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Terminal zone glacial sediment transfer at a temperate overdeepened glacier system

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ABSTRACT

Continuity of sediment transfer through glacial systems is essential to maintain subglacial bedrock erosion, yet transfer at temperate glaciers with overdeepened beds, where subglacial fluvial sediment transport should be greatly limited by adverse slopes, remains poorly understood. Complex multiple transfer processes in temperate overdeepened systems has been indicated by the presence of large frontal moraine systems, supraglacial debris of mixed transport origin, thick basal ice sequences, and englacial thrusts and eskers. At Svínafellsjökull, thrusts comprising decimetre-thick debris-rich bands of stratified facies ice of basal origin, with a coarser size distribution and higher clast content than that observed in basal ice layers, contribute substantially to the transfer of subglacial material in the terminal zone. Entrainment and transfer of material occurs by simple shear along the upper surface of bands and by strain-induced deformation of stratified and firnified glacier ice below. Thrust material includes rounded and well-rounded clasts that are also striated, indicating that fluvial bedload is deposited as subglacial channels approach the overdeepening and then entrained along thrusts. Substantial transfer also occurs within basal ice, with facies type and debris content dependent on the hydrological connectedness of the adverse slope. A process model of transfer at glaciers with terminal overdeepenings is proposed, in which the geometry of the overdeepening influences spatial patterns of ice deformation, hydrology, and basal ice formation. We conclude that the significance of thrusting in maintaining sediment transfer continuity has likely been overlooked by glacier sediment budgets and glacial landscape evolution studies.

1. Introduction

Elucidation of the mechanisms and pathways of sediment transfer in glacial systems is necessary because the efficacy of basal sediment transfer modulates rates of subglacial erosion and patterns of landscape evolution (e.g. Alley et al., 2003; Swift, 2011; Egholm et al., 2012; Cook and Swift, 2012). In addition, glacial sedimentary deposits are key to understanding ice dynamics and thermal regime (and hence palaeoclimate) in Quaternary and ancient glacial systems (e.g. Evans, 2003; Hambrey and Glasser, 2012). Challengingly, transfer within glacial systems occurs via a complex and varied array of pathways reflecting different entrainment sources and processes. These pathways may include basal transport within till (e.g. Alley et al., 1997) or basal ice layers (e.g. Lawson, 1979; Hubbard and Sharp, 1993; Sharp et al., 1994; Knight, 1994; Knight et al., 1994; Sugden et al., 1987) and in englacial debris bands (e.g. Knight, 1987, 1994; Hubbard et al., 2004; Swift et al., 2006). The number and type of active pathways influences the overall capacity of sediment transport within the system, the volume and nature of material in transport, and the

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character of deposits and landforms.

The terminal zones (i.e. snout areas) of many temperate, non-surging glacier systems in southeast Iceland, notably Svínafellsjökull and Kvíárjökull, exhibit locally high supraglacial debris loads, exposures of debris-rich englacial and basal ice, and extensive arcuate frontal moraine systems. Supraglacial and proglacial debris characteristics at these glaciers is indicative of mixed transport from diverse (including fluvial and subglacial) pathways (e.g. Spedding and Evans, 2002; Swift et al., 2006; Bennett and Evans, 2012; Lukas et al., 2013). Debris emergence has been observed to occur via the melt-out of thrusts (Swift et al., 2006), 'channel fills' (i.e. englacial eskers) (Spedding and Evans, 2002), and debris-rich basal ice (Cook et al., 2007, 2010, 2011a). The abundance of fluvial material in glacial transport has been attributed to deposition of fluvial bedload within terminal overdeepenings (Spedding and Evans, 2002; Swift et al., 2006), whilst extensive exposures of debris-rich basal ice have been attributed to freeze-on of sediment-rich subglacial water as it ascends the adverse slopes of overdeepenings (Cook et al., 2007, 2010; Larson et al., 2010).

Terminal depositional materials and processes are strongly influenced by glacier structure (e.g. Evans, 2009; Bennett and Evans, 2012) and the distribution and volume of different basal ice types (e.g. Cook et al., 2011b). However, our understanding of the processes of debris entrainment by glacier ice and the development of debris-bearing ice facies and structures remains far from complete. Notably, the scope of many studies has been limited to the study of particular entrainment or transfer processes in isolation from their wider glaciological context, and from other processes within the same glacial system that may be spatially or genetically related. Further, it is rarely possible to observe entrainment processes at first-hand, meaning interpretation of the origin of englacial and basal facies and structures relies on inference from largely descriptive analyses using process-identification criteria that remain subject to debate (cf. Hubbard et al., 2009; Moore et al., 2010).

