Debris-Covered Glaciers (Proceedings of a workshop held at Seattle, Washington, USA, September 2000).
IAHS Publ. no. 264, 2000.

Hydrological controls on sediment transport pathways: implications for debris-covered glaciers

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Abstract It is usual to associate the presence of an extensive debris mantle and large lateral moraine ramparts with passive transport of rockfall debris. This simple model does not provide sufficient explanation for past and present moraine formation at the Icelandic glaciers Gígjökull and Kvíárjökull. Here active transport of debris derived from subglacial bedrock makes important contributions to the drainage basin sediment budget. Extensive englacial debris bands, representing relict channel fills, and thick exposures of debris-rich basal ice are both thought to reflect a switch from subglacial to englacial drainage induced by terminal overdeepenings. This switch in hydrology disrupts the tendency of subglacial drainage to sweep the basal transport zone clear of debris. Incorporation of this concept of subglacial flushing into drainage-basin-scale models of debris transfer provides for a fuller understanding of debris-covered glaciers within the wider context of general glacier sediment transport theory.

INTRODUCTION

Recent work has significantly increased our understanding of the various ways in which glaciers entrain and transport sediment (see Kirkbride, 1995; and Alley *et al.*, 1997; for reviews). Particular emphasis has been given to subglacial sediment deformation (e.g. Murray, 1997), ice deformation (e.g. Hambrey *et al.*, 1999), and the direct and indirect impact of water flow within and beneath ice (e.g. Gustavson & Boothroyd, 1987; Kirkbride & Spedding, 1996; Näslund & Hassinen, 1996; Lawson *et al.*, 1998; Krüger & Aber, 1999; Glasser *et al.*, 1999; Ensminger *et al.*, 1999). Nevertheless, the idea that the sediment budget of temperate, alpine-type, debris-covered glaciers that build large moraines is dominated by passive transport of supraglacial rockfall debris remains established as a central feature of glacial geomorphic theory (e.g. Small, 1987a,b; Benn & Evans, 1998). [The terms "passive" and "active" transport, introduced by Boulton (1978), define the primary classification of glacier sediment transport processes: clasts in passive transport retain their original form, whereas clasts subject to active transport undergo extensive modification.] However, this simple rockfall/passive transport model does not provide sufficient explanation for the large Neoglacial moraine ramparts constructed by the Icelandic glaciers Gígjökull and Kvíárjökull. Rockfall source areas are limited at these glaciers, and clast analysis demonstrates that active transport of subglacially-derived debris accounts for a substantial part of both past and present moraine formation. This paper argues that glacier drainage acts as the key influence on these alternative transport pathways, and builds on the examples of Gígjökull and Kvíárjökull to suggest that a perspective giving fuller treatment to hydrology is likely to provide a more complete understanding of sediment transport by debris-covered glaciers.

STUDY GLACIERS: GÍGJÖKULL AND KVÍÁRJÖKULL

Both Gígjökull and Kvíárjökull drain small mountain ice caps (Fig. 1), which means that, in contrast to alpine valley glaciers, supraglacial debris inputs above the equilibrium line (EL) are small. Steep, long icefalls occupy the zones where the glaciers have cut through the volcanic escarpments; these give way to gentle terminal lobes at the junction of escarpments and *sandar* (outwash plains). Ice radar surveys show that pronounced overdeepenings lie beneath these terminal lobes (Fig. 2); observations of upwelling and moulin water levels standing within a few metres of the ice surface indicate high water pressures in these areas. However, direct data indicative of the glaciers' drainage systems are not available. Following Björnsson (1979), both glaciers are believed to be temperate. The volcanoes underneath Eyjafjallajökull and Öræfajökull last erupted in 1821–1823 and 1727 respectively, both events generating an outburst flood at the study glaciers. The time elapsed since makes it unlikely that the current patterns of sedimentation are dominated by the impact of *jökulhlaups*, although the possible impacts of elevated geothermal heat fluxes on the process regimes are unknown.

