Structural control of englacial conduits in the temperate Matanuska Glacier, Alaska, USA

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ABSTRACT. Fourteen englacial conduits were mapped within 2 km of the terminus of the temperate Matanuska Glacier, Alaska, USA, to ice depths of 65 m using speleological techniques. Detailed three-dimensional maps of the conduits were made over 3 years to characterize conduit relationships with glacier structural features and to track conduit evolution through time. All conduits consisted of single unbranching passages that followed fractures in the ice. All conduits were either too constricted to continue or became water-filled at their deepest explored point and were not able to be followed to the glacier bed. Conduit morphology varied systematically with the orientation of the glacier principal stresses, allowing them to be categorized into two broad classes. The first class of conduits were formed by hydrostatic crevasse penetration where a large supraglacial stream intersected longitudinal crevasses. These conduits plunged toward the glacier bed at angles of 30–40°. The second class of conduits formed where smaller streams sank into the glacier on shear crevasses. Many of these conduits changed direction dramatically where they intersected transverse crevasses at depth. These results suggest that the conduits observed in this study formed along fractures and, over their surveyed length, were not affected by gradients in ice overburden pressure.

INTRODUCTION

Englacial conduits are a critical component in glacier hydrological systems because they can rapidly convey large volumes of meltwater from glacier surfaces to glacier beds (Hooke, 1989; Fountain and Walder, 1998) where subglacial storage elevates basal water pressure and causes a transient increase in glacier velocity (Iken and Bindschadler, 1986; Willis, 1995). Despite their importance, little is known about the spatial distribution, mechanisms of formation or the longevity of englacial conduits. Conceptual models of englacial drainage have been deeply influenced by the theoretical model developed by Shreve (1972). According to this widely cited model, englacial hydrological systems should consist of arborescent systems of conduits that evolved from intergranular veins by exploiting the primary permeability of ice, roughly analogous to Darcian (advective) flow in a homogeneous isotropic medium. This model predicts that individual conduits should trend normal to equipotential surfaces controlled by elevation, ice overburden pressure and conduit radius. Because of its requirement that glacier ice is permeable, Shreve's theory only applies to englacial conduits in temperate glaciers because ice below the pressure-melting point is impermeable.

However, there is no direct evidence that Shreve-type conduits exist in temperate glaciers, and several other theories of englacial conduit formation have been advanced. Stenborg (1968, 1969) initially proposed that englacial conduits developed from crevasses. More recently, it has been suggested that englacial conduits could form when supraglacial streams incise along crevasse bottoms and either reach the glacier bed or enter a Shreve-type englacial drainage system at depth (Fountain and Walder, 1998). Investigation of boreholes on Storglaciären, Sweden, using downhole cameras led Fountain and others (2005) to conclude that englacial drainage systems are dominated by slow flow in fractures and that conduits only form under unspecified special circumstances. This theory also does not completely explain englacial conduit formation since slow flow in fractures is inconsistent with the sharply peaked hydrographs diagnostic of integrated conduit flow observed on many glaciers (e.g. Swift and others, 2005).

Recent speleological investigations of polythermal and debris-covered glaciers have demonstrated that englacial conduits can form by multiple mechanisms. These studies have shown that conduits form where high-hydraulic-conductivity glaciostructural features connect discrete recharge and discharge points (Gulley and Benn, 2007; Gulley and others, in press; Benn and others, 2009). Additionally, speleological mapping of moulins in the polythermal Storglaciären found conduits followed the orientation of the crevasse even at depths exceeding 60 m (Holmlund, 1988).

Other than direct observations of englacial conduits in primarily polythermal and cold-based glaciers (Benn and others, 2009; Gulley and others, 2009), most theories of englacial conduit formation have been developed by interpreting proxy data such as dye-tracing and geophysics (Willis and others, 2009). These proxy data limit understanding of the physical processes controlling their formation and distribution. Determining where, when or if each of these theories is applicable requires substantial direct observations as exemplified by studies of conduit morphologies in limestone, which have greatly facilitated interpretation of proxy data and refinement of numerical models (White, 1988; Palmer 1991, 2007; Ford and Williams, 2007). Similar to these studies of limestone conduits, morphological studies of englacial conduits should improve understanding of mechanisms of englacial conduit formation and glaciohydrological modeling efforts. This paper

