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The role of meltwater in glacial processes

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Abstract

Water plays a dominant role in many glacial processes and the erosional, depositional and climatic significance of meltwaters and associated fluvioglacial processes cannot be overemphasized. At its maximum extent c. 20,000 years ago, the volume of the Laurentide ice sheet was 33×10^6 km^3 (about the same as the volume of all ice present today on planet Earth). The bulk of this was released as water in little more than 10,000 years. Pulses of meltwater flowing to the Atlantic Ocean from large ice dammed lakes altered thermohaline circulation of the world's oceans and global climate. One such discharge event via Hudson Bay at 8200 years BP released 160,000 km^3 of water in 12 months. Global sea levels recovered from glacial maximum low stands reached at about 20,000 years ago at an average rate of 15 m per thousand years but estimates of shorter term rates suggest as much as 20 m sea level rise in 1000 years and for short periods, rates as high as 4 m per hundred years. Meltwaters played a key role in lubricating ice sheet motion (and thus areal abrasion) across the inner portions of the ice sheet where it slid over rigid crystalline bedrock of the Canadian Shield. The recharge of meltwater into the ice sheets bed was instrumental in generating poorly sorted diamict sediments (till) by sliding-induced shearing and deformation of overpressured sediment and soft rock. The transformation of overpressured till into hyperconcentrated slurries in subglacial channels may have generated a highly effective erosional tool for selective overdeepening and sculpting of bedrock substrates. Some workers credit catastrophic subglacial 'megafloods' with the formation of drumlins and flutes on till surfaces. Subglacial melt river systems were instrumental in reworking large volumes of glaciclastic sediment to marine basins; it has been estimated that less than 6% of the total volume of glaciclastic sediment produced during the Pleistocene remains on land. Fluvioglacial and glaciolacustrine sediments and landforms dominate large tracts of the 'glacial' landscape in North America. The recharge of subglacial meltwater into underlying bedrock and sediment aquifers created transient reversals in the long-term equilibrium flow directions of basinal fluids. With regard to pre-Pleistocene glacial record, meltwaters moved enormous volumes of terrestrial 'glaciclastic' sediment to marine basins and thus played a key role in preserving a record of glaciation, a record otherwise almost entirely lost on land.

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1. Purpose of this paper

This special volume of *Sedimentary Geology* honors an outstanding fluvial sedimentologist and colleague whose work includes seminal observations and facies models of the gravelly deposits of braided rivers and their downstream counterparts (Miall, 1977, 1978, 1983, 1992). These deposits are classically (though not uniquely) associated with glaciers and their sediment-charged, steep gradient meltwater rivers. Given the dominantly fluvial context of this special volume the intent of this paper is to look upstream from the well studied glacier-fed braided rivers themselves and present what is currently known of the habitat of meltwaters on the surface of glaciers (supraglacial), within (englacial) and under ice (subglacial). There is much debate regarding the relative role of strictly 'glacial' versus 'fluvial' processes during glaciation and

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we shall briefly explore the contentious issue of the role played by meltwaters in the origin of classic glacial landforms such as drumlins and sculpted rock surfaces. By and large, fluvial activity dominates at the end of glacial cycle when ice is melting at high rates. This allows glacially influenced marine successions to accumulate in offshore basins with a higher preservation potential than the accompanying terrestrial glacial record.

2. The source of meltwaters

Ice sheets are temporary (geologically) reservoirs of vast volumes of water both liquid and frozen that would otherwise flow to the world's oceans. Not surprisingly, given the fact that ice must eventually melt, glaciofluvial and glaciolacustrine deposits recording the rapid wastage of ice sheets and the reworking of older sediments by meltwaters, often dominate many Pleistocene 'glacial' landscapes in northern Europe and North America. Primary glacial deposits such as till and associated landforms at modern glaciers are extensively reworked by water during climatic warming and ice retreat (Kjaer et al., 2004; Fig. 1). It is worth remembering that initial skepticism of Agassiz's glacial theory in mid nineteenth century North America, was overcome when geologists saw evidence of (and were thus comforted by) water having been involved in the deposition of many glacial deposits; the term *glacio-aqueous* was introduced by Edward Hitchcock in 1841 and opened the door for many committed diluvialists.

Fig. 1. The margin of Scott Glacier in southern Alaska. Meltwaters have almost entirely reworked any primary glacial sediment (e.g., till) and associated landforms and is reworking glaciclastic sediment to the Gulf of Alaska. Though lack of preservation of terrestrial glacial sediments is enhanced here by the confined nature of the valley, estimates suggest that the bulk (>90%) of terrestrial sediment produced by continental ice sheets is transported to marine basins.

2.1. Water and glacier thermal regime

The role of water in the glacial depositional system varies according to regional climate and the corresponding thermal regime of glaciers. *Temperate* glaciers are defined as those whose ice temperatures are close to the melting point throughout. Except for a thin surface layer that freezes during winter (but is removed by melt next summer) ice remains at the pressure melting point. Large volumes of snow are added to the system in winter and are matched by equally large losses of snow and ice to meltwater each summer. These glaciers are characterised by flows of large volumes of ice (high mass transfer) from the accumulation to ablation zones and correspondingly enhanced ice flow velocities. Ice movement is achieved by internal deformation accentuated by the lubricating effect of water film at the ice base that allows basal sliding. Refreezing (regelation) may occur locally at the ice base and by so doing incorporates debris englacially (as a thin basal debris layer; Figs. 2 and 3) but overall the ice base is melting such that flow lines will converge on the bed as a result of basal melt and any englacial debris will eventually make contact with and then abrade the bed. This simple observation has major implications for where the bulk of debris is transported by temperate ice such as characterised the outer margins of most Pleistocene ice sheets. Most debris is transported not within the ice but beneath it (Section 3). This is perhaps one of the most significant findings in glaciology in the last 20 years, one with major implications for the formation of till (Boulton et al., 2001; see below).

