Experiments on the dynamics and sedimentary products of glacier slip

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Abstract

Experimental work in glacial geomorphology is focused almost entirely on processes in the thin shear zone at the beds of sliding glaciers, where ice at its pressure-melting temperature moves over either rigid rock or deformable till. Experiments with rotary shear devices illuminate constitutive behavior there, central to the dynamics of fast-moving glaciers, and provide a foundation for interpreting the sedimentary record of glacier slip and associated sediment transport. Results from experiments designed to study ice sliding over a rigid wavy bed, shear deformation of till, and plowing of clasts across the surface of a till bed point to a common conclusion: drag at the bed can decrease with increasing slip velocity, thereby concentrating driving stress elsewhere and promoting rapid glacier flow. This rate-weakening behavior at glacier beds is in contrast to the viscous slip resistance assumed in ice-sheet models and most efforts to determine distributions of basal drag from glacier surface velocities. Ring-shear experiments in which various basal tills and more idealized materials are sheared to high strains provide quantitative insight into grain size evolution, mixing at contacts between basal tills, microstructure development, particle-fabric development, and development of anisotropy of magnetic susceptibility. Preferred orientations of principal magnetic susceptibilities provide the most dependable and complete description of till shear patterns. When applied to basal tills of the geologic record, magnetic till fabrics measured along thick till sections and calibrated experimentally indicate that deformation of the bed by two lobes of the Laurentide ice sheet was shallow (<1 m), patchy, and occurred as till progressively accreted. Rates of sediment transport by bed shear were thus significantly less than estimates based on models that invoke deep, pervasive shear of the bed. The lack of an experimental tradition in glacial geomorphology leaves many research avenues open for exploration but also increases the challenge of demonstrating the relevance of experimental results to theoretical and field-based studies.

Keywords: experiments; glacier; sliding; bed deformation; till; fabric

1. Introduction

Laboratory experiments in geomorphology are increasingly viewed as scaled-down efforts to study landform evolution. For example, Paola et al. (2009), in a thought-provoking review of experimental work in geomorphology and stratigraphy, described scaled-down models of fluvial landscape evolution and sedimentation. These authors emphasized that, although formal scaling requirements cannot be met, experiments at greatly reduced scales help reveal the system behavior and self-organized complexity of evolving landscapes. Paola et al. commented that this emphasis on physical landscape-evolution models is ushering in ‘an era in which experimentation will assume fully its natural role alongside theory and field study in the triad of fundamental approaches in stratigraphy and geomorphology.’

Although we too would like to see experimentation in our field assume a prominent place alongside theoretical and field studies, we question whether study of landscape evolution should necessarily be the driving force for experimentation in geomorphology. Many geomorphological processes, of course, have profound importance outside the context of landscape evolution and affect human welfare over time scales that are—relative to those of most evolving landscapes—immediate. For example, in the study of glacial processes, experiments designed to shed light on slip dynamics at glacier beds can improve numerical models of flow acceleration of marine-terminating glaciers. Accelerations of such glaciers over the last few decades have been a major contributor to increasing rates of sea-level rise (Rignot and Kanagaratnam, 2006; Shepherd and Wingham, 2007; Rignot et al., 2011; Mouginot et al., 2014) and are one of the principal sources of uncertainty in predicting sea level over the next century (IPCC, 2013). Thus, if a new era of

experimentation in geomorphology is indeed underway, we hope it is motivated by immediate societal needs as well as by the natural interest of geomorphologists in landscape evolution.

Virtually all experiments in glacial geomorphology have been designed to investigate processes in the thin shear zone at the beds of glaciers that result from glacier slip. In this zone, ice at its pressure-melting temperature either slides over rough bedrock (i.e., hard bed) or moves on a deformable layer of wet sediment, usually till (i.e., soft bed). This experimental focus on glacier-bed processes is easy to appreciate: they are usually inaccessible to readily interpretable field measurements, can activate the most dynamic behavior of glaciers (e.g., Clarke, 2005), and commonly leave a sedimentary record that provides clues to that behavior.

Herein we describe experiments that bear on the constitutive behavior of the ice–water–till–rock system at glacier beds and on the products of movement there preserved in the geologic record—research that parallels in some ways extensive experimental work on crustal faulting (e.g., Logan et al., 1992; Scholz, 2002). The overriding goal is to provide constraints on slip dynamics and kinematics that can inform models of the flow of modern and past glaciers and of the origins of subglacial sediments and landforms. We confine our discussion to results obtained with rotary shear devices because progress on these problems generally requires large slip displacements that only rotary devices allow. Most such work has been done with two devices at Iowa State University, so this review focuses primarily on that work. We conclude with a discussion of scaling issues, implications of experimental work (to date) and future priorities.

