The use of salt injection and conductivity monitoring to infer near-margin hydrological conditions on Vestari-Hagafellsjökull, Iceland

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ABSTRACT. Vestari-Hagafellsjökull is a surge-type outlet glacier from the Langjökull ice cap, Iceland. Intensive hydrological investigations were carried out during non-surge conditions in the summers of 1999 and 2000, and 14 boreholes were drilled using pressurized hot water over an area 800 m from the margin and approximately 5000 m^2 in size, where ice thickness ranged from 60 to 70 m. Initial investigations showed that a large fraction of the boreholes drilled to the bed did not drain and were assumed not to connect to the subglacial drainage system. Subsequently, we investigated the hypothesis that boreholes which remain full may do so as a consequence of a balance between englacial inflow and basal drainage rather than the standard assumption that such boreholes are simply unconnected. In testing this hypothesis, we developed a new technique for measuring water motion within the borehole by monitoring the passage of a saline solution down the borehole's water column. The technique allows rates of motion to be established, as well as allowing the quantification of net addition and loss of water from the borehole. Observations based on the motion of saline plumes within the boreholes lead us to the conclusion that some boreholes do indeed remain full as a consequence of a balance between englacial inflow and subglacial drainage. The abrupt dilution that occurs at the top of these boreholes suggests inflow from a near-surface englacial water source, while the descent of the saline plumes implies that water is being lost at the base to the subglacial system. The system appears to be driven by excess water head in the boreholes over flotation and implies that the borehole/bedrock interface can be 'leaky'.

INTRODUCTION

Boreholes drilled using pressurized hot-water equipment provide a convenient method of accessing the glacier bed both for the installation of subglacial instrumentation and for measurements of the subglacial hydrological regime. In the latter studies, water level within the borehole is assumed to be controlled entirely by the pressure of the subglacial hydrological system of linked channels, cavities and water films (Fountain, 1994). Fluctuations in borehole water levels (as recorded visually or by pressure transducers) are taken as diagnostic of spatial and temporal variations within this system.

The level of flotation (h_f) of a borehole is defined as the water depth required for the pressure at the base of the water column to balance the pressure of the surrounding glacier ice

$$h_f = \frac{\rho_i h_i}{\rho_w} \approx 0.91 h_i,$$

where h_i is the depth of ice, ρ_i is the density of ice (910 kg m^{-3}) and ρ_w is the density of fresh water (1000 kg m^{-3}). The borehole is often assumed to be unconnected to the subglacial hydrological system if the water level within the borehole remains above the level of flotation for prolonged periods of time. We refer to such boreholes as 'full', while those operating at levels consistently below flotation are 'drained'. Gordon and others (1998, 2001) show that boreholes can be intermittently full or drained, and that drainage may take weeks or months to occur. Observations from two seasons (summers of 1999 and 2000) of borehole measurements on the Vestari-Hagafellsjökull outlet glacier of the Langjökull ice cap, Iceland, led us to formulate an alternative hypothesis to explain the existence of full boreholes. This is that high fluxes of supraglacial or englacial meltwater can infiltrate a borehole and buffer its water level above that determined by the subglacial hydrological system. In this case, the borehole no longer behaves as a passive manometer but is an active part of the glacier's hydrological system. This hypothesis is obviously only applicable to sites (such as Vestari-Hagafellsjökull) in the ablation zones of temperate glaciers with abundant meltwater present. Although it is common practice to locate boreholes on local topographic highs to avoid supraglacial inflow, this does not guard against englacial inflows or those occurring just below the ice surface.

In this paper, we report the results of a series of experiments aimed at determining the importance of supraglacial and englacial flows in the hydrology of Vestari-Hagafellsjökull. Direct observations of boreholes by video camera have been used (Copland and others, 1997) to provide visual information on the presence of englacial conduits and cavities, as well as the glacier bed (where low turbidity implies an unconnected borehole). Dye and solute tracing has also been used to monitor water routing to the glacier snout and in between boreholes believed to connect to the same drainage system (e.g. Engelhardt and Kamb, 1997). Gordon and others (2001) have extended this concept by injecting saline water to the base of drained boreholes that refilled diurnally, and used conductivity probes to monitor water mixing and inputs to the boreholes. We continue this trend by injecting saline water into the top of the borehole and monitoring its progress down towards