Sub-polar glaciers form under more rigorous climates at higher latitudes (or elevations) and have parts of their beds that are thawed but also have patches that remain frozen to the substrate especially in the furthermost upglacier areas (e.g., Bjornsson et al., 1996). Refreezing processes thus take on a more prominent role compared to temperate glaciers and they are able to incorporate larger volumes of englacial debris compared to temperate glaciers. In the case of *polar* glaciers in areas of more severe climate, ice temperatures are below the pressure melting point throughout so that melt is a minimal vehicle of mass wastage compared to direct sublimation or calving. Polar glaciers can move by internal creep in the absence of meltwater lubrication at their base but only slowly; these glaciers are ineffective agents of erosion and may protect their substrates.

It is worth emphasizing here that the above thermal classification is simplistic. Recent work on what has been termed 'glaciohydraulic supercooling' shows that

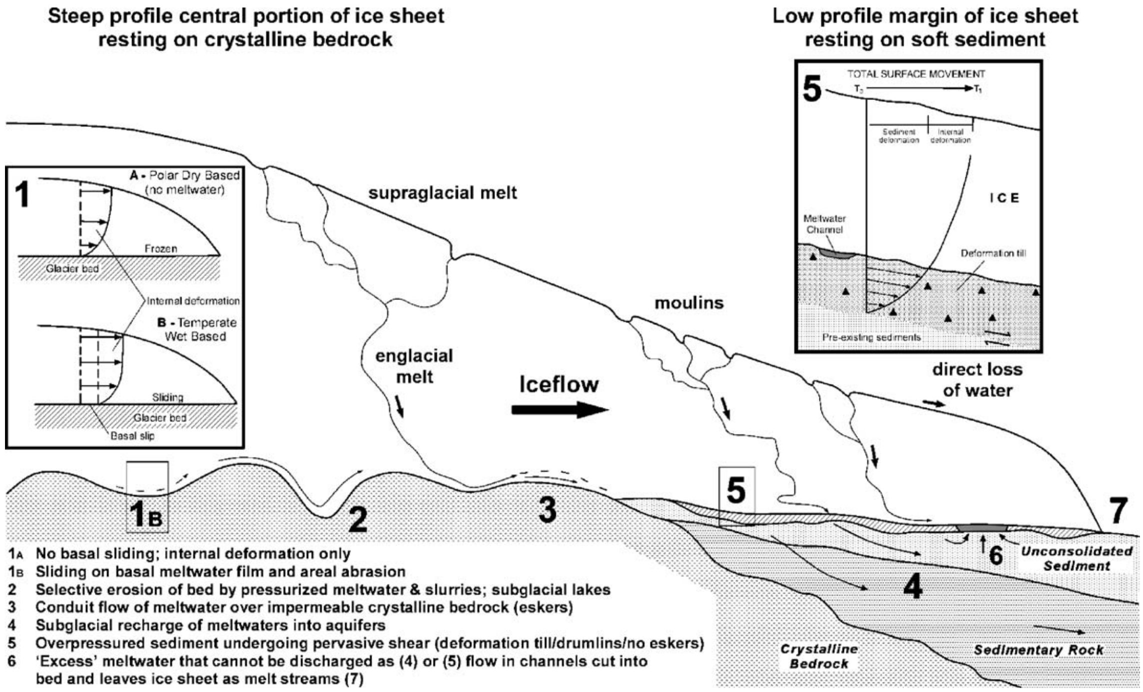

Fig. 2. Simplified summary diagram of sources and flow paths of meltwater through an ice sheet. Not shown are episodic high discharge events (such as jokulhlaups). The generation and movement of till as a deforming layer (5) occurs below the outer margins of the ice sheet; upglacier, local refreezing may incorporate sediment into the ice base (Fig. 3) and be deposited as lodgement or melt-out till (not shown).

freezing of sediment-laden meltwater can result in significant englacial sediment entrainment in temperate glaciers (e.g., Roberts et al., 2002). Polar and sub-polar glaciers too, may contain fast flowing 'ice streams' whose flow is facilitated by deformation of soft wet material below the ice base (Bennett, 2003; Anandakrishan and Winberry, 2004). In addition, Pleistocene and pre-Pleistocene ice sheets underwent a complex spatial and temporal evolution of thermal regime as they thickened and thinned in response to changing climate.

