Characterization of the englacial and subglacial drainage system in a high arctic cold glacier by speleological mapping and ground-penetrating radar

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Research Interests

- Response of debris covered glaciers to recent climate change, with particular reference to glacier lake outburst flood risk
- Dating and climatic implications of former glacier margins in the Everest region, Nepal and Tibet
- Precambrian glacigenic successions: implications for the Snowball earth hypothesis
- The palaeoclimatic implications of glacier fluctuations
- Modelling calving and dynamics of water-terminating glaciers

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Jason is primarily interested in understanding self-organizing hydrological systems in glaciers and ice sheets, as well as in carbonate aquifers. His research methodologies bridge the fields of geomorphology, physical hydrology and aqueous geochemistry.

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Heidi is a Postodoctoral Research Fellow in glaciology at the University of St Andrews, Scotland. In 2015, she was recently awarded her PhD by the University of Oslo, although she spent the 4 years of her thesis living and working on the archipelago of Svalbard, in the Norwegian Arctic. Her passion for glaciers stems from her childhood spent hiking up and down mountains in the French Alps. Before focusing on glaciology, her studies in geography and geology would take her to Annecy (France) and Aberystwyth (Wales, UK).

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Abstract

This paper presents new data obtained by speleological surveys and ground-penetrating radar (GPR) on a cut-and-closure conduit in Scott Turnerbreen, a small cold glacier in Svalbard, Norwegian Arctic. We use these data to propose criteria for the identification of cut-and-closure conduits from GPR data. In addition, we describe subglacial and englacial structures exposed in the conduit, which shed light on the former dynamic behaviour of the glacier. The glacier bed consists of a thick layer of subglacial traction till, from which till-filled fractures extend upward into the ice. These observations show that Scott Turnerbreen was formerly warm-based, and are consistent with a surge or surge-like behaviour. The channel system was also imaged using ground-penetrating radar. Varying channel morphologies have distinctive signatures on GPR profiles, allowing the identification and mapping of englacial drainage systems in situations where direct access is impossible.

Key words: englacial/subglacial drainage, glacier hydrology, ground penetrating radar, surge, basal crevasses, Svalbard

Introduction

Until recently, it was believed that the penetration of surface meltwater into deeper levels on cold and predominantly cold glaciers was very limited and also that such glaciers lacked complex englacial and subglacial drainage systems (Hodgkins, 1997; Fountain et al., 2005). It is now recognized, however, that surface-to-bed drainage can occur through cold ice by two distinct mechanisms (Gulley et al., 2009a; Irvine-Fynn et al., 2011). First, hydrologically-assisted fracture propagation or hydrofracturing can occur where stressed ice coincides with a sufficient water supply, and can allow water to access glacier beds through great thicknesses of cold ice (Boon and Sharp, 2003; Das et al., 2008; Benn et al., 2009a). This process has received considerable attention, because it shows that climatic signals can directly influence glacier dynamics (e.g. Hoffman et al., 2011; Zwally et al., 2002). The second process, described as the incision of surface streams followed by roof closure ('cut-and-closure'), can form low-gradient englacial conduits that can in some circumstances reach glacier beds, even where the basal ice is cold (Gulley et al., 2009b; Naegeli et al., 2014). Although this process has received less attention than hydrofracturing, cut-and-closure conduits are probably widespread, and may be the predominant form of drainage on many polythermal and cold glaciers (Gulley et al., 2009a; Benn et al., 2017). The possibility that perennial channels can occur at cold glacier beds has implications for the hydrological and geomorphological activity of high Arctic glaciers. Surface meltwater can be stored in cut-and-closure channels and released during the winter months, leading to accumulation of proglacial icings. The presence of such icings, therefore, does not necessarily imply the presence of warm-based ice (Hodgkins et al., 2004; Baelum and Benn, 2011). In addition, mechanical and chemical erosion can occur in subglacial cut-and-closure channels, contributing to the sediment yield from cold-based glaciers (Yde et al., 2008).

On several polythermal glaciers, the presence of englacial channels has been inferred from ground-penetrating radar (GPR) data (e.g. Jacobel & Anderson, 1987; Kennett, 1989; Moorman and Michel, 1998, 2000; Arcone and Yankielun, 2000; Stuart et al, 2003; Baelum and Benn, 2011), although in most cases the conduit-forming process is not known.

