Englacial water flow in Storglaciären - year two

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Introduction

How does meltwater move through a glacier? Röthlisberger (1972) and Shreve (1972) proposed that an arborescent network of conduits are maintained by the frictional heating of the flowing water against the creep closure of the surrounding ice. However, the origin of such conduits had not been studied. Fountain and Walder (1998) proposed that englacial conduits form from water flow along the crevasse bottom, and melting their way down into the glacier. One implication of this hypothesis is that the conduits are orientated parallel to that of the local crevasses.

To test these theoretical notions, we used a hot water drill to penetrate the glacier and deploy a small underwater camera to directly observe and measure the geometry of the englacial conduits (Pohjola, 1994, Harper and Humphrey, 1995). To complete the hydraulic description of the conduit we measured its depth and pressure variations via changes in water level in the borehole. Previous work at Storglaciären by Pohjola (1994) indicated that conduits were tubular in cross section and associated with blue-ice inclusions. The latter suggests a refrozen crevasse. Because the borehole was drilled to the bed, pressure measurements inferred from water level changes in the borehole are suspect because of the potential hydraulic connection between englacial and subglacial water systems. Unlike previous studies, our boreholes were not drilled to the glacier bottom, but terminated at an englacial connection where we performed our studies. Thus, our results are not affected by hydraulic variations at the bed or elsewhere in the borehole. During July of 2001, a study of the geometry and hydraulics of englacial conduits was initiated on Storglaciären (Fountain, *et al*., 2002) as part of a companion study by Jacobel *et al.* (2002) to remotely detect the conduits. Our combined study was continued during the summer of 2002 and this paper presents our most recent findings of borehole experiments that included borehole videography, tracer tests, and water level measurements. A companion paper to this study in this volume by Jacobel *et al*. that summarizes the results of radar studies.

Our study was conducted in the upper half of the ablation zone on a flat area of the glacier. The flat surface is a result of an over-deepened bottom where a lake would form if the glacier were to recede. Storglaciären is a polythermal valley glacier and the cold surface layer in the ablation zone extends to depths of 20–60m. The glacier surface in the flat area is marked by structural features of alternating bands of clear and white ice that sweep across the surface in this portion of the glacier (Figure 2).

Methods

Holes were drilled in a 3 x 3 grid with each hole 10m from the adjacent hole. In 2002 we drilled 2 such areas, which complement 2 areas drilled the previous year (Figure 1). In some instances, holes were drilled outside the grid to search for englacial features indicated by radar reflections. A high pressure hot water system was used that melted holes into the ice. The nominal diameter is about 10 cm at the surface and the drill rate was approximate 1 m min^{-1}. While drilling in impermeable ice, the water level in the hole remained at the surface as excess water flowed on to the glacier. When the water level dropped below the glacier surface and remained below the surface despite continued

