Subglacial conditions during and after stoppage of an Antarctic Ice Stream: Is reactivation imminent?

S. W. Vogel,[1,2] S. Tulaczyk,[1] B. Kamb,[3] H. Engelhardt,[3] F. D. Carsey,[4] A. E. Behar,[4] A. L. Lane,[4] and I. Joughin[4,5]

Received 8 January 2005; revised 9 April 2005; accepted 12 May 2005; published 20 July 2005.

[1] Borehole observations from the base of the West-Antarctic Ice Sheet (WAIS) reveal the presence of a 10 to 15 m thick accretionary basal ice layer in the upstream area of Kamb Ice Stream (KIS). This ice layer has formed over a time of several thousand years by freeze-on of subglacial water to the ice base and has recorded during this time basal conditions upstream of its current location. Analysis of samples and videos sequences from boreholes drilled to the bottom of KIS confirms that KIS-stoppage was due to basal freeze-on and that relubrication of the ice stream is well underway. These results further suggest that ice stream cyclicity may be shorter than expected (1000s of years) and that a restart of KIS may be imminent within decades to centuries. **Citation:** Vogel, S. W., S. Tulaczyk, B. Kamb, H. Engelhardt, F. D. Carsey, A. E. Behar, A. L. Lane, and I. Joughin (2005), Subglacial conditions during and after stoppage of an Antarctic Ice Stream: Is reactivation imminent?, *Geophys. Res. Lett.*, *32*, L14502, doi:10.1029/2005GL022563.

1. Introduction

[2] The West-Antarctic Ice Sheet contains enough ice to raise global sea level by 5 to 6m [*Vaughan and Spouge*, 2002]. One of the biggest uncertainties in predicting near-future WAIS mass balance changes arises from the unsteady behaviour of its ice streams. Inherent to them is a thermodynamically driven cyclicity, in which the flow regime switches between an active (purge) and an inactive (binge) mode [*MacAyeal*, 1993]. An example for such a switch is the stoppage of KIS, ~140 years ago [*Retzlaff and Bentley*, 1993; *Smith et al.*, 2002]. Together with the current deceleration of Whillans Ice Stream [*Joughin et al.*, 2002] the KIS-stoppage switched the Ross Sea sector into a positive mass balance, currently helping to counteract global sea-level rise [*Joughin and Tulaczyk*, 2002].

[3] Several mechanisms have been proposed to explain the stoppage of KIS. They all involve a decrease in ice flow lubrication by subglacial water, either due to changes in subglacial water drainage or due to basal freeze-on [*Anandakrishnan et al.*, 2001]. Since Antarctic ice streams have been monitored for just a few decades, it is unclear whether ice stream stoppage is a millennial-scale phenomenon or it is just part of century-scale fluctuations [*Bougamont et al.*, 2003b; *Fahnestock et al.*, 2000; *MacAyeal*, 1992]. The possibility of ice stream reactivation is supported by the fact that physical conditions beneath this stopped ice stream are only slightly different from those found beneath active ice streams [*Kamb*, 2001]. In addition, the upper reaches of KIS are still moving fast (Figure 1), which causes a build up of an ice bulge in the UpC area (UpC ice bulge) with thickening rates reaching ~0.5 to ~1 m yr^{-1} [*Joughin et al.*, 1999; *Price et al.*, 2001]. This growth has caused the surface in the ice stream to rise above the surface of the UpC Sticky Spot, which is frozen to its beds. Growth of ice bulges on glaciers is often associated with highly unsteady behaviour, such as surging [*Clarke et al.*, 1986; *Kamb et al.*, 1985; *Murray et al.*, 2003]. The unsteady nature of the UpC ice bulge may have already expressed itself in the recently documented flow reversal within the southernmost KIS tributary (KIS0) [*Conway et al.*, 2002], which is now spilling ice into WIS.

