DYE TRACING EXPERIMENTS AT MIDRE LOVÉNBREEN, SVALBARD: PRELIMINARY RESULTS AND INTERPRETATIONS

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Abstract

This report presents the preliminary results from a number of dye tracing experiments conducted at Midre Lovénbreen, Svalbard, in 2004 and 2005. The data presented shows similarities in glacial hydrology throughout the glacier basin. Average velocities > 0.2 m/s suggest many of the injection sites link to an efficient englacial system. High dispersion and low velocities characterise dye injection sites the upper western regions of the glacier. Traces in 2005 indicated the existence of a divergent hydrological system, potentially linked to a fracture flow network. We propose that the perennial, proglacial upwelling of internally routed meltwater is fed by surface runoff entering crevasses at elevations above 350m. However, only meltwater from the western-most reaches of the glacier feeds a subglacial system, which subsequently coalesces with the water flowing englacially from other cirques in the accumulation area. For polythermal glaciers in Svalbard there is, therefore, a need to consider a hydrological system which may be dominantly englacial and far different from existing conceptual models which are largely based on temperate glacier hydrology.

Эксперименты по окрашиванию на леднике Средний Ловен, Свальбард: предварительные результаты и интерпретация

Представлены предварительные результаты множества индикаторных экспериментов, проведенных на леднике Средний Ловен, Свальбар, в 2004 и 2005 гг. Представленные данные показывают подобия в ледниковой гидрологии по всему водосборному бассейну ледника. Средние скорости течения воды >0,2 м/с предполагают, что многие из мест введения красителей связанны с действующей внутриледниковой дренажной системой. Высокая дисперсия и низкие скорости характеризуют точки введения красителей, расположенные в верховьях западной части ледника. Красители в 2005 г. указали на существование расходящейся гидрологической системы, потенциально связанной с трещинной сетью потока. Мы предполагаем, что многолетний, прогляциальный апвеллинг, внутренне проводящий талые воды питается поверхностным стоком, проникающим через трещины на высотах более 350 м. Однако, только талые воды западного водосбора с наибольшим размахом ледникового питания подледной системы, которая впоследствии соединяется с водой, текущей внутриледниково из другого цирка расположенного в области аккумуляции. Для политермальных ледников Шпицбергена, поэтому, существует потребность рассмотреть гидрологическую систему, которая может быть преимущественно внутриледниковой и далеко отлична от существующих ныне концептуальных моделей, которые в большей степени основываются на гидрологии теплых ледников.

Introduction

Current understanding of high latitude glacier hydrology and dynamics remains relatively deficient at virtually all temporal scales, despite a steadily increasing number of investigations on sub-polar glaciers (e.g. Rabus and Echelmeyer, 1997; Zwally *et* al., 2002; Bingham *et al*., 2003). The questions regarding the hydrology of polythermal glaciers (which are common in Svalbard) are fundamental simply because hydrology is likely to be critical for determining glacier responses to climatic variation. However, due to the difficulties in observing the internal drainage system of glaciers directly, dye tracing has proven to be a powerful tool with which to examine sub-polar glacier hydrology (e.g. Seaberg *et al*., 1988; Kohler, 1995; Vatne *et al*., 1995).

One recent hydrological study presented by Hodson *et al*. (in press) proposed a proportion of the annual variability in polythermal glacier runoff could be explained by changing meltwater storage. However, tracer experiments conducted at polythermal glaciers Erikbreen (Vatne *et al*., 1995) and John Evans Glacier (Bingham *et al*., 2003) indicate the internal and/or subglacial drainage system becomes increasingly efficient over the course of an ablation season with transit times in the order of hours rather than days. It is therefore, unclear how and where surface meltwater enters the internal hydrological system, and is subsequently drained and or stored. Given these uncertainties surrounding polythermal glacier hydrology, this paper presents the preliminary results from dye tracing experiments on Midre Lovénbreen, Svalbard, and presents a conceptual model derived from the initial analysis.

Field Site

Midre Lovénbreen is a north-facing, polythermal glacier occupying 49% of a 10.8 km^2 basin on Brøggerhalvøya, Svalbard (78°50′N, 12°E). The glacier is underlain by schists, quartzite, phyllite and some sedimentary rocks (Hjelle, 1993). Glacier ice extends from approximately 50 to 600 masl with a maximum thickness of 180 m (Björnsson *et al*., 1996). The temperate ice zone, identified in geophysical investigations, is located in the accumulation area and at the bed in the upper ablation area, although velocity data suggests basal temperate ice may extend to lower elevations (Björnsson *et al*., 1996; Rippin *et al*., 2003; Kohler, *unpublished data*). The accumulation area is found as four cirques, characterised by slightly crevassed zones where the smaller catchments join the main body of the glacier (Fig. 1).

