Fast Glacier Flow Over Soft Beds

Peter U. Clark

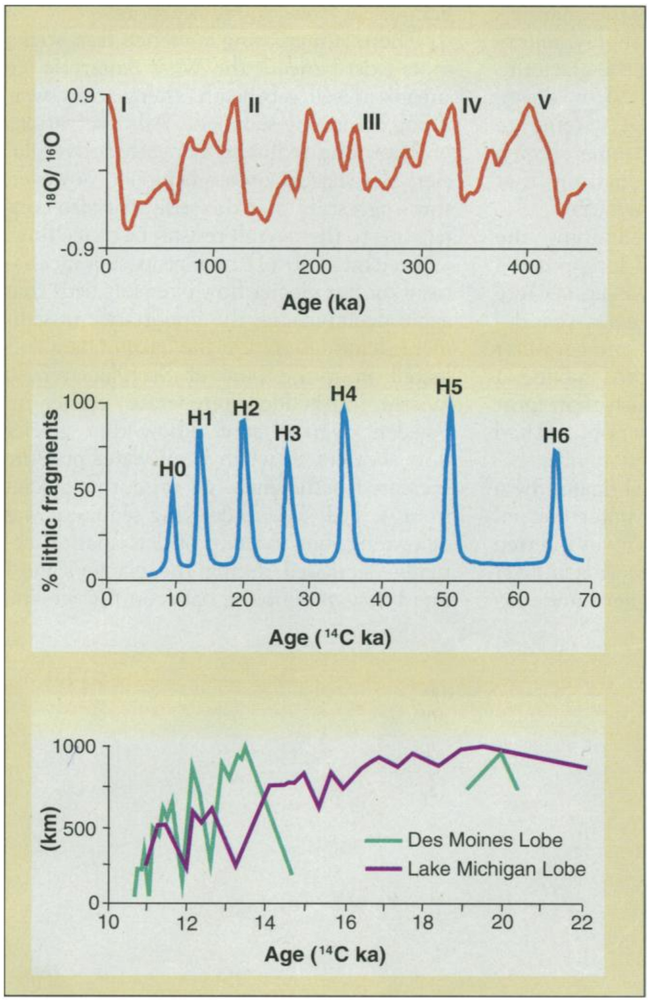
If, in the common vernacular, to move glacially is to move slowly, is fast glacier flow an oxymoron? Apparently not, according to research on modern glaciers and ice sheets and recent discoveries about past ice sheets. Instead, glaciologists now identify fast glacier flow as an important feature of glacier dynamics that may have contributed to past climate change. One leading mechanism for such glacier behavior attributes it to the rapid deformation of an underlying layer of water-saturated sediment, commonly referred to as a soft bed. As reported by Iverson *et al.* elsewhere in this issue (*1*), however, glaciologists studying a Swedish glacier found that the periods of fastest glacier movement corresponded to the slowest rates of sediment deformation, thus supporting recent arguments that the dynamics of modern and former glaciers and ice sheets resting on soft beds are controlled by conditions other than the intrinsic properties of those beds.

Rapid glacier flow in itself is not a new idea. Most modern glaciers move only meters to tens of meters every year as they steadily transfer snow and ice through their system to maintain mass balance. A change in climate results in a change in mass balance, and glaciers respond stably by either the advance or retreat of their margins. A small percentage of modern glaciers, however, surge. These glaciers alternate between brief periods of fast movement (several hundred meters per year) and much longer periods of slower flow. Such nonsteady behavior reflects an internal instability that yields large changes in the position of the ice margin that are unrelated to climate change. Similar unstable behavior has been suggested for the fast-flowing ice streams that drain parts of the West Antarctic ice sheet, raising concern over the potential threat of collapse of this ice sheet in response to global warming.

Until recently, however, glaciologists did not think that, other than during deglaciation, unstable behavior contributed to the dynamics of the former Northern Hemisphere ice sheets. The pioneering work by Hays *et al.* (*2*), which shows that the large changes in global ice volume are directly tied to changes in the Earth's orbit around the sun (Milankovitch theory), led many climate theorists to view ice sheets as relatively sluggish and passive systems that responded stably to insolation forcing. The one important and well-known exception to this idea is the 100,000-year cycle that dominates the ice volume record for the last 800,000 years but has virtually no amplitude in the orbital forcing. One possible solution to this enigma is suggested by the results of numerical models which successfully reproduce the 100,000-year cycle by introducing a source of mechanical ice sheet instability that, following achievement of some threshold, rapidly deglacites Northern Hemisphere ice sheets and produces the distinctive terminations (top of figure).

