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Borehole drainage and its implications for the investigation of glacier hydrology: experiences from Haut Glacier d'Arolla, Switzerland

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Abstract:

Studies of glacier hydrology rely increasingly on measurements made in boreholes as a basis for reconstructing the character and behaviour of subglacial drainage systems. In temperate glaciers, in which boreholes remain open to the atmosphere following drilling, the interpretation of such data may be complicated by supraglacial or englacial water flows to and from boreholes.

We report on a suite of techniques used to identify borehole water sources and to reconstruct patterns of water circulation within boreholes at Haut Glacier d'Arolla, Switzerland. Results are used to define a number of borehole 'drainage' types. Examples of each drainage type are presented, along with the manner in which they influence interpretations of borehole water-levels, borehole water-quality data, and borehole dye traces. The analysis indicates that a full understanding of possible borehole drainage modes is required for the correct interpretation of many borehole observations, and that those observations provide an accurate indication of subglacial conditions only under relatively restricted circumstances. Copyright © 2001 John Wiley & Sons, Ltd.

KEY WORDS subglacial hydrology; borehole drainage; temperate glaciers

INTRODUCTION

In recent years, there has been growing interest in subglacial hydrology and in the ways in which it interacts with the motion of glaciers and ice sheets (Iken, 1981; Bindschadler, 1983; Iken *et al.*, 1983; Kamb *et al.*, 1985; Iken and Bindschadler, 1986; Kamb, 1987; Alley, 1996; Harbor *et al.*, 1997). This has prompted detailed field investigations of the character and hydraulic behaviour of glacier drainage systems (Collins, 1979; Humphrey *et al.*, 1986; Fountain, 1992, 1993, 1994; Hock and Hooke, 1993; Sharp *et al.*, 1993; Stone and Clarke, 1993, 1996; Hooke and Pohjola, 1994; Hubbard *et al.*, 1995; Raymond *et al.*, 1995; Smart, 1996). Many of these investigations have used boreholes to provide direct access to the glacier bed and allow *in situ* measurement of subglacial conditions. Specifically, measurements of the water level in boreholes that are believed to have been connected to the subglacial drainage system are often used as an indicator of subglacial water pressure (e.g. Hodge, 1976; Hantz and Lliboutry, 1983; Iken and Bindschadler, 1986; Fountain, 1994; Hubbard *et al.*, 1995; Iverson *et al.*, 1995; Jansson, 1995; Murray and Clarke, 1995; Smart, 1996), a parameter which features prominently in existing theories of basal glacier motion (Iken, 1981; Boulton and Hindmarsh, 1987; Murray and Clarke, 1995). Less commonly, measurements of the solute and suspended sediment contents of waters at

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the base of boreholes have been used to identify major events within subglacial drainage systems (Stone and Clarke, 1996; Gordon *et al.*, 1998), and to help characterize the morphology and behaviour of such systems (Hubbard *et al.*, 1995; Tranter *et al.*, 1997). In addition, borehole response testing has been used to infer the hydraulic properties of drainage systems to which boreholes are connected (Stone and Clarke, 1993; Iken *et al.*, 1996; Stone *et al.*, 1997; Kulessa and Hubbard, 1998).

Most borehole-based studies make the implicit assumption that measurements of water level within boreholes and of water quality near the base of boreholes are representative of these parameters within the subglacial drainage system. Borehole water levels often fall during drilling, however, well before the borehole reaches the glacier bed, implying that the borehole has connected to some form of englacial drainage system. Borehole video (e.g. Pohjola, 1994; Harper and Humphrey, 1995; Copland *et al.*, 1997a,b), interborehole impulse testing (Kulessa and Hubbard, 1998) and interborehole electrical resistance tomography (Hubbard *et al.*, 1998) have confirmed this inference. As it is extremely difficult to prevent surface meltwater draining into open boreholes, either directly or through the weathered surface layer of glacier ice, the reality is that water enters and drains from many boreholes by englacial and supraglacial pathways, and not just via the borehole base. Supraglacial and englacial inputs may even result in open boreholes becoming temporarily, intermittently or permanently overpressured relative to the subglacial drainage system to which they are connected (e.g. Engelhardt, 1978). This not only limits the value of borehole water levels as a manometric indicator of subglacial water pressures, but also restricts the interpretation that can be placed on the rate at which dye tracers pass through them and on the origin of water sampled from within them.

Given these concerns, it is desirable to understand how individual boreholes are connected to glacier drainage systems, before trying to interpret borehole measurements. The goals of this paper are therefore:

1. to present a suite of methods to determine how an individual borehole is supplied with water, and to document how water circulates into, within, and out of the borehole—we refer to these properties of boreholes as 'borehole drainage';
2. to classify and illustrate the types of borehole drainage that were identified from studies of boreholes drilled at Haut Glacier d'Arolla, Switzerland, between 1992 and 1995;
3. To consider the implications of each type of drainage for the interpretation of measurements made in boreholes.

FIELD SITE

Haut Glacier d'Arolla is located at the head of the Val d'Hérens, Valais, Switzerland (Figure 1). It has an area of 6·3 km^2, spans an elevation range of 2560 to $\sim$3500 m.a.s.l., and is believed to be warm-based. Observations in subglacial cavities (Hubbard, 1992), and by borehole video (Copland *et al.*, 1997a,b) and bed penetrometry (Hubbard and Nienow, 1997) suggest that the glacier is at least partly underlain by unconsolidated sediments (Harbor *et al.*, 1997).

During the summers of 1992, 1993 and 1995, 70 boreholes were drilled close to the eastern margin of the ablation area of the glacier, some 1·5 km from the terminus (Figure 1). All the boreholes were drilled within an area extending *c.* 260 m E–W and *c.* 120 m N–S, in which the glacier flows towards due north. The location of the borehole array was chosen on the basis of interpretations of dye tracing results and theoretical reconstructions of the subglacial drainage system, which predicted the existence of a major drainage channel beneath this part of the glacier during the melt season (Sharp *et al.*, 1993). In the latter part of the 1993 melt season, Hubbard *et al.* (1995) found strong evidence for the presence of this channel, along which diurnal borehole water-level fluctuations were particularly marked relative to those over adjacent areas of the glacier bed.

Boreholes were drilled using pressurised, hot water, and varied in depth from 23 m near the glacier margin to 144 m near the centre-line. Boreholes are identified by the year in which they were drilled, followed by the number assigned during that year (e.g. BH 92-3 represents borehole number 3, drilled in 1992).