2. Rotary devices for study of subglacial processes

Two kinds of rotary devices are used to study motion at glacier beds and its effects. One kind of device (Fig. 1) shears only water-saturated sediment (Iverson et al., 1997; Larsen et al., 2006)

and apart from its larger size has the general configuration of some ring-shear devices used in geotechnical testing (Bishop et al., 1971). A second device, the Iowa State Sliding Simulator (ISSS), keeps a ring of ice (0.9 m O.D., 0.25 wide, ~0.22 m tall) at the pressure-melting temperature while the ring is dragged over either a hard or soft bed (Fig. 2) (Iverson and Petersen, 2011). Important design features are common to both kinds of devices:

- Shearing displacement is unlimited to allow the development of steady shear resistance or speed.
- Shearing is in a zone oriented perpendicular to gravity, as is close to being true subglacially. This orientation is essential for studying some subglacial processes in which body forces are relevant (e.g., till deformation) and rules out Couette-type devices (e.g., Brepson, 1979), in which the shear zone is orientated vertically between rotating and fixed cylinders.
- Shearing is capable of being actuated by applying either a steady shearing rate or shear stress and measuring the other parameter as a dependent variable. Having the option of either rate- or stress-controlled experiments broadens the range of processes that can be studied and the range of accessible parameter space.
- A vertical stress normal to the shear zone is applied and kept steady, while the volume of the sample chamber is allowed to change, as demanded by expansion or contraction of either cavities at the ice-bed interface or till pores.
- Water within cavities or till pores is allowed to move into or out of the sample chamber as they change their volume. Experiments are therefore *drained* in the vernacular of geotechnical testing (Clarke, 2005), although in the case of pore expansion or contraction of sufficiently impermeable till this drained state does not preclude development of nonhydrostatic pore pressure (e.g., Moore and Iverson, 2002).

- Sample chambers containing ice with an underlying bed or exclusively till are sufficiently large to accommodate essential bed properties, such as nonmatrix-sized grains within till (i.e., pebbles) and hard beds with sufficiently large roughness elements to allow testing of constitutive rules for sliding. Scaling limitations are discussed in section 5.0.
- Walls of sample chambers are either transparent or contain windows that allow direct observation of motion.

The ISSS must, in addition, keep the ice ring (Fig. 2B) at its pressure-melting temperature while minimizing melt rates along its periphery so that durations of experiments (~2 months) can be maximized. The device resides in a cold room kept at $1 \pm 0.5^\circ\text{C}$. A glycol-water mixture, with its temperature controlled by an external bath, circulates around the sample chamber to buffer temperature fluctuations in the cold room and provide the required small but steady heat flux to the ice ring (Iverson and Petersen, 2011). The fluid temperature is set to $\sim 0.001\text{--}0.005^\circ\text{C}$ —only a few hundredths of a degree above the pressure-melting temperature of the ice during experiments—with the sample chamber well insulated at its boundaries, so heat fluxes responsible for melting are, indeed, very small.

3. Constitutive behavior

3.1. Slip across a hard bed

Glacier sliding over a rough bedrock surface commonly accounts for most of a glacier's surface velocity (Cuffey and Paterson, 2010), and rates of bedrock abrasion (Hallet, 1979) and quarrying (Iverson, 2012) depend on sliding speed. The steady-state relationship between sliding speed and the drag on the bed (i.e., basal shear stress) is most fundamental and has probably received more theoretical attention, beginning with Weertman (1957), than any other single

glacial process. Weertman's theory, as well as subsequent theories that used more realistic roughness elements and more elegant mathematics (Nye, 1970; Kamb, 1970), indicated that drag should increase monotonically with sliding speed. This stabilizing viscous slip resistance is assumed in applying the basal boundary condition of ice-sheet models (Huybrechts, 1993; Pattyn et al., 2008) and in inverting measured glacier surface velocities to estimate patterns of basal drag (MacAyeal, 1992; MacAyeal et al., 1995).

