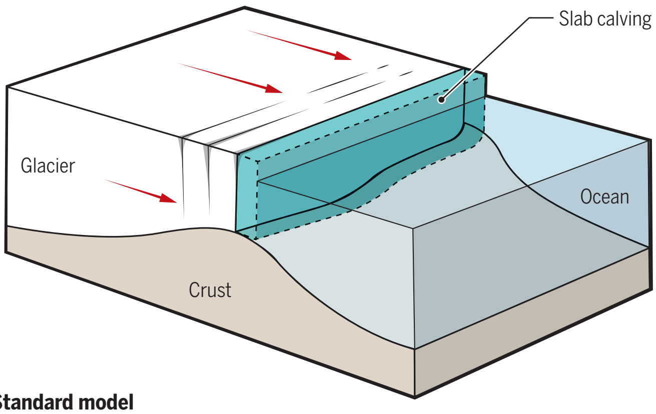
This dual mode of failure is where Bassis *et al.* make such an important advance. The authors' "m-ice" model simulates ice as a viscous material whose deformation rate is described by a power law only until its yield strength is reached, at which point it then deforms rapidly. Accumulation of plastic strain in the failed ice reduces its strength, allowing it to deform even more rapidly, progressively localizing failure within discrete bands. Thus, although not explicitly modeling the brittle processes of ice fracturing, the m-ice model uses a pioneering composite rheology that allows the flow and failure modes of ice cliff calving to be captured in a single continuum framework.

Bassis *et al.* use their model to explore the environmental and geometric controls on how a range of marine-terminating glacier margins might evolve. The authors find that resistive forces at the ice front, caused either by sea ice or the calved debris that typically chokes narrow fjords during winter months, can slow or even completely prevent the retreat of an ice cliff. But even without this kind of buttressing, Bassis *et al.* conclude that ice cliffs may be inherently stable if the speed of ice flow or slope of the bed underlying the ice are within certain bounds. Specifically, the authors find that the upstream gradient of ice thickness exerts a first-order control on the tendency of an ice cliff to reach a critical (collapse-prone) height, and that the rate at which ice flows toward the calving front exerts a secondary control. For the majority of thickness gradients considered, faster-flowing ice allows ice margins to advance, whereas slower-flowing ice produces cliff retreat. Where ice thickness gradients are greater than about 30 m per kilometer, ice cliffs tend to collapse regardless of the inflowing ice velocity.

The idea that brittle failure of vertical ice cliffs could lead to catastrophic collapse of a large part of the West Antarctic Ice Sheet has recently been put forward and is used to project sea level contributions from Antarctica of as much as 1 m by 2100 (*4*), under a future greenhouse gas emissions scenario that leads to an increase in radiative forcing of 8.5 W/m². These studies have done much to catalyze and focus research efforts within the glaciological community, and to highlight to policy-makers the deep uncertainty associated with Antarctic ice sheet retreat in particular. But parameterized models that use extrapolations from sparse observations of a poorly understood process mean that resulting predictions of retreat rates vary considerably between model versions (*1*, *4*, *5*), so the impact of ice cliff collapse on future sea level rise remains uncertain (*2, 12*). What is certain, however, is that if the processes involved in ice cliff collapse are to be included in models used for future sea level projections, they need to incorporate robust physics and be well-validated by comparison to observations. Bassis *et al.* have made a substantial leap forward in both of these areas with the m-ice model that offers exciting avenues for better understanding ice cliff behavior. ■

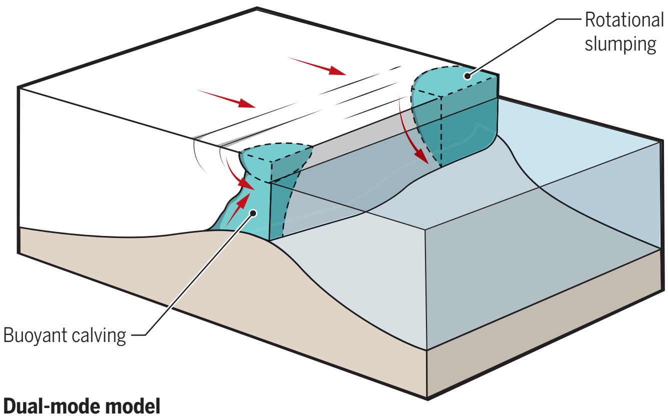
A refined mechanism of marine ice cliff retreat

The manner in which ice cliffs fail is important for projecting glacier retreat in a warming environment.



Standard model

Standard ice cliff modeling assumes no vertical difference in the internal stress. This leads to failure at a critical height above the ocean surface as a result of tensile stresses. The whole ice column retreats by a time-averaged horizontal wastage rate.



Dual-mode model

Dual-mode modeling simulates differences in the internal stress regime within the vertical ice column. This continually tracks the accumulation of plastic strain during deformation and allows zones of damaged ice to develop, which localize subsequent failure. The failure occurs by slumping, or by slumping and buoyant uplift of submerged blocks if the water is deeper.

GRAPHIC: C. BICKEL/*SCIENCE* BASED ON N. GOLLEDGE/ANTARCTIC RESEARCH CENTRE

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