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Obstruction of subglacial conduits by bedload sediment – implications for alpine glacier motion

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Abstract

Glacier motion is driven by gravity and resisted by boundary friction. Water pressure at the ice boundaries influences the effective stress between the ice and the boundary, and hence the frictional resistance to glacier motion. Ice-boundary water pressure is closely related to pressure in subglacial water conduits, which in alpine valley glaciers are likely to be coarse-sediment-bedded "Röthlisberger" channels in the basal ice. The cross-sectional geometry of these channels, and therefore water-pressure distribution within them, is affected by erosion and deposition of bedload sediment by the subglacial flow. This is particularly the case where the flow regime of the glacier drainage system is markedly unsteady. Research on bedload transport in closed conduits shows that conduit obstruction and blockage by bedload-sediment deposition are likely to be common under unsteady flow and sediment supply – conditions found in mountain valley glaciers. The effects of bedload-sediment on glacier motion have been largely overlooked in the past, but appear relevant to such phenomena as surging, kinematic waves, *jökulhlaups* and ice-quakes.

Keywords

glacier motion: basal water pressure; subglacial hydrology: hydraulics: bedload sediment transport; conduit flow: conduit obstruction.

Introduction

The presence, motion and pressure distribution of subglacial water have significant influences on the basal force balance of glaciers, and therefore on their motion, (e.g., Fountain and Walder, 1998), but the effects of bedload sediment erosion, transport and deposition on the subglacial water pressure have not yet received detailed attention. Much previous work on subglacial water pressure assumes equilibrium between water and ice pressures (e.g., Hooke, 1984; Walder and Fowler, 1994), and while this may be the case under long-term steady water flow, or as an average under repeated hydrographs where diurnal variations in melt rate dominate the flow, it is unlikely to apply under more substantial variations of water flow, such as those resulting from major precipitation events. This is particularly the case for glaciers in super-humid-environments, where the supply of water to the subglacial system is likely to vary markedly on a time scale of days or even hours. Herein we show that the presence and motion of bedload sediment in subglacial conduits have the potential to influence the water-pressure distribution and variation in these conduits, and hence the motion of the glacier.

We begin by describing the occurrence and effects of subglacial water and sediment, emphasising the role of bedload sediment, which can be rapidly deposited and wholly or partly block conduits under particular circumstances. We then investigate the processes of water and sediment motion in subglacial conduits, utilising engineering knowledge of the corresponding phenomena in pipes. Finally we apply these processes to conduits formed in ice, and consider the processes of conduit obstruction, blockage and clearance by sediment deposits, and the effects of these processes on basal water pressures. We relate the outcomes to the reported occurrence of rapid changes in water pressure and ice velocity, fissuring, kinematic waves, ice-quakes and *jökulhlaups*.

Subglacial hydrology and sediment

The motion of glaciers is sensitive to the pressure of water between the ice and the bounding material, and therefore to the water pressure in conduits, pores or cracks at the base and sides of the glacier. High basal water pressure has been shown to be associated with rapid glacier motion, because hydraulic uplift pressures on the base of the ice reduce the contact pressure between the ice and its boundaries, reducing the frictional resistance to glacier motion (Clarke, 2005; Fountain and Walder, 1998; Murray and Clarke, 1995; Walder and Fowler, 1994). Brocklehurst and Whipple (2006) deduce that subglacial hydraulic processes also play a significant role in erosion by glaciers.

Walder and Fowler (1994) show that water movement is more likely to take place in well-defined conduits than in extensive thin films; and that in mountain valley glaciers, channels in the overlying ice ("Röthlisberger" or "R" channels) are more stable – and thus more likely to be present – than channels in underlying material. Fountain and Walder (1998) illustrate such a channel (their Fig. 13), the bed of which comprises coarse clastic sediment. The basal glacier water pressure distribution depends on the hydraulics of water motion through the glacier. Water flow in conduits is driven by the pressure gradient and resisted by boundary friction, and the geometry of the conduits influences the resistance to flow, and hence the distribution of pressure in the system. Conduit geometry can change by alteration of cross-sections due to the ability of ice to flow under pressure differences and to melt (and water to freeze) under temperature and pressure differences (Shreve, 1972; Hooke, 1984; Alley *et al.*, 2003a, b); and also as a result of bedload sediment deposition.

