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Towards a morphogenetic classification of eskers: Implications for modelling ice sheet hydrology

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A R T I C L E I N F O

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A B S T R A C T

Validations of paleo-ice sheet hydrological models have used esker spacing as a proxy for ice tunnel density. Changes in crest type (cross-sectional shape) along esker ridges have typically been attributed to the effect of changing subglacial topography on hydro- and ice-dynamics and hence subglacial ice-tunnel shape. These claims assume that all eskers formed in subglacial ice tunnels and that all major subglacial ice tunnels produced a remnant esker. We identify differences in geomorphic context, sinuosity, cross-sectional shape, and sedimentary architecture by analysing eskers formed at or near the margins of the last Cordilleran Ice Sheet on British Columbia's southern Fraser Plateau, and propose a morphogenetic esker classification. Three morphogenetic types and 2 subtypes of eskers are classified based on differences in geomorphic context, ridge length, sinuosity, cross-sectional shape and sedimentary architecture using geophysical techniques and sedimentary exposures; they largely record seasonal meltwater flows and glacial lake outburst floods (GLOFs) through sub-, en- and supraglacial meltwater channels and ice-walled canyons.

General principles extracted from these interpretations are: 1) esker ridge crest type and sinuosity strongly reflect meltwater channel type. Eskers formed in subglacial conduits are likely to be round-crested with low sinuosity (except where controlled by ice structure or modified by surging) and contain faults associated with flank collapse. Eskers formed near or at the ice surface are more likely to be sharp-crested, highly sinuous, and contain numerous faults both under ridge crest-lines and in areas of flank collapse. 2) Esker ridges containing numerous flat-crested reaches formed directly on the land-surface in ice-walled canyons (unroofed ice tunnels) or in ice tunnels at atmospheric pressure, and therefore likely record thin or dead ice. 3) Eskers containing macroforms exhibiting headward and downflow growth likely record flood-scale flows (possibly GLOFs where a lake can be inferred). These conclusions suggest that esker crest type, sinuosity and geomorphic context, when understood along with sedimentary architecture, largely reflect formational position with respect to the ice-surface. Reconstructions of ice sheet hydrology need to account for variation in esker morphology because basing hydrodynamic inferences on the presence or absence of an esker alone ignores encoded differences in water source, supply, flow magnitude and frequency, and conduit position.

1. Introduction

Models of ice dynamics fundamentally rely on an accurate representation of ice-sheet hydrology (e.g., Schoof, 2010; Bartholomaus et al., 2011; Colgan et al., 2011): efficient subglacial drainage systems (channelized meltwater) tend to moderate ice flow whereas distributed subglacial systems tend to enhance ice flow (e.g., Sole et al., 2011; Sundal et al., 2011). Eskers record the casts of ice-walled meltwater channels, and as such esker spacing has been invoked as a proxy for subglacial ice tunnel density in validations of models of paleo-glacier hydrology (e.g., Boulton et al., 2009). In addition, changes in cross-sectional shape along esker ridges within the mapped extents of paleo-ice sheets have typically been attributed to the effect of changing subglacial topography on hydro- and ice-dynamics, and hence subglacial ice tunnel shape (Price, 1966; Shreve, 1985). However, both claims assume that eskers formed in subglacial ice tunnels and that all major subglacial ice tunnels produced a remnant esker. Research linking esker ridge morphology, sedimentary architecture, and geomorphic context to

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esker genesis and hence meltwater channel type (i.e. sub-, en-, or supra-glacial, or ice-walled canyon) rarely accompanies such claims, though such inferences could be inaccurate if underlying assumptions are found to be wrong.

Field research has shown that eskers may form in subglacial ice tunnels, englacial conduits, and supraglacial channels, as well as in ice-walled canyons, and may terminate subaerially or subaqueously (e.g., Price, 1966; Bannerjee and McDonald, 1975; Fitzsimons, 1991; Gorrell and Shaw, 1991; Syverson et al., 1994; Warren and Ashley, 1994). Past efforts to associate esker ridge morphology with esker genesis have generally focused on ridge cross-sectional shape (crest type) and the longitudinal topographic profile of the ridge crestline. Crest type has been associated with meltwater channel type: (1) sharp-crested ridges have been observed to form from the meltout and subsequent let-down of supraglacial channel sediments (e.g., Price, 1966; Syverson et al., 1994) but have also been associated with downslope water flow within subglacial ice tunnels (Shreve, 1985); (2) flat-crested ridges have been associated with water flow at atmospheric pressure, where non-pipe-full conditions maintain triple-point pressure (Hooke, 1984), and also with upslope water flow (Shreve, 1985). Given previous work has provided little quantification of cross-sectional shape (in many areas robust quantification awaits the availability of higher resolution digital elevation models (DEMs)), and has rarely provided clear definitions for cross-sectional shape classes (e.g., Burke et al., 2012b, 2015), comparisons between studies are fraught with uncertainty. Similarly, ridge crestline longitudinal topographic profile has also been associated with meltwater channel type: upslope segments have been attributed to pipe-full flow in subglacial ice tunnels (Bannerjee and McDonald, 1975), and englacial conduit or supraglacial channel sediment may meltout (be lowered) onto adverse topographic slopes (Price, 1966; Syverson et al., 1994).

