Magnetic fabrics of the Douglas Till of the Superior lobe: exploring bed-deformation kinematics

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ABSTRACT

The Superior lobe of the Laurentide ice sheet, during its last advance into northwestern Wisconsin, may have moved and transported sediment primarily through deep, widespread shear of its bed to high strains (>100). To study the kinematics of this deformation, we measured the anisotropy of magnetic susceptibility of 3750 intact samples of its basal till—the Douglas member of the Miller Creek formation—collected from eight profiles at 0.2 m depth increments. A benchmark for interpretations was provided by results of ring-shear experiments conducted on the Douglas Till, which provided fabric characteristics for the case of horizontal simple shear. Orientations of maximum susceptibility (k_1) were controlled by preferred orientations of silt-sized magnetite grains and were similar to sand-grain orientations measured in thin sections. Strengths of fabrics formed by orientations of k_1 indicate that most of the till sampled was deformed but to variable strains. Deformation averaged over the 20 km spanned by the study approximated horizontal simple shear. However, large differences in k_1 fabric azimuths ($>45°$) over lateral distances of meters to tens of meters indicate highly heterogeneous bed deformation, perhaps focused in anastomosing zones with associated divergent and convergent till shear. This interpretation is supported by orientations of principal susceptibilities that imply, in many cases, either that shear planes were steeply dipping, particularly transverse to the shearing direction, or that there were major components of pure shear. Variations in k_1 fabric azimuth with depth indicate that most of the till thickness did not shear simultaneously; rather, till accumulated at the bed as shear direction changed in response to temporally shifting zones of shallow deformation (<1 m). This heterogeneous, temporally variable deformation of the bed differs from many applications of the bed-deformation model but is consistent with subglacial measurements at modern glaciers.

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1. Introduction

Convincing evidence indicates that glaciers can deform their soft beds. Deformation has been measured beneath a handful of modern glaciers with instruments or markers inserted in the bed either through boreholes or from tunnels (Boulton and Hindmarsh, 1987; Blake et al., 1992; Iverson et al., 1995, 2003, 2007; Boulton and Dobbie, 1998; Boulton et al., 2001; Kamb, 2001; Kavanaugh and Clarke, 2006; Truffer and Harrison, 2006). Basal sediments deposited by former ice masses provide clear geologic evidence of deformation at both macroscopic (e.g., van der Wateren et al., 2000) and microscopic scales (see Menzies et al., 2006, for a review). These observations, considered with less certain but suggestive geophysical inferences (e.g., Blankenship et al., 1987; Anandakrishnan et al., 2007), provide support for suggestions that

ice masses can move through widespread, deep shear of their beds and that this shear can account for most glacier movement and basal sediment transport (e.g., Alley et al., 1987; MacAyeal, 1992; Jenson et al., 1995; Boulton, 1996).

Evaluating this hypothesis, however, requires addressing problems that are more challenging than simply determining whether the bed deformed. Were bed shear strains sufficiently large to account for most glacier motion? Was deformation widespread and pervasive over the bed area? Did deformation extend to significant depths in the bed? Observations beneath modern glaciers have not provided complete answers to these questions because subglacial deformation has been measured only over short periods (hours to months) and miniscule fractions of glacier beds. In contrast, the geologic record provides inherently time integrated data and access to broad areas of former beds. The challenge, in this case, however, is independently and quantitatively linking characteristics of bed sediments to strain magnitude and direction. This is a particular problem in studying macroscopically homogeneous basal tills that were commonly the substrates for vast areas of Pleistocene ice

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sheets. Without an independent foundation for interpreting the strain history of such tills, convergence on correct answers or even the development of clear consensus is unlikely. Consensus is clearly lacking regarding the importance of bed deformation in sediment transport. Consider, for example, the reviews of Boulton et al. (2001) and Piotrowski et al. (2001), who interpret characteristics of the glacial sedimentary record to reach strikingly different conclusions regarding bed deformation.

The goal of this work was to study the basal till of the last advance of the Superior lobe of the Laurentide ice sheet—the Douglas member of the Miller Creek formation (Fig. 1) (Johnson, 1983)—to evaluate the kinematics of its deformation. This till is well exposed along the south-shore bluffs of Lake Superior in northwestern Wisconsin. As a strain indicator, we measured till anisotropy of magnetic susceptibility (AMS) of intact samples collected in vertical profiles. AMS has been used as an indicator of till fabric previously (Fuller, 1964; Gravenor et al., 1973; Stupavsky et al., 1974; Gravenor and Stupavsky, 1975; Boulton, 1976; Eyles et al., 1987; Stewart et al., 1988; Principato et al., 2005), but in this study results of laboratory ring-shear experiments (Hooyer et al., 2008; Iverson et al., 2008) were used to calibrate AMS fabrics to the magnitude and direction of simple shear. This allowed quantitative evaluation of shear-strain magnitude, direction, and shear-plane orientations over lengths scales ranging from 0.2 m to 20 km. In addition, sand-grain fabrics were also measured at some locations for comparison with AMS fabrics. Results allow inferences regarding the state of strain in the bed that have not been possible in previous studies of glacial sediments.

