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Morphological dynamics of an englacial channel

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Abstract

Despite an interest in the hydraulic functioning of supraglacial and englacial channels over the last four decades, the processes and forms of such ice-bounded streams have remained poorly documented. Recent glaciological research has demonstrated the potential significance of so-called “cut and closure” streams, where englacial or subglacial flowpaths are created from the long-term incision of supraglacial channels. These flowpaths are reported to exhibit step-pool morphology, comprising knickpoints and/or knickzones, albeit exaggerated in dimensions in comparison to their supraglacial channel counterparts. However, little is known of the development of such channels’ morphology. Here, we examine the spatial organization of step-pools and the upstream migration of steps, many of which form knickzones, with repeated surveys over a 10 year period in an englacial conduit in cold-based Austre Brøggerbreen, Svalbard. The observations show upstream knickpoint recession to be the dominant process for channel evolution. This is paralleled by an increase in average step height and conduit gradient over time. Characteristic channel reach types and step-riser forms are consistently observed in each of the morphological surveys reported. We suggest that the formation of steps has a hydrodynamic origin, where step-pool geometry is more efficient for energy dissipation than meanders, and that the englacial channel system is one in rapid transition rather than in dynamic equilibrium. The evolution and recession of knickzones reported here result in the formation of a 37 m moulin, suggesting over time the englacial channel may evolve towards a stable end-point characterised by a singular vertical descent to the local hydraulic base level. In light of this, our observations highlight the need to further examine the adjustment processes in cut-and-closure channels to better understand their coupling to supraglacial meltwater sources and role and potential significance in cold-based glacier hydrology and ice dynamics.

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1 Introduction

Fluvial geomorphologists have long been intrigued by the similarities between supraglacial and alluvial streams when it comes to meandering, especially as ice walled streams typically lack an entrained sediment load (Leopold and Wolman, 1960; Zeller, 1967; Knighton, 1972; Dozier, 1976), and are typically characterised by a rapidly adjusting morphology (Dozier, 1974). This in turn motivated research focused on the controlling factors of form, meandering and adjustment of ice walled channels including both the extrinsic influences of glacier ice structure and rheology (Ferguson, 1973; Dozier, 1974; Hambrey, 1977) and intrinsic processes associated with water flow (e.g. Pinchak, 1972; Ferguson, 1973; Parker, 1975; Dozier, 1976; Knighton, 1981; Marston, 1983). Supraglacial observations have suggested that intrinsic processes also lead to the formation of staircase-like longitudinal profiles or step-pool sequence (Knighton, 1981, 1985; Carver et al., 1994); such features appear similar to the forms commonly found both in bedrock rivers (Wohl and Grodek, 1994; Howard, 1998; Whipple and Tucker, 1999; Hayakawa and Oguchi, 2006) and high-gradient alluvial channels (Grant et al., 1990; Abrahams et al., 1995; Chin, 1998; Church and Zimmermann, 2007; Comiti et al., 2009; Turowski et al., 2009; Molnar et al., 2010).

The term "step-pool" is commonly used for channel forms with tumbling flow, comprising alternating channel-spanning convexities (steps or knickpoints) and concave pools (Peterson and Mohanty, 1960). Such a morphological form is thought to be a characteristic of streams with slopes $> 2\,\%$ (Chin, 1989; Grant et al., 1990; Montgomery and Buffington, 1997) and may represent a process akin to meandering in the vertical dimension (Chin, 2002). Indeed, recent work on bedrock rivers (Hayakawa and Oguchi, 2014) suggests step-pool sequences may be related to intrinsic channel hydraulics and flow perturbations rather than more commonly cited extrinsic environmental controls (Phillips et al., 2010). Consequently, due to the rapidity of morphological adjustment in ice, supraglacial and englacial streams represent natural, experimental opportunities to investigate hydrodynamic processes of channel adjustment and meandering in both the horizontal and vertical dimensions. Yet despite this potential, the hydraulics and morphology of supraglacial streams have received surprisingly little attention over the last 25 years, despite a recent resurgence (Kostrzewski and Zwoliñski, 1995; Stock and Pinchak, 1995; Raymond and Nolan, 2000; Isenko and Mavluydov, 2002; Isenko et al., 2005; Jarosch and Gudmundsson, 2012; Karlstrom et al., 2013).

The continued interest in the hydraulics of ice-bounded streams arises because the long-standing assumption that englacial drainage is conditioned by hydraulic potential (Shreve, 1972) has given way to the realization that ice structure, in the form of crevasses, fractures, debris intrusions and variations in hydraulic permittivity (Stenborg, 1968; Mavlyudov, 2005; Gulley and Benn, 2007; Gulley, 2009) may be hydrologically significant. This in turn has given way to the increasing recognition that hydrologically assisted fracture propagation (Hambrey, 1984; Boon and Sharp, 2003; Benn et al., 2009) and the progressive incision of so-called "cut-and-closure" supraglacial streams (Vatne, 2001; Gulley et al., 2009a) also represent important mechanisms by which meltwater can be transferred from the supraglacial environment to a glacier's interior (Bælum and Benn, 2011; Naegeli et al., 2014).

Although rarely described specifically in the literature, step-pool geometry analogous to that found in supraglacial channels is widely reported in speleological investigations of englacial flowpaths and conduits (Pulina, 1984; Holmlund, 1988; Řehák et al., 1990; Pulina and Rehak, 1991; Griselin, 1992; Schroeder, 1998; Piccini et al., 2000; Vatne, 2001; Vatne and Refsnes, 2003). Maps and descriptions of englacial channels have referred to alternating geometries of water-filled depressions (pools), and steep cascades or waterfall segments (steps) typically 1–5 m in height. The prevalence of the steps in englacial flowpaths may mean > 80 % of an englacial conduits' vertical descent takes place in cascades (e.g. Vatne, 2001). Recent glaciological studies have referred to individual waterfall steps in the longitudinal channel profiles as knickpoints (e.g. Gulley, 2009). At these knickpoints, where slopes are steepest, hydrodynamic theory predicts heightened melt rates (Isenko and Mavluydov, 2002), and direct observations have reported that erosion rates at steps cause headward recession of the channel floor at rates of up to 47 cm day^{-1} (Gulley et al., 2009a). However, to date, the temporal evolution of the longitudinal profile of englacial conduits has rarely been described, and the formative processes of step-pools in englacial environment have not been addressed in detail.

With an increasing recognition that englacial flowpaths, particularly in non-temperate ice masses, may be comparable to karstic systems (e.g. Clayton, 1964; Mavlyudov, 2006; Gulley et al., 2009b), channel evolution in these non-pressurized channel systems is likely largely controlled by hydrodynamic processes. Here, this paper aims to follow ideas presented by Vatne and Refsnes (2003) to further examine the characteristics and progression of englacial conduits, with a focus on step-pool segments, their upstream migration and the hydrodynamic controls of channel evolution. Using the accessible part of an englacial conduit in Austre Brøggerbreen, Svalbard, we provide a detailed analysis based on direct, repeated observations made during five surveys over a 10 year period. Comparisons drawn with research in alluvial and bedrock stream systems address two key questions:

i. Do englacial conduits exhibit time-invariant morphological characteristics?

ii. Which factors control knickpoint face gradient and upstream recession rate?

These questions provide the basis for a conceptual model of the proposed process-form linkages, and advance our understanding of the causal mechanisms, development and maintenance of englacial channels.