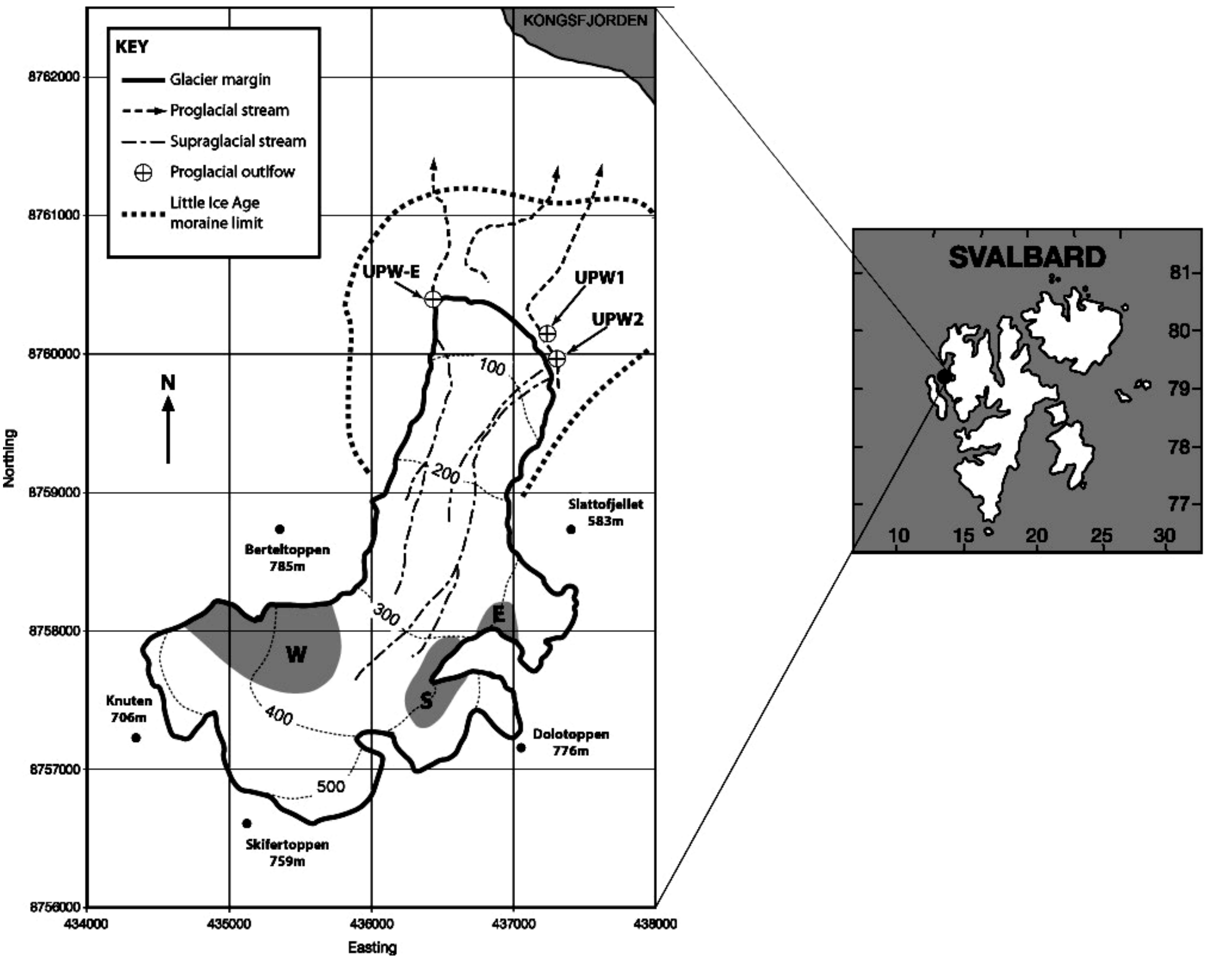

Figure 1: Sketch map of Midre Lovénbreen. Significant hydrological features are indicated. Note the positions of UPW-E (2004) and UPW1 and UPW2 (2005). Subglacial outflow was found proximate to the location of UPW-E in 1998 and 2003, and in close vicinity to UPW2 in other years. The shaded regions (W, S and E) on the glacier represent the three areas in which dye injections reached the en- and/or subglacial environment.

