# Laboratory study of the frictional rheology of sheared till

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[1] Deformation of till produces power law creep for low strain at stresses high enough to cause permanent deformation but below the shear strength. Experiments were conducted on till (a mixed size granular material) from Matanuska Glacier, Alaska, and the Scioto (Ohio) Lobe of the Laurentide Ice Sheet (Caesar till). We deformed till in double direct shear under fixed shear velocity or shear stress (creep). Normal stress ranged from 50 kPa to 5 MPa at shearing rates ranging from 1 to 300 $\mu$m/s for 1 cm thick samples. Creep was induced via small step perturbations in stress. Fabric development within till layers was investigated by varying shear strain prior to creep tests. In velocity-controlled experiments, till deforms as a nearly Coulomb plastic material with slight velocity strengthening, corresponding to a stress exponent, $n > 60$. Creep experiments conducted well below the shear strength indicate lower $n$ values, increasing as shear stress increases. With increasing initial strain and inferred fabric development, the creep strain rate decreases while $n$ increases. Experiments at a normal stress of 1 MPa and no initial strain show $n = 6.8$, increasing to $n = 17.5$ at higher shear strains; however, strain rate was still decreasing and thus these values represent maximum estimates. Our data show that in the absence of dilatant hardening till exhibits rate sensitivity at strain of order 1 or less. At low strains, $n$ likely depends on consolidation state, permeability, and dilation. Deformation is nearly rate insensitive (Coulomb plastic) at shear stress near the shear strength or at high strain.

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## 1. Introduction

[2] Glaciers can move by a variety of processes, with deformation of subglacial till playing a major role for some valley glaciers, ice streams, and ice sheets [e.g., *Paterson*, 1994; *Alley*, 2000; *Clarke*, 2005]. Seismic studies have shown that the material under fast-moving ice streams is highly porous water-saturated sediment (till) [*Alley et al.*, 1986; *Blankenship et al.*, 1986; *Peters et al.*, 2006]. The actively deforming layer, which ranges in scale between centimeters and several meters [e.g., *Kamb*, 1991; *Engelhardt and Kamb*, 1998; *Truffer et al.*, 2000], is produced by reworking of sediment or by wear processes such as abrasion or plucking. At high effective stress (overburden stress minus pore water pressure), the shear strength of till is larger than the shearing resistance of ice, so deformation only occurs within the ice; at low effective stress, till is more likely to deform than ice [e.g., *Engelhardt et al.*, 1990; *Paterson*, 1994]. Effective stresses may range from a few kPa or less to a few hundreds of kPa with channelized water drainage favoring higher values [*Alley et al.*, 1989a; *Engelhardt et al.*, 1990; *Paterson*, 1994; *Engelhardt and Kamb*, 1997]. Low effective stress can also limit bed deformation by allowing sliding at the ice-bed interface [e.g., *Kamb*, 2001; *Iverson et al.*, 2003].

[3] Early studies of bed deformation assumed a viscous or near-viscous relation for till deformation [e.g., *Boulton and Hindmarsh*, 1987]. Laboratory tests of till deformation are sparse [e.g., *Tulaczyk*, 2006], but have produced important results leading to the idea that till is more nearly a Coulomb plastic (treiboplastic) material [e.g., *Kamb*, 1991, 2001; *Iverson et al.*, 1997, 1998; *Tulaczyk et al.*, 2000]. However, debate still exists as to whether till is best characterized by a "viscous" rheology (with a nearly linear relation between shear stress and strain rate) or "plastic" rheology (for which shear stress is related to strain rate raised to a power of 10 or more) [e.g., *Kamb*, 1991; *Jenson et al.*, 1995; *Hindmarsh*, 1997; *Iverson et al.*, 1998; *Alley*, 2000; *Tulaczyk et al.*, 2000; *Fowler*, 2003, *Kavanaugh and Clarke*, 2006]. This study aims to couple current ideas on frictional rheology, drawn in part from studies in fault mechanics and granular materials, with those of Coulomb plastic failure and time-dependent viscous creep at stresses below the steady shear strength at high strain.

## 2. Terminology

[4] Technical terms differ between the various communities that study friction and the rheology of glacial and

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