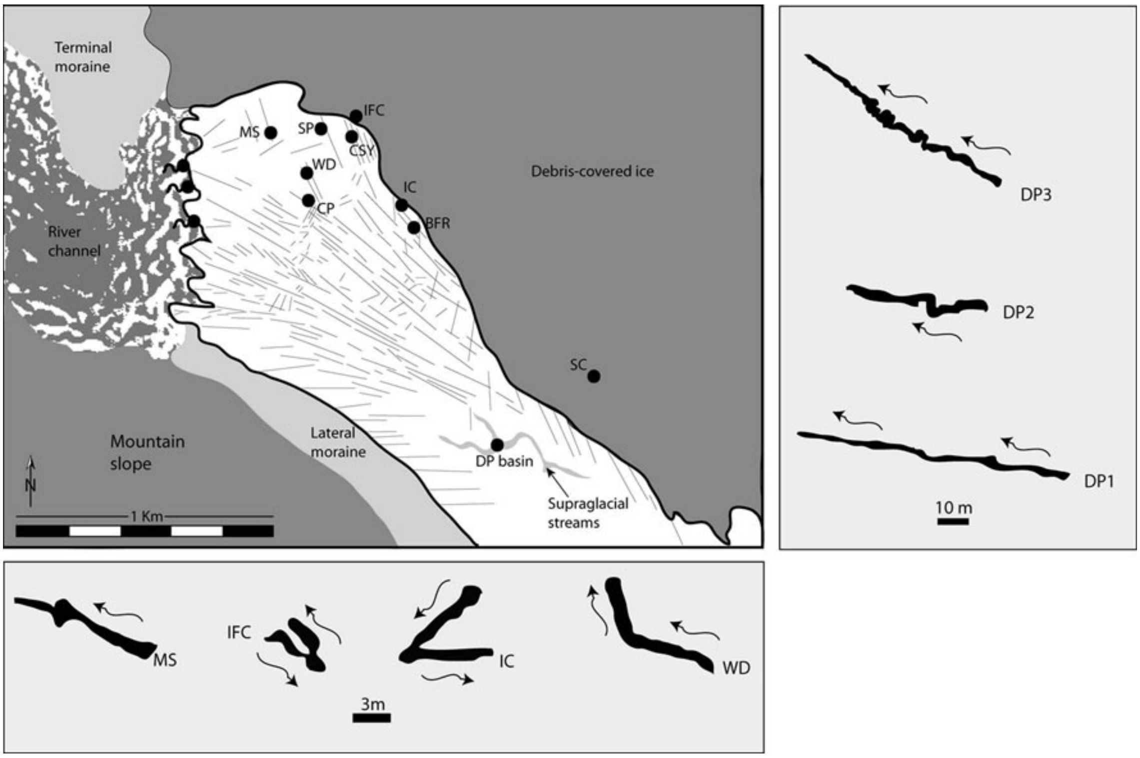

Fig. 1. Location of englacial conduit entrances and their relationship with crevasse patterns on Matanuska Glacier. Plan views of the conduits are included to show the general relationship between conduits and the overall fracture patterns of the terminus region. Arrows indicate the direction of water flow.

extends the speleological approach applied by Gulley and Benn (2007) in polythermal debris-covered glaciers, Gulley and others (2009) in polythermal and cold-based glaciers and Benn and others (2009) primarily in polythermal glaciers, to englacial conduits found in a temperate glacier. This paper reports the results of a 3 year englacial conduit mapping effort at Matanuska Glacier, Chugach Mountains, Alaska, USA, which includes detailed three-dimensional maps of englacial conduits and their relationship with glaciostructural features. These results are used to demonstrate substantial differences between observed englacial conduit morphologies and those predicted by the Shreve (1972) model.

STUDY AREA AND METHODS

Matanuska Glacier in the Chugach mountain range of south-central Alaska began advancing in about September 2002, impacting stagnant buried ice in the terminal zone (Baker and others, 2003; Chesley and others, 2005). Thrusting and deformation of proglacial sediments and buried ice have been reported in the near-terminus region (Baker and others, 2003; Pyke and others, 2003), and folds in laminated sediments near the terminal ice margin were observed in this study. Longitudinal crevasses extend ~2 km up-glacier from the terminus, immediately above which ice is less densely crevassed and a well-developed supraglacial stream network is present. Up-glacier-dipping transverse crevasses occur near the terminus and, during this study, were commonly associated with vents discharging supercooled water (Alley and others, 1998; Lawson and others, 1998). Several vents were found near the intersection of transverse and longitudinal crevasses during this study. The combination of these structural features leads to the characterization of the stress field of the central crevassed glacier tongue as longitudinal compression and transverse extension. Crevasses in the area where active ice flows past slower debris-covered ice on the northeast margin (Shumway and Goetz, 2005) and along the northwest lateral moraine are interpreted to be shear crevasses and frequently cut across both longitudinal crevasses and/or transverse crevasses. For logistical reasons, fieldwork was limited to within 3 km of the glacier terminus.

Conduits were surveyed on three expeditions between 2005 and 2007 using standard speleological techniques (Palmer, 2007) modified for glacier caves (Gulley and Benn, 2007). Distance was measured between two stations in a conduit with a Leica Disto laser distance meter. Azimuth and inclination were measured using a Brunton Sightmaster and a Brunton Clinomaster, respectively. Cross-section measurements were made at each station using the Disto. This process was repeated until the entire conduit had been surveyed. These data were used to draw scaled geomorphic maps of conduits in plan, profile and cross-section views.

Two conduits were explored but not surveyed in October 2005, nine conduits were surveyed in September 2006 and six conduits were surveyed in October 2007. Conduits that remained open between years were revisited to document their evolution. Surveys of englacial drainage networks were conducted at the end of the ablation season when meltwater flow had largely ceased but passages remained fully open. Survey data were reduced using the COMPASS cave survey software program, from which planimetrically accurate maps were drawn. Patterns of strain in the ice were inferred at each site by crevasse pattern analysis (Nye, 1952; Van der Veen, 1999).