2 Theoretical context

2.1 Knickzones, knickpoint and step-pools: character and stability

Delineation of channel reaches in stream morphology analysis is commonly based on a downstream section of consistent channel morphology, and with a length several times the channel width (Wohl et al., 1999). Within channel reaches, singular features of abrupt slope change over a limited length are referred to as knickpoints (Hayakawa and Oguchi, 2009) while reaches that are significantly steeper than adjacent reaches, consisting of both knickpoints and gentle stream segments, are termed knickzones (Hayakawa and Oguchi, 2006) (Fig. 1). Both knickpoints and knickzones migrate upstream by erosion rates that exceed those of adjacent reaches (Wohl, 1993; Wohl et al., 1999; Hayakawa and Matsukura, 2003, 2010), and this has been suggested to be the dominant mode of channel adjustment in response to either regional or local perturbation, for example, base level lowering (Shumm et al., 2000; Bishop et al., 2005; Larue, 2008) and flood events (Molnar et al., 2010). However, there is no consensus as to the origin and shape of knickpoints or the mechanisms causing knickpoint recession in bedrock channels over a range of annual to millennial time-scales (e.g. Sklar and Dietrich, 2001; Crosby and Whipple, 2006; Whittaker et al., 2007; Castillo et al., 2013; Cook et al., 2013; Phillips and Desloges, 2013; Hayakawa and Oguchi, 2014; Baynes et al., 2015). It is argued that knickpoint propagation is controlled by discharge and accordingly the contributing drainage area (e.g. Bishop et al., 2005; Crosby and Whipple, 2006; Loget and Van Den Driessche, 2009) and that substrate characteristics influence both recession rate and shape of the knickpoint face (Gardner, 1983; Larue, 2008; Phillips et al., 2010).

Step-pools form major geomorphological elements in knickzones in both bedrock (Miller, 1991; Wohl et al., 1999) and alluvial rivers (Chin, 1998; Wohl et al., 1999; Chin and Wohl, 2005; Chin and Phillips, 2007). A step-pool channel element consists of two components: an initial steep segment, and a downstream plunge pool. The channel-spanning steep segment is often termed the “step-riser” (Chartrand and Whiting, 2000) (Fig. 1), defined as where the occurrence of a critical slope segment is preceded and followed by shallow gradient segment (Milzow et al., 2006). Commonly, the step-riser is proceeded by a pool segment that is characterised by gradual changes in flow, although the high-velocity plunging flow or jet can cause erosional scour, thereby influencing pool geometry (Stein et al., 1993) and secondary circulation patterns (Venditti et al., 2014).

Step-pools form a series of distinct hydraulic conditions (Dust and Wohl, 2012) from subcritical flow upstream of the step (or knickpoint), to critical flow across the knickpoint, supercritical flow through the step-riser, and a turbulent plunge pool downstream which contains a hydraulic jump (Church and Zimmermann, 2007). They serve a fundamental role in steep streams because the steps reinforce bed stability (Church, 2002), and provide much of the elevation drop and channel roughness (Ashida et al., 1976; Whittaker, 1987; Chin, 1998). A downstream plunge pool dissipates energy by tumbling flow, turbulence, and eddies, which cumulatively generate heat and sound. For mountain streams, Montgomery and Buffington (1997) concluded that channel forms reflect specific roughness configurations adjusted to the relative magnitudes of sediment supply, slope and hydraulic regime; a conclusion which has been supported more recently (Wohl and Merritt, 2008).

Despite the importance of step-pool sequence geometries, surprisingly limited work has been done on different step morphologies or the character of the different types of jets and hydraulic jumps that occur in natural channels (Vallé and Pasternack, 2006; Wilcox et al., 2011), and even less is known of the morphological imprint different jets and jumps produce. Natural jets, where water flow changes from subcritical to supercritical, are reported to be (i) channel-bed supported sloping jets, or (ii) ballistic nappe flow, which is characterized by a free-fall water jet impinging on the downstream pool (Fig. 1). Downstream, within the subcritical pool segment, hydraulic jumps are observed to be both submerged and unsubmerged, controlled by the ratio of upstream hydraulic head and step-riser height relative to the pool or tailwater depth (Peterka, 1963; Vallé and Pasternack, 2006). For a knickzone where a succession of high steps are found, water flow typically decouples from the step risers and nappe flow dominates (Chanson, 1994). Under such conditions, energy is dissipated both by free-jet breakup in the air, by jet impact on the pool surface, and within the associated hydraulic jump (Chanson, 1994; Vallé and Pasternack, 2006). For sloping jets, energy dissipation processes will differ from ballistic jets, with greater influence of channel-bed roughness and friction. Vallé and Pasternack (2006) observed dichotomous hydraulic responses to a change in discharge for both sloping and ballistic jets: the projection length of the ballistic jet increased by 60 % in response to a doubling of discharge, but decreased by 20 % for the sloping jet. The effect of this is that the impact point of a ballistic jet changes more markedly with discharge, and will affect plunge pool geometry through the resulting flow circulation patterns (Venditti et al., 2014).

Independent of the types of jet and hydraulic jump, knickpoints provide exceptionally high hydraulic resistance and heat dissipation, and it has been argued that step-pool morphology is mutually adjusted with flow and energy expenditure (Abrahams et al., 1995; Chin, 2003; Curran and Wohl, 2003). Curran and Wohl (2003) assessed the relative influence of various channel elements on flow resistance in step-pool streams, and concluded that spill resistance, resulting from a sudden change in velocity where locally flow rapidly transitions from supercritical to (sub)critical, causes intense energy dissipation (Leopold et al., 1960). Such dissipation mechanisms may account for up to 90 % of total flow resistance (Curran and Wohl, 2003). Study reach averages have shown cumulative water surface drop associated with steps to serve as a first-order approximation of energy loss related to steps (Curran and Wohl, 2003). For steep steps, dissipation of kinetic energy as heat is dominant, although bulk stream water temperature change is independent of discharge; this contrasts to shallower gradient bed convexities where heat exchange with the bed may be more significant (Meier et al., 2003). The energy loss from steps depends on step size and discharge as small steps may be drowned out during high discharge when skimming flow dominates, a situation where energy dissipation is much less than under nappe flow conditions (Chanson, 1994).

2.2 Channels in ice

Supraglacial streams are distinct from their alluvial or bedrock counterparts: in the absence of clastics, a characteristic of most supraglacial streams, helical flow promotes meandering and results in a channel sinuosity inversely related to channel slope and stream power (Ferguson, 1973; Knighton, 1981; Marston, 1983). The at-a-station hydraulic geometry of supraglacial channels tends to respond to increases in discharge with heightened increases in flow velocity relative to changes in width and depth – the cross-sectional flow area (Knighton, 1981; Marston, 1983; Kostrzewski and Zwoliñski, 1995). Meltwater channel incision into, and lateral migration within, glacier ice results from heat exchange between flowing water in the channel and the ice walls. This heat exchange (q) is controlled by the temperature difference (ΔT) and the water velocity (v):

$$q = Bv\Delta T \tag{1}$$

where B is $2.64 \times 10^3\,\mathrm{J\,m^{-3}\,K^{-1}}$ for turbulent flow at 0 °C (Lock, 1990). Accordingly, the melt rate (M, in $\mathrm{m\,s^{-1}}$) associated with the flowing water can be estimated as:

$$M = \frac{q}{\rho_\mathrm{i} L_\mathrm{f}} \tag{2}$$

accounting for ice density ($\rho_\mathrm{i} = 900\,\mathrm{kg\,m^{-3}}$) and the latent heat of fusion ($L_\mathrm{f} = 334\,\mathrm{kJ\,kg^{-1}}$). More detailed numerical modelling approaches to this process are detailed by Jarosch and Gudmundsson (2012) and Karlström et al. (2013).

Isenko et al. (2005) showed theoretically that, in the absence of external energy (air temperature and incident radiation), water temperature in a straight ice-walled channel with constant gradient will reach a positive non-zero equilibrium temperature where the warming effect of viscous flow balances heat loss to the ice, which was in agreement with laboratory experiments. In the supraglacial environment, a meltwater temperature of 0.005–0.01 °C can account for rates of vertical incision between 20–58 $\mathrm{mm\,day^{-1}}$ (Pinchak, 1972; Marston, 1983).

However, due to the dependence between slope and water flow velocity, as slopes increase, so too do equilibrium water temperatures and potential incision rates (Isenko et al., 2005). Field observations of water temperature in glacier surface streams also suggest that heat generated by viscous flow is rapidly lost to the surrounding ice as water temperatures are found to be between 0.0 and 0.4 °C (Isenko et al., 2005).

Nonetheless, the proportion of down cutting energy explained by meteoric sensible heat and short-wave radiation fluxes compared to frictional heating of stream water remains ambiguous despite having been quantified (cf. Pinchak, 1972; Marston, 1983; Stock and Pinchak, 1995). Pinchak (1972) notes that the steep channel gradients needed for frictional heat genesis are not necessarily common on glacier surfaces. Moreover, the conditions controlling unstable, supercritical flow and its association with existing and/or resultant channel morphology is not well understood (Carver et al., 1994). Therefore, considerable uncertainty still remains over the transitions between meandering to stepped supraglacial channel profiles, and its relationship to surface slope; the nature of channel adjustment in three dimensions and over time remains poorly constrained (Irvine-Fynn et al., 2011).

