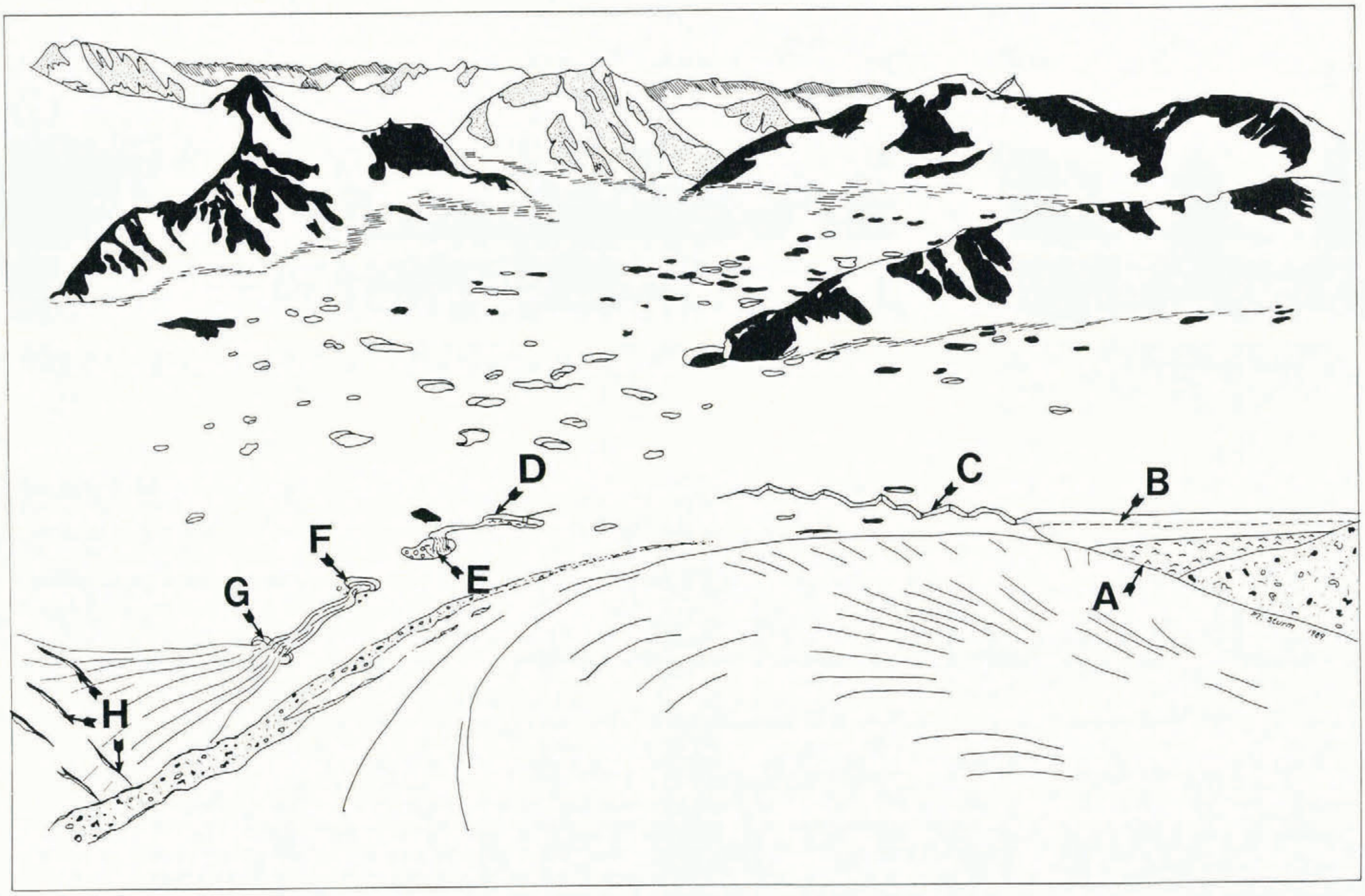

Fig. 1. The pothole field of Black Rapids Glacier in the Alaska Range, central Alaska. The glacier, which is about 4 km wide, is flowing from right to left. The view is south; the nearest potholes are between 20 and 150 m in diameter. In the foreground, a small tributary glacier is pushing into the main trunk glacier; the surface of this glacier is split by radial crevasses. Features marked with letters are explained in the text.