The longitudinal hydraulic gradient in a conduit has generally been taken as steady and equivalent to the ice overburden pressure (Shreve 1972), although atmospheric pressure has also been postulated (Hooke, 1984). Observations in boreholes connected to conduits show intermediate pressures with significant diurnal and longitudinal variation. According to the laws of turbulent pipe flow, longitudinal hydraulic gradients vary with the square of discharge and reflect local conduit geometry, with a particular concentration of pressure loss at restrictions. Local ice restrictions in a conduit will suffer intense local erosion melting, providing the conduit geometry permits sufficient concentration of pressure loss. Under complete blockage, zero flow and hydrostatic conditions, pressure will be uniform throughout contiguous conduit segments. Models of water pressure rising to ice overburden are correct at this limit. Above this pressure, the ice will tend to float, or the water will find an overflow, depending on the ice topography. Flotation, surface outbursts and even waterspouts are known to occur, but they are rare and ephemeral because a conduit normally adjusts to seasonal discharge within days or hours.

Most alpine valley glaciers export substantial quantities of coarse material in their proglacial streams (Loso *et al.*, 2004; Pearce *et al.*, 2003; Warburton and Fenn, 1994), so subglacial conduits may be inferred to be carrying significant bedload at times of high water flow, with a characteristic maximum grain-size comparable to the conduit diameter (e.g., Davies *et al.,* 2003, figure 7; Fountain and Walder, 1998, figure 13). The quantity of bedload material carried by subglacial water flow is exemplified by the Franz Josef glacier, a large humid-region glacier in Westland, South Island, New Zealand (Davies *et al.*, 2003). During its 1982-99 advance, this glacier delivered rounded gravels to its outwash fan sufficient to build up a wedge 2000 m long, 400 m wide on average and more than 10 m deep at its proximal end; this amounts to a volume of at least 4×10^6 m^3. The paucity of angular clasts, and the absence of a terminal moraine during the whole of the advance, indicates that most of this material was delivered via the subglacial drainage system. This glacier receives of the order of 10,000 mm of precipitation (water equivalent) per annum (Henderson and Thompson, 1999), with occasional intensities of up to 600 mm per day, so perhaps represents an extreme case of rainfall-dominated subglacial hydrology.

When water flow through a glacier is steady, the conduit-system geometry can adjust to an equilibrium state by ice/water processes alone. However, water flow in glaciers is rarely steady (Hubbard and Nienow, 1997). Most glacier-fed rivers exhibit marked diurnal flow variations, and those in humid environments are also affected by intense rain (Davies *et al.,* 2003). Seasonal snowmelt causes a slower variation upon which these changes are superimposed. When water flow through the glacier is markedly unsteady, rates of ice flow, melting and freezing may be too slow to allow the conduit system to maintain a series of geometries in equilibrium with the changing water discharge. The ability of the conduit system to alter its geometry depends also on the availability of sediment to be deposited or eroded within it, and the ability of the flow to mobilise the sediment. Hence under high and unsteady water flows the pressure distribution in the conduit system, and hence the glacier's basal pressure distribution, are likely to be significantly affected by sediment transport, erosion and deposition, which can all alter the resistance to water flow, and pressure distribution, in the system.

How rapidly a subglacial water-conduit system can achieve a new equilibrium configuration by ice flow, melting and freezing in response to a change in water flow rate is unclear. However, where coarse sediment is in transport as bedload, the rate of conduit modification by ice processes is very much slower than the (almost instantaneous) rate at which conduit cross-sectional area can alter by sediment erosion or deposition in response to a change in flow or sediment supply.