2.2. Meltwater drainage routes through glaciers

Sources of water and their drainage routes on, through and under temperate and sub-polar glaciers are reasonably well known (Fig. 2) but direct observation of much of this system is difficult. Many new data are emerging such as with regard to flow paths and pressures (e.g., MacAyeal, 2005). On those glaciers whose surfaces melt during the summer, complex internal plumbing systems akin to karst systems in fractured limestone, move water to the bed (Clarke, 1996; Fig. 2). This is the largest source of water within the glacier system and large supraglacial rivers (commonly of the meandering type) are a common summer phenomenon on the ablation zones of glaciers below the snowline. These drain into the body of the glacier via vertical shafts (called moulins) or flow between the ice and valley sides in lateral melt stream channels. Smaller amounts of water are produced by the thermal corrosion of meltwater moving in englacial conduits and also by geothermal warming of the ice base and any frictional heat produced during glacial abrasion of the bedrock or sediment over which the ice flows. Some glaciers slide faster in summer than in winter and this is attributed to the availability of surface generated meltwater at the ice base. Excess water that cannot be drained through sediment as groundwater, or which flows over relatively impermeable bedrock, moves through tunnels that may be cut into the bed (called Nye channels) or excavated up into the ice (Rothlisberger channels), eventually flowing out at the ice margin to feed melt streams (Clarke, 1996). Conduits plugged with sediment survive final ice melt as eskers (Brennand, 1994; see Benn and Evans, 1998 for a review). Given the thickness of ice upglacier, the hydraulic head is considerable and powerful artesian-driven water spouts are common at the ice front. Glacier fed rivers exhibit well marked diurnal changes in flow and are also 'flashy'. One or two precipitation-driven floods in the summer melt season accomplish much of the annual sediment transport by glacier-fed braided rivers (Ostrem, 1975). At other

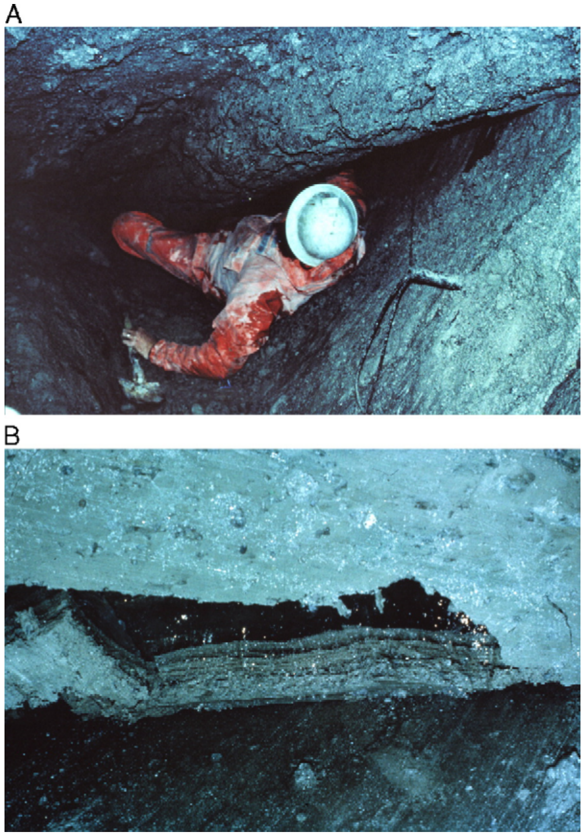

Fig. 3. (A) The dirty base of a temperate glacier (Glacier D'Argentiere, France) resting on striated bedrock. Excavation into the ice base (B) reveals that the debris layer is thin (~30 cm thick) and results from the refreezing of thin water films (and included debris). Basal melting then thins this layer. High sliding velocities that drag dirty ice across the bed create an effective erosional tool (Fig. 6). Most till is created where glaciers rest on sediment beds that are overpressured, deform and shear internally to create a concrete-like diamict facies (deformation till; #5 in Fig. 2).

times, much larger catastrophic discharges (jokulhlaups) occur by the failure of subglacial or ice marginal lakes or more unusually where ice is thawed by volcanic activity (e.g., Mathews, 1947; Smellie and Skilling, 1994; Fowler and Ng, 1996; Maizells, 1997; Bjornsson, 2002; Carrivick et al., 2004).

The Antarctic and Greenland ice sheets together cover a combined area of about 16×10^6 km^2; the total areal extent of all perennial ice is 10% of the planet's total surface area yet knowledge of processes operating at glacier bases is primarily limited to boreholes, broad scale radar imaging and seismic sounding of the beds of ice sheets. The greatest challenge is that sub-ice sheet processes are complex and it is more difficult to draw inferences as to deposits and processes on an ice sheet scale. Direct knowledge of subglacial processes and deposits gained by excavating short tunnels dug into till under the margins of modern glaciers, has been complemented by paleoenvironmental reconstruction of subglacial deposits left by ancient Pleistocene ice sheets (e.g., Boulton, 1996; Hooke et al., 1997; Boyce and Eyles, 2000; Hooyer and Iverson, 2002; Hildes et al., 2004). Nonetheless, there are contentious debates regarding the origin of drumlins as either a glaciofluvial or glacial landform (Shaw et al., 1989; Boulton, 1996; see below), and the genesis of the distinctive hummocky moraine that cover many thousands of square kilometres of the North American plains (supraglacial or subglacial?) (see Clayton and Moran, 1974; Boone and Eyles, 2001).

The known realm of subglacial water has been extended in recent years with confirmation of the existence of large subglacial lakes under the Antarctic Ice Sheet such as Lake Vostok that lies below ice 4 km thick. The total number of such lakes is now about 145 (Priscu, 2005; Siegert et al., in press). Presumably such lakes also existed in deeply eroded portions of the Canadian Shield inundated by the Laurentide Ice Sheet and within similar topographic positions in Scandinavia. How one would recognize the ancient deposits of such lakes is an intriguing question but they may contain lengthy preglacial sediment records that survived being covered by glacial ice. The deeper 'fiord lakes' of western Canada whose bedrock floors are in excess of 1.5 km below the surrounding land surface, are good candidates for preserving such facies and thus for exploration by deep drilling.

