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# The "Galloping Glacier" trots: decadal-scale speed oscillations within the quiescent phase

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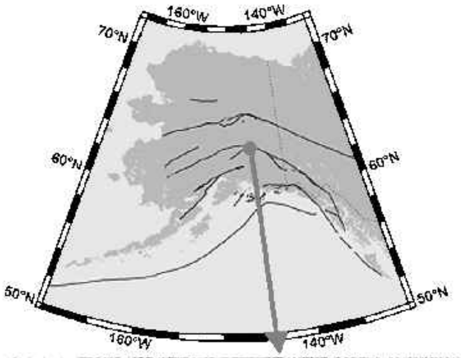
ABSTRACT. A 28 year record of annual surface speeds has revealed oscillations with a period of roughly 12 years during the quiescent phase of Black Rapids Glacier, Alaska, U.S.A., the original "Galloping Glacier". These oscillations are hypothesized to be the manifestation of slowly propagating waves of till failure and till healing, with at least the second cycle being initiated by the anomalous advance of a tributary glacier. Observations support the idea that such dynamics may have occurred, but are not conclusive. In the conceptual model describing the mechanisms of till failure and healing, temporal variations in longitudinal stress gradients are proposed to be more important in causing till failure than temporal variations in effective pressure.

## INTRODUCTION

Black Rapids Glacier, in the central Alaska Range (Fig. 1), was dubbed the "galloping glacier" by the popular press during its last surge (1936/37) as it threatened to dam the Delta River, close off a highway and crush a local roadhouse. Fortunately, the advance stopped before reaching that far, but the threat from future surges remains. Assessing the likelihood of that threat and the imminence of the next surge has been the focus of long-term research efforts by the United States Geological Survey (USGS), the University of Alaska Fairbanks (UAF) and the University of Washington since the early 1970s (Harrison and others, 1975; Sturm, 1987; Sturm and Cosgrove, 1990; Heinrichs and others, 1994, 1996; Raymond and others, 1995). Much of the glacier overlies the Denali fault, an active tectonic feature of central Alaska, and it is now known that a meters-thick till layer exists beneath much of the ice overlying this fault (Nolan and Echelmeyer, 1999a, b; Truffer and others, 1999, 2001). Jökulhlaups and spring speed-ups have been observed to occur annually for every year of observation (personal communication from W. D. Harrison, 1993). Detailed radio-echo sounding has produced a three-dimensional map of the bed (Gades, 1998), and interferometric synthetic aperture radar (InSAR) measurements have yielded surface velocities and strain at high spatial resolution (Fatland and others, 2003). Much is therefore understood about the quiescent-phase dynamics of this glacier.

However, a 28 year record of annual velocity, mass-balance and elevation measurements at several index sites (Heinrichs and others, 1996; Truffer and others, 2001) has yielded an unexpected, and as yet unexplained, finding. Two cycles of oscillation in surface speed with about a 12 year period have now been recorded (Fig. 2). Variations were strongest at the 14 and 20 km sites, with speeds ranging from 45 to 70 m a$^{-1}$ (i.e. amplitude of 25 m a$^{-1}$); no variations were seen at sites down-glacier of the Loket tributary (Fig. 1). The phase of these speed variations appears consistent between the sites, indicating strong longitudinal coupling, but both lead a similarly cyclic increase in surface elevation that also closely matches cumulative changes in local mass balance. It is difficult to believe, therefore, that the cycles in speed, elevation and mass balance are unrelated, but it is puzzling that the cycles in speed *lead* the others. Heinrichs and others (1996) showed that increases in ice deformation due to changes in elevation (assuming no change in basal motion) are insufficient by far to explain the speed variations. Truffer and others (2001) numerically modeled the effect of varying the amount of till at failure along the perimeter of a cross-section transverse to ice flow and found that this mechanism is sufficient to allow for the observed changes in speed, but offered no causal mechanism for the oscillation of the till failure itself. Therefore, as yet no complete theory adequately describes why these speed oscillations are occurring and how they relate to surge dynamics, if at all. These decadal-scale cycles are herein defined as "trotting" or "trot-cycles", with no causal attribution, to facilitate discussion and distinguish them from surge cycles.

One explanation for these trot cycles could be the long-term build-up and release of subglacial water at high pressure, as in Findelengletscher, Switzerland (Iken and Truffer, 1997), but there are no observations to confirm or refute this, and the beds of these glaciers are likely quite different (hard vs soft beds). How multi-year oscillations in the effective pressure of till could occur is poorly described in the literature as well. Another explanation is the hypothesis proposed here, in which a wave of till failure, initiated by the sudden advance of a tributary glacier, slowly propagates down-glacier, causing surface speeds to increase until the wavefront hits an obstacle it cannot pass, causing an up-glacier propagation of till healing and decreased speeds. The next section provides an overview of this proposed mechanism, followed by observational support for it and a brief discussion of its implications.



