HYDROLOGICAL PROCESSES, VOL. 11, 211–224 (1997)

THE USE OF BOREHOLE VIDEO IN INVESTIGATING THE HYDROLOGY OF A TEMPERATE GLACIER

LUKE COPLAND[1]*‡, JON HARBOR[1], SHULAMIT GORDON[2] AND MARTIN SHARP[2]

[1]*Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA and* [2]*Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada*

ABSTRACT

A GeoVision Micro® colour video camera was used to investigate the internal structure of 11 boreholes at Haut Glacier d'Arolla, Switzerland. The boreholes were distributed across a half-section of the glacier, with closest spacing towards the glacier margin. The boreholes were used to investigate the hydrology of the glacier through automatic monitoring of borehole water level and electrical conductivity (EC) at the glacier bed. EC profiling was undertaken in several boreholes to determine the existence of water quality stratification. Temporal variations in EC stratification were used to infer borehole water sources and patterns of water circulation. Borehole video was used to confirm the conclusions made from these indirect sources of evidence, and to provide an independent source of information on the structure and hydrology of this temperate valley glacier. The video showed variations in water turbidity, englacial channels and voids, conditions at the glacier bed and down-borehole changes in ice structure. Based on the video observations, englacial channels accounted for approximately 0·1% of the vertical ice thickness, and englacial voids for approximately 0·4%. Overall, the video images provided useful qualitative and semi-quantitative data that reinforce interpretations of a range of physical and chemical parameters measured in boreholes.

KEY WORDS: glacier hydrology; video; borehole; Switzerland; glaciers

INTRODUCTION

Recent advances in miniature video camera technology have allowed the observation of previously inaccessible locations such as the interior of pipelines, sewers and water wells (e.g. Westinghouse Savannah River Company, 1989). Previous glaciological applications of miniature video cameras have focused on down-borehole changes in ice structure (Harper and Humphrey, 1995), conditions at the glacier bed (Koerner *et al.*, 1981; Pohjola, 1993) and the occurrence of englacial voids (Pohjola, 1994). This paper describes video observations made in boreholes at Haut Glacier d'Arolla, Switzerland, and the information that video provides about temperate glacier hydrology.

Knowledge of glacier hydrology is important for understanding the relationship between water pressure and glacier sliding, the role of water in glacier surging and the chemistry of glacial meltwaters. Based on theoretical analyses by Röthlisberger (1972), Shreve (1972) and Weertman (1972), glacier drainage systems can be broadly classified as 'distributed' or 'channelized'. In a distributed system, water is transported over large areas of a glacier bed at low velocity, while in a channelized system water is transported at high velocity in a small number of channels. Distributed glacier drainage may occur as a thin film of water at the ice-bed interface (Weertman, 1969, 1972, 1986), as a series of linked cavities in the lee of bedrock bumps (Lliboutry, 1969; Walder, 1986; Kamb, 1987), through permeable sediment beneath a glacier (Boulton, 1974; Clarke, 1987) or through a network of broad shallow 'canals' above and within till (Walder and Fowler, 1994). Major drainage channels may be incised upwards into ice (Röthlisberger, 1972), downwards into bedrock or till (Nye, 1973) or be wholly englacial (Shreve, 1972).

* Author to whom correspondence should be addressed.
‡ Present address: Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta T6G 2E3, Canada.

CCC 0885–6087/97/020211–14

Accepted 28 August 1996

Most conclusions about the configuration of temperate glacier drainage have been based on indirect sources of evidence such as dye-tracing results (Seaberg *et al.*, 1988; Willis *et al.*, 1990; Fountain, 1993; Sharp *et al.*, 1993), meltwater chemistry (Raiswell, 1984; Tranter *et al.*, 1993), mapping of recently deglaciated bedrock (Walder and Hallet, 1979; Sharp *et al.*, 1989) and borehole water level fluctuations (Iken and Bindschadler, 1986; Fountain, 1994; Murray and Clarke, 1995; Waddington and Clarke, 1995). More recently, continuous *in situ* monitoring of EC and turbidity at the glacier bed (Stone *et al.*, 1993; Hubbard *et al.*, 1995) and EC profiling and artificial salt tracing (Gordon *et al.*, in press), have provided data that demonstrate how individual open boreholes are plumbed into a glacier's drainage system. These techniques allow the identification of water inputs and outputs from a combination of supraglacial, englacial and subglacial sources, and their relative contribution to borehole water level fluctuations. Profiling techniques can be used to determine how water circulates within a borehole, and thus facilitate interpretation of *in situ* EC and turbidity records. In analysing such records, borehole video can be used to determine whether the signals are from water flowing past the base of a borehole (i.e. a true basal signal) or from water flowing out of the base of a borehole as a result of an englacial or supraglacial input higher in the borehole. Only when the source of these signals has been determined can the *in situ* data be used to make broader inferences about the drainage system structure of a temperate glacier.

Borehole video can also be used as an independent tool to verify and refine interpretations based on other borehole measurements. For example, the locations of englacial channels and voids are commonly indicated by variations in borehole water (e.g. if a borehole drains and refills during drilling it is assumed that an englacial void of finite volume has been intercepted), by electrical conductivity profiling (e.g. intrusion of dilute water into a column of high EC water suggests an englacial input) and by salt tracing (e.g. sources of inflow/outflow can be identified in boreholes that have no natural EC stratification). Borehole video enables physical identification of englacial channels and voids (both above and below the water level), and supraglacial, englacial and subglacial water inputs. In addition, borehole video can be used to catalogue the frequency and morphology of englacial channels and voids, and to evaluate relationships between their location and the structure of the enclosing ice. Borehole video also allows direct observation of the character and morphology of the glacier bed, and information on whether a glacier rests on 'soft' till or 'hard' bedrock (Koerner *et al.*, 1981; Pohjola, 1993; Harper and Humphrey, 1995). This is important to know because the character of the glacier bed exerts a strong control on the basal drainage of a temperate glacier. In turn, the routing, residence time and storage characteristics of meltwater, together with the water pressure associated with a given meltwater input, are controlled by the structure of the glacier drainage system (Sharp, 1991).

In this paper we focus on the utility of video as an aid in interpreting the indirect information provided by other borehole-based studies. Borehole video allows independent testing of conclusions based on borehole measurements by providing direct observation of conditions within and at the bed of a glacier. It produces a continuous image that can be recorded for later analysis, and real-time viewing that allows the camera operator to focus on areas of interest as they are encountered.