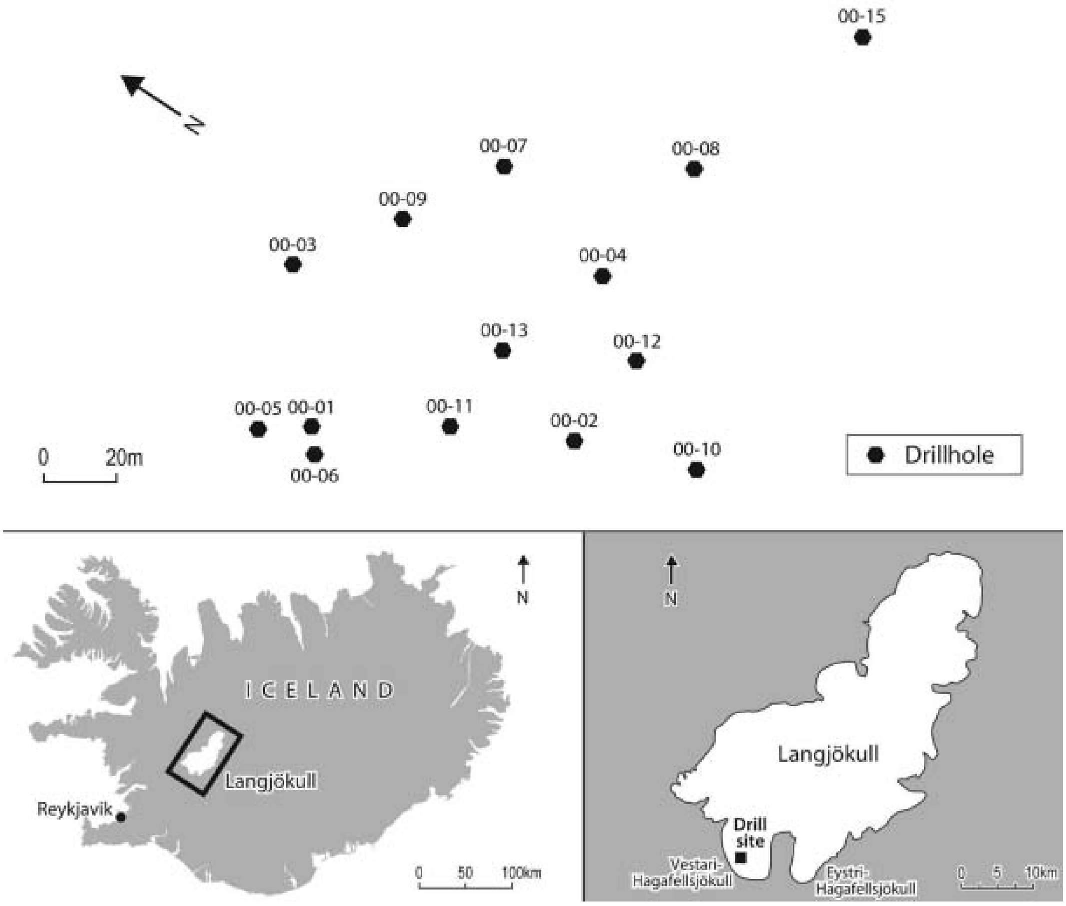

Fig. 1. Location of Langjökull ice cap and field area, along with the borehole array utilized in the experiments reported here.

the borehole's base. We employ simple mixture theory to determine rates and quantities of englacial water flow. We assume that the product of water conductivity (C) and volume (V) of a mixture is the sum of that of its component water masses

$$\bar{C}\bar{V} = \sum_{i=1}^{n} C_i V_i, \tag{1}$$

based on solute mass conservation and the assumption that conductivity is proportional to solute concentration (in an isothermal system). This type of analysis is routinely used to determine the discharge of rivers and has been used to study the bulk chemistry of glacierized catchments (Collins, 1982).