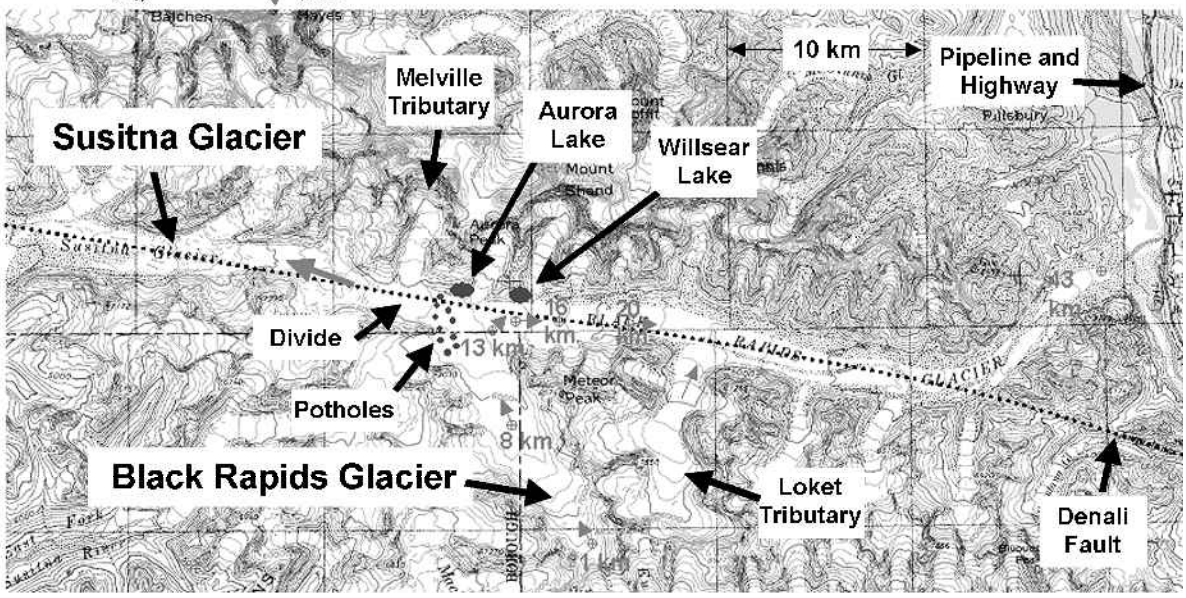




*Fig. 1. Black Rapids Glacier, lying along the Denali fault in the central Alaska Range. Several points from the local glacier coordinate system (e.g. 8 km) are shown here superimposed on the USGS map of the area. The trans-Alaska pipeline and a major highway are built on old surge moraines from this glacier.*

## A CONCEPTUAL MODEL OF HOW TILL FAILURE MAY PROPAGATE

Here the 14–22 km stretch of the glacier is modeled as having a uniform, straight longitudinal cross-section with uniform surface slope, underlain by a thick, fully saturated subglacial till with uniform properties (i.e. porosity, yield strength, thickness) throughout the ice perimeter. Note that this is only a conceptual model and the figures and text below are a description of it, not results from a computerized form of it. This till is modeled to have only two states: a competent state (gray regions in Fig. 3) which supports a high basal shear stress and does not allow basal motion, and a failed state (white) which essentially provides no resistance to basal motion. Once the till fails, the increased glacier motion that results helps to keep it in failure. This model of the till's resistance to flow is crudely analogous to the mechanisms of static and dynamic friction, such that once till fails, less driving stress is required to maintain it in the failed state than was required for transition to that failed state. In this model, ice thickness decreases uniformly down-glacier with a constant surface slope.

### Initial conditions (Fig. 3a)

Whether till fails depends on its effective pressure and the applied basal shear stress, all else being equal (which in this case it is by definition). In steady state, effective pressures within the till are modeled as uniform throughout the bed due to pore-water diffusion. Thus ice thickness largely controls bed strength (competent/failed, not till yield strength

