The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier

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[1] Observations from Ellesmere Island suggest that the connection between surface and subglacial drainage on a predominantly cold glacier is made abruptly by hydrologically-driven propagation of fractures from the surface to the bed. Where ice is 150 m thick, water ponded to a depth of 6.9 m within a supraglacial stream system before establishing a permanent bed connection. Multiple premonitory drainage events preceded the final drainage of ponded water, implying that fracturing is necessary, but insufficient, to establish a permanent link between surface and subglacial drainage. Refreezing of water that penetrates the first fractures to form may reseal the connection, while flow resistance within the subglacial system may delay the onset of continuous through-flow. A large volume of ponded water is required to enlarge fractures sufficiently by melting to maintain continuous drainage, while feedbacks between subglacial hydrology and ice dynamics may assist in maintaining the connection and initiating subglacial outflow. *INDEX TERMS:* 1827 Hydrology: Glaciology (1863); 1863 Hydrology: Snow and ice (1827); 9315 Information Related to Geographic Region: Arctic region. **Citation:** Boon, S., and M. Sharp, The role of hydrologically-driven ice fracture in drainage system evolution on an Arctic glacier, *Geophys. Res. Lett.*, *30*(18), 1916, doi:10.1029/2003GL018034, 2003.

1. Introduction

[2] Variations in the rate of surface meltwater delivery to the beds of temperate glaciers induce seasonal fluctuations in glacier velocity and shorter-term rapid motion events [*Iken*, 1972; *Iken and Bindschadler*, 1986]. Recently, seasonal velocity variations have been observed on the Greenland Ice Sheet in a region where ice is over 1200 m thick [*Zwally et al.*, 2002]. This suggests that surface waters can penetrate very thick ice at sub-freezing temperatures, reach the glacier bed, and affect rates of basal motion. The mechanisms by which penetration takes place, however, are not well understood. Here we present observations from a predominantly sub-temperate glacier on Ellesmere Island, which suggest that the penetration mechanism may involve water-pressure-induced ice fracturing.

2. Study Site and Methods

[3] John Evans Glacier (JEG) is a large valley glacier located at 79°40′N and 74°30′W, on the east coast of Ellesmere Island, Arctic Canada (Figure 1). It covers approximately 75% of a 220 km^2 catchment, and is 15 km long with an elevation range of 100–1500 m a.s.l. [*Skidmore and Sharp*, 1999]. Ice reaches a maximum thickness of ~400 m near the long-term equilibrium line (750 m a.s.l.). The glacier is cold-based in the accumulation area and at the glacier margins where ice is thin; basal ice reaches the pressure melting point over much of the ablation zone [*Copland and Sharp*, 2001]. Ice temperature at 15 m depth is recorded annually, and ranges from −15.1°C at 1173 m a.s.l. to −10.9°C in the area where observations were made (~615 m a.s.l.).

[4] The drainage system was monitored at the downstream limit of a 3 km long supraglacial stream where it enters the glacier via a crevasse oriented perpendicular to the stream (Figure 1). This location is 4 km from the glacier terminus, and the local ice thickness is ~150 m [*Copland and Sharp*, 2001]. A Druck 1830 pressure transducer connected to a Campbell Scientific CR10 datalogger was installed in the stream, 2 m from the crevasse, to monitor water level half-hourly from 1600 on 16 June, to 1730 on 21 July, 2002 (Figure 2). Additional observations were provided by thrice-daily time-lapse photography, and regular site visits.

[5] Meteorological variables were measured every ten seconds at a weather station located at 824 m a.s.l. (MWS, Figure 1), and hourly averages were recorded. A point-based energy balance melt model (EBM) was used to compute hourly rates of surface melt from these data (Figure 2) [*Brock and Arnold*, 2000].

[6] A linear reservoir model was used to simulate the role of the snowpack in delaying the transfer of melt calculated with the EBM to the supraglacial channel [*Oerter et al.*, 1981]. The results of a windowed cross-correlation analysis, and field observations of changing snowpack thickness and saturation, were used to generate temporally variable values of the model storage coefficient (k). Values of k were varied to obtain an optimum fit between normalized (by maxima) time series of modeled reservoir outflow, which drives water level (WL) change in a closed basin, and measured WL change (final $r^2 = 0.87$, $p = 0.95$). This approach maximizes the proportion of the variance in water level that is attributed to surface melt and runoff processes. The difference between the two standardized time series thus highlights events that may be attributable to other processes, such as drainage into newly-formed fractures.