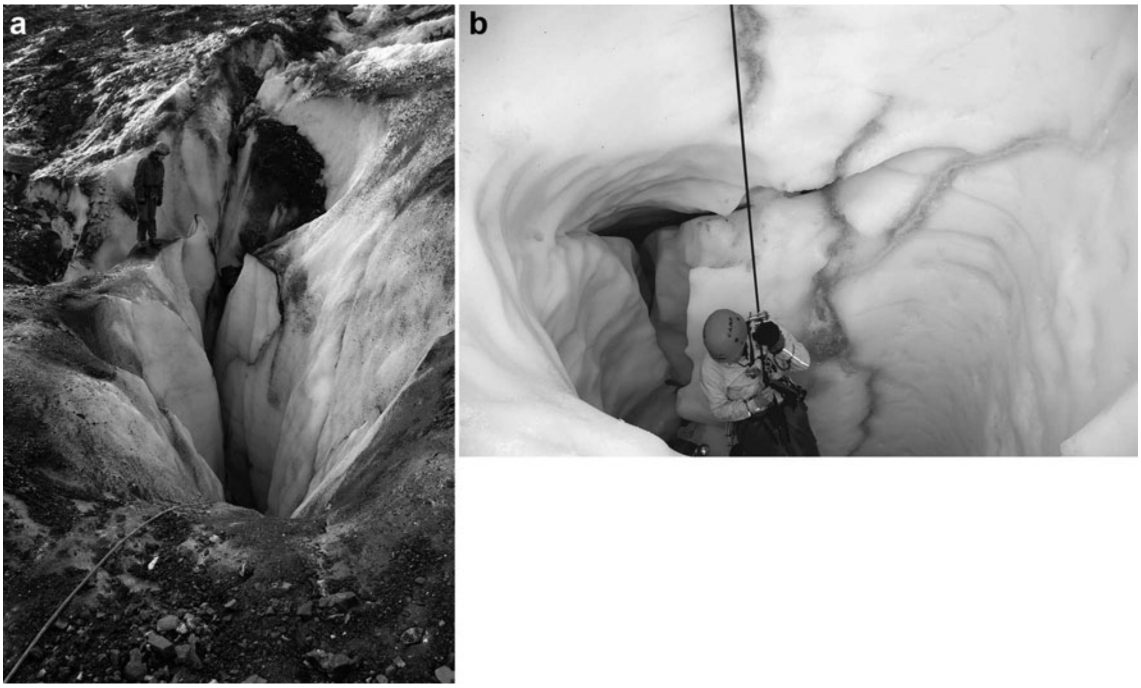

Fig. 2. (a) The entrance to englacial conduit IC is located along a shear crevasse formed where active ice shears past dead debris-covered ice on the northern margin of Matanuska Glacier. (b) Conduit CP briefly exploited this transverse crevasse before developing a free-surface stream and incising as a vadose canyon to create this T-shaped cross-section.

RESULTS

A total of 15 conduits were explored and 14 were surveyed to a maximum ice depth of 65 m. Mapping ended in seven of the conduits because they were water-filled, and ended in eight of the conduits where constrictions were too small to pass through. All conduits showed clear structural controls and fall into two separate classes based on glacier stress patterns and conduit morphology. Twelve conduits that formed along shear crevasses or transverse crevasses comprise one class. These conduits were investigated along the northeastern clean-ice boundary within 2 km of the glacier terminus, where active ice shears past slower or stagnant debris-covered ice (Shumway and Goetz, 2005). The remaining three conduits (DP 1–3) were formed at the up-glacier limit of three adjacent longitudinal crevasses and are placed into the second group. The second class of conduits was located in a basin (DP in Fig. 1; site names used in this paper (e.g. DP) are abbreviations of field designations) at the confluence of three supraglacial streams about 2.1 km from the glacier terminus. The locations of all conduit entrances are shown in Figure 1. No additional conduit entrances large enough for human entry were found in the serac zone between the DP basin and the terminus despite extensive searches during all three field seasons.

Transverse crevasse and shear zone conduits

Entrances for this class of conduit formed where shear crevasses and/or transverse crevasses intersected supraglacial streams. Conduits associated with shear crevasses had vertical shafts or enlarged fissure entrances (Fig. 2a). Entrance shaft depths increased systematically from a few meters near the terminus to 20 m at the furthest site up-glacier (SC; Fig. 1). Six of the conduits were simple shafts or fissures following shear crevasses. Five conduits formed along shear crevasses that intersected and exploited transverse or other crevasses at depth, and one conduit (CP) formed along a transverse crevasse only (Fig. 2c). Conduit orientations changed, often dramatically, at fracture intersections (Figs 3 and 4). A legend for the englacial conduit maps is provided in Figure 4c. Conduits that formed along intersecting shear crevasses and transverse crevasses change direction at the fracture intersection and follow the transverse crevasse obliquely to strike and dip. Conduits branching off from the shaft entrance (shaft drain) (Figs 4 and 5) displayed a classic 'keyhole' cross-sectional morphology indicative of a transition from phreatic to vadose flow (Gulley and Benn, 2007). One tube-shaped conduit (WD; Fig. 1) increased in elevation in a downstream direction (Figs 5 and 6), indicating that water flowed uphill under pipe-full conditions. The shaft drain of conduit WD extended from the entrance shaft as a horizontal phreatic tube following a shear crevasse (Fig. 6a). Three meters from the entrance, the tube increased 1.5 m in elevation over a distance of 4.9 m before turning 63° and plunging 45° along an intersecting crevasse and terminating in a pool of water. A narrow vadose canyon with migrating nickpoints incised the middle of the tubular cross-sections (Fig. 6) and was graded to the terminal pool where the conduit continued underwater.

The evolution of conduit CP is more complicated than that of conduit WD. In 2006, conduit CP was formed entirely along a transverse crevasse and the conduit was draining in an up-glacier direction down the dip of the crevasse. In 2005, the same location hosted an englacial conduit formed along a shear crevasse (Fig. 7), which drained toward the clean-ice margin. In 2005, this conduit was followed for 70 m down a series of progressively higher nickpoints until it terminated in a pool of water at the bottom of a 10 m deep shaft. A fracture was visible in the ceiling of the conduit for its entire length. When revisited in 2006, the

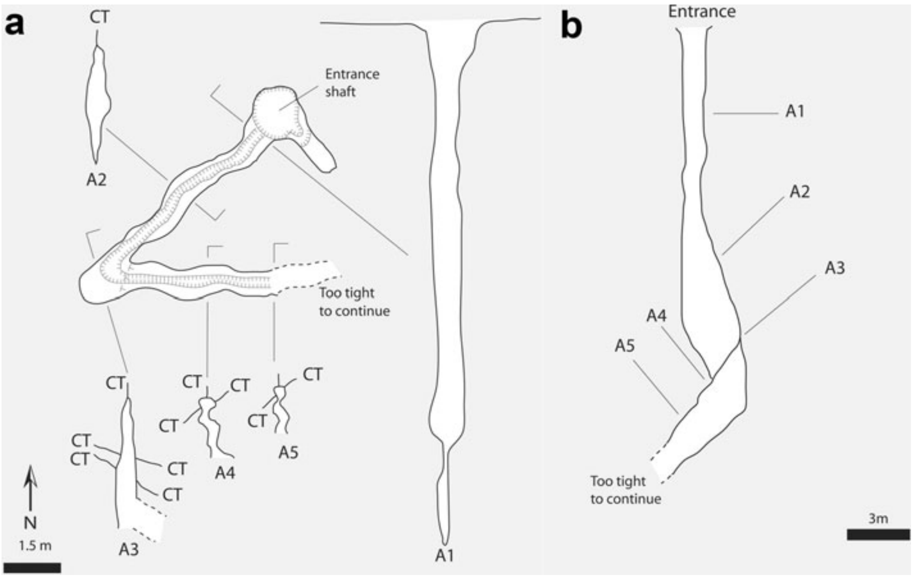

Fig. 3. (a) Plan view and (b) profile view of conduit IC.

conduit roof had melted completely to create a nearly linear supraglacial canyon. Conduit CP had formed in the middle of the supraglacial channel sometime in the ablation season of 2006 when the supraglacial stream incised deeply enough to expose part of an intersecting transverse crevasse. All of the stream discharge was pirated from the supraglacial channel into the englacial conduit, which formed as water flowed down the dip of the transverse crevasse in an up-glacier direction. From Figure 2b, it can be seen that water briefly exploited the transverse crevasse before developing a free-surface stream and vadose incision created the canyon resulting in the T-shaped cross-section.