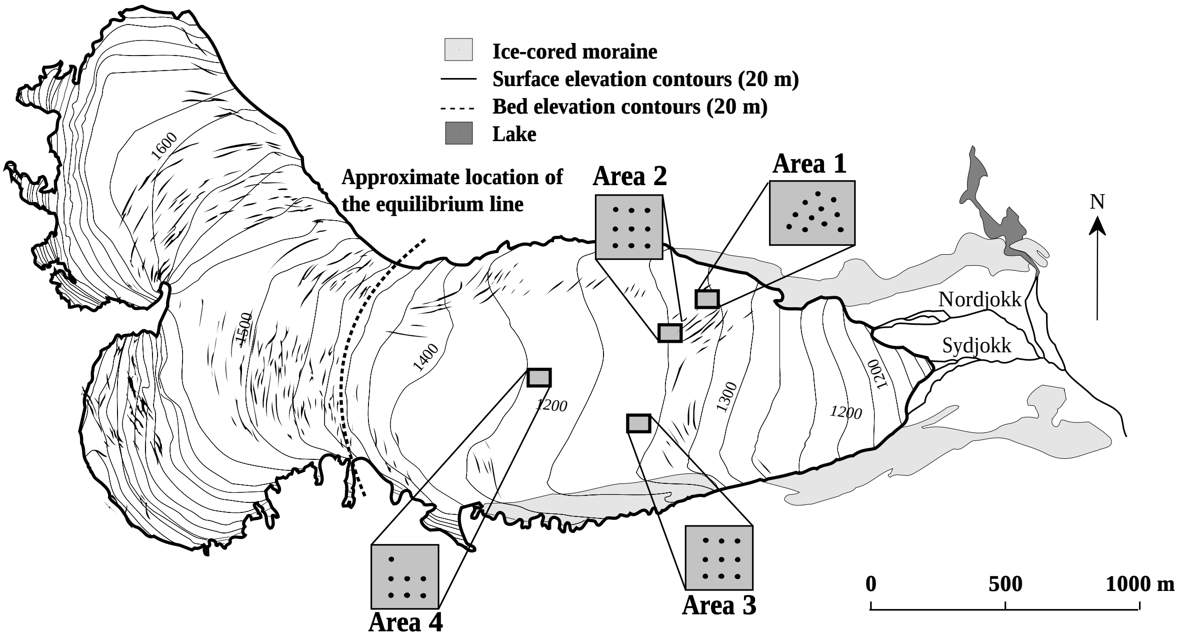

Figure 1. Location map of Storglaciären showing drilling areas.

drilling, we infer that an englacial connection was established. We often encountered isolated cavities where the water level dropped and after a few moments to a few minutes the water level rose to the surface again. When an englacial connection was made, drilling ceased, and we lowered an underwater video camera to visually inspect the drainage feature and measure its depth, size, orientation, and geometry. Water flow speeds were measured by observing deflection of dye and glass spherules; they were introduced adjacent to the englacial opening via vinyl tubing. Longer distance flow speeds were estimated using a salt solution, injected in a similar manner, and electrical conductivity measured in adjacent holes. Pressure transducers were placed in selected holes to monitor water level variation at 10 minute intervals.

Results

During the 2002, we drilled 17 holes, bringing the total to 39 boreholes drilled. Of these, 31 intersected englacial drainage features (79%). Nearly 3700 m of ice were drilled, resulting in an average of 1 drainage feature per 86 meters of ice. The physical appearance of the drainage features showed a steeply sloping and "crack-like" opening (Figure 2). Apparent crack width ranged from a few millimeters to 10 cm, but horizontal and vertical extent could not be discerned. The orientation of the near-surface drainage features was generally parallel to

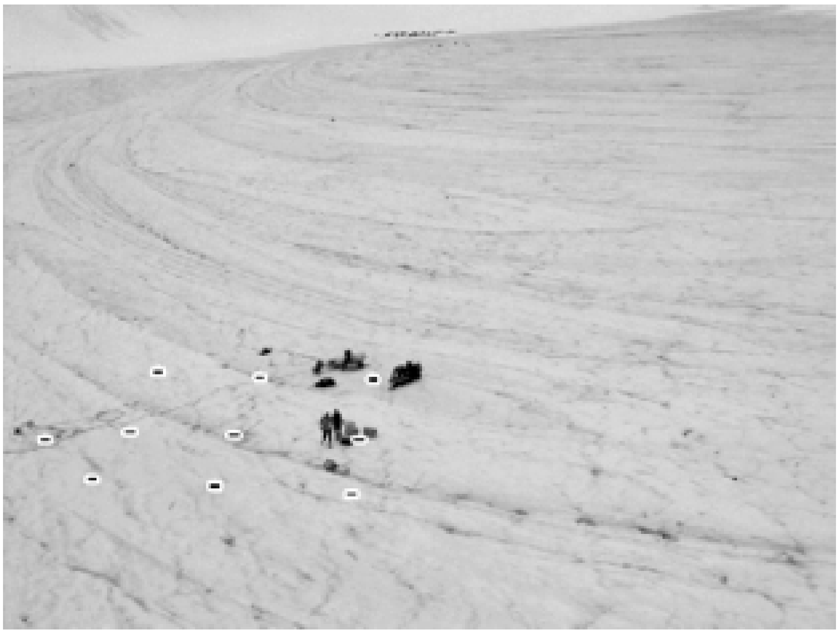

Figure 2. Surface of Storglaciären in the vicinity of drilling area 3. Approximate positions of boreholes are shown.

the structures on the ice surface and/or crevasses. At depth, the features were generally oriented perpendicular.