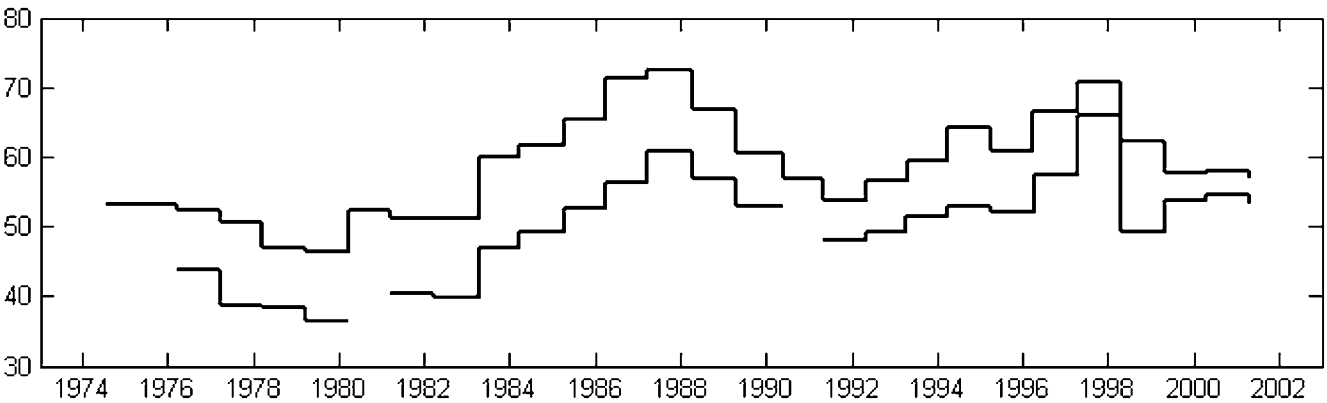



*Fig. 2. Annual glacier speed at 14 and 20 km. Average annual speed is computed typically from two measurements per year, in spring and fall. Data from 1995–2001 provided by M. Truffer of UAF.*

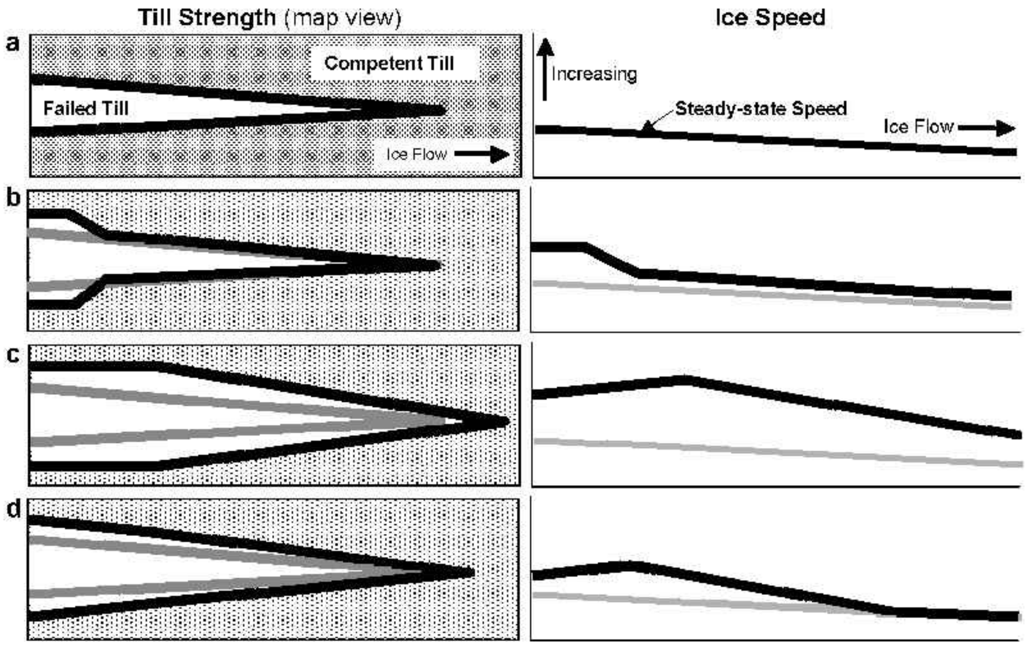



*Fig. 3. Conceptual model of a propagating wave of till failure. Till is modeled as having two states: competent (dotted) and failed (white); thick line indicates competence near its yield stress. The first column shows till state in map view; the second column shows center-line ice-surface speed as a function of distance down-glacier. (a) In the initial state, the amount of till in failure is proportional to driving stress (ice thins down-glacier). (b) A perturbation up-glacier pushes on the ice down-glacier. (c) This causes a propagating wave of till failure, increasing glacier speeds everywhere. (d) A down-glacier obstacle, or attenuation in the ablation area, stops the ice motion, allowing till to recover strength and slow the ice further.*

itself), such that failed till concentrates under thicker ice where ice driving stress (ice weight times surface slope) exceeds till strength. Transitions to the failed state can initiate from at least two causes, including decreases in effective pressures (e.g. due to a jökulhlaup within the model area) or increases in shear stress via increases in longitudinal stress (e.g. due to the sudden rapid motion of a tributary glacier up-glacier of the model area). Initial strain regime is the canonical model of extending flow in the accumulation area and compressive flow in the ablation area (Paterson, 1994); note that the up-glacier edge of this model is near the equilibrium line.