Some theoreticians, however, have also long suspected that separation of ice from the lee of bed obstacles—a process for which there is considerable geomorphic (Walder and Hallet, 1979; Hallet and Anderson, 1980; Hooyer et al., 2012) and glaciological (Iken et al., 1983; Anderson et al., 2004) evidence—could radically change this simple proportionality between slip resistance and sliding speed (Lliboutry, 1968, 1979; Fowler, 1987; Schoof, 2005). Specifically, as cavities form in the lee of bed obstacles ice will contact only part of the upglacier face of the obstacle immediately downstream. Because bed obstacles have convex stoss surfaces for progressively higher sliding speeds and larger cavities ice will be in contact with progressively smaller slopes higher on bed obstacles. Therefore, the drag on the bed at low speeds should increase with increasing speed, but once cavities extend beyond points of inflection of stoss surfaces, drag should decrease with increasing speed. This *double-valued drag* hypothesis cannot be tested with field data because local basal drag cannot be measured subglacially.

Experiments with ISSS, using a sinusoidal bed designed so that stoss surfaces have radially uniform slopes (Fig. 2B), provided the first test of this hypothesis (Zoet and Iverson, 2015). Experiments were conducted at constant sliding speeds or shear stresses and carried out until the other of these variables became steady, together with the development of cavities of steady size (Fig. 3A). Effective pressure, which was equal to the vertical stress on the ice ring (500 kPa)

because water pressure was atmospheric, was kept steady. Results indicated that the drag response is indeed double-valued: basal shear stress (drag) peaked at a small sliding speed ($\sim 5 \text{ m y}^{-1}$) and then decreased at higher speeds once steady-state cavities extended beyond the inflection point of stoss surfaces (Fig. 3B). Lliboutry's (1968, 1979) theory of sliding with ice-bed separation provides a good estimate of the measured speed-drag relationship (Fig. 3B). Although ice in the experiments was synthetic, during ice deformation associated with sliding the ice acquired a single maximum (Fig. 4) or multiple maximum C-axis fabric (Iverson and Petersen, 2011) centered on a pole normal to the bed, like that of ice near the beds of temperate glaciers (Hooke, 2005). Ice rheology in the experiments was thus expected to be comparable to that of the basal ice of glaciers.

3.2. Till deformation

3.2.1. Elasticity

Elastic deformation of subglacial till accounts for negligible glacier motion but can provide a rare means of estimating local shear stress on the bed from records of deformation provided by tiltmeters (e.g., Blake et al., 1994; Iverson et al., 2003, 2007; Harrison et al., 2004; Kavanaugh and Clarke, 2006). Iverson et al. (1999) used the ring-shear device of Fig. 1 to determine the shear modulus of till studied subglacially with tiltmeters at Storglaciären, Sweden. The modulus, $G = d\tau/d\gamma_e$, where τ is the shear stress and γ_e is the resultant elastic strain, is larger at higher effective stress, P_e , and with smaller increments of elastic strain, $d\gamma_e$. Detrending a record of till deformation from Storglaciären to remove permanent strain and accounting for the dependence of G on P_e and $d\gamma_e$, allowed the local shear stress on the till to be calculated from the record of till deformation. Local shear stress varied in proportion to $P_e^{1.7}$. The nonlinearity resulted from

water flooding most of the ice-bed interface when P_e was low, thereby causing decoupling of ice from the bed (Iverson, 1999)—an effect also observed in subsequent field experiments at Engabreen, Norway (Iverson et al., 2007).

3.2.2. Rheology

Experiments have been central in demonstrating that till—as a two-phase material consisting of rock grains in frictional contact and pore water of negligible shearing resistance—does not obey a fluid rheology if sheared at glacial rates. At sufficiently high strains in its so-called critical state, once till has attained a porosity and shearing resistance that are steady under the ambient effective stress, experiments with various devices indicate that idealizing till as a Coulomb plastic is a good approximation (Kamb, 1991; Iverson et al., 1998; Tulaczyk et al., 2000). Thus, steady shearing resistance, τ_u , is insensitive to strain rate (Fig. 5A) and increases linearly with effective pressure (Fig. 5B): $\tau_u = c + P_e \tan \phi_u$, where ϕ_u is the ultimate (steady-state) friction angle, and c is cohesion that might persist in the critical state. Evidence for viscous or viscoplastic fluid behavior—a direct proportionality between shearing resistance and strain rate—is thus lacking and an obstacle for modelers who seek straightforward ways to determine glacier velocity and till flux from basal shear stress. Note that the data indicate a slight tendency toward till weakening with increasing shearing rate (Fig. 5A), a requirement for stick-slip motion displayed by some soft-bedded glaciers (Wiens et al., 2008; Winberry et al., 2009).