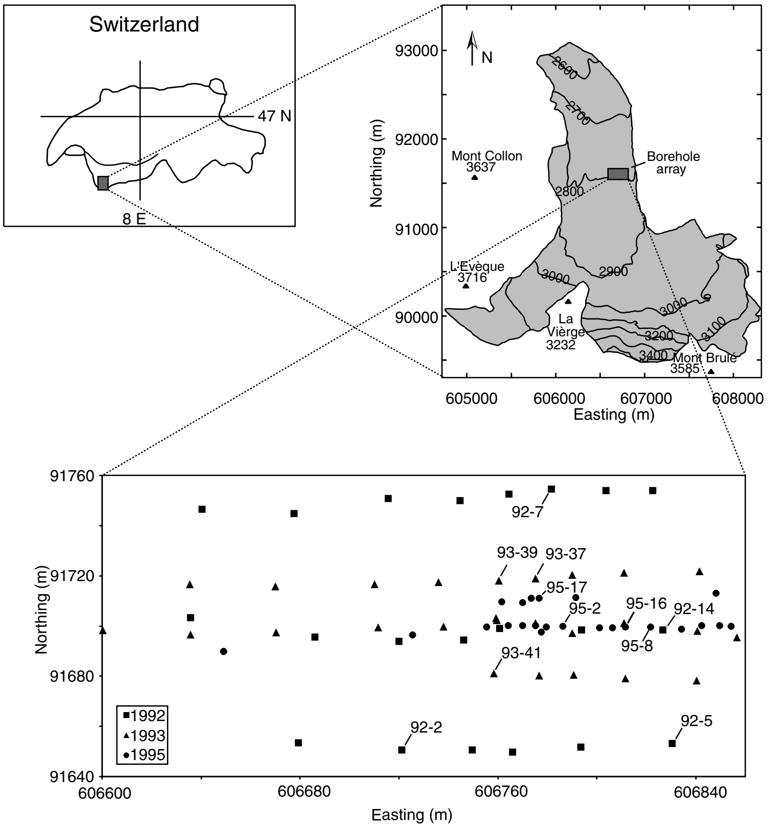

Figure 1. Haut Glacier d'Arolla, showing the location of the borehole array. The inset shows the distribution of boreholes drilled in 1992, 1993 and 1995. Boreholes referred to in the text are labelled

METHODS

Seven types of data were used, in varying combinations, to determine borehole drainage. These were: (i) drilling records; (ii) borehole water-level records; (iii) electrical conductivity (EC) measurements from the base of boreholes; (iv) turbidity records from the base of boreholes; (v) measurements of EC profiles along boreholes; (vi) salt trace experiments within boreholes; and (vii) borehole video imagery. In general, the quality of an interpretation of borehole drainage will increase with the number of data sources on which that interpretation is based.

Drilling records

Records were kept of both the contact between the drill tip and the borehole ice base, and the behaviour of the borehole water level. Water normally overflows continuously from the top of the borehole during drilling. Any sudden free-fall in the rate of advance of the drill, or change in borehole water level (which may fall or become overpressurised), was therefore interpreted in terms of the presence of some form of englacial void. If the borehole water level subsequently restabilised following a drop during drilling, it was inferred that an englacial void of finite volume had been intercepted. If the borehole did not refill, interception of an active englacial channel was inferred.

As the glacier bed is at the pressure melting point, all boreholes that penetrate to it must be connected to the local subglacial drainage system. Borehole water levels, however, do not respond in a uniform manner upon intercepting the glacier bed. Indeed, water levels commonly do not respond at all to this connection.

As it is unlikely that the local subglacial water pressure is exactly that created in the borehole, such a response generally is interpreted in terms of the presence of an ineffective local water transport system in the immediate vicinity of the borehole base. Often the pressure gradient established between the borehole base and the surrounding drainage system will force an effective connection and the borehole water level will be drawn down accordingly. This fall in water level may occur immediately upon contacting the glacier bed and last for some seconds (a 'hard' connection). Alternatively, it may occur days or months after the borehole has been drilled—depending on the evolution of local pressures and hydraulic conditions near the borehole base.

Borehole water-level measurements

Subsequent to drilling, water levels were measured in all boreholes, either manually or automatically. Manual measurements were made using heavy duty EC probes (Smart and Ketterling, 1997). If a borehole was not full, the probe was lowered down the borehole until the water level was detected by a sudden EC increase from 0 to $>0{\cdot}5$ μS cm^{-1}, at which point the depth was recorded. Manual water level measurements were made at irregular intervals during the day (usually between 0900 and 2000 hours), and normally only in boreholes that were not monitored automatically. In holes of the latter type, pressure transducers were suspended within a few decimetres of the borehole base. Pressure measurements were logged as the mean of 30 readings every 10 min using Campbell Scientific CR-10 data loggers, providing water level measurements accurate to within $\pm 0{\cdot}5$ m (Hubbard *et al.*, 1995). The resulting water-level data provide an indication of whether a borehole is connected effectively to the glacier's (basal or englacial) drainage system, and of how the water pressures in that system fluctuate. An array of such boreholes therefore represents a powerful investigative tool, because spatial patterns of water-level fluctuations may be used to reconstruct corresponding englacial or basal pressure fluctuations and their transmission within or beneath the glacier. Borehole water levels alone, however, cannot inform researchers unequivocally of the source of the recorded water level fluctuations. To understand this, the quality of the water within the borehole water column is investigated.

Continuous electrical conductivity (EC) measurements

Electrical conductivity is proportional to the concentration of ions in solution, and can be used as a surrogate for total dissolved solids (Fenn, 1987). The degree of solute acquisition by glacial meltwaters depends on the initial chemistry of the source waters, the supply of protons to meltwaters, the duration of contact between meltwaters and weatherable rock material, the grain size, shape and mineralogical properties of particulate rock material, and the ratio between meltwater volume and the surface area of rock material available for weathering (Sharp, 1991). As different types of drainage system will display different characteristic values of the above properties, the degree of mineralization of borehole waters provides some insight into their provenance. Dilute water with an EC similar to that of supraglacial meltwater (0–5 μS cm^{-1}) is unlikely to have spent any significant time in contact with weatherable rock material. In general, increasing degrees of mineralization reflect increased contact between the water and weatherable subglacial material, such that meltwaters with high EC values ($>c.50$ μS cm^{-1}) are interpreted to have experienced extended contact with reactive rock material at the glacier bed. In 1993 and 1995, EC was recorded continuously by sensors placed within a few decimetres of the glacier bed. Measurements were logged as the mean of 30 readings every 10 min using Campbell Scientific CR-10 data loggers, and are referred to as *'in situ'* EC.

Continuous turbidity measurements

Turbidity results from the entrainment and transport of sediment particles in water. Periods of enhanced turbidity recorded at the base of boreholes reflect changes in the concentration, size distribution or mineralogy of fine sediment suspended in meltwaters. These changes may be caused by: (i) increased meltwater flow velocities, which exert a shear stress sufficient to dislodge and suspend particles that previously were located at the ice–bed interface; (ii) episodes of rapid glacier sliding (e.g. mini-surges; Humphrey *et al.*, 1986), which mechanically dislodge previously stable particles; or (iii) changes in the extent of ice–bed separation, which may expose new areas of the bed to turbulent meltwater flow (e.g. Stone and Clarke, 1996).

Turbidity was measured continuously in 13 boreholes in 1993 using sensors placed within a few decimetres of the bed. Measurements were logged as the mean of 30 readings every 10 min using Campbell Scientific CR-10 data loggers. Turbidity measurements are presented in terms of relative turbidity (Tu_r), defined as

$$Tu_r = (Tu_c - Tu_s)/Tu_c \qquad (1)$$

where Tu_c and Tu_s are the voltage signals recorded in clear water and the sample, respectively. Thus, the value of Tu_r varies between 0 in perfectly clear water and 1 in absolutely opaque water. Continuous turbidity measurements are referred to as *'in situ'* turbidity. In this study, these measurements are used solely to provide evidence for the flow of sediment-laden water into or past the base of a borehole, and there is no need to calibrate turbidity measurements in terms of sediment concentration, grain size or mineralogy.

