Tidally Controlled Stick-Slip Discharge of a West Antarctic Ice Stream

Robert A. Bindschadler,[1]* Matt A. King,[2] Richard B. Alley,[3] Sridhar Anandakrishnan,[3] Laurence Padman[4]

A major West Antarctic ice stream discharges by sudden and brief periods of very rapid motion paced by oceanic tidal oscillations of about 1 meter. Acceleration to speeds greater than 1 meter per hour and deceleration back to a stationary state occur in minutes or less. Slip propagates at approximately 88 meters per second, suggestive of a shear wave traveling within the subglacial till. A model of an episodically slipping friction-locked fault reproduces the observed quasi-periodic event timing, demonstrating an ice stream's ability to change speed rapidly and its extreme sensitivity to subglacial conditions and variations in sea level.

Concern that the West Antarctic Ice Sheet did, does, and will contribute to increasing sea level has driven two decades of extensive research on ice-flow dynamics (*1*, *2*). Evidence for periods of rapid retreat abounds (*3–5*). Currently northward-draining parts of this ice sheet are thinning rapidly, but not at rates sufficient to provide a large fraction of the present rate of sea level rise (*6*). The rest of the ice sheet is now close to equilibrium or slightly thickening (*7*, *8*).

For the West Antarctic Ice Sheet to raise sea level rapidly in the near future would require a substantial acceleration of its ice streams, the fast-moving rivers of ice that discharge much of the ice sheet back into the oceans (*9*). Some of these outlets are accelerating or have accelerated recently (*10*). Elsewhere, the major ice streams feeding the Ross Ice Shelf have either stopped, are decelerating, or are maintaining their velocity (*7*). In the case of Whillans Ice Stream (WIS), the current rate of deceleration is 1 to 2% per year, a rate that would result in stagnation if sustained over the next 50 to 100 years.

Recent field global positioning system (GPS) measurements from a 2-week survey on the "ice plain" in the mouth of WIS revealed that this portion of the ice stream moves by brief, rapid motion events separated by extended periods of no motion (*11*). Position solutions every 5 min illustrate this stick-slip motion of the ice plain (Fig. 1) (*12*). Quiescent periods were from 6 to 18 hours long. Slip events lasted from 10 to 30 min, during which the ice moved downstream a distance of a few tens of centimeters at rates of about 1 meter per hour, at least 30 times faster than the already high velocity of the ice stream feeding the ice plain. There was no measurable vertical motion associated with this phenomenon. For any particular site, flow reached approximately the same speed during each slip event. These speeds corresponded closely to the speeds calculated assuming a frictionless bed (*13*). Differential processing of GPS data for pairs of stations permitted a finer temporal view of the evolution of slip events (*14*). Acceleration to frictionless speeds was accomplished in as little as 30 s, the limiting temporal resolution. Deceleration was somewhat slower, but usually occurred within 2 to 5 min. Minor upstream rebound also was observed in the first hour of stagnation, typically amounting to about 10% of the downstream displacement.

Slip occurred across the ice plain, but was not exactly synchronous. Interpolation of slip displacements from the 5-min positions at up to five simultaneously occupied stations produced typical lags of a few minutes between the times of maximum speed. To quantify the speed and direction of this propagation effect, trios of sites were examined (*15*). From 17 sets of data, a mean speed of propagation of 88 ± 79 m/s was determined. This speed is close to the 150 m/s shear wave speed measured in the subglacial till farther upstream (*16*). The large uncertainty may represent some spatial heterogeneity in the propagation effect. The general direction of plane wave propagation was northward, nearly transverse across the ice plain, but there were significant variations from this direction. The propagation through the floating ice shelf is probably as a much faster-moving elastic body wave because the ice shelf coupling to water is inefficient (*17*).

A few deviations from stick-slip behavior were noticed, all at the edges of the ice plain (*18*). During periods of no motion on the ice plain, ice-shelf stations moved gradually downstream with larger displacements in synchrony with slips of the grounded ice plain. Occupation times at most sites were short, spanning only two to four slip events; therefore, a full characterization must await subsequent field studies.