Experiments also indicate, however, that transient deformation of insufficient magnitude for porosity to have adjusted to the ambient effective stress can lead to more complicated behavior than the critical-state relationships of Fig. 5. For example, an overconsolidated till, with porosity adjusted to a previously higher effective stress, will dilate upon shearing (e.g., Damsgaard et al.,

2013). If the time scale for dilation is less than the time scale for pore-pressure diffusion into the opening pore space, pore pressure will decrease during dilation, increasing effective pressure and shearing resistance (Clarke, 1987; Iverson et al., 1998, see also Reynolds, 1885). Stress-controlled experiments demonstrate how this strengthening can stabilize slip events, which are eventually triggered once slip and associated dilation have slowed sufficiently to allow pore pressure to increase back to a threshold magnitude (Fig. 6) (Moore and Iverson, 2002). Thus, through this hydraulic effect, Coulomb-plastic behavior can give rise to episodic pseudo-viscous slip responses that can potentially influence the development of subglacial landforms, such as drumlins (e.g., Piotrowski, 1987). Such responses cannot persist under a particular effective stress past the early stages of deformation when till is dilating.

3.2.3. *Slip across a soft bed*

Ring-shear experiments also demonstrate how feedbacks between slip and pore pressure can weaken the ice-till interface and accentuate slip there. Field measurements with instruments in the soft beds of glaciers indicate that when effective stress is falling or low, the tendency is strong for basal motion to be focused at or very near the bed surface (Fischer and Clarke, 1997; Iverson et al., 1999, 2007; Engelhardt and Kamb, 1998; Boulton et al., 2001; Truffer and Harrison, 2006). The leading hypothesis for such motion is that it occurs largely by plowing, in which sliding ice drags clasts at the bed surface across the bed, with yielding of till downglacier from clasts to enable their motion (Brown et al., 1987; Alley, 1989; Iverson, 1999; Tulaczyk, 1999). Experiments in which rigid hemispheres of different sizes were dragged across the surfaces of till beds demonstrate the pore-pressure feedback that reduces drag at the till surface as clasts plow: compaction of till downglacier from plowing clasts can occur at a rate that outpaces pore-pressure diffusion away from the compacting zone, so that pore pressure

increases, reducing the till strength and allowing clasts to plow at a lower shear stress (Thomason and Iverson, 2008; Iverson, 2010) (Fig. 7). The resultant inverse relationship between the steady drag on clasts and rate of slip constitutes another mechanism for *rate-weakening* at a glacier bed.

4. Sedimentary record

Interpretations of the sedimentary products of glacier slip historically have overwhelmingly relied on geologic inferences from the sedimentary record (e.g., Flint, 1957) and field observations at the beds of modern glaciers (e.g., Boulton, 1970). Unlike study of the fluvial sedimentary record with its long history of experimental work (e.g., Gilbert, 1914), glacial geomorphology does not have an analogous experimental tradition. Not surprisingly, therefore, the last two decades of experiments with rotary shear devices have provided a useful complement to field observations. To date, the focus of such work has been on the products of bed deformation, rather than on sediment transport in basal ice, owing to the only recent availability of a rotary device that can accommodate sliding ice (Fig. 2).

4.1. *Comminution and grain size evolution during bed shear*

Iverson et al. (1996) used the ISU ring shear device (Fig. 1) to study grain size evolution as a function of shear strain in a deforming bed. To speed up the process of grain comminution, a brittle but weak material was sheared: mudstone particles initially 2.0–3.3 mm in diameter that were about two orders of magnitude weaker than common crystalline rocks. The rate of shearing displacement (320 m y^{-1} , at the centerline of the sample chamber) and effective normal stress (84 kPa) were kept steady. Motivation for the experiments came from the hypothesis that crushing and abrasion of grains within grain bridges or networks—groups of grains that support anomalously high shear and normal stresses during shear—produce a grain size distribution with

a steady-state fractal dimension of $m = 2.8-3.0$ (Hooke and Iverson, 1995). The fractal dimension is defined so that if N is the number of particles of diameter d , then

$$N(d) = N_0 \left(\frac{d}{d_0} \right)^{-m} \quad (1)$$

where N_0 is the number of particles of a reference size class d_0 . A small load cell and platen (18 mm diameter) in the normal-load plate of the ring-shear device recorded local normal stresses to study grain bridging.

Results demonstrated that the grain size distribution did indeed become fractal with progressive crushing and abrasion of grains, and with sufficient shearing attained a steady-state fractal dimension of ~ 2.85 (Fig. 8) (Iverson et al., 1996). Local normal stresses fluctuated with amplitudes of 50-250 kPa during the initial phases of shear, but fine sediment produced by crushing of grains caused homogenization of intergranular stresses that promoted abrasion over crushing, with a steady fractal dimension larger than that from crushing alone (~ 2.6 , Biegel et al., 1989).

