Genesis of glacial flutes inferred from observations at Múlajökull, Iceland

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FIELD AREA AND SAMPLING METHODOLOGY

The two flutes of this study are on the southwestern (parallel-sided, UTM 27W 608565 E 7171433 N) and eastern (tapered, UTM 27 W 611395 E 7172120 N) sides of Múlajökull and inside the limit of the minor 2008 surge of the glacier (Fig. 1 of article). This surge caused the margin to advance about 20 m (Benediktsson et al., 2016). A third flute was studied during the previous summer in 2013 (Ives, 2016), but data were not spatially referenced sufficiently that year to compute longitudinally grouped fabrics like those of Figure 2 of the article or till density distributions like those of Figure 3 of the article.

The boulders at the heads of the two flutes are streamlined (“bulleted”) with quarried surfaces. Striations on the stoss sides of the boulders diverge. The parallel-sided flute (Fig. DR1 and Fig. 1 of the article) and other flutes in its “swarm” are located on a highland that is bounded on either side by meltwater drainages. The highland is of relatively low relief but was identified as a drumlin by Johnson et al. (2010) and Jónsson et al. (2014). The up-glacier end of the flute is located ~200 m from the 2014 glacier margin. The 2008 moraine is absent in this area of the foreland, but the boulder on the stoss end of the flute is located up-glacier of the 2008 glacier margin (Sigurkarlsson, 2015). The tapered flute (Fig. DR1 and Fig. 1 of the article) is not part of a flute swarm and occupies a flat area between drumlins, with its tail ~100 m up-glacier from the 2008 moraine. This flute is curved with a trend that changes ~10º from its head to its tail.

Although not true of either of these flutes, some flutes in the Múlajökull foreland intersect crevasse-fill ridges, thought to be characteristic of surge-type glaciers (Sharp, 1985).

Several sites were selected along the lengths of the two flutes to collect till samples for measurements of AMS (anisotropy of magnetic susceptibility) and bulk density (Fig. DR1). Plastic sample boxes (18 mm cubes) were pressed into excavated horizontal platforms (< 1 m^2) in the till (Fig. DR2). Where flutes were sufficiently tall, samples were gathered from platforms at multiple depths at the same site (Fig. DR1). Samples were collected in sets of 25 or more from these platforms to compute local till fabrics, and the position of each sample was measured to allow longitudinal grouping of AMS principal-susceptibility orientations (Fig. 2 of article). A total of 529 and 383 samples were collected from the parallel-sided and tapered flute, respectively, and used to assess both AMS and bulk density of the till.

Clast fabrics were not measured in flutes, as a complement to AMS-based fabrics, because limited time and personnel in the field did not allow both techniques to be used. AMS-based fabrics were deemed the higher priority because such measurements are less prone to error and human subjectivity and have higher spatial resolution than clast-fabric measurements. See Iverson et al. (2008) for a more detailed discussion of the advantages of AMS-based fabrics. Importantly, shearing orientations indicated by AMS fabrics and clast fabrics are similar, such that comparing fabric orientations from the two types of measurements is a valid exercise (Iverson et al., 2008; Gentoso et al., 2012)

AMS METHODOLOGY

The AMS of each till sample was measured using an AGICO Geophysika MFK1-FA Multifuction Kappabridge located at University of Wisconsin–Milwaukee. AMS samples were measured in a 976 Hz applied field at room temperature with a 200 Am-1 peak intensity, using the MFK1-FA's spinning-specimen method (Jelinek, 1997).

For each till sample, a second rank, primary magnetic susceptibility tensor, its associated principal susceptibilities ($k_1>k_2>k_3$), and their orientations were calculated (Jelinek, 1977; 1997). To determine if principal susceptibilities were significantly different from each other, F statistics as defined by Hext (1963) were calculated and used to reject samples with insignificant anisotropy. For a population of samples, orientation distributions of each of the principal susceptibilities were used to compute eigenvectors (V_1, V_2, V_3), as measures of fabric orientation, and eigenvalues (S_1, S_2, S_3), as measures of fabric strength (Mark, 1973). Values of eigenvalues can range, in principle, from 0.33 (fully isotropic) to 1.0 (perfectly aligned) and always sum to 1.0.