In climatic settings whereby stream channel incision outpaces general glacier surface ablation, supraglacial streams may progressively deepen, and become entombed englacially due to snow bridging the channel's surface expression, or progressive ice creep closure of the inactive near-surface channel boundaries (Rothlisberger and Lang, 1987; Gulley et al., 2009a; Irvine-Fynn et al., 2011). However, in the englacial environment, stream waters are separated from meteoric influences, and heat transfer from kinetic energy and friction necessarily plays a more prominent role in channel adjustment. The loss of potential energy by flowing water, assuming conservation of energy, can increase water temperature at a rate of $0.002\,^{\circ}\mathrm{C\,m^{-1}}$ in the vertical dimension (Zotikov, 1982: cited in Isenko, 2006, and Isenko et al., 2005). A water temperature profile recorded for an englacial channel with 14 step-pool sequences descending 57 m suggested rates of water temperature increase may be higher than theoretically expected (Isenko, 2006) with resulting increases in stream incision rates at depth downstream. However, it is important to recall that, englacial channels are subject to creep closure as the ice responds to effective stresses: the rates of closure are dependent on the depth of overlying ice, ice temperature, and the channel water pressure (Nye, 1953; see also Jarosch and Gudmundsson, 2012; Evatt, 2015). Accordingly, the morphological development, evolution and maintenance of ice-bounded channels in glaciers deserves further scrutiny.

3 Field site and methods

3.1 Austre Brøggerbreen

The glacier Austre Brøggerbreen (78°55′ N, 11°46′ E) is a 10.2 km^2 north-facing valley glacier in north-western Svalbard (Fig. 2). With a long-term negative net balance of -0.4 m water equivalent (w.e.) a^{-1} since 1967 (Hagen and Lefauconnier, 1995), and current thinning rates of -0.6 m w.e. a^{-1}, the glacier is downwasting rapidly in both its ablation and accumulation areas (Barrand et al., 2010; James et al., 2012) and exhibits reduced dynamics, with ice flow rates of $< 3\,\mathrm{m\,a}^{-1}$ (Hagen and Liestøl, 1990). The glacier is now assumed to be entirely cold-based (cf. Björnsson et al., 1996) and drainage system is predominantly supraglacial characterised by deeply incised surface streams and a few isolated moulins (Hagen et al., 1991). Seasonal meltwater flow into these moulins follows englacial flowpaths, with channel (or conduit) heights in the order of ≤ 10 m, likely remaining at atmospheric pressure for much of the ablation season (Hagen et al., 1991; Vatne, 2001; Stuart et al., 2003). Contemporary runoff chemistry confirms the apparent absence of meltwaters draining to or from the glacier's bed (Hodson et al., 2002), and dye tracer experiments suggest typical englacial throughflow velocities and discharges of 0.1–0.55 $\mathrm{m\,s}^{-1}$ and 1.5–3.5 $\mathrm{m}^3\,\mathrm{s}^{-1}$, respectively, are common during the summer ablation season at the site of meltwater emergence at the ice margin (Vatne, 2001; Holtermann, 2007).

3.2 Conduit survey measurements

The longitudinal englacial channel profile from the entrance point approximately 200 m a.s.l. (Fig. 2) was surveyed for the first time in October 1998 (Vatne, 2001), resurveyed in April 2000 (Vatne and Refsnes, 2003) and then again in spring 2004, 2005 and 2008. The switch from autumn to spring surveying was to ensure in-stream pools were frozen, to enable access to greater depths. Although the deeper parts of the conduit showed clear signs of closure by creep over the winter; all the surveys, except that in 2004, were halted due to unfrozen pools and water-filled conduit segments rather than impassable channel dimensions.

The position of the entrance for individual channel surveys was determined by Garmin handheld GPS receivers, with an average horizontal accuracy of 15 m (Garmin, 2015). For all surveys, the morphological assessments was conducted with a laser distance meter (Leica Disto Classic, with precision of < 2 mm), a folding rule, and a magnetic compass. Similar to the methods reported by Gulley and Benn (2007), the conduit was divided into linear segments, based on breakpoints in the longitudinal profile (e.g. the foot and crest of a step), or corresponding to limits to a line of sight. The orientation of each segment was measured using a magnetic compass. Channel width was measured at locations considered representative for the channel reach, either with the laser or folding rule both near the bed, and at 1 and 2 m above the apparent channel floor, respectively. Although laser measurements are precise, it is hard to assess the errors involved in the measurements, as many were acquired in challenging positions, but uncertainties are estimated to be less than a few percent (see Gulley and Benn, 2007).

Step-riser morphology varied from steep rapids to vertical waterfalls. In this study, rather than arbitrarily define a critical step riser slope by fitting cumulative distribution functions to observed data (Milzow et al., 2006), steps were provisionally defined as where the vertical elevation change (V) was larger than the concurrent horizontal distance (H) (see Fig. 1). Each vertical step height was measured from the top of the ice lid in the downstream pool to the top of the knickpoint convexity upstream (Fig. 1). During winter surveys, although approximate pool area could be discerned, conduit air temperatures and water surface freezing precludes access to quantify three-dimensional pool geometries. We acknowledge the fact that this also leads to measurement of minimum rather than actual step height, as pool depth is not included; however, observations suggest that the submerged portion of the step height is inversely related to step height. The channel morphology data were then further constrained to reflect step-pool sequences: only steps exhibiting an abrupt downstream increase in channel width, indicating the presence of a hydraulic jump, and excess energy dissipation, were used in the analyses which follow. Conduit segments that did not fulfil the both the step and step-pool criteria were considered simply as channel rapids.

Series of longitudinal grooves parallel to the channel bed were commonly observed, producing a characteristic cuspate channel wall morphology (Marston, 1983). At one step riser, the distances between the cuspate forms separating the individual grooves were measured perpendicular to the channel floor. Actual conduit height could not be observed in most cases, due to narrow and complex conduit roof geometry, and therefore was not measured. Except for the near-surface and the deepest sections of the channel, estimated conduit heights typically exceeded 10 m, yielding cross-sectional areas of $> 5\,\mathrm{m}^2$.

4 Results and data analysis

4.1 Longitudinal profile evolution and channel reach characteristics

The individual profiles for the five englacial channel surveys are presented graphically in Fig. 3. The profiles document englacial channel position extending between 42 and 85 m from the glacier surface and across horizontal thalweg lengths of 174 to 301 m. To facilitate direct comparison between surveys, the elevation of the start point of each of the individual surveys is adjusted to be relative to the 1998 ice surface elevation, using an annual mean ice surface lowering of $0.9\,\mathrm{m\,yr^{-1}}$ at ~ 200 m a.s.l. according to contemporary data from neighbouring Midtre Lovénbreen (Kohler et al., 2007) and accounting for the mean difference between the two glaciers' thinning rates between 1990 and 2003 (Barrand et al., 2010). The accompanying summary data for the profile characteristics is shown in Table 1. Due to the horizontal uncertainty in the absolute location of the conduit entrance, caution must be taken when comparing and interpreting changes in horizontal position of individual features from one survey to another using Fig. 3. This is further compounded by the observed changes in planform (see Sect. 4.3): apparently large upstream horizontal migration in the profile can relate to changes in planform curvature. Nonetheless, data reveal marked changes in channel profile, and specifically the progressive development of a vertical shaft (moulin) descending from the conduit entrance location, and apparent lateral recession of step-risers or kickzones and the incision of low gradient sections. The low gradient segments interrupted by much steeper knickzones are a characteristic morphology in all surveys.

Here, we define channel reaches as segments more than 10 times the average channel width, with a consistent channel gradient markedly different from the immediate upstream and downstream reaches. Individual reaches are typically delineated by marked breaks in channel gradient. Consequently, three main types of channel reach were identified in the conduit profile data (Fig. 4): (i) low gradient (LG) reaches with slopes $< 0.06\,\mathrm{m\,m^{-1}}$, (ii) medium gradient (MG) reaches ($0.06 < \text{slope} < 0.5\,\mathrm{m\,m^{-1}}$), and (iii) high gradient knickzones (KZ) exhibiting slopes $> 0.5\,\mathrm{m\,m^{-1}}$. The descriptive statistics for the three categories of channel reach are presented in Table 2.