The glacier surface has a typically low gradient yet is deeply incised by supraglacial streams parallel to glacier flow, particularly in the lower 1 km of the ablation area. There are no moulins on the lower 1.5km of the main tongue of Midre Lovénbreen. Despite the cold ice margins, glacier-derived meltwater reaches the proglacial region throughout the year. Such hydrology is evidenced by the perennial breakthrough of subglacial meltwater as upwellings close to or at the glacier margin, and the annual formation of an icing over winter months (Hodson *et al*., 2000). Interestingly, the upwelling site is not consistent, with subglacial outflow appearing on the eastern side of the snout in 1992, 1994, 1996, 1997, 1999, 2000, 2001 and on the western margin in 1998 and 2003 (see Fig. 1).

Hydrological studies on Midre Lovénbreen are moderately limited, although discussions of internal and basal drainage configurations can be found in Rippin *et al*. (2003) and Kulessa *et al*. (2003). Additional reports on the glacier's hydrological system include nutrient budgets (Hodson *et al*., 2005) and analysis of suspended sediment in proglacial streams (Irvine-Fynn *et al*., 2005). The study presented by Hodson *et al*. (in press) indicated between 24% and 32% of the runoff from Midre Lovénbreen was routed through the subglacial drainage system. However, the functionality of the glacier's hydrological system remains unclear and requires further investigation.

Observations and Research Methods

Hydrological investigations were undertaken during the ablation season in both 2004 and 2005. The two years exhibited distinctly different hydrological configurations. In 2004, the subglacial upwelling had occurred prior to the commencement of fieldwork (JD190), and appeared as a portal on the western margin of the glacier (UPW-E; Fig. 2a) about 2 – 3 m above the marginal stream. In 2005, subglacial breakthrough was more complex: on JD182 outflow occurred at UPW1 (Fig. 1, 2b) continuing thereafter, and at UPW2 (Fig. 2c) on JD213 which also continued for the remainder of the season. Over the course of the field campaigns, a number of dye injections were conducted using entry points and moulins found in the crevasse zones close to the accumulation zone cirques (see Figure 1). Dye injection involved the release of 25 – 800 ml of Rhodamine WT into the supraglacial streams draining into the moulin or crevasse. Dye input was instantaneous because injection time was negligible compared to the duration of dye breakthrough. Injections typically occurred in the afternoon corresponding to highest melt and discharge. Surface streams were also examined with dye traces during 2004. Dye emergence was detected by continuous fluorometry using CR10 data loggers and Chelsea Instruments and Seapoint Sensors fluorometers. To guarantee sufficiently detailed dye breakthrough curves an averaging sample interval of 120s was used.