FIELD SITE AND METHODOLOGY

Haut Glacier d'Arolla is a temperate valley glacier at the head of the Val d'Hérens in Valais, Switzerland (45°58′N, 7°32′E) (Figure 1). The glacier ranges in elevation from approximately 2560 to 3500 m, faces predominantly north and is about 4·5 km long. Recent work has focused on a network of boreholes drilled with high pressure hot water towards the eastern margin of the glacier, approximately 1·5 km from the terminus (Hubbard *et al.*, 1995; Lamb *et al.*, 1995; Tranter *et al.*, in press; Copland *et al.*, in press a,b). Drilling has been to the glacier bed, and a maximum depth of 142 m has been reached. The drilling area was chosen on the basis of hydrological measurements that predicted the existence of a major subglacial channel beneath this part of the glacier (Sharp *et al.*, 1993; Hubbard *et al.*, 1995).

A total of 25 boreholes were drilled to the base of Haut Glacier d'Arolla in July and August 1995 (Figure 2). Eleven of these were investigated with a commercially available borehole video camera system supplied by Colog Inc., and manufactured by Marks Products Inc. The GeoVision Micro™ system

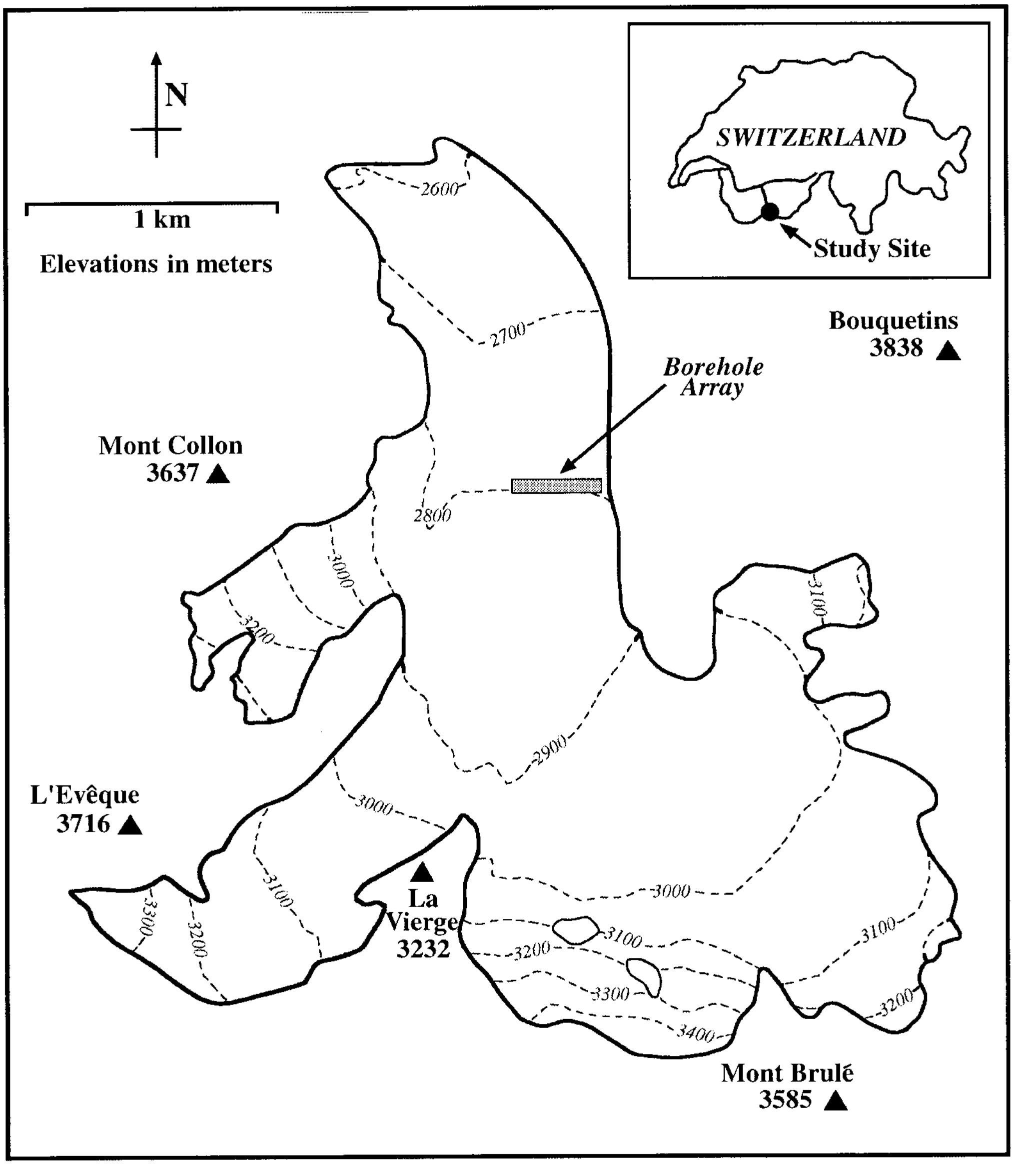

Figure 1. Haut Glacier d'Arolla. The borehole array was located towards the eastern margin of the glacier, approximately 1.5 km from the terminus

consisted of a miniature colour video camera housed in a 3 cm wide by 30 cm long waterproof stainless steel container, 230 m of cable on a hand-operated winch, a small combined colour monitor/VCR, a microphone, several side-looking mirrors and a mounting tripod (Figure 3). An in-front lighting attachment, consisting of a small bulb on the end of a thin rod, allowed exploration of boreholes more than 3 cm in diameter. Alternatively, a 7·6 cm diameter ring lighting attachment of four high-intensity bulbs could be mounted around the end of the camera. A side-looking mirror could also be attached to give a 360° view of the side of the borehole when the camera was rotated. An on-screen display showed the depth below the ice surface to an accuracy of $\pm 1\%$, and this was used as the basis for all depth measurements referred to in this paper. The borehole video images were recorded on standard small-sized video cassettes for later viewing and analysis.