Electrical conductivity (EC) profiling

Electrical conductivity profiles along the borehole water column were constructed using a heavy-duty probe (Smart and Ketterling, 1997) to measure EC at 5-m intervals from immediately below the water surface to the glacier bed (Gordon *et al.*, 1998). A sharp EC gradient in the borehole water column is termed a 'condocline', and temporal changes in the elevation of such features may be used to investigate the dynamics of water supply to, and loss from, individual boreholes.

Borehole salt tracing

Dissolved salt (NaCl) was used as an artificial tracer of water flow within a borehole water column. Salt tracing was particularly useful for testing inferences about borehole circulation patterns derived from movements of the condocline, and for determining circulation patterns in boreholes with no natural EC stratification.

To conduct a salt trace, a 1-cm-diameter plastic hose was taped to a length of weighted cable so that the hose outlet was positioned directly above the weight, and both could be lowered to depths of up to 100 m below the glacier surface. The hose and cable were lowered to the desired injection depth and secured. The saline solution (normally 1 kg of salt dissolved into 14 L of supraglacial water) was then poured into the top of the hose, followed by several L of fresh supraglacial meltwater to flush the remainder of the saline solution from the base of the hose. Following the injection, EC profiles were measured at 1 m vertical resolution every 20 to 30 min until the experiment was terminated.

Borehole video

In 1995, a GeoVision Micro colour borehole video camera was used to record the internal properties of 11 boreholes (Copland *et al.*, 1997a,b). Real-time viewing through a small colour monitor allowed careful inspection of features considered to represent englacial channels, while simultaneous recording of the imagery on video cassette permitted detailed logging of borehole characteristics after the field season. Borehole logs focused on: (i) the properties of the borehole walls, especially the occurrence of englacial channels and voids, which could be compared with the position of such features inferred from other evidence; (ii) assessment of water inputs derived from englacial and supraglacial sources located above the water level in connected boreholes; (iii) the clarity of the borehole water column, which provided evidence for the intrusion of turbid subglacial water into a borehole; and (iv) the nature of the glacier bed (bedrock or unconsolidated sediment), where this interface was visible.

BOREHOLE DRAINAGE CLASSIFICATION

Our classification of borehole drainage, presented in Table I, is based on experiences at Haut Glacier d'Arolla, and is guided by our current understanding of the nature of glacier drainage (e.g. Hooke, 1984; Lawson, 1993;

Table I. Classification of borehole drainage. Terminology is explained in the text

Connection status			Stratification status
Unconnected	Blind	Simple/complex	Unstratified/stratified
	Apparently unconnected	Simple/complex	Unstratified/stratified
Connected	Englacially connected	Simple/complex	Unstratified/stratified
	Subglacially connected	Simple/complex	Assumed stratified
	Multiply connected	Simple/complex	Assumed stratified

Hubbard and Nienow, 1997; Fountain and Walder, 1998). First, boreholes are classified as either 'connected' or 'unconnected'. The former group includes boreholes with physical properties that respond to variations in the glacier's drainage system. In contrast, boreholes with properties that remain static, and do not appear to respond to the glacier's drainage system, are classified as 'unconnected'. Unconnected boreholes that terminate englacially are referred to as 'blind', and unconnected boreholes that terminate basally (but fail to respond to, the glacier's drainage system) are referred to as 'apparently unconnected'. In contrast, connected boreholes may link to the glacier's englacial drainage system (subclassified as 'englacially connected'), basal drainage system ('basally connected'), or both ('multiply connected'). A borehole that repeatedly fluctuates between any unconnected and any connected status is termed sporadically connected. We introduce two further subclassifications into this scheme. First, a borehole in which the water column is EC stratified or turbidity stratified is subclassified as 'stratified', and a borehole in which the water column is of a uniform EC and turbidity is subclassified as 'unstratified'. Unless stated otherwise, all basally connected or multiply connected boreholes are stratified, as they are characterized by some influx of relatively high-EC subglacial water. Second, a borehole (connected or unconnected) that intersects a cavity that is not itself connected to the glacier's drainage system is subclassified as 'complex'. Conversely, a borehole that does not intersect any form of cavity is subclassified as 'simple'. Below, we exemplify this classification with reference to records of particular boreholes drilled at Haut Glacier d'Arolla between 1992 and 1995.

Unconnected boreholes

Unconnected boreholes remain filled with drill water of a fixed composition for extended periods of time. Our subclassification of unconnected boreholes as either 'blind' or 'apparently unconnected' discriminates between boreholes that do not reach the glacier bed (the former) and boreholes that reach it at a location where ineffective subglacial drainage prevents the borehole water column from equilibrating with the local subglacial drainage system (the latter). Many references to 'unconnected' boreholes in the existing literature therefore may relate to boreholes that we would classify as 'apparently unconnected'. In practice, it may be very difficult to discriminate between blind and 'apparently unconnected' boreholes, because neither responds to changes in the subglacial drainage system, and either may eventually make a hydraulic connection with that system. This is true even for blind boreholes because they commonly end close to the glacier bed.

Example 1: BH 92-2 (unconnected and unstratified). The water level in BH 92-2 remained at the glacier surface for an extended period (at least 20 days) following drilling. The EC profiles taken over this period illustrate that the water column consisted entirely of low-EC water, inferred to be the initial drill water. These characteristics are consistent with the borehole ending in debris-poor englacial ice if blind, or at an unreactive basal interface, such as one composed of clean, rigid bedrock, if apparently unconnected. In the latter case, it is likely that effective borehole connection was inhibited by relatively high local basal water pressures, such as would occur if the borehole intersected the glacier bed at the stoss face of a subglacial hummock.

Example 2: BH 92-7 (unconnected and stratified). The EC profiles in BH 92-7 indicated a stable stratification, in which a 25-m-thick layer of high-EC water in the base of the borehole was overlain by a column of low-EC water that extended to the top of the borehole. These characteristics are consistent with the borehole ending in debris-rich basal ice if blind, or at a reactive basal interface, such as one composed of unconsolidated sediments, if apparently unconnected.

Example 3: BH 95-8 (unconnected and complex stratified). Borehole 95-8 drained during drilling, when the drill tip was located 20·5 m above the bed (a.b.). The borehole refilled as drilling continued, and remained full for the rest of the field season. This implies that an englacial void of finite volume was intercepted, the borehole drained into this void until the void was filled, and then the borehole refilled with the continued input of drill fluid. Video imagery showed a narrow void *c.* 0·6 m high and 0·07 m wide at a depth of 20·2 m a.b., which may have been a partially closed remnant crevasse. The EC profiles and video imagery from the borehole also indicated the presence of a sharp EC and turbidity transition at *c.* 11 m a.b., both being characterized by higher values below this level. The location of this transition did not change over time, indicating an otherwise blind or apparently unconnected status.