Large Neoglacial moraine ramparts enclose the glaciers' termini (Dugmore, 1989; Thórarinsson, 1956; Guðmundsson, 1998): Gígjökull's is ~60 m high, Kvíárjökull's ~100 m high. These motivated study of the two glaciers, although fieldwork focused on the character of contemporary sediments and transport pathways. Clast roundness analysis using standard procedures (Benn & Ballantyne, 1994), supported by observations of the sediments' matrix properties and wider field relationships (e.g. the spatial arrangement of debris relative to other debris, the glacier margins, and ice structures such as foliation), identified three distinct types of debris. Tephra forms a fourth distinct category, but its overall volume relative to the other three is negligible, so it was excluded from this study. Tables 1 and 2 summarize the most important details; Fig. 3 depicts the spatial distribution of the major debris types.

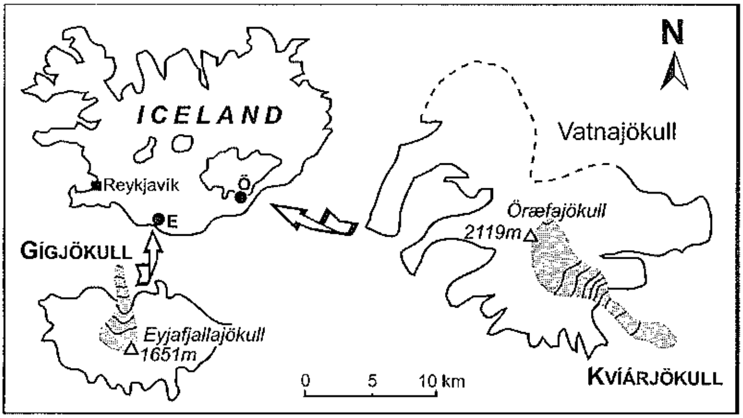

Fig. 1 Location of Gígjökull and Kvíárjökull. Surface contours shown for study glaciers at 200 m intervals.

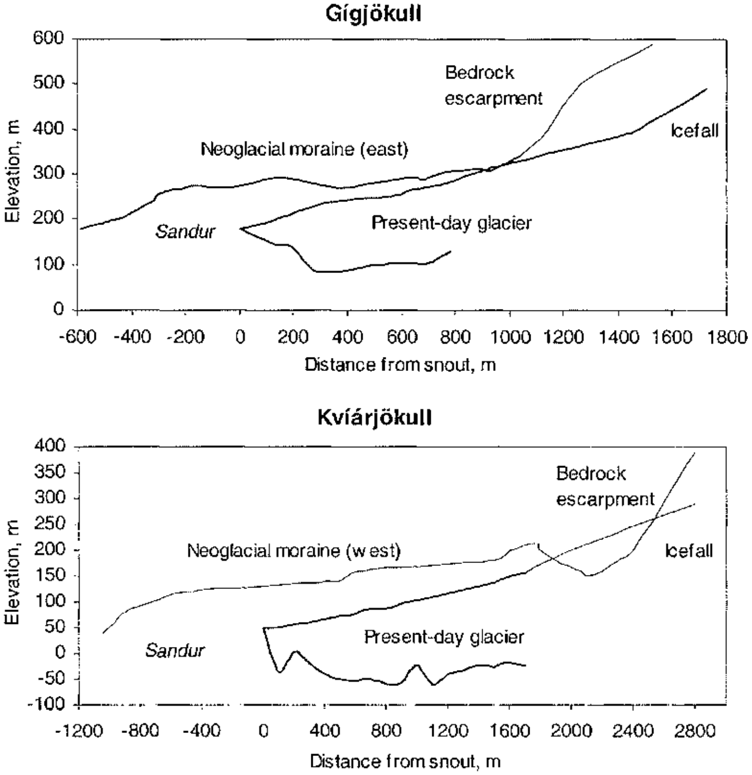

Fig. 2 Gígjökull and Kvíárjökull: long profiles of the Neoglacial moraine ramparts set against present-day, centre-line surface and bed topography. Thick lines represent data obtained by field survey, thin lines data taken from published maps. Although crude (centreline survey only, no migration of bed-return data), these profiles support the inference that the magnitude of the adverse bed slope relative to the ice surface slope is sufficient to induce glacio-hydraulic supercooling beneath the termini of both glaciers. Gígjökull ice depth data courtesy of A. J. Dugmore.