3. Results

[7] When observations began on 16 June, water was flowing into the crevasse at the monitoring site (Figure 3a). Within three days, the crevasse had filled and meltwater had begun to pond within the stream channel. Water level continued to rise for 11 days, reaching a maximum of

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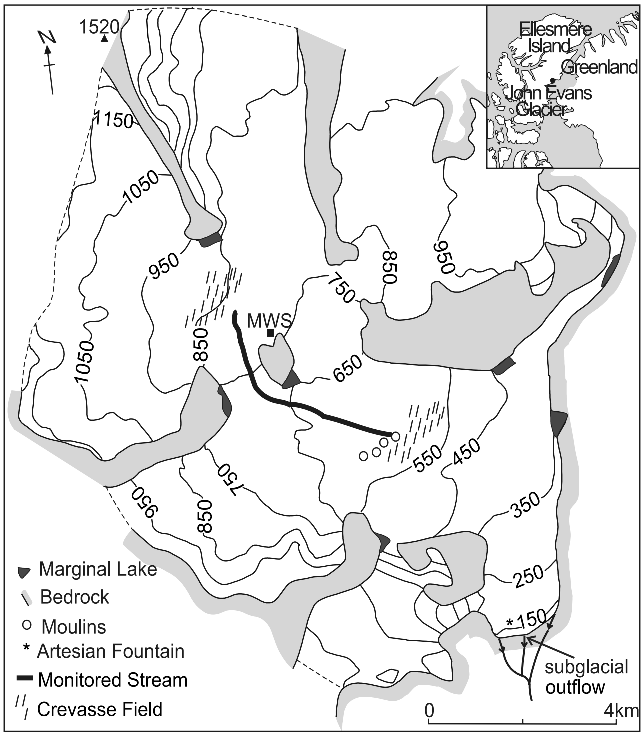

Figure 1. Location of John Evans Glacier (inset); location of monitored and adjacent crevasse/moulins (open circles), meteorological station (MWS), and artesian fountain (asterisk).

6.9 m above the channel floor and creating a pond that extended ~200 m upstream of the crevasse (Figure 3b). At this time, the snowline was at ~500 m a.s.l., and supraglacial streams were flowing on the lower glacier. During the period of ponding, crevasses at the pond margins widened by ~0.03 m. Deep cracking noises were often heard, and air bubbles were observed rising from fractures in the channel bed.

[8] The rate of measured WL change fell below zero on four occasions from 16–18 June, indicating that drainage was taking place (Figure 4). A plot of the difference between the normalized time series of modeled reservoir outflow and measured WL change identifies these same periods. It also identifies a further four periods between 19–23 June when the rate of WL change was less than expected given the modeled transfer of surface melt to the channel (Figure 4). This suggests the occurrence of eight events during which drainage was initiated, but not sustained.

[9] Starting at 0100 on 29 June, the monitored pond drained completely within one hour (Figures 2 and 3c). Following drainage, five fresh crevasses ~0.20 m wide and oriented perpendicular to the direction of water flow were observed (Figure 3c). Although they were not monitored continuously, similar drainage events occurred in three other supraglacial streams in the same area in the