THE FIELD AREA

Vestari-Hagafellsjökull is an outlet glacier of the Langjökull ice cap in western central Iceland (Fig. 1). Langjökull is Iceland's second largest ice cap, with an area in 1973 of 953 km^2 and a maximum elevation of 1450 m. The equilibrium-line altitude is approximately 1000 m and summer ablation rates are $\sim$5 cm d^{-1} (based on our own observations). The ice cap is believed to rest upon deformable sediments (Hart, 1995; Fuller and Murray, 2000). The Hagafell ridge separates Vestari-Hagafellsjökull and neighbouring Eystri-Hagafellsjökull, and the outlets drain most of the southern sector of the ice cap. These outlets are the only ones from the ice cap to have a history of surging, and both were in a quiescent phase during our fieldwork (Sigurðsson, 1998).The margin of Vestari-Hagafellsjökull is lobate, with a low surface slope ($\sim$3.8°), and extends over a large Holocene basalt lava field which contains numerous subglacial landforms (Hart, 1995). The ice is thought to be temperate throughout and the widespread presence of moulins implies that meltwater can reach the glacier bed freely. A large ($\sim$20 m wide) drainage conduit was found at the margin adjacent to the study area. All results reported here are based on our second (2000) field season that ran from mid-July to early September. A total of 14 boreholes were drilled (see Fig. 1). Care was taken to position the boreholes so that no water entered them through direct surface runoff.

FIELD TECHNIQUES

Two methods were used to measure borehole water levels at Vestari-Hagafellsjökull: direct manual measurements and a single water-pressure transducer. Direct manual methods, although simplistic, offer the opportunity of monitoring the daily variability in all boreholes, while access to a pressure transducer allows a detailed, continuous record of water levels in one borehole to be obtained.The water levels in full boreholes (i.e. all boreholes except 00-2) were monitored regularly during the day by physically measuring the water level relative to both sides of the borehole. Measurements were taken between approximately 0900 and 1700 h daily. A 10 m deep blind hole (00-6) was drilled as a control, which was isolated from the basal and most englacial systems. This borehole therefore enables the impact of surface and near-surface hydrological systems on the boreholes to be

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Table 1. Borehole water-level data (relative to bed; underlined data refer to boreholes that drained during the study)

Borehole	Ice depth m	Flotation level m	Observed min. level m	Observed max. level m	Range of level m	Comment
00-1	60	54	58.30	60.00	1.70	Conductivity expt.
00-2	60	54	11.30	24.70	–	Drained after 5 days Conductivity expt.
00-3	60	54	58.88	60.00	1.12	Conductivity expt.
00-4	63	57	62.76	63.00	0.24	Conductivity expt.
00-5	60	54	58.38	60.00	1.62	Pressure sensor
00-6	10	9	9.41	10.00	0.59	Blind borehole
00-7	67	61	66.48	67.00	0.52	
00-8	67	61	66.01	66.85	0.84	Conductivity expt.
00-9	65	59	64.72	65.00	0.28	Conductivity expt.
00-10	57	52	55.33	56.40	1.07	Drained after 12 days
00-11	57	52	56.03	57.00	0.97	Conductivity expt.
00-12	59	54	56.34	58.63	2.29	Drained after 16 days
00-13	59	54	58.40	59.00	0.60	
00-15	59	54	58.39	59.00	0.61	Conductivity expt.

identified. Water levels in the drained borehole (00-2) were monitored by lowering a conductivity meter down the borehole until measurements similar to the background levels found elsewhere were obtained (i.e. by locating the air–water interface).

A commercial water-pressure sensor was used to record diurnal variability in water-level variations in one borehole. The sensor was weighted with thick steel tubing and secured 5 m above the base of borehole 00-5 to avoid any basal turbulence. The sensor was calibrated to water depths by lowering it at 0.5 m intervals from the water surface in borehole 00-5. The readings were recorded using a data logger over a period of 7 days, in conjunction with meteorological data collected from a weather station situated close to the glacier margin. Conductivity experiments within individual boreholes were carried out with salt as a tracer and monitored using a commercial CM25 conductivity meter. The meter was calibrated in water at 2°C with varying salt concentrations. The probe was weighted to enable it to be lowered down each borehole at 1 m intervals for profiling. Conductivity experiments were performed on a total of eight boreholes, with repeat experiments on three. The experiments were conducted manually, and more could not be performed because of the labour- and time-intensive nature of the operation.

