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Subglacial till formation: Microscale processes within the subglacial shear zone

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ABSTRACT

This was a study of subglacial deformation till genesis from a modern temperate glacier, at Skálafellsjökull, Iceland. Detailed microscale properties of till samples (from Scanning Electron Microscope [SEM] and thin section analysis) were examined from a glacial site with *in situ* subglacial process monitoring and an exposed subglacial surface in the foreland. Two lithofacies were examined, a grey sandy till derived from the ash and basalt, and a silty reddish brown till derived from oxidized paleosols and/or tephra layers. These also represented a clay-content continuum from low (0.3%) to high (22.3%). The evolution from debris to subglacial till was investigated. This included a reduction in grain-size (21% for grey lithology, 13% reddish brown lithology), and reduction in rounding (RA) (32% for the grey lithology, 26% for the reddish brown lithology), and the quantification and analysis of the different grain erosion/comminution processes in the resultant till. It was shown that the microstructures within a till were dependent on shear strain and glaciological conditions (deformation history). The low clay content tills were dominated by linear structures (lineations and boudins, and anisotropic microfabric) whilst the higher clay content tills were dominated by rotational structures (turbates and plaster, and isotropic microfabric). These results are important in our understanding of the formation of both modern and Quaternary tills and informs our reconstruction of past glacial dynamics.

1. Introduction

Temperate glacier motion is due to creep, sliding and subglacial deformation; and so subglacial hydrology and sediment deformation play a key role in modulating glacier behaviours (Boulton and Jones, 1979; Murray and Dowdeswell, 1992). The study of their interaction is vital for any prediction of glacier response to climate change, and the reconstruction of past glacier behaviour from glacial sediments. Understanding the subglacial environment must include a combination of *in situ* subglacial experiments (Fischer and Clarke, 2001; Murray and Porter, 2001; Hart et al., 2011a), geophysical and geodetic survey (Woodward et al., 2003; Smith et al., 2007; Hart et al., 2011b), geotechnical experiments (Kamb, 1991; Iverson et al., 1998; Sane et al., 2008; Altuhafi et al., 2009; Iverson, 2010) and sedimentology (Hart and Rose, 2001; Evans et al., 2006; Ó Cofaigh et al., 2011; Trommelen et al., 2014). Such studies have illustrated that the processes within the subglacial environment can vary rapidly on both a spatial and temporal scale, with 20–85% of glacier motion occurring in a subglacial deforming layer (typically to 0.3 m depth) (Truffer et al., 2000; Boulton et al., 2001; Cuffey and Paterson, 2010).

The key driver for subglacial till sedimentation is pore-water pressure (Alley et al., 1986; Boulton and Hindmarsh, 1987; Brown et al., 1987; van der Meer et al., 2003; Iverson, 2010). Where pore-water pressures are very low, the till cannot be deformed. At intermediate pore-water pressures, subglacial sediments are deformed and behave as a shear zone (Hart and Boulton, 1991; Benn and Evans, 1996). At extremely high pore-water pressures, there is ice-bed decoupling and/or shallow deformation (Fischer and Clarke, 1997; Engelhardt and Kamb, 1998; Iverson et al., 1999; Boulton et al., 2001; Damsgaard et al., 2013). Hart et al. (2011a) was able to demonstrate, from *in situ* wireless probe data from Briksdalsbreen, Norway, the deformation patterns (discussed above) forming in response to an annual cycle of pore-water pressure changes. The resultant till is a mixture of all these processes.

Till is a granular material with complex geotechnical behaviour (see detailed discussions in Menzies, 2012; and Damsgaard et al., 2016) and involves the movement of particles at both microscopic

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(clast and matrix) and macroscopic (bulk rheology) scale. Although there have been debates about till behaviour, between a linear viscous model (Alley et al., 1986; Boulton and Hindmarsh, 1987) or plastic behaviour (Kamb, 1991; Tulaczyk et al., 2000); more recently it has been argued that there is a continuum in behaviour from 'stick' (little motion) to 'creep' (pre-failure, nonlinear deformation) to 'slip' (plastic failure) (Hindmarsh, 1997; Sane et al., 2008; Altuhafi et al., 2009; Hart et al., 2011a; Damsgaard et al., 2016). During deformation, the particles (both grains and matrix) are rearranged, leading to grain erosion (comminution) (Gjessing, 1965; Hooke and Iverson, 1995; van der Meer et al., 2003; Hart, 2006a) which itself makes a contribution (due to changes in grain size and arrangement) to the deformation process.

The aim of this study was to investigate the formation of subglacial deformation till from beneath a modern glacier. To do this, sedimentological techniques (SEM, thin section and microfabric) are used alongside data collected from the unique Glacsweb *in situ* subglacial wireless probes (Hart et al., 2006; Martinez and Hart, 2010). There are three specific aims: i) the comparison of erosional characteristics between the debris and the subglacial tills; ii) the investigation of the styles of deformation (strain patterns) within the till; and iii) the influence of lithology and particularly clay content, on subglacial processes. The study of till genesis requires an understanding of both temporal changes (from modern studies) and spatial changes (often easier to determine from Quaternary studies), so that till can be actively used as a tool for the reconstruction of former glacier behaviour.