The erosion, transport and deposition of bedload sediment are fundamentally different from those of suspended sediment. This is because a large quantity of fine sediment can be carried in suspension with little or no deposition on the bed; whereas the coarser bedload sediment is by definition always (if sometimes discontinuously) supported by the bed (Bagnold, 1966). In particular, the transport, erosion and deposition of suspended sediment have relatively minor effects on channel geometry and hence pressure distribution, whereas the bedload processes can rapidly alter channel geometry and hence pressure distribution (Carstens, 1969).

Transport of bedload in closed conduits differs fundamentally from that in open channels (Graf, 1971). Whereas deposition of bedload in an open channel has only a minor effect on the local pressure gradient (because the flow can avulse laterally to circumvent the deposit, as in braiding), deposition of bedload sediment in a closed conduit partly obstructs the conduit, altering the pressure gradient along the reach if the flow rate is independently determined; or, as in the case of glacial conduit flow where the pressure driving the flow is limited by the height of the ice surface (Davies *et al.*, 2003), causing the flow rate (and hence the bedload transport capacity) to decrease. This latter situation sets up a positive feedback, resulting in conduit blockage, as we shall demonstrate.

To understand the effect of sediment transport on glacier motion, we should therefore be concerned with bedload erosion, transport and deposition in subglacial conduit systems – at least in systems where bedload sediment transport is significant. This suggestion receives substantial support from the known effect of bedload on the morphology of karst drainage systems (Bruthans and Zeman, 2003). It is also becoming clear that bedload makes up a significant proportion of the total sediment load of subglacial conduits (Beecroft, 1983; Alley *et al.*, 1997; Pearce *et al.*, 2003; Loso *et al.*, 2004). In spite of this, the effects of bedload erosion, transport and deposition in subglacial conduit systems on conduit geometry and hence basal ice pressures have not to date been seriously addressed in the literature; the present work outlines the hydraulic basis of the phenomena involved.

Subglacial water and sediment motion

The mechanics of flow and bedload transport in subglacial conduit systems are in principle similar to those in rigid-boundary pipes of similar cross-sectional shapes, with the exception that the glacial conduits can alter in cross-section over time as a result of ice flow, melting and freezing. The instantaneous relationships among flow rate, bedload transport rate, cross-section and pressure gradient are however identical in the two cases, so the mechanics of bedload transport in pipes is a logical starting-point from which to approach subglacial bedload motion. While the following outline is based on phenomena in pipes of circular cross-section, the principles apply to pipes of any shape, and therefore to glacial conduits of any shape (Fountain *et al.*, 2005).

Flow and bedload transport in pipes

We concentrate on concepts of bedload sediment transport in pipes flowing full, i.e., in the absence of a free water surface. In this situation the pressure gradient driving the flow is independent of the topographic gradient of the pipe itself, so the pipe may be horizontal, or slope down in the flow direction, or have reverse (negative) slope so that the water flow is uphill. If the pipe is flowing partly full, the free water surface must be nearly parallel with the pipe axis unless the reach length is very short; and in such reaches open-channel flow principles apply.

The hydraulic principles of pipe-flow are well-known (e.g., Webber, 1968); the pressure gradient h_f/l required to drive a flow at an average velocity of v ms^{-1} in a pipe of diameter d m with a dimensionless resistance coefficient f is given by the Darcy-Weisbach equation

$$\frac{h_f}{l} = \frac{4fv^2}{2dg} \qquad (1)$$

Here h_f is the water pressure loss over a length l of pipe, and g is the acceleration due to gravity. Since discharge Q = vA, where A is the pipe cross-sectional area = $\pi d^2/4$, then Eq. (1) becomes