For most populations of samples analyzed in this study, orientation distributions for one or more of the principal susceptibilities did not cluster but instead formed a girdle or exhibited no significant preferred orientation (isotropic). To distinguish anisotropic from isotropic orientation distributions, the isotropy indices of Benn (1994a) ($I= S_3/S_1$) and Woodcock (1977) ($C=\ln(S_1/S_3)$) were calculated. If $I \geq 0.20$ (equivalent to $C \leq 1.6$), the orientation distribution was deemed isotropic and of no directional value. Remaining orientation distributions defined as anisotropic were then characterized as either clustered or girdled, using cluster-girdle indices: $CGI = (S_1-S_2)/(S_1-S_3)$ (Benn, 1994a) and $K = \ln(S_1/S_2)/\ln(S_2/S_3)$ (Woodcock, 1977). Orientation distributions were considered to be clustered if $CGI \geq 0.5$ or $k \geq 1.0$. Remaining anisotropic orientation distributions were considered to be girdled. These girdled distributions were best-fit with a great circle following Allmendinger et al. (2012) (Fig. 2 of article, Figs. DR3 and DR4).

Clustered orientation distributions of principal susceptibilities have orientations of maximum clustering given by V_1 eigenvectors, but additional analysis is required to place confidence limits on V_1 orientations. Using the criterion of Fisher et al. (1987), clusters were defined as symmetric or asymmetric, and respectively, either a Watson or Bingham probability density function (Tauxe et al., 2016a) was fit to the cluster following Tauxe et al. (2016b). This process allowed 95% confidence limits to be assigned to V_1 orientations (Fig. 2A of article, Figs. DR3 and DR4).

RING-SHEAR EXPERIMENTS

Using a ring-shear device (Iverson et al., 1997), till from the study area was sheared to study AMS fabric development as a function of shear strain to help guide interpretations of the field data. The till was water-saturated, stirred to randomize particle orientations, and consolidated under a 65 kPa, a value chosen to reflect the low effective normal stress beneath most soft-bedded glaciers (e.g., Engelhardt and Kamb, 1997). The till was then sheared under drained conditions (e.g., Lambe and Whitman, 1979) at a steady rate of 320 m a^{-1}, comparable to the speeds of some ice streams (Engelhardt and Kamb, 1998) and to a strain rate of approximately ~3.5×10^{-4} s^{-1}. Experiments with till indicate that AMS fabric development in shear is highly insensitive to both effective normal stress and strain rate (Jacobson and Hooyer, 2015). Separate experiments were conducted to various strains and then the till was sampled for AMS analyses by pressing into the till and excavating plastic boxes of the type used at Múlajökull.

Experimental AMS fabric strengths and orientations (Fig. DR5) mimic those of experiments on other tills (Hooyer et al., 2008; Iverson et al., 2008). All three principal susceptibilities become clustered if shear strains exceed 7.6, and k_1 and k_3 cluster at strains < 3.0. Moreover, for the case of a horizontal shear plane as in these experiments, clusters of k_1 and k_3 orientations are parallel to shear and plunge, respectively, gently up-shear and steeply down-shear. Orientations of intermediate susceptibility (k_2) cluster perpendicular to the shearing direction and in the shear plane. As in experiments on others tills (Hooyer et al., 2008), various indices of anisotropy magnitude, which can be computed for each sample, do not vary systematically with strain.