In this paper we pursue whether a combined consideration of esker morphometric variables and geomorphic context may be diagnostic of esker genesis and meltwater channel type by exploring the relationships between esker geomorphic context, morphology, sedimentary architecture and genetic inference. To this end we map the distribution, and summarize the geomorphic context and morpho-sedimentary character (from ground penetrating radar (GPR) and electrical resistivity tomography (ERT) surveys, and limited exposure sedimentology) of eskers formed at or near the margins of the last Cordilleran Ice Sheet on British Columbia's southern Fraser Plateau (Fig. 1). Results lead to a morphogenetic esker classification, which aids in reconstruction of local patterns of ice sheet retreat, and is a step towards improving the use of eskers as verification for numerical ice sheet models that include channelized meltwater flow.

2. Study area and previous research

Work was carried out on a ~7800 km^2 area of the southern Fraser Plateau, confined by the Fraser River on the west, and the Bonaparte Lake region in the east (Fig. 1). The southern Fraser Plateau is located between the Coast and Columbia mountain ranges in south-central BC and averages around 1175 m asl (Fig. 1B, Holland, 1976; Geobase®). The relatively low relief plateau surface is primarily composed of Miocene basalt flows which have generally in-filled basement topography (Andrews et al., 2011); intrusive igneous and sedimentary rocks outcrop or subcrop in a third of the study area. Regional mapping suggests bedrock is overlain by $\leq$ 20 m of till (Andrews et al., 2011), but study area outcrops consistently revealed typical thicknesses of 1–2 m. Glaciofluvial sediments (eskers, kames) and glaciolacustrine sediments and landforms (including deltas) are also common (Plouffe et al., 2011; Perkins et al., 2013; Perkins and Brennand, 2014). The location of the study area was chosen based on its accessibility, preliminary work on glacial history (Tipper, 1971a, b, c; Plouffe et al., 2011) and the identification of a concentration of eskers, including one of the longest eskers in south-central BC (the Chasm esker, Tipper, 1971b; Burke et al., 2012b).

Regional ice flow history, reconstructed from the orientation of streamlined forms, meltwater channels, till geochemistry, pebble lithologies and supplemented by striae orientations (Tipper, 1971b; Plouffe et al., 2011), indicates that during Marine Isotope Stage 2 ice flowed onto the plateau from source areas in the Coast Mountains to the west and the Cariboo Mountains (a sub-range of the Columbia Mountains) to the east, eventually coalescing somewhere west of the Fraser River and forcing flow north and south (Heginbottom, 1972; Tipper, 1971b, c; Plouffe et al., 2011). During deglaciation, the ice is thought to have regionally stagnated because of a rapid rise in equilibrium line altitude (Fulton, 1991), with minor marginal backwasting across the interior plateaus (Fulton, 1967; Clague and James, 2002). This concept is supported by the presence of hummocky topography interpreted as ice-disintegration moraine (Fulton, 1967) and a perceived lack of recessional moraines across the plateau surface (Tipper, 1971a). However, reconstructions of nearby glacioisostatic tilt (Johnsen and Brennand, 2004) and late-glacial ice-marginal lake evolution on the southern Fraser Plateau suggest a systematic southeast to northwest pattern of ice margin retreat, accompanied by regional thinning (Perkins et al., 2013; Perkins and Brennand, 2014).

To date, beyond basic mapping of esker distribution (crestlines) from topographic data and aerial photographs (Tipper, 1971b; Bednarski, 2009; Huscroft, 2009; Plouffe, 2009a, b), detailed investigation of eskers on the southern Fraser Plateau has been limited to the exploration of two genetically different eskers: the Chasm esker (Burke et al., 2012b), and the Young Lake esker-like ridge (Perkins et al., 2013), both recording formative meltwater flow to the southeast.

2.1. Chasm esker

Chasm esker (Fig. 1B) is a ~32 km long, discontinuous (93% continuity, with relatively long gap lengths generally >100 m), low sinuosity (1.09), largely round-crested, single ridge with long upslope segments, set within a broader canal (meltwater corridor) landsystem (Burke et al., 2012a, b; Network 29 Table S1). This landsystem is interpreted to have formed subglacially during a glacial lake outburst flood (GLOF) with esker formation occurring as flow collapsed from broad canal flow into a smaller ice tunnel (Burke et al., 2012a, b). Round-crested segments of the esker are interpreted to have formed largely through vertical and headward accretion at local depocentres (separated by zones of non-deposition) under pressurized flow in the absence of a free water-plane (Burke et al., 2012b). The presence of ridge-scale macroforms (observed in geophysical profiles) and overall lack of fine materials (inferred from geophysical profiles and confirmed in sedimentary exposures) within round-crested segments indicates rapid deposition of esker materials associated with high magnitude flows. Multi-ridged segments are genetically associated with zones of glaciological structural weakness, likely where canal roof collapse resulted in the formation of significant crevassing (Burke et al., 2012b). Flat-crested segments dominated by vertical accretion suggest that local unroofing of the ice tunnel occurred within thin ice in the final stages of esker formation (Burke et al., 2012b). The majority of faulting and slumping observed was at landform flanks and likely relates to post-depositional processes (flank collapse as ice walls melted). A few short (<1 km) ridges connect to the trunk ridge at acute angles. Most are likely discontinuous multi-ridged segments rather than true tributaries.