Partial exploitation of a transverse crevasse can be seen in conduit MS, the trajectory of which was guided entirely by a separate longitudinal crevasse. The conduit formed as a phreatic tube along this crevasse except for where it intersects a transverse crevasse (A4; Fig. 8). The transverse crevasse was enlarged in the vicinity of the conduit in an up-dip direction, resulting in a composite cross-section midway between a tube and a T-shape (A4; Fig. 8).

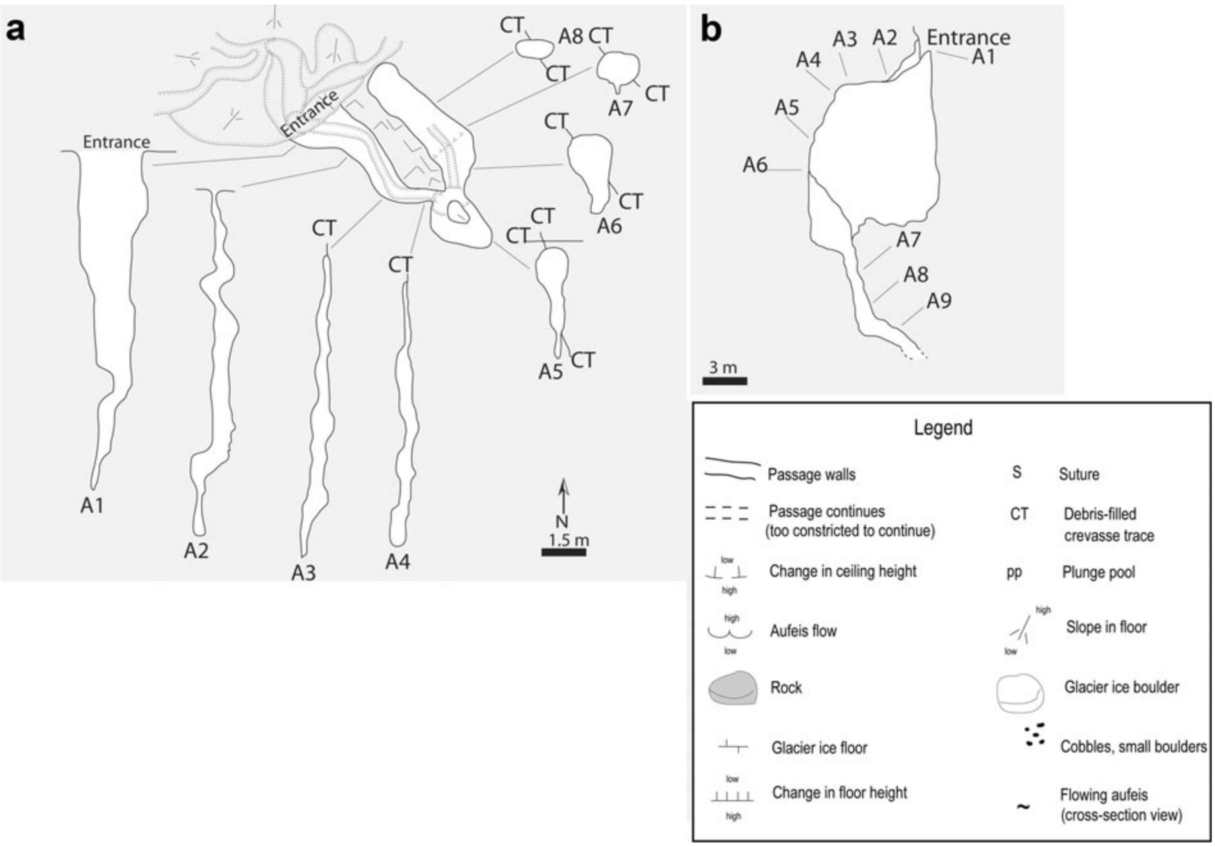

Fig. 4. (a) Plan view and (b) profile view of conduit IFC.