DETERMINING SHEARING DIRECTION FROM AMS FABRICS

Azimuths of shearing were computed from V_1 orientations of k_1 and k_3 clusters, both of which lie parallel to the shearing direction for a shear plane with no lateral dip component, as indicated by the ring-shear experiments on the Múlajökull till (Fig. DR5) and other tills (e.g., Hooyer et al., 2008). Girdled k_1 orientation distributions that develop at lower shear strains than clustered distributions are symmetrically disposed about the shearing direction (Hooyer et al., 2008), so k_1 girdle bisectors were also used to compute shearing direction. Flow azimuths will have been slightly different than indicated by azimuths of k_1 and k_3 clusters or the bisectors of k_1 girdles, owing to nonzero transverse components of shear plane dip (Iverson, 2017); however, these azimuthal deviations are generally less than 5º, as indicated by k_2 orientations that cluster locally in the two flutes and indicate shear planes close to horizontal (Ives, 2016). This use of shear azimuths uncorrected for the transverse component of shear plane dip follows standard practice in the analysis of clast fabrics in which, unlike the case for AMS analysis, no ancillary information about shear-plane orientation is available and all measurements are thus "uncorrected." A final caveat is that inferred shearing directions are predicated on simple shear dominating the overall state of till strain, as was true in ring-shear experiments.

CLAST-FABRIC METHODOLOGY

Pebble orientations reported in 83 clast fabrics measured in flutes from five glacier forelands were re-analyzed using the methods that were applied to the AMS data (Fig. 2 of article). Clast fabric data from flutes in the forelands of the following glaciers were used: 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). Pebble orientations from these studies were referenced to their flute orientations, regrouped by flute position, and analyzed. Other fabric studies of flutes were excluded because data for individual clasts or clast fabrics locations were not provided.

More methodological details can be found in Ives (2016).