The LG reaches are characterized by very stable gradient all years ($X_\mathrm{w} = 0.04\,\mathrm{m\,m^{-1}}$ $\sigma_\mathrm{w} = 0.015\,\mathrm{m\,m^{-1}}$) (Table 2); they account for small quantities of heat dissipation because they are responsible for less than 10 % of the vertical descent despite representing from 44 to 74 % of the horizontal channel thalweg length. Additionally, the LG reaches display relatively small variations in channel width ($\sigma = 0.32\,\mathrm{m}$), insignificant or absent bed roughness elements, and broadly parallel channel walls (Fig. 4a). Channel widths for MG reaches are larger and more variable compared to the LG reaches (Table 2) and concomitant meandering morphologies are commonly observed (Fig. 4b). Channel width typically more than doubled through channel meander bends, and many bends consist of small (typically 0.3 m) steps immediately upstream of a channel curvature, with a small (~ 1–$3\,\mathrm{m}^2$) elongated pool forming just upstream the meander apex and/or throughout the local conduit bend. Knickpoints of up to 3 m in vertical de-

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scent are also found in the MG reaches. Morphologically, the knickzones (KZs) are the most varied reaches: for all surveys, they are dominated by either a few large or many smaller knickpoints, or step-pools cascades (Fig. 4c and d). Summary statistics for channel width are not presented for knickzones as a representative channel width was poorly defined for most step-risers, and arguably definition of channel bed widths is not necessarily hydrologically meaningful, particularly where the jet detaches from the bed (Fig. 1). Channel planform for KZ reaches varied from highly sinuous to almost straight. Steps and knickzones are responsible for a significant proportion of the conduit's vertical descent, typically ranging from 74 to 85 %, except for the 1998 channel survey in which they accounted for only 40 % (Table 1). In general, the higher the steps or knickzones, the larger the fraction of the step-riser that is vertical.

Although the number of LG and KZ reaches is broadly similar for the surveys between 1998 and 2008, the KZs progressively became steeper and are located at a more upstream position closer to entrance point B throughout the period (Fig. 3, Table 1). At the same time average channel slope increased from 0.20 to 0.44 $\mathrm{m\,m^{-1}}$. From 1998 until 2005 average step height increased and step density reduced, suggesting that larger knickpoints appear to capture smaller knickpoints by incising upstream at a faster rate. The most striking change observed between 1998 and 2008 was the entrance to the englacial system which changed from near horizontal to near vertical (Fig. 3). By 2008, the entrance exhibited a near classical moulin form, descending vertically 37 m from the contemporary surface, and the conduit profile is broadly characterized by a few very large steps, but this is interspersed by many small convexities (< 1 m step height). This is reflected in the records of average step height, which is more than doubled from 1998 to 2005, but then shows a small decline from 2005 to 2008, despite by far the largest single step evident in 2008 (Table 1).

4.2 Knickpoint morphology and wall grooves

Although channel knickpoints exhibit large morphological variations that are difficult to place into discrete categories, we suggest knickpoint morphology to be divided into three major types based on the morphology at the knickpoint lip, and the presence, size and shape of appurtenant downstream pools and conduit void spaces (Fig. 1). Here, enlarged conduit void spaces (or englacial caves) are often associated with step-riser and pool sequences or channel knickzones. The two dominant knickpoint lip morphologies we consider to be endpoint members of a continuum, where the Type 1 is characterized by a gradual transition from the upstream low gradient channel to the riser face, typically with distinct channel wall groves extending to the pool lip (Figs. 1 and 5). For many step-risers, the grooves extend throughout the step riser to the downstream pool lid, enabling reconstruction and comparison of channel incision rates upstream and throughout the knickpoint (Table 3). This knickpoint type may be further subdivided into two endpoint types based on the shape of the downstream pool. The first type, Type 1A, is characterized by highly elongated pools downstream of the step riser and was most pronounced where the step riser had a shallower slope. The second, Type 1B, is where the step-riser reaches a near vertical nature, and the downstream pool may exhibit a near circular plan-form geometry with a well-developed associated cave. For very large risers of this type, cave dimensions can attain diameters more than ten times the downstream channel width. In 2000, the cave found downstream of the vertical step extending from ∼ 40 to 65 m depth, was estimated to have a volume of ∼ 400 m^3 (Vatne and Refsnes, 2003). At the other end of the continuum, knickpoints are characterized by a sharp knickpoint lip and a vertical face. This type (Type 2) is almost exclusively found where a pool is located immediately upstream of the knickpoint, and is often observed to exist in series with two or more step pools, without intervening reaches (Fig. 1). For these cases, wall grooves are absent, and characteristic channel width is often not clearly determinable. The associated downstream pools had near circular shape and a width more than three times the average channel width found in upstream and downstream LG and MG reaches (Fig. 4d). As all these types of knickpoints incise and migrate upstream, but downstream caves and pools are left remnant, resulting in channel segments exhibiting highly variable channel width, with undulating walls and channel floors (Fig. 4c and d).

4.3 Planform changes

In all surveys channel incision was observed to broadly follow the pattern of the old channel, with the largest deviations coinciding with upstream migration of knickpoints. Uncertainties in manual compass readings for individual reach measurements are likely to be responsible for slight deviations in the general directional trend of the surveyed channel (Fig. 6). Also some of the observed variations in channel curvature and sinuosity, which vary between 2.0 and 2.3 $\mathrm{m\,m^{-1}}$ for the individual surveys, may be explained by these uncertainties. Observations of near parallel channel walls extending for more than 10 m in LG sections confirmed a more or less vertical incision (Fig. 4a). The observed changes in planform profile mainly manifested as variations in channel curvature, resulting in a maintained overall conduit sinuosity. Meander bend migration is apparent, for example at ~ 50 m horizontal distance from entrance B, but rates of development were slow compared to channel incision rates, as evident from Figs. 4 and 6. However, the repeat surveys did not suggest significant lateral channel meandering was dominant, rather observations implied vertical incision and knickzone recession was the prominent morphological adjustment in the englacial conduit. As noted above, incision and knickpoint migration is likely to mask the nature of changes in channel planform adjustment. Consequently, here, our analysis and discussion focusses on the conduit's longitudinal rather than planform profile.

5 Discussion

5.1 Overview of morphological channel change

The 10 years of repeated englacial conduit surveys at Austre Brøggerbreen show that the studied channel underwent subtle, progressive planform changes: the channel maintained the same overarching orientation but showed minor variations in overall sinuosity. This evolution has more or less continued according to data presented in a conduit survey in 2014 (Myreng, 2015). This contrasts with results shown by Pulina (1984) at Werenskioldbreen, a more dynamic polythermal glacier, where increased sinuosity, downstream elongation were observed for a low gradient englacial channel without a markedly stepped profile. However, here, the most interesting observation is that over the surveying period, the initially gently sloping englacial channel entrance evolved to a vertical moulin form. This challenges the prevailing assumption that crevassing or ice fracture is necessary for the development of a moulin (e.g. Stenborg, 1969; Boon and Sharp, 2003). The changing profile shown in Fig. 3 is analogous to that of the Holocene bedrock channel profile development reported by (Baynes et al., 2015) for the Jökulsárgljúfur canyon, Iceland, albeit over markedly differing time-scales. While glacial streams are mechanistically different from bedrock channels, processes may be equivalent: roles of bedload (e.g. Sklar and Dietrich, 2001; Cook et al., 2013) and bedrock strength (e.g. Jansen, 2006) are replaced with the thermal erosion and structure and crystallography of the ice substrate. For the englacial conduit, potential influences from extra-channel clastic supply, flood events or periodic increases in contributing drainage area are largely absent. The diurnally varying discharge that characterises the active flow regime of the conduit is superimposed upon the seasonal trend associated with the increase in melt volumes as snow cover declines, with "flood" events likely linked to synoptic forcing since summer season precipitation in the locality is low (Hodson et al., 1998; Førland et al., 2011). Therefore, the flow regime through the conduit is likely to be moderately stable compared to other terrestrial channels. Furthermore, the base-level for the channel outlet at the glacier margin remained essentially constant over the duration of the surveys ensuring only changes in local (reach-scale) base level may have roles to play in rates of channel adjustment. Consequently, comparisons between bedrock and ice-bounded channels may be drawn, yet with focus primarily on hydraulic processes.

