Ice flow dynamics at Storglaciären's frozen margin

Peter L. Moore¹, Neal R. Iverson¹, Keith A. Brugger², Denis Cohen¹, Thomas S. Hooyer³, and Peter Jansson⁴

¹Dept. Geological & Atmospheric Sciences, Iowa State University, USA
²Dept. Geology, University of Minnesota-Morris, USA
³Wisconsin Geology and Natural History Survey, USA
⁴Dept. Physical Geography & Quaternary Geology, Stockholm University, Sweden

Abstract. Since the summer of 2006, more than 30 boreholes have been drilled where warm-based ice meets the frozen margin of Storglaciären to determine the influence of the frozen margin on ice flow dynamics. Numerous instruments have been deployed in these boreholes, including thermistors and slidometers. A surface stake network in the same region has also been surveyed with dGPS and total station to determine surface velocities on various timescales. Preliminary results support the commonly-held belief that basal motion decreases sharply toward zero where the zero-degree isotherm intersects the bed, suggesting that the basal thermal transition is also a slip/no-slip transition. However, the surface velocity field indicates that longitudinal stress gradients induced by no-slip within the frozen margin are not large.

Introduction

Like many other polythermal valley glaciers, Storglaciären has a cold surface layer in the ablation zone that is frozen to the bed near the terminus. Although basal sliding and bed deformation have been documented in cold-based ice (e.g., Echelmeyer and Wang, 1987; Cuffey et al, 1999), the observed rates (~ 10⁻³ m a⁻¹) are typically negligible compared to basal motion in temperate-based ice. Where sliding, temperate-based ice encounters a frozen margin (the basal thermal transition or BTT) longitudinal compression is expected. A common suggestion is that the BTT in a polythermal glacier should represent a slip to no-slip transition and should cause substantial stress concentrations, potentially leading to thrust-faulting in the ice (e.g., Hutter and Olunloyo, 1980; Hambrey et al, 1999). A major motivation for this idea is that upglacier-dipping bands of apparently basally-derived debris often outcrop in the terminus of glaciers with this type of temperature structure. This logic, combined with detailed analysis of ice and sediment properties, small-scale structures and isotopic variations in the ice, led Glasser and others (2003) to suggest that a conspicuous debris band in the northern part of Storglaciären’s terminus originated by thrust-faulting. A long-term objective of our work on the terminus of Storglaciären is to attempt to measure the stress and velocity fields in this part of the glacier and to either document conditions favorable for thrust faulting or to offer an alternative explanation for the origin of the debris band. This report discusses a subset of preliminary results from our first 18 months of field measurements.

Field Methods

Six boreholes were drilled in July of 2006 and 25 were drilled in July and August of 2007 using the Tarfala Research Station hot-water drill. Effort was focused on the northern half of the terminus where the bed was thought to transition from thawed to frozen (Figure 1). In three of the 2006 boreholes along a flow-parallel transect near the glacier centerline (hereafter called the “southern transect”), we deployed strings of 28 thermistors each. Shorter thermistor strings (7-11 thermistors per string) were installed in nine boreholes in 2007. The thermistors (Fenwal Uni-curve, 5kΩ) were soldered at intervals onto a long multiconductor cable, each with one dedicated wire and a common excitation wire. Solder joints and jacket incisions were then re-sealed with vinyl electrical tape and self-fusing splicing tape and covered with adhesive-lined heat-shrink tubing.

In 2007, slidometers were successfully installed in four boreholes along the same flow-parallel transect near the glacier centerline. Each slidometer consisted of a wire-rope extensometer (Micro-Epsilon, model MK46 WPS-1250) coated with dielectric grease and sealed in a plastic box. Each extensometer had 1.25 m of spooled wire leading out to an additional 0.5 m wire leader with a small (40 mm tall) cone-shaped stainless-steel anchor. Before deployment of the slidometers,
Figure 1 (above). Map of the stake and borehole transects. Grid coordinates on the map axes are the RT90 2.5gV system. An arbitrary coordinate system X-Z is used throughout much of this report, where Z is elevation above mean sea level in meters and X is horizontal distance in meters along the 2007 stake profiles, where the westernmost stake in each profile is set to X = 0.

