Studies of englacial water in Storglaciären using GPR - year two

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Abstract
This report describes the activities and preliminary findings of the second year of our project on Storglaciären during the summer of 2002. Ice penetrating radar studies were used together with borehole video and other down-hole experiments to investigate englacial water flow. The radar surveys together with the borehole experiments suggest a new model for englacial drainage, wherein crevasse-like features are the main conveyors of water and form a fracture-like network consisting of numerous pathways, rather than the traditional view of a few melt-enlarged conduits in ice.

Introduction

The flow of water during the summer melt season from the surface of a glacier to streams emerging at the terminus has been a problem of longstanding interest for glaciologists. A recent review of subject by Fountain and Walder (1998) proposed a model of englacial conduits that evolve from water entering crevasses and melting its way toward an equilibrium configuration of passages draining toward the bed. Previous studies of the problem have utilized a variety of techniques including dye/salt injections, borehole water pressure measurements, down-hole video and remote sensing with ground (ice) penetrating radar, GPR. In our study, GPR was used in conjunction with borehole video to investigate englacial water movement in the ablation area of Storglaciären. This paper describes the radar contributions to this study after the second year of field work. Results from the first year are reported by Jacobel *et al.*, 2002. A companion paper in this volume by Fountain *et al.*, details the results of the borehole experiments.

Storglaciären is a polythermal valley glacier in northern Sweden with an area of 3 km^2 (figure 1). It has a perennial cold surface layer in the ablation area that is 20-60 m thick (Holmlund and Eriksson, 1989). The cold layer is essentially impermeable to water, so surface water in this part of the glacier must enter through moulins or crevasses (Schneider, 1999). According to Östling and Hooke (1986), water storage is generally built up during late May to early June and is more or less constant from early summer to August. The present study was carried out during July, 2002 when englacial storage was likely high. The bed topography in the ablation area beneath Storglaciären is characterized by a riegel (transverse bedrock ridge) near the middle of the ablation area (Holmlund and Eriksson, 1989). Moulins develop in crevasses over the riegel admitting water from the surface in this part of the glacier. Up glacier from this area water is present in slush ponds and streams running over the surface extending back to the accumulation area.

During the 2002 field season on Storglaciären, radar experiments were again carried out with two radar systems: A low-frequency impulse radar transmitting pulses at 10 MHz was used to penetrate the full ice thickness to provide details of the bedrock topography in the study locations. Also a high-frequency RAMAC ground penetrating radar (GPR) transmitting at frequencies of 50 and 100 MHz was deployed in grid surveys of selected areas to locate and further investigate englacial water and possible conduits. All together 126 profiles covering approximately 17.6 km of surface travel were carried out in the 2002 field season, most of them in closely spaced grids coinciding with the borehole experiments. Radar profiles were processed in the field to give immediate feedback and