2. AMS fabric development in sheared till

When an intact sediment sample is subjected to a magnetic field of strength, H, the strength of the magnetization induced by the sediment, M, is kH, in which the constant k is called the susceptibility (Tarling and Hrouda, 1993). Susceptibility usually results from minute quantities ($<1\%$) of any combination of ferromagnetic, paramagnetic or diamagnetic grains. The value of k commonly varies with direction. Thus, k is characterized with a second-rank tensor and visualized with an AMS ellipsoid. The ellipsoid has lengths of its long, intermediate, and short axes proportional to the principal susceptibilities k_1, k_2, and k_3, respectively (Fig. 2). The AMS ellipsoid can be oriented with respect to either grain morphologic
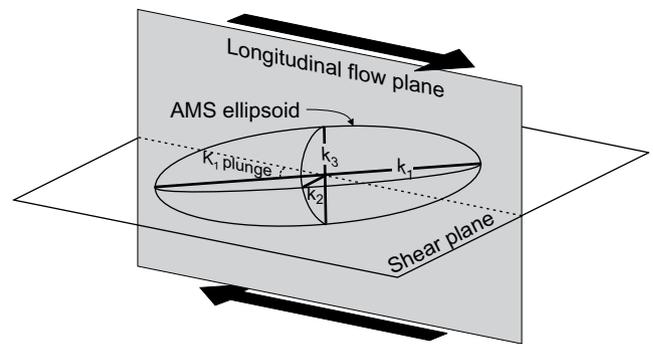

Fig. 2. AMS ellipsoid showing steady-state average orientations of principal susceptibilities in simple shear, attained at strains greater than ~ 25 in ring-shear experiments (Hooyer et al., 2008; Iverson et al., 2008).

or crystallographic axes, depending upon the magnetic mineralogy. For the till of the Douglas member, the dependence of susceptibility on temperature and the hysteresis properties of induced fields indicate that silt-sized magnetite grains dominate susceptibility (Hooyer et al., 2008). Magnetic anisotropy induced by magnetite is morphologically controlled (Tarling and Hrouda, 1993), such that the long axis of the AMS ellipsoid is parallel to the long axes of magnetite grains, as averaged over the volume of a till specimen.

The rotational strain induced by shear of till rotates silt-sized magnetite grains, thereby affecting the orientation of the AMS ellipsoid for a particular sample. Collection of 25 or more samples provides a sufficient number of k_1 orientations to compute a "k_1 fabric," with its strength and direction systematically related to strain magnitude and direction. Unlike direct measurements of particle orientations in outcrop or thin section, there is virtually no human subjectivity in AMS measurements, and each measurement reflects the volume-averaged effect of many grains, such that orientation data are inherently less noisy. Moreover, unlike traditional particle fabrics in which the intermediate and short axes of grains contain little information, directions of k_2 and k_3 help further define the state of strain.

To determine the relationship between AMS fabric characteristics and the state of strain in the Douglas Till, ring-shear experiments were conducted with it to various strains up to 714. The procedure (Hooyer et al., 2008; Iverson et al., 2008) and apparatus (Iverson et al., 1997) have been described in detail elsewhere. A thoroughly mixed, water-saturated till specimen was contained in an annular chamber with an outside diameter of 0.6 m, a width of 0.115 m and height of 0.08 m. This till was first consolidated under a normal stress of 65 kPa and then sheared at a speed of 400 m yr^{-1}; both values are appropriate for some soft-bedded glaciers (e.g., Engelhardt and Kamb, 1997, 1998). Fabrics are not expected to be sensitive to these variables, as long as shearing rates are non-inertial (Iverson et al., 2008). 25–75 intact till samples were collected in plastic boxes (18 mm cubes) after each experiment from a zone in which strain closely approximated uniform simple shear, as indicated by displacement markers. Shear strain was calculated by dividing the shearing displacement at the specimen centerline by the measured shear-zone thickness.

Results illustrate how AMS fabric develops in the Douglas Till during progressive simple shear (Fig. 3). Orientations of k_1 at zero shear strain form a weak girdle pattern as plotted on a lower-hemisphere stereonet, with an S_1 eigenvalue (Mark, 1973) of ~ 0.52 (no fabric would yield $S_1 = 0.33$). This weak fabric prior to shearing reflects the effect of pre-shearing consolidation on grain rotation. Clustering of k_1 orientations increases as shear strain accrues but at an exponentially decreasing rate until fabric strength becomes steady at a strain of ~ 25. We call the strain at which fabric becomes steady the critical strain (Iverson et al., 2008). Properties of the
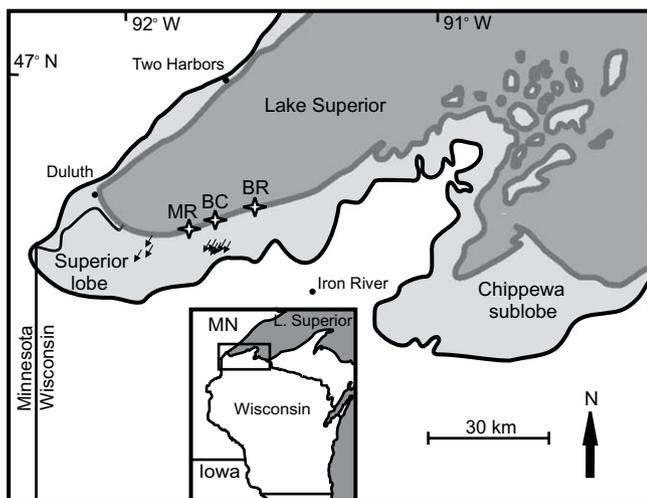

Fig. 1. Maximum extent of the Lakeview advance of the Superior lobe (light gray), with the locations of the three sampled exposures: Middle River (MR), Bardon Creek (BC) and Brule River (BR). Short arrows schematically indicate locations and trends of low-relief flutes identified by Clayton (1984).