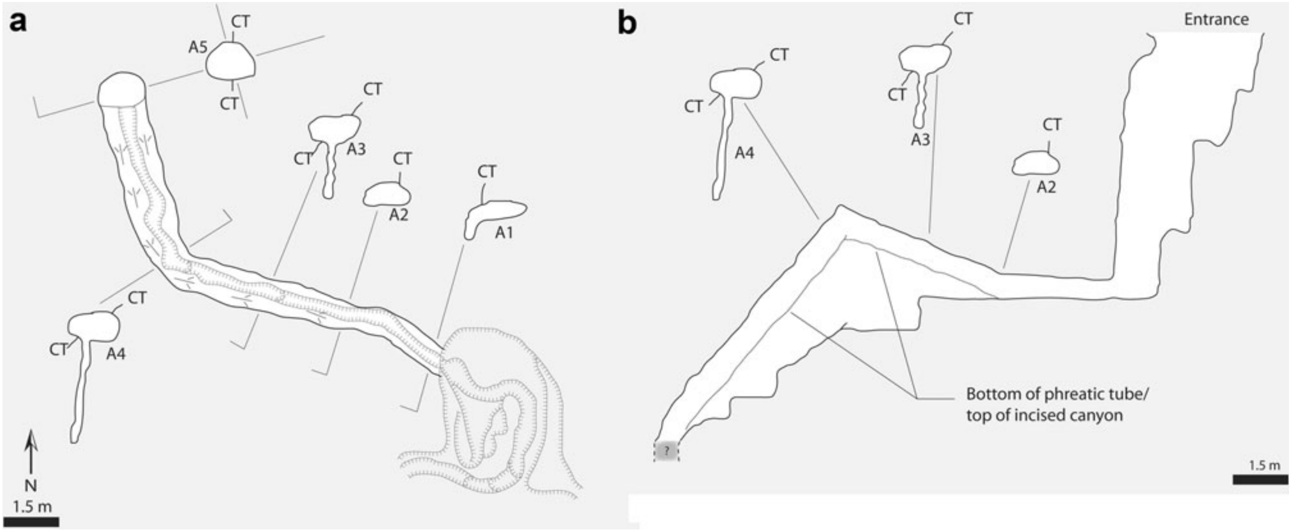

Fig. 5. (a) Plan view and (b) profile view of conduit WD.

Compression-zone hydrostatic crevasse penetration conduits

In 2007, three conduits (DP1–3; Fig. 1) were surveyed in a deep supraglacial basin where three supraglacial streams sank into englacial conduits. Nickpoint migration and meltback of the channel walls had created a basin ~30 m deep and the conduit entrances were located in the bottom of the basin. All three conduits were fracture-guided low-sinuosity passages plunging at angles between 30° and 40°. The conduit entrances were located on adjacent longitudinal crevasses. Conduit DP1 was actively receiving water from a supraglacial stream. Conduit DP1 (Fig. 9) was separated from DP2 (Fig. 10) by a 4 m high meander cutbank at the top of which was an abandoned supraglacial channel leading into the entrance of DP2. DP3 (Fig. 11) was located in the third longitudinal crevasse from the active stream.

Conduit DP2 was explored briefly during 2006 (Benn and others, in press), but unseasonably warm weather, which rapidly melted out ice screws, and high flow in the conduit stream prevented access. In 2006, the accessible portions of the conduit had vertically oriented lenticular cross-sections with crevasse traces visible in the floor and the ceiling of the cross-sections (similar to cross-sections in DP1 and DP3). In 2007, much of the ice face in which DP2 was developed had melted out and the conduit dimensions rapidly

Fig. 6. Conduit WD flows uphill in a downstream direction and exhibits a classic 'keyhole' conduit cross-section indicative of a transition from phreatic to vadose flow. The association between the conduit and formative crevasse can be seen clearly in this picture.

Fig. 7. The crevasse in which this conduit formed is visible in the conduit roof in 2005. By 2006, the conduit roof had melted out and the conduit, designated as CP in Figures 1 and 2, formed when this conduit incised down to a transverse crevasse.

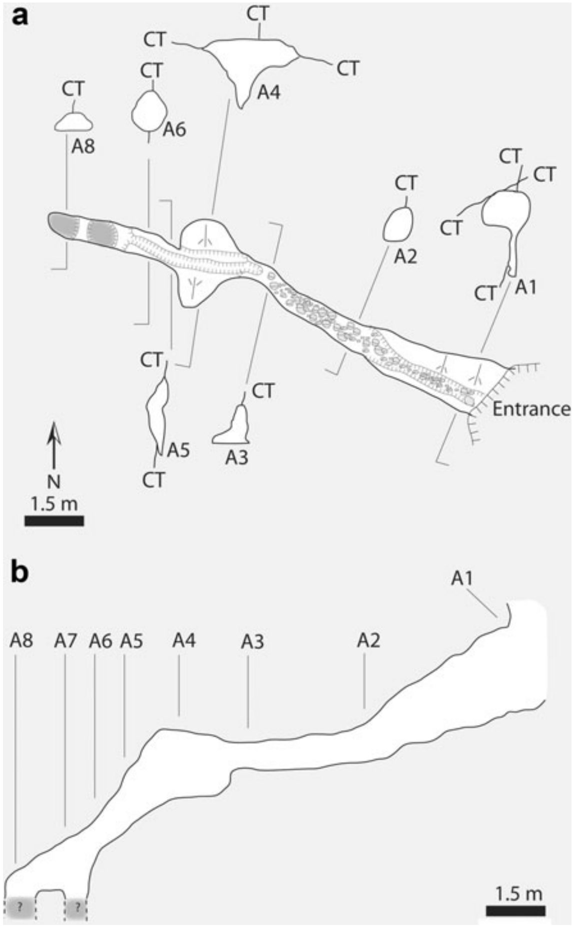

Fig. 8. (a) Plan view and (b) profile view of conduit MS.

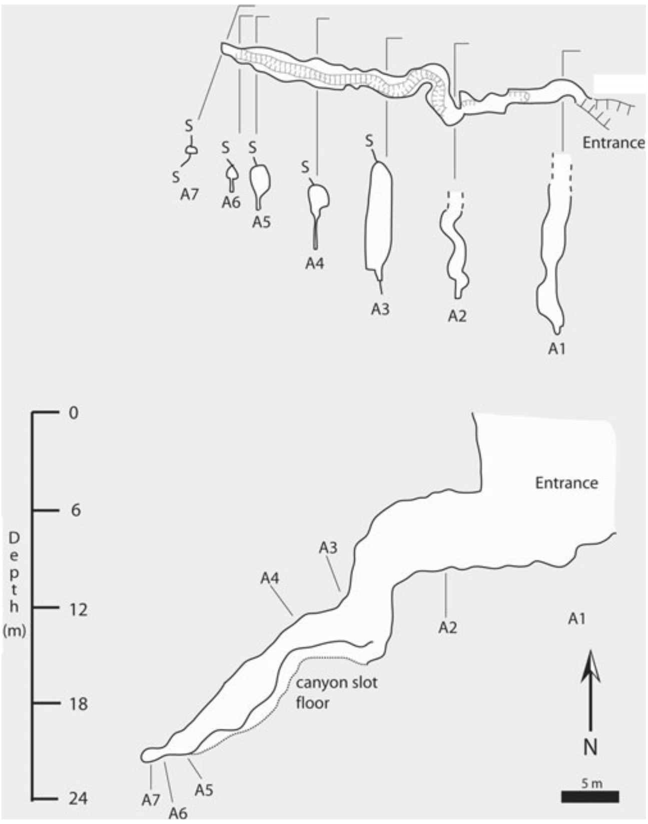

Fig. 10. (a) Plan view and (b) profile view of conduit DP2.