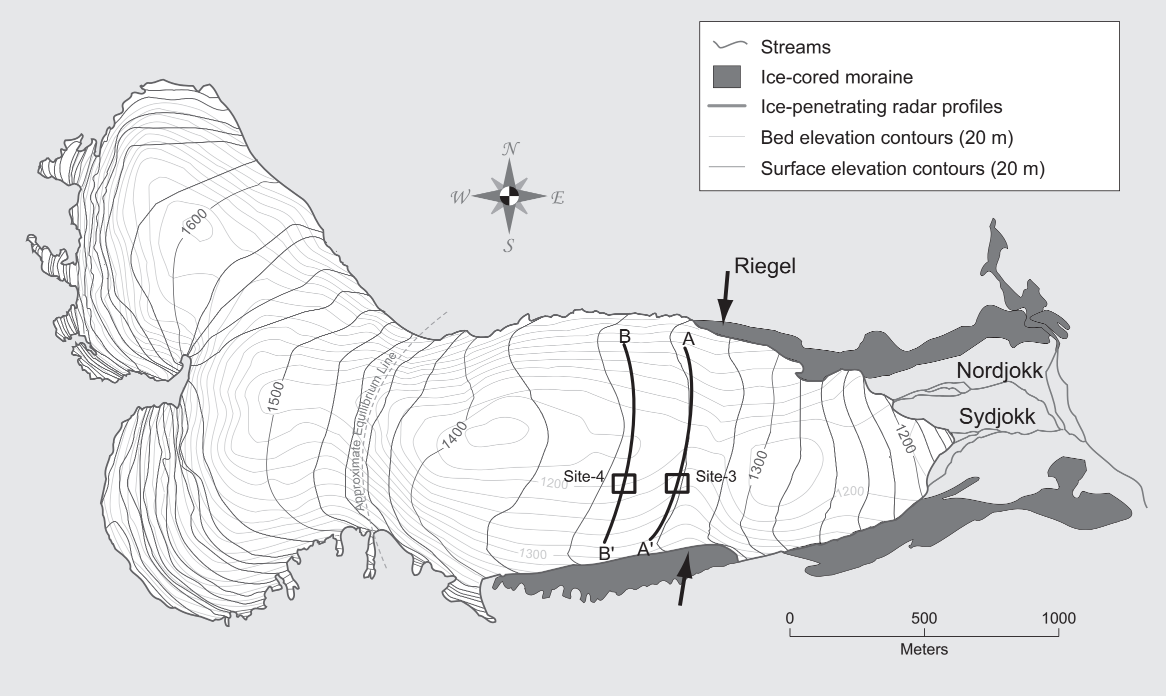

Figure 1. Map of Storglaciären (modified from P. Jansson, Stockholm University) showing surface and bed contours and locations of the cross-glacier profiles A–A' and B–B' as well as the two drill sites where extensive radar and borehole investigations were carried out.

guidance for further surveys. Figure 1 is a map of Storglaciären indicating the location of radar profiles discussed in the text below.

Deep Penetrating Radar

Figure 2 shows data from the cross-glacier radar profile A-A' (figure 1) acquired at 10 MHz. The profile is typical of results in the overdeepening above the bedrock ridge near where borehole studies were carried out in July 2002. Englacial echoes show the presence of water within the ice but individual water bodies are not well resolved at these frequencies, though the radar gives a fair depiction of their overall distribution. Radar at 5 or 10 MHz is an effective tool for imaging bedrock because it is relatively insensitive to shallow areas of ponded surface water and also to scattering from englacial cavities and channels, both of which make it difficult to penetrate deeper ice at higher frequencies.

Water in Nordjokk, the main subglacial drainage on the north side of the glacier shows up prominently near the margin of the glacier (right). The radar data have been migrated to correct for the finite antenna beamwidth and the bright echoes from the water are enhanced by the processing algorithm. A faint trace of the riegel (bedrock ridge) is seen between approximately 200 and 350 meters at an apparent depth of 225 meters. The ridge is off the axis of the traverse in the down-glacier direction and has a favorable geometry for returning energy to the broad beam antennas. Ice thickness decreases as the glacier flows over the riegel and its location is well-constrained by previous radar surveys, eg. Björnsson, 1981.

50 MHz Surveys

In the first part of the field season we carried out a number of large scale surveys with the 50 MHz radar to search for englacial cavities and to define the boundary between cold surface ice and temperate water-filled ice below. Figure 3 shows results from the cross-glacier profile B-B' in the overdeepening above the bedrock ridge near where borehole studies were carried out in July 2002. The radar data have again been migrated to correct for the finite antenna beamwidth. The cold layer (upper 20 to 40 meters) is characterized by the general absence of echoes in contrast to the warmer ice below where echoes from individual scattering sources are prevalent. These show up as hyperbolic diffractors in the unmigrated profiles indicating source sizes on the order of the wavelength of the radar, ~3 meters or smaller.

The surface cold layer of this polythermal glacier is essentially impermeable to water, so surface snow melt in the ablation area is present on the surface until it enters the ice through moulins or crevasses. This presents a challenge for high-frequency radar