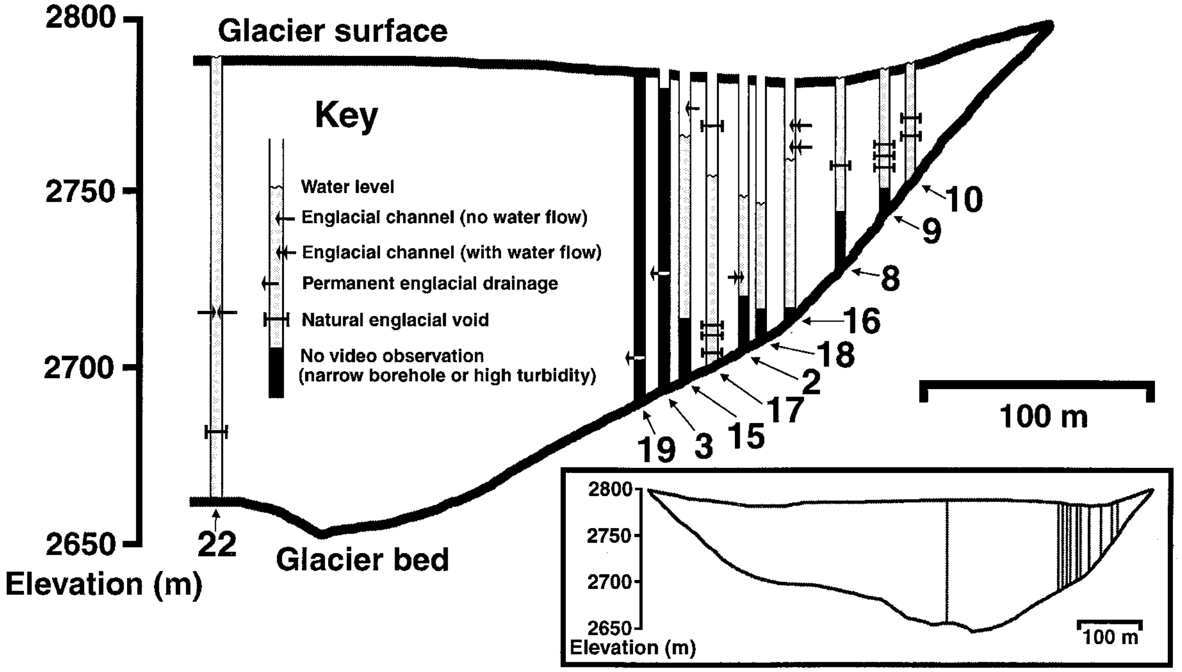

Figure 2. Cross-section of Haut Glacier d'Arolla showing location and characteristics of boreholes referred to in the text. The location of permanent englacial drainage in boreholes 95/3 and 95/19 was identified by a permanent fall in borehole water level during drilling. Note that the borehole widths in the figure are exaggerated; true borehole widths were approximately 10 cm. Basal topography was determined by radio–echo sounding

RESULTS AND DISCUSSION

Openings in borehole walls

Openings were observed in nearly every borehole, and were most common in the upper 30 m of the ice column. No openings were recorded between 30 and 59 m depth, although some were observed closer to the glacier bed. It is possible that more openings existed at depth, but could not be seen owing to high water turbidity in several boreholes, and because the borehole was sometimes too narrow for the video camera to pass all the way to the glacier bed. Based on the video observations, the openings were classified into three categories; englacial channels, natural voids and drilling-produced voids (Table I). Channels were identified by the flow of water into the borehole from an opening, by the intersection of a tubular feature by the borehole or by direct observation of the interior of a longitudinal tube. The remaining openings in the borehole walls were classified as voids if they could not be conclusively identified as channels. A void was defined as natural if it could not be linked to drilling features on the borehole wall, and had an uneven shape or interior structure. A void was defined as drilling-produced if it had a well-rounded shape, a relatively large horizontal or vertical extent compared to its depth into the ice or if it could clearly be linked to drilling features on the borehole wall. These drilling-produced voids are likely to have resulted from the melting of the borehole wall when the drill tip remained in one location for an extended period of time. The drilling process is also likely to have enlarged natural voids, although it was difficult to determine which ones and by how much. The size of an opening, as with all other features, was estimated with reference to the width of the mirror on the in-front lighting attachment (approximately 2·5 cm) or the diameter of the borehole (approximately 10 cm).

Englacial channels

Five of the nineteen openings were classified as englacial channels. The most distinctive was observed entering borehole 95/15 at a depth of 10·9 m (Figure 4). The channel opening, which was located 7·0 m above the water level in the borehole, was approximately 15 cm high and 4 cm wide, and had a thin crack

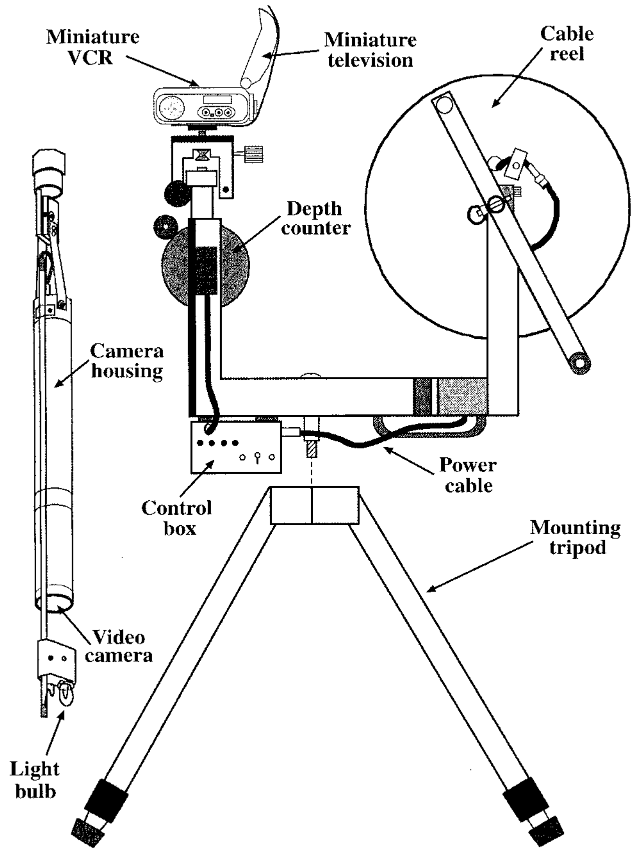

Figure 3. The GeoVision Micro® borehole video camera system (reproduced with permission from Marks Products, Inc.)

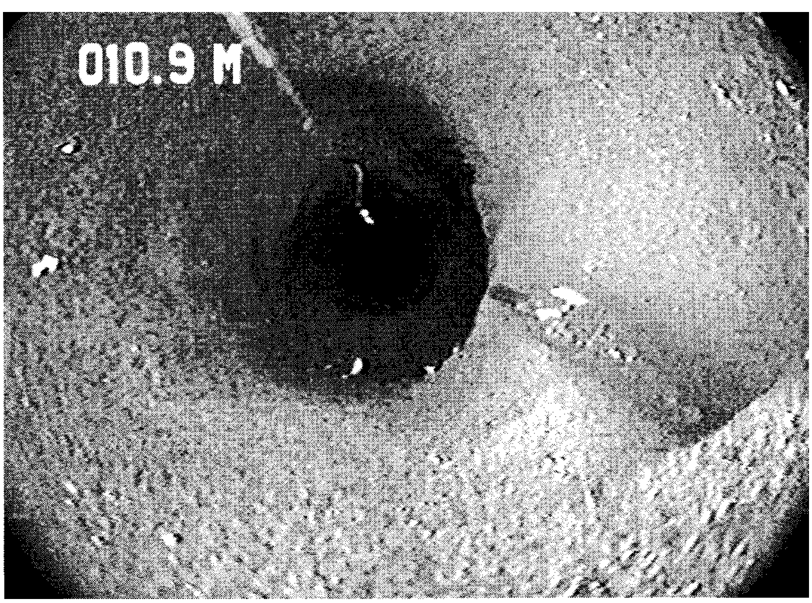

Figure 4. Video image of the englacial channel observed entering borehole 95/15 at a depth of 10·9 m (lower right hand corner of image). Borehole is approximately 10 cm in diameter