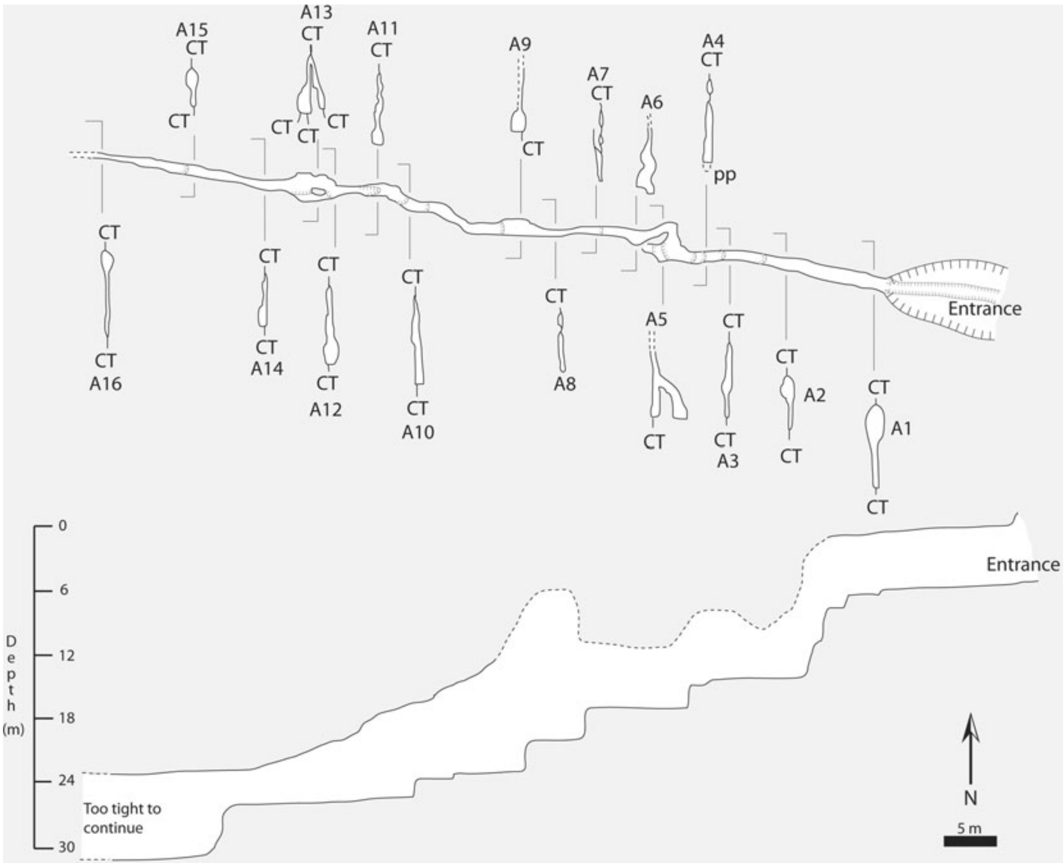

Fig. 9. (a) Plan view and (b) profile view of conduit DP1.

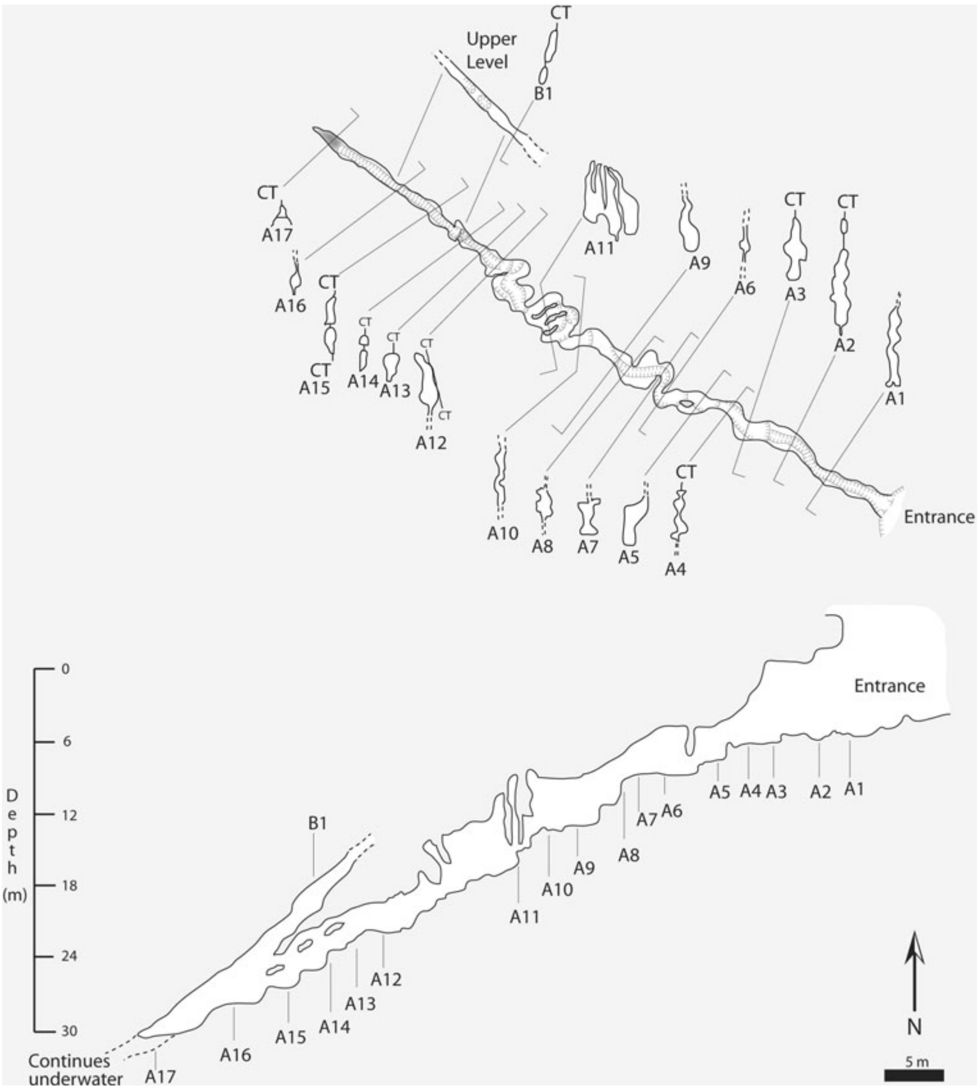

Fig. 11. (a) Plan view and (b) profile view of conduit DP3.