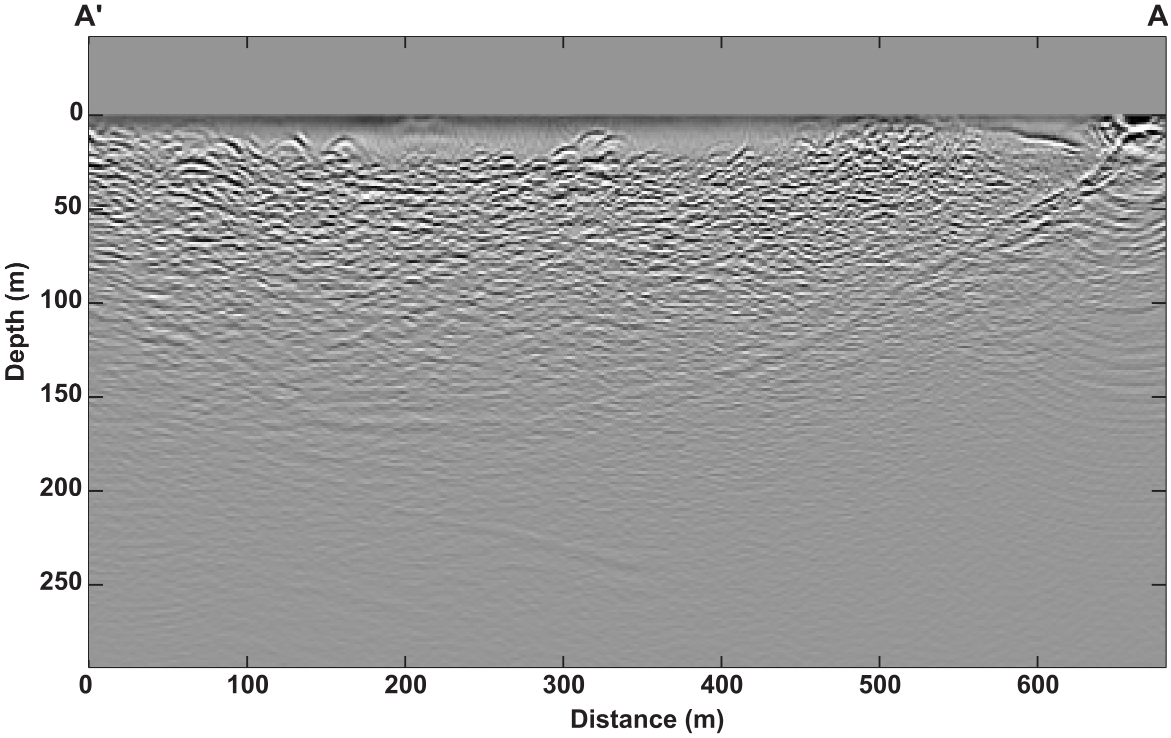

Figure 2. Cross glacier profile A–A' acquired at 10 MHz depicting the bed and the large-scale distribution of englacial water. View is up glacier with north at the right. The bright echo at approximately 690 m at the right is water in Nordjokk. The faint dipping echo below the bed at approximately 100–350 m is sideswipe from the lip of the Riegel.

