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Submarginal debris transport and till formation in active temperate glacier systems: The southeast Iceland type locality

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ABSTRACT

Exhaustive sedimentological analysis of freshly exposed subglacial surfaces and moraines in southern Iceland provides diagnostic sedimentological signatures of: a) debris transport pathways through active temperate glacier snouts; and b) till production in subglacial traction zones dominated by deforming layers. Three till end members are recognised based on stratigraphic architecture: 1) thin and patchy tills over eroded bedrock; 2) single push moraines and complexes; and 3) overridden moraines or outwash fans. Typical till thicknesses are 0.10–1.40 m, with each till relating to a deformation event driven by the seasonally tuned processes of glacier sub-marginal shearing, freeze-on, squeezing and bulldozing. Clast form trends demonstrate progressive modification towards mature forms in subglacial traction zones with till being clearly differentiated from scree and glacifluvial deposits. Clast macrofabric strengths are variable, rarely matching those of laboratory shearing experiments, except where obviously lodged clasts are abundant. They also consistently record former glacier flow directions. But localized variability is introduced by bedrock protuberances, cavity infill, clast interference and freshly imported plucked clasts. Within tills, macrofabrics strengthen from lower (B horizon) to upper (A horizon) tills but at the outer edges of sub-marginally thickening till wedges or push moraines, seasonally-driven cycles of squeezing/flowage, freeze-on/melt-out and bulldozing give rise to a range of clast macrofabric strengths as well as superimposed deformation signatures. This reflects two extremes of till emplacement including the more mobile, flowing and often liquefied matrixes in push/squeeze moraines and, in contrast, the lodgement, deformation and ploughing at the thin end of sub-marginal till wedges.

1. Introduction and rationale

The glacial geomorphology and sedimentology of the forelands of the piedmont glacier lobes in southern Iceland are well established as modern analogues for active temperate glacial landsystem signatures in the palaeoglaciological record (e.g. Price, 1969; Eyles, 1979, 1983; Boulton, 1986; Russell et al., 2001, 2006; Evans and Twigg, 2002; Evans, 2005; Evans et al., 2009, 2016a; 2017a; b; Bennett et al., 2010; Bennett and Evans, 2012; Bradwell et al., 2013; Evans and Orton, 2015; Chandler et al., 2016a; b). The well preserved subglacial surfaces and latero-frontal moraines that characterize these forelands are ideal for the sampling of glacigenic debris in order to assess: a) debris transport pathways through active temperate glacier snouts; and b) the sedimentological signature of glacier bed conditions associated with subglacial deformation and other till production processes. Hence processes, specifically direct glacial sediment (till) production and emplacement, can be confidently related to form or sedimentological signatures, providing Quaternary palaeoglaciologists with diagnostic criteria with which to identify ancient tills.

A number of previous studies around the receding snouts of temperate glaciers have elucidated the patterns of debris transport pathways in glacial systems (Matthews and Petch, 1982; Benn, 1989; Evans, 1999; Spedding and Evans, 2002) by using intensive sampling of clast forms along latero-frontal moraines as a surrogate for glacigenic modification of debris down-glacier flowline. This demonstrated that the moraines contain a mixture of passively and actively transported debris, the ratio of which varies according to distance down-moraine; more angular, slabby and elongate clasts,

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typical of passive glacial transport, at the upper ends of lateral moraines gradually give way to less angular and more blocky clasts, typical of active transport, in frontal moraines. Thereby a spatial pattern of clast form characteristics on recently deglaciated forelands has been used to infer the diminishing input of passively transported clasts from valley sides towards the glacier centre-line, where subglacially transported and abraded debris, in the form of stoss-and-lee or bullet-shaped clasts with surface wear or striae, gradually becomes more dominant (Boulton, 1978). This down-glacier modification of clasts is a surrogate specifically for abrasion in the basal traction zone, a process that has been quantified by Lliboutry (1994) and MacGregor et al. (2009) to be an exponential change from angular to "fully rounded" clasts between the 400 and 4000 m points along a glacier's centre line. However, the localized subglacial incorporation of debris that occupied the foreland prior to glacier advance can significantly increase the percentage of rounded and blocky clasts in a sample collected from frontal moraines, thereby diluting the subglacial abrasion signature with an inheritance signal, especially in areas of widespread glacifluvial deposits (e.g. Evans, 2000; Evans and Twigg, 2002; Lukas et al., 2013). In contrast, the quarrying of fresh blocks from bedrock protuberances that bridge the subglacial deforming layer can introduce anomalously angular material to down-glacier till deposits (Evans et al., 2016b).