There is a clear association between this stick-slip phenomenon and the ocean tide, which has a dominant diurnal component beneath the Ross Ice Shelf (*19*). During the survey, the tidal cycle ranged from weak, neap tides with a minimum amplitude of 0.15 m to a nearly 1-m amplitude during

[1]Ocean and Ice Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. [2]School of Civil Engineering and Geosciences, University of Newcastle, Newcastle Upon Tyne, NE1 7RU, UK. [3]Department of Geosciences and EMS Environment Institute, Pennsylvania State University, University Park, PA 16802, USA. [4]Earth and Space Research, Seattle, WA 98102–3620, USA.

*To whom correspondence should be addressed. E-mail: Robert.A.Bindschadler@nasa.gov

the following spring tide. A continuous record of the tide was not available, so a model was used (*20*). Our GPS data from ice-shelf sites confirmed the tidal phase, but measured magnitudes were smaller than calculated, probably due to proximity to grounded ice.

During spring tides, the occurrence of slip events for most grounded ice plain sites was extremely regular, with one event shortly after high tide followed by a second event in the middle or toward the end of falling tide (Fig. 2). Roughly half of the average daily motion occurred during each event. During neap tides, this periodicity broke down, including some otherwise unobserved events on the rising tide (Fig. 2). Tidal influence on ice flow has been observed on tidewater glaciers, with the faster speeds occurring during the lower portion of the tidal cycle (*21–23*). Tidally synchronous flow variations have also been seen on floating ice shelves (*24*). Nearby ice streams C and D also show flow response in antiphase to tidal variation. On ice stream D, GPS data show a ±50% variation in flow speed (*25*). Ice stream C still moves primarily by basal processes, rather than by internal deformation, but slowed about 150 years ago to a speed for which collected GPS data are not sufficiently accurate to reliably capture the tidal variations in flow; however, basal seismicity caused by motion of the ice stream is modulated by the tide and peaks near the grounding line at low tide (*26*). In contrast to data from the WIS ice plain, C and D show upglacier propagation and damping of the tidal signal, with much lower propagation velocities of 1.5 m/s on C and 5.6 m/s on D.

A consistent interpretation of these observations is that till beneath C and D is behaving as a (pseudo)viscous material whereas that under WIS is behaving in a plastic or frictional manner (*27*). The slow propagation velocities on C and D are consistent with viscous delay by subglacial till of an elastic wave in ice (although additional modeling is planned for D to better quantify the role of the ice-stream sides as well as the basal till in slowing the propagation). Nonsteady conditions in a dilatant Coulomb-plastic till can introduce a strain-rate dependence on stress, or pseudo-viscosity (*28–30*). Increased deformation at a point in till can produce dilatancy, water-pressure drop, and strengthening of that till until water inflow is complete. The greater the stress, the greater the strengthening of the till, up to some failure level. Exceedance of the failure level (which is lowered by approach to steady state) allows the usual plastic behavior of the till to be evident.

Regions of enhanced basal resistance to flow, or "sticky spots," can be caused by bedrock asperities sticking through till or perhaps by other processes (*31*). Repeated microearthquakes from specific sites beneath C show that such sticky spots are common (*32*), so breakage of one or a few may not raise the stress on intervening till to the failure level. Partial restraint of ice stream D by its sides may also keep basal stress on till there below the failure level. However, the thick till (*33*) of the ice plain of WIS likely has left the region with very few sticky spots, and the great width limits the effect of side drag; therefore, breakage of one or a few sticky spots could load the till past failure and thus expose the plastic nature.

To test this hypothesis for the WIS ice plain, we constructed a simple model that balances the forces encouraging and resisting the motion of an ice plain resting on a plastic till. The motion of the ice stream (speed V) presses on the ice plain (thickness H and length L) at a constant rate as ice tries to move downstream.