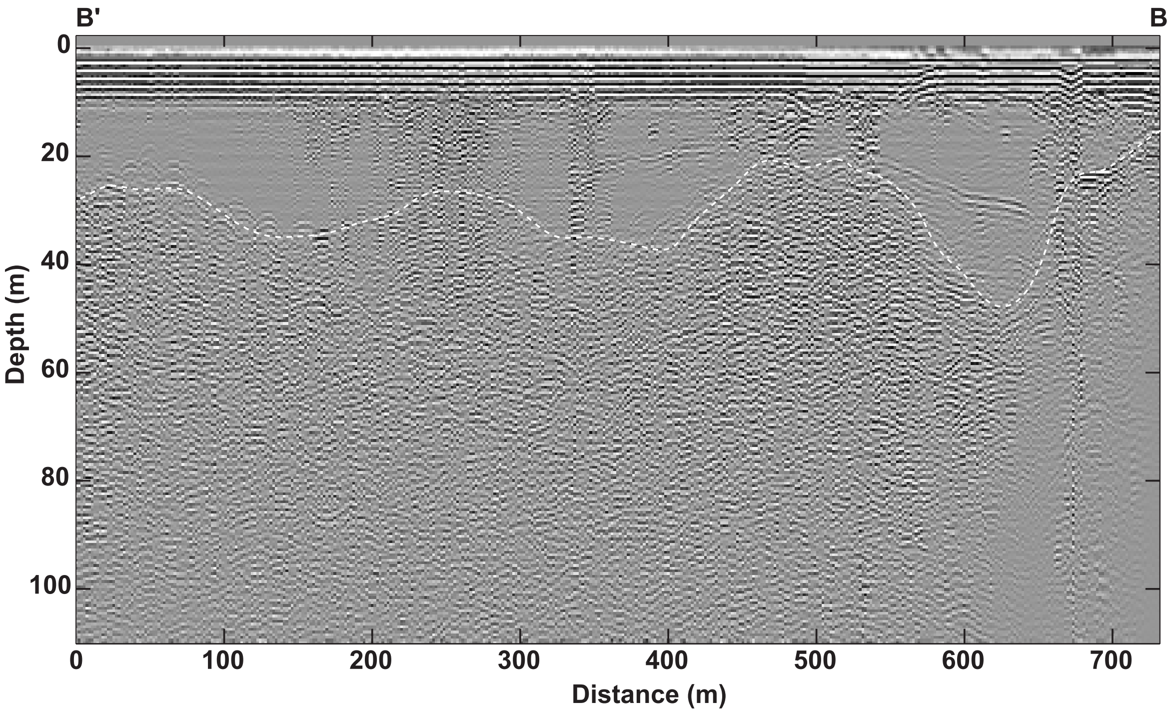

Figure 3. Cross glacier profile B–B' acquired at 50 MHz depicting the surface cold layer with relatively water-free ice and the temperate layer below with scattering from widely distributed englacial water bodies. A dashed line indicates the approximate lower boundary of the cold layer. Ponded water at the surface produces ringing in some locations, eg. between 200–300m, at 340m and between 450–500m. Bright echo near 690m and 25m depth at the right is water in Nordjokk.

attempting to image englacial reflectors because of the ringing that contaminates the upper portion of the record in several places. Nevertheless, in these surveys we identified two candidate sites with potential englacial water bodies for further characterization.

Englacial echoes in profiles like Figure 3 reveal the presence of copious amounts of water that is widely distributed throughout the temperate ice, but it is difficult to pick out extended channels. Nevertheless, unusually bright and sometimes extended echoes do appear occasionally. Based on the initial radar surveys, two areas were chosen to characterize further with radar and borehole studies. These areas are indicated by the boxes in figure 1.

Drill Site 3

Based on the radar surveys in 2001 and our early profiles done in 2002, two potentially promising locations were chosen to investigate with further radar and borehole studies (figure 1): Site 3 in the temperate ice near the valley center, just above the rigel near where a cavity was located in 2001 and, Site 4 in the overdeepened area approximately 200 meters up glacier from Site 3.

In each of these locations we carried out closely-spaced profile grids to locate more precisely the position and orientation of englacial water bodies in three dimensions. In this we have been aided by software developed in our lab that enables us to see glacier cross sections as frames in a ‘movie’, that depicts the location of bright reflectors. Site 1 was investigated with a series of grid studies oriented longitudinal, transverse and at several oblique angles to the ice flow direction at both 50 and 100 MHz. In each of these profile grids we found a prominent dipping reflector, originating at approximately 40 meters depth and localized to an area about 10 by 20 meters when projected onto the surface. This reflector is confined to the region of water-filled temperate ice below about 25 meters in this part of the glacier.

Figure 4 shows one of the radar profiles acquired at Site 1 at 50 MHz. The panel at the left was acquired before drilling began and the panel at the right after. Both reveal a sloping reflector between approximately 40 and 55 meters depth. The figure is scaled with a horizontal/ vertical aspect of 1:1 so that point diffractors will plot as hyperbolas with asymptotes at 45 degrees. The linear feature has a slope considerably less than this and therefore we believe it is an extended water-filled cavity dipping toward the center of the glacier. Additional radar profiles acquired at this site were used to estimate the strike and dip of the reflector in preparation for drilling. The dip

