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An ice-sheet scale comparison of eskers with modelled subglacial drainage routes

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ABSTRACT

Eskers record the signature of channelised meltwater drainage during deglaciation providing vital information on the nature and evolution of subglacial drainage. In this paper, we compare the spatial pattern of eskers beneath the former Laurentide Ice Sheet with subglacial drainage routes diagnosed at discrete time intervals from the results of a numerical ice-sheet model. Perhaps surprisingly, we show that eskers predominantly occur in regions where modelled subglacial water flow is low. Eskers and modelled subglacial drainage routes were found to typically match over distances of <10 km, and most eskers show a better agreement with the routes close to the ice margin just prior to deglaciation. This supports a time-transgressive esker pattern, with formation in short (<10 km) segments of conduit close behind a retreating ice margin, and probably associated with thin, stagnant or sluggish ice. Esker-forming conduits were probably dominated by supraglacially fed meltwater inputs. We also show that modelled subglacial drainage routes containing the largest concentrations of meltwater show a close correlation with palaeo-ice stream locations. The paucity of eskers along the terrestrial portion of these palaeo-ice streams and meltwater routes is probably because of the prevalence of distributed drainage and the high erosion potential of fast-flowing ice.

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1. Introduction

Eskers are slightly sinuous ridges composed of glaciofluvial sand and gravel that are deposited in subglacial, englacial, or supraglacial drainage channels (e.g., Banerjee and McDonald, 1975; Brennand, 2000; Storrar et al., 2014a). They can extend for tens to hundreds of kilometres (taking into account small gaps), reach in excess of 50 m in height, and are typically arranged roughly parallel to each other (e.g., Prest et al., 1968; Banerjee and McDonald, 1975; Shilts, 1984; Shreve, 1985a,b; Aylsworth and Shilts, 1989; Clark and Walder, 1994; Boulton et al., 2009; Storrar et al., 2014a,b). Eskers may therefore provide vital information about channelised drainage. This is significant because observations from modern ice sheets reveal the important role of water in lubricating the bed and facilitating rapid ice flow (Bartholomew et al., 2011; Sundal et al., 2011). In particular, the configuration of the subglacial drainage network and how it evolves to accommodate water inputs is critical (e.g., Budd et al., 1979; Alley et al., 1986; Iken and Bindschadler, 1986). Two end-member drainage configurations are typically envisaged (e.g., Walder and Fowler, 1994): (i) an efficient channelised system commonly associated with lower water pressures, lower ice velocities, and higher water discharges; and (ii) an inefficient distributed system (e.g., linked cavities, braided canals, and porous till layer) commonly associated with higher water pressures, higher ice velocities, and lower water discharges. However, because of the difficulties in directly observing the drainage of water at the bed of ice masses, we have a limited understanding of the distribution and geometry of the subglacial drainage network and a lack of data at the spatial and temporal scales necessary to constrain or test subglacial hydrological models (e.g., Hewitt, 2011; Werder et al., 2013).

Presently, investigating eskers located under contemporary ice sheets is physically difficult. Thus the imprint of eskers recorded on the bed of former ice sheets has a clear advantage over data from contemporary ice sheets because we can directly observe the expression of meltwater drainage over large spatial scales. However, despite the use of eskers to reconstruct and constrain ice-retreat histories (e.g., Dyke and Prest, 1987; Margold et al., 2013), very few studies have investigated their pattern at the ice-sheet scale (Aylsworth and Shilts, 1989; Clark and Walder, 1994; Storrar et al., 2014a,b). This is because it is not known whether eskers form synchronously in long conduits (cf. Brennand, 1994) or if they represent a time-integrated signature of drainage deposition throughout deglaciation (e.g., Banerjee

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and McDonald, 1975; Shilts, 1984; Dyke and Dredge, 1989; Kleman et al., 1997; Hooke and Fastook, 2007). Consequently, the extraction and interpretation of information about where they form in relation to subglacial water generation and ice dynamics is difficult.

A new approach to understanding the pattern of eskers is to compare their distribution and orientation with numerical models of subglacial meltwater drainage at discrete intervals throughout deglaciation. In this study our aim is to compare the expression of eskers on the bed of the former Laurentide Ice Sheet (LIS) with subglacial drainage routes predicted from the results of a numerical ice sheet model. This builds on previous work that has compared eskers and hydraulic gradient routes at glaciers (e.g., Syverson et al., 1994), but represents the first attempt to compare modelled drainage with eskers at the ice-sheet scale and at discrete time intervals.

2. Methods

2.1. Mapping esker networks

This paper uses 3749 interpolated eskers (mostly >2 km long) mapped by Storrar et al. (2013). The crestlines of esker ridges were mapped from Landsat 7 Enhanced Thematic Mapper (ETM) + imagery of Canada, which has a resolution of ~30 m and ~15 m in the panchromatic band. Eskers were typically mapped at a scale of 1:40,000 and were identified based on the criteria set out by Margold and Jansson (2012). Shorter eskers (<2 km long) were more difficult to identify in Landsat imagery. Comparison with mapping from aerial photographs suggests that ~75% of eskers were identified and that 81% of those missed are <2 km long (Storrar et al., 2013).

