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Subglacial drainage by groundwater-channel coupling, and the origin of esker systems: Part 1—glaciological observations

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Abstract

Overall: This work is presented in two parts. *Part I* presents observations on the coupling between subglacial channel flow and groundwater flow in determining subglacial hydraulic regime and creating eskers from an Icelandic glacier that is suggested as an analogue for many parts of Pleistocene ice sheets. *Part II* develops a theory of perennial subglacial stream flow and the origin of esker systems, and models the evolution of the subglacial stream system and associated groundwater flow in a glacier of the type described in Part I. It is suggested that groundwater flow may be the predominant mechanism whereby meltwater at the glacier bed finds its way to the major subglacial streams that discharge water to glacier margins.

Part I: Boreholes drilled through an Icelandic glacier into an underlying till and aquifer system have been used to measure variations in head in the vicinity of a perennial subglacial stream tunnel during late summer and early winter. They reveal a subglacial groundwater catchment that is drained by a subglacial stream along its axis. The stream tunnel is characterised by low water pressures, and acts as a drain for the groundwater catchment, so that groundwater flow is predominantly transverse to ice flow, towards the channel.

These perennial streams flow both in summer and winter. Their portals have lain along the same axes for the 5 km of retreat that has occurred since the end of the Little Ice Age, 100 years ago, suggesting that the groundwater catchments have been relatively stable for at least this period. In the winter season, stream discharges are largely derived from basal melting, but during summer, water derived from the glacier surface finds its way, via fractures and moulins, to the glacier bed, where it dominates the meltwater flux. Additional subglacial streams are created in summer to help drain this greater flux from beneath the glacier, through poorly integrated and unstable networks. Summer streams cease to flow during winter and tend not to form in the same places in the following summer. Perennial streams are the stable component of the system and are the main sources of extensive esker systems.

Strong flow of groundwater towards low-pressure areas along channels and the ice margin is a source of major upwelling that can produce sediment liquefaction and instability. A theory is developed to show how this could have a major effect on subglacial sedimentary processes.

1. Introduction

Melting is widespread at the base of modern glaciers, including the ice sheets of Antarctica and Greenland (Hughes, 1975; Huybrechts, 1986). Surface-derived meltwater readily reaches the bed of valley glaciers through fractures, crevasses, moulins and cavities between the glacier and flanking valley walls (Sharp et al., 1993; Holmlund, 1988; Fountain et al., 2005), and may also penetrate to the beds of ice sheets during the summer melt periods, at least in marginal zones (Reynaud, 1989). Understanding the processes whereby meltwater drains from beneath glaciers is a central problem in glaciology. The drainage system controls water pressures at the ice/bed interface, which is strongly coupled to glacier flow dynamics. Inefficient meltwater drainage beneath a glacier will lead to build up of basal water pressure, a reduction in basal friction and easy movement of the glacier over its bed. In contrast, efficient drainage will drawdown water pressures producing large effective pressures, enhancing

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friction and thereby inhibiting basal decollement. This coupled hydraulic/rheological system is thus a key to understanding many aspects of glacier dynamics and basal processes. Although much glaciological research over the last 30 years has been concerned with it, we are not yet able to generalise about the operation of the system and how it is coupled to the glacier/ice sheet flow system.

It is recognised, however, that there is a major functional distinction to be made between:

(a) Strongly canalised drainage in which large water fluxes are discharged by strongly turbulent flows along subglacial channels in which the water flow draws down water pressure, and in which the water pressure tends to decrease as the water flux increases (Röthlisberger, 1972) and channel pressures are relatively low compared with ice pressures.
(b) Distributed flow systems in which water is drained by a thin film at the ice/bed interface (Weertman, 1972), by systems of linked cavities on irregular bedrock surfaces (Kamb, 1987), by systems of "canals" on subglacial soft sediments (Walder and Fowler, 1994) or by groundwater flow through subglacial materials (Boulton and Hindmarsh, 1987). Because of the relative inefficiency of distributed drainage systems, flow is relatively slow, water pressures are thought to increase as the water flux increases and can be very close to the ice overburden pressure.

