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Genesis of glacial flutes inferred from observations at Múlajökull, Iceland

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ABSTRACT

Flutes are flow-parallel till ridges that form subglacially and are conspicuous geomorphic indicators of slip at glacier beds. Flutes commonly have a boulder at their head, lodged in the former till bed of the glacier. In the leading model of flute genesis, weak till of the bed flows into a water-filled cavity where ice separates from the lee surface of the boulder. This cavity is displaced downstream as it progressively fills with till and the flute lengthens. To test this hypothesis, we studied in detail a parallel-sided flute, 250 m long, and a tapered flute, 5 m long, at the surge-type glacier, Múlajökull, in Iceland. More than 900 measurements of till magnetic susceptibility anisotropy, calibrated experimentally, show that spatially averaged till flow converged toward flute long axes, consistent with the cavity-fill hypothesis, and that till shear strains were small (<7.6). Till density patterns indicate that decreasing water pressure in cavities, decreasing slip velocity, and associated increases in ice pressure on the distal ends of the flutes consolidated and strengthened till—an effect far more prominent in the long flute. This till strengthening resolves the fundamental mechanical problem that undermines the cavity-fill hypothesis: how a leeward cavity can be sustained well beyond the pressure shadow in ice created by a boulder. Also resolved is how convergent fabrics in flutes are preserved, despite significant slip of ice across them. These results provide the first evidence that flute elongation beneath wet-based glaciers may require fluctuating water pressure and slip velocity.

INTRODUCTION

Slip at the beds of glaciers intensifies their dynamic response to climate change, sometimes with global environmental feedbacks (e.g., Ritz et al., 2015). Although this slip is difficult to observe directly, streamlined bedforms that can result from it encode slip processes and subglacial conditions. Developing mechanically viable models of bedform genesis, therefore, is of widespread interest (Stokes, 2018).

In the forelands of many glaciers are flutes: low-relief, flow-parallel ridges that usually consist of basal till. They are typically decimeters to a few meters in width and height and several meters to >1 km in length. On their up-glacier ends, they commonly have a boulder, lodged in the till bed during glacier slip, that motivates the leading conceptual model of flute formation by temperate glaciers (Boulton, 1976; Benn, 1994a; Hubbard and Reid, 2006; Roberson et al., 2011; Eyles et al., 2015; Ely et al., 2017; Hart et al., 2018). In this model, weak till of the bed flows laterally and upward into a cavity in ice in the lee of the boulder, where low ice pressure allows the cavity to form. As till fills the cavity, the cavity is propagated downstream so that the flute extends. Convergent clast fabrics of some flutes support this idea (see Benn and Evans [2010] for a summary).

Although flutes are associated with glaciers with vastly different slip velocities and thermal regimes, some hypotheses link flute length and shape to basal conditions. Benn and Evans (1996, 2010) suggested that "parallel-sided" flutes, commonly hundreds of meters long, reflect low-viscosity till that flows into cavities faster than ice creep closes them; shorter flutes with widths and heights that decrease downstream ("tapered" flutes) were attributed to till of higher viscosity that squeezes less easily into cavities. Evans and Rea (2003) noted that flutes of surge-type glaciers in Iceland tend to be substantially longer than those of non–surge-type glaciers and suggested that periods of fast flow under steady conditions elongated flutes. Ely et al. (2017) showed that widths and heights of flutes are related to their boulder size but flute length is not.

We collected data from flutes of the warm-based, surge-type glacier, Múlajökull, in Iceland (Fig. 1), with the goal of resolving a fundamental mechanical problem that undermines the cavity-fill model: how does till sufficiently weak to squeeze into a cavity also hold the cavity open on the flute's downstream end, outside the pressure shadow of the boulder? We applied two techniques that have not been applied to flutes previously: we measured patterns of till density (to assess past stresses on till) and of till fabrics based on till anisotropy of magnetic susceptibility (AMS), calibrated to results of ring-shear experiments, to assess till-deformation patterns. These measurements point to a new hypothesis for flute growth by cavity filling, redefine the glaciological conditions for flute growth, and resolve how till fabrics that reflect lateral till flow into cavities are preserved, despite significant slip of ice across flute surfaces. Our interpretations rest, in part, on demonstrations (Iverson et al., 1998; Tulaczyk et al., 2000) that tills do not behave as viscous fluids but rather as Coulomb, compressible materials, with shear strengths dependent on effective stress and bulk density.