Unconnected boreholes are of limited value for investigating the character and temporal dynamics of the active components of subglacial drainage systems. However, the spatial distribution of apparently unconnected boreholes may be used to inform researchers about the characteristic spacing of active drainage pathways, because boreholes are most likely to connect to such pathways. Observations of the water column characteristics of apparently unconnected boreholes also may provide some insight into the properties of the glacier bed at the base of the borehole.

Englacially connected boreholes

Englacially connected boreholes intersect the channelized englacial drainage system. Such boreholes are not connected at the base, but may be englacially connected at multiple locations and also may intersect finite volume voids (i.e. they may be complex). Englacially connected boreholes are either unstratified or characterized by a stationary condocline, as high-EC basal water does not enter or leave the base of the borehole. Water-level variations in such a borehole may result from the initial connection to the englacial drainage system and, subsequently, from variations in supraglacial inputs to the borehole and/or pressure variations within the englacial system. These may be linked to pressure variations within the subglacial system if the englacial and subglacial systems are connected.

Example 4: BH 95-2 (englacially connected and stratified). Immediately upon completion, BH 95-2 was apparently unconnected and characterized by a condocline located 30 m a.b. Two days later, the borehole drained to a depth of 32 m a.b., indicating connection. The EC profiling revealed that the drained water column was similar to that prior to drainage and composed of a 30-m column of high-EC water overlain by a 2-m cap of low-EC water. The location of the condocline was therefore unaffected by the drainage event, suggesting that drainage occurred via an englacial channel located at or just above 32 m a.b., and not via the base of the borehole. Water level and *in situ* EC probes were installed at the base of the borehole 6 days after it drained (Figure 2). Basal EC rose steadily from 18 to 28 $\mu S\ cm^{-1}$ over a 10 day period, probably as a result of solute acquisition from suspended fine sediment. Water-level fluctuations in the borehole were coincidental with high temperature days (10 and 15 August), rainfall events (13 August) or reaming activities (16 August), often followed by overnight falls back to 32 m a.b. These fluctuations were achieved solely through variations in the thickness of the upper layer of low-EC water. This evidence points strongly to the presence of an englacial channel or fracture at a height just above 32 m a.b. through which borehole drainage took place.

Video imagery identified a circular englacial channel *c.* 20 mm in diameter intersecting the borehole walls a short distance above the top of a region in which the turbidity of the underlying water column increased significantly. This turbidity increase probably is coincident with the top of the stable layer of high-EC water below *c.* 30 m a.b. (Figure 2). It thus seems likely that the channel identified on the video imagery is the path by which the borehole drained. Our combined water level, EC and video evidence therefore suggests

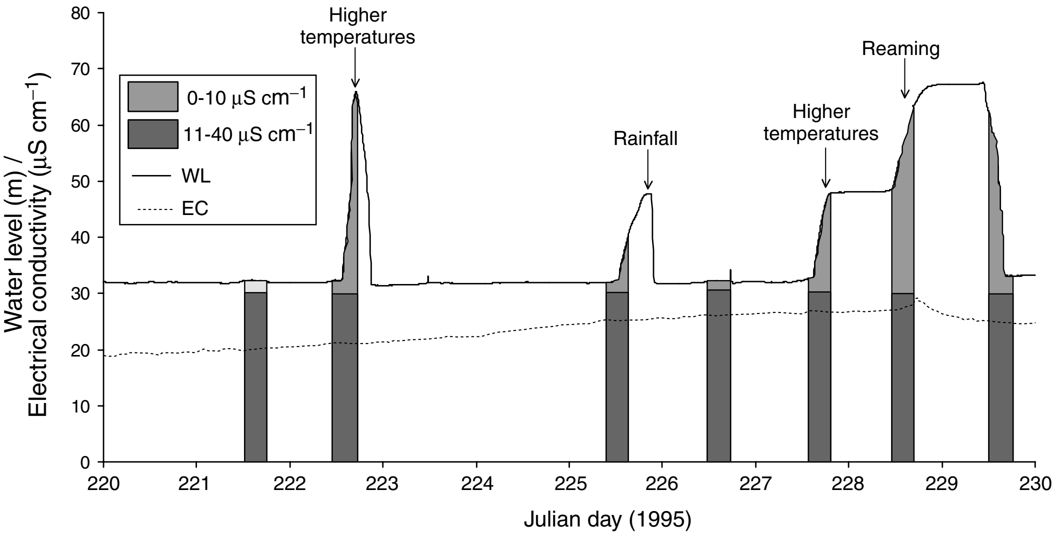

Figure 2. *In situ* water-level and electrical conductivity records, and electrical conductivity profiles, from BH 95-2 (96·5 m deep) for the period 8–18 August 1995. Inferred causes of water level rises are identified

that water-level variations in this borehole arose from varying supraglacial and englacial inputs and that there was no significant water flow into or from the borehole at the glacier bed.

Water quality records from englacially connected boreholes do not provide useful information about the dynamic behaviour of the subglacial drainage system. Equally, dye traces conducted from such boreholes will give meaningful results only if the dye is inserted in the borehole above the level of the englacial connection and at a time of falling water level. Even then, it cannot be assumed that the dye has been injected directly into the subglacial drainage system.

Subglacially connected boreholes

Subglacially connected boreholes intersect the basal drainage system, and respond to variations in that system. Such boreholes may not be englacially connected, but they may be complex. Subglacially connected boreholes are normally stratified and characterized by a non-stationary condocline that rises and falls in parallel with the overall borehole water level. However, this is not always the case, because subglacially connected boreholes may also be supraglacially fed, often to an unconstrained degree. Such holes may be characterized by a more complex relationship between water level and condocline level.

Example 5: BH 93-37 (subglacially connected and stratified). Borehole 93-37 drained on the night that it was drilled and subsequently exhibited high amplitude (80–90 m), diurnal water-level fluctuations and *in situ* EC cycles (*c*. 3–20 μS cm^{-1}) (Figure 3). The EC profiling data collected over diurnal cycles (Figure 3a) showed that high-EC water entered the base of the borehole in the late morning or early afternoon, followed by low-EC water later in the day. The high-EC water initially rose up the borehole at a rate equal to the water-level rise, indicating that the borehole was fed solely from the bed. On some days, however, a thin cap-layer of low-EC water formed, indicating additional supraglacial inputs (assumed in the absence of evidence that the borehole was englacially connected). The importance of basal inflow is underlined by the results of a salt trace (Figure 4). A layer of saline water (introduced at 7 m a.b. before the start of the diurnal water level rise) rose up the borehole as a discrete unit at the same rate as the water level rose. This layer was forced upwards by more dilute water entering the base of the borehole.