Microfossils in some sediments, for example marine sediments that contain populations of pennate and centric diatoms, allow comminution associated with bed deformation to be assessed. Ring-shear experiments with sediments from the Ross Sea indicate that shearing increases the relative abundance of centric diatom tests to values $> 90\%$, owing to preferential comminution of elongate, more fragile pennate diatoms (Scherer et al., 2004). In contrast, hemipelagic muds of the Antarctic continental shelf not subjected to bed deformation generally contain $> 50\%$ pennate diatoms. Diatom comminution in this case, therefore, provides evidence of whether marine sediments have been sheared subglacially.

4.2. *Mixing across sedimentary contacts during bed shear*

Basal tills in a sedimentary succession may display mixing across their contact proportional to the magnitude of bed shear, thereby allowing mixing to serve as a proxy for strain magnitude. This hypothesis was tested with the ISU ring-shear device by shearing layers of beads of different colors and tills with different shale-particle contents (Hooyer and Iverson, 2000a).

Results indicated that mixing can be successfully modeled as a diffusive process, using Fick's second law written in terms of cumulative shear strain rather than time. Mixing did indeed increase with shear strain, but the diffusivity decreased significantly with cumulative strain such that diffusive mixing became progressively less rigorous as strain accrued. Random vertical displacements of particles associated with shear are unlikely to give rise to inherently non-linear diffusive mixing. Thus, this decrease in diffusivity with increasing strain may have reflected either the initial roughness of the contact between layers or strain localization as shear progressed, both of which could have yielded more vigorous, uniform mixing during the early stages of shear (Hooyer and Iverson, 2000a).

4.3. *Microstructure development during shear*

Microstructures in deformed tills, studied optically in thin sections, have been used extensively to make inferences about stresses, pore-water pressures, and deformation within former subglacial till layers of the geologic record, nearly always without the benefit of experimental results to help guide interpretations (e.g., van der Meer, 1993; Menzies, 2000). The most ubiquitous microstructures in deformed tills are microshears, visible under polarized light as thin, birefringent lineaments. Citing experimental studies of sheared clay and fault gouge (Morgenstern and Tchalenko, 1967; Logan et al., 1992), Thomason and Iverson (2006) suggested

that the combined lengths of microshears parallel or subparallel to the plane of shearing in tills should increase with increasing strain. They suggested that strain magnitude might be proportional to a dimensionless index, I_L , that reflects the degree to which low angle shears accommodate strain:

$$I_L = \frac{\sum_{i=1}^n L_i \cos \Psi_i}{\sum_{i=1}^m H_i \cos \theta_i + \sum_{i=1}^n L_i \cos \Psi_i} \quad (2)$$

where, respectively, n and m are the numbers of low-angle and high-angle shears (the division arbitrarily set at 25°), L and H are the lengths of low-angle and high-angle shears, and ψ and θ are the acute angles between the macroscopic shearing direction and low-angle and high-angle shears.

Experiments carried out to high shear strains with different tills indicate that this index does tend to increase monotonically with strain. Thomason and Iverson (2006) studied microshear development in a sandy till (5% gravel, 72% sand, 23% silt and clay) and found that microshears became more pervasive and parallel to the shearing direction as strain increased, although values of I_L increased by only 10% between a shear strain of 5 and 108 (Fig. 9). Using a finer-grained till (2% gravel; 44% sand, 54% silt and clay) and a similar ring-shear device, Larsen et al. (2006) measured a larger, more progressive increase in I_L over the same range of strain (Fig. 9). Their attempts to experimentally correlate the frequency of other microstructural features, such as grain stacks and lineations and turbate structures, to strain magnitude did not reveal useful trends.

4.4. Grain and magnetic fabric development during bed shear

Deformation of basal tills of the geologic record causes preferred orientations of particles (fabrics) and magnetic anisotropy that results from preferred orientations of some ferromagnetic mineral grains (e.g., magnetite). Field studies have resulted in at least four hypotheses for fabric development resulting from subglacial shear of till: (i) it causes weak fabrics parallel to the shearing direction (Dowdeswell and Sharp, 1986; Hicock, 1992; Hart, 1994; Clark 1997); (ii) with sufficient strain it causes transverse fabrics (Glen et al., 1957; Carr and Rose, 2003); (iii) it causes variable fabric strength dependent on till porosity, water content, or layer thickness (Dowdeswell et al., 1985; Hart, 1994; Evans et al., 2006); and (iv) with sufficient strain it results in strong flow-parallel fabrics (Benn, 1995; Benn and Evans, 1996, 2010).