Observations did not allude to a conduit geometry controlled by englacial hydraulic potential (Shreve, 1972), but rather conformed to observations of sub-horizontal, stepped channels made through speleological investigations at numerous glaciers (e.g.

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Pulina, 1984; Holmlund, 1988; Griselin, 1992; Vatne, 2001; Gulley, 2009; Gulley et al., 2009a). Our contention is that englacial knickzone (KZ) recession, coupled with progressive albeit slow vertical incision, dominates englacial channel adjustment, thereby concealing the nature of any meander bend migration and development over the study period. This notion is reaffirmed from observations made in low gradient (LG) reaches that revealed the former conduit could be observed above the contemporary channel floor (Fig. 4a); such perched meander bends have been observed in other englacial channels (e.g. Gulley et al., 2009a). Similarly, during the study period, there was no evidence of englacial channel re-routing due to conduit blockage (e.g. Griselin, 1992; Gulley et al., 2009a). Therefore, the remaining discussion focuses on morphological characteristics of the different reaches, and variations therein, over the decade of observations, and explores potential controls in step-riser morphology and how this relates to upstream knickzone migration rates.

5.2 Do englacial conduits exhibit time-invariant morphological characteristics?

Knighton (1985) suggests supraglacial streams are capable of developing and maintaining characteristic forms. This may be exaggerated particularly in perennial supraglacial stream channels, which commonly carry heightened proportions of supraglacial runoff discharge and lack tributary systems, and exhibit elongated channel patterns (Ewing, 1972). Here, our analysis and classification of the longitudinal profiles suggest that primary reach morphologies also exist in annually reoccupied cut-and-closure englacial conduits; their characteristics are relatively easily defined based on channel gradient and the presence of step-pools forms. These reach forms have contrasting rates of channel adjustment, which in turn conditions the overall morphology of the englacial flow path, and results in a time-variant, evolving channel.

The LG reaches constitute the major reach type for conveying water horizontally; on average, including data detailed in Myreng's (2015) re-survey, they represent about 62 % of the horizontal channel length. This type of reach has uniform morphology and consistent channel gradients, both within and between individual surveys. They are observed to incise with near constant cross-sectional form, which is in line with observations in supraglacial streams (Marston, 1983). Therefore, commonly, LG englacial channels walls are comparatively parallel, only containing gentle undulations. This form suggests conditions of reduced friction and low heat dissipation hence channel incision rates are low compared to adjacent MG or KZ reaches. Vatne and Refsnes (2003) identified the old channel bed in LG reaches in two consecutive surveys and measured incision rates of 1–1.8 $\mathrm{m\,a^{-1}}$. Although these rates are lower than those observed in supraglacial streams (Dozier, 1976; Marston, 1983; Müller, 2007), this is unsurprising: (i) the typical gradient in LG reaches reported here (0.04 $\mathrm{m\,m^{-1}}$) is lower than that reported in the literature for supraglacial streams, and (ii) the meltwater in the englacial channel is isolated from the meteoric energy contributions that can contribute to heat in supraglacial streams, and which may account for 25–50 % of the incision rate (Dozier, 1976; Stock and Pinchak, 1995). The roles and influence of increasing temperatures as water loses potential energy in descending through knickzones (Isenko, 2006) or secondary circulation patterns (Venditti et al., 2014) remain unclear.

From the sequential longitudinal profiles (Fig. 3), it appears that LG reaches are produced downstream of KZ reaches as these migrate laterally upstream. This process of channel evolution has been implied previously (Gulley et al., 2009b) but not clearly evidenced. The KZ reaches are unable to incise vertically beyond any plunge pool formed at their base as they are constrained by the downstream LG channel which serves as a local base level. As a knickzone recedes upstream, as a consequence of step-riser erosion, it will leave behind a gently sloping channel reach, which will retain its fundamental channel characteristics until it is captured by the next downstream knickzone incising upstream. This suggests LG channel reaches to be stable, quasi-equilibrium reach type that conforms to a conceptual model of channel evolution and down cutting that is dominated by wave trains of knickzones migrating upstream, as has been suggested for bedrock channels (Loget and Van Den Driessche, 2009).

Our observations also suggest KZs to be a typical reach type, as they are found in all surveys and it is likely that the same KZs are observed from one survey to the next, the next, albeit migrated to an upstream location. The data show the KZ evolves towards increased steepness (Table 1), which is a result of a general increase in step riser height. This is paralleled by a general increasing proportion of the vertical descent taking place through the KZ. It is therefore suggested that that, once formed, KZs are self-reinforcing features as they will sustain higher heat dissipation and incision rate than immediate upstream and downstream channel reaches. Apart from an evolution in KZ steepness, KZs may also gain height over time. Although the KZ height evolution is influenced by the incision rate of the downstream LG reach, it will be dominated by the gradient of the upstream reach it captures by headward erosion, and the rate in which it does so.

The progressive evolution of the englacial conduit at Austre Brøggerbreen appears to be dominated by KZ reaches that, over time, have evolved from MG into KZs. The KZs have subsequently recede headward and ultimately reached the channel entrance location. Arguments supporting a transition from MG to KZ reaches can be found both in the observed evolution of the conduit profile, observations in supraglacial streams, and studies of flow and secondary currents in meander bends. In meander bends, incoming flow creates a transverse bed slope which in turn creates a curvature and topography driven secondary flow (Blanckaert and De Vriend, 2004; Chen and Tang, 2012). These secondary currents leads to spatially and temporally varying patterns of energy dissipation on the channel walls, particularly in sharp bends (Blanckaert and De Vriend, 2004) and potentially these secondary currents lead to knickpoint development as seen in supraglacial channels (Fig. 7). An important consequence of this evolution is a significant reduction in slope and hence driving forces for the remaining downstream conduit reach.

Support for these overarching notions of channel change can be made from the observations of smaller-scale conduit morphology: acknowledging that grooves on the channel walls are morphological markers representing high discharge events (Marston, 1983), they can be used as a proxy to reconstruct incision rates for channel reaches of differing gradient. The number and size of individual grooves, compared to average annual rate of channel incision in near horizontal reaches (Fig. 5), rule out the possibility that the observed grooves result from diurnal discharge cycles (Marston, 1983). At Austre Brøggerbreen, with an englacial system solely fed by diurnally varying supraglacial meltwater volumes, we anticipate the grooves to result from dominant or recurrent peak discharges relating to synoptic periods or specific flow regimes that last for periods of the order of days or perhaps weeks during the ablation season. Although measured only at one location, observations at several step risers show groove size increases as the channel enters steeper gradients at a knickpoint (Table 3), which demonstrate the effect of gradient and water velocity on incision rate, confirming the theoretical predictions (Isenko et al., 2005). The observations, however, do not show an unambiguous pattern in groove size with gradient, hence acquiring more data is critical to improve our understanding of riser evolution. However, we anticipate that direct upstream controls on water velocity and water temperature (e.g. channel reach width, slope and length; heat production and heat transfer; and the overall shape of the knickpoint lip) influence groove size for a given gradient. Crucially, if grooves are a proxy for incision rates, the pattern reported here implies there is the potential for a gradual steepening of step-riser segments. Over short timescales, our data can only be used for qualitatively comparing incision rates between low gradient reaches and non-vertical steps. The direct effect is that step-risers migrate upstream by headward recession at rates several times the vertical incision of near horizontal channel reaches. Our results highlight the KZ recession rates are an order of magnitude higher than vertical incision of low gradient reaches. This is in line with observations both in ice-walled conduits (e.g. Gulley et al., 2009) and in bedrock channels (e.g. Hayakawa and Matsukura, 2003; Turowski et al., 2008a, b).

Both hydrodynamic theory (Isenko and Mavluydov, 2002; Jarosch and Gudmundsson, 2012) and field observations (Knighton, 1972; Ferguson, 1973; Dozier, 1976) suggest that slope controls formation and evolution of glacier channel planform geometry.