are connected by complex englacial and supraglacial drainage systems that persist from year to year. We conclude this because the transition between surface and englacial flow observed in the 1989 jökulhlaup could only have occurred if the surface water had connected with an existing tunnel system. However, the tunnel system must evolve slowly, since the drainage pattern of the 1985 and 1987 jökulhlaups differed from that observed in 1989. Secondly, the drainage system in the area of the potholes differs from the drainage system found elsewhere on the glacier. In the pothole field, most surface features (primarily potholes) connect to an englacial water system; elsewhere, most surface features (crevasses) do not. This is illustrated by the fact that within the pothole field the water flowed from one pothole to another, but elsewhere, the spreading sheet of water filled only those crevasses that were directly in its path, and none of these crevasses diverted the flow into an englacial water system.

We do not know why the drainage system in the pothole field develops in such a distinctive manner, nor if it is connnected to the basal water system, which is known to play a key role in surging (Kamb and others, 1985). We feel that it would be valuable to monitor the pothole field through an entire surge cycle in order to understand better the relationship between potholes and surging.

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SIR,

Comments on: "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"

Dye tracing through glaciers provides one means of studying the inaccessible glacial drainage system. Unfortunately, the complex, unstable character of the drainage system, rapid variations of discharge, and high sediment concentrations make the tracing in the glacial environment challenging. The recent paper by Seaberg and others (1988) constitutes perhaps the best work to date on glacier tracing by virtue of high-quality data, replicate tracing, and systematic analysis. However, there may be alternative explanations for some of their data.

The tracer break-through curve obtained at the glacier snout results from dispersion, dilution, and flow routing. Seaberg and others considered the englacial flow route to be a homogeneously braided open channel with dramatic increases in sinuosity with stage accounting for the proportional relationship between travel time and discharge. They attributed occasional multiple-peaked break-through curves to temporary development of a few dominant flow routes from the homogeneously braided channel.

In contrast, the velocity-discharge plot of Seaberg and others (1988, fig. 5) suggests closed-conduit flow (Smart, 1981), an inference they disproved by considering hydraulic gradient changes from a minimum (S_0) to maximum (S_1) and corresponding discharge (Seaberg and others, 1988, p. 225). Figure 1 shows that lower minimum hydraulic gradients (e.g. S_2) are possible, and can account for

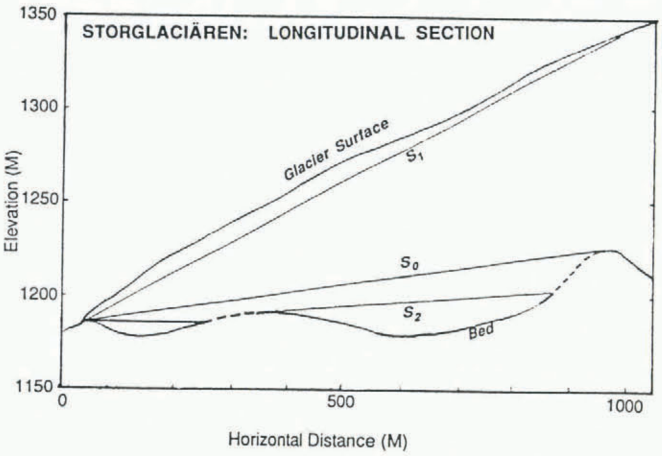

Fig. 1. Sketch cross-section through Storglaciären along the straight-line tracer route (from Seaberg and others, 1988, fig. 1).

observed variations in discharge. For example, if S_2 were 0.0045, it would account precisely for a six-fold increase in discharge when the drainage system filled to the surface. The implied system is largely water-filled, but with a variable free-surface component.

Travel time in such a hybrid system is a combination of closed-conduit and free-surface components. Tracer travel times in open-channel systems are more rapid on rising stage than falling stage (e.g. Collins, 1982), giving a wide hysteretic scatter to velocity-discharge plots reflecting the changing storage in the conduit. This does not appear to be the case for the Storglaciären traces, suggesting a predominantly closed conduit. (Although most glacier traces are made in late morning–afternoon by force of circumstances, they may not demonstrate diurnal hysteresis.) This inference may be tested by plotting "system volume" against discharge. System volume is a measure of the volume of water passing through a drainage system in the travel time of a tracer. In a simple conduit, it is the volume of water which must be emptied as a tracer passes from one end to another. It is calculated using the integral of output discharge over the travel time (e.g. Smart, 1988b), but can be loosely approximated by multiplying mean discharge (Q_p; Seaberg and others, 1988) by the travel time as shown in Table I. Figure 2 indicates that volume changes