**Perturbations (Fig. 3b)**

As an initial perturbation causes more till to fail along a cross-section transverse to ice flow, more of the driving stress is redistributed to the competent till elsewhere, such as along the margins or longitudinally. This increases the glacier speed locally. As more of the glacier's driving stress

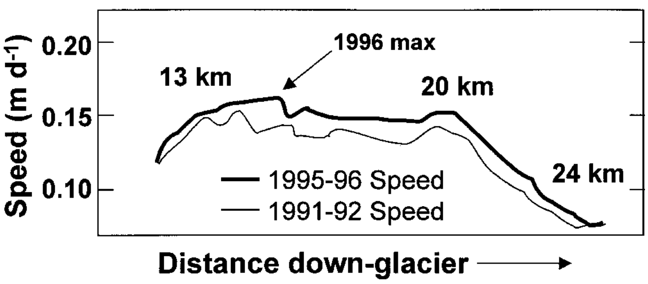



*Fig. 4. Longitudinal distribution of surface speed from SAR; adapted from Fatland and others (2003) by fitting smooth curves through data presented there. An increase in speed is observed over the 4 year interval, and the location of maximum surface speed has migrated down-glacier.*

is placed on till down-glacier, any till that was at the failure point also fails, creating a positive feedback that places even more shear stress on the down-glacier till. As the overall percentage of failed till increases longitudinally, the glacier moves faster everywhere because of the increase in basal motion and decrease in net bed resistance.

**Propagation (Fig. 3c)**

As these effects propagate down-glacier, the location of the boundary between extending and compressing flow moves with them, though likely less rapidly than the till-failure wavefront itself. Within the extending flow area, once the till fails there are few processes acting to restore strength or limit continued motion. Therefore, the leading edge of extending flow leaves a weakened bed in its wake and decreases the net bed resistance as it travels. The primary forces acting to retard fast glacier flow are located in the normally compressive ablation area, since the driving stress is lower (thinner ice) and therefore the till is farther from failure. Thus as the peak moves further into the normally compressive zone, the wave attenuates more rapidly than in the extending area.

**Dissipation (Fig. 3d)**

Initial and continued failure is due mainly to the additional applied basal shear stress caused by the longitudinal shoving of ice. Once the ice can no longer be shoved forward (either due to decreased shove from up-glacier or due to an immovable object down-glacier), the basal shear stress decreases (due to decreased longitudinal stress) below the failure point and till heals. Thus the wave of bed failure stops propagating when the additional longitudinal forces created by the failing bed are balanced or exceeded by the opposing forces down-glacier (e.g. pinning points, tribu-



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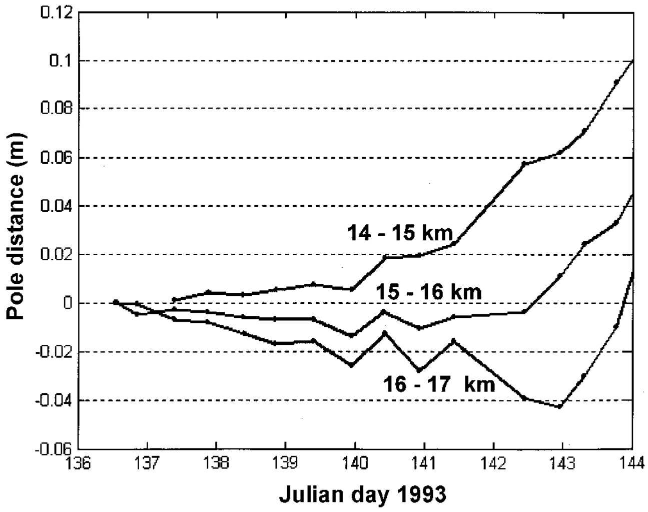


*Fig. 5. Strain-pole displacements in 1993. Distances between the survey tripod near 15 km and several poles moving along the same flowline are presented. For clarity, the records have been adjusted by removing the initial distance from the curve, showing that longitudinal extension in winter 1993 occurred between 14 and 15 km but compression occurred between the other two regions down-glacier. Also seen is the propagation of the initial spring speed-up, which appears to show up first about day 140 between 14 and 15 km.*

taries or sticky spots). In this thought experiment, any such obstacles would be considered the down-glacier boundary condition. Because of the increase in longitudinal coupling created by the wake of failed till (i.e. the ice acts more like a single block with little basal resistance), a decrease in basal motion at the wavefront would cause a wave of till healing to propagate up-glacier, restoring the initial proportions of competent/failed till and decreasing longitudinal coupling towards its initial state.