This lack of common understanding provides clear motivation for experimentally studying particle and magnetic fabric evolution as a function of shear-strain magnitude and orientation (Hooyer and Iverson, 2000b; Thomason and Iverson, 2006; Hooyer et al., 2008; Iverson et al., 2008; Shumway and Iverson, 2009). To date, experiments have been carried out with five different tills and a linear-viscous putty subjected to a state of strain in the ISU ring-shear device close to simple shear. In the center of the shear zone of the device (Fig. 1B), where particle orientations are measured at different strains, strain is approximately uniform (see Fig. 2 of Iverson et al., 2008).

Experiments with isolated, pebble-sized, prolate clasts, initially oriented normal to the shear plane (vertically) in putty and various tills, illustrate the kinematics of particle rotation in a shearing bed (Hooyer and Iverson, 2000b). Particles in the putty obey very closely the theory of Jeffery (1922), who predicted that in a shearing, linear-viscous, laminar fluid particles will rotate indefinitely, slowing their rotations when their orientations are near that of the shear plane but rotating through it (Fig. 10). In contrast, particles in till behave very differently: they also rotate

toward the shear plane but with sufficient strain attain a steady orientation parallel to the shearing direction and with a mild plunge upglacier (Fig. 10). Clasts generally do not rotate through the plane of shear. Experiments in which sand-grain rotation was monitored illustrate the same behavior (Thomason and Iverson, 2006). The difference in behavior reflects how the till matrix interacts with larger clasts. Unlike in a viscous fluid, fine matrix particles can slip across surfaces of rotating clasts (Hooyer and Iverson, 2000b), and Riedel shears develop in the shear zone at orientations that differ from that of the macroscopic shear plane (Thomason and Iverson, 2006); the result is that particles stop rotating and are held at a steady-state orientation, with their plunges upglacier. Jeffery (1922) speculated further that at high strains particles would attain an orientation that minimized their energy dissipation, with particles rolling about long axes and transverse to the shearing direction. Unsurprisingly, because particles quit rotating during the early stages of shear, this additional effect predicted by Jeffery has also not been observed in experiments with till, despite shear strains in some experiments exceeding 700.

Thus, with sufficient strain shear deformation of till with initially near-random particle orientations results in strongly clustered fabrics, with particle long axes oriented parallel to the shearing direction and plunging mildly upglacier (Fig. 11). Effects of deformation rate and effective pressure on fabric development are small, so cumulative shear strain is the dominant independent variable that causes fabric evolution (Hooyer and Iverson, 2000b; Iverson et al., 2008).

Fabrics based on the anisotropy of magnetic susceptibility (AMS) of multiple intact till specimens ($\sim 6 \text{ cm}^3$ each) from ring-shear experiments are consistent with experimental particle-fabric data and provide additional information about deformation kinematics. When till deforms, elongate magnetic grains rotate and partially align, such that the till magnetic susceptibility

varies with direction, as indicated by the principal susceptibilities of the susceptibility tensor, k_1 , k_2 , and k_3 (Tarling and Hrouda, 1993). If the magnetic mineral has so-called shape anisotropy (e.g., magnetite), the orientation of greatest susceptibility, k_1 , is parallel to the preferred orientation of particles. Experiments with several basal tills indicate that this preferred orientation mimics that of grains measured directly and show how fabric develops progressively with shear strain (Fig. 12). At small strains, grain long axes rotate toward the shear plane forming an asymmetric girdle that becomes clustered at higher strains, parallel to the shearing direction and plunging up to 30° upglacier. Steady-state, strongly clustered k_1 fabrics develop at strains of 7-30, comparable to strains required for the development of grain fabrics measured directly. Unlike the case of grain fabrics, the orientation of the longitudinal flow plane (which contains k_1 and k_3) and of the shear plane (which contains k_2) can be inferred from AMS fabric data (Fig. 13) (e.g., Shumway and Iverson, 2009). In addition, AMS fabric measurements, by allowing the difficult and subjective task of measuring grain long axes directly to be avoided and by averaging over many magnetic grains in a single intact till specimen, provide a more reproducible and accurate measure of fabric strength and orientation than do traditional grain fabrics (Iverson et al., 2008).