Although both systems are known to occur beneath valley glaciers (e.g. Fountain, 1994), only the high water pressures that are characteristic of distributed flows have yet been measured beneath modern ice sheets (e.g. Kamb and Engelhardt, 1991). However, on the assumption that the esker systems that are almost ubiquitous on the igneous and metamorphic rocks of the shield areas formerly covered by Pleistocene ice sheets in mid-latitudes (e.g. UNESCO, 1967–80; Prest et al., 1968) are evidence of former channelised flows (Clark and Walder, 1994), it is clear that the beds of these ice sheets must have been drained in part at least by major channelised flows. These widespread esker systems appear to terminate proximally at the boundary between the shield areas and the fringing zones of Palaeozoic and younger rocks, that also tend to be covered by thick unlithified sedimentary sequences. Clark and Walder (1994), therefore, suggested that a largely channelised drainage regime gave way at this boundary to one dominantly characterised by a distributed drainage system (Piotrowski, 1999, has produced sedimentary evidence of "canals" at a number of sites in this latter area). On the other hand, this outer zone is also characterised by "tunnel valleys" or "tunnel channels", which, although their precise origin remains a matter of debate, are generally believed to be the product of major, channelised subglacial meltwater fluxes.

The principal motivation of this work is to understand the nature and evolution of the drainage systems of ice sheets such as those that have invaded the mid-latitudes of the northern hemisphere from time to time during the Late Quaternary, primarily because of the evidence that their exposed beds give of the drainage processes beneath them. However, our starting point is a study of the drainage system of a modern glacier, Breidamerkurjökull in S.E. Iceland, a broad outlet of the Vatnajökull ice cap, that flows over a thick, unlithified sedimentary stratum, and which we believe to be a better analogue for the extensive sediment-based areas of Pleistocene ice sheets of Europe and North America than narrow, rock-floored valley glaciers. We suggest this for four reasons:

(i) In its terminal 15 km, it flows over a relatively flat plain (Fig. 1b), 20 km wide at the glacier margin, so that the influence of the bounding valley walls are insignificant in the central area of the glacier, and bedrock topography plays little role in controlling the geometry of drainage.
(ii) Bedrock is overlain by a thick sedimentary sequence in which groundwater flow plays an important role in conditioning water pressures at the ice/bed interface.
(iii) Major esker systems occur on the recently deglaciated forefield plain (Price, 1969; Evans and Twigg, 2002), and a valley about 200 m deep and up to 3 km in width (Fig. 1b) extends from the proglacial area to deep beneath the glacier (Boulton et al., 1983; Björnsson, 1996).
(iv) A high regional geothermal flux, up to five times the normal continental rate (Flovenz and Saemundsson, 1993), enhances the rate of basal melting, such that even in winter, when there is little or no supraglacial water available to penetrate to the bed, significant cumulative subglacial water discharges can be maintained. An enhanced geothermal melt rate of up to $4.5 \times 10^{-8}\,\mathrm{m\,s^{-1}}$ from a flowline length of 50 km from a subglacial catchment 2 km across can deliver a winter stream discharge of about $4.5\,\mathrm{m^3\,s^{-1}}$. It can thus provide an analogue for large ice sheets, where even low rates of basal melting along very long (order 1000 km) flowlines can generate significant winter discharges at the terminus, contrasting with small glaciers with similar geothermal fluxes and melting rates, but flowlines of order 10 km that generate winter fluxes 5–10 times less.

In Part I of the paper, we report field observations of the hydraulic system beneath the glacier. In Part II, we use these to develop a theory of large-scale drainage evolution on the bed of such a glacier and use the theory to simulate the time-dependent evolution of its drainage system. In a later paper we apply the theory to explore the structure and character of the hydraulic system beneath the last European ice sheet and to infer some of its glaciological properties.