$$\frac{h_f}{l} = \frac{16fQ^2}{\pi^2 d^5 g} \qquad (2)$$

The pressure gradient required to maintain the flow rate varies inversely with the *fifth* power of the pipe diameter; hence any reduction in pipe diameter causes a very large increase in the pressure gradient required to maintain the flow. If the available pressure gradient is limited, the flow rate will similarly be very sensitive to any reduction of pipe diameter, as we see by putting h_f/l constant in (2) and obtaining

$$Q^2 = \frac{\pi^2 d^5 g(h_f/1)}{32f} \qquad (3)$$

in which Q varies with $d^{2.5}$. Hence reducing the pipe diameter by, for example, 30% and maintaining the original pressure gradient reduces the flow to $0.7^{2.5}$ = 41% of its original value, a reduction of 59%. If the bedload transport capacity of the flow varies with the stream power Ω (Bagnold, 1966, 1980), then

$$Q_b = k(\Omega - \Omega_0)^{1.5} \qquad (4)$$

where k is a constant for a given conduit, Ω is (Qh_f/l) and Ω_0 is the value of Ω at the onset of bedload motion. In this case we would expect the sediment transport capacity of the flow in the above example to be reduced to $(59\%)^{1.5}$ = 26% if Ω_0 = 0, and to a much smaller proportion if (as in reality) $\Omega_0 >> 0$. Bedload transport rate is therefore in principle extremely sensitive to conduit cross-sectional area, and hence to conduit obstruction.

Because of the economic significance of solids transport in pipes, much of the published work on this topic is concerned with establishing the conditions under which sediment will form a stationary bed in pipe flow, *and designing the system to avoid them.* This is because of the high probability of sediment accumulation blocking the pipe if a stationary bed ever forms (Graf, 1971, p 472). Thus knowledge of bedload transport in pipe flow is limited; Condiolos *et al.* (1963), Carstens (1969) and ASCE (1975) provide introductions to the main features of the phenomenon, which are drawn on in the following.

Figure 1 illustrates the way in which pressure gradient (or energy dissipation rate) P varies in a pipe of given diameter with changing water flow rate Q and sediment concentration C. The higher the sediment concentration C, the greater the pressure gradient needed to maintain a given flow rate Q, and at a given flow rate, an increase in sediment concentration will tend to cause sediment to settle on the bed as conditions move to the left of the dashed line.

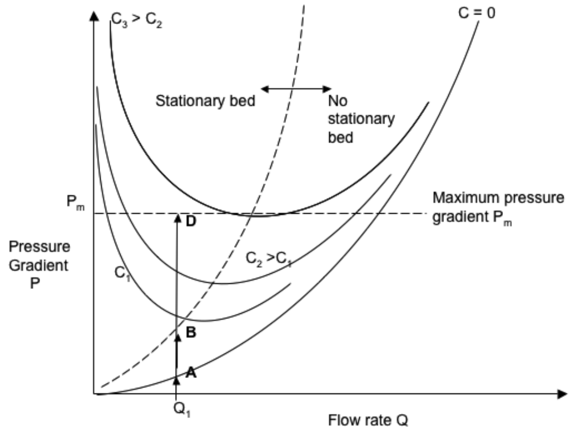

Figure 1 – Pressure gradient P vs water flow rate Q for gravity-driven flow in a pipe with various sediment concentrations C.

In a glacial conduit system, the maximum pressure gradient that can be applied between two points is limited by the ice-surface level, because that is the maximum possible elevation of the water system (Fig. 2); if the water rises above the glacier surface at any point it flows away as free-surface flow without increasing the water pressure in the conduits to which it is connected (and causing flow rate in the conduit to decrease). Thus the maximum pressure that can be applied to any reach of the system is the difference between the glacier snout level and the highest ice level over that reach, and the maximum pressure gradient is that value divided by