It is within the above context that we present evidence for complex, geomorphologically important terminal zone sediment transfer pathways at Svínafellsjökull in Iceland (Fig. 1). We describe transverse englacial debris-rich bands (Fig. 2) that contribute substantially to sediment transfer at the terminus, supplementing transfer in thick sequences of debris-rich stratified and dispersed facies basal ice (cf. Cook et al., 2007, 2010, 2011a). We present new physical analyses of debris band and basal ice exposures and sediments that provide novel insight into the geography and environments of their formation. From our observations, we propose that the overdeepened bed, which produces high longitudinal deviatoric stress and limits subglacial drainage system efficiency, results in transfer of locally high volumes of basal material of fluvial and subglacial origin in (1) englacial thrusts and (2) varied basal ice facies that reflect the hydraulic connectivity of the bed.

2. Field site and background

Svínafellsjökull (Fig. 1) is a temperate valley glacier that descends via a prominent icefall from the Oræfajökull icecap. Below the icefall, the tongue occupies an overdeepened basin situated behind an arcuate frontal moraine system (Fig. 1a, c), and well-developed band-type ogives are the dominant glacier structure. The terminus position has demonstrated little change since 1945 (Fig. 1c) and is presently situated on the adverse slope of a large frontal moraine system, where it upholds a series of minor ice-contact lakes (Fig. 1a). The subglacial topography of Svínafellsjökull (Fig. 1c) has been derived from limited point survey radar survey undertaken in 1998–2006 (Magnússon et al., 2012).

Stratified debris-rich basal ice and anchor-ice terraces have been observed at many glaciers in southeast Iceland (Swift et al., 2006; Cook et al., 2007, 2010; Larson et al., 2010), all of which terminate on adverse slopes. Anchor-ice and stratified basal ice have physical characteristics similar to those at Matanuska Glacier, Alaska, that arise from glaciohydraulic supercooling of subglacial waters (Lawson et al., 1998). Larson et al. (2010) found that stratified basal ice samples from eight glaciers in southeast Iceland, including Svínafellsjökull (their Fig. 5F), contained thermonuclear-derived radioactive ^{3}H and was enriched in heavier isotopes (in δ^{18}O by ~2.4‰ and in δD by ~12‰) relative to subglacial water emerging from vents. These observations indicated that stratified ice was younger than the englacial ice and was consistent with open-system freezing of supercooled subglacial waters (cf. Alley et al., 1998; Creyts and Clarke, 2010). Cook et al. (2007, 2010), however, identified five distinct subfacies of stratified basal ice Svínafellsjökull, only two of which were found to be consistent with supercooling. These two accounted for 42% of the stratified facies exposed at Svínafellsjökull and an estimated 83% of the stratified facies debris flux.

Englacial debris bands and dispersed facies basal ice have also been observed in southeast Iceland (e.g. Swift et al., 2006; Evans, 2009; Cook et al., 2011a). At Kvíárjökull, ~8 km to the southeast of Svínafellsjökull, Swift et al. (2006) observed that isotopic and sedimentary characteristics of debris bands were consistent with the thrusting of stratified basal ice to the glacier surface. Drawing on previous research showing that ogive formation is associated with transfer of basal material to the glacier surface along folds or thrusts (e.g. King and Ives, 1956; Goodsell et al., 2002; Swift et al., 2006; Cook et al., 2011a), Swift et al. (2006) concluded that band-type ogives had been reactivated by longitudinally compressive flow (cf. Moore et al., 2010) created by the adverse slope of Kvíárjökull's terminal overdeepening. Cook et al. (2011a) subsequently proposed that dispersed facies ice at Svínafellsjökull originated from strain-induced deformation and mixing of englacial (i.e. meteoric) ice with ogive-origin debris-band ice during travel in the basal zone of the glacier.

Work at Kvíárjökull indicates that deposition of material out of fluvial transport as channels enter overdeepenings could contribute significantly to the englacial and supraglacial debris loads of glaciers in the region. Spedding and Evans (2002) observed the melt-out of fluvial debris from channel-fills (i.e. englacial eskers) that indicated the presence of overdeepening-spanning englacial conduits. These have subsequently been documented by Bennett and Evans (2012) and Phillips et al. (2017). Swift et al. (2006) further observed the melt out of mixed subglacial and fluvial debris from englacial debris bands, implying thrusts were entraining fluvial materials deposited at the glacier bed. Our observations at Svínafellsjökull indicate similar complexity of sediment sourcing and a similarly large subglacial-to-supraglacial sediment flux in the terminus zone (e.g. Fig. 2).

3. Methods

Fieldwork was conducted in August 2005 and 2007 and in April 2015. Debris-bearing ice sequences and structures were observed and sampled at the glacier margin (where unobstructed by frontal lakes) and along three longitudinal (i.e. flow-parallel) transects (positioned where margin and glacier surface accessibility permitted) (Fig. 1a). Extensive crevassing of the terminus provided near-vertical, approximately flow-parallel views of englacial and basal ice structure. Basal and englacial ice facies and structures were characterised following Lawson (1979), including thickness, mean crystal diameter, debris distribution and concentration, and appearance, including the nature of internal layering and debris disposition (cf. Cook et al., 2011a). Structural information, including