Prior to each conductivity experiment, a background conductivity profile of each borehole was carried out at 1 m depth intervals to identify any pre-existing conductivity variations. In all cases, no systematic variations were identified in any of the boreholes. For these and all subsequent profiles, three readings were recorded at each depth, and the mean used for the profiles. For each experiment, 1 kg of common household salt (NaCl) was dissolved in the upper metre of the borehole by suspending the salt in a perforated container. It was not possible to add salt solution directly to the boreholes because of the high water levels, which may have resulted in tracer water being lost over the ice surface or into the near-surface ice. Once a visual inspection indicated the salt had fully dissolved, conductivity profiles were carried out at 2–3 hour intervals during daylight access to the site. This proceedure was repeated to track the motion of the tracer water until background levels were regained. Unfortunately, safety-of-access issues mean that our records suffer from overnight gaps. All results are presented after background conductivity has been removed from the conductivity profiles.

BOREHOLE-MONITORING RESULTS

Table 1 records flotation and observed water levels for the boreholes used in this study. Records of water levels were made from the time of drilling, but the table only includes values after the initial 5 days, to allow any disturbance caused by drilling to settle.With the exception of borehole 00-2, which drained within 5 days of being drilled, all boreholes have observed minimum water levels far in excess of flotation. This includes boreholes 00-10 and 00-12, which subsequently drained 12 and 16 days (respectively) after drilling. The control borehole (00-6) shows water-level variations of ~0.6 m, which is the same order of magnitude as boreholes 00-4, 00-7, 00-9, 00-13 and 00-15. During the early afternoon (1400–1600 h) the majority of these boreholes were regularly observed to be full and occasionally overflowing. Areas close to the boreholes were seen to experience strong surface sheet flows at these times.

The boreholes that drained during the observations (00-10 and 00-12) show water-level variations of 1.0–2.3 m prior to draining. Similar variations can be seen in boreholes 00-1, 00-3, 00-5 and 00-11, yet none of these boreholes subsequently drained. These non-draining boreholes were periodically full, as were the boreholes with lower water-level fluctuations, but this did not occur in the boreholes that drained.

Borehole 00-5 was also monitored using the pressure transducer. Results show very little variation in water level and are therefore not shown here. The transducer estimate of the range of water depths is ~1.5 m, with all recorded levels well above flotation. The transducer record is well correlated to recorded air temperatures, with a lag of 3–5 hours.

CONDUCTIVITY EXPERIMENT RESULTS

Typical results for the conductivity experiments are demonstrated in Figure 2 and Table 2, which illustrate the data and