This paper presents data obtained by speleological surveys and ground-penetrating radar (GPR) on a cut-and-closure conduit in Scott Turnerbreen, a small cold glacier in Svalbard, Norway. We use these data to propose criteria for the identification of cut-and-closure conduits from GPR data. In addition, we describe subglacial and englacial structures exposed in the conduit, which shed light on the former dynamic behaviour of the glacier.

Study area

Scott Turnerbreen is a 4.5 km long valley glacier, situated at 78°07'N, 15°56'E in central Spitsbergen, 15 km southeast of the town Longyearbyen (Fig. 1 and 2). It faces towards the northeast, extending from 968 to ca. 200 m altitude. The proglacial area is characterized by a ca. 500 m broad zone of moraines, which in upflow direction pass into sediment covered glacier ice. In our study area the glacier was up to 63 meters thick, composed entirely of cold ice, and is dynamically inactive with maximum measured surface velocities of 0.48 m a^{-1} (Hodgkins et al., 1999). The glacier has undergone considerable retreat and thinning since mapped by Norsk Polarinstitutt in 1936, at which time it was probably warm-based (Hodgkins et al., 1999). According to Liestøl (1993), the glacier surged around 1930, and this interpretation is supported by sedimentary structures exposed on and around the glacier (Sletten et al., 2001). In 2008, the mean annual air temperature at 400 m a.s.l. in the catchment area was -9.2°C, based on extrapolated values from Svalbard airport, 19 km northwest of the glacier. The monthly mean air temperature is only positive in July and August, while glacier meltwater is released at the terminus two to three months a year (Lønne

& Lauritsen, 1996). Two main melt streams emerge from the glacier, one on each side of the tongue. The eastern stream has supraglacial, englacial and subglacial reaches, and forms the focus of this study. The englacial reach of the channel has a clear surface expression in summer, in the form of meandering lines of old snow and chains of gravel and dirt cones. Several holes in the snow allow the active meltwater channel to be observed at depth. In the winter months, some of the holes are utilized by local tour operators to gain access to the channel. We used one of these entry points (78°06'188''N and 15°56'119''E at 429 m a.s.l.) in the ablation zone on the upper part of the glacier to gain access to the channel.

Methods

The channel system (hereinafter referred to as 'the conduit') was investigated using speleological mapping and surface ground-penetrating radar (GPR) surveys. The speleological survey was conducted using standard cave mapping techniques modified for glaciers (Gulley and Benn, 2007). A series of stations was established on the conduit walls, and running surveys conducted using a compass, clinometer and Leica Disto laser rangefinder. The distances were measured to the nearest mm using the Distomat, while angles (vertical and horizontal) were to the nearest degree. Additional sources of error include positioning of handheld instruments at the survey points. The survey was not closed, so there is no independent check on survey accuracy. Overall, estimated precision of survey point position is in the range ±5 cm. The errors should be random, not systematic, so should not be additive over the length of the survey. The survey lines were then used as the basis for detailed drawings of the conduit in plan and long profile. In addition, conduit cross-sections were measured and drawn for most parts of the system.

GPR surveys were conducted on the 29th and 30th of March 2009 using a Malå ProEx system with 25, 50 and 100 MHz Rough Terrain Antennae with an in-line configuration. A higher frequency leads to finer resolutions but also to a decrease of the depth to which the signal can penetrate (Reynolds, 1997). As the reflections turned out very clearly in the images little processing was needed. In the radargrams the traces are plotted against two-way travel time which is converted into depth. All data were collected before the start of the melt season which would promote surface-antenna coupling that remains as constant as possible (Copland and Sharp, 2000). The radar profiles (fig. 3) cover the region from the entrance downglacier up to the end of the englacial survey line (fig. 4a). Profiles were recorded parallel and transverse to the conduit system on foot with a constant walking speed of 2 to 3 km/h, and a data recording frequency of 0.5 s^{-1}. A trace was sent every 0.3 to 0.4 m. The propagation of radar waves through glacier ice could not be measured directly due to the configuration of the antennae, but instead a fixed velocity of 0.17 m ns^{-1} was assumed for time-depth conversions. This value is considered to be appropriate for cold ice in Svalbard (Baelum and Benn, 2011). The effect of surface snow or firn was not taken into account, because the conduit was entirely in the glacier ablation zone, where glacier ice was directly overlain by a thin (< 1 m) snow cover at the time of the surveys.