INTERPRETATION

Its angular character identifies Type A sediment as rockfall debris; field relationships demonstrate both above-EL sources (debris bands at Kvíárjökull) and below-EL sources (debris directly supplied to the ice surface at both Gígjökull and Kvíárjökull). Type B debris is clearly different from either Types A or C debris. The rounded character of the larger clasts, and the crude sorting of the matrix deficient in fine particles is atypical of rockfall or basal debris, but strongly suggests modification of the debris by water transport. The debris content of the source debris bands is unusually high (~60–70% debris concentration by mass), and a sharp contact exists between the debris bands and the surrounding, debris-free englacial (i.e. of meteoric origin) ice. Accordingly, Kirkbride & Spedding (1996) conclude that the debris bands from which Type B debris is derived represent channel fills, formed by sediments deposited in an englacial drainage system, subsequently to become separated from the water and returned to ice transport. This relict channel hypothesis is preferred to a

Table 1 Summary of clast roundness analysis.

Location	Debris type	No. of clasts in sample	Clast roundness: RA%	Mean	Std Dev.
Gígjökull	A	248	64.92	2.27	0.62
	B	487	1.03	3.86	0.75
	C	396	39.90	2.60	0.55
	Rampart	1083	15.82	3.17	0.76
Kvíárjökull	A	635	95.28	1.95	0.38
	B	545	19.27	3.11	0.77
	C	560	54.82	2.46	0.57
	Rampart, P	877	65.34	2.30	0.61
	Rampart, M	1291	52.98	2.52	0.71
	Rampart, D	1082	28.10	2.92	0.76

Clast roundness was assessed by Power's standard six-point scale. Very angular clasts were given the value 1, angular clasts 2, ...well-rounded clasts 6, so allowing calculation of roundness mean and standard deviation.

RA% This is the RA index, a non-parametric measure of sample clast roundness (Benn & Ballantyne, 1994). It indicates the percentage of clasts in each sample classified as very angular or angular.

Rampart: Debris making up the Neoglacial lateral moraine ramparts enclosing the study glaciers. Because of the size of Kvíárjökull's Neoglacial moraine, the data set was divided into three parts according to distance along the ridge crest. These are denoted P (proximal), M (middle) and D (distal).

Table 2 Other important characteristics of the three major debris types.

Debris type	Matrix properties	Source of debris	Interpretation
A	Poorly sorted. Coarse matrix, deficient in fine sands, silts and clays.	(i) Sits on ice surface as clast-supported deposit, or, (ii) largely continuous englacial debris septa; irregular contact with surrounding ice; high debris content.	Rockfall debris; PASSIVE supraglacial or englacial transport.
B	Crude sorting. Medium–coarse matrix, often deficient in silts and clays.	Various englacial debris bands: continuous debris septa, interspersed with lenticular or trough-like pockets of sediment; smooth, sharp contact with surrounding ice; high debris content; ice occupies interstices.	Englacial channel fill deposits: "relict channel" debris bands. ACTIVE transport by running water; thereafter passive transport in englacial ice.
C	Poorly sorted; usually all grades of particles from gravels to silts and clays well represented.	Dirty ice exposures, sometimes >10 m thick; debris occurs as clots or sub-horizontal laminae, enclosed within ice; debris concentrations low to medium; occasional clasts >30 mm diameter; distinct bubble layers common; otherwise ice largely bubble-free.	Basal debris enclosed in basal ice; ACTIVE transport in the subglacial traction zone.

thrust origin because the debris bands are commonly wavy, closely spaced, and with a shallow dip; only in one instance was a connection to the glacier bed observed. These features do not match published accounts of thrusts (e.g. Hambrey *et al.*, 1999). If thrust development was responsible for debris band formation at the study glaciers, it is reasonable to expect entrainment of basal debris also, but this is not the case: the debris bands contain Type B material only. This observation further supports their inferred origin as channel fills.