FIELD AREA AND METHODOLOGY

Múlajökull is a piedmont glacier of the Hofsjökull ice cap (Fig. 1) that has surged eight times since A.D. 1924, with intervening quiescent periods of 5–30 yr (Björnsson et al., 2003). Stacked basal tills deposited during surges compose the drumlinized glacier foreland (Fig. 1) (Johnson et al., 2010; Benediktsson et al., 2016; McCracken et al., 2016).

Two flutes—located up-glacier from the limit of the last surge in 2008 and with streamlined boulders (~1 m in diameter) at their heads (Fig. 1)—were studied in detail (see the GSA Data Repository[1]). One flute is ~250 m long and parallel-sided, with a height of 0.7 m and width of ~1.4 m (Fig. 1). The other flute is of approximately the same height and width near its head, but tapers down-glacier and is 5 m long

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[1]GSA Data Repository item 2019131, field area and sampling methodology, clast-fabric methodology, AMS methodology and fabric data, and ring-shear data, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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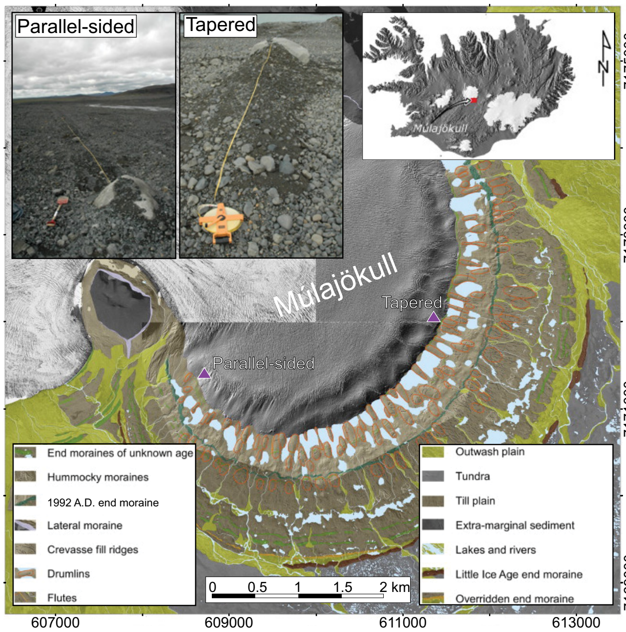

Figure 1. Múlajökull (Iceland) and its foreland in A.D. 2008 (from Jónsson et al., 2014). The two flutes of this study (purple triangles) are located inside the 2008 margin of the glacier. Northing and easting UTM coordinates are shown. Also shown are oblique photographs of the studied parallel-sided and the tapered flutes, looking down-glacier and up-glacier, respectively. Boulder widths are ~1.5 m.

(Fig. 1). Horizontal platforms (<1 m^2) at various locations and depths in the flutes (Fig. DR1 in the Data Repository) were excavated, and 25 or more intact till samples were collected in each platform by pressing plastic boxes into the till (~18 mm cubes, volume of 6 cm^3) and excavating them (Fig. DR2).

The AMS of the Múlajökull till is controlled by silt-sized, pseudo–single-domain and multi-domain particles of titanomagnetite and titanomaghemite (Ives, 2016). Importantly, these minerals have shape anisotropy, so orientations of principal magnetic susceptibility reflect the preferred orientations of grains (Tarling and Hrouda, 1993). The measurement of each AMS sample provided three principal magnetic susceptibility orientations. The distribution of these orientations for multiple samples allowed fabrics to be computed. Following Woodcock (1977) and Benn (1994b), these distributions were defined as isotropic, girdled, or clustered. To help assess the generality of the AMS results, they were compared to clast fabrics (83 fabrics, 2594 clasts) compiled from studies of five other glacier forelands (see the Data Repository; Rose, 1989; Gordon et al., 1992; Benn, 1994a; Evans et al., 2010; Eyles et al., 2015). Insufficiently complete data presentation precluded using other flute studies.

To calibrate AMS fabrics to strain orientation and magnitude, the Múlajökull till was sheared in laboratory experiments (see the Data Repository) and then sampled following the field methodology. Results reinforce those of experiments on other tills (Hooyer et al., 2008) and indicate that orientations of the three principal susceptibilities become strongly clustered and steady at shear strains between 3.0 and 7.6. Orientations of maximum (k_1) and minimum (k_3) susceptibility cluster in the longitudinal flow plane with azimuths parallel to shear, with k_1 clusters plunging up-flow 21°–29° and k_3 clusters plunging 62°–69° down-flow. Systematic and strong clustering of principal susceptibility orientations with strain also demonstrates that till disturbance during sampling does not significantly disrupt the preferred orientations of grains—a conclusion supported by AMS-based fabrics from previous field studies of the Múlajökull till (McCracken et al., 2016).