Geologic records now show that unstable behavior was also an important attribute of ice sheet dynamics during the course of a glaciation as well as during deglaciation. The most dramatic discovery of such behavior comes from recent studies showing that the Laurentide Ice Sheet partially collapsed several times during the last ice age (Heinrich events) while other ice sheets apparently remained stable (*3*). Former ice sheets were thus dynamic systems that experienced several time scales of variability (see figure), and instability is implicated in each of these. First-order variations in ice-sheet size occurred at orbital time scales (10^4 to 10^5 years) as ice sheets responded stably to changes in insolation until they reached some limiting size, became unstable, and rapidly deglaciated (top of figure). At higher frequency, suborbital time scales (10^3 to 10^4 years), ice sheets episodically became unstable and partially collapsed (middle of figure). Corresponding second-order changes in ice volume may have been large but remained a fraction of the orbitally driven global changes. Finally, still higher frequency (third-order) oscillations of the ice margin occurred at millennial time scales (10^3 years) with a quasi-cyclicity of 1000 to 2000 years (bottom of figure) and a comparatively small change in ice volume.

Research on ice age climates has emphasized climate change arising from orbital forcing, but in the last decade, high-resolution climate records have revealed that the Earth's climate also experienced significant variability at millennial and suborbital frequencies. The fact that this temporal hierarchy of climate variability closely



Geologic records showing temporal hierarchy of ice sheet variations. (Top) Deep-sea oxygen-isotope record of global ice volume variations over the last 450,000 years (*10*). Rapid deglaciation every 100,000 years (terminations) indicated by Roman numerals. (**Middle**) Schematic illustration of the percentage of lithic fragments in deep-sea sediments from the North Atlantic basin over last 70,000 years [based on data in (*3*)] showing episodic fluxes of debris-laden icebergs during Heinrich events. (**Bottom**) Oscillations of the margins of the Des Moines lobe (dark line) and Lake Michigan lobe (light line), southern Laurentide Ice Sheet, between 22,000 and 10,000 years [based on data in (*7*)].

The author is in the Department of Geosciences, Oregon State University, Corvallis, OR 97331, USA.

corresponds to the hierarchy of ice sheet variability (see figure) suggests that ice sheets may have played an active role in a broad spectrum of climate variability. Interest in the mechanisms for unstable ice sheet behavior and rapid glacier flow has thus extended beyond the realm of glaciology to the climate research community at large as scientists try to understand further the role of dynamic ice sheets in the climate system.

Research on fast glacier flow initially focused on the role of subglacial water on hard beds. Glaciers that receive water at their base from surface and englacial sources (temperate glaciers) normally have a well-integrated network of subglacial tunnels that efficiently drains subglacial water, leaving most of the ice in direct contact with the bed. It has long been observed, however, that a sudden increase in water supply to the channels draining through a temperate glacier causes water in them to "back up" to near the surface, increasing their pressure and forcing water out of the channels into cavities or films along the bed (*4*). The glacier rises and speeds up as the basal water decouples it from much of its bed, leaving the stress concentrated on a few bedrock highs ("mini-surges"). This situation is strictly transitory, however, as the channels adjust to the increased water supply, relieving the pressure and allowing the glacier to sink back to its bed and slow down. Switches in subglacial drainage systems are also responsible for at least some surging behavior, although the mechanism that triggers the switches is unknown (*5*).

Fast-flowing ice streams draining the West Antarctic ice sheet had long posed a glaciological conundrum, however, because they move up to 1000 meters every year despite having no sources of surface water (subpolar glaciers) and despite having a much smaller gravitational push than most slower moving ice. Researchers postulated that these ice streams flowed rapidly because their bases were well lubricated by a thin, distributed or filmlike water system. In the early 1980s, however, it was inferred from results of seismic surveys that a layer of weak, water-saturated sediment underlay one of the ice streams (*6*). Drilling to the base of the ice stream confirmed this interpretation, and subsequent seismic surveys of one other ice stream have found evidence for a soft bed at its base.