Are the model assumptions valid? Perhaps the most speculative assumption is treating effective pressure as constant and uniform throughout this stretch of the glacier, and much of the argument follows from this assumption. If effective pressure is constant and uniform, the only variable left in controlling till state (failed/competent) is applied shear stress (Paterson's (1994) review reveals that only these two variables are typically included in till "flow laws"); that is, till state (via basal shear stress) switches from initially being a function of driving stress to being a function of driving stress plus longitudinal stress in the oscillatory state. This allows for both easier initiation and propagation of till-failure waves in the accumulation area where driving stress is high (and therefore more till initially closer to failure) and attenuation of the wave in the ablation area where driving stresses are lower (and therefore till less prone to failure). The effective-pressure assumption is clearly of doubtful validity, but is made mostly for illustrative purposes; in practice, effective pressures could likely still vary considerably without invalidating the model. The assumption that failed till supports zero shear stress can similarly be relaxed without invalidating the model (as long as the shear stress is substantially lower than that supported by competent till). Whether a till with uniform properties exists along the margins is also speculative, but this assumption is made for illustrative clarity, rather than being an actual requirement; in fact, having no till at the margins improves the argument that the ablation area is more prone to attenuating till-failure waves, because there is more wall surface area there. One assumption that cannot be relaxed is the inability of till to heal itself while deforming. On the time-scale of several decades, it has been hypothesized that basal freeze-on mechanisms can slow or stop Siple Coast (Antarctica) ice streams (Anandakrishnan and others, 2001), but as yet no one has proposed a mechanism that allows deforming till to heal itself beneath temperate glaciers on time-scales of days to years, other than an increase in effective pressure. Paterson's (1994) review also discusses several studies which support the notion that deforming till recovers strength only *after* deformation stops.

## OBSERVATIONAL SUPPORT FOR A PROPAGATING WAVE OF TILL FAILURE

It is possible that the trotting observed over the past 28 years at Black Rapids Glacier is a manifestation of a propagating wave of till failure induced by the abrupt rapid motion of the Melville tributary observed by InSAR (Fatland and others, 2003). Following along the lines of the conceptual model, it is hypothesized that high-pressure water build-up beneath the Melville tributary in 1991 caused rapid ice motion there due to decreased bed friction. This motion should have increased longitudinal stresses on the down-glacier ice. Such increases would cause more till to fail there, raising glacier speed along the entire stretch of the glacier between the Melville and Loket tributaries through continued down-glacier increases in longitudinal stresses. This wave of till failure then propagated down-glacier, causing the location of the maximum speed of the glacier to move with it, leaving a wake of failed till and increased surface speeds. The wave continued until hitting either sticky spots at the bed or the Loket tributary, or both, at which point glacier speeds decreased. The remainder of this section describes the observational and collateral support for this hypothesis.

### Long-term storage and release of liquid water beneath the Melville tributary

Curious and unexplained releases of water in winter have been observed to occur in the region near the Susitna–Black Rapids Glacier divide for many years. Sturm (1987) and Sturm and Cosgrove (1990) describe the filling and draining of potholes and lakes here in late winter, long before the possibility of fresh snowmelt could have occurred. Others (Raymond and others, 1995; Nolan and Echelmeyer, 1999a; Raymond and Nolan, 2000) report that some of these same lakes drain later in summer (May and June), likely on an annual basis. In spring, at least some of these lakes are filled by snowmelt runoff from the adjacent hillsides; other lakes are filled by the draining of lakes up-glacier. These jökulhlaups ($10^5$–$10^6$ $m^3$ of water) were observed to cause up to four-fold increases in glacier speed, though these increases lasted only a few days. It is not known whether the mid-winter jökulhlaups caused subsequent fast motion, nor has the water source for the mid-winter events been previously explained.

Ground-water may be a key to understanding these dynamics. Black Rapids Glacier lies at the base of a series of several large mountains with steep south-facing slopes. Snowmelt has been observed at 3000 m in March on dark-colored, south-facing rock in nearby valleys (personal communication from P. Marshall, 2002). Water that melts from these slopes can either run over the surface, forming lakes such as Aurora and Willsear Lakes, run beneath the glacier in tunnels, or enter into the rock through cracks. Because of the large fault running through the region, it is conceivable that substantial quantities of meltwater can enter into the strained and cracked surface, to be slowly transported downhill over a period of days to decades. Because of the scouring and deepening of the valley by glacier erosion, the subglacial valley walls intersect these channels, producing what would be called springs if they were observed on the surface; such springs are observed near the terminus where the ice surface is substantially lower than the scour of previous advances. These springs supply a relatively steady amount of water to the bed of the glacier at a pressure proportional to the head that drives them; this head can be substantially higher than the head of englacial or subglacial storage. M. Truffer (unpublished data) describes the existence of a subglacial aquifer in April found in a borehole at 16 km that substantially exceeds the ability of mechanical pumps to remove, before substantial snowmelt began there. Large rivers in the adjacent valleys, fed from the local mountains, are known to run beneath the river ice year-round. These observations all support the concept of ground-water aquifers that hydrologists have described since the early days of that science.