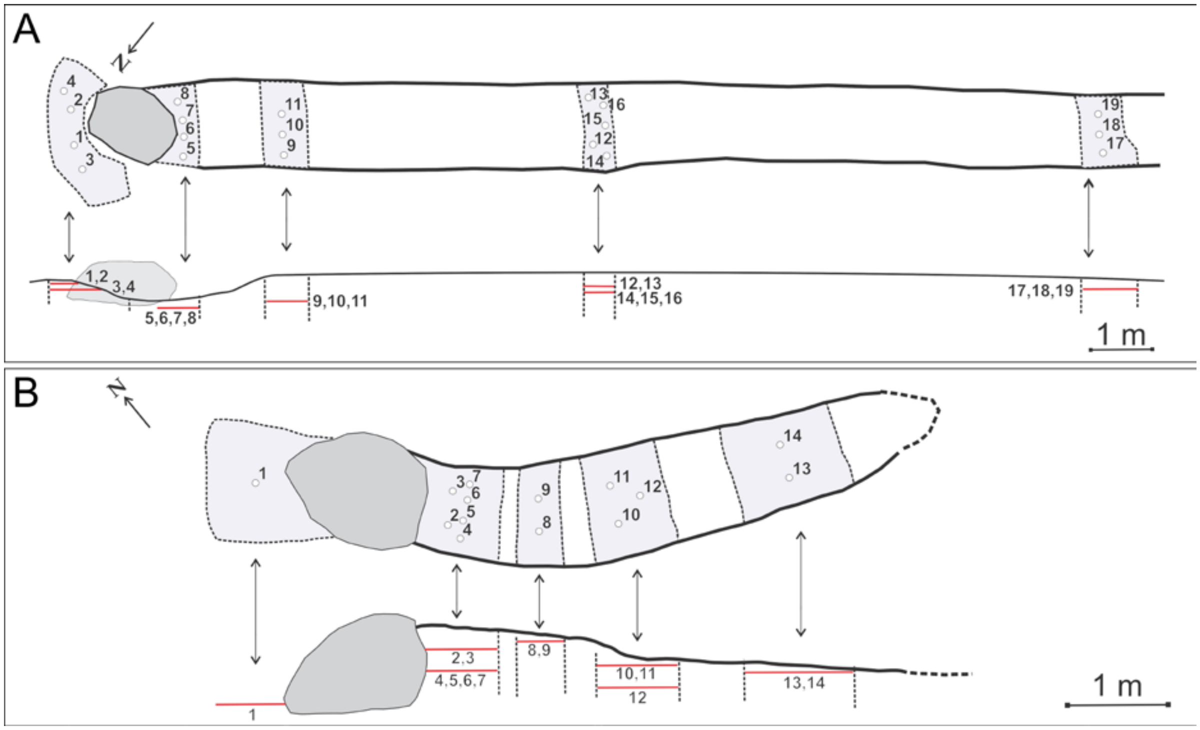

Figure DR1. Sampling locations in the (A) parallel-sided and (B) tapered flutes. 25 or more samples were collected surrounding the locations of each point in the plan-view drawings.

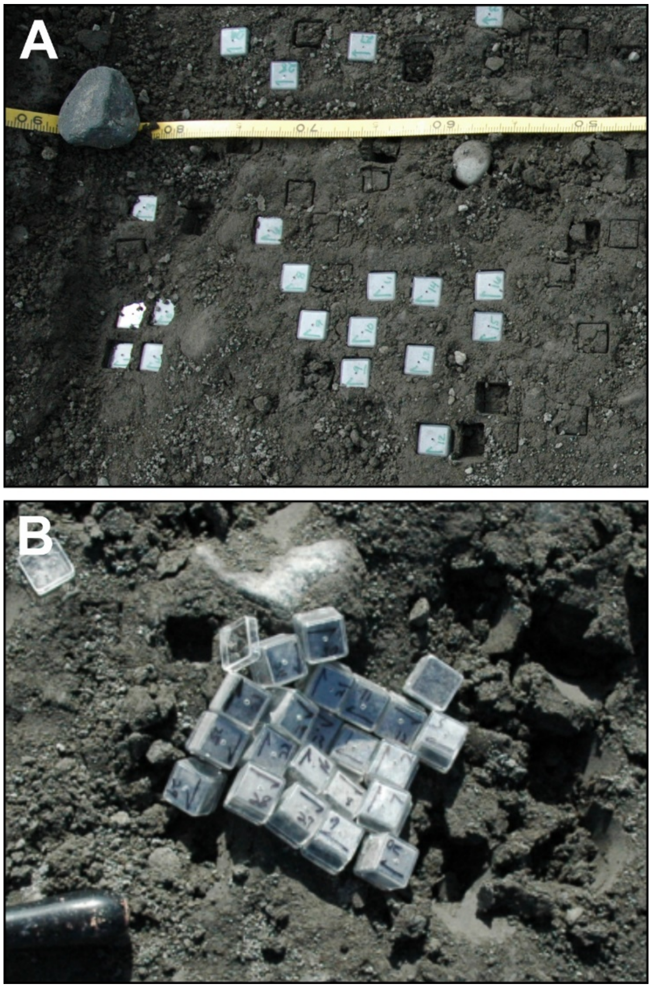

Figure DR2. Plastic boxes for AMS sampling inserted in a horizontal platform excavated in a flute. Owing to stones in till that commonly prevented boxes from penetrating, sampling grids tended to be irregular, as shown. (B) Boxes after having their orientations marked in situ and after their excavation and capping.