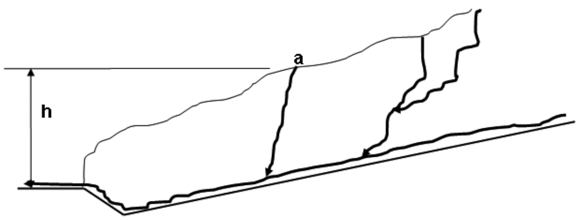

Figure 2 – The maximum pressure difference over the lower reach of the conduit system is h. Any greater pressure difference would cause water to back up and spill out of moulin a.

the length of the reach (here we assume for simplicity a single-conduit system). The limit on pressure gradient is represented in Figure 1 by the horizontal dashed line P_m. Different parts of the conduit system will have different values of P_m. If the water flow rate through a particular part of the system is Q_1, and the sediment concentration is zero, then the flow conditions in the pipe are represented by point A. If bedload sediment now enters the system, conditions move up towards B, but no sediment is deposited on the lower part of the pipe. If the concentration of bedload reaches C_1, point B is reached and sediment begins to be deposited, thus reducing the cross-sectional area of the pipe. The pressure gradient must now increase rapidly to maintain the flow rate Q as C increases. If the sediment input to the reach under consideration now increases to C_2, the pressure gradient must increase to transport this additional sediment, and conditions are now represented by point D. Since no further increase in pressure – and therefore pressure gradient – is possible, *any further increase in sediment input concentration will result in deposition of the extra sediment and reduction in flow rate.* Once sediment starts to be deposited, the cross-section of the conduit decreases, increasing the flow resistance and reducing the flow rate still further, reducing the sediment transport capacity and causing increased deposition. Any conditions above the line P_m will thus lead to conduit blockage.

Since

(i) the water flow rate is independent and determined by melting and/or precipitation;

(ii) P_m depends on the geometry of the glacier and the conduit system, inherited from earlier conditions; and

(iii) C depends on the rate of sediment delivery from an independent upstream reach of the system,

there is in principle nothing preventing such blockages in this natural system. Any system operating at maximum pressure gradient P_m, which receives increased bedload input or whose conduit reduces in area while carrying bedload, *must block*.

Since the conditions under which bedload transport concentrations are high are associated with above-average water flow rates, or to inputs of sediment from the glacier sole or from the subaerial environment, there is again no reason to believe that the conduit system will be capable of transporting substantial concentrations of bedload without blockage.

Bedload processes in glacial conduit systems

Gradient change

The above assumes that the conduit system is uniform in slope and unchanging in cross-section. In reality, neither assumption is true; conduit gradients vary, parts of the conduit system can have negative slope (Davies *et al.*, 2003), and variations in conduit cross-section are common due to unevenness of the bed and differential ice motion. Further, the cross-sections of the system can vary – albeit relatively slowly – in time, due to melting and freezing.

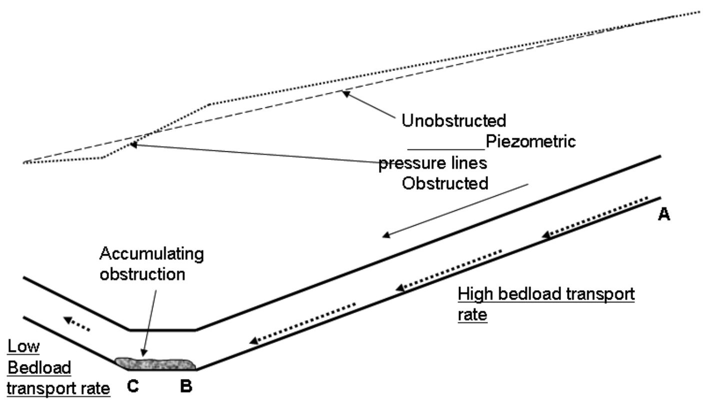

Figure 3 – Sediment accumulation in a conduit reach of decreasing or reversing slope.