Once at the bed, the interactions between ground-water and recent meltwater likely become intertwined. During periods of high meltwater transport, conduit systems are easier to maintain, particularly if the amount of melt greatly exceeds ground-water release, based on standard glaciological theory (Paterson, 1994). Once melting ends in fall, the conduit size would be determined largely by ground-water and englacially stored water. If such flow is low, as seems likely, conduits may be impossible to maintain at all. Because of the high elevation near the ice divide, it is likely that these discharges there are low because source areas are at a high elevation. In such low flows, the motion of deforming till in contact with the spring may also affect its flow rate due to blockage. Thus, one might expect the water to pond until sufficient pressure is created to force movement past a blockage to a lower location. It is dynamics along these lines that may explain the sudden filling of Aurora Lake during winter and the persistent presence of potholes on the surface of the glacier near the pass. That is, the existence of the potholes may be due to their continued reactivation from below, when they act as relief valves during sudden releases of pressurized ground-water; field measurements show that their individual supraglacial storage capacity is on the order of $10^5$ m$^3$. If this is correct, the likely source for both water and water pressure is the valley containing the Melville tributary, which extends $>1000$ m above glacier surface at the pass.

## InSAR measurements of initiation event

InSAR data from winter 1991/92 reveal anomalous motion of the Melville tributary, which enters directly at the divide between Black Rapids and Susitna Glaciers (Fatland and others, 2003). Note that the timing of this motion anomaly is immediately prior to the onset of increased annual glacier speeds in 1992 (Fig. 2). Over a 1 month period beginning in January, 10 observations record an elliptical pattern of anomalous motion (termed a "phase bull's-eye") that was observed to move down the tributary and enter Black Rapids Glacier at a rate of roughly 30 m d$^{-1}$, traveling a total of about 800 m. The pattern is roughly 3.5 km long and 1.7 km wide. This motion cannot be explained by processing artifacts or other errors and is largely interpreted as an increase in surface elevation. The surface rise at the migrating center of the bull's-eye was measured at 2–4 cm d$^{-1}$, with uplift at any given location of about 9 cm. If the motion is interpreted purely as uplift, Fatland and others (2003) indicate it would yield a subglacial lake with a final volume of roughly $10^6$ m$^3$.

The InSAR measurements that detected the anomalous motion cannot distinguish between hydraulic jacking and emergent velocity as the cause of the vertical signal measured. Given our knowledge of glacier dynamics in this region, however, it is unlikely that the formation of a subglacial lake could occur here *without* rapid basal motion and the consequent increase in emergent velocity (such as through an index site). For example, three jökulhlaups were observed in summer 1993 that caused significant increases in speed only several kilometers down-glacier of the phase bull's-eye (Nolan and Echelmeyer, 1999a). A curious feature of the bull's-eyes, which remained unexplained in Fatland and others (2003), is the fact that the glacier surface never returned to "normal" once the hypothesized subglacial lake passed through. If the measured elevation signal were due to rapid forward motion, however, the relaxation time needed to restore the surface to normal via enhanced deformation would be on the order of months (Paterson, 1994). Fatland and others (2003) ruled out the possibility that sudden forward motion is the primary cause of the signal, because the ice down-glacier of the anomaly would prevent such motion.

There is some reason to believe, however, that the ice immediately down-glacier would not offer that much resistance. Ice leaving the Melville tributary and entering Black Rapids Glacier abruptly receives less resistance to driving stress from the bedrock margins because these side-walls largely disappear where tributaries enter from both north (the Aurora tributary) and south (the main accumulation area) (Fig. 1). Therefore it is likely that the bed provides much of the resistance to increased flow here, and we know from prior research that the bed here is weak and prone to failure (Nolan and Echelmeyer, 1999a, b). Thus the advance of the Melville tributary could have increased longitudinal stress on the down-glacier ice, beginning a wave of till failure as described by the model and perhaps supported by the observations described next.