Table I. Description of the englacial channels and voids observed in Haut Glacier d'Arolla

Borehole	Depth (m)	Size (cm)*	Inferred opening type and description
95/2	59·7	2,2,?	Natural channel, identified by plume of water entering borehole. No relation to ice structure or sediment bands
95/8	26·5	60,7,?	Natural void, large vertical extent, no water flow, partially closed crevasse? Some sediment resting on base of void
95/9	22·2	7,7,5	Natural void, base of rough ice covered in a little sediment. Ice foliations present less than 5 cm away
	25·6	7,6,5	Natural void which extends into borehole wall. No relation to ice structure, but lots of sediment on base
	27·4	2,7,2	Horizontal indentation with lots of sediment on base. Probably a sediment layer that was enlarged by drilling
	29·2	6,8,8	Natural void off to one side and down from main borehole. Close (< 10 cm) to foliations and sediment bands in ice
	29·8	20,10,5	Drilling-produced void, very smooth interior, increase in size with depth, thin veneer of sediment on base
	30·5	20,10,8	Drilling-produced void, very smooth interior, increase in size with depth, thin veneer of sediment on base
95/10	14·3	14,10,7	Relatively large natural void, marked relationship to vertical ice foliation, no sediment on base or in ice
	19·8	50,20,20	Borehole intersects large natural void, uneven in shape, some sediment on base, but none in surrounding ice
95/15	10·9	15,4, > 30	Natural channel, longer than seen with mirror, keyhole shape in cross-section, surrounding ice is homogeneous
95/16	14·9	6,6,?	Natural channel, identified by water entering borehole above water level, intersects near-vertical ice foliation
	20·7	8,6,?	Natural channel, identified by water entering borehole above water level, near to vertical ice foliation
95/17	14·6	20,8,?	Natural void, interior consists of mosaic of interconnecting ice fragments, occurs in area of relatively blue ice
	83·8	7,7,3	Natural void, rounded sides, some sediment on base, but no relation to ice structure or sediment frozen in ice
	86·0	8,7,3	Drilling-enlarged void, very rounded sides, sediment band visible on opposite side of borehole
	91·8	6,6,5	Natural void, rounded, lots of sediment on base, close to sediment band in ice NB: There are many indentations in the side of borehole 95/17 between 83.8 m and the bed at 93.0 m — almost all of these occur in relation to sediment bands frozen into the ice
95/22	74·1	12,10,?	Natural channel crosses borehole, openings on both sides, no relation to ice structure, but lots of sediment in ice
	109·8	14,8,5	Drilling-enlarged void, rounded sides, lots of sediment covering base and in surrounding ice

* Size of englacial channel/void (respectively): vertical size of opening, horizontal size of opening, horizontal depth into ice (? = undetermined)

4 cm long leading down from its base. The tubular channel extended further back into the ice than could be seen with the side-looking mirror (30 cm), had no detectable water flow through it and was keyhole in shape (Figure 5). It occurred in an area of homogeneous bubbly white ice, and bore no relationship to variations in ice structure seen in other parts of the borehole. The absence of water flow and the fact that the opening intersected only one side of the borehole suggests that this feature was an abandoned englacial channel isolated from the presently active drainage system. The keyhole shape of the channel is similar to that predicted by Shreve (1972) and Sugden and John (1976) for the upper part of a glacier in a zone of fluctuating water level. Using a model based on an analogy with tunnels in karst, Shreve (1972) argued that high water levels would produce an englacial channel that is circular in shape. The channel would be deepened by preferential melting of the channel base during periods of low water flow. The final result would be an englacial channel with a 'keyhole-shaped' cross-section.

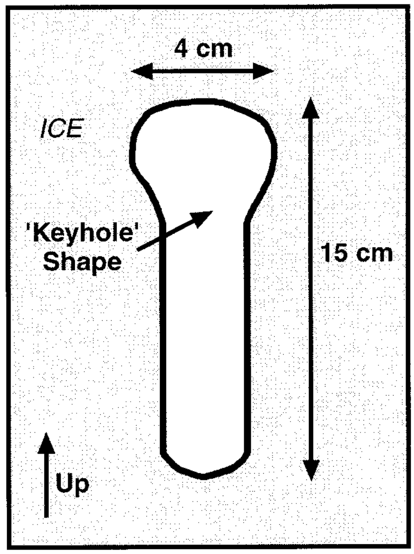

Figure 5. Sketch of the 'keyhole' shape of the englacial channel observed entering borehole 95/15 at a depth of 10.9 m

The best example of an active englacial channel below the water level was observed in borehole 95/2 at a depth of 59·7 m. It was identified by a plume of turbid water entering the water column from a circular opening in the borehole wall. The opening was approximately 2 cm high by 2 cm wide, and showed no relation to the surrounding ice structure. The plume of turbid water reached up and down the borehole from the channel opening, and resulted in a zone of turbid water within an area of generally low turbidity. This channel did not continue on the opposite side of the borehole.

Active englacial channels above the water level were observed at depths of 14·9 and 20·7 m in borehole 95/16. The water level in this borehole was at a depth of 23·4 m. The englacial channels were identified by the flow of water out of an opening and into the borehole at both locations, although conclusive identification was difficult. This is because supraglacial water running down the borehole wall may have given the same impression as water flowing out of a real opening if it ran along the inside of a depression. The discharge of water from both openings seemed to be more than was running down the borehole walls, however, which suggests that they were real englacial channels.

The only englacial channel that completely crossed a borehole was observed at a depth of 74·1 m in borehole 95/22. Circular openings approximately 12 cm high and 10 cm wide were observed on both sides of the borehole, and sediment could be seen frozen into the surrounding ice and resting on the base of the openings. Water movement below the water level was investigated by watching for the deflection of suspended sediment particles in the water column, and the movement of a piece of red thread attached to the end of the ring lighting system. With the exception of borehole 95/2, there was no detectable water flow from any englacial channel observed below the borehole water level. This does not necessarily mean that water flow from most englacial channels never occurs, however, as discussed later.