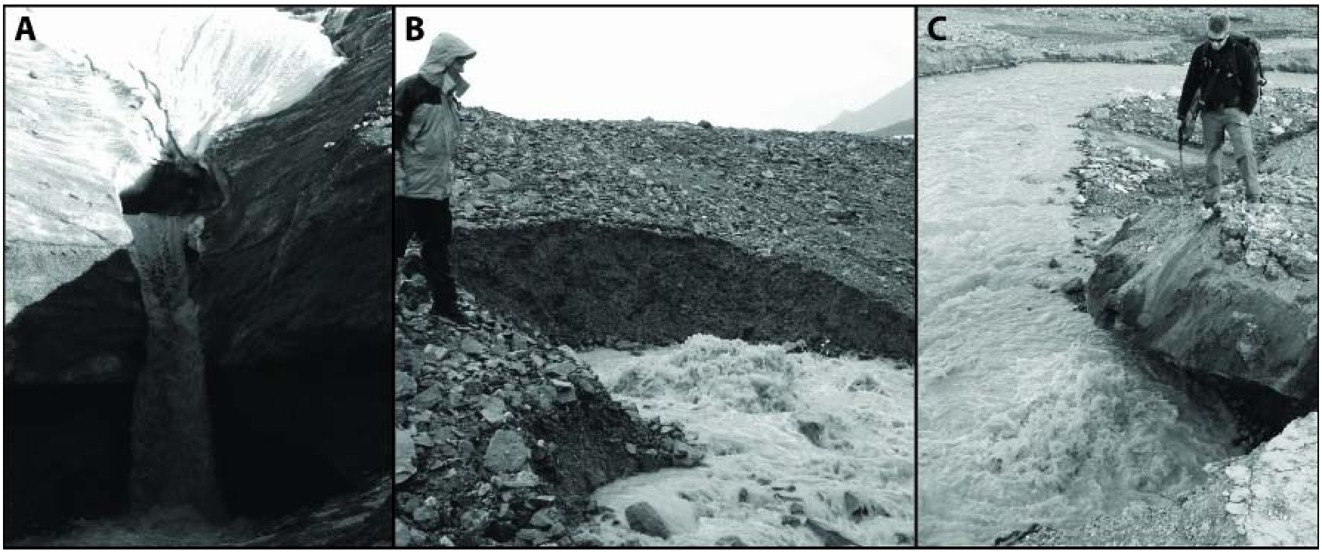

Figure 2: Illustrations of subglacial outflow. A) UPW-E in 2004; B) UPW1 and C) UPW2, both in 2005

Results and Analysis

Figure 3 shows several breakthrough curves, typifying the fluorometry data, and indicating the asymmetry found for all tracer injections. Because of the uncertainties involved in accurately measuring outflow discharge, dye concentration and background fluorescence associated with suspended sediment variations, dye recovery is somewhat limited in significance (Schuler, 2002).

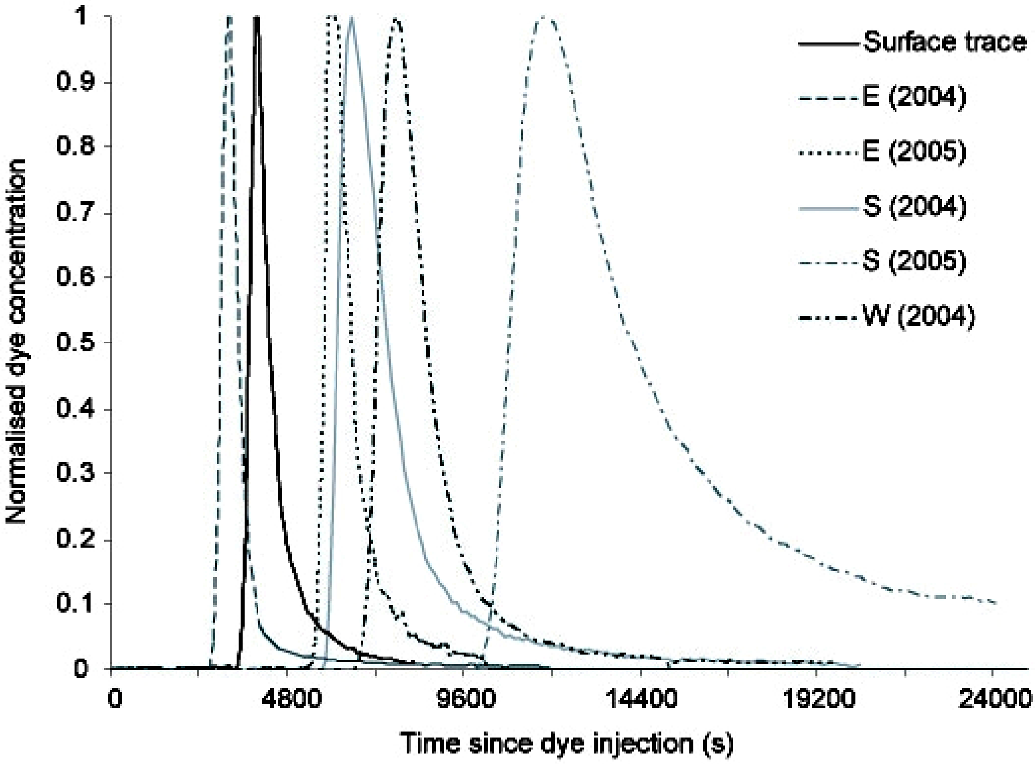

Fig. 3. Schematic of example dye returns from injections in the three areas investigated on Midre Lovénbreen