diminished with depth and pinched out completely at 22 m below the conduit entrance (~52 m ice depth).

Conduit DP3 was formed along the longitudinal crevasse furthest from the main active stream, suggesting it is the oldest conduit. However, it was in an inaccessible portion of the basin in 2006, so its developmental history remains uncertain. Regardless of when it formed, DP3 exhibited strong fracture control and plunged toward the glacier bed at an angle of 30°. Crevasse traces extended from the ceiling of all conduit cross-sections and were frequently noted where the conduit floor was visible. In cross-section and profile views, DP3 clearly demonstrates that some parts of the crevasse were not conducive to conduit formation. Cross-sections A4, A14, A15 and B1 (Fig. 11) show intact 'bridges' of glacier ice bifurcated by a crevasse trace (Fig. 12a). DP3 terminated in a pool of water ~65 m below the ice surface, but the conduit was observed to continue underwater.

The history of DP1 is well constrained. In 2006, all drainage entered DP2 from the main supraglacial channel via a 15 m high nickpoint, but sometime between the winter of 2006 and fall of 2007 DP1 formed in the middle of this supraglacial stream and pirated all stream discharge. Paired sills that form by vadose incision (Gulley and others, 2009) at the entrance indicate the supraglacial stream had incised ~2.4 m since the conduit formed under phreatic conditions. DP1 is similar to DP3 in plan, profile and cross-sectional views. Again, vertically oriented lenticular cross-sections taper into crevasse traces in the ceiling and floor (Fig. 12b). Cross-sections A4, A7 and A8 (Figs 9 and 12a) show that only portions of the initial fracture were exploited. Discontinuous fractures (Fig. 12a) suggest fracturing may have occurred in stages or in narrow swarms. DP1 was surveyed to an ice depth of ~60 m where the conduit became too narrow to continue.

DISCUSSION

All conduits mapped for this study were unbranching, followed glaciostructural features and did not lead into an accessible arborescent network of passages. Despite the hydraulic low that these conduits create within temperate ice, they did not drain systems of in-feeder conduits nor did they enter a Shreve-type drainage system. Because the bed was not reached in any of the conduits, the possibility that these conduits entered a Shreve-type network at greater depth cannot be ruled out by this dataset, but based on observations of englacial conduits in many other glaciers

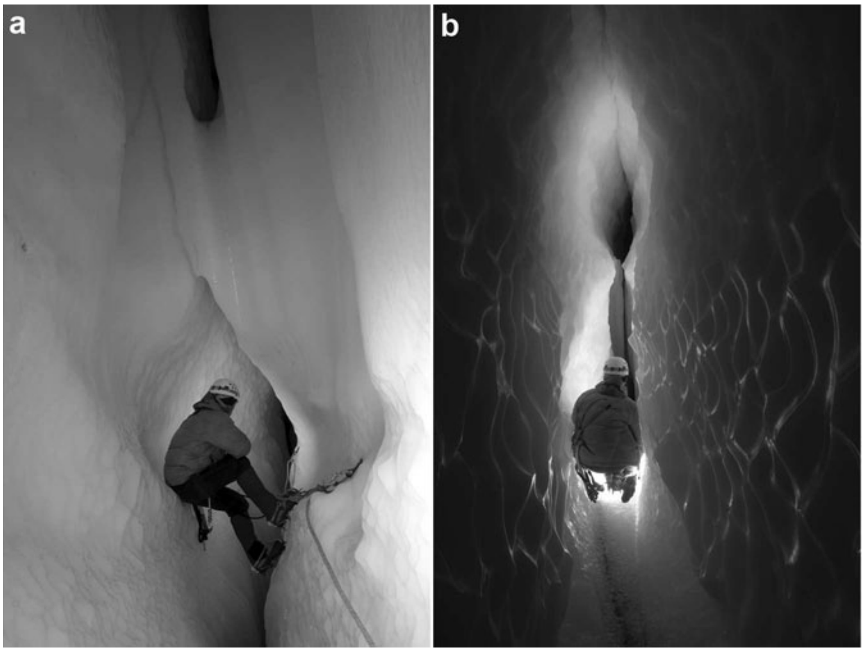

Fig. 12. (a) Conduit formation by hydrofracturing switched from one fracture to an adjacent fracture or a splay fracture in this portion of conduit DP1. This photograph corresponds to cross-section A7 in Figure 9. (b) The hydrofracture trace can be seen in the floor and ceiling of conduit DP1. This cross-section corresponds to cross-section A16 in Figure 9.

worldwide (Gulley and others, in press) this is considered unlikely. All conduits cross-cut foliation and bubbly ice veins without deviation. These observations indicate that temperate glacier ice is not sufficiently permeable to influence englacial water flow at the macroscopic scale. Rather than the simple circular cross-sections predicted by classical theory (Rothlisberger, 1972; Shreve, 1972), cross-sections were oriented on fractures instead of in intact glacier ice and varied from planar to tubular where they formed under phreatic conditions and transitioned to canyons when free-surface streams developed. The differences in observed conduit morphology with Shreve theory result because the model makes the primary assumption of permeable ice and because it does not consider that fractures provide high hydraulic conductivity pathways through effectively impermeable glacier ice.