However, the observations made within Austre Brøggerbreen, suggest both LG and KZ to only moderately change their own channel planform as vertical incision dominates the erosion of the ice substrate. LG reaches seem to largely inherit the planform geometry left behind by the upstream KZ recession that forms them, hence it is unclear if, over time, meandering can develop in LG reaches. KZ appear to adopt and adapt the existing upstream planform geometry and simultaneously appear to reduce channel sinuosity. MG reaches, on the other hand, show clear evidence of lateral erosion in meander bends (Fig. 4b), which also is commonly observed in supraglacial environments (Knighton, 1972; Ferguson, 1973; Dozier, 1976). MG reaches show the highest variability with respect to percentage of descent and horizontal channel length both within and between surveys (Table 2), and also highly variable channel widths caused by lateral incision in meander bends. We interpret the varying importance of MG reaches in the observed conduits to represent an unstable reach type that tends to evolve toward a KZ geometry, as seen from the ten year evolution of the uppermost part of the conduit. While characterisitc reach types were found in all surveys, the morphology was continually changing and is suggestive of an englacial system that is in the process of rapid, transient development (particularly prior to 2005) through which evolution of KZs, and KZ recession, lead to a single, high step-riser (moulin), and LG englacial reaches are controlled by the drainage system base level.

5.3 Factors controlling knickpoint face gradient and upstream recession rate

Vatne and Refsnes (2003) suggested that large step-risers retreat at a faster rate than smaller risers, and hydrodynamic theory predicts heightened melt rates at high and steep risers (Isenko and Mavluydov, 2002). However, these notions are challenged by the data presented here; the evolution of the KZ reaches shows no simple relation between step-riser/knickzone height and knickpoint/knickzone recession rate (Fig. 3). To resolve this apparent absence of a direct relationship, we propose a conceptual model of process form linkages where knickpoint lip shape, which controls the type of jet that forms, influences knickpoint recession rate by determining the amount of heat that is transferred directly to the step-riser face.

For an ice walled channel, incision rates will mainly be controlled by heat produced locally, as heat is rapidly lost to the surrounding ice (Isenko et al., 2005). Therefore, incision rates are correlated with water velocity (Lock, 1990) and rate of heat loss to the channel boundaries (Jarosch and Gudmundsson, 2012). This is observed for the channel segments immediately upstream of Type 1 knickpoints (Fig. 1) where cuspate erosion forms (grooves) on the channel walls witness amplified incision over the lip as the channel-bed gradient increases. The grooves found at Type 1A knickpoints attest to the presence of a dominantly bed supported jet. As long as the jet is bed supported, heat is lost along the entire step-riser, and recession rates will be highest on the downstream end. The typically elongated downstream pools associated with Type 1A knickpoints suggest that much of the momentum, and thus heat, is transferred and dissipated throughout the pool in a downstream direction. Limited heat is dissipated laterally and reduces channel widening. We, therefore, suggest Type 1A knickpoints effectively transfer heat to the channel bed at the lower end of the step-riser, steepening the step, and thus enable the highest headward recession rates of all the observed knickpoint types.

Step-risers of Type 1B differ from Type 1A in that the associated cuspate forms are only found in the upper part of the step-riser aligned with the knickpoint, which suggest water flow detaches from the riser face and becomes ballistic. Combined with the observation of englacial caves associated with Type 1B step-risers, this leads us to suggest that only part of the heat is dissipated over the channel bed, and that headward recession rates are subdued compared to Type 1A knickpoints. The knickpoint morphology of Type 1B suggest nappe flow with a ballistic jet with jet breakup in the air (Chanson, 1994) plays an important role in energy dissipation and heat transfer. Jet breakup will provide ample water spray, which along with air circulation, transfers heat dissipated by the jet break up. This heat will be transferred to cave walls by advection, with direct conduction from the circulating air and water particles to the ice walls. In the case of ice wall temperatures below the pressure melting point, refreezing of water spray will release additional latent heat that accelerates the melt process. However, the combination of a partly bed supported and partly ballistic jet may lead to higher recession rates in the upper part of the riser face. This process is likely reversed during low flows as water to a less degree detaches from the step riser. Strong evidence of this process is seen on many risers where the late season low flows have incised narrow furrow in the step riser face (Fig. 8).

Englacial caves formed in association with the conduit's plunge pools are likely to approach an equilibrium size with energy dissipation; hence they should reflect step height at some characteristic discharge. For caves with broadly spherical or cylindrical shapes, the surface area of the walls is proportional to the square of the cave radius. Hence, a small increase in cave radius is accompanied by a greater increase in surface area on which heat exchange can occur. Step-riser height and discharge that, combined, control the controls the degree of flow detachment, will control cave size as both the jet impact point and the degree of jet breakup will vary. The cave size will likely adjust to energy dissipation under high discharge conditions, with respect to the rate of ice creep closure.

Within the pools themselves, jet impact causes a submerged hydraulic jump and immediate heat dissipation. Exit channels from these caves are typically near horizontal and rapidly attain a cross sectional area similar to that found immediately upstream the knickpoint, suggesting most of the heat is dissipated locally within the plunge pool and cave, as water rapidly attains equilibrium temperature (Isenko et al., 2005) and secondary circulation currents (Venditti et al., 2014) rapidly reduce the excess heat energy.

Type 2 knickpoints are typically found within sequences of step-pools with no intervening straight low gradient conduit (Fig. 4d). Here these step-risers were more or less vertical, suggesting the shape of the step-riser to retain an equilibrium longitudinal profile where the flow is in contact and effectively incising the riser face. However, this type of knickpoint also forms associated caves, but typically with lower englacial void volumes than Type 1B caves. Here, it is the lateral recession of the step-riser which produces the more canyon-like cave form.

In solid rock, headward erosion of waterfalls has for long been attributed to undercutting at the base of the waterfall followed by a collapse of the overhanging rock (Gilbert, 1890), a model later referred to as the undercutting model or caprock model (Hayakawa and Matsukura, 2010). However, this process only applies to certain lithological settings. Englacial step risers were rarely observed to be undercut and overhanging, suggesting undercutting being an insignificant process in step evolution and migration. This is markedly similar to many bedrock step-pool sequences. In a recent study of erosion at Niagara falls, Hayakawa and Matsukura (2010) concluded that the waterfall recedes gradually by the fluvial erosion erosion driven by bed surface surface water flow and gradual detachment of small particles from the fractured rock of the waterfall face, and that frost weathering may be responsible for keeping its overhanging shape.

5.4 Perennial conduit persistence and morphological maintenance

The persistence of the conduit itself is of interest, with clear evidence that the mapped conduit is reoccupied each melt season. Using published ice temperature profiles from two sites on Austre Brøggerbreen (Hagen et al., 1991) and by crudely assuming circular channel cross-section, with a conduit radius of 1 m, the hypothetical time for englacial conduit closure was estimated, following Nye (1953) and Röthlisberger and Lang (1987):

$$u = rA\left(\frac{p_\mathrm{i} g h_\mathrm{i}}{n}\right)^n \tag{3}$$

in which u is the closure rate, p_i is glacier ice density, g is gravitational acceleration, h_i is overlying ice thickness, n is an ice creep parameter (≈ 3) (Hooke, 1981). The value A, a second ice flow parameter, can be approximated (Hooke, 1981) as:

$$A = A_0 e^{\left(\frac{-Q}{RT_\mathrm{i}} + \frac{3C}{(T_\mathrm{r} - T_\mathrm{i})^k}\right)} \tag{4}$$

in which, $A_0 = 9.302 \times 10^{-7}\,\mathrm{kPa}^{-3}\,\mathrm{a}^{-1}$, $Q = 78.8\,\mathrm{kJ\,mol}^{-1}$, the gas constant $R = 8.321\,\mathrm{J\,mol}^{-1}\,\mathrm{K}^{-1}$, $C = 0.16612\,\mathrm{K}^{k}$ for which $k = 1.17$, T represents temperature for ice and a reference temperature of 273.39 K (subscripts i and r, respectively). Figure 9 illustrates that, assuming a 70 day long hydrologically active summer season that typifies the study site's location (Hodson et al., 2000), the perennial persistence of enlarged channel forms at depths of ∼ 30 m or more is, theoretically, compromised. This clearly contradicts our observations of an open conduit reaching depths of 85 m (2008) following the winter period, with evidence suggestive of the persistence of the overall channel longitudinal profile. Commonly, the persistence of englacial and subglacial channels at depth has been ascribed to a reduction in conduit closure rate through water storage (e.g. Schroeder, 2007; Benn et al., 2009; Irvine-Fynn et al., 2011). As detailed in Sect. 3.2, the exploration of the englacial channel at Austre Brøggerbreen was halted due to unfrozen pools or water-filled conduit segments at depths considerably below the theoretical and modelled limits. These open channel water-free conduit conditions have been observed elsewhere at depths > 70 m below the glacier surface (see Table 2 in Gulley et al., 2009b; Myreng, 2015; Vatne, unpublished data).