Dry bulk densities of AMS samples from flutes were measured to detect spatial differences in consolidation. The large number of these samples (912 in the two flutes) yielded systematic density patterns. Grain-size distributions of till within and outside flutes were also measured.

Additional methodological details can be found in the Data Repository, and in Ives (2016).

RESULTS

Dividing the two flutes into three longitudinal sectors—left, middle, and right—and considering all the samples within a sector as a single fabric indicates that only k_3 orientations cluster, and that AMS fabrics tend to converge toward flute centerlines (Fig. 2A). This convergence is shown by the orientations of k_3 clusters (recalling that k_3 clusters have azimuths parallel to shear) and in two of the zones by k_1 orientations that are distributed along great circles (girdles) and symmetrically disposed about orientations of k_3 clusters. The clast fabrics from other glacier forelands, if computed over these same longitudinal zones, also indicate convergent fabrics (Fig. 2A). Despite this tendency, local AMS fabrics measured and computed over areas of <1 m^2 (a single platform) (Figs. DR3 and DR4) display nearly 180° of variability in shearing azimuth, as indicated by k_1 and k_3 orientations, with some major fabric modes indicating divergent flow (Fig. 2B), especially in the immediate lees of the boulders (Fig. DR4). Clast fabrics measured locally in flutes from other forelands also display divergent modes (Fig. 2B).

The average density of till is higher in the long, parallel-sided flute (1624 ± 150 kg m^{-3}) than in the tapered flute (1519 ± 140 kg m^{-3}) and varies systematically (Figs. 3A–3D). In both cases, a local density minimum exists within ~1.3 m downstream of the boulder at the flute head. Upstream from the boulders, till density is higher than in flutes. Across the widths of the flutes, till density tends to increase toward their centers, particularly in the parallel-sided flute. Till grain-size distribution varied little and unsystematically within flutes and between flutes and adjacent till (Ives, 2016).

DISCUSSION

Despite local fabrics that are variable in the flutes of this study and of other glacier forelands (Fig. 2B), fabrics overall indicate that flow was convergent (Fig. 2A), consistent with till squeezed into the lee of an obstruction. This local flow would not require high till shear strains. In agreement with this inference, in both flutes only k_3 orientations are clustered, suggesting, on the basis of the ring-shear experiments (Fig. DR5), shear strains too low to cluster k_1 (<3.0) and k_2 orientations (<7.6).

Preservation of convergent fabrics and low strain indicate that after till deposition, down-glacier slip of ice across flutes did not shear them significantly (see also Evans and Rea, 2003). For example, a modest slip velocity of 200 m yr^{-1} (e.g., Björnsson et al., 2003) during a 6 month surge would shear a 1-m-thick till layer to a strain of 100 if ice moved by bed deformation. Strains of <10 would have reset the AMS fabric parallel to the flute and would also have clustered the three principal susceptibilities (Fig. DR5).

Why did ice not shear the till and reset its fabric if the till were weak enough to be squeezed into a cavity? More fundamentally, how was this weak till able to support a cavity in the lee of a growing flute, well down-glacier from the pressure shadow of the boulder (Gordon et al., 1992; Schoof and Clarke, 2008), when to sustain a leeward cavity the bed immediately upstream must support high ice pressure (Röthlisberger and Iken, 1981; Iverson, 1991)?

Till densities help answer these questions. The tendency for till density to be high up-glacier from boulders at the heads of flutes and low immediately down-glacier (Figs. 3A and 3B) is expected from the pressure distribution in ice as it flows past bed obstacles (e.g., Weertman, 1957). More surprising are density variations across the widths of the flutes (Figs. 3C and 3D). Till density might have been expected to be smallest at the flute center where the leeward ice-pressure deficit associated with slip was most severe. Instead, density tends to increase toward flute centers, especially in the long, parallel-sided flute (Fig. 3C). This density distribution must have arisen when basal