The injection sites linking to the en- and subglacial system were grouped into three Areas (E, S and W; see Fig. 1), and Table 1 presents the mean and standard deviation of three parameters providing an objective way to compare results. The results from the tracing experiments conducted on the supraglacial streams are also summarized. The mean velocity ($u = x/t$ where x is the straight line distance and t is time to peak) for the surface traces was 0.57 m/s, compared to a 0.24 m/s for all the internal drainage routes. Such rapid internal transit velocities compare well to mean tracer velocities recorded at other polythermal glaciers: 0.18 m/s documented both at Erikbreen in 1990 (Vatne *et al*., 1995) and Storglaciären (Hock and Hooke, 1993), and 0.23 m/s at Stagnation Glacier (Irvine-Fynn *et al*., in review). One notable finding is that velocities from Areas E and S are markedly higher than those from W, from which relatively few returns were recovered (Table 1).

Table 1

Details of parameters calculated from dye traces conducted in 2004 and 2005 on Midre Lovénbreen. σ_i is the standard deviations for sample *i*. Trend gives the R^2 for the regression of repeated trace parameters against time, and a negative sign indicates a decreasing trend over time.

Injection / Zone / Parameter	2004	2004	2004	2004	2005	2005	2005
	Surface	E	S	W	E	S	W
% of injections recovered	83	80	100	66	100	80	17
Mean X (m)	2226	2215	2930	2346	2102	2362	3859
σ_X	859	49	40	412	6.7	154	
Mean u (m/s)	0.57	0.31	0.37	0.28	0.19	0.22	0.08
σ_u	0.20	0.07	0.11	0.08	0.02	0.04	
Mean D (m^2/s)	3.52	2.37	2.57	6.64	3.25	5.73	12.10
σ_D	2.59	0.60	2.66	5.52	1.57	7.29	
Mean d (m)	7.81	7.95	6.11	27.39	17.12	26.99	151.02
σ_d	9.89	3.58	5.39	27.46	8.20	36.92	
Trend (D)	n/a	-1	-1	-1	-0.95	-0.50	n/a
Trend (d)	n/a	-1	-1	-1	-0.93	-0.45	n/a

Austre Brøggerbreen is a dominantly cold-based glacier adjacent to Midre Lovénbreen, where internal drainage is thought to be predominantly if not solely englacial (Vatne and Refsnes, 2003). Tracer experiments conducted in 2005 yielded mean transit velocities of 0.23 m/s (C. Holtermann, *pers. comm.*, 2005). The velocities for Midre Lovénbreen are thus comparable to efficient englacial routes. Further, with the majority of tracer tests approaching the surface stream velocities, results indicate the internal drainage system is likely to be composed of discrete routes with low roughness elements. Importantly however, tracer transit time is likely to be strongly linked to discharge (melt) variations, so no significance can be readily attached to trends in these data presented here without further analysis of discharge at both the injection and emergence sites.

Dispersion (D) and dispersivity (*d*) were calculated after Seaberg *et al*. (1988) and Nienow *et al*. (1996): $D = x^2(t_m - t_i)^2 / 4t_m^2 t_i\ (\ln(2(t_m/t_i)^{0.5})$ where t_m is the modelled time to dye peak and t_i is time to half the peak dye concentration. The equation is solved simultaneously using t_i on both the rising and falling limbs of the breakthrough curve. Dispersivity is given as $d = D/u$. Data from Midre Lovénbreen showed D and *d* ranged between 0.3 – 151.0 m^2/s and 0.07 – 22.0 m, respectively. Broadly, these results are consistent with other tracer data from polythermal glaciers, but means are slightly distorted by several solitary outliers which are more highly dispersed traces from Areas S and W. Where repeat traces were made, the trend over time is indicated on Table 1 which displays the average coefficient of determination (R^2) between time and D or *d* for each injection area. In all cases, there was a trend towards reduced values of D and d with $R^2 > 0.4$. Following a normalization of the breakthrough parameters using a log-transform, a single factor ANOVA test showed with > 95% confidence that values of D and *d* were similar for tracer tests on the surface and internal hydrology. This suggests, as seen in many glaciers, a trend towards more efficient drainage as the ablation season progresses, and one that appears to exhibit similar dispersivity to a subaerial, ice-walled channel.