In addition to the englacial channels discussed, several others have been indicated in the past at Haut Glacier d'Arolla. Evidence has come from a sudden and permanent drop in borehole water level during drilling, and from the occasional sound of rushing water within boreholes. Permanent englacial drainage occurred twice during drilling in 1995, at depths of 60 and 85 m in boreholes 95/3 and 95/19, respectively, although these boreholes could not be accessed with the video camera. Englacial channels have also been observed in other glaciers. Raymond and Harrison (1975) identified them in ice cores from the Blue Glacier, Washington. Using borehole video, Pohjola (1994) observed them in Storglaciären, Sweden, while Harper and Humphrey (1995) observed them in Worthington Glacier, Alaska. By comparing the vertical size of the observed englacial channels with the total length of observed boreholes, it is estimated that englacial channels account for approximately 0·1% of the vertical ice thickness in the study area. However, the 1995

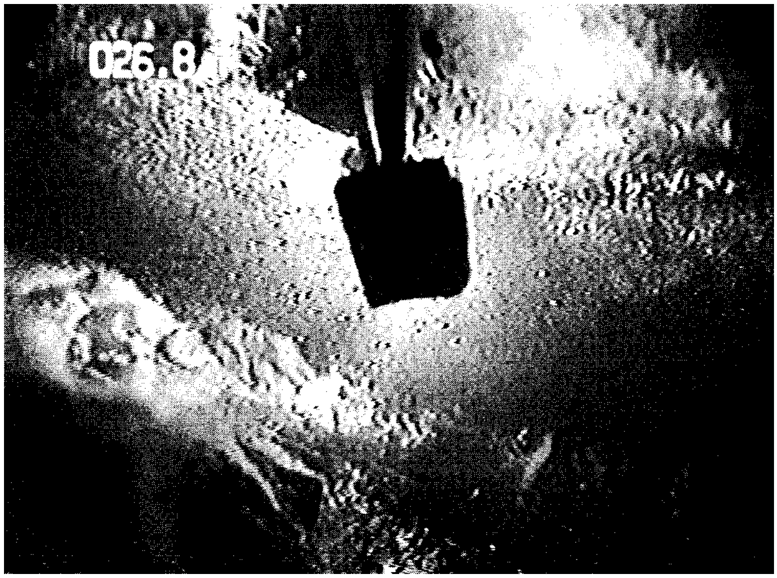

Figure 6. Video image of the large longitudinal void observed in borehole 95/8 at a depth of 26·8 m. The centre of the image is the view directly down the open void, while the upper and lower edges of the image are the ice at the edge of the void. Void is approximately 12 cm wide

drilling programme was focused on the only area of the glacier where previous more widespread drilling had identified englacial channels. Thus 0·1% is probably an overestimate for the glacier as a whole. Overall, the video observations suggest that the small englacial channels intersected by the boreholes do not drain a large proportion of the meltwater from Haut Glacier d'Arolla.

Natural and drilling-produced voids

The largest and most distinct englacial void was observed intersecting borehole 95/8 at a depth of 26·8 m (Figure 6). It was approximately 60 cm high, 12 cm wide and undefined in length. The borehole water level remained at the glacier surface during the drilling of this borehole, except for a temporary fall to the depth of the void when the void was first intersected. This indicates that the void was probably air-filled prior to drilling, finite in volume and unconnected to any active crevasse or drainage pathway. This interpretation was reinforced by the lack of detectable water flow within it. There are many small surface crevasses in the region around borehole 95/8, and the elongate shape of the void suggests it was an old crevasse that had become closed to the atmosphere.

The voids in the other boreholes were smaller in size, not detected during drilling and most appeared to be natural in origin. For example, the void observed in borehole 95/17 at a depth of 14·6 m was approximately 20 cm high, and unique because its interior consisted of a mosaic of interconnecting ice fragments. This suggests that the void may have contained partially frozen water before it was intersected by the borehole. Two of the observed 19 openings did appear to have a drilling-produced origin, however, owing to their rounded shape and close relationship to the location of the borehole. By comparing the vertical height of the observed englacial voids with the total length of observed boreholes, natural englacial voids accounted for approximately 0·4% of the ice thickness.

Particular attention was paid to the relationship between openings and surrounding ice structure and debris content during video inspection of the boreholes. As shown in Table I, most of the englacial channels and voids occurred in association with blue-ice inclusions and/or debris bands, although a few occurred in areas of apparently homogeneous ice. Sediment was also observed resting on the base of several openings, which probably originated from the intersection of local debris bands during drilling, or the settling of material in the water column after it was disturbed from the glacier bed by the drill.

The observed relation between blue-ice inclusions and englacial openings at Haut Glacier d'Arolla is similar to that described by Pohjola (1994). From borehole video observations in Storglaciären, Sweden, Pohjola identified a close association between blue-ice inclusions and englacial voids, and argued that the origin and development of these features was coupled. The burial and horizontal movement of water-filled crevasses in the accumulation areas of Storglaciären was identified as an important process in the development of blue-ice inclusions. The contact between blue-ice inclusions and firn was thought to act as a weakness along which water could flow, and a way in which englacial channels and voids could form. It is possible that a similar process occurs at Haut Glacier d'Arolla as several crevasses are present in the upper part of the glacier, although there is no evidence that any of these are ever water filled. The fact that not all openings were coupled with blue-ice inclusions also suggests that other processes are important.

The observed relation between debris bands and englacial openings at Haut Glacier d'Arolla suggests that debris may play a role in the formation of englacial channels and voids. The debris bands probably originated from the shearing of ice formerly in contact with the glacier bed (Copland *et al.*, in press a), the incorporation of avalanche and rock fall material from the slopes surrounding the glacier or the burial of patches of dirt and wind-blown dust on the glacier surface by new snowfall at the end of the summer melt season. The debris bands may provide a weakness in the ice which is exploited by meltwater to form englacial channels and voids. Alternatively, the debris bands may be relatively resistant features in the ice that restrict downward water movement and force the localization of water flow along their upper surface. The formation of englacial channels and voids may occur if the localization of meltwater continues over time and results in the melting of ice.

Water quality

Of the eleven boreholes filmed, seven had accompanying EC profiling data. EC profiles consisted of point measurements of EC at 5 m intervals from just below the borehole water level to the glacier bed. Marked spatial variations in borehole water quality were observed, superimposed upon a general increase in water turbidity with depth. Alternating zones of relatively clear and turbid water were also occasionally encountered within a single borehole. After combining the EC data with the video logs, three types of relationship between EC and turbidity stratification were identified.

(i) No turbidity or EC stratification. The video log of borehole 95/17 showed that the entire water column was composed of clear, low turbidity water. An EC profile taken 45 minutes prior to recording showed that the EC of the entire water column was <2 μS cm^{-1}. In this case clear water was characterized by low EC values. The sources of water suggested by these EC values are either from the drill water from surface meltwater streams, or supraglacial or englacial inputs. At the time of filming, this borehole was full and no water level fluctuations were observed, thus implying that it was unconnected to the basal drainage system. Borehole 95/15 also displayed no turbidity or EC stratification.