To enable the effective comparison of eskers with modelled subglacial drainage routes, we used the interpolated esker data set produced by Storrar et al. (2014a). This data set was derived by interpolating a straight line (over short distances in the majority of cases) between aligned esker ridges that appear genetically related (i.e., formed in the same conduit) and merging with the mapped ridges to produce a single esker. It was produced to fill gaps that may have resulted from fragmentary deposition, post-depositional erosion or, submergence beneath lakes and is therefore thought to give a better indication of where the esker-forming conduits were located (Storrar et al., 2014a). We refer to this data set throughout the paper simply as 'eskers'.

2.2. Modelling subglacial meltwater drainage

Subglacial meltwater drainage was modelled using the method outlined in Livingstone et al. (2013a,b). Hydraulic potential surfaces (ϕ) of the LIS were calculated from the Shreve equation (Shreve, 1972):

$$\phi = \rho_w g h + \rho_i g H \tag{1}$$

where ρ_w is the density of water; ρ_i is the density of ice; g is the acceleration of gravity; h is the bed elevation; and H is the ice thickness. We calculated the subglacial drainage routes every 500 years for the period between 12 and 7 ka BP, which encompassed the largest retreat distance (hundreds of kilometres) during deglaciation and was over the predominantly hard crystalline bedrock on the Canadian Shield (see Dyke, 2004). The bed elevation data (h) were constructed at 5-km resolution from Gebco_08 digital elevation model (DEM), and the palaeo-ice surfaces and palaeo-bed topographies (corrected for isostasy) were derived from ice-sheet model output from one of the higher probability runs (LT9927) from the ensemble-based analyses of the LIS using the three-dimensional (3D) Glacial Systems Model (GSM) (Tarasov et al., 2012). The GSM includes a 3D thermomechanically coupled shallow ice-sheet model, bed-thermal model, visco-elastic bedrock response, and coupled surface drainage and pro-glacial lake solver. The GSM is calibrated against a large set of observational constraints, including geological and geomorphological evidence and is able to reproduce ice stream locations and ice-margin positions (Stokes and Tarasov, 2010; Tarasov et al., 2012). The LT9927 is from the subensemble of runs used by Livingstone et al. (2013a,b). Their analysis showed that the modelled distribution of subglacial lakes and major drainage routes is a robust result achieved irrespective of the model run used from this subensemble (see Fig. 8 from Livingstone et al., 2013a,b). Given this and the time required for analysing each run, we base our analysis just on LT9927 for this study. The 1° longitude by 0.5° latitude resolution model output was regridded at 5-km cell size. Subglacial drainage routes (i.e., the direction that water flows) were constructed from the hydraulic potential surfaces, using simple GIS routing tools as per Livingstone et al. (2013a,b). Basal meltwater production (cm/y) generated from the GSM was used to weight flow accumulation down subglacial drainage routes. Each cell was given an accumulative basal meltwater value of all the cells that flow into it, hereafter referred to as the 'modelled subglacial flow concentration'. Output cells with a high flow accumulation represent a drainage route along which subglacial meltwater is concentrated. To allow for basal meltwater production caused by likely subgrid topographic variation, we set a minimum basal meltwater output (0.1 cm/y) in regions of the bed where the temperature was 0 to −2 °C below pressure melting point. Meltwater may also enter the subglacial system from supraglacial sources, although these are not reproduced here because of the difficulty of modelling this process. Thus, we use basal meltwater production simply to indicate where meltwater is likely to concentrate rather than suggesting that all meltwater is necessarily *produced* at the bed.

2.3. Comparison of eskers and modelled subglacial drainage routes

To our knowledge, a comparison between the pattern of eskers and modelled subglacial drainage routes has not been previously undertaken at the ice-sheet scale. Thus, in this analysis, we explore first-order relationships between the location and orientation of eskers and modelled drainage routes (Fig. 1). Approaches for these two comparisons are described below.

2.3.1. Spatial conformity of eskers and modelled subglacial flow concentration

Output cells with a high subglacial flow concentration indicate regions where large volumes of meltwater are routed, and these represent potential meltwater conduit locations (Fig. 1A). These should correspond to esker locations, as this is where Röthlisberger channels are theorised to form (e.g., Röthlisberger, 1972; Shreve, 1972).

To investigate how the spatial pattern of eskers relates to the routing of subglacial meltwater beneath the LIS, we compared modelled subglacial flow concentration with the esker pattern at 500-year time slices from 12 to 7 ka BP (Fig. 1A). At each time slice we extracted flow concentration values of all cells that contain eskers and all cells covered by ice in the model domain. We also identified cells that match with the spatial extent of palaeo-ice stream locations recently compiled in Margold et al. (2015) and cells that match the terrestrial portion of the palaeo-ice sheet bed (i.e., where the mapping was carried out) (Storrar et al., 2013). The probability density function of modelled subglacial flow concentration was calculated for each of the variables extracted and results displayed as a ratio between each probability density function and the probability density function of all the cells covered by ice in the model domain. Statistical significance was evaluated with a binomial test.

To further identify any spatial match between eskers and major subglacial drainage routes we used a flow concentration of >20 cm/y to identify potential meltwater conduit locations (Fig. 1A). A value of 1 was assigned to cells where the flow concentration exceeded 20 cm/y and a value of 0 to those that did not (see also Livingstone et al., 2013b). This was done for every time slice and the values (0 s and 1 s) then summed together to produce a composite map of potential meltwater conduits and their persistence over time.

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