Consider a conduit system reach that has varying slope (Fig. 3). As water flows along the steep part of the conduit from A to B, it is able to transport bedload at the rate it is supplied from upstream. Upon reaching the flat section BC, and then the reverse slope section CD, however, the bedload transport capability declines dramatically (ASCE, 1975), because instead of the weight of the sediment assisting the water to transport it, or having no effect on transport apart from friction, the water now has to lift the mass of sediment upwards against gravity. Therefore sediment will accumulate in the vicinity of B and C, causing an obstruction and reducing the flow rate and the pressure gradients from A to B and C to D. This further reduces the flow's ability to move sediment from C to D, in spite of the increased pressure gradient (the dotted line in Figure 3) and causes the obstruction to increase in size at C. The same effect will tend to occur, but less drastically, if the conduit slope reduces instead of reversing; the opposite effect occurs where the conduit gradient increases downstream.

If the bedload contains a wide range of grain sizes, the effect of the rising reach CD may be to cause deposition of all sediment grains larger than a particular size, causing an accumulation of large grains at C and allowing finer grains to proceed through the system. Evidence for such accumulations was provided by Davies *et al.* (2003, Fig. 7) and has also been observed in karst systems (Schroeder and Ford, 1983). Hydraulic lifts in caves (where conduits convey water upwards at a steep angle) are commonly marked by accumulations of exquisitely well-sorted, rounded cobbles (Schroeder and Ford, 1983). Similar deposits are found amongst supraglacial debris on the Mueller Glacier, New Zealand (Kirkbride and Spedding, 1996) and at points where basal streams beneath the Laurentide ice sheet rose over the Niagara escarpment (Kor and Cowell, 1998).

The ability of the conduit to widen by melting at an obstruction due to the increased pressure gradient along the obstruction will tend to offset the above effects, but not necessarily rapidly enough for them to be eliminated. In particular, if the obstruction causes a positive-feedback that rapidly leads to complete blockage of the conduit with heterogeneous sediment, it will take a long time for melting under a high pressure gradient but low flow rate to release the obstruction.

In general, we expect the presence of gradient changes in the subglacial conduit system to make the system more likely to block.

Cross-section non-uniformity

There is no reason to expect that subglacial conduits will be uniform in cross-section geometry and area, so this pipe-flow assumption is not generally valid. The flow behaviour of a non-uniform pipe can be represented by an equivalent uniform pipe

(Webber, 1968), but this is not necessarily true of its bedload transport capacity. In particular, the variation in sediment transport capability of a non-uniform pipe can lead to increased possibility of blockage, particularly when the sediment in transport has individual clasts with intermediate axes greater than about 30% of the minimum conduit minor axis dimension (Davies *et al.*, 2003).

A particular mechanism of cross-section (or even location) change is available when a subglacial conduit has as its invert the sediment bed of the glacier. This then serves as a source of sediment that can be eroded under appropriate conditions, deepening the conduit, particularly if the sediment is unconsolidated (Clarke, 2005). The eroded sediment is then in transport and available for deposition farther downstream.

Obstruction by ice

Partial or complete collapse of conduits is frequently observed at the exit of the glacial drainage system; it is probably more common at this location than elsewhere because of the greater variation of air temperature, the possibility of radiated heat from proximal sediment deposits, and lack of structural support. Collapse of ice within the conduit system provides material that can obstruct flow, but is less likely to do so than bedload sediment because it has an excess specific gravity of about -0.1 compared to +1.65, and ice blocks of all sizes are thus much more easily transported by water than sediment clasts of the same volumes. Further, a partial ice blockage can itself reduce in volume by ice flow or melting in response to the steep local pressure gradient it causes in a conduit. Nevertheless, the large quantity of ice deposited on the outwash fan following high-volume water discharges from glaciers (e.g., Davies *et al.*, 2003) indicates that obstruction of conduits by ice is common.

Obstruction by a combination of ice and bedload sediment can presumably also occur, exhibiting behaviour that is a combination of sediment- and ice-obstruction behaviours.