The most probable source for the sediment in these debris bands is the subglacial bedrock some distance upglacier of the termini. Supraglacial debris sources above the ELs are limited, whereas entrainment of debris by surface streams at lower elevations is difficult to reconcile with the observed volume and routing of supraglacial drainage below the icefalls, and the transport distance likely to be required for significant rounding of the debris to occur. Thus it is inferred that the channels that gave rise to the debris bands must once have run subglacially. This switch from subglacial to englacial drainage is difficult to account for, but it is consistent with current ideas on the behaviour of water in overdeepenings (Lliboutry, 1983; Röthlisberger & Lang, 1987; Fountain, 1994; Hooke & Pohjola, 1994; Fountain & Walder, 1998). The adverse slope of an overdeepened basin acts to raise water pressures to levels sufficient to render discrete subglacial channels unstable. Recent work has focused on the impact of freezing induced by an energy deficit as water flows upslope beneath progressively thinner ice: growth of frazil and anchor ice accelerates the process of channel closure and rising water pressures, so that, in certain cases, water (and debris also) is diverted into smaller channels at higher levels within the ice (Hooke & Pohjola, 1994; Alley *et al.*, 1998; Ensminger *et al.*, 1999). This envisaged switch from subglacial to englacial drainage involves a loss in flow competence and capacity, likely to induce deposition of sediment within the ice—a process that clearly favours the production of channel fill debris bands (Kirkbride & Spedding, 1996).

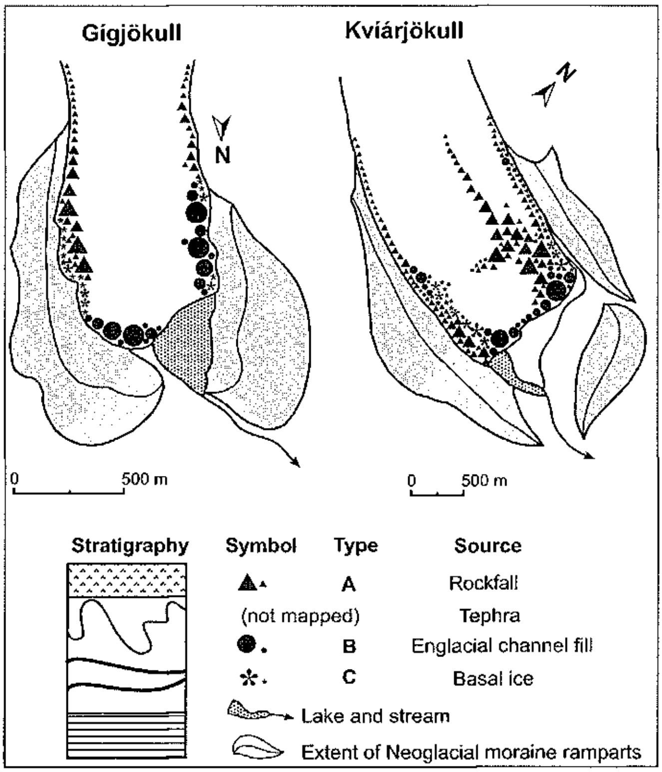

Fig. 3 Sketch maps of the termini of Gígjökull and Kvíárjökull, showing the distribution of the major debris types.