3. Meltwater and the generation of subglacial till

Subglacial water plays a key role in generating till. Traditionally geologists thought that ice moved debris as englacial load where debris was incorporated into the base of the glacier by refreezing of basal meltwaters. Until recently, till was considered to result from two principal processes involving the passive in situ melt-out of englacial debris below stagnant ice and lodgement (the plastering of debris held within the moving ice base (Fig. 3) onto the substrate, akin to smearing peanut butter on toast). In contrast, the outer margins of Pleistocene ice sheets flowed over sediment such that the bulk of debris was moved *below* base of the ice sheet. Subglacial debris was transported as part of a so-called 'soft bed' resulting from pervasive deformation of soft sediment under the ice (Boulton, 1996; Iverson et al., 1999). This setting closely resembles a giant slickenside along a fault plane with the attendant formation of gouge. The development of excess pore water pressures, where the supply of water exceeds the permeability of underlying materials, is required and the regelation of water infiltrating into sub ice sediment may allow coupling of the overriding ice to underlying materials (Iverson, 2000). In this fashion, extremely large volumes of poorly sorted debris can be moved subglacially in a few thousand years (Hooke and Elverhoi, 1996; Boulton et al., 2001). The zone of deformation can be likened in a simple conceptual way, to a laterally extensive concrete mixer and indeed, explains the typical concrete-like appearance of till produced by pervasive shear of preexisting sediment and soft rock (*deformation till*). Any significant reduction in pore water pressures will cause the till bed to 'freeze' and cease motion much like a debris flow that is dewatering. Excess water escaping from the till may initiate stream flow and channeling at the ice base (the 'canals' of Clark and Walder, 1994; Fig. 2).

4. Meltwaters and drumlins

Drumlins are elongate streamlined ridges of varying widths, found in swarms of many thousands oriented parallel to the direction of former ice flow. A Canadian novelist Catherine Parr Traill (1850) made one of the earliest descriptions of drumlins in 1850. She wrote that in the Peterborough drumlin field of what is now Southern Ontario they 'lie in regular ridges running from north to south' carved by a 'rushing flood', each ridge being the 'wreck that remained'. Her interpretation of the drumlins and the bouldery till that they are made of was strictly Noachian in keeping with the 'diluvial' notion of her time (her residence in the area was named Mt. Ararat).

The 'megaflood' hypothesis of J. Shaw and colleagues (Shaw, 1983; Shaw and Kvill, 1984; Shaw and Sharpe, 1987; Shaw et al., 1989) arose from observations made in the early 1980s that the cores of drumlins often contain glaciofluvial sediments. This developed into a model that entire drumlin swarms had been generated by catastrophic floods moving as sheet flows under the margin of the ice sheet (Fig. 4A, B). It was proposed that these flows were of sufficient magnitude to carve elongate erosional scoops in the ice base that were then filled with glaciofluvial sediment when the ice margin lowered itself on the bed. In this model, the final drumlin form is a 'cast' resembling the well known 'flute casts' formed at the base of turbidity flows moving over a muddy substrate (Fig. 4C, D). This hypothesis stimulated a new look at drumlins but, in retrospect, was applied uncritically and without recognition of alternative explanations. The source of such waters, the mechanical implausibility of ice margin 'lift off' on the scale and timeframe required, the absence of evidence for the massive outburst floods themselves other than drumlins, the ruler straight form of drumlins compared with meandering flute casts, the inability to explain till cored moraine ridges that often run transverse across drumlin fields and the number of flood events require to explain numerous drumlins swarms, are all flaws in the hypothesis (Benn and Evans, 1998; Clarke et al., 2005). In addition, the model is not supported by observations of modern glacial processes. Drumlins formed during the Little Ice Age expansion of glaciers have been widely exposed by ice retreat since 1900 A.D. (e.g., Fig. 5). These are composed of till with no evidence of the work of floodwater in shaping these landforms. Furthermore, those large floods that have occurred from modern glaciers (such as in Iceland) have not produced drumlins (Bjornsson, 2002) but instead, vast spreads of exceptionally coarse-grained boulder and ice-block strewn outwash gravels and deeply cut channels. Large flood events almost certainly occurred from below the margins of Pleistocene glaciers (in contrast to the sudden release of ice marginal lakes) but there is a general consensus that subglacial floodwaters moving over an unconsolidated bed become channelised forming large conduit flows within 'tunnel valleys' rather than sheet flows.

Discussion and analysis of the megaflood hypothesis, together with the results of recent work on the subsurface sedimentology of drumlins, has confirmed the importance of subglacial 'soft bed' shearing processes in their formation (Boulton, 1996; Hart, 1999; Eyles and Boyce, 1999; Fowler, 2001). Other processes account for the significant volumes of glaciofluvial facies (and other sediments) within drumlin cores. These include overriding of outwash as the glacier advances over and cannibalizes its own frontal deposits, or the activity of subglacial streams. Despite clear evidence of its weaknesses, the megaflood hypothesis still lingers on among a small cadre of geomorphologists (and creation scientists) in Canada.