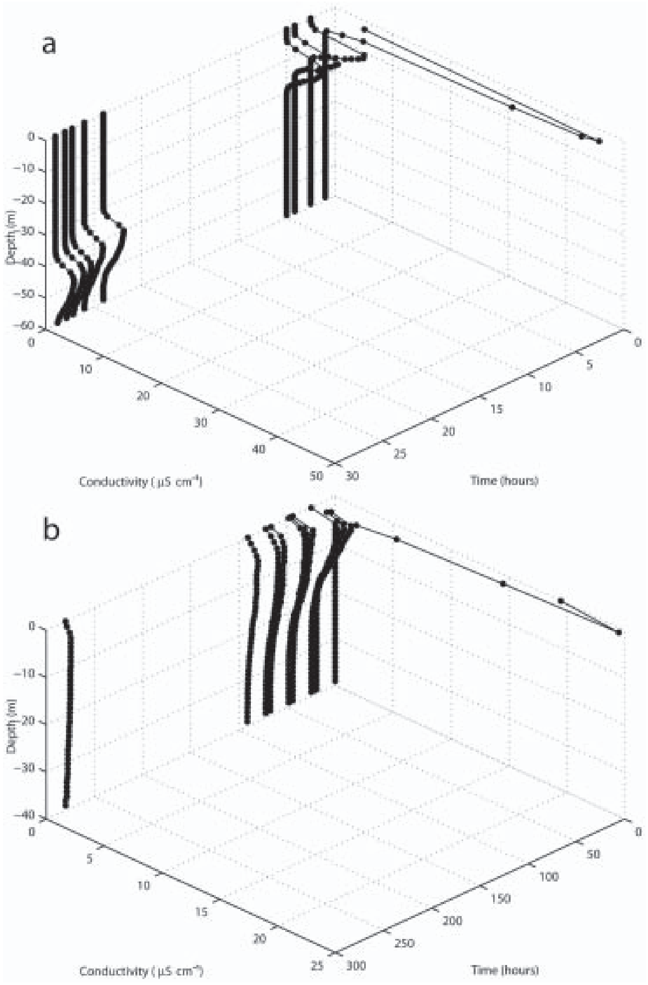

Fig. 2. Conductivity profiles for (a) borehole 00-3 and (b) borehole 00-9. A total of nine profiles are shown for 00-3 and eleven for 00-9. Note that the time axis in (a) extends over ~30 hours, while that of (b) extends over 280 hours. Conductivity values are shown above background.

calculations for two particular boreholes. The full results are summarized in Table 3. Figure 2a shows the descent of the plume of high-conductivity water down borehole 00-3 over a 30 hour period. The successive conductivity profiles appear to reflect an advection–diffusion process. The size of the plume is increasingly elongated through time (diffusion) in addition to being advected down the borehole. There is an indication that diffusion occurs preferentially in the down-borehole direction (conductivity gradients are lower on this side of the peak). In addition to this, the area under successive profiles is reduced, especially at the start of the experiment. The results shown (Fig. 2b) for borehole 00-9 are different, primarily because the plume of saline water is not advected down the borehole to any great extent. Other features of the 00-3 profiles are replicated, including their asymmetry. This borehole was revisited ~12 days after initial injection and showed residual traces of saline water. Two types of analysis were performed on these basic data (Table 2): the first measures the speed of descent of the plume (using the depth of the peak in conductivity); and the second measures the change in the equivalent mass of salt within the plume (by integrating each conductivity profile and comparing it to the conductivity of the initial profile). The rates of descent in borehole 00-3 are fairly uniform and fall between 1.0 and 1.5 m h^{-1}, except for two brief periods of acceleration to >3.0 m h^{-1}. The rate of descent over the 19 hour data gap (at 24 hours) agrees well with the rates shortly before and after this time. It appears that most (~65%) of the solute is lost in the first ~2 hours of the experiment and in the first ~5 m of the borehole. The salt mass within the plume is then constant until it approaches the bed, at which time mass starts to become lost again but at a far slower rate. The plume in borehole 00-9 experiences initially similar rates of descent but then stagnates at ~5 m depth. It also experiences similar amounts of solute loss in the initial parts of its descent. Table 3 summarizes results from all of the experiments. All boreholes show maximum solute loss within the upper 0–6 m. The boreholes can broadly be divided into two groups based on the average descent rate of the peaks: >1 and <0.5 m h^{-1}. Three boreholes fall into the fast category of descent rates: 00-1, 00-2 and 00-3. Borehole 00-2 is important because it is one of three that drained to below flotation during the course of the field season. Borehole 00-3 was the only one in which sufficient saline water was able to reach the base of the borehole for records to be made of its interaction with the bed. Readings during the latter stages of these experiments (when the saline water was close to the bed) showed far greater high-frequency variability (amplitude ~10 s) than observed at any other time or borehole. This could be interpreted as the turbulent interaction of the saline borehole water with fresh basal water. The initial experiment in borehole 00-3 (3a conducted 7 days prior to 3b) showed a very rapid rate of plume descent. The repeat experiment (3b) confirms rapid descent within this borehole, although not at the rates initially observed.

INTERPRETATION OF BOREHOLE CONDUCTIVITY RESULTS

We divide our discussion into two sections: analysis of the motion of the solute and analysis of the loss of solute from the plume. The first point to note is that the plume descended to depth in many of the experiments, while in some others it remained close to the point of injection. The most complete experiment is 00-3b in which the plume began to interact with the bed. The constraints of our field programme meant that several experiments had to be left with the saline plume still actively descending, albeit at a far slower rate than in 00-3b. The other end-member is 00-9, where the plume stagnated soon after injection within the upper ~5 m of the borehole.