## Propagation of the wave down-glacier

There are several observations that support the down-glacier propagation of a wave of high surface speed over a 4 year period. This region of Black Rapids Glacier is coincident with approximately the equilibrium-line altitude and this glacier-wide transition from extending to compressing flow. Comparison of the two SAR transects indicates that this transition migrated down-glacier between the two measurements (Fig. 4). While there is little observational basis for suggesting that it was accompanied by a peak in surface elevation, such a peak might help explain the high spatial-frequency variations in speed observed with SAR as an artifact of unaccounted-for emergent velocities (see Fatland and others, 2003, fig. 3 inset). In any case, this wave did not cause any significant surface cracking on this remarkably smooth glacier. If progression of this wave of high velocity was linear, the peak might have moved past our 15 km survey location in 1993. Figure 5 indicates that prior to the 1993 spring speed-up, the winter flow regime was such that the 14–15 km region experienced extension, 15–16 km experienced slight compression, and 16–17 km experienced even more compression. During the subsequent spring speed-up and the entire speed record from that summer, the 15–16 km strain record switched to primarily extending flow. While no survey data exist to support the continuation of this trend later in summer or in subsequent years (field data from 1997 use a different spatial interval for longitudinal strain), winter flow in 1997 between 13 and 16 km was extending, and the onset location of the spring speed-up moved down-glacier between 1993 and 1997 (M. Nolan and M. Truffer, unpublished data). Whether or not a down-glacier wave of increased motion can be said to be observed using these survey data is perhaps debatable, but the fact that such a progression and a speed-up occurred is certain, given the SAR and annual speed record, respectively.

### Wave dissipation

The peak in annual surface speeds (Fig. 2) occurred in 1998, following the last field season in which we have detailed survey records or InSAR. While we have no actual observations of the dissipation of a wave of bed failure, we can nonetheless constrain the conditions in which such a wave might have dissipated. Annual survey data show that the oscillations observed at the 14 and 20 km sites did not occur down-glacier of the Loket tributary (Heinrichs and others, 1996). This tributary vigorously enters Black Rapids Glacier, steadily pushing a moraine across the flow path (Fatland, 1998). This ice and moraine is truncated during Black Rapids Glacier surges and transported down-glacier; several previous moraine loops are identifiable. Similarly, a comparison of the two InSAR speed transects (Fig. 4) shows that, in both years, the Loket tributary caused a strong compression gradient in speed up-glacier of its entry point. Thus if a wave of bed failure propagated down-glacier, it was apparently blocked by the Loket tributary; it is possible that the only waves of fast motion (or bed failure) that extend past this point are surges. Another potential obstacle to continued bed failure may be a 60 m overdeepening near 17 km revealed by radio-echo sounding (Gades, 1998). The down-glacier portion of such an overdeepening could act as a sticky spot, with both different till properties/distribution and opposing force due to its projection into the ice, and the thinner ice downstream reduces basal shear stress, leading to more till in the competent state than up-glacier.

## DISCUSSION

Do the observations support the model adequately? There are three things that we know for sure: (A) decadal-scale oscillations in surface speed have occurred and this motion is driven by basal processes; (B) the onset of the last cycle was coincident with prolonged anomalous motion of the Melville tributary; and (C) comparisons of 1991 to 1995 surface speeds show that the location of maximum speed migrated down-glacier. Here it was argued that these observations are the manifestations of a wave of propagating till failure by suggesting that (1) the Melville tributary anomaly was an advance caused by the release of high-pressure ground-water; (2) this advance would shove the ice in front of it out of the way by causing till to fail, creating a positive feedback by increasing the amount of unbalanced longitudinal stress; (3) once the wave hits thinner ice in the ablation area and/or the Loket tributary, the restraining forces are more likely to exceed the additional longitudinal stress; and (4) once this occurs, till will begin to heal back towards its initial state because the applied shear stress has been reduced. Observational support exists for all of these interpretations, but is not truly conclusive, and interpretation 2 is the one that is really the heart of the argument and perhaps the most speculative and novel. While it is well established that basal shear stress is the dominant control on till failure, the glaciological literature rarely considers the amount of applied shear stress an important glaciological variable, preferring effective pressure as the most likely cause of transient change in basal motion (Paterson's (1994) treatment of till deformation treats basal shear stress as a constant).

Iken and Truffer (1997) measured surface strains over a number of years at Findelengletscher and found that variations in longitudinal shear stresses played only a minor role in controlling annual variations in surface speeds, while lateral drag was most significant. There are two reasons why their results may not conflict with the mechanism proposed here. First, the bed of that glacier is likely not underlain by a thick, deformable till under most of its length, and thus the role of subglacial pockets of water is likely much different. Second, during the period of Iken and Truffer's study, the annual surface speeds over much of the glacier length decreased. Therefore, even if a wave of till failure had occurred there, it would be healing at this point, and longitudinal forces would not be expected to play an important role, while lateral forces would. Qualitatively, Iken and Truffer's findings suggest a similar finding to the till-failure hypothesis: temporal changes in bed resistance occur and transfer driving stress either laterally or longitudinally. Their study does, however, highlight the fact that there is no substitute for field measurements when testing models; such measurements are now underway on Black Rapids Glacier (personal communication from M. Truffer, 2002), and re-analysis of the two InSAR velocity fields to calculate basal shear stresses using strain networks is planned (personal communication from D. R. Fatland, 2002).