(ii) Concordant turbidity and EC stratification. The video log of borehole 95/9 showed that the water column was clear from the glacier surface to 8·8 m depth, below which it became progressively more turbid until the bed was reached. The EC profile showed that from 0–10 m below the glacier surface the EC of the water was <10 μS cm^{-1}, and below 10 m depth was 10–30 μS cm^{-1}. Consequently, there was a good correspondence between the water quality boundary seen in the video and the stratification identified from the EC profile. Clear water was characterized by low EC values, while more turbid water was associated with higher EC values. As no water level changes in this borehole were registered, stratification of the water column was likely to represent supraglacial water from drilling and melt overlying drill fluid which had churned up the bed and then acquired solute from the suspended sediment. Boreholes 95/8 and 95/2 also displayed concordant turbidity and EC stratification.

(iii) Discordant turbidity and EC stratification. The video log of borehole 95/18 showed that turbidity of the water was uniformly high along the length of the water column. EC profiling carried out two hours after filming showed that there was a boundary at 65 m below the glacier surface, where water of <10 μS cm^{-1} overlay water of 18–25 μS cm^{-1}. In this case the water quality seen in the video did not correspond to the EC stratification. A likely explanation for this phenomenon is that the borehole was reamed at the bed (the drill was lowered down the existing hole to widen it and free a stuck probe) prior to filming and

profiling. This probably disturbed unconsolidated sediment from the bed and distributed it throughout the water column. It appears that the EC stratification was then able to restabilize to the level that was recorded in a profile on the previous day, before the turbidity of the water returned to its natural state. Borehole water sampling in 1993 also produced some samples that displayed high EC, clear water, and other samples that displayed low EC, turbid waters.

Video identification of englacial channels inferred from water quality data

Borehole 95/2 was 96·5 m deep and drained to 60 m below the glacier surface two days after drilling. The water level remained constant at this level unless reaming or the input of supraglacial meltwater caused a temporary rise in water level. During one of these temporary rises in water level, EC profiling showed that below 60 m the water had stable EC values of >10 μS cm^{-1}, while above 60 m the water had EC values of <10 μS cm^{-1}. This suggests that there was an englacial output at 60 m because the dilute water above drained to this level overnight, while the EC stratification below 60 m remained stable.

As a result of these EC profiles, attention was paid to the area around 60 m when this borehole was viewed with the video camera. The video log showed that the water column was clear until 56·7 m, when wisps of turbid water were encountered. At 59·7 m an englacial channel was observed that appeared to be feeding the borehole with a plume of turbid water. In addition, the borehole displayed a distinct water quality split with one side of the borehole filled with turbid water, and the other side with clear water. Beyond 60·6 m the water column was clear again, until 62·5 m where more turbid water was encountered (Figure 7). It seems likely that the plume of turbid water was the result of turbid water returning to the borehole after it was forced into the englacial channel by reaming two hours prior to video observation. There are few sources of turbidity 40 m above the glacier bed, and reaming probably disturbed the turbid layers below.

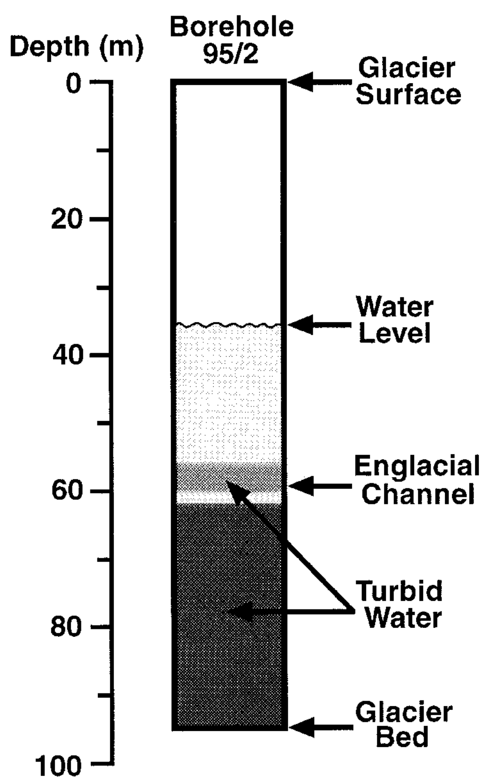

Figure 7. The patterns of water turbidity observed in borehole 95/2. Note the zone of relatively turbid water where the englacial channel enters the borehole

Further information about the water circulation and 'plumbing' of boreholes at Haut Glacier d'Arolla was provided by borehole 95/16. This borehole was drilled to a depth of 55·2 m, and drained to 24 m below the glacier surface 30 minutes after drilling had stopped. Subsequent daily EC profiles showed that the water level remained at a depth of 24 m for the following two weeks of observation, and that the water column consisted of $< 3\ \mu S\ cm^{-1}$ water throughout. The video log confirmed this water level and showed that the water column was clear. The video log also showed the presence of two active englacial channels above the water level at 10·9 and 14·9 m, and the input of supraglacial water down the sides of the borehole walls.

The observations in borehole 95/16 pose an interesting question. How does the water level stay constant throughout the day when there is such an obvious input of supraglacial and englacial water into the borehole? It appears that the water output adjusts continually to match the input, so that the two are always equal. As the water column was not stratified, the output was likely to be basal as no other englacial channels were observed in this borehole; however, the adjustment process remains to be explained in detail. Had this borehole not been inspected by video, the interpretation from EC profiling would have been that the borehole connected to an englacial channel at a depth of 24 m after drilling, or to a subglacial void with the capacity to lower the borehole water level by the observed amount, and then remained passive. Now the interpretation is that the borehole water level is regulated in some way by basal water flow.

Bed conditions

The glacier bed was observed in boreholes 95/10, 95/17 and 95/22 at depths of 32·0, 93·0 and 131·7 m, respectively. The bed could not be seen in the other boreholes owing to high turbidity, or because the camera was too wide to pass all the way down the borehole. The glacier bed in borehole 95/10 consisted of subrounded and subangular clasts in a matrix of unconsolidated fine sediment (Figure 8). The bed in borehole 95/17 consisted predominantly of a relatively large, thin rock protruding vertically up into the borehole. Surrounding the rock was a layer of fine sediment. In borehole 95/22 the glacier bed consisted of fine sediment, contained no clasts or other large material and was directly in contact with the ice at the bottom of the borehole.