4.5. *Optically stimulated luminescence*

Bateman et al. (2012) used a ring-shear device similar to that of Fig. 1 to test the hypothesis that bed shear can reset natural luminescence signals, thereby potentially allowing basal tills to be dated using luminescence-based techniques. Results of shearing a quartz sand with a known naturally acquired paleodose indicated that stresses on grains during shearing—likely maximized during grain bridging events—produced an increase in the number of zero-dose grains. However,

some grains responded differently than others, preventing a simple relationship between shear-strain magnitude and the degree of resetting.

5. Scaling problems

In experiments with ISSS (Fig. 2) aimed at testing the double-valued drag relationship for glacier slip (Zoet and Iverson, 2015), a fundamental scaling problem involves the wavelengths of bed undulations. Recent theoretical models neglect regelation, both for convenience and because the small wavelengths of bedrock undulations for which regelation tends to be dominant—less than a few decimeters—tend to be rare on deglaciated bedrock, presumably because these small wavelengths are most susceptible to being smoothed by abrasion (Hooke, 2005). Thus, in experiments, in which bed wavelengths larger than a few decimeters are impractical (Iverson and Petersen, 2011; Zoet and Iverson, 2015), regelation is inhibited by using a bed material with a thermal conductivity approximately an order of magnitude smaller than that of most rocks. Ice, therefore, in these experiments moves past bed undulations by enhanced creep, rather than by melting and refreezing, consistent with theoretical models that consider only larger bed undulations. Another scaling condition that must be met, to allow application of the constitutive rule for ice deformation, is that ice crystals be smaller than bed undulations, so that crystal aggregates rather than individual crystals deform adjacent to bed undulations (Iverson and Petersen, 2011). In experiments to date with ISSS, average sizes of crystals that develop during sliding (Fig. 4) are ~25 times smaller than the wavelengths of bed undulations. A third potential scale-related problem in the hard-bed experiments is that the stress and velocity fields in the ice associated with sliding over bed undulations could be influenced by the rigid upper platen that grips the ice ring and drives it across the bed. To date, however, bed undulations have been used with heights that are smaller, by a factor of ~6, than the thickness of the ice ring. Thus, the

boundary layer where ice flow past undulations occurs is a small fraction of the total ice thickness (Iverson and Petersen, 2011; Zoet and Iverson, 2015).

In ring-shear experiments, aimed at studying bed deformation and associated processes, the largest grains in the till studied need to be removed—typically grains larger than 6-8 mm in diameter. Their removal satisfies the standard geotechnical testing protocol that no grains exceed one-tenth of the minimum dimension of the sample chamber (Head, 1989). Satisfying this protocol typically involves removing about 3-8% of the till volume (Iverson et al., 2008). For this reason, and for the related reason that shear zones are narrower experimentally (by up to about two orders of magnitude) than subglacially, some authors have questioned the viability of laboratory tests for inferring Coulomb-plastic behavior (Fowler, 2002; Schoof, 2007). However, the fact that tills with vastly different grain size distributions display this behavior indicates a clear lack of sensitivity to grain size distribution. Also, there is no mechanical reason why the fundamentally frictional behavior of rock grains sliding past each other would break down if the largest few percent of the grain size distribution is absent. The same is true if strain occurs over a zone decimeters in thickness (e.g., Cuffey and Paterson, 2010), rather than centimeters in thickness (Iverson et al., 2008), remembering that grain bridging is suppressed in tills owing to their poor grain sorting (Fig. 8). Worth noting is that these same grain size limitations have not slowed experimental progress in the field of geotechnical engineering, which since its inception has relied, with great success, on testing of small soil specimens to guide geotechnical design.

Removal of the largest particles from till may indeed, however, increase the steady-state strengths of particle and AMS fabrics that develop during shear. Deflection of till as it shears past large clasts would be expected to reduce the preferred orientation of smaller grains, although the extent of this effect upon removing only a few percent of the total till mass in experiments is

difficult to predict. Data from preliminary experiments with an extremely coarse-grained till (Johnson et al., 2010) yielded steady-state S_1 eigenvalues—a measure of the strength of k_1 clustering—of 0.75-0.77 (McCracken et al., 2014), less than the range measured with less stony tills, 0.83-0.96 (Hooyer et al., 2008; Iverson et al., 2008). Thus, there is some evidence that coarse texture reduces the degree of k_1 clustering. Fabric orientations (orientations of clustering as indicated by V_1 eigenvectors), however, will not differ between field and laboratory measurements, as long as samples for fabrics are collected in the field over areas that are large relative to the largest till grains within or near the sampling area.