Results and interpretation

Conduit survey

The surveyed length of the conduit was 2029.6 m (1998m horizontal length). From the entrance, 1285.8 m were surveyed downglacier (A-stations) and 701.2 m were surveyed upglacier (B-stations). Between station A34 and A35 a sidechannel was found, with a total length of 42.6 m (C-Stations) (Table 1 and Fig. 4). Progress was blocked both at the upper and lower ends by snow and ice filling the passage, so the total length may have been a few hundreds of metres greater. The conduit had a strongly meandering planform with a sinuosity index of 3.4. The only parts of the channel which are relatively straight were observed in the upper part of the conduit between stations B26 and B36 and at the end of the channel between stations B69 and B81. The formation of straight passages can be explained by high flow velocities which induce a high rate of heat release to the conduit walls, and therefore eroding both the inner and outer bends of the meanders so that straightening dominates over meandering. The total elevation difference of the surveyed conduit was 104.1 m, with a mean gradient of 0.05. In detail, however, the gradient of the conduit floor was highly variable, with long, gently sloping sections interspersed with steep and also vertical steps. For much of its length, the passage had a narrow canyon-like morphology, with a ceiling of snow or refrozen meltwater (aufeis). The maximum measured ceiling height was 19 m at station A120. In the straight sections, the conduit walls were close to vertical but at the meander bends the walls were inclined, with an overhanging wall on the outside of the bend and a sloping wall on the inside. Several more restricted passages were found, where the upper parts of the conduit were blocked by masses of icicles.

At the end of the upper part of the cave (from station B81 to B71) a huge amount of snow was found, covering the roof, the walls and the floor. In this part and further downglacier (B81-B60) five smaller nickpoints less than two meters high had to be climbed. Here the passage walls were relatively narrow with a ceiling height of seven to eight metes. From Station B81 to B61 refrozen meltwater was common along the walls. A 6 m high vertical nickpoint was found between station B60 and B58. In March 2009, between stations B60 and B59, a section of the conduit wall collapsed, depositing large blocks of ice on the floor (Fig. 8 and 9). According to our field observations these collapses appear to have been happening repeatedly for several years. If no other englacial route was available, such blockages could have led to a rerouting of the water back to the surface resulting in the formation of a new supraglacial stream that will incise again and eventually possibly evolve into a new englacial channel. Such collapses followed by the rerouting of water explain the existence of abandoned meltwater channels underneath the original conduit as it is the case underneath stations A153 and A154. As the conduit was not completely blocked by the collapse at station B59 it is unlikely that a new channel will develop there, though future collapses might cause a rerouting of water. Collapses can result from structural weaknesses in the ice, fluvial erosion or gravitational collapses of the conduit roof. The highest ceiling heights of the upper part occur at stations B57-B55 with up to 18 m. At stations B58 and B55 and between B50 and B41 gravel was found. Between the stations B58 and B57 the channel was blocked with collapsed blocks of ice from a height of approximately 2 m to the top of the cave (Fig. 6 and 7). It is obvious that the stream made a new path under the blocks. In some places, the passage was bridged by horizontal layers of ice ('false floors'), marking former levels of standing water (Fig. 5). False floors typically form at the end of the melt season when the water inside the channel partly froze and partly ran off. One of those false floors occurred between B54 and B53. The absence of ice blocks on the floor suggests that they have been evacuated by fluvial transport. A plugged canyon morphology was observed from station B58-B47. No evidence for creep closure like in Longyearbreen (Gulley et al., 2009a) was found. Continuing further downglacier the ceiling height increased and icicles (B30-B21) and hoarfrost (B20-B18) were found on the upper parts of the walls. Between station B17 and B15 gravel was found inside the glacier ice. In this part of the cave the ceiling height was alternating between one and ten meters.

Looking at the lower part of the conduit (A-stations) the ceiling height is usually a lot higher than in the upper part. From stations A2 to A6 the roof and parts of the walls were snow covered. The channel was slightly dipping downglacier up to a vertical nickpoint of 7 m after station A10. In the lower part 4 big nickpoints of up to 10 meters high interrupted the otherwise straight or slightly dipping channel, namely between the stations A10 and A11, A39 and A40, A44 and A45 (Fig. 10) and A45 and A46. Six smaller nickpoints of about 1-3 m were found close to the bed between the stations A152 and A157. In this part at the end of the cave (A133-A161) ceiling heights of more than 10 meters were common. At station A160 after 1260.8m horizontal length (1285.8m channel length) from the entrance, the conduit reached the glacier bed (Fig. 11). A height difference of 66.3m was covered. The bed was about 30m below the surface (at the entrance the survey started 6m below the surface). The bed consisted of crudely sorted bouldery gravel. The conduit walls were generally vertical, but in several places were deeply undercut by horizontal notches formed by lateral migration of the stream. The conduit terminated in a vertical suture filled with frozen snow. Frozen till up to ~1 m thick was exposed at the base of the passage walls (Fig.12), from where narrow bands of till extended upward for several metres (Fig. 13). No liquid water was observed, neither in the englacial channel, nor to the glacier bed.