This clast form signature is part of the sedimentological imprint of temperate glaciation, manifest in the various characteristics of subglacial tills, including granulometry, fabric and internal structure, which together are increasingly being employed to infer former glacier bed conditions. In the Icelandic setting, till sedimentology associated with active temperate glaciers has been reconciled with subglacial observations on deforming substrates (cf. Boulton and Hindmarsh, 1987; Benn, 1995) but has been, and is increasingly being related to more localized conditions associated with substrate inheritance/till overprinting (Evans, 2000; Evans and Twigg, 2002; Evans et al., 2016b), glacitectonic disturbance and clastic dyke intrusion (van der Meer et al., 1999; Evans and Twigg, 2002; Le Heron and Etienne, 2005), push moraine formation (Sharp, 1984; Boulton, 1986; Chandler et al., 2016a; b) and seasonal changes to sub-marginal thermal regimes (Krüger, 1993, 1994, 1995, 1996; Evans and Hiemstra, 2005). From this research we now appreciate that the subglacial to sub-marginal footprints of former glacier margins, in the Icelandic setting represented by the sediment-landform imprints of the recently deglaciated Little Ice Age forelands, record an integrated signature of till production by temperate glacier processes. The architecture of this footprint has been described as a marginal-thickening wedge (Evans and Hiemstra, 2005; cf. Eyles et al., 2011), which is represented in the landform record by push/squeeze moraines (Boulton, 1986; Krüger, 1993, 1994; Evans and Twigg, 2002; Chandler et al., 2016a; b). This broad scale architecture has been explained by Boulton (1996) as a result of the operation of a strongly coupled ice/deforming bed interface, which leads to the production of an erosional subglacial zone beneath the accumulation area and the advection of deforming layer sediments through the ablation zone towards the glacier snout. Notwithstanding the localised influences introduced by bed roughness, a range of other processes also operate in concert with subglacial deformation beneath temperate glacier snouts to produce up-ice erosional zones and outer depositional zones a few hundred metres wide, including net adfreezing, supercooling, debris-rich ice thickening by thrusting, folding and overriding, and the concentration of subglacial fluvial sediments (cf. Boulton, 1987; Alley et al., 1997; Evans, 2018 and references therein). The outermost limit of this depositional zone is characterized by increasing sediment availability and the concomitant production of marginally thickened glacigenic sediment sequences. In terms of till production this is manifest in the gradual cessation of subglacial processes such as lodgement, ploughing and deformation, increasing volumes of melt-out debris and the initiation of ice-marginal squeezing, bulldozing and seasonal cycles of till slab freeze-on and melt release (cf. Price, 1970; Krüger, 1996; Evans and Twigg, 2002; Evans and Hiemstra, 2005; Chandler et al., 2016a; b).

Clast macrofabrics from Icelandic tills have been employed alongside textural characteristics and internal structures to formulate diagnostic sedimentological criteria for different styles of subglacial sediment deformation and lodgement (Benn, 1995; Evans and Hiemstra, 2005). However, these field data have been difficult to reconcile with laboratory based experiments aimed at the simulation of subglacial shearing (Evans et al., 2006; Iverson et al., 1996, 1997, 1998, 2008; Evans, 2018 and references therein). Specifically, despite the development of a "steady state fabric" (S_1 eigenvalues > 0.78) at shear strains of 7–30 in laboratory experiments (Iverson et al., 2008), field sampling of Icelandic till fabrics yields relatively weak S_1 eigenvalues ranging from 0.44 to 0.74 even though a bed deformation origin implies that shear strains should be in excess of 100. By separating out the macrofabrics of unequivocally lodged boulders, which are predictably strong (0.77–0.81), from the more weakly aligned sub-boulder sized clasts in subglacial traction tills, Evans and Hiemstra (2005) and Evans et al. (2016b) have demonstrated that the weaker S_1 eigenvalues likely reflect perturbation of the deforming matrix and smaller clasts in the leeside pressure shadows of the boulders (cf. Kjær and Krüger, 1998; Carr and Rose, 2003). The study of multiple till stacks by Evans et al. (2016b) demonstrates also that superimposition of tills can result in the overprinting of deformation styles but not necessarily the strengthening of existing clast macrofabrics. A representative sample of strain indicators from modern till assemblages created at monitored glacier beds (e.g. Icelandic piedmont lobes typified by Breiðamerkurjökull; Boulton and Hindmarsh, 1987; Boulton et al., 2001) is therefore required in order to ensure a set of diagnostic field criteria for subglacial traction till identification in the ancient geological record, even though strain magnitude cannot be measured by such data (cf. Clarke, 2005; Iverson et al., 2008).

Detailed above are the reasons why the sedimentology of contemporary sub-marginal till wedges, recorded either in single push moraines/till wedges (i.e. continuous annual active recession) or in till stacks (i.e. composite push moraines/till wedges of stationary snouts), is critical not only to deciphering former subglacial deformation signatures in the traction zones of active temperate glacier snouts but also assessing the role of debris modification versus inheritance by subglacial processes in such settings. Hence the aims of this study are to quantify, firstly, the impact of glacial transport pathways on debris as it moves through an active temperate glacier snout and, secondly, the depositional signature of subglacial deformation and other till production processes. From this we compile a set of diagnostic sedimentological criteria that relate till production and emplacement to process in the type area for subglacial deforming layers.

In order to assess the role of these process-form relationships, the sedimentology of seven local till sites, each representing a variant of the active temperate glacial landsystem but related to glaciers of similar size and morphology, is presented here (Fig. 1). The first aim of quantifying the impact of glacial transport pathways on debris characteristics can be achieved only in settings where latero-frontal moraines exist and hence can be used as a surrogate for down-glacier modification of clasts (cf. Matthews and Petch, 1982; Benn, 1989; Evans, 1999, 2010; Spedding and Evans, 2002). In only one south Iceland foreland can this be effectively executed, that of Fláajökull, and therefore this site is used exclusively to evaluate the principles of down-glacier debris