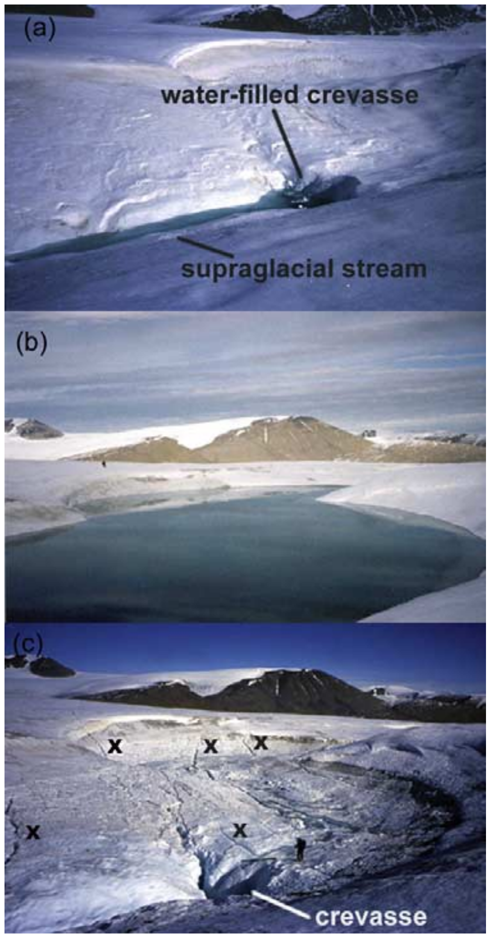

Figure 3. Sequence of crevasse development: (a) initial water-filled crevasse and supraglacial stream (16 June); (b) maximum fill depth (28 June); and, (c) following drainage (30 June). Fresh crevasses marked with an ‘x’.

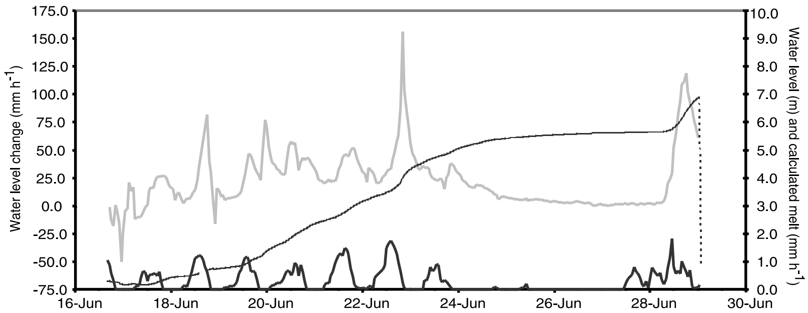

Figure 2. Water level (dashed black) and rate of water level change (grey) in the crevasse, and melt calculated with EBM (black). Note the magnitude of the final drainage event.

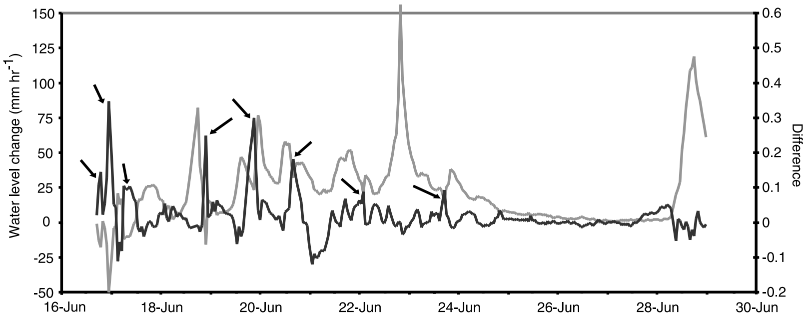

Figure 4. Rate of water level change (grey), and difference between standardized time series of reservoir outflow and water level change (black). Premonitory drainage events marked with arrows.

period 27–28 June. These four drainage events were followed at 1800 on June 30 by the appearance of a slightly turbid, solute-rich upwelling at the glacier toe (electrical conductivity (EC) = 0.065 S m^{-1}). Subsequently, an artesian fountain, also fed by solute-rich water (EC = 0.050 S m^{-1}), formed on the ice surface ~200 m from the glacier terminus at 0800 on July 1 (Figure 1).

4. Discussion

[10] Field data indicate that multiple, relatively abrupt, drainage events occurred while the crevasse was water-filled or overfilled. These events culminated in a major drainage event that established a permanent hydrological connection between the surface and subglacial drainage systems, and initiated subglacial outflow at the terminus. The abruptness of these events suggests hydrologically-driven ice fracture as the most likely means of drainage development. This is supported by the deep fracturing noises heard, the widening of existing crevasses during the ponding period, and the creation of new crevasses during the drainage event. The occurrence of ice fracture in this situation is consistent with the results of previous theoretical analyses of the process. They concluded that, so long as the tensile stress acting normal to the crevasse is $\geq$100 kPa, water-filled crevasses will penetrate to the glacier bed regardless of ice thickness or crevasse spacing within a crevasse field [*Van der Veen*, 1998].