The character of the glacier bed observed with the video camera at Haut Glacier d'Arolla is similar to the till seen in areas recently exposed by glacier retreat, as well as in cavities at the glacier margin. It supports the

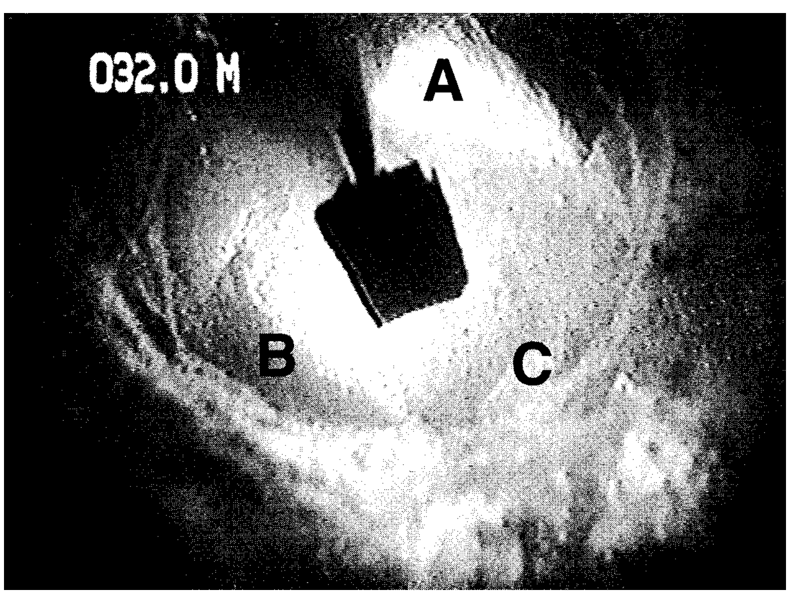

Figure 8. Video image of the glacier bed observed in borehole 95/10 at a depth of 32·0 m. Borehole is approximately 12 cm in diameter. Marker A is a clast projecting out into the borehole a few centimetres above the bed, B is a clast resting on the base of the borehole and C is a clast resting on the base of the borehole and partially frozen into the surrounding ice

conclusions of Hubbard *et al.* (1995) that Haut Glacier d'Arolla lies at least partly on an unconsolidated bed. In addition, the video logs confirm that boreholes really do reach the glacier bed. This is important as it confirms that automatic sensors are located at the glacier bed, although it must be remembered that the conditions measured by the sensors are not necessarily basal (e.g. input of supraglacial water may cause low EC outflow at the base of a borehole).

Particular attention was paid to the movement of suspended sediment particles near the glacier bed in the boreholes in which the bed could be seen. As with the englacial channels observed below the water level, water flow was not detected, although flow may still have occurred for the following reasons.

1. Water velocities may have been too low to be detected. For example, a water level rise of 20 m per hour (which was high by 1995 standards) in a 5 cm radius hole would require a flux of only 0·00004 $m^3 s^{-1}$, and a vertical velocity of 5 mm s^{-1}, if driven by basal inflow.

2. All basal water flow may have been through the unconsolidated sediment observed beneath the glacier, rather than at the glacier bed.

3. Basal water flow probably introduces high turbidity water into the base of boreholes, therefore precluding video observations in the boreholes where water flow is most likely.

4. Most video observations were in the afternoon, which may have been a period of relatively little englacial water movement. Salt trace studies in 1993 indicate that the direction of the hydraulic gradient between boreholes and englacial channels can change during a day. It appears that water can enter englacial channels from boreholes as the water level rises in the late morning, and then be returned to the boreholes from englacial channels in the early evening as the water level drops. We speculate that the initial water level rise is driven by both supraglacial and subglacial inputs. As a result, the borehole becomes overpressured relative to the natural pressure in the drainage system. This dams flows in the englacial conduit. Over time, the overpressure is reduced and eventually eliminated by basal outflow. This can occur once the hydraulic gradient between the borehole and channel starts to fall as discharge stabilizes in the afternoon. As the overpressure is reduced, flow recommences in the englacial conduit and this starts to feed the borehole. Consequently, water flow from englacial channels intersected by boreholes may be intermittent, and would not necessarily be expected during the afternoon.

SUMMARY AND CONCLUSIONS

Borehole video provides real-time viewing of the interior and bed of Haut Glacier d'Arolla, and can generate a continuous record of water clarity. It provides important additional information that greatly aids interpretations based on indirect sources of evidence such as EC profiling and water level variations, and allows observation of englacial features such as channels and voids that are difficult to document otherwise. By comparing the vertical height of the observed englacial channels and voids with the total length of observed boreholes, it is estimated that englacial channels account for approximately 0·1% of the vertical ice thickness, and natural voids for approximately 0·4%. Many of the englacial channels and voids are coupled with blue-ice inclusions or debris bands in the ice. This suggests that some of the englacial openings are linked to the closure of crevasses in the upper parts of the glacier, or the diversion of water flow along layers of sediment frozen into the ice. Variations in the shape of the englacial channels correlate with predictions by Shreve (1972), based on an analogy with tunnels in karst. Where the openings of a channel could be observed they were keyhole-shaped above the borehole water level, and circular below it. Finally, video observations of the glacier bed have supported inferences from borehole water level records (Hubbard *et al.*, 1995) that Haut Glacier d'Arolla lies on a bed composed at least partly of till.

HIGHLIGHTS VIDEO

A 23-minute composite video tape of the 'highlights' of the Haut Glacier d'Arolla video recordings has been produced for educational and research use. Please contact Jon Harbor to obtain a copy of this video.

ACKNOWLEDGEMENTS

This research was funded by US National Science Foundation grants OPP-9321350 and OPP-94963450, the Geological Society of America and the Canadian Natural Sciences and Engineering Research Council. The field assistance of Bryn Hubbard, Marie Minner, Simon Cross, David Gaselee and all other 1995 Arolla Glaciology Project members is greatly appreciated.

REFERENCES

Boulton, G. S. 1974. 'Processes and patterns of glacier erosion', in Coates, D.R. (Ed.), *Glacial Geomorphology*. State University of New York, Binghamton, pp. 41–87.

Clarke, G. K. C. 1987. 'Subglacial till: a physical framework for its properties and processes', *J. Geophys. Res.* **92**(B9), 9023–9036.

Copland, L., Harbor, J., Gordon, S., and Sharp, M. in press a. 'Borehole video observation of englacial and basal ice conditions in a temperate valley glacier', *Ann. Glaciol.* **24**.

Copland, L., Harbor, J., Minner, M., and Sharp, M. in press b. 'The use of borehole inclinometry in determining basal sliding and internal deformation at Haut Glacier d'Arolla, Switzerland', *Ann. Glaciol.* **24**.

Fountain, A. G. 1993. 'Geometry and flow conditions of subglacial water at South Cascade Glacier, Washington State, USA; an analysis of tracer injections', *J. Glaciol.* **39**, 143–156.