[4] Here, we show that the binge stage of ice stream activity may be shorter than expected (1000's of years [*Bougamont et al.*, 2003b; *MacAyeal*, 1993]) and that a restart of KIS may be imminent within decades to centuries. Evidence supporting this hypothesis comes from analysis of samples and videos sequences from boreholes drilled to the bottom of KIS.

2. The UpC Basal Ice Layer

[5] During the Antarctic field season 2000–01, several boreholes were drilled to the bottom of KIS at the UpC Sticky Spot, at the transition between the active upper part of KIS and its stopped main trunk. The boreholes were drilled in a profile transverse to the general flow direction, from the UpC Sticky Spot into the southern ice stream branch (Figure 1). In three of these boreholes we obtained video sequences from the ice stream base using the JPL Ice Borehole Camera [*Behar et al.*, 2001; *Carsey et al.*, 2002]. These video sequences reveal the presence of a 10-to-14-m-thick layer of accretionary ice at the base (hereafter basal ice layer, BIL). Similarly to the Byrd Station basal ice, which was interpreted as ice formed by refreezing of basal melt water [*Gow et al.*, 1979], the UpC basal ice is stratified, sediment-laden and devoid of air (Figures 2 and 3). The transition from the bubbly and macroscopically sediment-free glacial ice to the clear (bubble-free), debris-bearing accretionary basal ice occurs within a few centimetres. Macroscopic appearance and isotopic composition of an

[1]Department of Earth Sciences, University of California, Santa Cruz, California, USA.
[2]Now at the Byrd Polar Research Center, Ohio State University, Columbus, Ohio, USA.
[3]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, USA.
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.
[5]Now at Polar Science Center, Applied Physics Lab, University of Washington, Seattle, Washington, USA.

0094-8276/05/2005GL022563$05.00

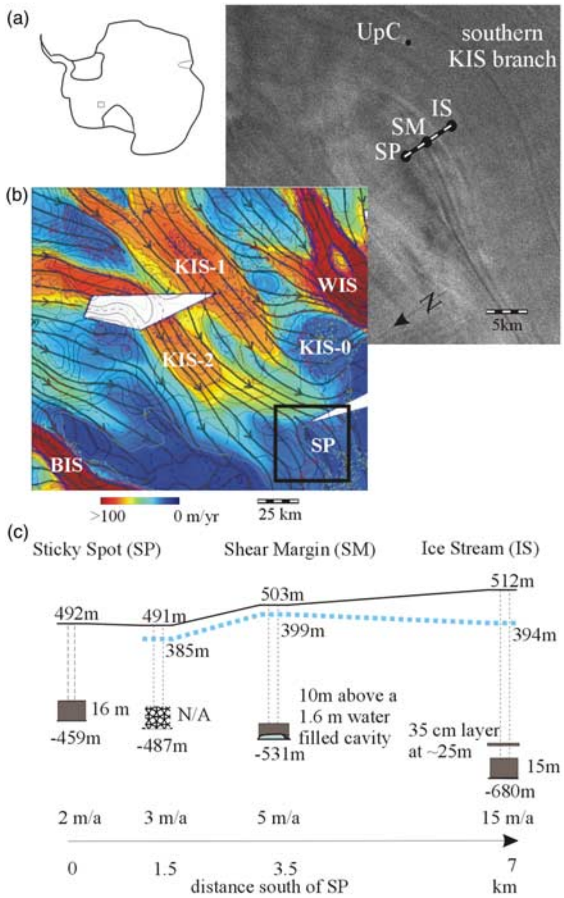

Figure 1. KIS flow regime and borehole locations in the UpC area: (a) ice velocities in the tributary-ice stream transition (tributaries KIS 0-2 labelled south to north) [*Joughin et al.*, 1999]; (b) RAMP SAR mosaic [*Jezek*, 1999] with borehole locations and camp UpC; (c) cross profile into the southern KIS branch, showing (top to bottom) surface elevation, hydraulic head (blue dotted line), basal-ice layer thickness, bed elevation and measured ice velocities with distance from SP. SM: former shear margin, IS: ice stream, SP: camp Sticky Spot (S 82°22′–W136°24′).