The *in situ* EC data from this borehole can be interpreted by relating them to the results of the EC profiling. As the borehole water level rose each day, *in situ* EC decreased from *c*. 20 to 3 μS cm^{-1}, before returning

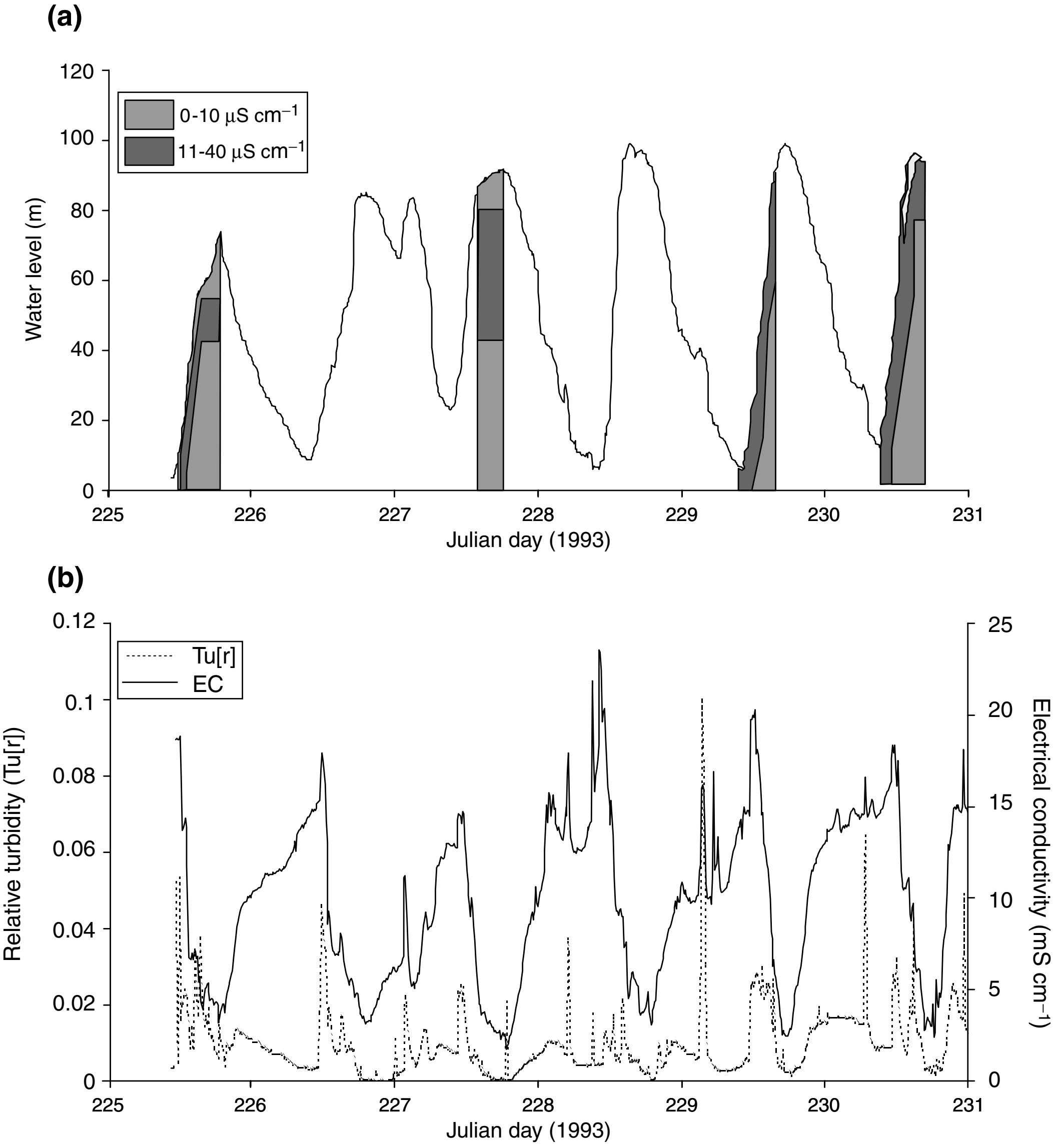

Figure 3. (a) *In situ* water level records and electrical conductivity profiles and (b) *in situ* electrical conductivity and turbidity records from BH 93-37 (102 m deep) for the period 13–19 August 1993

to *c*. 20 μS cm^{-1} as the water level fell overnight (Figure 3b). The EC profiling data indicate that this cycle resulted from high-EC water being forced up the borehole by low-EC water during periods of rising water level, and then returning to the base of the borehole as the water level fell (Figure 3a). As a result, we can be sure only that the *in situ* EC signal reflected the true properties of basal water when the water level was rising (as a result of water entering the base of the borehole). *In situ* measurements made when the borehole was draining therefore appear to reflect only the composition of the water stored in the borehole during the day.

Peaks occurring when there was a change in the direction of water-level variation dominated the *in situ* turbidity record from this borehole (Figure 3b). This is consistent with local disturbance of an unconsolidated

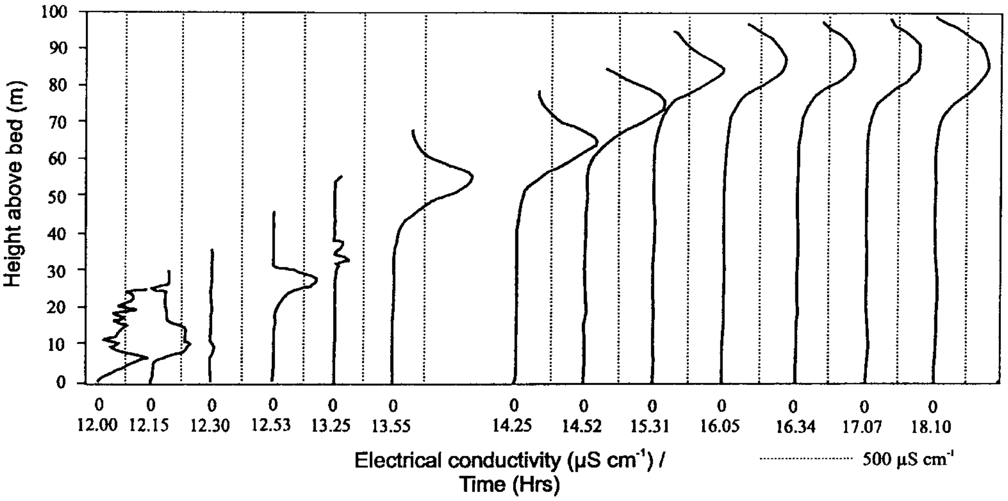

Figure 4. Electrical conductivity profiles measured in BH 93-37 during the salt trace conducted on 20 August 1993. The time at which each profile was measured is shown below the x-axis. Vertical dashed lines define an electrical conductivity of 500 μS cm^{-1}

sedimentary bed caused by water flow into and out from the base of the borehole. This evidence points strongly to BH 93-37 being filled and drained primarily via the base of the borehole.

Basally connected boreholes are most useful for investigations of the dynamics of subglacial drainage systems. Rising borehole water levels are driven by influxes of subglacial water, and basal water quality measurements taken at these times provide insight into solute and sediment transport at the glacier bed. Conversely, dye can be injected directly into subglacial drainage systems at times when water is draining from the borehole. Further, when the borehole water level and the condocline move in parallel, borehole water levels probably provide an accurate measure of subglacial water pressure.

Multiply connected boreholes

In practice, many boreholes are connected to both the englacial and the subglacial drainage systems. Such boreholes are classified as multiply connected, and their water level and stratification properties respond to temporal variations in both of the drainage systems to which they connect.