Mechanisms other than the one proposed here are clearly responsible for some portion of transient rapid motion at Black Rapids Glacier. Events like summer jökulhlaups and the associated speed increases demonstrate that conduit water pressures increase enough to cause hydraulic jacking (Nolan and Echelmeyer, 1999b). Similarly, annual spring speed-ups are associated with the onset of snowmelt, but how either of these phenomena relates to pore-water pressure has not been adequately explained. It is possible that the local decreases in bed resistance that these events cause may also trigger a till-failure mechanism similar to that described here, with the wave of failure being proportionally narrower than longer time-scale waves. Alternatively, the effects of these seasonal events may react nonlinearly with the progress of till-failure waves, such that the same jökulhlaup might cause proportionately higher surface speeds when more of the till is already at failure. Truffer and others (1999) also describe how decreased bed resistance (by whatever mechanism) can lead to enhanced ice deformation near the margins as more stress becomes concentrated there and also how the percentage of till in failure can amplify the effects of small changes in surface slope. In practice, it is probable that any positive feedback of till failure is also associated with feedbacks in enhanced ice deformation and conduit water pressures.



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## IMPLICATIONS

If this conceptual model is valid, it has several implications that bear directly on surging and tidewater glacier cycles, as well as perhaps ice streams. The surface speeds of these types of glaciers periodically increase dramatically. Perhaps more significantly, they switch from the canonical mode of extending accumulation areas and compressing ablation area (Paterson, 1994) to extending flow throughout the entire length (ice streams are a bit different, but are indeed extending when active). In this thought experiment, it was argued that till cannot heal itself unless shear stress is reduced due to the ice flow itself being blocked by some obstacle (or simple attenuation of stress in the ablation area). In the case of Black Rapids Glacier, if an obstacle of sufficient size does not exist (or the perturbation is sufficiently large), then the positive feedback would continue until the entire glacier was experiencing extending flow, i.e. until it was surging. In the case of surge-type glaciers, a jökulhlaup or "mini-surge" causing a local decrease in effective pressure (high water pressure) might be sufficient to initiate a surge, but only if conditions are prime for bed-failure waves to propagate; that is, perhaps recharged surface slopes are required to get enough of the till initially in failure before a perturbation will cascade into an uncontrollable positive feedback. A sudden opening of the drainage system could end the surge by decreasing the longitudinal force applied to the till down-glacier, but this would not necessarily heal till that had recently failed, leaving the glacier primed for another surge event should another blockage occur, as has been observed on Variegated and Bering Glaciers, Alaska. That is, this primed state is dictated by driving stress, and until this is reduced sufficiently by a surge, the potential for surge remains high.

Tidewater glaciers and ice streams, however, indicate that lowering driving stress is not necessarily sufficient to heal till. Numerous examples exist of high basal motion coincident with low driving stress (e.g. Siple Coast ice streams; Columbia Glacier, Alaska); in these cases, longitudinal coupling is so large, and existing restraining forces so low that even low driving stresses can continue to keep till in the failed state. It is simpler to discuss tidewater glaciers in this case because they do not have the added complications of till freezing as a healing mechanism. The initiating perturbation in the case of tidewater glaciers might be a change in longitudinal stress distribution resulting from a small retreat off a terminal moraine. These glaciers typically over-ride sediments (deposited during previous retreats) with low yield strengths, such that they may always be in the primed state. Thus in the absence of a restraining force at the terminus, the basal motion increases dramatically and the ice actually speeds up even as it retreats. This "catastrophic" retreat coincident with extending flow throughout the glacier length may be evidence of a wave of till failure propagating up-glacier with a positive feedback, such that only new terminal restraining forces (i.e. pinning points) or the retreat above sea level will slow the retreat. That is, these "catastrophic" retreats may actually be more analogous to the "galloping" advances of surging glaciers than previously considered.

At the IGS Symposium on Fast Glacier Flow, it was suggested during discussion that one difference between the brief but vigorous "Alaskan-type" surges and the prolonged but slower "Arctic-type" surges was the lack of an outlet flood following surge termination, suggesting that mechanisms other than trapped basal water at high pressure may lead to positive feedbacks in basal motion. Unresolved discrepancies between the dynamics of tidewater glaciers, outlet glaciers and ice streams were also discussed. Future consideration of the till-failure feedback mechanism described here may help elucidate both the similarities and differences in all of these observations of fast glacier flow.

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