Here, the estimated rate of closure (Eq. 4) applies to a conduit with a circular cross section, which differs from the observed canyon-like forms with vertical extents of an order of magnitude greater than widths. In alternative numerical simulations of englacial incision of channels with hydraulic geometry akin to supraglacial channels that leads to the formation of deep, narrow conduits, and their preservation, unpressurised conditions could persist for a year although likely limited to depths < 50 m (see Jarosch and Gudmundsson, 2012). It is possible that the surveyed conduit has been periodically water filled during the winter months between the surveys, but this is not known. However, over the last two decades, AB has never formed a proglacial icing, which suggests winter drainage and emptying of water filled englacial conduits does not take place, contrary to observations at many other cold glaciers in Svalbard (e.g. Hodgkins et al., 1998). Consequently, our observations highlight that contemporary models utilised to estimate englacial conduit closure rates may not be appropriate and more field data is needed to constrain the nature of channel closure and processes that contribute to channel maintenance. This is particularly critical with the growing recognition of the role englacial channel incision may hold for meltwater flowpaths in valley glaciers (Gulley et al., 2009b; Naegeli et al., 2014) or potentially areas within Earth's ice caps and the Greenland Ice Sheet where evidence suggests the potential for laterally flowing or tortuous englacial channels (e.g. Reynaud and Moreau, 1994; Ahlstrøm, 2007; Catania et al., 2008; McGRath et al., 2011; Andrews et al., 2014). With recent work seeking to revise the mechanics of englacial conduit behaviour (Evatt, 2015), results here demonstrate that there is clear justification for further examination of the mechanisms of englacial conduit formation, maintenance, closure and morphological change. The combined approach of speleological investigations of englacial cave morphology coupled with numerical models to simulate conduit change may serve to clarify channel forming processes.

6 Conclusions

This research presents a unique time-series of morphological observations of an englacial channel in a cold-based glacier, and provides new insight into dynamic channel adjustment and processes controlling conduit evolution and providing the basis for a conceptual model of process form linkages of step-riser geometry. We found that englacial channels develop and maintain characteristic channel reaches, namely low gradient, medium gradient and knickzone reaches. The consistencies in channel form over the survey period suggest these channel reach types to be considered time-invariant equilibrium morphological features. Knickzones are responsible for the majority of the geomorphic work, as recession rates are a magnitude higher in knickzones than vertical incision in low gradient reaches. Knickpoint lip type controls the type of jet produced, either bed supported, ballistic, or a combination, which in turn controls knickpoint headward recession rates. We argue that bed supported jets are more efficient in transferring heat to the channel bed compared to ballistic jets, hence they are responsible for higher recession rates. However, ballistic jets can contribute to the development of englacial caves associated with knickzones through aiding melt processes at the ice walls. The multiple surveys reported here demonstrate that deep vertical moulins may be formed by the incision of supraglacial streams in combination with headward recession of knickzones. This morphological development coupled with the apparent deficiencies in being able to model conduit closure rates successfully highlight the importance of continuing research in englacial hydrological behaviour.

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Table 1. Summary of channel data for individual surveys. H_t, V_t and S_A denotes total horizontal length along thalweg (in m), total vertical height (in m), and average slope gradient ($\mathrm{m\,m^{-1}}$), respectively. LG, MG and KZ denotes number of reaches classified as low gradient, medium gradient and knickzones, respectively. K_d denotes step density calculated as number of steps divided by total channel length along thalweg, and K_H average step height (m).

Year	H_t	V_t	S_A	LG	MG	KZ	K_d	K_H
1998	208	42	0.20	4	1	2	0.07	2.0
2000	295	68	0.23	2	2	3	0.04	3.3
2004	301	59	0.20	3	1	2	0.03	5.6
2005	274	85	0.31	3	1	4	0.03	8.5
2008	174	77	0.44	2	2	2	0.08	4.8

Table 2. Statistics of reach characteristics for individual surveys. Here, *n* denotes number of reaches in the survey, *H* % and *V* % denotes the percentage of the horizontal and vertical distance of the total surveyed channel length by the different reach types. *S* denotes slope, and X_w and σ_w represent mean channel width and standard deviation, respectively. Note, the channel geometry of KZ reaches often precluded the robust measurement of a meaningful channel width.

	LG					MG					KZ			
Year	*n*	*H* %	*V* %	*S*	X_w/σ_w	*n*	*H* %	*V* %	*S*	X_w/σ_w	*n*	*H* %	*V* %	*S*
1998	4	44	6	0.03	0.90/0.31	1	46	54	0.25	1.11/0.67	2	11	40	0.80
2000	2	48	7	0.04	0.94/0.33	2	38	18	0.11	1.08/0.62	3	14	74	1.30
2004	3	73	5	0.04	0.93/0.32	1	18	10	0.11	1.13/0.64	2	7	85	2.10
2005	3	74	9	0.04	0.92/0.31	1	13	6	0.14	1.15/0.66	4	13	85	2.50
2008	2	68	6	0.04	0.96/0.33	2	24	16	0.30	1.17/0.66	2	9	78	4.08

Table 3. Statistics of variations of groove size over the 1.5 m high knickpoint located 70 m downstream from the entrance in 1998. Individual grooves tend to be blurred downstream from the apex and with distance from the bed (Fig. 5), hence measuring errors related to accurately identifying groove borders vary but are estimated to be ~ 2 cm. Headers refer to groove number measured from the stream bed (#) and measurements made 2 m upstream of the knickpoint convexity (2 m), at the knickpoint apex (Apex) and at the downstream pool (*P*).

#	2 m	Apex	*P*
1	4	9	17
2	25	36	51
3	36	48	66
4	23	33	47
5	17	26	38
6	29	44	63
7	22	31	47

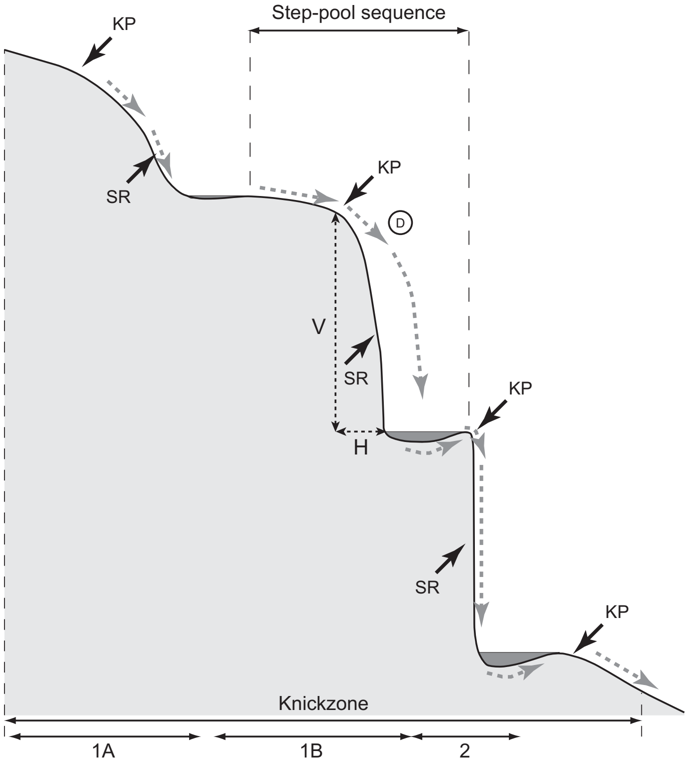

Figure 1. Schematic to illustrate step-pool sequences and the terminology for knickzone (KZ) morphology. SR and KP denote step riser and knickpoint respectively, and *D* flow detachment. Note the classification of step form type (1A, 1B and 2) used in this paper.