ice core taken across the glacial ice – basal ice transition provides further evidence that the BIL formed by freeze-on of basal water (Figure 2). The isotopic composition of the basal ice (∼3‰ difference between the glacial and accretionary basal ice) is consistent with the basal ice originating from freeze-on of basal water having same or similar isotopic composition as the lowermost section of the glacial ice. The period of basal freeze-on needed to produce the observed thickness of basal ice is at least several thousand years [*Vogel et al.*, 2003]. During this time, the ice had moved from the WAIS interior to its present day location, recording basal conditions on its way.

[6] Within the BIL, bands of clear ice, of variable thickness, alternate with debris-bearing layers, containing variable amounts of sediment (Figure 3). The layering in the BIL is (sub) horizontal and the basal ice shows no macroscopic signs of shear deformation. The thickness and sediment content of individual debris-laden ice layers generally increases towards the current ice base. The thickest and densest debris-bearing layer, a 60 cm-thick layer of frozen-on till (Figure 3c), was found in the borehole drilled into the former shear margin (SM). Distinct from this frozen-on till layer is a 27 cm thick layer directly below, which is located above a 1.6 m tall water-filled cavity (Figures 3c and 3d). In the ice-stream borehole (IS) a similar layer of clear ice exists at the ice base (Figure 2). Here this layer is ∼10 cm thick and lies over a thin (mm to cm scale) subglacial water layer. Within the IS borehole the sediment content in the 160 cm of ice above the clear ice layer is elevated (visually estimated at ∼10–20% by volume), which however is much less than the estimated sediment content in the frozen-on till layer in the SM (∼50%).

3. Basal Conditions and KIS Stoppage

[7] In both boreholes the lower two meters of basal ice show no discontinuities, indicating that the ice was accreted in one single event. This is concurrent with estimates of basal freeze-on rates for the time leading to the shutdown of KIS and since this event. Present day estimates of basal freeze-on rates for the UpC area range from 4 to 4.5 mm yr^{-1}, calculated using observed basal temperature gradients (βb = 52 and 54.5 K km^{-1} [*Engelhardt*, 2005]), geothermal flux (GT) of 70 mW m^{-2} [*Engelhardt*, 2004] and basal shear stresses (πb) of 4–5 kPa [*Kamb*, 2001]. Post stagnation thickening of ∼75 m [*Price et al.*, 2001] corresponds to an decrease in basal freeze-on of 0.8 to 1 mm yr^{-1} (βb ∼4–5 K km^{-1}). For the time prior to the shutdown such higher freeze-on rates are likely lowered by ∼1 to 2 mm yr^{-1} due to higher frictional heating as a result of higher pre-stagnation ice velocities (>80–100 m yr^{-1}). However current freeze-on rate at UpD, in the fast flowing Bindschadler Ice Stream (∼360 m yr^{-1} at UpD), is 4.8 mm yr^{-1} (βb 61 K km^{-1}, GT 70 mW m^{-2} [*Engelhardt*, 2004] and πb 1kPa). Therefore an average basal freeze-on rate of 4 ± 1 mm yr^{-1} may reliably be applied to the period before and after the shutdown of KIS 140 years ago. Taking into account the sediment content in the ice, the lowest two meters of the basal ice layer formed over the past 300 to 400 yrs. Assuming a relationship between the availability of basal water (indicator for basal conditions) and the sediment content one can deduce changes in basal conditions during this period from this basal ice layer section. Such a relationship is supported by observations [*Alley et al.*, 1997] and modelling of subglacial freeze-on [*Christoffersen and Tulaczyk*, 2003].