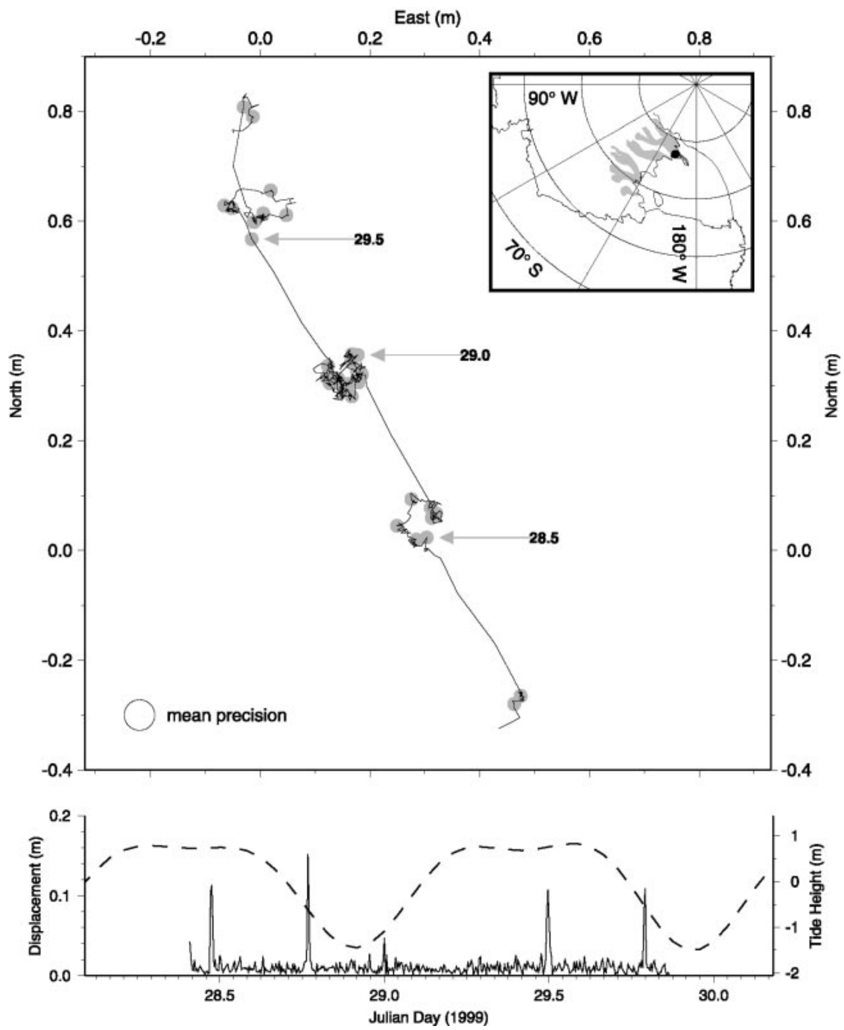

Fig. 1. Motion of site G2. (Top) Horizontal position every 5 min connected by straight lines. Gray dots indicate the beginning of each hour with Julian day indicated by arrows. Inset shows location of ice streams (shaded) and site G2 (solid circle). (Bottom) Horizontal displacement (solid line) between successive 5-min positions and modeled ocean tide (dashed line) at a nearby location.

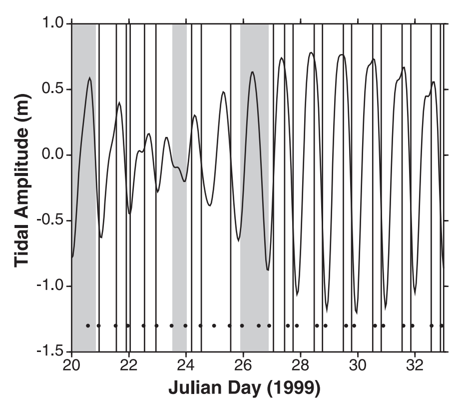

Fig. 2. Comparison of observed slip events (vertical lines) and predicted slip events (solid circles) superimposed on tidal height at station J10. Shaded areas are times when no observations were made.