GPR profiles

The drawings of cross-sections made inside the cave were then compared to the GPR data collected on the glacier surface over the conduit. GPR does not give us a clear cross-section of the subsurface but detects materials that have different dielectric properties to that of the host medium, and therefore we are able to detect the conduit. But we can not get exact information on its dimensions and shape (Reynolds, 1997). Therefore we are comparing the radargrams to the detailed mapping to investigate the response of radar waves to different conduit shapes.

In all these radargrams we do not identify a noisy response that warm ice would typically yield. Cold ice prevails all the way to the glacier bed.

Figure 14 shows a radargram collected with a 25 MHz antenna, along a 260 m long profile extending downglacier from the cave entrance, following the conduit (see profile 87 in Fig. 3c). Only with the 25MHz antenna we were able to reach the glacier bed over the whole length of our survey line because a lower frequency leads to an increase of the depth to which the signal can penetrate. The thermal structure of the glacier appears to be relatively homogenous over this study area, apart from the anomalies formed by the conduit and debris. The series of shallow hyperbolae (arrow a) show where the radar waves detected a reflector that we interpret as being the englacial channel. Due to the conical propagation of radar waves, the channel is detected even when the instrument is not directly over it. The strong continuous reflector marked by arrow b is interpreted as being the glacier bed lying 65 m under the surface at the beginning of this profile and 50 m at the end. The bed is a relatively plain reflector and does not show as many changes in geometry as the englacial channel, thus it appears as an almost straight line and not as hyperbolae in the radargram.

Figure 15 shows a comparison of the mapped conduit cross-section at station A1 and the corresponding radargram collected over the same section. The top of the conduit was mapped ~6 m below the surface. Its cross-section is of tubular shape with a maximum height of 1.45 m and a maximum width of 1.08 m. The conduit is clearly picked up by the radar waves in the form of composite hyperbolae focused around the same reflector (arrow a). The glacier bed is clearly visible at about 63 m below the surface (arrow b). The vertical reflection pattern (arrow c) left of what we interpret as englacial conduit was caused by a metal dog chain on the surface, which was crossed during the survey. Apart from the reflections caused by this object and the channel no other diffraction patterns were observed, so it can be assumed that the glacier ice is quite homogenous in this location and no water bodies or other voids were detected.

At station A134 the conduit consisted of an inclined canyon 9.2 m high, with the floor 12.5 m below the surface (Fig. 16, arrow a). The glacier bed at this location is ~35 m below the surface, and slopes down towards the north-west (arrow b). On the radargram, a very prominent set of englacial reflectors coincides with the mapped position of the englacial conduit. The diffraction patterns consist of stacked, slightly offset hyperbolae, that we believe are due to radar waves bouncing on the sloping walls. The conduit has a canyon-like morphology, thus the diffraction patterns are not as clear as in the case of a simple tubular passage. 25 m south east of the channel a second diffraction pattern generated by a point-source reflector (possibly debris) is visible (arrow c).

In Figure 17, the radar profile crossed the englacial channel twice, 8 m apart.. The diffraction hyperbola on the left (arrow a) represents the conduit at station A154 with a height of 5.7 m. At station A153 (arrow b) which was crossed further upglacier, the channel becomes taller (10.9 m). The diffuse and orderless diffraction patterns are what would be expected for a canyon-like morphology of the conduit where the walls are not completely vertical. As the distance between the stations is only of 8 m they do not turn out clearly and the image is rather ambiguous, as expected for a resolution of 25 Mhz. The strong reflector made of several hyperbolae peaking at a depth of 30 m is interpreted as the bed (arrow c). The change in reflection pattern to that of Figures 16 could be the result of a change in bed lithology (presumably till) and topography. Between the known conduit position and the glacier bed a set of stacked hyperbolae is visible (arrow d). This feature represents most likely an old, abandoned conduit below the level of the actual channel. The old conduit has probably been blocked by aufeis accumulation or creep closure. Thus the water backed up to the next available pre-existing outlet leading to an upward rerouting of the channel.