[8] Evidence suggesting a mechanism leading to the shutdown of KIS is found in the change from relatively clear ice to sediment-laden ice ∼170 cm above the ice base in the IS, and in the 60 cm thick layer of frozen-on debris in the SM. For the IS, we estimate that a change from abundant basal water (clear, sediment-poor ice) to a more restricted availability (sediment-rich ice) occurred ∼300 years ago. Whatever process has caused this reduced availability of basal water [*Alley et al.*, 1994; *Anandakrishnan et al.*, 2001; *Retzlaff and Bentley*, 1993], the timing of this reduction correlates well with the oldest crevasses indicating the onset of inward shear margin migration in the UpC area [*Retzlaff and Bentley*, 1993; *Smith et al.*, 2002]. We therefore hypothesize that freeze-

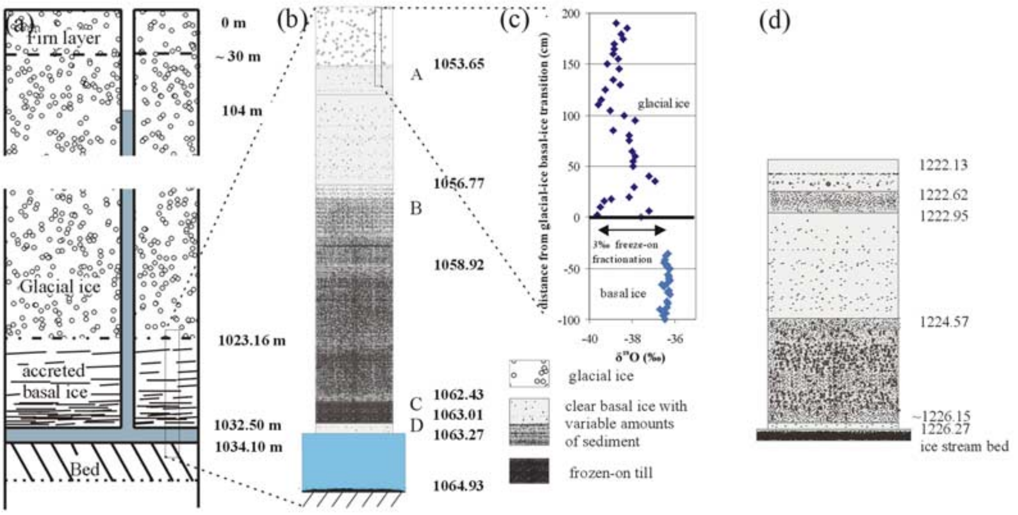

Figure 2. The UpC basal ice layer: (a) schematic vertical profile of KIS at SM; (b) vertical profile of the BIL at SM, with approximate location of recovered ice core (depth labels are borehole camera counter measurement (1 = 1.0298 m); labels A-D correspond to Figures 3a–3d) and (c) $\delta^{18}O$ record of ice across the glacial ice – basal ice transition; (d) schematic drawing of the lower 4 m of the basal ice layer from the IS borehole.

on of ice onto the subglacial topographic high in the center of the KIS may have resulted in the formation or effectiveness of the UpC "Sticky Spot." Such Sticky Spot formation would cause diversion of ice around this location and restrict the supply of ice to the KIS trunk. While ice velocities in the downstream ice stream trunk may initially be unaffected, a restriction in ice supply would promote further thinning of the trunk. This would subsequently steepen the basal temperature gradient and enhance heat escape from the base. Basal freeze-on rates then could exceed the resupply of basal water from upstream, inducing the stoppage of KIS. Further restriction within and possibly destruction of an existing subglacial hydrological system due to the shutdown is corroborated by the formation of the frozen-on till layer, indicating a further decrease in the availability of basal water in the UpC region and a disconnection of areas from the upstream basal water system.