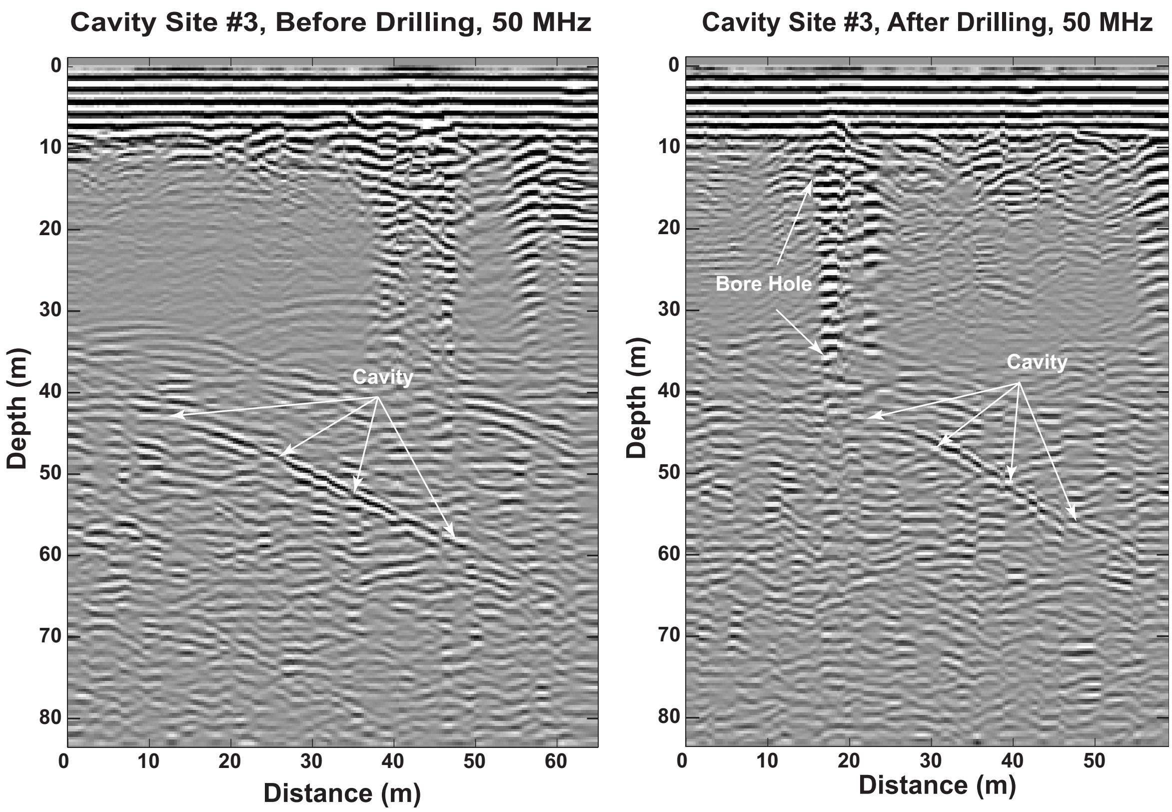

Figure 4. Radar profiles at 50 MHz depicting the englacial cavity at Drill Site #3. Panel at the left shows results before drilling. Panel at the right shows the borehole that intersected the cavity at approximately 38 meters.

and extended dimensions of the reflector suggested it was not a point-like object, but our attempts to determine its strike by measuring differences in the slope for different profile orientations on the surface gave ambiguous results. The one consistent result was that reflections were absent when the radar was located on the south side of the cavity, suggesting a roughly east-west strike and dip generally toward the glacier center to the north.

The first attempts to intersect the reflector with a series of boreholes were unsuccessful. Five boreholes were drilled approximately a meter apart to intersect the central part of the reflector in the brightest part of the slope (approximately at 35 m in figure 4). None of these made an englacial connection. A closer inspection of figure 4 suggests that the reflector might have its shallowest point several meters to the south (left) of the bright sloping flank at approximately 37 or 38 meters, though the echo is not very bright there. If an englacial water body in that location were oriented roughly east-west and dipping roughly to the north, this geometry would account for the fact that no energy could be detected by the radar when it was south of the shallowest point, that is in the left part of the profiles shown in figure 4.

With this hypothesis in mind, our colleagues drilled a single borehole 5 meters south of the previous holes near the top of the sloping echo and intersected an englacial water-filled cavity at 38 m depth. The water in this borehole drained immediately after the intersection, indicating a connection to the englacial water system of the glacier. Figure 4 (right) is a radar profile in the same location as figure 4 (left) shortly after the borehole connected to the cavity showing the relationship of the borehole to the cavity. Ringing in the upper portion of the records is produced by water at the surface.

Video studies of the borehole in the vicinity of 38 meters showed a narrow and elongated crack dipping toward the north or northwest. Subsequently two additional holes were drilled, approximately one meter to the north and one meter northwest. Both intersected the same cavity and borehole video studies indicated a crevasse-like structure aligned roughly northeast-southwest and dipping toward the northwest. A still image from the borehole camera (figure 5) reveals an oblate opening about 0.5 meter long and 4 cm across. Hydraulic tests in the borehole show very slow water flow speeds as discussed by Fountain *et al.* in this volume.