5. The role of meltwater in glacial erosion

Meltwaters play a significant though as yet poorly quantified part in 'glacial' erosion. Erosion rates in fluvial basins are dependent on topography and climate with wet high mountainous areas having the greatest sediment yields on the order of 1500 tons/km^2/year. Sediment production from glaciated basins is significantly higher by comparison (Hallet et al., 1996). Fast flowing temperate glaciers with high rates of mass

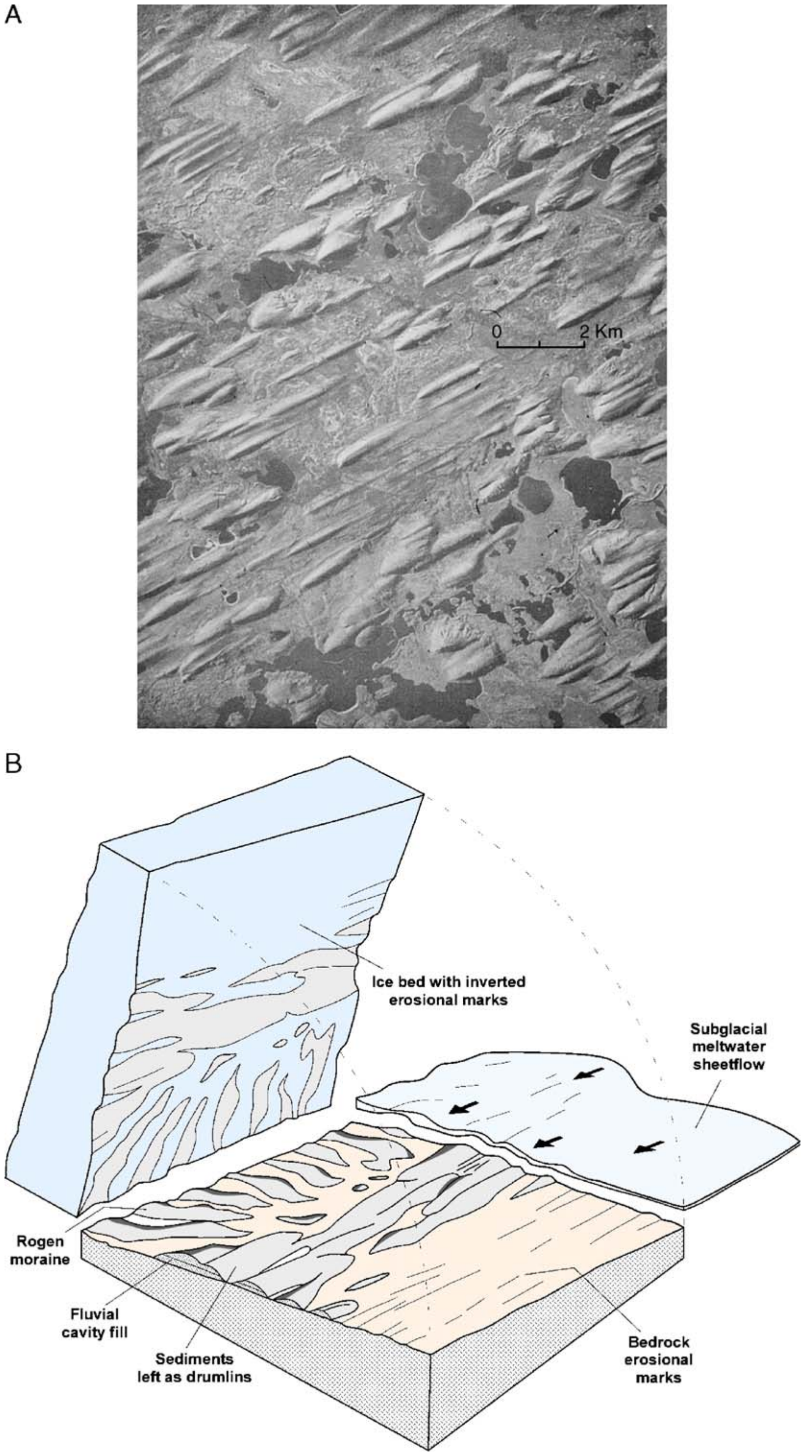

Fig. 4. (A) Portion of Livingstone Lake drumlin field in northern Saskatchewan (National Air Photograph Library of Canada copyright) and (B) fluvioglacial model for drumlins and other subglacial landforms such as Rogen moraines (after Shaw and Kvill, 1984). The basis for this model is not any detailed sedimentologic or hydrodynamic appraisal but simply the perceived similarity between the shape of drumlins and that of sole marks produced by current scour of muds (such as below turbidity currents) and the casts that result when later filled with sand (C, D).

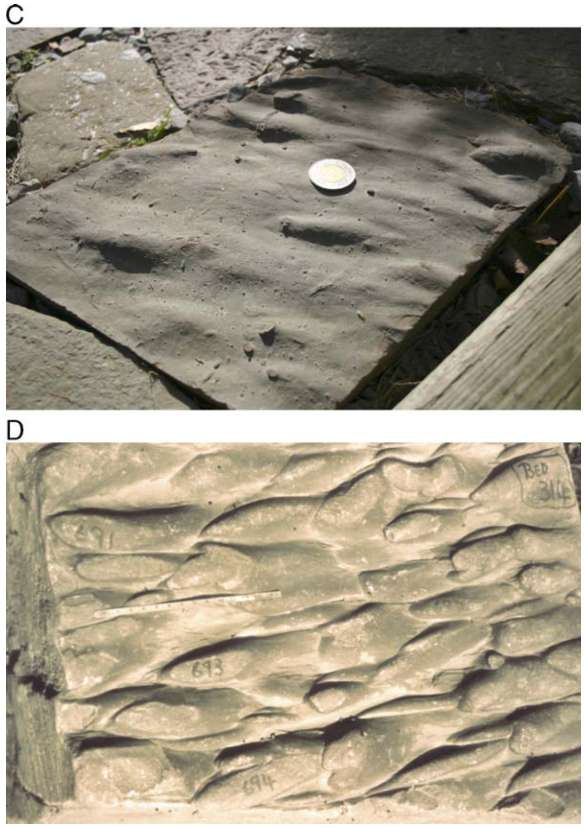

Fig. 4 (*continued*).