Discussion

Processes of conduit formation

The morphology and planform of the conduit are typical of a formation by 'cut-and-closure' processes (cf. Gulley et al., 2009a) (Fig. 18). Key characteristics include: a meandering planform; a generally low gradient punctuated by steep steps or nickpoints; a narrow, canyon-like morphology; and the presence of snow plugs in the ceiling visible on the glacier surface.

For most of its length, the conduit was englacial but the lowermost part (downstream from station A157) was incised into the glacier bed. This subglacial reach appears to be a stable feature of this conduit in Scott Turnerbreen, which was observed for several years in succession. Gulley et al. (2009a) argued that deeply incised sections of cut-and-closure conduits are very susceptible to blockage by ice creep and aufeis accumulation, in which case water tends to be re-routed at a higher level within the glacier. For example, a subglacial reach of cut-and-closure conduit formed ~30 m below the surface of Longyearbreen between 2001 and 2003, but was abandoned following a blockage in 2004 (Humlum et al., 2005; Gulley et al., 2009a). The persistence of the subglacial reach at the lower end of the Scott Turnerbreen conduit probably reflects thin overlying ice and the relative ineffectiveness of blockage processes. Persistent subglacial reaches of cut-and-closure conduits have been observed below thin ice on other Svalbard glaciers, including Paulabreen (Benn et al., 2009b), Tellbreen (Baelum and Benn, 2001; Naegeli et al., 2014) and Rieperbreen (Gulley et al., 2012;). Such subglacial conduits may be common below the termini of cold and polythermal glaciers, providing storage for surface-derived water over the winter months.

Although part of the Scott Turnerbreen conduit is at the glacier bed, water flow is restricted to the channel itself because the glacier is frozen to its bed. So despite a hydraulic connection between the surface and the bed, the glacier will not experience a dynamic response when surface recharge rates increase in spring. On the other hand, subglacial water flow will permit erosion of the bed and entrainment of solid particles and solutes, thus influencing sediment yields and runoff chemistry.

Past dynamics of Scott Turnerbreen

The till-filled fractures observed above the glacier bed in the subglacial part of the conduit are interpreted as basal crevasses (also called ‘crevasse-fill ridges’ or ‘crevasse-squeeze ridges’). They are widely considered to be characteristic of surging glaciers, reflecting the combination of high stresses and high basal water pressure needed to crack the basal ice and inject saturated debris upward from the bed (Rea & Evans, 2011).

After a surge, during the early part of the quiescent phase when the glacier sinks into its bed, weak till beneath the glacier is compacted and forced under pressure into basal crevasses.

(Sharp, 1985; Benn & Evans, 1998). Therefore an elevated pore fluid pressure is needed that allows the material to be squeezed up into the crevasses. This happens due to the pressure gradient that exists between sediment overlain by glacier ice and unconfined sediments on the glacier foreland, or beneath low pressure cavities (Benn & Evans, 1998). This adds support to the idea that Scott Turnerbreen could have surged in the past (Liestøl, 1993). Due to its strongly negative mass balance measured over the recent years, it is very unlikely that Scott Turnerbreen will undergo another surge in the foreseeable future (Hodgkins, 1994).

Using GPR to characterize englacial and subglacial conduits

Typical point- and line-source reflectors detected on glaciers are meltwater channels, voids, debris bands and crevasses. Crevasses are uncommon over our survey area on Scott Turnerbreen. Debris bands that contain rocks of different sizes and shapes would result in more scattered diffraction patterns than the ones found in our radargrams. Moreover, during the direct survey only a limited amount of debris was found (Figure. 16 arrow c). The GPR data clearly shows that Scott Turnerbreen is cold over the survey area. There are distinct reflections from the bed and the overlying ice appears almost transparent to radar waves.

In warm-based polythermal glaciers, there is typically a well-defined transition zone from cold ice to warm ice (Irvine-Fynn et al., 2006; Sund & Eiken, 2004; Pälli, 2003; King et al., 2008), due to changes in water content in the ice water bodies within temperate ice lead to a backscattering of GPR waves. This is indicated in the data by a shift from a clear layer with few reflections to a noisy layer with numerous small reflections. Such a change was not observed anywhere on Scott Turnerbreen which indicates that the glacier is cold based.