TABLE I. SUMMARY OF TRACER RESULTS OF SEABERG AND OTHERS (1988) WITH IMPLICIT TRAVEL TIMES AND SYSTEM VOLUMES

Trace reference	*Discharge*	*Velocity*	*Time*	*Volume*
	$m^3\,s^{-1}$	$m\,s^{-1}$	s	m^3
84–1	0.62	0.14	6790	4210
84–2	0.52	0.10	9500	4940
84–4	0.50	0.14	6790	3390
84–5	0.57	0.16	5940	3380
84–6	0.28	0.11	8640	2420
85–1	0.38	0.044	21 600	8210
85–2	0.43	0.11	8640	3710
85–3	0.49	0.14	6790	3330
85–4	0.73	0.16	5940	4330
85–5	0.31	0.076	12 500	3880
85–7	0.33	0.092	10 300	3410
85–8	0.50	0.125	7600	3800
85–9	0.12	0.032	29 700	3560

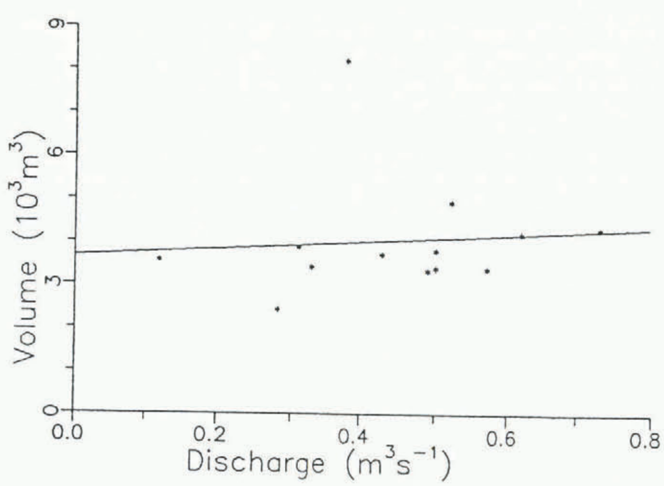

Fig. 2. Volume of subglacial drainage system beneath Storglaciären based on data of Seaberg and others (1988).

surprisingly little with discharge, confirming the predominantly closed conduit. The intercept of a line drawn through these points indicates static storage of 3700 m^3. (The linear regression used is arbitrary, a simple function is not necessarily appropriate.) The high static storage may indicate that the conduit follows the bed and is ponded behind the lower riegel (Fig. 1). In contrast, the maximum dynamic storage implied by the line is only 640 m^3. This shows that discharge variation is accomplished with relatively small volume changes.

The estimated volume is very approximate, in part due to the use of an estimated mean discharge, but also because applying a single travel time for the traced route to all tributaries of a dendritic or anabranching network is inaccurate. Some volume variability may also result from changing proportions of open and closed channels. However, the consistently high volume indicates that the drainage system is largely closed. Any stage-dependent morphological changes must occur in restricted parts of the channel, probably "paraphreatic" parts experiencing frequent inundation and drainage. The balance of changes results from other processes such as erosional and tectonic processes (e.g. Seaberg and others, 1988, p. 224) which will be especially active in glaciers. However, karst systems recharged by glacial melt also show irreproducible break-through curves, and erosional and tectonic explanations are not reasonable in such cases. Hydraulic effects associated with varying flow are inferred (Smart, 1988a). It is possible that these processes may also be active in glaciers, and some examples are described below.

Under rising stage, an unknown part of run-off is routed under high hydraulic potential away from subglacial conduits into "off-line" stores such as the subglacial film or cavities. The water subsequently returns to the conduit as discharge and conduit potential decline. Any dye labelling this component will exhibit secondary peaks during falling stage.

"Hydraulic damming" results when variations in flow through the traced route and a diluting tributary interact to alter the proportion of tracer entering their junction. "Hydraulic switching" occurs when tracer routing at a distributary junction is controlled by an independent tributary to one of the branches down-stream of the junction. The exact effect depends upon the discharge of each element and the change in volume required to produce a matching hydraulic potential. The result can be highly irregular, non-reproducible break-through curves, with little apparent change in discharge.