Occurrence of sediment blockages

A sediment obstruction or blockage occurs when the sediment supply from upstream exceeds the transport capacity of the conduit at a section. At low water flow rates sediment movement is likely to be small; any accumulation will therefore grow slowly, and it is possible that the conduit can evolve rapidly enough by ice-flow or melting to prevent a blockage occurring.

At very high water flow rates the sediment transport capacity of the freely-flowing conduit will be very high due to the steep pressure gradient, and it is unlikely that any sediment deposition will occur (Fig. 1, region to right of dashed line). At intermediate flows, however, to the left of the dashed line in Fig. 1, neither of these conditions applies, and sediment deposition is possible, particularly where the conduit slope decreases. We therefore expect obstructions to develop on the rising limb of outflow hydrographs; the obstructions may then be eroded by later more competent flows or, if they have developed into blockages, by the consequential high pressure gradients. Obstructions developing on the falling limb we would expect to remain until sufficiently high pressures develop to release them – which may be in the next high-flow event – or until melting sufficiently enlarges the conduit. An outburst from Franz Josef glacier described by Davies *et al.* (2003) occurred towards the end of a long-duration storm, and may well have resulted from a blockage during the falling limb.

There is empirical evidence compatible with the concept of sediment blockages of subglacial conduits; for example, Davies *et al.* (2003) invoked sediment blockage as the only acceptable explanation for a *jökulhlaup* at Franz Josef glacier, New Zealand during the final stages of a 3-day flood, and for other reported events there. Warburton and Fenn's (1994) description of events at the Bas Glacier d'Arolla also suggests conduit obstruction and release, associated with large sediment outputs.

Nature of blockage and release

A blockage is by definition an obstruction that makes contact with the roof of the conduit. It may be very permeable, if composed of large clasts; or, if the initial blockage causes ever smaller clasts to accumulate, the blockage may become relatively impermeable. Any permeable blockage clearly allows sediment to be carried to it but inhibits the movement of sediment past it, and so grows longer with time as sediment accumulates upstream. As a blockage grows longer, the boundary friction force increasingly resists its being pushed along the conduit by the pressure force acting on it. The increased pressure gradient across an obstruction generates a downstream force on it, and if this force is large enough the obstruction can move bodily downstream, disaggregate and clear itself. However the pressure force is limited by the elevation of the glacier surface, so in general we would expect a permeable blockage to become less likely to clear as it grows longer.

A blockage may, of course, clear spontaneously if the stresses in the surrounding ice become so great that the ice itself fails. This appears to be the release mechanism for the 1995 outburst from the Franz Josef glacier (Davies *et al.*, 2003) which caused a ~50 m high by ~100 m wide cave to develop at the glacier snout, allowing a very large outflow of water and sediment.

A consequence of blockage or obstruction may be sudden alteration of active conduit network geometry. As suggested by Kavanaugh and Clarke (2000), alternative conduits may be available if the currently active conduits can access them; we suggest that generation (or clearance) of a blockage may contribute to such flow switching.

Effects on basal pressures and glacier behaviour

If we assume that a glacier is not frozen onto its bed, then it seems reasonable to suppose that the water pressure in subglacial conduits is transmitted more or less directly to much of the glacier base and sides, and that the frictional resistance to sliding therefore is influenced by subglacial conduit hydraulics. As we have seen, the distribution of conduit pressures along a glacier is sensitive to variations in conduit system geometry caused by erosion, transport and deposition of bedload sediment. This suggests that the basal pressure distribution can change very rapidly at times of moderate to high subglacial sediment transport. Such pressure changes have been recorded in a number of glaciers, often associated with inferred dramatic changes in conduit system geometry (e.g., Kavanaugh and Clarke, 2000; Warburton and Fenn, 1994) or with surging (e.g., Björnssen, 1998); however, with the exception of the surge-initiation mechanism proposed by Turnbull and Davies (2002), the possible role of bedload deposition and erosion in these changes has not previously been suggested.

