Quaternary Science Reviews 115 (2015) 50–77

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

The role of sediment supply in esker formation and ice tunnel evolution

Matthew J. Burke [a], Tracy A. Brennand [a, *], Darren B. Sjogren [b]

[a] Department of Geography, Simon Fraser University, 8888 University Drive, Burnaby, BC, V5A 1S6, Canada
[b] Department of Geography, University of Calgary, 2500 University Drive, Calgary, AB, T2N 1N4, Canada

A R T I C L E I N F O

Article history:
Received 18 August 2014
Received in revised form
23 February 2015
Accepted 25 February 2015
Available online 29 March 2015

Keywords:
Esker
Ice tunnel
Glacial hydrology
Ground-penetrating radar (GPR)
Electrical resistivity tomography (ERT)
Geomorphology
Sedimentary architecture

A B S T R A C T

Meltwater is an important part of the glacier system as it can directly influence ice sheet dynamics. Although it is important that ice sheet models incorporate accurate information about subglacial meltwater processes, the relative inaccessibility of contemporary ice sheet beds makes direct investigation challenging. Former ice sheet beds contain a wealth of meltwater landforms such as eskers that, if accurately interpreted, can provide detailed insight into the hydrology of former ice sheets. Eskers are the casts of ice-walled channels and are a common landform within the footprint of the last Laurentide and Cordilleran Ice Sheets. In south-western Alberta, esker distribution suggests that both water and sediment supply may have been important controls; the longest esker ridge segments are located within meltwater valleys partially filled by glaciofluvial sediments, whereas the shortest esker ridge segments are located in areas dominated by clast-poor till. Through detailed esker ridge planform and crest-type mapping, and near surface geophysics we reveal morpho-sedimentary relationships that suggest esker sedimentation was dynamic, but that esker distribution and architecture were primarily governed by sediment supply. Through comparison of these data with data from eskers elsewhere, we suggest three formative scenarios: 1) where sediment supply and flow powers were high, coarse sediment loads result in rapid deposition, and rates of thermo-mechanical ice tunnel growth is exceeded by the rate of ice tunnel closure due to sediment infilling. High sedimentation rates reduce ice tunnel cross-sectional area, cause an increase in meltwater flow velocity and force ice tunnel growth. Thus, ice tunnel growth is fastest where sedimentation rate is highest; this positive feedback results in a non-uniform ice tunnel geometry, and favours macroform development and non-uniform ridge geometry. 2) Where sediment supply is limited, but flow power high, the rate of sedimentation is less than the rate of thermo-mechanical ice tunnel growth. Here the ice tunnel enlarges faster than it fills with sediment and its evolution is independent of sedimentation, resulting in more uniform ice tunnel geometry. In these cases esker architecture is dominated by extensive vertical accretion of tabular units and ridge geometry is more uniform. 3) Where sediment is truly supply-limited the sedimentation rate is negligible regardless of water supply and, like scenario 2, ice tunnel growth is independent of sediment deposition, forming a relatively uniform ice tunnel (or eroding the bed). Because meltwater flows transport few gravel clasts the ice tunnel is not completely filled with gravel and, instead, saturated and pressurized diamicton or bedrock (if deformable) from beneath the surrounding ice is “squeezed” into the relatively low pressure ice tunnel during waning flow (or after ice tunnel shutdown), resulting in deformation of limited gravels deposited within the ice tunnel and a landform cored with diamicton or deformed bedrock, and with a relatively uniform ridge geometry. Our data demonstrate that an esker map is a minimum map of ice-walled channel location and that continued detailed investigation of morpho-sedimentary relationships is essential to gaining a complete picture of esker forming processes. Validating the morpho-sedimentary relationships identified in south-western Alberta (and other areas) with a larger data set may allow improved remote predictive esker mapping over larger areas and inferences to be made about spatial and temporal variations in esker depositional environments and ice tunnel evolution.

* Corresponding author. Tel.: +1 778 782 3617; fax: +1 778 782 5841.
E-mail address: tabrenna@sfu.ca (T.A. Brennand).