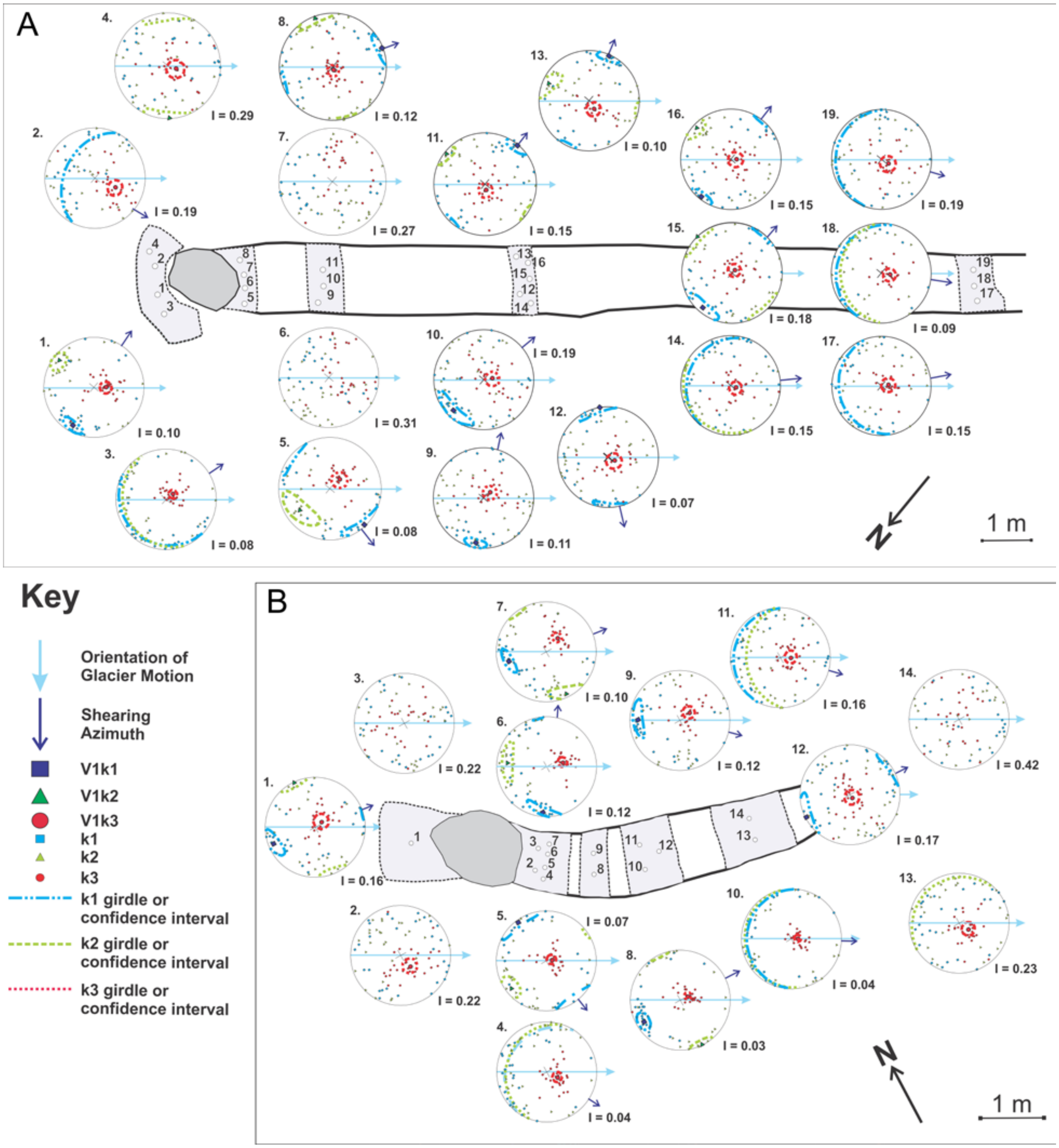

Figure DR3. AMS fabrics in the (A) parallel-sided and (B) tapered flutes. Ranges of orientations enclosed by dashed lines are 95% confidence intervals for V_1 eigenvectors computed for clustered orientation distributions. Values of I (see DR text) are inversely proportional to the anisotropy of k_1 orientations. Data are displayed in lower-hemisphere, equal-area stereonets that are numbered by fabric location, as indicated at center (see also Fig. DR1).