Figure 2 (left). Deployment of a slidometer (black box below right hand of operator) using the hammer and insertion tool. On average, three attempts were required to get a slidometer anchor successfully lodged in the subglacial sediment. Photo by Keith Brugger.
candidate boreholes were probed to determine whether till at the base of the borehole was sufficiently thick to firmly bury a slidometer anchor. Deployment of the slidometers proceeded much as described in Blake and others (1994), using a cable-drawn borehole hammer attached to an insertion tool. The slidometer housing was loosely bound to the insertion tool (see Figure 2) with plastic zip ties, and the wire extended down to the steel anchor that was loosely fit onto the tip of the insertion tool using a scrap of paper wedged along the anchor-tip interface. The entire system was then lowered to the bottom of the borehole while maintaining moderate tension on the electrical cable leading up from the slidometer housing in order to prevent it and the anchor from slipping off of the end of the insertion tool (Figure 3). Once at the bottom, the anchor was pounded into the bed until it was clear that it could not be buried deeper. This deep-burial tactic presumably allows not only basal sliding to be recorded but also any till deformation that accommodates motion at the bed. The hammer and insertion tool were then withdrawn carefully to ensure that the anchor slipped off.
the insertion tool and that the hammer would not tangle with the electrical cable as it was lifted out of the hole. For most slidometers there were several unsuccessful installation attempts before the anchor finally set.

Thermisters, slidometers, and other instruments were logged at 30-minute intervals throughout the year with Campbell CR10X dataloggers. The dataloggers were powered with gel cell batteries trickle-charged with solar panels.

Surface velocities were determined by repeated surveys of velocity stakes using a Trimble 4600 differential GPS system and a Geodimeter total station.

Figure 5: Horizontal and emergence velocities for stake networks. a) Mean velocities from July 2006 through July 2007 from dGPS. b) Mean velocities during July and August of 2007. Symbols in the upper plot that also appear in the lower plot correspond to new stakes set along the same transects.

Figure 6: Slidometer records during fall 2007. Slidometer 8 (blue), which recorded steady slip velocity of 2.7 mm/day during October, is upglacier of slidometer 7 (red), which had a sliding speed of about 1.2 mm/day during the same period.
Stakes were set along three profiles oriented approximately parallel to flow in 2006, and reset in two flow-parallel profiles and two transverse profiles in 2007. The 2006 stakes were surveyed with dGPS in late July 2006 and re-surveyed with dGPS in July 2007. The new stake network was installed in mid-July 2007 and surveyed approximately every two days with a total station located on the bedrock ridge near the southern edge of the glacier terminus.

Results

Most of the thermistors installed in 2007 still appeared to be recording transient cooling signals as of late November (about 3.5 months after deployment). As a result, we focus herein primarily on the thermistors installed in 2006, which have provided records of local steady temperatures. Figure 4 shows the temperature field interpolated between the three thermistor strings installed in 2006 and a fourth installed in 2007 closer to the terminus located on the bedrock ridge near the southern edge of the glacier terminus.

Horizontal surface velocity and emergence velocity are shown in Figure 5 for stake transects that are approximately parallel to flow. As is normally observed in grounded, ablating glacier termini, both velocity components decrease downglacier. Not surprisingly, mean velocity components over the period including winter of 2006-2007 are slightly lower than the summer 2007 velocities. However, the lowest stakes were in thin (< 5m) ice and two of them record negative emergence velocities. At least one of those was resting on a boulder beneath the ice when recovered in July 2006, so its vertical displacement may not be representative of the ice motion there. Surveys of stakes set in 2007 will be conducted again in summer 2008 to see if this winter effect is reproduced.