Conclusions

Direct exploration of the englacial drainage system in Scott Turnerbreen and the results of GPR investigations reveal that the conduit was formed by 'cut-and-closure' processes. The lack of basal motion means that glacier surface velocities are small, so that surface crevassing is limited. Thus drainage of surface meltwater occurs entirely supraglacially. A large catchment area leads to high discharges and enables the formation of a supraglacial stream which downcutting rate is higher than surface ablation, due to the cold climatic conditions. After downcutting of the supraglacial stream into the ice, long-lasting snow bridges and rafted ice blocks created a plugged canyon. Additional signs for the formation by cut-and-closure are the almost horizontally running tunnel that is interrupted by nickpoints and the fact that the canyon is strongly meandering under a roof closed by drifted snow and ice blocks. The channel was followed to the glacier bed where it forms a subglacial drainage system. This proves that englacial and subglacial conduits can develop in uncrevassed, cold based glaciers, although this was ruled out by previous studies (Hodgkins, 1997). The thick layer of till at the glacier bed provides evidence of former shear deformation and thus could have contributed for a large proportion to the forward movement of the glacier during a surge. The basal crevasses that were observed at the bed give clear evidence that a surge has happened which was most likely supported by the water saturated till. It has shown that the use of ground penetrating radar is a reasonable method to detect the englacial channel and the glacier bed. Although the comparison of the radar profile and the drawings of cross-sections have shown that direct surveys are much more precise and cannot be replaced by radar measurements alone, GPR is invaluable when it comes to detection of inaccessible parts of the englacial drainage system which cannot be directly explored. Most important and effective for the study of englacial drainage systems is the combination of direct speleological exploration (if possible) and geophysical surveys from the surface.

Acknowledgements

MT was funded by a scholarship from the DAAD (German Academic Exchange Service). We highly appreciate field work support from the logistics department of the University Centre in Svalbard.

We thank Kathleen van Hoof and Annelie Bergström for field assistance, and Adam Booth and Karoline Baelum for help with processing of GPR data.

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Fig. 1. The Svalbard archipelago (Toposvalbard, Norwegian Polar Institute)

Fig. 2. Location of Scott Turnerbreen 15km southeast of the town Longyearbyen (Toposvalbard, Norwegian Polar Institute)

Fig. 3.(a) GPR lines on Scott Turnerbreen, recorded on 29 March 2008 with 100 MHz. (b) GPR lines on Scott Turnerbreen, recorded on 30 March 2008 with 50 MHz. (c) GPR lines on Scott Turnerbreen, recorded on 30 March 2008 with 25 MH.

Fig. 4.(a) Plan view of the englacial conduit surveyed in Scott Turnerbreen. (b) Plan view of the englacial conduit from station B1 to B17 and A1 to A11. (c) Plan view of the englacial conduit from station B18 to B39. (d) Plan view of the englacial conduit from station B39 to B58. (e) Plan view of the englacial conduit from station B60 to B81. (f) Plan view of the englacial conduit from station A133 to A161.

Fig. 5. Wall collapse at station B59 in March 2009

Fig. 6. Wall collapse at station B59 in March 2009

Fig. 7. looking from B57 to B58

Fig. 8. looking from B58 to B57

Fig. 9. False floor at station B9

Fig. 10. Nickpoint between stations A44 and A45

Fig. 11. Bed of Scott Turnerbreen

Fig. 12. Till at the bed of Scott Turnerbreen

Fig. 13. Basal crevasses at the bed of Scott Turnerbreen

Fig. 14. Radargram recorded with 25 MHz. Not corrected for topography. GPR line 87 in fig. 3c

Fig. 15. Comparison of cross section and corresponding radargram at station A1. Recorded with 25 MHz. Not corrected for topography. GPR line 94 in fig. 3c

Fig. 16. Comparison of cross section and corresponding radargram at station A134. Recorded with 50 Mhz. Not corrected for topgraphy. GPR line 73 in fig. 3b

Fig. 17. Comparison of cross sections and corresponding radargram at stations A153 and A154. Recorded with 50 MHz. Not corrected for topography. GPR line 72 in fig. 3b

Fig. 18. Model of conduit development by cut and closure. Left: Long profiles; right: cross sections. (a) Conduit begins to form as a supraglacial stream. (b) If incision is faster than surface ablation, the conduit cuts deeper. Upper reaches of the canyon become plugged with snow and aufeis. (c) Incision continues, closure by aufeis accumulation and ice creep. (d) Lower levels become plugged by aufeis accumulation or creep closure; water backs up to the next available pre-existing outlet. (e) Winter freezing of ponded water propagates the blockage upstream. In the following summer water finds the next lowest outlet point. Water flowing over the glacier surface incises new channels.
(Modified from Gulley et al. 2009)

Description of supplemental information:

The supplemental information includes long profiles (part a), plan view of the conduit (part b), cross sections that were drawn at each station (part c), all recorded GPR images (part d) and the survey data (part e).