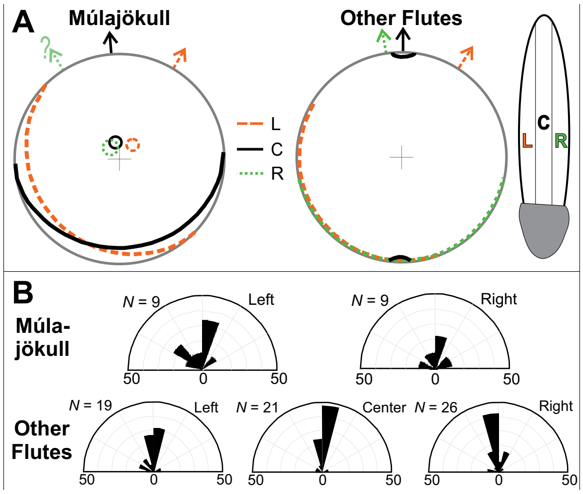

Figure 2. Generalized principal magnetic susceptibility orientations of till from flutes studied at Múlajökull (Iceland) and clast fabrics of flutes from five other glaciers (Austre Okstindbreen, Norway [Rose, 1989]; Lyngsdalen, Norway [Gordon et al., 1992]; Slettmarkbreen, Norway [Benn, 1994b]; Sandfellsjökull, Iceland [Evans et al., 2010]; and Saskatchewan Glacier, Canada [Eyles et al., 2015]) generalized in same way (see text). A: Results, shown in lower-hemisphere, equal-area stereoplots, based on grouping of individual anisotropy of magnetic susceptibility (AMS) samples and clasts in left-hand (L), central (C), and right-hand (R) longitudinal zones of flutes. Arrows indicate inferred shearing azimuths (question mark indicates azimuth based on clustering of only minimum susceptibility, k_3). For Múlajökull flutes, lines indicate best fits to girdled maximum susceptibility, k_1, axes, and rings indicate 95% confidence limits for V_1 (mean-axis eigenvector) orientations of clustered k_3 axes. If orientations of k_1 or k_3 axes are isotropic, they are not plotted. Plot is based on 713 AMS measurements. For flutes elsewhere, lines indicate best fits to clast long-axis orientations that were girdled, and rings (black) indicate 95% confidence limits for orientations of clustered clast long axes. Plot is based on 2594 clasts. B: Rose diagrams indicating shearing orientations computed from AMS and clast fabrics measured locally in three longitudinal zones. Each fabric was based on at least 25 sample or clast orientations. Perimeter of diagrams is 50%. *N* is number of fabrics, excluding those that were isotropic. See the Data Repository (see footnote 1) for criteria used to define isotropic, girdled, and clustered orientation distributions.

water pressure and slip velocity decreased, and the leeward cavity shrunk to confine the till. As cavity water pressure decreased, glacier weight would have shifted from the water in the cavity to the weak till of the flute—as when ice increases stresses on rock near cavities during falling cavity water pressure and associated quarrying of bedrock (Röthlisberger and Iken, 1981; Iverson, 1991; Anderson, 2014). The resulting ice pressure would have been highest at the flute center, maximizing consolidation there. However, in cases without sufficient confinement by ice, such as in the immediate lee of a boulder where cavities in the ice would have been largest, this enhanced ice pressure at the flute center would have squeezed till outward causing divergent fabrics (Fig. DR4) and reducing till consolidation (Figs. 3A and 3B).

HYPOTHESIS FOR FLUTE GROWTH

These observations provide a new, mechanically viable hypothesis for flute growth by cavity filling (Fig. 4). Both surge-type and non–surge-type glaciers undergo fluctuations in basal water pressure and speed, daily and seasonally (Cuffey and Paterson, 2010). Till is squeezed into cavities when subglacial water pressure and slip velocity are high, effective stress is low, and till is weak, creating convergent till fabrics (Fig. 4A). Subsequently, when cavity water pressure and slip velocity decrease, the newly accreted till at the flute's end is consolidated by the associated increase in ice pressure (Fig. 4B). This consolidation increases till shear strength by increasing friction angle and is largely irreversible when effective stress later decreases (Lambe and Whitman, 1979). The strengthened till provides a sufficiently rigid substrate to support a cavity during the next period of high water pressure and slip velocity and so allows the flute to grow downstream (Fig. 4C). Moreover, strengthening of the till preserves its convergent fabric and inhibits its erosion as ice slips over the flute. Sufficient till consolidation would allow cavity position and till deposition to propagate down-glacier to form a long, parallel-sided flute. Alternatively, if consolidation after a water-pressure decrease were insufficient, the cavity would remain confined to the lee side of either the boulder or the last consolidated increment of till added to the flute, causing it to taper and end its growth. The lower mean density and transverse density gradient (Fig. 3D) of the tapered flute support this idea.