transfer located in mountainous areas have the highest yields (as much as 2000 tons/km^2/year; Butt et al., 2001). This is typified by the coastal glaciers of the Gulf of Alaska (Fig. 1) where as much as 5 km thickness of glacially-produced sediment has accumulated in an offshore fore arc basin in the last 5 million years (Lagoe et al., 1993). Polar glaciers on the other hand are much less productive (<40 tons) reflecting the lack of basal sliding and meltwater production. Extrapolation of these rates to Pleistocene ice sheets in mid-continent areas is not straightforward, as the extent and degree of glacial erosion is poorly constrained. In North America, White (1972) argued for deep glacial erosion of the central portion of the Shield by ice sheets based on the supposed glacial origin of Hudson Bay. The latter is instead, a sag basin and was not glacially overdeepened. Others have argued that areal abrasion below ice in mid-continent North America was of limited importance compared to selective erosion along bedrock structures (Sugden, 1978). According to this view, Pleistocene glacial erosion 'averaged' across the Canadian Shield has been minimal (<60 m of vertical lowering in 2.5 million years or a few metres per glacial cycle). This is based on the volume of sediment transported to marine basins and the apparent preservation of large areas of ancient Proterozoic-aged peneplains (e.g., Ambrose, 1964) that are thought to have been largely untouched by glacial erosion. It has to be said here that the age of these surfaces is poorly constrained and at the same time there is steadily increasing evidence for deep pre-Pleistocene weathering of the Shield and the later removal of a thick clayey regolith by ice (Migon and Lidmar-Bergstrom, 2001; Dore et al., 2002). What can be said is that glacial erosion was highly selective and took advantage of bedrock structure to cut deep fiord basins well below sea level, together with overdeepened portions of the Great Lake basins around the periphery of the Shield. The fast flow of ice lobes aligned along topographic lows and lubricated by wet sediment may have been a very effective erosive agent. The use of cosmogenic isotopes for precise dating of exposed bedrock surfaces across the Shield offers great potential for determining ancient glacial erosion rates (e.g., Briner and Swanson, 1998; Colgan et al., 2002).

Fig. 5. Large flute (A) and drumlin (B) made of deformation till (#5: Fig. 2) exposed by the retreat of Saskatchewan Glacier, Alberta.

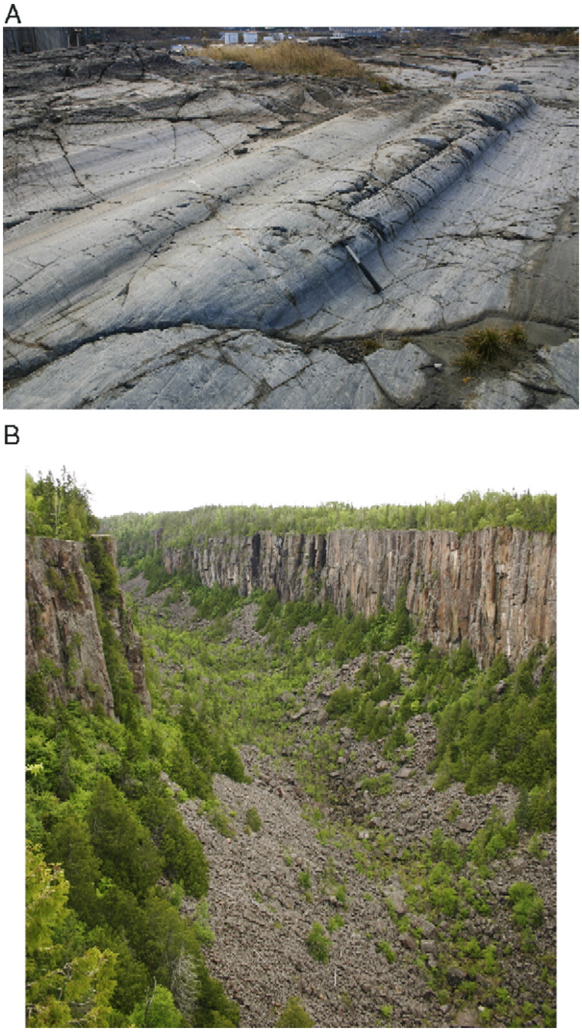

Fig. 6. (A) Glacially sculpted bedrock surface at Sudbury, Ontario. (B) Ouimet Canyon, near Thunder Bay, Ontario, cut by meltwaters. The canyon is 500 m wide and 70 m deep.

In North America, sculpting and grooving of bedrock surfaces is a common feature across the Canadian Shield (Fig. 6A) together with the limestone surfaces that protrude through sediment covers to the south. These forms record glacial abrasion by basal debris being dragged (or jetted) over the bed (e.g., Fig. 3). In addition, they have also been attributed to scouring by high-pressure subglacial water (Kor et al., 1991; Shaw, 1994) in support of catastrophic 'megaflood' events (see above). In fact the erosive capability of fast flowing subglacial waters charged with suspended sediment and coarse bed load is a well-known 'steady state' erosional process below temperate glaciers (Vivian, 1970, 1975). Some pressurized basal meltwater flows likely formed hyperconcentrated slurries capable of cutting grooves in bedrock (Drewry, 1986) and deep canyon-like incisions (Fig. 6B).