Its reduced angularity, indicative of active clast modification, differentiates Type C debris from the rockfall material, and supports an origin within the basal traction zone. The dirty ice from which it is derived shows many characteristics of basal ice produced by sliding over a hard bed (e.g. Jansson *et al.*, 1996): using the classification of Hubbard & Sharp (1995), the ice can be described as "stratified", consisting largely of a mixture of "laminated" and "clear" facies. Debris laminae suggest "Weertman-type" regelation (Hubbard & Sharp, 1993); clear pockets with muddy clots suggest flow of meltwater containing fine sediments through the vein network (Lliboutry, 1993; Knight & Knight, 1994), accompanied by plastic deformation and ice metamorphism; coarse clasts indicate bedrock fracture and tractive entrainment of debris. The climate is not conducive to net accretion of basal ice by freezing-on, so the observed thicknesses of basal ice are probably produced by tectonic thickening (cf. Sharp *et al.*, 1994). However, given the ice radar evidence of overdeepenings, which suggests that the adverse bed slopes exceed the ice surface slopes by more than the critical factor of 1.2–1.7 (Fig. 2), formation of basal ice by glacio-hydraulic supercooling in a residual subglacial drainage network is also plausible (Lawson *et al.*, 1998). The debris band evidence for englacial drainage is also consistent with this hypothesis.

Clast roundness analysis shows that much of the debris contained in the rampart moraines is not derived from rockfall: very angular or angular clasts make substantial contributions to the proximal (i.e. adjacent to the escarpment) portions only. Much of the moraine material closely resembles Type B or C sediments, so it is inferred that the same active transport pathways identified today operated for much of the Neoglacial, contributing large quantities of relict channel and basal debris to the moraine ridges.

DISCUSSION

Hydrological influences on sediment transport

It is the transition from icefall to overdeepening that seems to govern the disposition of sediments at the termini of Gígjökull and Kvíárjökull. This section explores the possibility that these circumstances permit development of a thick debris cover at temperate glaciers even in the absence of extensive rockfall inputs. At the core of this hypothesis is the inferred switch from predominantly subglacial to predominantly englacial drainage, induced by the ice and bedrock geometry. This favours both production of debris, and its retention within the ice for subsequent delivery to the glacier margins.

It is likely that much of the Types B and C debris mapped in Fig. 3 is produced by bedrock erosion associated with rapid sliding, widespread cavity formation and variable water pressures at the base of the icefalls (Hooke, 1991). Some of this debris will be picked up and carried away by the subglacial drainage; some will be incorporated into basal ice. Debris-rich basal ice of the type found at Gígjökull and Kvíárjökull is unlikely to survive in close proximity to major elements of subglacial drainage, because high power flows melt ice and remove debris (Hubbard & Sharp, 1995); however, destruction of basal ice, and consequent evacuation of its debris, beneath icefalls is likely to be limited because sliding suppresses both the growth and migration of channels. As noted above, both theoretical and empirical studies indicate that rising water pressures within an overdeepening can force a switch from predominantly subglacial to predominantly englacial drainage. The relict channel debris bands provide firm evidence of this at Gígjökull and Kvíárjökull (Kirkbride & Spedding, 1996), and provide clues to the possible structure of water flow. Their location, size and spacing imply distributed englacial networks of numerous small channels (cf. Hooke & Pohjola, 1994), possibly exploiting pre-existing fractures (cf. Ensminger *et al.*, 1999), preferentially routed close to the sides of the glaciers (cf. Lliboutry, 1983; Fountain & Walder, 1998).

It is possible that the extensive exposures of basal ice also represent ramifications of this hydrological switch:

(a) water running within englacial ice cannot attack basal ice and sediments, favouring accumulation of relatively thick, debris-rich basal ice layers;
(b) the transition from a lubricated "wet" bed to a sticky "dry" bed will enhance the compressive flow acting to thicken basal ice, and so carry it away from areas immediately adjacent to the glacier bed where it is most likely to be destroyed.