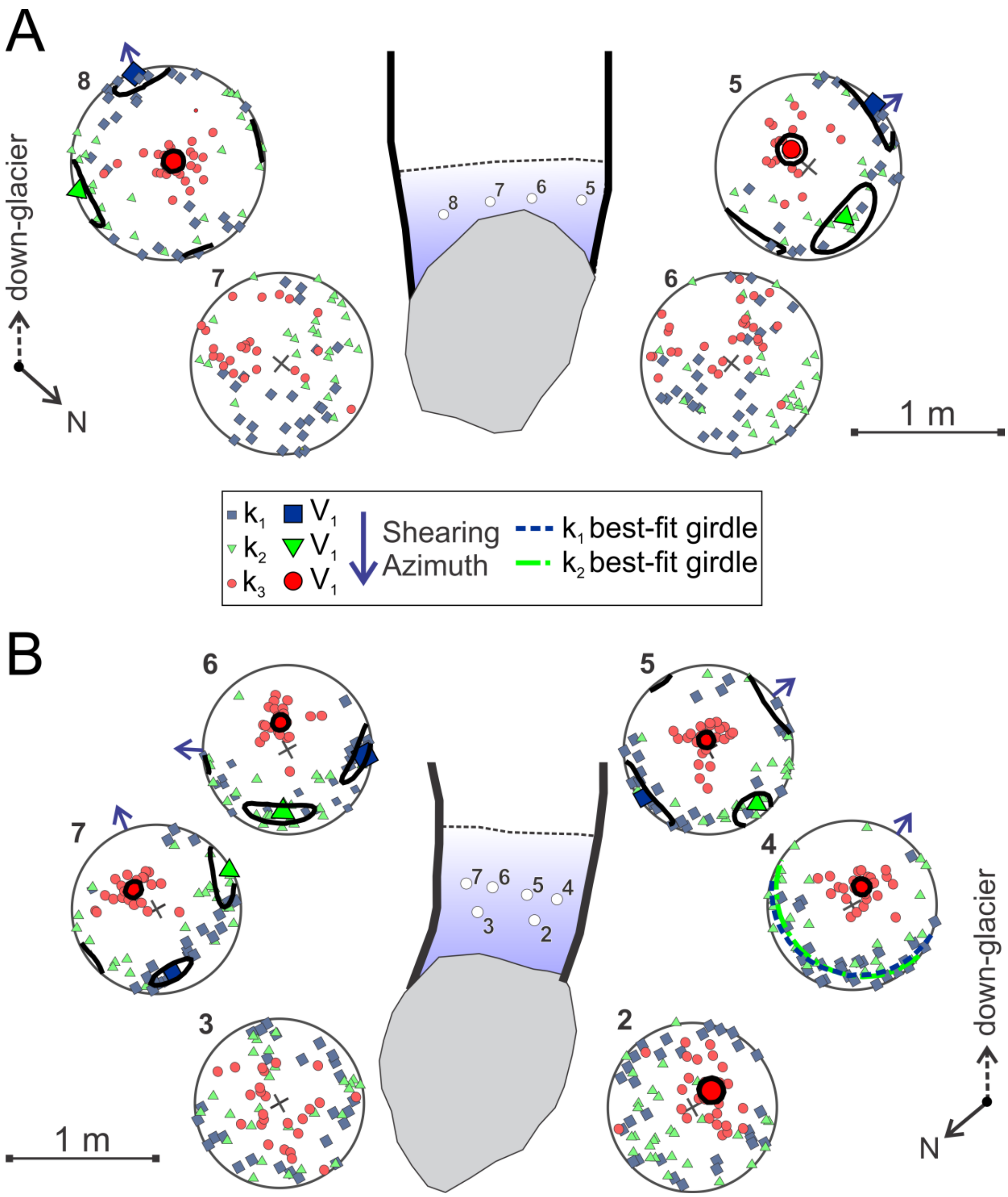

Figure DR4. AMS fabrics from till immediately in the lees of the boulders that head the (A) parallel-sided and (B) tapered flutes. Ranges of orientations enclosed by black lines are 95% confidence intervals for V_1 eigenvectors computed for clustered orientation distributions. Data are displayed in lower-hemisphere, equal-area stereonets that are numbered by fabric position, as indicated at center (see also Fig. DR1).