4. Ice Stream Reactivation and Implication on Ice Stream Cyclicity

[9] The lowermost parts of the IS and SM boreholes contain decimetre-thick layers of sediment-free ice located over layers of flowing basal water. These observations indicate that more basal water is currently available than can be used in the freeze-on process. Access to the basal hydrological system was reestablished first in the SM location. Based on the 27 cm thick layer of clear ice at the ice base, we estimate that the SM reconnected to the basal hydrological system ~60 years ago. Within this time the re-supply of basal water from areas of basal melting further upstream [*Joughin et al.*, 2003; *Parizek et al.*, 2003; *Vogel et al.*, 2003], led to the formation of the 1.6 m-tall water-filled cavity. Unrestricted availability of basal water in the ice stream borehole was delayed by ~35 years limiting the accretion of clear ice at the base of the IS borehole to 11 cm over the last ~25 years. It is uncertain whether this increased availability of basal water is associated with the formation of the UpC ice bulge or not. However, observations from surging glaciers indicate that migrating ice bulges can be associated with simultaneous downstream propagation of enhanced basal lubrication, mainly in the form of free basal water [*Clarke et al.*, 1986; *Kamb et al.*, 1985; *Murray et al.*, 2003].

[10] In the case of KIS, the resupply of basal melt water to the ice stream trunk may enhance basal lubrication and shorten the time to a restart of the ice stream. Under current conditions (~0.5 m yr^{-1} thickening) [*Price et al.*, 2001] it would take several thousand years to switch the basal energy balance from freezing to melting and to increase basal melting to a degree allowing a restart of the ice stream.

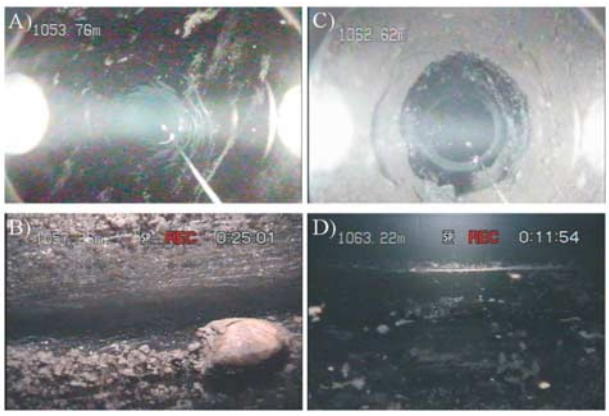

Figure 3. Borehole video images illustrating the appearance of the BIL in the SM borehole. (a) Clear basal ice with sediment with sediment inclusion from ~30 cm below the glacial ice – basal ice transition. (b) Laminated basal ice with a sediment layer and ~1 cm pebble. (c) Frozen-on till layer with a small pebble (5 cm) underlain by a 27 cm thick clear ice layer at the ice base. (d) Clear, sediment-poor basal ice near the ice base.

The resupply of basal melt water from further upstream to the ice stream trunk in excess of water used in the freeze-on process could decrease basal resistance and in return promote a restart of the ice stream within a few decades to centuries. Pending further investigation reactivation within decades to centuries could indicate that ice stream cyclicity may rather be a century scale phenomena controlled by changes in the subglacial hydrological system than a thermo-dynamically driven millennium scale phenomena. Due to the UpC ice bulge formation, reactivation of KIS could make a significant contribution ($\sim$0.5 mm yr^{-1} [*Bougamont et al.*, 2003a]) to global sea-level rise over the scale of decades to centuries.

[11] **Acknowledgments.** We thank all members of the research team participating in the Sticky Spot field campaign 2000/01, in particular R. Bolsey. Additional members of the Caltech-NASA-JPL ice borehole camera team were K.Manatt, K. Boykins, R. Ivlev, F. Nicaise and R. Bolsey. We are grateful for helpful comments and review of the paper by E. D. Waddington, I. Howat and P.Christoffersen. A. E. Behar, F. D. Carsey, and I. Joughin performed this work at the JPL, Caltech, under contract with NASA. We thank NSF-OPP for logistical support of this and former S-157 field campaigns. Funding was provided by NSF grants OPP-9615420 and OPP-0096302.