If this hypothesis is correct, the simultaneous presence of extensive relict channel debris bands and thick exposures of basal ice at Gígjökull and Kvíárjökull is causally-connected, not coincidental, and moraine formation, both present and past, is (was) related to a context dominated by water flow. The possibility of glacio-hydraulic supercooling enhancing basal ice formation strengthens this idea.

Implications for debris-covered glaciers

Although large areas are buried beneath sediments, Gígjökull and Kvíárjökull cannot be described as debris-covered; however, this does not mean that similar processes to those described above are not important at debris-covered glaciers. Arguably it is because their termini are not smothered by rockfall debris that alternative, active sediment transport pathways can be identified at Gígjökull and Kvíárjökull. It is probable that similar non-rockfall debris is buried in the surface mantles and lateral moraines of many debris-covered glaciers: e.g. relict channel debris features strongly in the debris cover of the Tasman and Mueller Glaciers in New Zealand (Kirkbride & Spedding, 1996), and both water-worked cobbles and polished, striated basal clasts are found amongst the rockfall debris of the Ghiacciaio del Miage in the Italian Alps (author's observations). This study highlights the impacts of overdeepenings, but it is feasible that other circumstances, such as storm events (e.g. Warburton & Fenn, 1994), surges (e.g. Sharp, 1985; Bennett *et al.*, 2000) or floods (Näslund & Hassinen, 1996; Krüger & Aber, 1999) that generate high basal water pressures will also give rise to relict channel debris bands. It is also clear from this study that the construction of large moraines is not restricted to glaciers with sediment budgets dominated by rockfall and passive transport.

A corollary of the passive transport model is the assumption that paucity of debris cover and small moraines are the result of restricted debris supply: e.g. because of resistant rocks, or small areas of supraglacial rockwalls. This is not necessarily true: sediment availability for moraine formation is a function of both debris supply and debris *retention*. Hydrology exerts a critical control on the latter. Highly erosive glaciers cannot build large moraines at the end of active transport pathways if the bulk of debris generated subglacially is swept away by the action of aggressive subglacial water flows. Alley *et al.* (1997) emphasize the efficacy of subglacial water transport, a notion which is also implicit in the use of proglacial sediment discharge to estimate subglacial sediment yields and erosion rates; however, the potential impact of subglacial flushing on the distribution of debris between different transport pathways and the ability of glaciers to form moraines does not figure strongly in the glacial geomorphic literature (Kirkbride, 1995), despite the rapid growth in our knowledge of glacier hydrology in the last 20 years or so. Gígjökull and Kvíárjökull can build large moraines without the aid of abundant rockfall inputs precisely because this flushing constraint is broken: large quantities of debris evade removal by water beneath the icefalls (sliding constraints on channel growth and migration), at the base of the overdeepenings (collapse of the subglacial drainage network), and within the ice of the terminal lobes (deposition of the relict channel debris bands). If this concept of flushing is applied to debris-covered glaciers, their thick debris mantles and large moraines are seen to indicate not only the presence of effective, rockfall-dominated debris supply, but also the *absence* of effective debris removal. Rockfall debris sits upon, or returns quickly to, the glacier surface, whereas water tends to find its way rapidly towards the glacier bed, so creating the necessary separation of debris and competent water flows required to break the flushing constraint for the high level part of the transport system.

CONCLUSION

The examples of Gígjökull and Kvíárjökull demonstrate the importance of hydrology as an influence on glacier sediment budgets, and suggest that the passive transport model provides a partial, and possibly misleading, account of debris cover formation and moraine accumulation. Accounts of sediment transport that stress the source and primary mode of entrainment of debris risk ignoring the possibility of more complex transport histories: debris can be shifted between different pathways within ice, or removed from ice transport altogether (in which case it cannot form true moraines). Glacier drainage is a major factor controlling this redistribution of debris. This study forms a small part of a growing body of work indicating that hydrology must be included alongside established factors such as relief, geology, climate and thermal regime when formulating glacier sediment transport models; use of such an extended framework provides for a more complete understanding of debris-covered glaciers in the full context of the different types of ice masses found worldwide.