http://dx.doi.org/10.1016/j.quascirev.2015.02.017

1. Background and rationale

Given that evolution of the subglacial hydrologic system can directly influence ice dynamics, it is important that ice sheet models incorporate accurate information about the timescales and the processes responsible for ice tunnel evolution. However, the relative inaccessibility of contemporary ice sheet beds makes direct investigation of subglacial hydrologic systems challenging (Fricker and Scambos, 2009). Former ice sheet beds contain a wealth of glaciofluvial landforms such as eskers that, if correctly interpreted, can provide detailed insight into the hydrology of former and contemporary ice sheets. Eskers, typically defined as ridges of stratified sand and gravel, are the main depositional signature of channelized meltwater flow on, within or beneath ice masses (Banerjee and McDonald, 1975) and record the location of ice-walled channels on former ice sheet beds. Consequently, eskers have been used to infer former ice sheet dynamics (e.g., Shilts, 1984; Aylsworth and Shilts, 1989; Clark and Walder, 1994; Brennand, 2000; Storrar et al., 2014) and to test numerical models (e.g., Boulton et al., 2009). However, much debate remains as to the processes responsible for esker formation (Cummings et al., 2011) and, although recent work has shown that the glacial hydrologic system is never in steady state (e.g., Gray, 2005; Wingham et al., 2006; Fricker et al., 2007; Bell, 2008; Stearns et al., 2008; Bartholomaus et al., 2011), and that eskers may actually record relatively short lived and dynamic events (e.g., Brennand, 1994; Burke et al., 2008, 2010, 2012a; Cummings et al., 2011), numerical models have typically assumed steady state esker formation (e.g., Hooke and Fastook, 2007; Boulton et al., 2009). Detailed work on glacial lake outburst flood (GLOF) eskers at contemporary glaciers has demonstrated that the balance between water supply and sediment supply drive esker formation (Burke et al., 2008, 2010). These observations are echoed in the landform record and suggest that dynamic esker deposition is fundamentally controlled by variations in ice tunnel geometry (accommodation space) and sedimentation rate (Brennand, 1994; Brennand and Shaw, 1996; Burke et al., 2012a). Over the short timescales of transient events often recorded in eskers (Shulmeister, 1989; Brennand, 1994, 2000; Brennand and Shaw, 1996; Cummings et al., 2011), ice tunnel geometry is a balance between growth by frictional melting and mechanical excavation, and ice tunnel closure through sedimentation, rather than ice creep (Burke et al., 2012a). It is imperative that numerical models are consistent with the landform record, thus they should incorporate both the transient conditions, as well as seasonal drainage patterns (Burke et al., 2012b). However, most investigations of eskers have focused on regions containing the largest examples and the largest examples within regions (Shilts, 1984; Brennand, 1994; Burke et al., 2008, 2010, 2012a; Cummings et al., 2011; Storrar et al., 2014) where there was both a ready supply of meltwater (Brennand, 2000; Storrar et al., 2014) and sediment (Brennand, 2000). The lack of large eskers on the Prairies has resulted in only limited investigation of these landforms (Stalker, 1960), yet understanding what controlled their architecture and apparent regionally deranged distribution (Brennand, 2000) could provide further insight into the fundamental controls on esker formation. The assertion that esker distribution in North America was primarily substrate controlled (Clark and Walder, 1994; Boulton et al., 1996) is clearly insufficient to explain the presence of 506 esker ridge segments in south-western Alberta (Fig. 1). The suggestion that meltwater supply controlled the presence of the longest eskers on the Canadian shield (Brennand, 2000; Storrar et al., 2014), fails to address what controlled the distribution of the eskers in the western Canadian sedimentary basin. It is only through investigation of these smaller esker systems, coupled with our knowledge of their larger counterparts, and observations from contemporary ice masses that a unifying theory of the controls on esker formation can be achieved.

In this paper we combine detailed geomorphic and geophysical data from four eskers in south-western Alberta in order to assess the controls on their formation and distribution. Because these eskers have distinct geomorphic characteristics and depositional settings we compare their morpho-sedimentary characteristics to identify the controls on their variability. Through comparison of these data with detailed morpho-sedimentary investigations of eskers elsewhere, we suggest models for esker formation that provide insight into the major controls on the evolution of the subglacial hydrologic system at the ice tunnel scale and, ultimately, take a step closer to a unified understanding of the controls on esker formation.

1.1. Regional setting

The plains of southern Alberta are situated on south-west dipping Tertiary and Cretaceous aged sandstones and shales that thin eastward from the foothills of the Rocky Mountains. This bedrock is overlain by a carapace of glacial material, which, due to the friable nature of local bedrock, typically has a fine-grained texture, particularly in areas overlaying Cretaceous shales (Pawluk and Bayrock, 1969). These sediments record the coalescence of ice flowing eastward from the Cordilleran Ice Sheet and ice flowing westward from the Laurentide Ice Sheet (Jackson et al., 2011). These flows converged and deflected toward the south-southeast across the plains of southern Alberta (Klassen, 1989; Evans et al., 2008), reaching a maximum extent about 20–21 ^{14}C ka BP (Dyke et al., 2002). This southerly ice flow and its associated meltwater have generated a wealth of glacial landforms including mega-flutes, mega-lineations, tracts of smoothed terrain, moraines, meltwater channels, eskers, and buried valleys (e.g, Sjogren and Rains, 1995; Munro and Shaw, 1997; Sjogren et al., 2002; Evans et al., 2008, 2012). Although till is often thin and fine grained, it thickens at large moraine complexes where multiple units are stacked (Evans et al., 2008). Together these sediments and landforms have been assigned to landsystems associated with rapid ice flow (Evans, 2000; Evans et al., 2008; Ó'Cofaigh et al., 2009), or inferred to record meltwater erosion (Rains et al., 1993; Shaw et al., 1996). Eskers in south-western Alberta range in length, but the two longest eskers (Strathmore and Clear Lake eskers) are located within broad meltwater valleys (Fig. 1) that are orientated northwest-southeast and probably occur downflow of ice-dammed lakes (St-Onge, 1972). Despite the plethora of eskers in south-western Alberta (Shetsen, 1987, 1990; Evans et al., 2008) they have received little detailed attention, probably due to their relatively small size (making identification in aerial photographs and on digital elevation models (DEMs) difficult) and lack of major sediment exposures.

2. Methods

2.1. Landform mapping and quantification

We mapped esker ridge segment crestlines, esker system geomorphology, meltwater valley walls and the geomorphology of meltwater valley fill in a GIS. Esker crestlines and meltwater valley walls were mapped as polylines using LiDAR-derived DEMs (15 m postings, vertical and horizontal accuracies of 0.3 m and 0.5 m, respectively; AltaLIS, 2014) with multiple hillshade illuminations. We used sub-regional patterns to differentiate eskers from moraines and used elevated linear breaks in slope to delineate meltwater valley walls. Meltwater valleys typically contain underfit