One of the key findings in 2005 was the divergence of internal water flow. Following the appearance of UPW2, tracer tests from locations in both E and S were recovered in *both* upwellings. Figure 4 shows a typical split return, and indicates the difference in transit time to UPW1 and UPW2. Table 2 gives additional details on the split returns. The transit velocity to UPW2 was on average 0.1 m/s more rapid and implies a more efficient drainage route. Importantly, the time lapse between emergence at UPW2 and UPW1 indicates flow divergence is likely to occur shortly after injection point rather than close to the upwelling sites, and this is supported by the similarity in *d* for each injection area. It would appear two singular englacial drainage systems coexist and exhibit similarities despite the contrast in transit time.

Table 2
Details of divergent injections undertaken in 2005.

Injection / Parameter	2005 E-UPW1	2005 S-UPW1	2005 E-UPW2	2005 S-UPW2
Mean X (m)	2102.378	2362	1792.804	2078.447
σ_X	6.705434	154.4395	7.186769	165.2197
Mean u (m/s)	0.185426	0.218065	0.267431	0.337608
σ_u	0.021617	0.039541	0.04916	0.077903
Mean D (m^2/s)	17.11526	26.99221	1.73472	0.48395
σ_D	8.201311	36.92271	1.261393	0.358023
Mean d (m)	3.249784	1.56634	4.372085	1.38593
σ_d	5.726821	7.287908	7.190445	2.117117

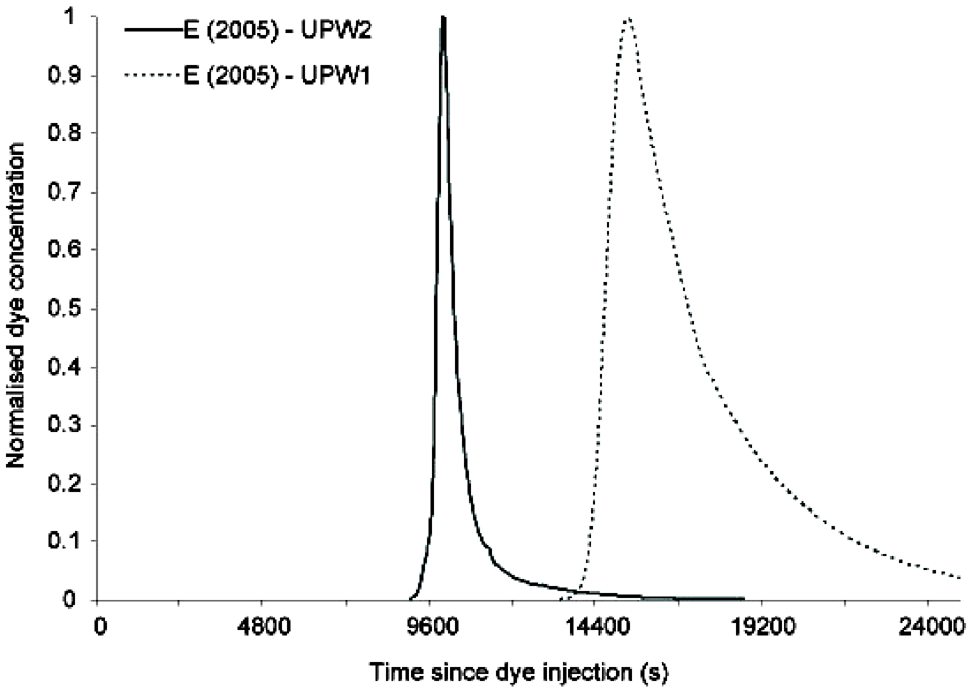

Fig. 4. Illustration comparing the dye breakthrough from a single injection which reached both UPW1 and UPW2.

Discussion and interpretations

The through-flow velocities indicated by the dye traces show englacial flow may dominate much of the hydrological system of Midre Lovénbreen. The lack of reduced velocities, with the exception of injections in Area W, shows channelised, fast drainage routes water from the accumulation area cirques to the proglacial outflow. The similarity of englacial to surface traces, coupled with almost negligible dispersion suggests that dye slugs particularly towards the end of the ablation season form Areas E and S exhibited little or no dilution by other water. The low values of *d* indicate short residence time, with minimal turbulence causing dynamic mixing. This is particularly exemplified by drainage to UPW2 in 2005.

The slowest and most dispersed dye traces were seen from Area W in 2005, and although transit dispersion was high in 2004, velocities were indicative of an efficient channelised system. For 2005, the low velocities and high dispersion indicate a distributed drainage characteristic with a subglacial system. High dispersion may explain the difficulties in recovering traces from Area W. Further, with all traces showing statistically significant similarity to dispersion in subaerial channels, it is possible the internal drainage system at least partially operates in an open-channel or atmospheric pressure state.