In outline, then, if a subglacial conduit becomes obstructed or blocked by sediment it no longer discharges water at the rate it is supplied from upstream, so water accumulates, increasing the pressure at the base of the system until either (a) the additional pressure gradient removes the obstruction or (b) the water surface rises to the level of an alternative outlet – either the glacier surface or an alternative en- or subglacial pathway. If situation (b) occurs, and the water finds its outlet at the glacier surface, then the basal water pressure is H m of water, where H is the depth of the glacier at that section; since ice is less dense than water, the basal ice contact pressure at that section will then be zero. However, just downstream of the obstruction the basal ice contact pressure may be very high, the difference generating large vertical shear stresses in the ice in the vicinity of the obstruction (Fig. 4). This is a possible explanation for the whole-width fissuring of the Bas Glacier d'Arolla noted by Warburton and Fenn (1994) during a large outburst flood. Alack (1974) also describes full-width detachment of the front part of the Franz Josef glacier during heavy rain in the 1930s. The dramatic outburst from Franz Josef glacier, New Zealand in 1995 reported by Davies *et al.* (2003), clearly resulted from high internal water pressures close to the snout, and was explained by blocking of the subglacial conduit in a rising section beneath the snout.

McSaveney and Gage (1968) described rapid fluctuations in surface ice velocity on the Franz Josef glacier, New Zealand, in the form of "kinematic waves" travelling down-glacier. More recently Ekström *et al.* (2003) have interpreted glacial seismic activity as indicating the rapid motion of huge ice masses (in the order of 10^{13} kg) over distances of the order of 10 m in times of the order of 10 s. Velocity fluctuations (accelerations or decelerations) such as these require similarly rapid fluctuations in driving force or basal friction to cause them. Variations in driving force would be reflected by variations in ice surface slope, level or character, which were not reported. It thus appears necessary to postulate variations in basal friction, or basal ice contact pressure, which the mechanisms described above are able to explain by repeated throttling of the glacial drainage system by deposition and erosion of sediment obstructions. The downstream motion of a "slug" of sediment, for example, in the form of (a series of) partial obstructions, would cause a region of low basal ice contact pressure, and thus of low friction, to accompany it downstream through the basal drainage system.

Kavanaugh and Clarke (2000) report that sudden, local, large, short-term fluctuations of basal water pressure in Trapridge Glacier, Alaska, were *followed* shortly by evidence of increased force on ploughmeters and increased detection of microseisms by geophones. It seems reasonable to suggest that the basal pressure increase reduced the basal resistance to motion, transferring stress to the ice which responded mechanically by increased sliding.

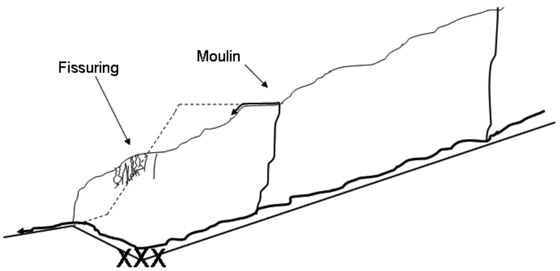

Figure 4 – Piezometric pressure (dotted line) in subglacial conduit system with partial blockage (XXX) in lowest point of system causing high longitudinal pressure gradient.

Conclusion

We have shown that the erosion, transport and deposition of bedload sediment in subglacial conduit systems have the potential to cause significant local short-term variations in conduit cross-section and thereby both the conduit water pressure and the basal ice contact pressure distributions of a glacier, under high water flow and bedload sediment transport conditions. The mechanics of this situation have not been previously examined in this way. The well-established sensitivity of glacier motion to subglacial conduit geometry suggests that these variations will be reflected in similar changes in the sliding velocity of the glacier, such those in as kinematic waves, and may also influence other phenomena such as ice-quakes and *Jökulhlaups.*

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