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.

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SIR,

Implications of glacial sculpture on Hans Island, between Greenland and Ellesmere Island (Nares Strait)

Hudson (1983) reported evidence for glacial activity on Hans Island, but discussed two directions of ice movement over the island. In 1988, while studying the Palaeozoic strata in the vicinity of Nares Straight, I observed well-preserved rock sculpturing which indicated a clear direction for glacial movement across the island. The implications of this evidence to the glacial history of the High Arctic are discussed briefly in the following correspondence.

Scours, grooves, and crescent fractures are present near the summit of the island, on dolomitic limestones essentially void of till; yet, erratics are ubiquitous. Striae and plucked bedrock record movement from south-south-west to north-north-east, essentially parallel to the nearby coasts of Nares Strait. Striae occur on relatively smooth dolomitic limestone approximately 160 m a.s.l. (Figs 1 and 2). The highest point on the island, recorded very close to the observed glacial sculpturing, is 168 m as measured by the Geodetic Survey of Canada. Channel bottom, within a 10 km radius of the island centre is between 473 and 264 m below sea-level. The island is cross-cut by numerous normal faults, probably related to early Tertiary tectonism, but stratigraphic offset is less than 10 m. Thick-bedded dolomitic limestone of the island dips 10–15° towards the north-west, following the attitude of contiguous Palaeozoic strata of north Greenland. These strata are in marked contrast to those of northern Ellesmere Island, a tightly folded and faulted carbonate and clastic sequence.

Two ideas pertinent to the present observations are that Nares Strait was a conduit for extensive Innutian and Greenland ice flux (Weidick, 1978; Blake, 1987) until the latest deglaciation which commenced 8–9 ka B.P., or that it was subject to three episodes of glaciation, occurring approximately at 8, 80, and 500 ka to 1 Ma B.P. However, the two latest, areally restricted glacial episodes produced glaciers which probably did not occupy Nares Strait, implying that the strait was glacier-free from perhaps 500 ka to 1 Ma (England, 1987). It is possible that the oldest (500 ka to 1 Ma B.P.) glacial advance of Greenland ice

Fig. 1. View of glacial striae observed at 160 m a.s.l. on Hans Island. Note plucking on north-north-east side of outcrop (Geological Survey of Canada (GSC) photograph 204814).

Fig. 2. Detail of striae and well-developed crescent fractures on limestone. Arrow indicates articulate megalodont bivalve, a typical fossil component of Hans Island strata. The notebook at the top of the photograph is 21 cm long (GSC photograph 204815A).

on to Ellesmere Island may have produced the Hans Island glacial features, but this would require that striae be preserved in relatively good condition on carbonates since ice retreat about 500 ka to 1 Ma B.P.

The relationship between striae-preservation potential and weathering is unclear but, if the weathering characteristic of the Hans Island glaciated carbonates is generally comparable to glaciated rocks of Baffin Island (Dyke, 1979), it would indicate that Hans Island striae were inscribed considerably more recently than during a glacial episode about 500 ka to 1 Ma B.P. A similar case was made for glacial striae on Pim Island (Blake, 1978). There, the age of organic sediments in lakes, the occurrence of striae at a high elevation, and the precariously positioned erratics constrain glaciation to within a similar time frame to that hypothesized for Hans Island. Thus, the relative lack of glacial drift at this locality, the occurrence of striae higher than the recorded position of sea-level during the latest "full glacial sea" (120 m according to England (1987)), and the vulnerability of the carbonates to weathering support a relatively recent time of formation. If, indeed, these structures were the result of an earlier glacial event (e.g. >500 ka B.P.), one would expect erosion of the evidence but, until a quantitative study of weathering of these strata is done, the relationship of time and striae preservation is a moot point.

The implication of the observed glacial structure is that Nares Strait was a conduit for a large glacier which moved *from* the south. Additional evidence for contiguous (?) glacial movement is recorded from east-central Ellesmere Island, on Pim Island, and vicinity. There, abundant sculpturing and scouring of granites indicates a southward ice movement. The present data support the theory of a large grounded glacier in Nares Strait. Ice flowing from two source areas, Ellesmere Island and Greenland, perhaps coalesced in Kane Basin and moved north and south between Greenland and Ellesmere Island (the hypothesis of Blake (1978)). The good preservation of striae may indicate a more recent time for Nares Strait glaciation than that previously hypothesized, for example, occurring up to 10 ka B.P., thereby agreeing with similar episodes of Nares Strait glaciation proposed by Blake (1978) and Weidick (1978); but, clearly, more definitive glacial chronostratigraphy and additional field data would facilitate a more accurate interpretation.

I am grateful to W. Blake of the Geological Survey of Canada (GSC) for drawing my attention to the significance of these observations and for proof-reading a draft of this letter.

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