Slidometers in four boreholes along the southern borehole transect were functioning in August 2007. Figure 6 shows the fall 2007 record from the two slidometers that are farthest downglacier and whose anchors were inserted 90 mm (Slidometer 7) and 210 mm (Slidometer 8) deep in the subglacial sediment. Sliding velocities of about 2.7-4.5 mm/day and 0.8-1.2 mm/day were recorded fairly clearly by the upglacier and downglacier slidometers, respectively. A third (Slidometer 6), whose anchor penetrated only 40-50 mm of till, began to show intermittent, slow displacement (< 0.5 mm/day) in late November, 2007. Because the recorded displacement rates of this slidometer are significantly smaller than those of two instruments farther downglacier, we infer that its anchor has been entrained by the sliding ice, so that its record is not an accurate measure of basal motion. A datalogger recording data from a fourth slidometer at the upglacier end of the transect experienced power failure shortly after deployment and has, thus far, yielded no data.

Discussion and Preliminary Conclusions

There is not yet enough information to fully characterize the pattern of basal slip velocity approaching the BTT at Storglaciären. However, if a variety of
simple functions are extrapolated, guided by our existing sliding velocity measurements (Figure 6), these extrapolations suggest that the slip/no-slip transition occurs somewhere between 105 m and 115 m along the southern borehole transect. This inferred transition to no-slip coincides well with the projection of the zero-degree isotherm (the ice solidus) on to the bed, as illustrated in Figure 7. This correspondence suggests that there is a robust link between the transition from slip to no-slip conditions at the bed and the transition from temperate-based to cold-based ice.

How does this apparent slip/no-slip transition affect ice flow at the BTT? We consider two end-member cases of how driving stresses at a glacier terminus might be resisted that are both convenient for modeling. In the first case, the bed and lateral margins of the sliding portion of the glacier offer no resistance to motion, transferring the burden down-slope glacier weight to the frozen margin. In the second case, basal drag everywhere balances the local driving stress.

Idealized mathematical models of ice flow across a perfect-slip to no-slip transition implicitly make the former assumption. Results of such models suggest that basal slip velocity should decrease abruptly as ice approaches the no-slip boundary (e.g., Hutter and Olunloyo, 1980). This abrupt velocity reduction will result in substantial longitudinal stress gradients and stress concentrations in the ice and bed at the BTT. To preserve continuity (and assuming that transverse strains are negligible), ice must be deflected away from the bed and toward the surface, resulting in enhancement of emergence velocity (or more aptly, a peak in the component of velocity away from the bed) over the BTT (cf. Balise and Raymond, 1985). If emergence is balanced by ablation, the horizontal velocity should also decrease significantly over the BTT.

In the other end-member case, driving stress in sliding portions of the glacier is fully supported locally by basal resistance, so that no additional stress burden is shifted to the bed within the frozen margin. Gradients in basal slip velocity and horizontal surface velocity will be gentle and monotonic. Longitudinal compression in excess of hydrostatic, excluding effects of topography, are therefore absent, so there is little vertical strain or enhancement of bed-normal (or emergence) velocity. In this case the frozen margin is dynamically inconsequential.

The actual behavior of most polythermal glaciers probably lies between these two end-member cases. The relatively gradual gradient in slip velocity approaching the BTT and the lack of a definite peak in emergence velocity over the BTT, as indicated by the data (Figure 5), seem to indicate that longitudinal stress gradients are small at Storglaciären, such that the second end-member case is the better approximation. Thus, conditions may not favor development of thrust-faults by compressive ice fracture, consistent with ongoing calculations with a numerical model (Moore et al., 2007).

In the 2008 field season, we hope to get a better idea of how basal motion changes as ice approaches the BTT. To do so, we will install more slidometers along the southern borehole transect and will re-occupy several holes with a borehole inclinometer.

Acknowledgements

We are very grateful to Rickard Pettersson for his energetic and expert assistance in many aspects of this work. We also thank Henrik Tornberg for logistical support and Matt Dettinger for assistance with fieldwork.

References Cited