Depositional evidence for subglacial conduit flow below the last North American ice sheet is provided by

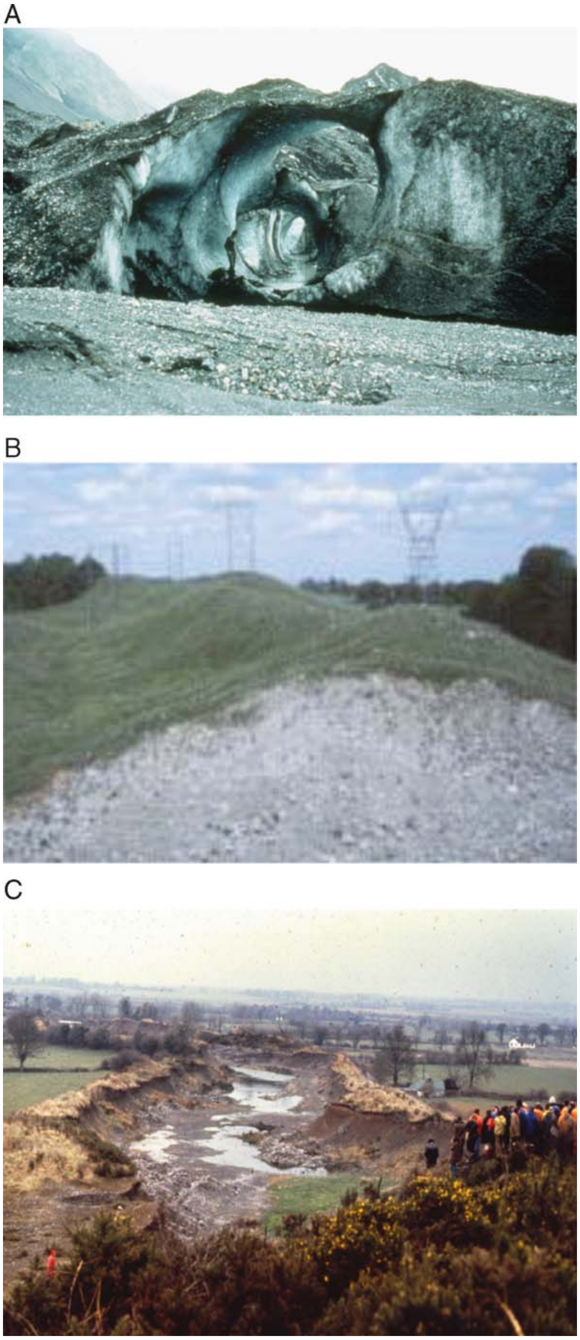

Fig. 7. (A) Englacial conduit at Kviarjokull Glacier, Iceland, figure for scale. Eskers are the sediment-plugged remains of conduits (#3, Fig. 2) and form sinuous ridges built of fluvioglacial sands and gravels (B); in C an esker has been completely excavated for aggegate exhuming the lower part of the conduit floor on which it was deposited.

thousands of eskers (Fig. 7) that extend radially out from ice centres on the Shield. Some are several hundreds of kilometres long (Shilts et al., 1987). Subglacial conduit meltwater flows remove 'excess' meltwater that cannot be drained through the bed as groundwater and cut deep incisions (tunnel valleys; see Boulton et al., 1996; Piotrowski, 1997). Other evidence of subglacial water flows takes the form of channel fills contained within till successions, marked by a wide variety of deposits including 'clots' of debris dropped from the ice base. In parts of northeast England, these permeable sediments under drain the overlying till promoting deeper weathering and alteration of matrix colour. Multiple till units of different colour separated by glaciofluvial deposits had long been thought to record multiple glaciations; recent work suggests that such successions may record spatially adjacent accumulation of till and subglaciofluvial sediment under the ice margin (Eyles et al., 1982; Boyce and Eyles, 2000).

5.1. Chemical erosion by meltwaters

Significant geochemical processes are associated with meltwaters because of the enhanced ability of cold water to dissolve carbonate such as limestone (Fairchild et al., 1994). Pleistocene subglacial meltwaters created Castleguard Cave in the Albertan Rocky Mountains, the largest cave system in Canada with more than 20 km of explored tunnels (Ford, 1983, 1987). Geochemical denudation rates for polar catchments are much lower than for temperate glacierized catchments (see Sharp et al., 1995; Hodson et al., 2000; Wadham et al., 2000 and refs therein) reflecting the high flux of meltwater through the temperate glaciers.

6. Meltwaters and basin fluids

As related above, eskers are the result of englacial and subglacial meltwater conduits being plugged with sediment and thus provide useful information about subglacial drainage routes. Eskers are more prevalent on impermeable crystalline bedrock of the Canadian and Fenno-Scandian shields compared to areas of sedimentary rock. This implies that much subglacial meltwater was lost as groundwater under the outer margins of the ice sheet where it rested on sediment and soft bedrock (e.g., Boulton et al., 1993, 1996; Boulton and Caban, 1995; Section 5). This model has been confirmed in Canada by studies of basinal fluids in the Western Canada Sedimentary Basin (WCSB) where the equilibrium interglacial south to north movement of deep basin brines from high standing areas in the Cordillera were reversed during glaciation. This is because the thickness of the central portions of the ice sheet (3 km) even allowing for significant glacioisostatic depression was sufficient to reverse the interglacial topographic profile. In the WCSB, basin brines are normally characterised by geochemical and isotopic signatures typical of evaporated seawater whereas many modern brine springs indicate dilution by meteoric waters of glacial origin (Grasby and Chen, 2005). Funnel shaped 'hydrodynamic blow outs' formed by the sudden dewatering of glacially overpressured aquifers and evidence of enhanced dissolution of evaporites in the form of collapsed overburden, provide further evidence of subglacial recharge to aquifers (Christiansen et al., 1982; Christiansen and Sauer, 2002). Quantitative hydrogeological modelling of current 'steady state' water flow through areas of thick glacial sediments is a very active area of research in Canada given its applied importance for water resource management in urban areas (e.g., Meriano and Eyles, 2003). The challenge for glacial geologists is to model the dynamic 'transient' conditions that occurred during glaciation as sediments were being deposited subglacially and thick sections of relatively impermeable till began to be built up.