[11] Our observation of multiple premonitory drainage events raises two significant questions: what limited the development of the first eight fractures into drainage connections, and why was a permanent drainage connection with the bed established during the ninth and final event?

[12] The development of the first fractures was likely initially limited by the elastic nature of the fracture process, which results in almost immediate closure of the fracture in the absence of an opposing force [*Van der Veen*, 1998]. These fractures would likely have been thin, with a large surface area to volume ratio, resulting in inefficient water penetration. As 15 m ice temperature measurements indicate that the fracture walls were likely at −5°C to −10°C, the first meltwater to penetrate the fracture may have refrozen on contact with this cold ice, re-sealing the fracture. Water that was able to reach the glacier bed may have experienced significant flow resistance within the subglacial drainage system, especially since dye tracing experiments indicate that this system had contracted substantially during the previous winter [*Bingham et al.*, 2003]. This would have slowed drainage from the fracture and reduced the rate of turbulent heating of water descending into the fracture, thus limiting the potential for fracture enlargement by wall melting and causing the fracture to re-seal by freezing.

[13] Eventually, however, fracturing allowed the development of a drainage system capable of transmitting a sustained flux of water. Several factors may have allowed this to happen. The release of latent heat from refreezing during the previous events would have warmed the ice walls, allowing water to penetrate deeper into the ice during successive fracture events. In addition, the continued filling of the surface pond increased the water pressure acting on the crevasse tip, making it easier for the fracture to penetrate to the bed [*Van der Veen*, 1998]. Surface ponding also increased the availability of water to drain into the fracture, thus increasing the potential for both turbulent heating of falling water, and rapid enlargement of the fracture through wall melt [*Nye*, 1976]. Thus fracture closure was no longer limited by the elastic response or refreezing, but by ice deformation, which was offset by both water pressure and turbulent heating.

[14] Successive episodes of water input to the glacier bed may have driven progressive development of the subglacial drainage system, reducing the resistance to surface inputs and allowing more continuous inflow. Water reaching the bed would have increased water pressures in the subglacial drainage system downstream from the crevasse, causing subglacial cavity growth and basal uplift, and reducing basal shear traction, resulting in local acceleration of ice flow [*Iken et al.*, 1983; *Kamb and Engelhardt*, 1987; *Kavanaugh and Clarke*, 2001]. The longitudinal velocity gradient and tensile stress in the vicinity of the crevasse would have increased, resulting in a feedback between crevasse widening, increased drainage of ponded water, and fracture enlargement due to wall melting. This is supported by ice velocity measurements from 2000 and 2001, which indicate that both horizontal and vertical ice velocities downstream of the crevasse region increased prior to major high velocity events in late June and early July [*Bingham et al.*, 2003]. These events were also associated with the drainage of water ponded on the glacier surface and the seasonal onset of subglacial outflow at the glacier terminus.

5. Conclusions

[15] Field observations of the seasonal development of a drainage connection between the surface and bed of a

predominantly cold glacier provide insights into the rapid response of cold glacier flow dynamics to changes in surface melt rate. Propagation of water-filled crevasses to the glacier bed seems to play a major role in seasonal establishment of the surface-bed connection, but is not the sole process responsible for establishing a sustained drainage connection.

[16] In temperate glaciers, fracture propagation alone may be sufficient to develop seasonal drainage, as ice is everywhere at the pressure melting point and water penetrating fractures is unlikely to refreeze. In cold glaciers, however, refreezing of percolating meltwater, which may be facilitated by flow restrictions in the subglacial drainage system, likely impedes drainage development along fractures. As a result, formation of a sustained connection is preceded by a number of premonitory drainage events. Warming of glacier ice due to initial refreezing events increases the likelihood of a permanent surface-bed connection developing during subsequent events. In addition, surface water ponding raises the water pressure at the crevasse tip; this stored water contributes to crevasse enlargement by wall melting when it eventually drains.