Fountain, A. G. 1994. 'Borehole water-level variations and implications for the subglacial hydraulics of South Cascade Glacier, Washington State, U.S.A.', *J. Glaciol.* **40**, 293–304.

Gordon, S., Sharp, M., Hubbard, B., Willis, I., Smart, C. C., and Ketterling, B. In press. 'Seasonal reorganisation of subglacial drainage inferred from borehole measurements', *Hydrol. Process.*

Harper, J. T. and Humphrey, N. F. 1995. 'Borehole video analysis of a temperate glacier's englacial and subglacial structure: implications for glacier flow models', *Geology*, **23**, 901–904.

Hubbard, B. P., Sharp, M. J., Willis, I. C., Nielsen, M. K., and Smart, C. C. 1995. 'Borehole water-level variations and the structure of the subglacial hydrological system of Haut Glacier d'Arolla, Valais, Switzerland', *J. Glaciol.* **41**, 572–583.

Iken, A. and Bindschadler, R. A. 1986. 'Combined measurements of subglacial water pressure and surface velocity of the Findelengletscher, Switzerland. Conclusions about drainage system and sliding mechanism', *J. Glaciol.* **32**, 101–119.

Kamb, B. 1987. 'Glacier surge mechanism based on linked cavity configuration of the basal water conduit system', *J. Geophys. Res.* **92**(B9), 9083–9100.

Koerner, R. M., Fisher, D. A., and Parnandi, M. 1981. 'Bore-hole video and photographic cameras', *Ann. Glaciol.* **2**, 34–38.

Lamb, H., Tranter, M., Brown, G. H., Gordon, S., Hubbard, B., Nielsen, M., Sharp, M., Smart, C. C., and Willis, I. C. 1995. 'The composition of meltwaters sampled from boreholes at the Haut Glacier d'Arolla, Switzerland', *Int. Assoc. Hydrol. Sci. Pub.* **228**, 395–403.

Lliboutry, L. 1969. 'Contribution à la théorie des ondes glaciaires', *Can. J. Earth Sci.* **6**, 943–953.

Murray, T. and Clarke, G. K. C. 1995. 'Black box modelling of the subglacial water system', *J. Geophys. Res.* **100**(B7), 10231–10245.

Nye, J. F. 1973. 'Water at the bed of a glacier', *Int. Assoc. Hydrol. Sci. Publ.* **95**, 189–194.

Pohjola, V. A. 1993. 'TV-video observations of bed and basal sliding on Storglaciären, Sweden', *J. Glaciol.* **39**, 111–118.

Pohjola, V. A. 1994. 'TV-video observations of englacial voids in Storglaciären, Sweden', *J. Glaciol.* **40**, 231–240.

Raiswell, R. 1984. 'Chemical models of solute acquisition in glacier melt waters', *J. Glaciol.* **30**, 49–57.

Raymond, C. F. and Harrison, W. D. 1975. 'Some observations on the behaviour of the liquid and gas phases in temperate glacier ice', *J. Glaciol.* **14**, 213–233.

Röthlisberger, H. 1972. 'Water pressure in intra- and subglacial channels', *J. Glaciol.* **11**, 177–203.

Seaberg, S. Z., Seaberg, J. Z., Hooke, R. LeB., and Wiberg, D. W. 1988. 'Character of the englacial and subglacial drainage system in the lower part of the ablation area of Storglaciären, Sweden, as revealed by dye-trace studies', *J. Glaciol.* **34**, 217–227.

Sharp, M. 1991. 'Hydrological inferences from meltwater quality data: the unfulfilled potential', *British Hydrol. Soc. Third National Hydrology Symposium*, 5·1–5·6.

Sharp, M., Gemmell, J. C., and Tison, J.-L. 1989. 'Structure and stability of the former subglacial drainage system of Glacier de Tsanfleuron, Switzerland, *Earth Surf. Process. Landf.* **14**, 119–134.

Sharp, M., Richards, K., Willis, I., Arnold, N., Nienow, P., Lawson, W., and Tison, J.-L. 1993. 'Geometry, bed topography and drainage system structure of the Haut Glacier d'Arolla, Switzerland', *Earth Surf. Process. Landf.* **18**, 557–571.

Shreve, R. L. 1972. 'Movement of water in glaciers', *J. Glaciol.* **11**, 205–214.

Stone, D. B., Clarke, G. K. C., and Blake, E. W. 1993. 'Subglacial measurement of turbidity and electrical conductivity', *J. Glaciol.* **39**, 415–420.

Sugden, D. E. and John, B. S. 1976. *Glaciers and Landscape*. Edward Arnold Ltd., London. p. 290.

Tranter, M., Brown, G., Raiswell, R., Sharp, M., and Gurnell, A. 1993. 'A conceptual model of solute acquisition by alpine glacier meltwaters', *J. Glaciol.* **39**, 573–581.

Tranter, M., Sharp, M. J., Brown, G. H., Willis, I. C., Hubbard, B. P., Nielsen, M. K., Smart, C. C., Gordon, S., Tully, M., and Lamb, H. R. 1997. 'Variability in the chemical composition of *in situ* subglacial meltwaters', *Hydrol. Process.* **11**, 59–77.

Waddington, B. S. and Clarke, G. K. C. 1995. 'Hydraulic properties of subglacial sediment determined from the mechanical response of water-filled boreholes', *J. Glaciol.* **41**, 112–124.

Walder, J. S. 1986. 'Hydraulics of subglacial cavities', *J. Glaciol.* **32**, 439–445.

Walder, J. S. and Fowler, A. 1994. 'Channelized subglacial drainage over a deformable bed', *J. Glaciol.* **40**, 3–15.

Walder, J. and Hallet, B. 1979. 'Geometry of former subglacial water channels and cavities', *J. Glaciol.* **23**, 335–346.

Weertman, J. 1969. 'Water lubrication mechanism of glacier surges', *Can. J. Earth Sci.* **6**, 929–942.

Weertman, J. 1972. 'General theory of water flow at the base of a glacier or ice sheet', *Rev. Geophys. Space Phys.* **10**, 287–333.
Weertman, J. 1986. 'Basal water and high-pressure basal ice', *J. Glaciol.* **32**, 455–463.
Westinghouse Savannah River Company. 1989. 'Demonstration of innovative monitoring technologies at the Savannah River integrated demonstration site', *Report for US Department of Energy Contract DE-AC09-89SR18035*. Westinghouse Savannah River Company, Aiken, South Carolina.
Willis, I. C., Sharp, M., and Richards, K. 1990. 'Configuration of the drainage system of Mitdalsbreen, Norway, as indicated by dye-tracing experiments', *J. Glaciol.* **36**, 89–101.