7. Meltwaters, climate and sea level

Oxygen isotope curves from deep-sea cores indicate that rates at which Pleistocene ice sheets first grew and then subsequently decayed were markedly different. The Laurentide Ice Sheet grew over some 80,000 years but disappeared in little more than 10,000 years. During any one glacial cycle, water is withdrawn relatively slowly from the world's oceans but is returned rapidly. Floods from ice dammed lakes along the periphery of the Laurentide Ice Sheet released huge water volumes along the Mississippi, Hudson, Mackenzie and St. Lawrence rivers. These events discharged so much fresh water and fine sediment to the North Atlantic they cooled global climates by disturbing the ocean conveyor belt thermohaline circulation. The largest event occurred at 8200 years BP when a large proglacial lake (Agassiz) spilled out through Hudson Bay to the North Atlantic (Fig. 8). An estimated 160,000 km^3 of meltwater was discharged in 12 months (Clarke et al., 2003, 2004) but see Lowell et al. (2005) for a recent test of this model. It follows that the recovery of eustatic sea levels from the low stand reached at about −150 m by 20,000 years BP, was not constant. Average rates of rise (15 m/1000 years) hide abrupt increases of as much as 20 m/1000 years at or around 12,000 years BP with 'instantaneous' rises of as much as 4 m in 100 years

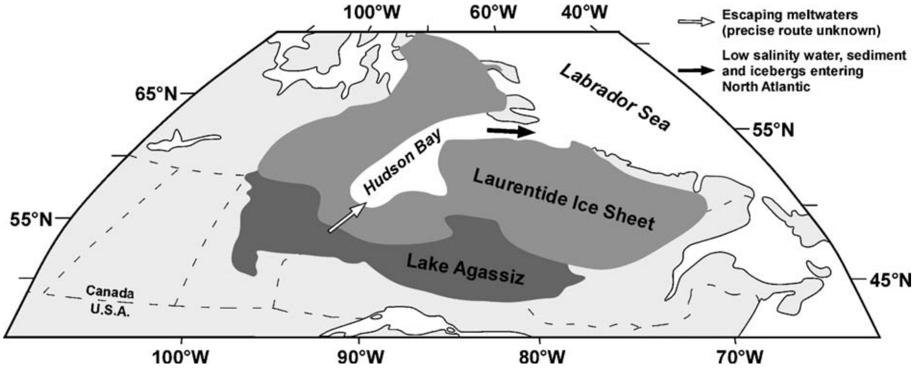

Fig. 8. Schematic representation of the 8200 years BP meltwater flood event triggered by the drainage of Glacial Lake Agassiz into Hudson Bay. It is not known whether floodwaters escaped by flowing beneath the ice or by overtopping, but the oceanographic and climate response is well preserved in ocean sediments.

recording the abrupt escape of meltwaters from large ice dammed lakes onland (Fairbanks, 1989). It is interesting to note that the marine record of the effects of such events is much better constrained then the terrestrial geomorphic evidence of the events themselves; the routes of lake overflows are still poorly known and it has not yet been determined whether the 8200 years BP Agassiz flood event escaped *under* or *over* the ice sheet on its way to Hudson Bay.

8. Discussion and conclusions

Meltwaters play a highly significant, if not dominant, role in 'glacial' processes. Indeed the case could be made for regarding the glacial realm as a cold climate subcategory of the fluvial environment. Ice flow, glacial erosion, sediment transport and deposition are all fundamentally dependent on (and thus controlled by) the availability of meltwaters. In the ancient past, the record of pre-Pleistocene glaciations is selectively preserved in marine successions containing great thicknesses of fine sediment, which give testimony to the delivery of glaciclastic sediment by meltwaters. Meltwaters are the key to glaciers being able to move, erode and deliver sediment; it has been estimated that of the total volume of glaciclastic sediment produced by Pleistocene ice sheets in North America, less than 6% remains on land having been swept into marine basins (see Eyles, 1993, pp. 46–50 for a discussion). Recent models that envisage extremely cold global temperatures (−50 °C) and a permafrozen planet during one or several 'Snowball Earth' events in the Neoproterozoic (Hoffman and Schrag, 2000) ignore this (Allen et al., 2004; Eyles and Januszczak, 2004). The widespread (and voluminous) glacially influenced marine record from this time interval speaks to a normally functioning glacial system where meltwaters (and sediment) were produced by temperate glaciers. Finally, with regard to the future, meltwaters may well dictate the long-term environmental well being of human society in an anthropogenically-warmed global climate. The Antarctic Ice Sheet has a volume of 30×10^6 km^3 equivalent to a eustatic sea level rise of 65 m.

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