References

Alley, R. A., S. Anandakrishnan, C. R. Bentley, and N. E. Lord (1994), A water-piracy hypothesis for the stagnation of Ice Stream C, Antarctica, *Ann. Glaciol.*, *20*, 187–194.

Alley, R. B., K. M. Cuffey, E. B. Evenson, J. C. Strasser, D. E. Lawson, and G. J. Larson (1997), How glaciers entrain and transport basal sediment: Physical constraints, *Quat. Sci. Rev.*, *16*, 1017–1038.

Anandakrishnan, S., R. B. Alley, R. W. Jacobel, and H. Conway (2001), The flow regime of Ice Stream C and hypotheses concerning its recent stagnation, in *The West Antarctic Ice Sheet: Behavior and Environment*, *Antarct. Res. Ser.*, vol. 77, edited by R. B. Alley and R. A. Bindschadler, pp. 283–294, AGU, Washington, D. C.

Behar, A., F. Carsey, A. Lane, and H. Engelhardt (2001), The Antarctic ice borehole probe, paper presented at IEEE Aeroconf 2001, Institute of Electrical and Electronics Engineers, Big Sky, Montana.

Bougamont, M., S. Tulaczyk, and I. Joughin (2003a), Response of subglacial sediments to basal freeze-on: 2. Application in numerical modeling of the recent stoppage of Ice Stream C, West Antarctica, *J. Geophys. Res.*, *108*(B4), 2223, doi:10.1029/2002JB001936.

Bougamont, M., S. Tulaczyk, and I. R. Joughin (2003b), Numerical investigations of the slowdown of Whillans Ice Stream, West Antarctica, *Ann. Glaciol.*, *37*, 239–246.

Carsey, F., A. Behar, A. Lane, V. Realmuto, and H. Engelhardt (2002), A borehole camera system for imaging the deep interior of ice sheets, *J. Glaciol.*, *46*, 622–628.

Christoffersen, P., and S. Tulaczyk (2003), Response of subglacial sediments to basal freeze-on: 1. Theory and comparison to observations from beneath the West Antarctic Ice Sheet, *J. Geophys. Res.*, *108*(B4), 2222, doi:10.1029/2002JB001935.

Clarke, G. K. C., J. P. Schmok, C. S. L. Ommanney, and S. G. Collins (1986), Characteristics of surge-type glaciers, *J. Geophys. Res.*, *91*, 7165–7180.

Conway, H., G. Catania, C. F. Raymond, A. M. Gades, T. A. Scambos, and H. Engelhardt (2002), Switch of flow direction in an Antarctic ice stream, *Nature*, *419*, 465–467.

Engelhardt, H. (2004), Ice temperature and high geotherm flux at Siple Dome, West Antarctica, from borehole measurements, *J. Glaciol.*, *50*(169), 251–256.

Engelhardt, H. (2005), Thermal regime and dynamics of West Antarctic ice streams, *Ann. Glaciol.*, in press.

Fahnestock, M. A., T. A. Scambos, R. A. Bindschadler, and G. Kvaran (2000), A millennium of variable ice flow recorded by the Ross Ice Shelf, Antarctica, *J. Glaciol.*, *46*, 652–664.

Gow, A. J., S. Epstein, and W. Sheehy (1979), On the origin of stratified debris in ice cores from the bottom of the Antarctic ice sheet, *J. Glaciol.*, *23*, 185–192.

Jezek, K. C. (1999), Glaciological properties of the Antarctic ice sheet from Radarsat: 1. Synthetic aperture radar imagery, *Ann. Glaciol.*, *29*, 286–290.

Joughin, I., and S. Tulaczyk (2002), Positive mass balance of the Ross ice streams, West Antarctica, *Science*, *295*, 476–480.