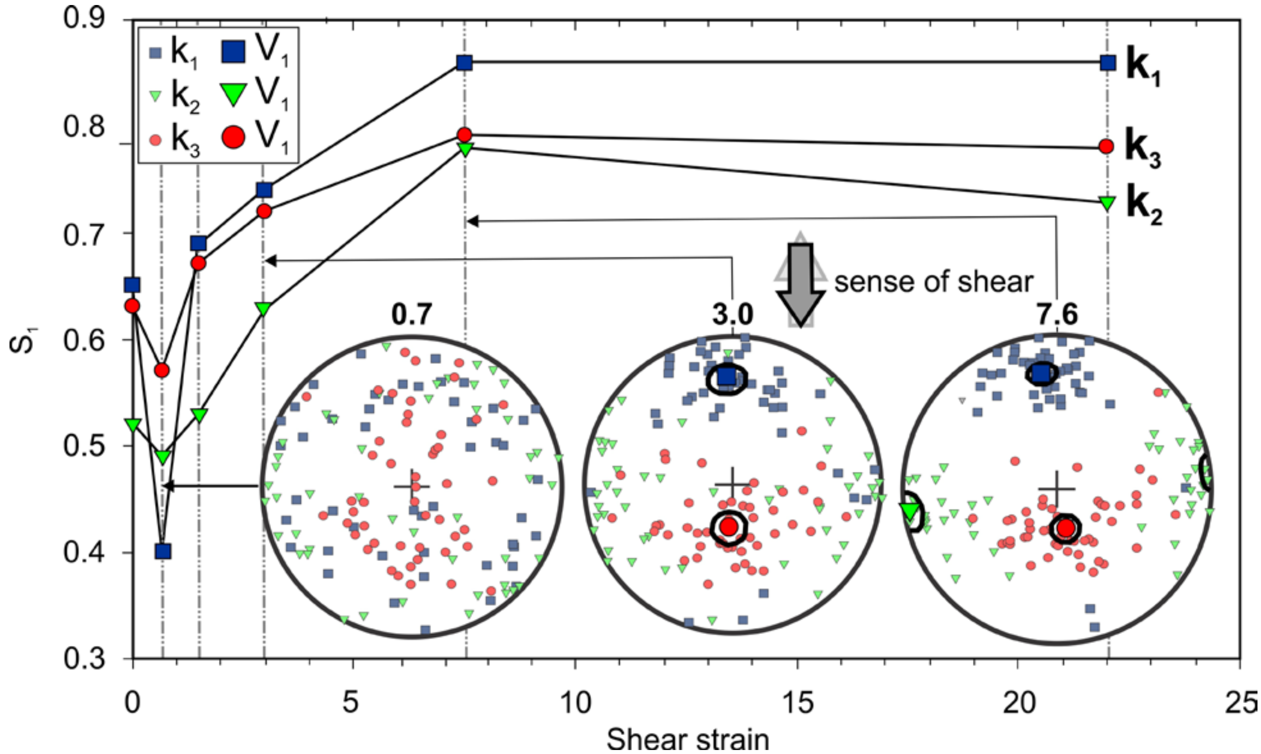

Figure DR5. Degree of clustering of principal-susceptibility orientations, as indicated by S_1 eigenvalues (Mark, 1973), as a function of shear strain, in ring-shear experiments on the Múlajökull till. Lower-hemisphere, equal-area stereoplots show principal susceptibility orientations at selected strains; numbers above stereonets are shear-strain values. Black rings in stereonets indicate 95% confidence limits for V_1 orientations of clustered orientation distributions. If confidence limits are absent, criteria for clustering of principal susceptibility orientations are not met. Shear stains of 3.0-7.6 are required for clustering of all of the three principal susceptibilities.

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