Example 6: BH 92-14 (multiply connected). Diurnal water-level variations in this borehole resulted mainly from variations in the thickness of an unstratified column of low-EC water (Figure 5). However, EC profiling revealed that a thin layer of higher EC water entered the base of the borehole on a daily basis, usually quite late in the period of water-level rise. Had this higher EC water not been recorded, the water-level variations might have been interpreted as originating solely from supraglacial and/or englacial inputs, but its presence (and periodic disappearance) indicates that basal inputs and outputs were at least partially responsible for the observed variations.

Example 7: BH 93-41 (multiply connected). The water level in BH 93-41 started to fall during drilling, when the drill tip was located 5 m a.b. Despite the falling water level, drilling was continued to the bed, after which the water level fell to 15 m a.b. Subsequently, diurnal water-level variations were recorded throughout the observation period (Figure 6a). The *in situ* EC and turbidity records (Figure 6b) generally exhibited semidiurnal cycles, with peaks on both the rising and falling limbs of the water-level cycle. The EC profiles measured over diurnal cycles (Figure 6a) indicated that the borehole was filled initially with dilute (probably supraglacial and/or englacial) inputs. Subsequently, turbid, high-EC water entered the base of the borehole,

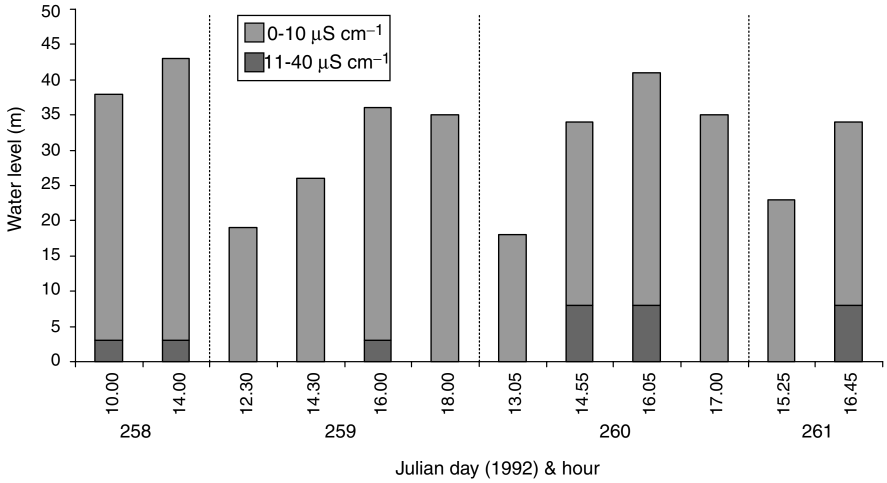

Figure 5. Electrical conductivity profiles measured in BH 92-14 (48 m deep) during the period 15–18 September 1992

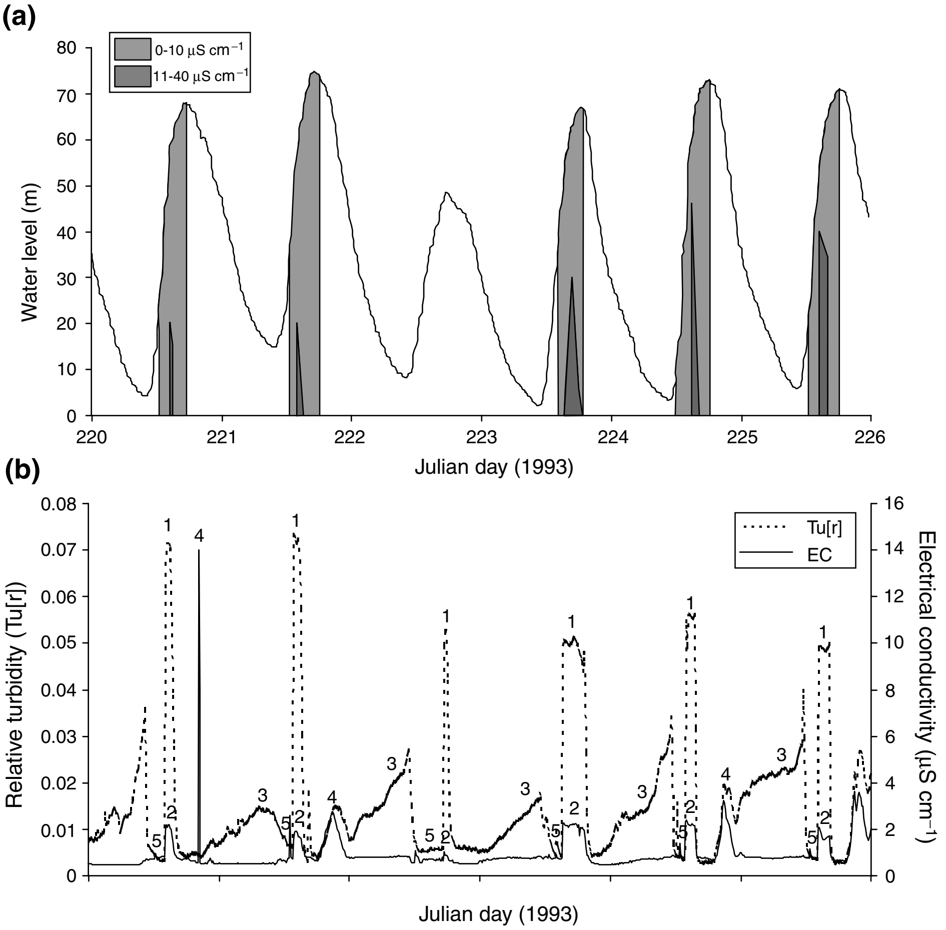

Figure 6. (a) *In situ* water-level records and electrical conductivity profiles, and (b) *in situ* electrical conductivity and turbidity records from BH 93-41 (107 m deep) for the period 8–14 August 1993. Numbers on (b) identify events referred to in the text

producing sharp, ephemeral peaks in the *in situ* EC and turbidity records. However, this water drained from the base of the borehole while the water level continued to rise, indicating that continued inputs from supraglacial and/or englacial sources overpressurized the borehole relative to the subglacial drainage system.

A salt trace conducted on 19 August, together with *in situ* EC and turbidity data (Figure 7), shed further light on the complex patterns of water circulation that developed within BH 93-41. Saline water was injected 20 m a.b. at 13·25 hours, when the water level was 39 m a.b. and the natural spike of high-EC water had already been registered at the bed (event (i) on Figure 7b). The EC profiles 1 to 13 on Figure 7a illustrate the movement of the saline water within the borehole. In profile 1, a well-defined water layer of *c*. 4000 μS cm^{-1} (A) was capped by water displaying lower, but variable, EC (B). This variability was probably attributable to failure to completely flush the saline water from the injection hose before the hose was removed from the