Joughin, I., L. Gray, R. Bindschadler, S. Price, D. Morse, C. Hulbe, K. Mattar, and C. Werner (1999), Tributaries of West Antarctic ice streams revealed by Radarsat interferometry, *Science*, *286*, 283–286.

Joughin, I., S. Tulaczyk, R. Bindschadler, and S. F. Price (2002), Changes in west Antarctic ice stream velocities: Observation and analysis, *J. Geophys. Res.*, *107*(B11), 2289, doi:10.1029/2001JB001029.

Joughin, I. R., S. Tulaczyk, and H. E. Engelhardt (2003), Basal melt beneath Whillans Ice Stream and Ice Streams A and C, West Antarctica, *Ann. Glaciol.*, *36*, 257–262.

Kamb, B. (2001), Basal zone of the West Antarctic ice streams and its role in lubrication of their rapid motion, in *The West Antarctic Ice Sheet: Behavior and Environment*, *Antarct. Res. Ser.*, vol. 77, edited by R. B. Alley and R. A. Bindschadler, pp. 157–199, AGU, Washington, D. C.

Kamb, B., C. F. Raymond, W. D. Harrison, H. Engelhardt, K. A. Echelmeyer, N. F. Humphrey, M. M. Brugman, and T. Pfeffer (1985), Glacier surge mechanism: 1982–1983 surge of variegated glacier, Alaska, *Science*, *227*, 469–479.

MacAyeal, D. R. (1992), Irregular oscillations of the West Antarctic Ice Sheet, *Nature*, *359*, 29–32.

MacAyeal, D. R. (1993), Binge/purge oscillations of the Laurentide ice-sheet as a cause of the North-Atlantics Heinrich events, *Paleoceanography*, *8*, 775–784.

Murray, T., T. Strozzi, A. Luckman, H. Jiskoot, and P. Christakos (2003), Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions, *J. Geophys. Res.*, *108*(B5), 2237, doi:10.1029/2002JB001906.

Parizek, B. R., R. B. Alley, and C. L. Hulbe (2003), Subglacial thermal balance permits ongoing grounding-line retreat along the Siple Coast of West Antarctica, *Ann. Glaciol.*, *36*, 251–256.

Price, S. F., R. A. Bindschadler, C. L. Hulbe, and L. R. Joughin (2001), Post-stagnation behaviour in the upstream regions of Ice Stream C, West Antarctica, *J. Glaciol.*, *47*, 283–294.

Retzlaff, R., and C. R. Bentley (1993), Timing of stagnation of Ice Stream-C, West Antarctica, from short-pulse radar studies of buried surface crevasses, *J. Glaciol.*, *39*, 553–561.

Smith, B. E., N. E. Lord, and C. R. Bentley (2002), Crevasse ages on the northern margin of Ice Stream C, West Antarctica, *Ann. Glaciol.*, *34*, 209–216.

Vaughan, D. G., and J. R. Spouge (2002), Risk estimation of collapse of the West Antarctic Ice Sheet, *Clim. Change*, *52*, 65–91.

Vogel, S. W., S. Tulaczyk, and I. Joughin (2003), Distribution of basal melting and freezing beneath tributaries of Ice Stream C: Implication for the Holocene decay of the West Antarctic Ice Sheet., *Ann. Glaciol.*, *36*, 273–282.

A. E. Behar, F. D. Carsey, and A. L. Lane, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA.

H. Engelhardt and B. Kamb, Division of Geological and Planetary Sciences, California Institute of Technology, MS 170-25, Pasadena, CA 91125, USA.

I. Joughin, Polar Science Center, Applied Physics Lab, University of Washington, 1013 NE 40th Street, Seattle, WA 98105–6698, USA.

S. Tulaczyk, Department of Earth Sciences, University of California, 1156 High Street, Santa Cruz, CA 95064, USA.

S. W. Vogel, Geology and Environmental Geoscience, Northern Illinois Univ., DeKalb, IL 60115, USA. (svogel@geol.niu.edu)