For several reasons, conduits in this study cannot have formed as free-surface streams that flowed along crevasse bottoms and later became isolated by creep closure of the upper crevasse walls, a mechanism Fountain and Walder (1998) proposed for englacial conduit development in temperate glaciers. The clear association of all conduits with fractures in conduit ceilings and especially floors (Fig. 12b) precludes this possibility. If conduits had formed by incision along crevasse bottoms, canyon sutures (Gulley and others, 2009) and not fractures would have been present in conduit ceilings and there would be no fractures in conduit floors. Ice bridges separating upper and lower conduit segments in D1 and D3 (Fig. 12a) additionally argue against this formation mechanism. Finally, conduit CP and an unmapped conduit formed along an adjacent shear crevasse were crevasse-bottom streams in 2005, but when revisited in 2006 the original conduits had melted out completely. The unroofing of these englacial conduits occurred between October 2005 and September 2006, reflecting the fact that surface ablation rates outpaced down-cutting rates in the ice despite the conduits having a ‘head start’ by forming within the glacier along a crevasse bottom. The unroofing is a consequence of high ablation-season temperatures and the small contributing areas (and hence discharges and incision rates) of surface streams in the crevasse field. Englacial conduits can form by the incision of supraglacial streams; however, the environmental conditions necessary for this mechanism of formation (termed ‘cut and closure’) appear to restrict them to uncrevassed regions of polythermal and debris-covered glaciers (Gulley and others, 2009).

While all conduits in this study formed along fractures, there are important differences in the mechanisms of formation between those formed along shear crevasses and transverse crevasses and the conduits in the DP basin. Both shear crevasses and transverse crevasses are pre-existing fractures which, if they are kept open by continued slip during glacier motion, create discrete zones of high hydraulic conductivity. Because these transverse crevasses already connect to the bed, there is no need for water to penetrate them hydrostatically from the top down. However, high basal water pressures may be important for their formation (Ensminger and others, 2001). Shear crevasses provide vertically oriented fracture pathways that readily capture supraglacial streams and provide direct access to the transverse crevasses to form conduits from the top down. Alternatively, transverse crevasses can function as englacial discharge features if subglacial water pressure is high (Ensminger and others, 2001). Transverse crevasses interpreted to be thrust faults have formed low and wide conduits discharging subglacial water in the compressive tongues of polythermal glaciers in Svalbard (Mavlyudov, 2005), thus forming englacial conduits from the bottom up. Therefore, transverse crevasses might be important for both subglacial recharge and discharge in glacier compression zones such as where glaciers, like Matanuska, advance into an ice-cored moraine (Baker and others, 2003) or at the leading edge of surge bulges in polythermal glaciers (Murray and others, 1998).

The three conduits in the DP basin formed at the up-glacier limit of longitudinal crevasses associated with the compressive glacier tongue. All three conduits clearly followed longitudinal crevasses and attained glacier depths of 65 m, which is much deeper than typical 'dry' crevasses (Van der Veen, 1998). It is concluded that these conduits formed when a combination of longitudinal compressive stress and water pressure led to hydrostatic crevasse penetration (e.g. Benn and others, 2009). Discontinuous segments of overdeepened fractures and intervening ice bridges suggest fracturing occurred either in swarms or in stages (Fig. 12a).

Because of the clear association of all investigated conduits with fractures it is proposed that englacial conduits can only form on temperate glaciers either where large amounts of supraglacial meltwater are diverted englacially along a pre-existing line of high hydraulic conductivity linking recharge and discharge points, or where high hydraulic conductivity zones are created by crevasse penetration in stressed ice. Englacial conduits are unlikely to form in uncrevassed parts of temperate glaciers because the surface ablation rates and supraglacial stream incision rates are too similar to allow conduit formation by the cut-and-closure mechanism (Gulley and others, in press). Indeed, no conduits were found in uncrevassed parts of Matanuska Glacier.

The hypothesis of structural control of conduits is attractive for many reasons. Hydrologically connected fractures are abundant throughout low-permeability glacier bodies (Pohjola, 1994; Fountain and others, 2005) and, where present, would create preferential flow paths to form conduits if they were connected to supraglacial recharge sources such as lakes and streams. Structural control of englacial conduits explains conduit formation in both temperate ice as well as cold ice. If conduits require a combination of fractures, which are a function of the principal stresses of a glacier, and a large source of supraglacial recharge, the locations of englacial conduits and, by extension, the general location of discrete subglacial recharge become predictable.

CONCLUSIONS

This research on conduits in the temperate Matanuska Glacier builds on past work in polythermal, debris-covered and cold-based glaciers which has systematically demonstrated that the formation of englacial conduits requires pre-existing lines of high hydraulic conductivity linking recharge and discharge points (Gulley and Benn, 2007; Gulley and others, 2009; Benn and others, in press). The recognition that zones of high hydraulic conductivity are a prerequisite for conduit development in temperate glaciers is particularly important because classical englacial hydrological theory was initially developed specifically for temperate glaciers. No evidence of Shreve-type conduits was found within the accessible parts of any conduit explored within 3 km of the terminus of the temperate Matanuska Glacier. If intact glacier ice were sufficiently permeable to form conduits, arborescent tributary conduits should have been found feeding into the structurally controlled low-pressure conduits. No such in-feeders were discovered. Instead, all conduits followed fractures for their entire observable length. The observations presented in this paper suggest that the concept of Shreve-type drainage systems in temperate glaciers may need re-evaluation.

ACKNOWLEDGEMENTS

This research was funded by the US National Speleological Society, the Evolving Earth Foundation, Sigma Xi, the Cleveland, OH, Grotto Science Fund, the University of Florida Department of Geological Sciences, the American Alpine Club and the US National Science Foundation Graduate Research Fellowship Program. I thank S. Keene, L. Nicholson, M. Reece and A. Bergstrom for field assistance, and Matanuska Glacier Park for logistical support. Conversations with D. Benn and J. Martin helped to improve the manuscript.

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MS received 7 October 2008 and accepted in revised form 29 March 2009