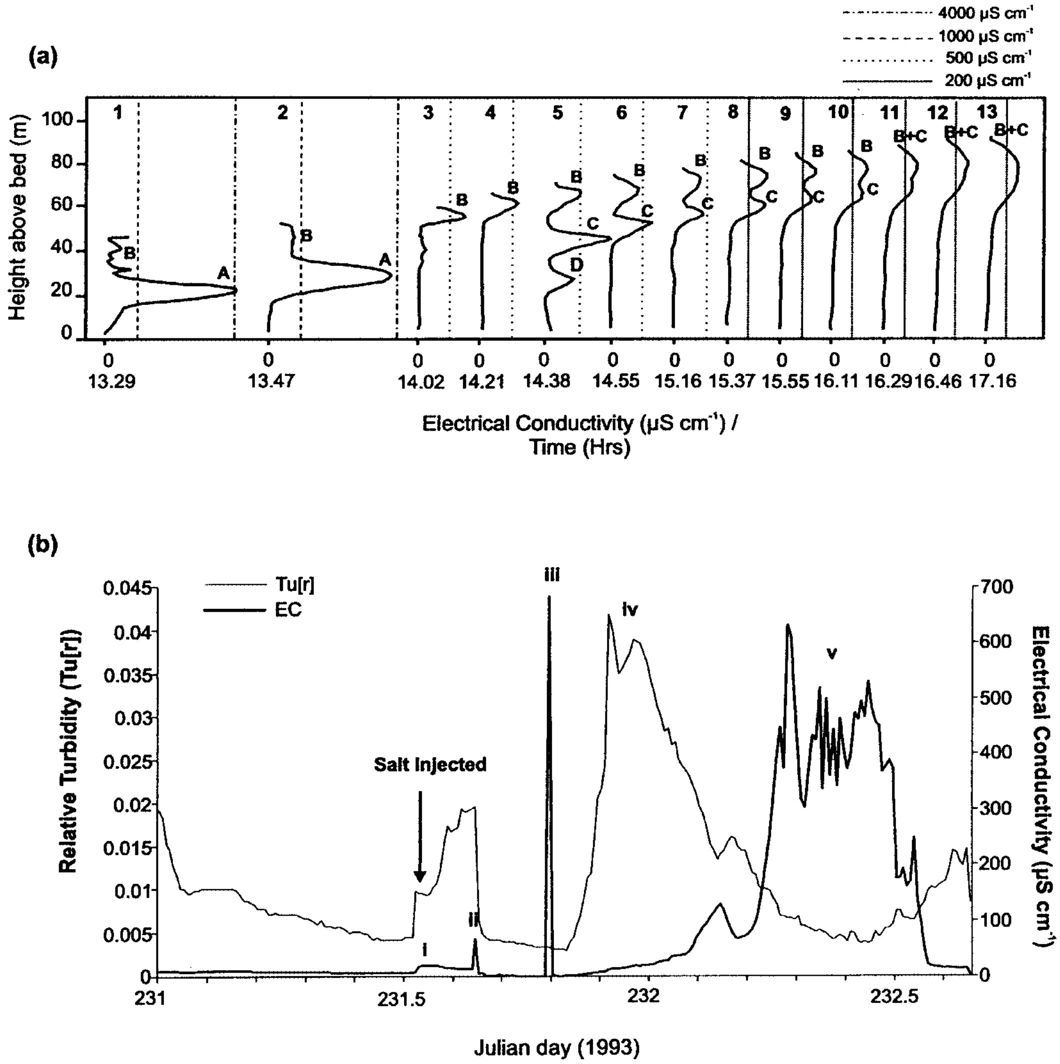

Figure 7. (a) Electrical conductivity profiles measured in BH 93-41 during the salt trace conducted on 19 August 1993 and (b) *in situ* electrical conductivity and turbidity records from the same borehole for 19–20 August 1993. In (a), the time at which each electrical conductivity profile was measured is shown below the x-axis. Vertical dashed lines provide a scale for the electrical conductivity profiles. In (b), events referred to in text are identified by lower case Roman numerals

borehole, allowing small amounts of saline water to enter higher levels of the water column as the hose was withdrawn. Profile 2 shows that (A) was forced up the borehole by lower EC water entering the borehole from below. By the time this profile was measured (13·47 hours), layer (B) had become a coherent unit with EC of *c*. 750 μS cm^{-1}, probably as a result of mixing by the electrical conductivity probe. Profiles 3 and 4 show that (A) disappeared from the water column between 13·47 and 14·21 hours, whereas (B) became a well-defined peak with EC of *c*. 500 μS cm^{-1}, which rose up the borehole. We interpret the loss of (A) from the borehole in terms of outflow via an englacial channel or fracture located *c*. 30–40 m a.b.. For this to occur, the hydraulic head in the borehole must have exceeded that in the connecting englacial system. After 14·21 hours, two new peaks of saline water (C and D) appeared in the borehole water column (profiles 5 and 6). These peaks appear to have originated englacially, and are interpreted in terms of the reintroduction of (A) to the borehole from the englacial system into which it had earlier drained. Following the reintroduction of (A), continued inflow of dilute englacial water split the peak into (C) and (D), forcing the former up the borehole and the latter down the borehole. Indeed, (D) completely exited the base of the borehole later in the day, registering as a distinct peak in the basal *in situ* EC record at 15·00 hours (event ii on Figure 7b) and failing to register in EC profiles 6–13. The rate of inflow of (A) back into the borehole, and the subsequent influx of low-EC water, preclude a diffusion-based explanation for the reappearance of (A) within the borehole. Instead, we interpret these changes in terms of reversals in the hydraulic gradient between the borehole and the englacial drainage system, perhaps driven by relative changes in water flux delivered to the basal and englacial drainage systems.

This observation illustrates a point that is extremely important for the interpretation of *in situ* water quality records—namely, that rising water level in a basally connected borehole does not necessarily indicate influx of water at the borehole base (D exited the borehole base while the water level was still rising; B and C continued to rise up the borehole as it was filled from below by englacial inflow).

Water level in BH 93-41 started to fall between the measurement of profiles 12 and 13. The EC profiling was terminated at 1716 hours, and at 1824 hours (*c*. 35 min after the water level started to fall) a second salt trace was undertaken in an attempt to determine the location of water loss from the borehole as the water level fell. Four minutes after the salt was injected at 20 m a.b., the *in situ* sensor registered a very high EC peak (event iii on Figure 7b), indicating rapid water outflow from the base of the borehole. Subsequently, the second turbidity peak of the semidiurnal cycle occurred as the borehole drained (event iv, Figure 7b). The EC peak (B + C) was recorded leaving the base of the borehole between 0432 and 1248 hours on 20 August as the water drained overnight (event v, Figure 7b).

The salt trace experiments demonstrate the complex nature of water circulation within BH 93-41, and illustrate the influence of englacial inputs and outputs on this circulation. Although water was introduced to the borehole via its base during the day, englacial channels or fractures acted initially as a sink for some of this water, and subsequently as a source of additional water. A reversal in the hydraulic gradient between the borehole and an englacial channel/fracture initiated water outflow from the base of the borehole while the borehole water level continued to rise. In this instance, the water that drained from the base of the borehole overnight was not exactly the same water that entered via the base during the day.

It is only with this improved knowledge of water circulation within BH 93-41 that the full *in situ* EC and turbidity records (Figure 6b) can be interpreted with confidence. Thus, we now know that the high, ephemeral EC peak (labelled 1 on Figure 6b) represents subglacial water which entered the base of the borehole, but which exited again soon after, when the englacial input *c*. 30–40 m a.b. was activated. The coincident turbidity peak demonstrates water flow at the base of the borehole. *In situ* records of turbidity peaks during the initial period of falling water level (labelled iv) indicate that basal sediments may be suspended some distance into the borehole even though the net direction of water flow is out from the borehole base. Low-EC values separating events (ii) and (iv) represent englacial inputs to the borehole reaching the bed after activation of the englacial input. According to this interpretation, true basal water quality is recorded by the *in situ* probes only during the initial input of basal water to the base of the borehole. The remaining measurements represent the flow of basally and englacially derived water out of the borehole base and subsequent mixing of this water with water flowing across the bed.