[17] Drainage may also be facilitated by a positive feedback involving ice flow dynamics. The rate of ice flow downstream from the fracture increases once water penetrates to the bed, increasing the tensile stress in the ice surrounding the fracture, widening the fracture and increasing water delivery to the bed. This mechanism likely plays an important role in the seasonal development of glacier drainage systems [e.g., *Flowers and Clarke*, 2000; *Bingham et al.*, 2003], provides a means by which the flow of large ice sheets may respond rapidly to climatically-induced changes in surface melt rates [e.g., *Arnold and Sharp*, 2002; *Zwally et al.*, 2002], and may also contribute to ice shelf break-up and tidewater glacier calving [*Van der Veen*, 1998; *Scambos et al.*, 2000].

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References

Arnold, N., and M. Sharp, Flow variability in the Scandinavian ice sheet: Modelling the coupling between ice sheet flow and hydrology, *Quat. Sci. Rev.*, *21*, 485–502, 2002.

Bingham, R. G., P. W. Nienow, and M. J. Sharp, Short-term variations in glacier dynamics in the ablation zone of a High Arctic polythermal glacier: Relation to seasonal changes in subglacial drainage system structure, paper presented at EGS/AGU/EUG Joint Assembly, Nice, France, 6 –11 April, 2003.

Brock, B. W., and N. S. Arnold, A spreadsheet-based (Microsoft Excel) point surface energy balance model for glacier and snow melt studies, *Earth Surf. Process. Landforms*, *25*, 649–658, 2000.

Copland, L., and M. Sharp, Mapping hydrological and thermal conditions beneath a polythermal glacier with radio-echo sounding, *J. Glaciol.*, *47*, 232–242, 2001.

Flowers, G. E., and G. K. C. Clarke, An integrated modelling approach to understanding subglacial hydraulic release events, *Ann. Glaciol.*, *31*, 222–228, 2000.

Iken, A., Measurements of water pressure in moulins as part of a movement study of the White Glacier, Axel Heiberg Island, NWT, Canada, *J. Glaciol.*, *11*, 53–58, 1972.

Iken, A., H. Röthlisberger, A. Flotron, and W. Haeberli, The uplift of Unteraargletscher at the beginning of the melt season - a consequence of water storage at the bed?, *J. Glaciol.*, *20*, 28–47, 1983.

Iken, A., and R. A. Bindschadler, Combined measurements of subglacial water pressure and surface velocity of Findelengletscher, Switzerland: Conclusions about drainage system and sliding mechanism, *J. Glaciol.*, *32*, 101–119, 1986.

Kamb, B., and H. Engelhardt, Waves of accelerated motion in a glacier approaching surge: The mini-surges of Variegated Glacier, Alaska, U.S.A., *J. Glaciol.*, *33*, 27–46, 1987.

Kavanaugh, J. L., and G. K. C. Clarke, Abrupt glacier motion and reorganization of basal shear stress following the establishment of a connected drainage system, *J. Glaciol.*, *47*, 472–480, 2001.

Nye, J. F., Water flow in glaciers: Jökulhlaups, tunnels and veins, *J. Glaciol.*, *17*, 181–207, 1976.

Oerter, H., D. Baker, H. Moser, and O. Rienwarth, Glacial-hydrological investigations at the Vernagtferner Glacier as a basis for a discharge model, *Nordic Hydrol.*, *12*, 335–348, 1981.

Scambos, T. A., C. Hulbe, M. Fahnestock, and J. Bohlander, The link between climate warming and break-up of ice shelves in the Antarctic Peninsula, *J. Glaciol.*, *46*, 516–530, 2000.

Skidmore, M. L., and M. J. Sharp, Drainage system behaviour of a high Arctic polythermal glacier, *Ann. Glaciol.*, *28*, 209–215, 1999.

Van der Veen, C. J., Fracture mechanics approach to penetration of surface crevasses on glaciers, *Cold Reg. Sci. Technol.*, *27*, 31–47, 1998.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen, Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, *297*, 218–222, 2002.

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