Acknowledgements This study was part-funded by the Royal Society of London and the Carnegie Trust for the Universities of Scotland. Thanks to Peter Jansson and Andrew Fountain for their constructive appraisals of the original manuscript.

REFERENCES

Alley, R. B., Cuffey, K. M., Evenson, E. B., Strasser, J. C., Lawson, D. E. & Larson, G. J. (1997) How glaciers entrain and transport basal sediment: physical constraints. *Quatern. Sci. Rev.* **16**(9), 1017–1038.

Alley, R. B., Lawson, D. E., Evenson, E. B., Strasser, J. C. & Larson, G. J. (1998) Glaciohydraulic supercooling: a freeze-on mechanism to create stratified, debris-rich basal ice: II. Theory. *J. Glaciol.* **44**(148), 563–569.

Benn, D. I. & Ballantyne, C. K. (1994) Reconstructing the transport history of glacigenic sediments: a new approach based on the co-variance of clast-form indices. *Sediment. Geol.* **91**(1–4), 215–227.

Benn, D. I. & Evans, D. J. A. (1998) *Glaciers and Glaciation.* Edward Arnold, London.

Bennett, M. R., Huddart, D., McCormick, T. & Waller, R. I. (2000) Glaciofluvial crevasse- and channel-fills as indicators of subglacial dewatering during a surge, Skeiðarárjökull, Iceland. Accepted for *J. Glaciol.*

Björnsson, H. (1979) Glaciers in Iceland. *Jökull* **29**, 74–80.

Boulton, G. S. (1978) Boulder shapes and grain size distributions as indicators of transport paths through a glacier and till genesis. *Sedimentology* **25**(6), 773–799.

Dugmore, A. J. (1989) Tephrochronological studies of Holocene glacier fluctuations in south Iceland. In: *Glacier Fluctuations and Climatic Change* (ed. by J. Oerlemans), 37–55. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Ensminger, S. L., Evenson, E. B., Larson, G. J., Lawson, D. E., Alley, R. B. & Strasser, J. C. (1999) Preliminary study of laminated, silt-rich debris bands: Matanuska Glacier, Alaska, USA. *Ann. Glaciol.* **28**, 261–266.

Fountain, A. G. (1994) Borehole water-level variations and implications for the subglacial hydraulics of South Cascade Glacier, Washington State, USA. *J. Glaciol.* **40**(135), 293–304.

Fountain, A. G. & Walder, J. S. (1998) Water flow through temperate glaciers. *Rev. Geophys.* **36**(3), 299–328.

Glasser, N. F., Bennett, M. R. & Huddart, D. (1999) Distribution of glaciofluvial sediment within and on the surface of a High Arctic valley glacier: Marthabreen, Svalbard. *Earth Surf. Processes and Landforms* **24**, 303–318.

Guðmundsson, H. J. (1998) Holocene glacier fluctuations and tephrochronology of the Öræfi district, Iceland. PhD Thesis, University of Edinburgh, UK.

Gustavson, T. C. & Boothroyd, J. C. (1987) A depositional model for outwash, sediment sources and hydrologic characteristics, Malaspina Glacier, Alaska: a modern analogue of the south-eastern margin of the Laurentide Ice Sheet. *Geol. Soc. Am. Bull.* **99**(2), 187–200.

Hambrey, M. J., Bennett, M. R., Dowdeswell, J. A., Glasser, N. F. & Huddart, D. (1999) Debris entrainment and transfer in polythermal valley glaciers. *J. Glaciol.* **45**(149), 69–86.

Hooke, R. Le B. (1991) Positive feedbacks associated with erosion of glacial cirques and overdeepenings. *Geol. Soc. Am. Bull.* **103**(8), 1104–1108.