Many boreholes are multiply connected and their properties must be interpreted with care if they are to provide useful information relating to the dynamics of subglacial drainage systems. For example, *in situ* records from the base of multiply connected boreholes provide information on the nature of subglacial water inputs at times when water is known to be entering from the borehole base. It should be stressed, however, that such conditions may not apply for much of the time—even when borehole water level is rising. A knowledge of borehole drainage is therefore essential for the successful conduct of dye traces, and for interpretation of water level and basal water quality measurements in multiply connected boreholes.

Sporadically connected boreholes

Although most boreholes fit readily at any one time into one of the categories described above, many also repeatedly change category over time. These may be referred to as sporadically connected boreholes.

Example 7: BH 95-17 (sporadically connected). Borehole 95-17 drained to the bed the day after it was drilled on 5 August, refilled slowly over a 5-day period, and then was refilled completely by reaming activities on 11 August. Early on 12 August (Julian day 224), the borehole drained abruptly to its base (Figure 8), indicating that a connection had been made with a component of the subglacial drainage system that was flowing at atmospheric pressure. Over the following 12 days, however, the borehole refilled with a combination of supraglacial and reaming water. On 15 August, there was a step increase in *in situ* EC, after which EC profiles indicated a stable EC stratification in the base of the borehole. By 22 August the borehole was filled completely, but it drained to the bed again on 24 August. This behaviour suggests the sporadic development of a connection to the subglacial drainage system at times when the bed was locally overpressurized by the borehole water column, but it also indicates that this connection could not be maintained by the water flux entering the borehole from englacial and supraglacial sources.

Sporadically connected boreholes are of little value to investigations of subglacial drainage system behaviour when unconnected. When connected, their utility depends upon whether the connection is englacial or basal, and is subject to the restrictions outlined above.

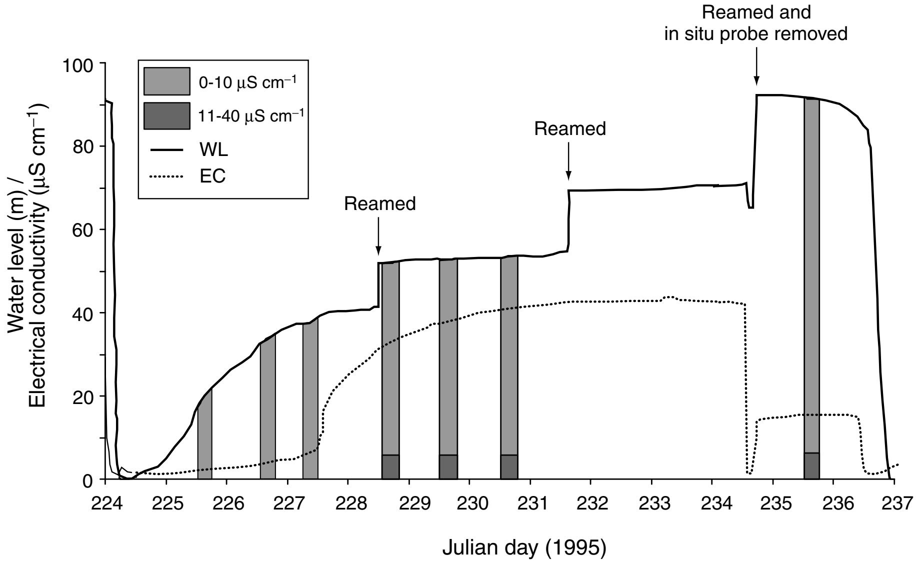

Figure 8. *In situ* water-level and electrical conductivity records and electrical conductivity profiles measured in BH 95-17 (91·5 m deep) during the period 12–25 August 1995. Borehole reaming episodes are marked

DISCUSSION AND CONCLUSIONS

We have used a suite of techniques to reconstruct the sources of water responsible for water level variations in open boreholes drilled at Haut Glacier d'Arolla, Switzerland. The resulting information has been used to construct a classification of borehole drainage that we believe applies to all temperate glaciers. Understanding the relative importance of different water sources, and the way in which those waters circulate within boreholes, is critical to the interpretation of *in situ* measurements of EC (and ionic chemistry where borehole waters are sampled) and turbidity. These patterns of water circulation are also critical to the accurate interpretation of the results of borehole-based dye trace experiments. Indeed, only under certain relatively restricted circumstances do *in situ* sensors record the true properties of subglacial water. In general, it is necessary to demonstrate that a borehole is basally or multiply connected before any attempt is made to interpret *in situ* water quality records. Even then, such records document the changing properties of subglacial water only at times when that water is entering the base of the borehole. This is most likely to occur during periods of rising water level, but it is not safe to assume that rising water level in a multiply connected borehole necessarily results from basal inflow. Cases of basal outflow during periods of rising water level, driven by large supraglacial/englacial inputs, have been documented. Such cases indicate that boreholes can become overpressurized relative to the subglacial drainage system, and demonstrate that caution is required in automatically taking borehole water level measurements as a proxy for subglacial water pressure.

When a borehole is multiply (i.e. both basally and englacially) connected, complex patterns of borehole water circulation can develop. Basally derived waters may be diluted by englacial inputs, and they may leave the borehole via englacial pathways. Initiation of englacial inputs during periods of basally fed water-level rise can cause the rising column of (high-EC) basally derived water to be split, and even induce basal outflow while water level continues to rise. Englacial channels and fractures can act as both sinks and sources of borehole water during the course of a single diurnal cycle. Boreholes, and englacial channels/fractures that are connected to them, can act as sites for long-term storage of water within a glacier. It is difficult to determine whether water-level variations in englacially connected boreholes are driven by water-pressure variations in the englacial system *per se* (e.g. Shreve, 1972), by water-pressure variations in the subglacial system to which the englacial channels may be connected (e.g. Röthlisberger, 1972), or, more simply, by the water flux into the top of the borehole from supraglacial sources. In reality, water-level fluctuations in englacially (and multiply) connected boreholes are probably a complex, spatially and temporally variable function of all three controls.

These results have major implications for the conduct of dye traces from boreholes (e.g. Fountain, 1993). If the results of a borehole dye trace are to be interpreted correctly, it is essential to know how long the dye spent in the borehole before it entered the glacier drainage system. It is also necessary to determine whether the dye left the borehole as a single slug, and to identify the pathway by which it left the borehole. Our evidence from Haut Glacier d'Arolla strongly indicates that researchers intending to conduct borehole dye trace experiments should first attempt to reconstruct the drainage characteristics of their chosen boreholes in as much detail as possible. Such information may provide essential guidance to the optimum time and location within the borehole at which to conduct the trace and to the interpretation of the results produced.

In the light of these findings, it is argued that the classification and analysis of borehole water sources and circulation should be an integral part of any study of glacier hydrology that relies upon measurements made in open boreholes.

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