In examining dispersion, effective decreases in roughness will lead to decreases in D (Schuler 2002). Thus the trends in D and d observed here potentially indicate morphological change in the internal drainage pathways, and the reduction of roughness elements. As Fountain (1993) and Mavlyudov and Solovyanova (2003) observe, ice temperature may strongly influence cavity and crevasse sizes which, in a polythermal glacier, may lead to structurally governed, spatial variability in drainage route dimensions, and the resultant water flow velocity, thereby potentially explaining elevated dispersion and dispersivity. Following observations by Vatne and co-workers (2001;

2003; *unpublished data*), englacial routes such as those that appear to exist draining Areas E and S may exhibit step-pool morphology. Such roughness was observed in the field for the surface streams draining Midre Lovénbreen. This suggests that, for the apparently englacial routes from Areas E and S documented here, either conduit area enlarges, or there is a reduction in the channel complexity.

However, as Schuler (2002) points out, changes in dispersivity may also result from variations in hydrological damming, rather than channel change. We suggest two possibilities exist: a) high dispersion may accrue through a drainage pathway joining a larger «conduit» where the higher flow velocity in the arterial channel retards the incorporation of the dye slug into the main flow, effectively leading to a diluted dye slug; and b) where a «conduit» has a restricted outlet (i.e. within the cold ice margin) causing water to be backed up and allowing both turbulent and advective dispersion within the stored water prior to any emergence. Both these scenarios may be applicable to Midre Lovénbreen, and reductions in dispersion would indicate decreases in hydraulic damming and/or possible enlargement of the restricted outlet.

The above arguments also provide an explanation of the difference in returns from UPW1 and UPW2. In addition to suggesting divergent, non-arborescent drainage, the time lapse between dye emergence at the two sites indicates flow divergence is early on in the flow path. The subsequent difference in velocity and dispersion furthers assertion for hydraulic damming and/or channel change in the route to UPW1. However, to explain the cause of divergence, we suggest fracture flow as a causal process. Fountain *et al.* (2005) used data from Storglaciären to hypothesise that water flow within glaciers may occur in fractures and relict crevasses advected down glacier. Crevasses in cold ice may commonly be > 30 m in vertical extent, and it is plausible to assume from one injection at the ice surface, dye may reach the base of a fracture, and travel in both directions along the fracture into the temperate ice zone. Given field observations of numerous, closely spaced crevasse cracks on the glacier surface, we suggest that there may be sections of Midre Lovénbreen's hydrology that could be described as a 'fracture network'.

In addition to the seasonal variation in hydrological configuration, we also noted an annual switch in location of upwelling. Rippin *et al.* (2003) suggested that for some years the internal drainage system is established under moderate subglacial water pressures leading to upwelling in the eastern side of the snout. In the years where upwelling occurs on the west side of the glacier, Rippin et al. (2003) implies the activation of a relict drainage channel. However, the velocity and dispersivity data for UPW2 strongly indicates occupation of an existing channel, rather than one undergoing enlargement. This also is evidence for rapid but significant hydrological reorganisations, potentially reactivating old hydrological features.

We suggest that antecedent channel routes should be considered in order to explain the annual variability in upwelling site and the rapid englacial water transport. The relict drainage system would be preserved by low closure rates (particularly in cold ice), and would indicate the source and routing of runoff generating the icing feature in winter.