Hooke, R. Le B. & Pohjola, V. A. (1994) Hydrology of a segment of a glacier situated in an overdeepening, Storglaciären, Sweden. *J. Glaciol.* **40**(134), 140–148.

Hubbard, B. & Sharp, M. J. (1993) Weertman regelation, multiple refreezing events and the isotopic evolution of the basal ice layer. *J. Glaciol.* **39**(132), 275–291.

Hubbard, B. & Sharp, M. J. (1995) Basal ice facies and their formation in the western Alps. *Arct. Alpine Res.* **27**(4), 301–310.

Jansson, P., Kohler, J. & Pohjola, V. A. (1996) Characteristics of basal ice at Engabreen, northern Norway. *Ann. Glaciol.* **22**, 114–120.

Kirkbride, M. P. (1995) Processes of transportation. In: *Modern Glacial Environments: Processes, Dynamics and Sediments* (ed. by J. Menzies), 261–292. Butterworth-Heinemann, Oxford.

Kirkbride, M. P. & Spedding, N. (1996) The influence of englacial drainage on sediment transport pathways and till texture of temperate valley glaciers. *Ann. Glaciol.* **22**, 160–166.

Knight, P. G. & Knight, D. A. (1994) Glacier sliding, regelation water flow and development of basal ice. *J. Glaciol.* **40**(136), 600–601.

Krüger, J. & Aber, J. S. (1999) Formation of supraglacial sediment accumulations on Kötlujökull, Iceland. *J. Glaciol.* **45**(150), 400–402.

Lawson, D. E., Strasser, J. C., Evenson, E. B., Alley, R. B., Larson, G. J. & Arcone, S. A. (1998) Glaciohydraulic supercooling: a freeze-on mechanism to create stratified, debris-rich basal ice: I. Field evidence. *J. Glaciol.* **44**(148), 547–562.

Lliboutry, L. (1983) Modifications to the theory of intraglacial waterways for the case of subglacial ones. *J. Glaciol.* **29**(102), 216–226.

Lliboutry, L. (1993) Internal melting and ice accretion at the bottom of temperate glaciers. *J. Glaciol.* **39**(131), 50–64.

Murray, T. (1997) Assessing the paradigm shift: deformable glacier beds. *Quatern. Sci. Rev.* **16**(9), 995–1016.

Näslund, J.-O. &. Hassinen, S. (1996) Supraglacial sediment accumulations and large englacial water channels at high elevations in Mýrdalsjökull, Iceland. *J. Glaciol.* **42**(140), 190–192.

Röthlisberger, H. & Lang, H. (1987) Glacial hydrology. In: *Glacio-fluvial Sediment Transfer: an Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 207–284. Wiley, Chichester, UK.

Sharp, M. J. (1985) Sedimentation and stratigraphy at Eyjabakkajökull—an Icelandic surging glacier. *Quatern. Res.* **24**, 268–284.

Sharp, M. J., Jouzel, J., Hubbard, B. & Lawson, W. (1994) The character, structure and origin of the basal ice layer of a surge-type glacier. *J. Glaciol.* **40**(135), 327–340.

Small, R. J. (1987a) Englacial and supraglacial sediment: transport and deposition. In: *Glacio-fluvial Sediment Transfer: an Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 111–145. Wiley, Chichester, UK.

Small, R. J. (1987b) The glacial sediment system: an alpine perspective. In: *Glacio-fluvial Sediment Transfer: an Alpine Perspective* (ed. by A. M. Gurnell & M. J. Clark), 199–203. Wiley, Chichester, UK.

Thórarinsson, S. (1956) On the variations of Svínafellsjökull, Skaftafellsjökull and Kvíárjökull in Öræfi. *Jökull* **14**, 67–75.

Warburton, J. & Fenn, C. R. (1994) Unusual flood events from an Alpine glacier: observations and deductions on generating mechanisms. *J. Glaciol.* **40**(134), 176–186.