Video observation of dye and spherule injections indicated slight to no deflection. Flow speeds were slow, about 1 cm s^{-1}. In one case, 24 hours after initial injection of dye and spherules, the dye appeared in two adjacent boreholes suggesting that the holes were englacially connected, despite 10's of meters difference in depth of englacial connection. These observations prompted us to inject brine into one hole, while monitoring electrical conductivity levels in an adjacent hole. The results confirmed the dye and spherule deflection experiments that flow speeds were about 1 cm s^{-1}.

Water level measurements via pressure transducers corroborated the highly interconnected nature of the englacial drainage features. Figure 3 shows water level data from three holes at area 3. The depth of the feature in hole 32 is 129 m, in hole 311 it is 38 m, and in hole 39 the englacial drainage feature is 119 m. Note that they show practically the same water level indicating that they are most likely hydraulically connected. The water levels corresponded to 80–90 % of overburden pressure.

In two cases where we were directed to drill by the location of ice radar echoes, we encountered englacial features. In one case, we detected a drainage feature and in the other, we encountered an isolated cavity. For further discussion see companion article by Jacobel *et al*.

Discussion and conclusions

Based on the "crevasse-like" geometry of the observed drainage features, englacial conduits do not appear to behave in the manner that Röthlisberger (1972) and Shreve (1972) suggest. Meltwater enlargement by frictional heating of conduit walls does not appear to play a significant role in the englacial drainage pathways observed. This conclusion is further supported by the low flow velocities observed (1 cm s^{-1} or less). This is not to say that conduits do not form, indeed we are aware of a "classic" conduit at the margin of Storglaciären. Perhaps in the gently sloping ice where our field investigations took place, conduits do not readily form and instead water flows in many different passageways as suggested by Hooke and Hock (1993).

The structure of the englacial drainage features suggest relict crevasses – pre-existing crevasses, occupied by melt water. Their association with blue ice (clear ice) suggests that at least part of the crevasse has been refrozen (Pohjola, 1994). The source of the crevasses, whether advected from the accumulation zone or created in situ is unclear. The highly correlative water levels observed between various holes with vastly different englacial connection depths, and the observation of migration of dye from one borehole to numerous other holes englacially (within 10's of meters) suggests that the drainage features form a highly interconnected network of fractures. A simple calculation of laminar flow between parallel planes, a simplification of crevasse geometry, indicates that measured crack widths are an order of magnitude larger than required to match flow speeds. Perhaps the crack width narrows along the flow path and restricts the flow. Alternatively, the observed crack opening has been enlarged by the warm water created by the drill. Although both explanations may apply, we believe the latter to be more important in our situation since warm drill water has to escape from the borehole into the crack for us to observe a drop in water level. Furthermore, to confirm detection of an englacial feature we continue to drill and deepen the hole to be sure the water level remains low. Consequently, we continue to pump warm water into the crack for several minutes. Rough calculations show that the warm water can easily enlarge the crack opening to the observed widths.

Our working hypothesis for englacial drainage pathways is a network of direct "crack-like" openings reminiscent of crevasses. The relatively frequent encounters of these features during drilling, combined with the measured hydraulic characteristics, indicates a broad interconnected array of numerous thin fractures that serve to convey surface water to the bed of the glacier.