2. Skálafellsjökull

2.1. Field site

The study was undertaken at Skálafellsjökull, Iceland (Fig. 1). This is an outlet glacier of the Vatnajökull icecap resting on Upper Tertiary grey basalts with intercalated sediments (oxidized paleosols and/or tephra layers) (Jóhannesson and Sæmundsson, 1998). The area of the glacier is approximately 100 km^2 with a length of 25 km (Sigurðsson, 1998). In order to study the till sedimentology we collected the till from two locations (Fig. 1b). One site that has been the focus of wireless *in situ* subglacial experiments (Site A) (Hart et al., 2015; Martinez et al., 2017); and a second from the proglacial foreland where there was an exposed subglacial surface (Site B). At the glacier site (Site A), bulk samples of supraglacial, englacial and proglacial material were collected alongside subglacial samples (collected via borehole). A second site was investigated in the foreland because it provided access to a recently exposed subglacial surface, where bulk and undisturbed subglacial till samples were collected from both a push moraine and a flute. The choice of two sites enabled us to use a wide range of sampling techniques and compare *in situ* subglacial processes and recently deposited subglacial till.

2.2. Site A

Site A (792 m a.s.l.) was chosen for subglacial monitoring because the glacier was flat and relatively crevasse free. Clast-rich till and small push moraines (<1 m high) were present along the greater part of the glacier margin. Numerous englacial debris bands and debris cones were also visible on the glacier surface throughout the glacier ablation zone (Figs. 1c and 2). These typically consisted of thin clast-rich layers (1–2 cm thick) with 4–10 layers in approximately 1 m thickness (Fig. 2). Almost all the clasts were less than 1 cm in length (a-axis). Towards the margin, there were two sites where the debris-rich layers contained small lenses (a-axis less than 1 cm) of reddish brown clay-rich debris.

At this site, it has been shown from borehole and Ground Penetrating Radar (GPR) studies that the glacier rests on a till base, which comprises a patchwork of different till strengths (Hart et al., 2015). The till/bedrock interface is clearly seen on the GPR, and is close to the surface (less than 1 m) at the margin and inclines beneath the glacier at approximately 30° degrees, so that at 150 m from the margin the till is approximately 2 m thick.

In addition, a wireless subglacial sensor network was installed to measure subglacial processes (Hart and Martinez, 2006; Martinez and Hart, 2010; Martinez et al., 2017). Three wireless *in situ* probes were deployed in the till in 2008. In order to insert probes into the till, the boreholes were drilled to the base of the glacier and the presence of till checked with the video camera. If till was present it was hydraulically excavated (Blake et al., 1992) by maintaining the jet at the bottom of the borehole for an extended period of time. The probes were then lowered into this space, enabling the till to subsequently close in around them. The measured depth of the probes within the till is not known, but is approximated at 0.1–0.2 m beneath the glacier base, estimated from video footage of the till excavation at ice/till interface prior to deployment. The probes were deployed where the ice was 60 m thick and approximately 100 m from the glacier margin.

The Glacsweb probes show that throughout the year, the till was dominated by either stable high water pressure (>90% water pressure as a percentage of glacier depth), or variable water pressures (typically 67–86% water pressure as a percentage of glacier depth) with regular patterns of stick-slip motion (Hart et al., 2015).

2.3. Site B

Site B (60 m a.s.l.) was dominated by flutes and moraines. In the south west of the area the moraines were 50–100 m long and 1–3 m high, with a proximal slope of 10–20° (located along the transect shown in Fig. 1d). Each moraine comprised an upper clast-rich till (0.2 m thick), and a lower unit comprising layers of silt, sand and gravel (Fig. 3). Samples were taken from three moraines located between 40 and 163 m (along the transect) from the 2008 glacier margin. At sites B1-3, within the lower laminated unit, were small (0.15 m high) folds, kink folding (0.1 m high), brittle faulting (Fig. 3) and possible water escape structures.

To the north east of the transect, the foreland comprises a series of flutes and streamlined bedrock (with no underlying proglacial deposits). Site B4 was an exposure of reddish brown till (35 m from the 2008 margin, 175 m east of the transect) in a fluted area. This till lithofacies was also observed within three adjacent flutes (approximate size, 0.7 m high, 0.6 m wide, over 100 m long).

At the 2008 glacier margin, a saturated fluted till surface was being exposed. Throughout the foreland, till depth was variable (ranging from 0 to 3 m) and in places the bedrock was exposed relatively close to the surface, either as small streamlined outcrops (up to 2 m in area) or larger crags.

2.4. Recent glacier movement and till depositional setting

The recent changes in the position of the glacier margin are recorded from air photographs since 1945, Landsat 7 (Google Earth) 2000 image, Cnes/Spot 2013 image and measurement in the field 2008. At the south eastern margin (Site B), Skálafellsjökull retreated from 1945 to 1978 at approximately 24 m a^{-1}; then advanced until 2000 at approximately 6 m a^{-1}, and subsequently retreated at 19 m a^{-1} between 2000 and 2008 and 37 m a^{-1} between 2008 and 2013 (Fig. 1a). The 1978 air photograph shows the minimum glacier position, and during this time there was a large proglacial lake (414 m × 143 m) at the glacier margin. This lake was also present in the 1982 and 1989 air photographs, although becoming smaller