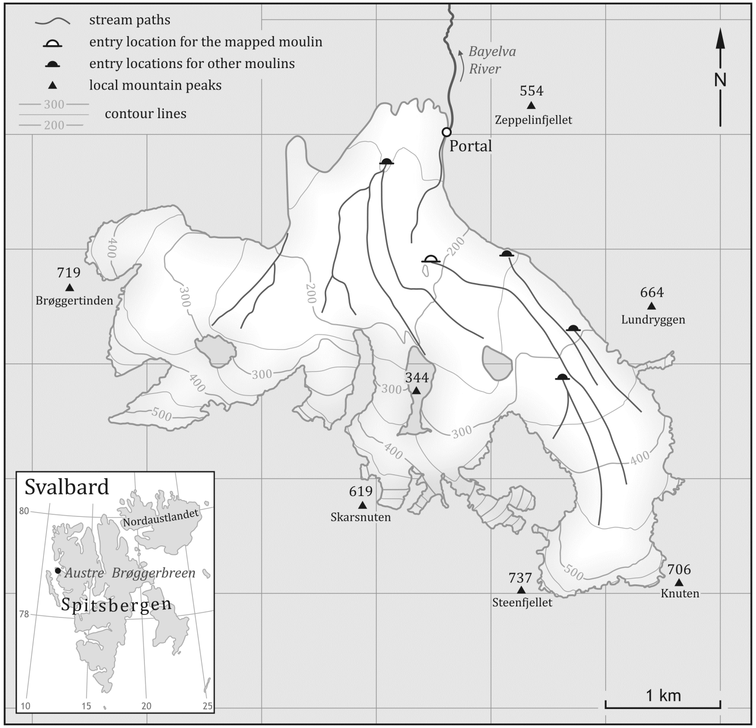

Figure 2. Location map of Austre Brøggerbreen. Contour lines are based on a 1990 elevation data set, with the glacier area according König et al. (2013). Location of moulins and the portal, which is where the main meltwater stream emerges from within the glacier, are from fall 2004.

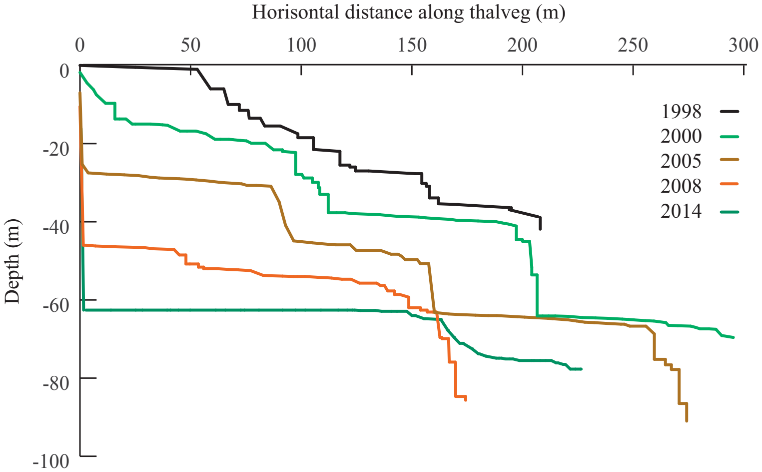

Figure 3. Longitudinal profiles of the englacial channel for individual surveys. The data from 2004 is not shown due to significant uncertainty in the position of the entry point relating to the access location through seasonal snow cover. Note that the *x* axis shows distance measured along the thalweg, not horizontal distance. Included are data from a resurvey of the conduit in spring 2014 (see Myreng, 2015).

Figure 4. Illustration of various englacial channel forms: **(a)** low gradient (LG), **(b)** medium gradient (MG), **(c)** knickpoint (KP) Type 1, **(d)** knickpoint (KP) Type 2.

Figure 5. Cuspate channel wall morphology over a knickpoint lip in 2005.

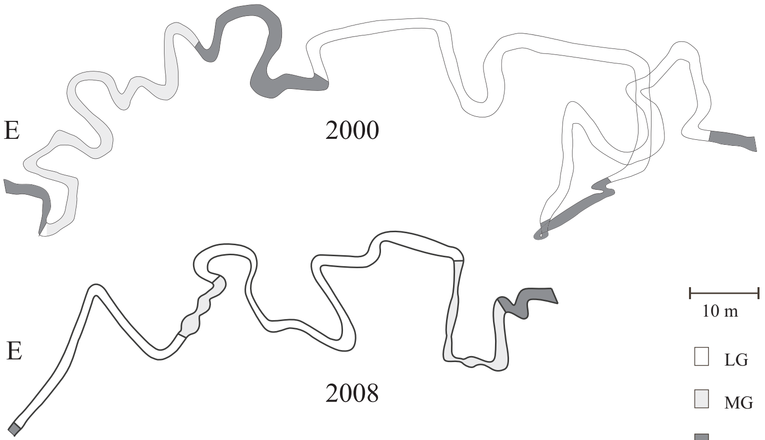

Figure 6. Schematics of englacial channel planform for 2000 and 2008, shaded to indicate the proportions of the channel classed as low gradient (LG), medium gradient (MG), and knickzone (KZ). *E* denotes the entrance to the channel.

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Figure 7. Development of a knickpoint in a supraglacial meander bend at Austre Brøggerbreen, August 2007.

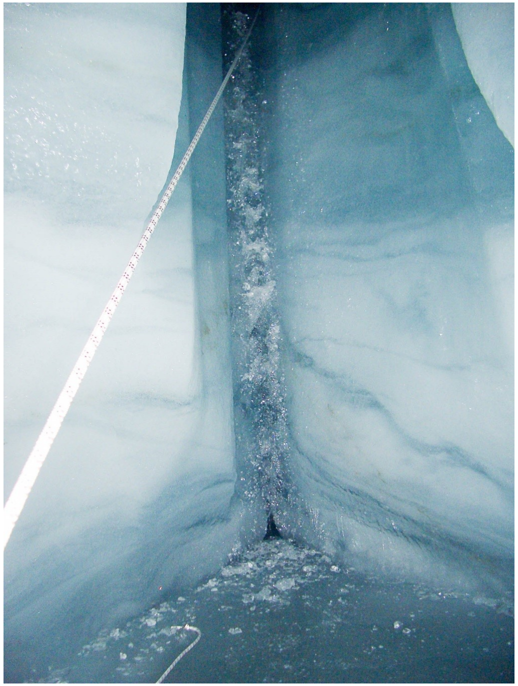

Figure 8. Step riser with narrow furrow incised during low discharge at the end of the ablation season.

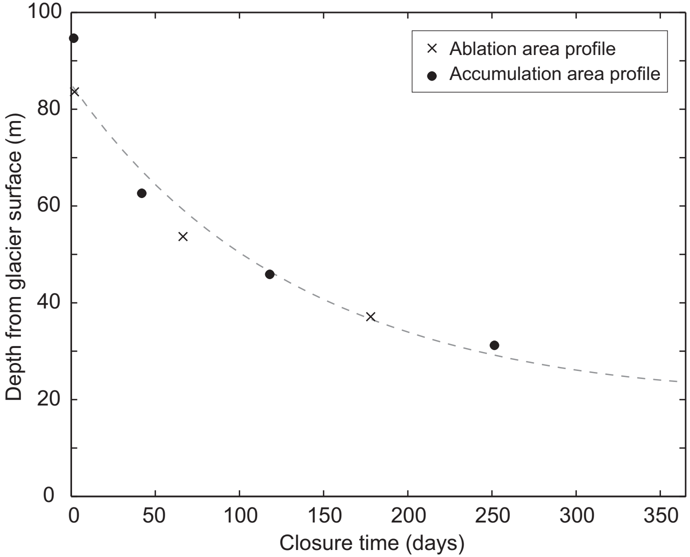

Figure 9. Theoretical closure time for a circular conduit at varying depth for ice temperatures measured at Austre Brøggerbreen (Hagen et al., 1991).