The observed motion could result from one of two effects: the force generated by dense water overlying lighter water; or passive advection in the water column of the borehole. In the former case, the motion is simply an artefact of the introduction of saline water; in the latter, motion reflects pressure-driven flow from englacial (near-surface) sources to a subglacial sink. The main argument against the former is that we would expect this to occur in all experiments; however, the plume was observed to stagnate in several experiments (although much of the solute mass remained). We conclude that the motion is a consequence of water flow down the borehole and, presumably, into the subglacial hydrological system. This would imply that contact between the borehole base and the glacier bed is ‘leaky’. The pressure difference driving such a flow can be estimated from the difference between the flotation depth and the observed

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Table 2. Estimated plume-descent rates and mass ratios for boreholes 00-3 (experiment B) and 00-9

Time since start of experiment		Depth of concentration peak		Rate of descent		Solute mass ratio	
00-3	00-9	00-3	00-9	00-3	00-9	00-3	00-9
hours	hours	m	m	$m\,h^{-1}$	$m\,h^{-1}$		
1.0	0.8	1.14	0.98	1.14	1.16	1.00	1.00
2.4	19.4	5.37	1.49	3.00	0.03	0.35	0.44
4.1	22.4	7.13	2.00	1.02	0.17	0.33	0.40
5.0	24.9	8.06	2.52	1.05	0.21	0.32	0.41
24.0	44.4	35.74	2.98	1.46	0.02	0.31	0.38
26.0	46.5	38.02	4.01	1.14	0.49	0.30	0.38
27.3	49.0	42.56	4.99	3.62	0.39	0.31	0.36
28.0	67.6	43.60	5.41	1.41	0.02	0.29	0.32
29.0	73.1	44.63	5.99	1.04	0.11	0.25	0.31
–	91.3	–	5.50	–	-0.03	–	0.24
–	280.1	–	6.00	–	0.00	–	0.17
Mean		–		1.55	0.02	–	

water depths in a borehole (Table 1). A minimum estimate is therefore ~5 m or 50 kPa. The resistance to the flow created by this pressure head could come from the sides of the borehole itself or from the interface between the borehole and the subglacial hydrological system. An estimate of the former can be obtained by applying Manning's equation (Paterson, 1994, p. 116) for turbulent flow in a vertical pipe using values appropriate to 00-3b:

$$\rho_W g + \frac{dP}{dz} = \rho_W g (mu)^2 \left(\frac{4\pi}{S}\right)^{\frac{2}{3}},$$

where dP is the pressure difference driving the flow, dz is the pipe length (60 m), S is the pipe cross-sectional area ($0.03\,m^2$), u is the water velocity (estimated from the rate of plume descent as $4 \times 10^{-4}\,m\,s^{-1}$), g is acceleration due to gravity and m is Manning's roughness coefficient for a smooth ice surface ($0.01\,m^{-1/3}\,s$). The calculated pressure difference (dP) is a very weak 5×10^{-4} Pa in excess of gravitational head. The Hagen–Pouiseuille (Paterson, 1994) formula for laminar flow yields similar values for this pressure difference. It therefore appears that the flow leaving the borehole is throttled at the contact with the bed as water is forced either through subglacial sediment or through a narrow orifice.

The observation of fluctuating conductivity measurements near the bed in borehole 00-3 is further evidence that the borehole water is interacting with the subglacial system. We therefore speculate that the range of plume-descent rates observed from different boreholes reflects a spectrum of borehole connectivity ranging from the poorly connected borehole 00-3 to the isolated borehole 00-9.

The simple interpretation of the solute ratio results is that most of the boreholes experience a great deal of englacial water inflow close to the surface, which dilutes the saline-water plume. An approximate estimate of this inflow can be made by applying mixture theory to (for example) borehole 00-3. The difference in conductivity (Equation (1)) between the start and end of the initial, ~2.5 hour, period can be used to estimate an inflow rate of ~0.1 $m\,h^{-1}$ averaged over the first 5 m of the borehole (assuming a borehole radius of 0.1 m and a saline-plume depth of 2 m).

We suggest that this englacial inflow maintains high borehole water levels which then drive infiltration into the subglacial system depending on the nature of the borehole–bed contact (see above). The varying water-level ranges in the boreholes (Table 1) offer some support to this idea, in that boreholes that experience high rates of plume descent (e.g. 00-1 and 00-3) also experience relatively high ranges. One would expect higher water-level ranges if the borehole had some form of (partial) drainage.