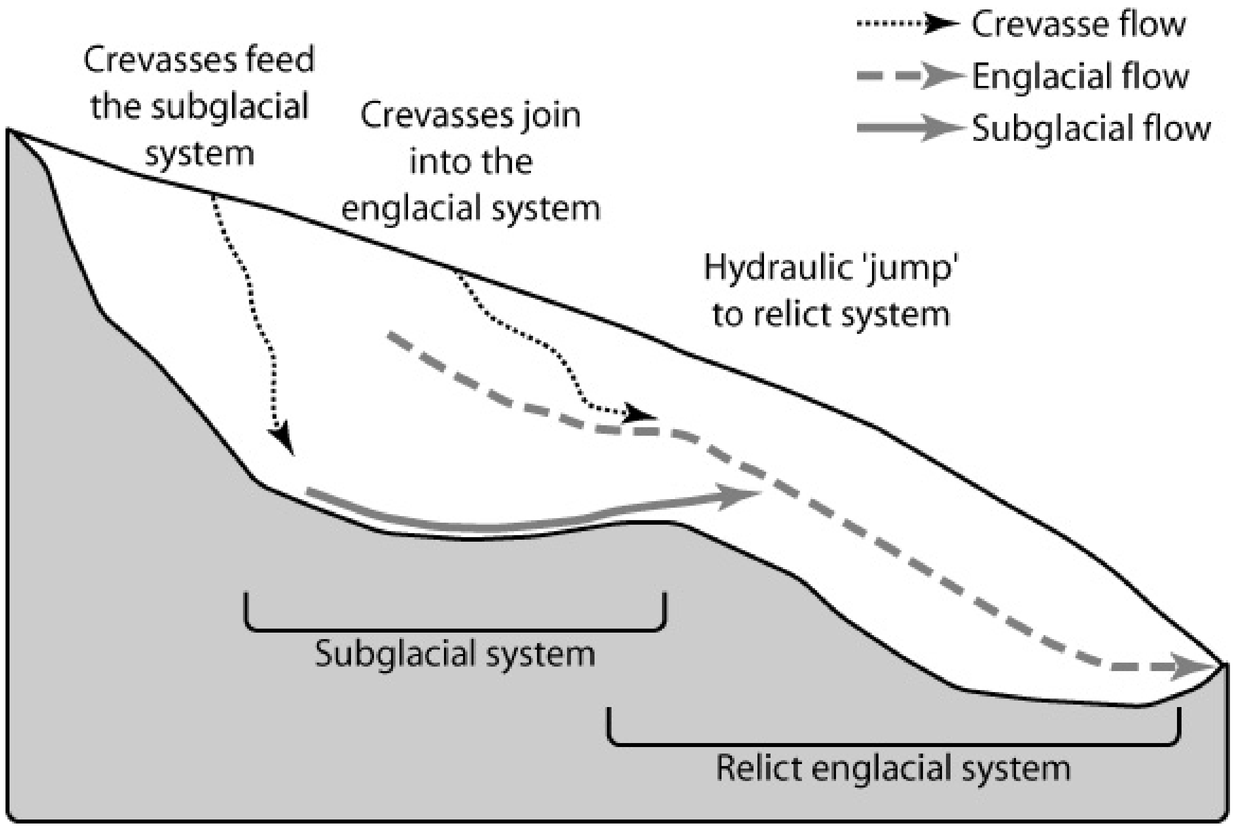

Fig. 5. Schematic illustrating a predominantly englacial hydrological system in which subglacial waters «jump» into (relict) englacial locations.

The frequent burial of glacier ice by surface debris and parabolic vertical cross-section of a glacier snout does not preclude the ability for an englacial system to feed a proglacial upwelling. Such a model has been developed for Stagnation Glacier (Figure 5; Irvine-Fynn *et al*., in review). The upglacier subglacial system may «jump» into an existing, preserved englacial system through either topographic or hydraulic pressure forcing as has been discussed by Kirkbride and Spedding (1996). Such a jump could also lead to hydraulic damming of the subglacial system against the more efficient englacial route, and thus result in further increasing dispersivities from Area W. This conceptual model clearly differs from the annually formed, arborescent and dominantly subglacial system seen in temperate glaciers (e.g. Nienow *et al*., 1996). And further, if indeed existing drainage architecture is preserved year-to-year, end-of-season water drainage from the accumulation areas may be stored in the existing channel network. And, such a configuration may potentially explain an annually variable volume of stored water as suggested by Hodson *et al*. (in press).

Conclusions

Dye tracing evidence shows that the subglacial hydrological system is probably located and supplied by melt in upper western-most regions of Midre Lovénbreen supported by dispersion values and paucity of recovered traces. Outflow emergent at the proglacial upwellings appears to be a combination of subglacially and englacially routed waters which are sourced at elevations > 350 m, and the two distinct systems coalesce somewhere within the main body of the glacier. This assertion remains to be assessed by using hydrochemical analysis and continued modelling. However, dispersivity and velocity data support the notion of a predominantly englacial, partially open-channel hydrological system. Researchers focusing on the hydrological system of polythermal glaciers should perhaps ensure they move away from assumptions of the temperate glacier model which has remained the *status quo* despite its potential limitations for many high latitude ice masses.

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