Unfortunately, it is not yet possible to obtain the data necessary to establish firmly complete explanations of complex break-through curves. It is essential that alternative hypotheses be evaluated before undertaking modelling based on such data.

A final comment addresses the early season trace 85-1 which is the outlier on Figure 2. It indicates anomalously large system volume despite modest discharge. Assuming no

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radical alteration in system topology, this indicates substantial springtime storage of water within the glacier without highly efficient drainage, an effect already inferred from other data (e.g. Iken and Bindschadler, 1986).

The paper by Seaberg and others constitutes a valuable example of the contemporary approach to studying glacier hydrology. Yet we are still unable to monitor adequately the complex, erosionally and tectonically active subglacial system with typically unsteady flows and corresponding complications in tracer dilution, routing, and storage. This makes strict structural interpretation of tracer break-through curves difficult. However, there is some evidence that the system beneath Storglaciären might be a simple, largely water-filled conduit with distributaries rather than the complex braided free-surface stream described.

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SIR,

Reply to: "Comments on: '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'"

Smart (1990) has made some interesting suggestions for alternative interpretations of our dye-trace data from Storglaciären. We will take up his two main points in order.

1. Tracer travel times and system implications

Smart argues that, under low flow conditions, the hydraulic head driving the flow may have been lower than we originally thought was reasonable, and that the slope of unity in the velocity–discharge relation (Seaberg and others, 1988, fig. 5) can thus be attributed solely to variations in head in a closed-conduit system. We agree, and had come to the same conclusion independently on the basis of additional tracer studies.

Smart's system–volume calculations provide another interesting way of elucidating drainage systems from relatively few tracer experiments. However, caution is required in interpreting these calculations in the present case because dye was injected at only one input point, whereas the discharge used in the calculation is that at the terminus, which is the sum of discharges entering the glacier at several different input points. If the ratios of the discharges among the various tributaries changed between tests, the amount of water discharged at S-1 during the time required for the dye to pass from the injection point to S-1 would change, even if there were no change in the geometry of the system.

Smart suggests that the large system–volume calculated for test 85-1 may be a consequence of spring-time storage within the glacier. This would require that storage decrease between 28 June (test 85-1) and 10 July (test 85-2). However, Östling and Hooke (1986) found that, after increasing in May and early June 1984, storage was roughly constant until early August. There is no reason to suspect that conditions were substantially different in 1985. It is possible that there is extensive drainage through the snow cover in late June. Such drainage would contribute to the discharge used in the system–volume calculation without having to pass through the glacier.

Incidentally, Östling and Hooke suggested that storage during the middle of the melt season might be in subglacial cavities. Hooke and others (1989), however, showed that the reasoning leading to the conclusion that such subglacial cavities existed was faulty. We presently infer that the storage is principally in snow and firn.

2. Multiple peaks in dye-return curves

Smart suggests that the multiple peaks in the dye-return curves might be the result of dye being routed into blind storage locations on a rising stage and subsequently released back into the flow on a falling stage. In test 84-2, the peak discharge, 625 l/s, occurred at about the time of the second peak in dye concentration, and by the time of the third peak the discharge had fallen to *c.* 460 l/s. In test 84-6, the peak discharge, 380 l/s, again occurred at about the time of the second peak in dye concentration, and by the time of the third peak it had fallen only 10 l/s, to *c.* 370 l/s. Thus, this mechanism probably cannot explain three of the four secondary peaks.

Furthermore, to drive significant quantities of dye into blind passages, the passages must either be only partially full of water or the hydraulic gradient away from the conduit must be substantial. The former is possible, though, owing to closure, such storage locations would not be large, and the probability of their filling at precisely the time of passage of the dye cloud is, perhaps, remote. The latter is contradicted by bore-hole water-pressure measurements.

Smart's alternative mechanism for producing multiple peaks, involving variations in discharge in a tributary, also seems unlikely in this case, as the discharge curves did not have multiple peaks.

Conclusions

We are in agreement with Smart's explanation for the linear velocity–discharge relation, and had come to the same conclusion ourselves. We also like the system–volume calculation, but feel that caution is required in its interpretation. We thank C.C. Smart for his interest in our work, and for pointing out these alternative interpretations.

Acknowledgement

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