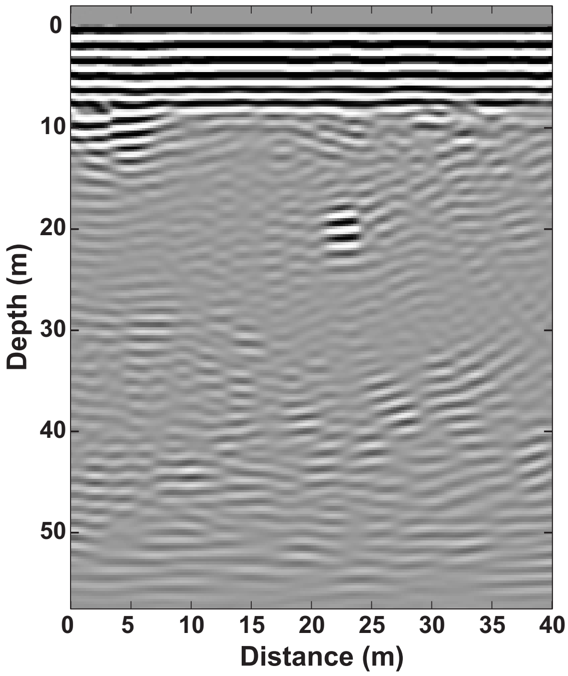

Figure 5. Borehole camera image showing the opening of the cavity detected by the radar.

Drill Site 4

Figure 6 is one of the 50 MHz radar profiles at Site 2 showing a cavity about 20 meters below the surface. This bright echo was present in both longitudinal and transverse profiles near the center of the grid and detailed surveys were carried out with the 50 MHz radar to determine its location to within a meter or so. A borehole was drilled at this location and intersected a cavity at 20 meters depth. Hydraulic tests and imagery from the down-hole camera revealed this to be an isolated cavity on the order of a meter in size and not connected to the rest of the englacial water system. The radar profile has been migrated to correct the hyperbolic signature typical of near point-like objects illuminated from the surface.

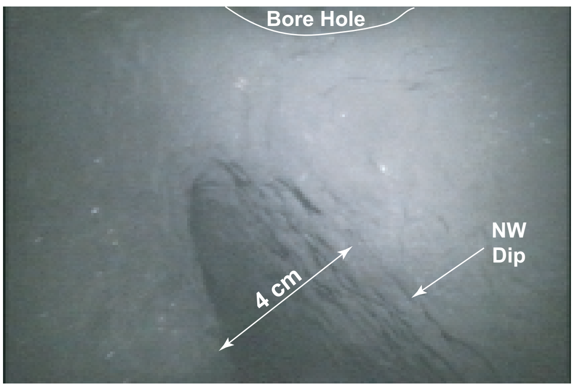

Figure 6. Radar profile at 50 MHz from Drill Site #4. An isolated cavity at approximately 20 meters depth is seen clearly within the cold layer of the glacier.

Discussion and Conclusions

Our findings this season confirm and enhance the picture that began to emerge after our first year at Storglaciären. At all frequencies we used in this study, the radar shows returns from copious amounts of water from widely dispersed englacial scattering sources within the temperate layer of the glacier. This distribution seems to be confirmed by the high success rate of intersecting water bodies with the borehole drill (Fountain *et al.*, this volume). Radar at 50 MHz also seems to be particluarly well suited to depicting the thickness of the surface cold layer in this polythermal glacier. Water from snow melt at the surface produces ringing that is an impediment to acquiring clutter-free images of deeper reflectors, but reasonable results can still be obtained by selecting sites clear of slush and running water for more detailed studies.

Radar at 50-100 MHz appears to be an appropriate tool for studying individual englacial water bodies. Our radar surveys showed that success in imaging englacial water bodies from multiple positions on the surface in order to locate them spatially depended on object size and orientation, as would be expected for an extended reflector and particularly for one with complex geometry. Like radar surveys on many glaciers, we often detected reflectors in single profiles that could not be imaged from multiple orientations of the radar, and thus not located precisely. Likewise, the borehole drill intersected a number of water-filled channels that were not prominent in the radar records, most likely because of unfavorable geometry or orientation. This result confirms the difficulty of imaging and locating small objects with a broad beam antenna. At the same time, the correspondence between borehole and radar results in those cases where a cavity and a crack-like channel were located by both methods provides a "ground truth" for the remote sensing and shows the utility of the technique.

The radar surveys together with the borehole experiments suggest a new model for englacial drainage, wherein crack-like features are the main conveyors of water and form a fracture-like network consisting of numerous pathways, rather than the traditional view of a few melt-enlarged conduits in ice. We look forward to extending our conclusions to make the picture more quantitative using additional results from the radar, some of the hydraulic tests and modeling studies.

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