Glaciologists argued that fast glacier flow develops on soft beds when the water-saturated sediment becomes so weak that it can no longer withstand the shear stress applied by the overlying ice, and the sediment begins to deform. Much of the glaciological community quickly embraced this mechanism for its ability to explain ice stream behavior. Furthermore, as the evidence mounted that Northern Hemisphere ice sheets behaved unstably (middle and bottom of figure), glaciologists also identified sediment deformation as the likely culprit (*7*).

But in 1991, Kamb challenged the theory that soft beds control the flow of ice streams (*8*). Whereas previous theory considered the viscous behavior of the deforming sediment, he argued from soil mechanics that deforming sediment would behave as a nearly perfect plastic. Such a nonlinear system should lead to highly unstable behavior. Because the ice streams are not highly unstable, however, Kamb proposed that resistance to their flow is largely provided by localized bedrock knobs that support high basal shear stress, or "sticky spots."

There is increasing evidence that sticky spots exist beneath the West Antarctic ice streams as well as beneath other glaciers overriding deforming sediment. All observations of deforming sediment beneath active glaciers also suggest viscous behavior, however, thus suggesting that the sediment also contributes to the overall resistance to ice flow.

Iverson *et al.* (*1*) now propose a mechanism for fast glacier flow over soft beds that again deemphasizes the importance of sediment deformation. On the basis of data collected from the base of Storglaciären, a mostly soft-bedded temperate glacier in Sweden, Iverson *et al.* show that glacier flow accelerated when basal water pressure increased sufficiently to raise the glacier from its bed. The underlying sediment was deforming, but the rate of deformation actually decreased during the glacier's most rapid flow as coupling between the ice and the bed decreased.

Iverson *et al.* further suggest that fast glacier flow over soft beds occurs by a longer-lived version of this mechanism, in which persistently high water pressures beneath fast-moving subpolar glaciers cause continued decoupling from soft sediments. As acknowledged by Iverson *et al.*, however, whether the transient effect observed at Storgläciaren has direct relevance to fast-moving subpolar ice masses remains an important question; hydrologic models for temperate glaciers with significant ice-rock contact and with large external forcing are not transferable to subpolar ice sheets on widespread soft beds (*9*).

Nevertheless, Iverson *et al.* also found evidence that sticky spots are present beneath Storgläciaren, again highlighting their importance to the flow of modern glaciers and ice sheets. How to model a "mixed bed" of sticky spots and deforming sediment remains uncertain. It is interesting, however, that bedrock knobs are all but absent from most areas of fine-grained glacial sediments deposited by the Northern Hemisphere ice sheets, indicating either that sticky spots were relatively unimportant in controlling former ice sheet dynamics over soft beds or that they were manifested in some different form.

References and Notes

1. N. R. Iverson, R. LeB. Hooke, B. Hanson, P. Jansson, *Science* **267**, 80 (1994).
2. J. D. Hays, J. Imbrie, N. J. Shackleton, *ibid.* **194**, 1121 (1976).
3. J. T. Andrews and K. Tedesco, *Geology* **20**, 1087 (1992); G. Bond *et al.*, *Nature* **360**, 245 (1992); W. S. Broecker *et al.*, *Clim. Dyn.* **6**, 265 (1992).
4. A. Iken, H. Röthlisberger, A. Flotron, W. Haeberli, *J. Glaciol.* **29**, 28 (1983).
5. B. Kamb *et al.*, *Science* **227**, 469 (1985).
6. D. D. Blankenship, C. R. Bentley, S. T. Rooney, R. B. Alley, *Nature* **322**, 54 (1986).
7. G. S. Boulton and A. S. Jones, *J. Glaciol.* **24**, 29 (1979); D. R. MacAyeal, *Paleoceanography* **8**, 775 (1993); P. U. Clark, *Quat. Res.* **41**, 19 (1994).
8. B. Kamb, *J. Geophys. Res.* **96**, 16585 (1991).
9. R. B. Alley, *J. Glaciol.* **35**, 108 (1989); J. S. Walder and A. Fowler, *ibid.* **40**, 3 (1994).
10. J. Imbrie *et al.*, *Paleoceanography* **8**, 699 (1993).

11. I thank R. B. Alley, N. R. Iverson, and D. R. MacAyeal for comments. This work was supported by National Science Foundation grant NSF EAR-9405334.