Below 5–10 m depth, little further dilution was observed except when the bed was approached in borehole 00-3. The observed dilution here could be a consequence of either mixing with the subglacial system or dilution in a subglacial cavity (perhaps created by the hot-water drilling). The thesis outlined above favours the former, although in the latter case the basal dilution observed in 00-3 implies only approximately a tripling of the borehole radius.

An alternative explanation for the observed dilution in the early part of the experiments is that some salt remained undissolved and sank out of the plume. We consider this very unlikely since all profile measurements were conducted over the whole depth of the borehole and no accumulation of saline water below the main plume was ever observed. In addition, all of our calculations are made with respect to the

Table 3. Summary of borehole conductivity results (boreholes in which the experiment was repeated are labelled with a letter)

Borehole	Mean descent rate	Depth of maximum solute loss	Did plume reach base of borehole?	Maximum depth of peak
	$m\,h^{-1}$	m		m
00-1a	1.3	0–5	no	7
00-1b	1.3	0–4	no	9
00-2	1.0	0–5	no	25
00-3a	10.0	0–15	yes	45
00-3b	1.6	0–5	yes	45
00-4a	0.2	0–6	no	12
00-4b	0.2	0–2	no	16
00-8	0.4	0–4	no	8
00-9	0.0	0–2	no	6
00-11	0.3	0–5	no	10
00-15	0.1	2–10	no	2

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first measured profile for each experiment, which is unlikely to have included a contribution from any undissolved salt. A further possibility is that the salt was lost during the occasional periods when the boreholes flooded. Again we think this unlikely since the dilution occurred relative to an initial profile that was already lying at 1–6 m depth (Fig. 2), and therefore beyond the risk of loss by flooding.

CONJECTURE ON HYDROLOGICAL SYSTEMS OPERATING AT VESTARI-HAGAFELLSJÖKULL

Our observations shed light on two aspects of the glacial hydrology of Vestari-Hagafellsjökull: the nature of the basal hydrological system and the existence of a near-surface, englacial system.

The water-level results imply that the subglacial hydrological system is at least partially channelized. The three boreholes (00-2, 00-10 and 00-12) that were observed to drain during the 2000 field season are located close to one another in the southern sector of the study area. This clearly implies the existence of a subglacial channel in this area to which these boreholes gradually (after 5, 12 and 16 days) became connected (e.g. Gordon and others, 2001). It is interesting to note that 00-2 was characterized by high plume-descent rates prior to its drainage. The implication is that the rate of plume descent may be a diagnostic for the likelihood of future drainage. The rapid plume-descent rates found in 00-1 and 00-3 could therefore imply the existence of a second channel to the northwest of the study site. The two other boreholes in this area (00-5 and 00-6) were not subjected to conductivity experiments.

The range of water levels recorded for the boreholes (Table 1) partially supports this interpretation if large ranges are assumed to be indicative of an enhanced link to the subglacial system. In particular, 00-1, 00-3, 00-5, 00-10 and 00-12 experience the widest ranges and are all located in the southern or northwestern sectors of the field site. However, the interpretation of the ranges shown by the other boreholes is more equivocal.

The majority (11 from 14) of the boreholes in this study did not, however, drain. We believe that in several cases drainage was prevented by strong inflow from a near-surface (<5–10 m) englacial water source. All conductivity experiments revealed strong dilution (>50%) within this region. Surface water was extremely abundant during our field season and was generated by local ablation, rainfall and drainage from up-glacier. We took every precaution to prevent this surface water from flowing into the boreholes (e.g. locating them on topographic highs). However, the boreholes occasionally became flooded with water flowing out over the glacier surface. We suggest that both the dilution and this flooding can be attributed to lateral water flow through a system of cm-scale conduits that has developed within the shallow surface ice of Vestari-Hagafellsjökull. On a few occasions, such conduits could be seen draining into the boreholes at approximately 1 m depth. Much of the surface ice on the glacier had a laminated appearance, which could perhaps offer foci for the development of these conduits. The origin of these laminations is unclear, but may be connected to repeated melt- and rainwater refreezing.

We suggest that down-hole conductivity monitoring adds a further dimension to our ability to investigate a glacier's hydrology. We have illustrated its use in determining rates of near-surface water inflow and in investigating the nature of the bed contact in full boreholes. Further applications exist in locating englacial water pathways and determining the size of the basal cavities thought to be generated by hot-water drilling.

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