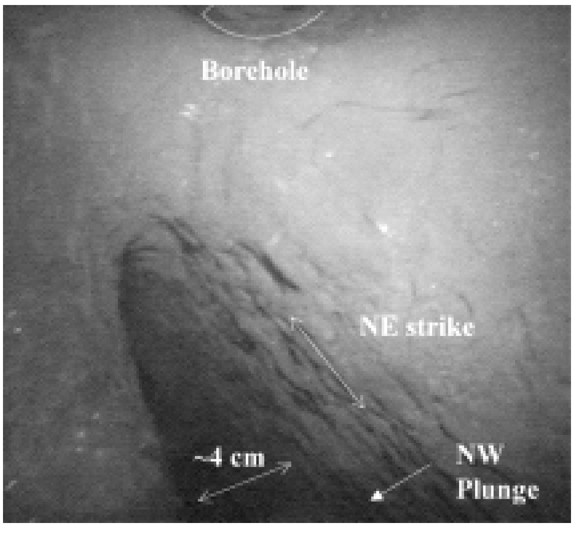

Figure 3. Picture of englacial drainage feature from borehole 311 at englacial connection depth of 38 m.

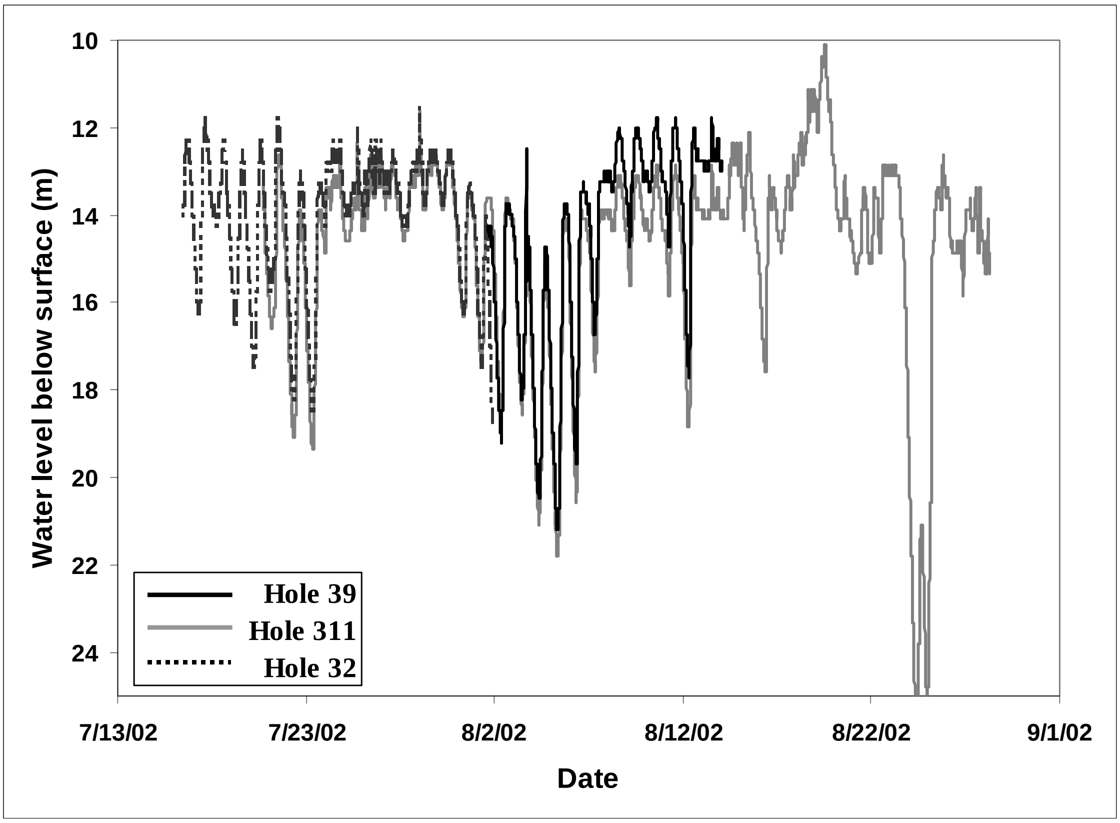

Figure 4. Water levels from 3 holes at area 3. Englacial connections depths are 119 m for hole 39, 38 m for hole 311, and 130 m for hole 32.

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