IMPLICATIONS

Although the unsteady basal water pressure and slip velocity that typify many glaciers are well established, this study provides the first evidence that these unsteady conditions are required for flutes to extend beyond the pressure shadow of their boulders. Water-pressure decreases are required to compact and strengthen the distal till of the flute to allow subsequent cavity growth when the glacier speed again increases. This process allows the flute tip itself to become the obstacle from which the next cavity launches, allowing parallel-sided flutes to extend. Such flutes may indeed be more likely to form beneath glaciers that sometimes slip rapidly (e.g., Benn and Evans, 2010) because high basal water pressure and fast slip would be associated with weak mobile till and long cavities. However, these results do not preclude flutes of all lengths from forming beneath slow-moving glaciers (e.g., Eyles et al., 2015; Hart et al., 2018) if they change their speeds diurnally or seasonally, or during a surge as water pressure and ice speed fluctuate (Kamb et al., 1985). Also, flute-forming processes tied

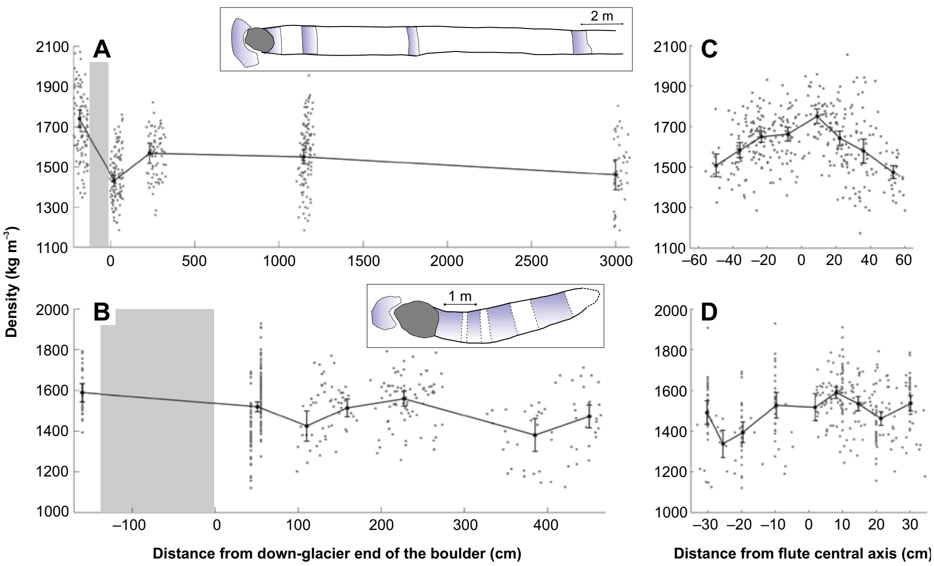

Figure 3. Dry bulk density of till at various positions along lengths of parallel-sided (A) and tapered (B) flutes and across widths of the parallel-sided (C) and tapered (D) flutes at Múlajökull, Iceland. Purple zones within inset drawings show sampling regions. Error bars indicate 95% confidence limits for means of samples (connected by black line) grouped over longitudinal increments sufficient to include 10 or more samples. These limits indicate that across the widths of flutes, particularly the parallel-sided one, variations in mean till density are significant. Gray bands in A and B are boulder locations. See the Data Repository (see footnote 1) for more specific sample locations and depths.

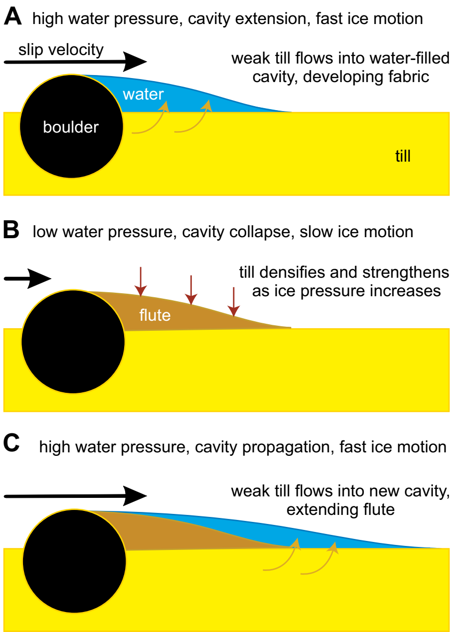

Figure 4. Hypothesis for glacial flute growth. A: Weak till flows into the cavity down-glacier from a boulder when basal water pressure and sliding speed are high. B: When water pressure and sliding speed decrease, the cavity shrinks, ice pressure on the till increases, and the till consolidates and strengthens. C: When water pressure and sliding speed again increase, the consolidated, strengthened till allows the separation point of ice at the head of the cavity to move downstream.

to non-standard ice rheology (Schoof and Clarke, 2008) or polythermal glaciers (e.g., Baranowski, 1970; Roberson et al., 2011) are not precluded. These results highlight how steady-state models of bedform streamlining may fail to describe essential physics.

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