Overall, although the necessarily reduced scales of experiments will always require that experimental results complement, rather than substitute for, field and theoretical approaches, scaling problems are less severe for these experiments than in scaled-down studies of landscape evolution in which sediment transport by turbulently flowing water is a central process.

6.0. Discussion

6.1. Constitutive behavior: implications

As noted, ice-sheet models, which are in part aimed at helping to predict glacier accelerations and associated sea-level rise, almost invariably have a boundary condition at the bed in which drag there increases monotonically with increasing sliding speed (Huybrechts, 1993; Pattyn et al., 2008; Pollard and DeConto, 2009). Furthermore, initial spatial distributions of basal drag in such models are commonly determined from measured surface velocities by using control methods in which bed drag is assumed to be directly proportional to depth-averaged speed (MacAyeal, 1992; MacAyeal et al., 1995). These practices are rooted in the idea that basal slip is

characterized by viscous deformation resistance, as described by classical theories of basal slip that do not include ice-bed separation (e.g., Weertman, 1957; Nye, 1970).

Experiments with rotary devices, to date, whether focused on hard-bedded sliding (Fig. 3), critical-state (steady) till deformation (Fig. 5), or plowing (Fig. 7), indicate the same surprising result: that over wide ranges of relevant glacier speed there can be a decrease in basal drag as the speed of basal slip increases. This rate-weakening has important implications for glacier flow dynamics (Schoof, 2005). If portions of a glacier bed weaken at progressively higher sliding speeds, forced say by weather or climate variability, the downslope component of the glacier weight that drives flow must be shifted to the glacier sides, ice shelves, or other parts of the bed that may offer viscous deformation resistance by virtue of their geometry or hydrology. Resultant increased lateral or longitudinal stresses would provide a feedback that promotes still more rapid glacier flow.

By adjusting the basal boundary conditions of flow models that can fully describe the three-dimensional state of stress in ice sheets, efforts should be made to explore the possible effects of rate-weakening at the bed on ice flow. Similarly, modelers who require inversions for basal drag based on control methods, rather than assuming viscous deformation resistance at the bed, should consider inverting directly for basal shear stress (e.g., Joughin et al., 2004).

Rate-weakening also has implications for modeling of bedrock erosion and sediment transport. Viscous deformation resistance during basal slip is invariably assumed in models of large-scale glacial erosion in orogenic belts, in which the speed of sliding over a hard bed must be calculated to determine rates of bedrock erosion (Egholm et al., 2009, 2012; Herman et al., 2011). Such models capable of including lateral and longitudinal stress gradients should explore

the possible effects of rate-weakening on slip-velocity distributions and the resultant evolution of erosional landforms. Rate-weakening in a soft bed, either by plowing (Fig. 7) or till deformation not associated with plowing (Fig. 5), will naturally tend to focus deformation in a thin zone and thereby limit the thickness and hence flux of till that moves by bed deformation. Data compiled by Cuffey and Paterson (2010) from studies of basal slip at soft-bedded modern glaciers indicate that deformation usually extends to depths of a few decimeters, with most motion usually occurring very near the glacier sole, broadly consistent with experimental results. Thus, experiments and field observations indicate that models that consider subglacial till to be a viscous or viscoplastic fluid that shears pervasively to depths of several meters (Alley et al., 1987; MacAyeal, 1989; Jenson et al., 1995; Boulton, 1996) probably greatly overestimate subglacial sediment fluxes from bed shear.

The actual implications of constitutive relations determined from experiments will depend on the extent to which theoreticians are willing to embrace experimental results, sometimes at the expense of convenience. Consider the formulation of models that attribute subglacial bedforms, such as ribbed moraine and drumlins, to a flow instability at the ice-till interface (Hindmarsh, 1998; Schoof, 2007; Fowler, 2009; Chapwanya et al., 2011). The idea that such landforms can develop from an interfacial, flow instability is intrinsically appealing, as is the mathematical formalism that is brought to bear on the problem. This family of models, however, to produce the instability that creates the amplification of bedforms, requires till properties that contradict experimental data. The till must have a *viscosity* (presumed to be much smaller than that of the ice); till flux by bed deformation must be proportional to the shear stress on the bed, which amounts to a viscous or viscoplastic rheological assumption for till. Till viscosity, rather than the stress at which till yields plastically, must increase with increasing effective pressure, and the

effective stress distribution is considered to depend only on total normal stress, such that the till pore-water pressure distribution is neglected. Thus, in these models till is treated as a fluid, despite little justification for doing so from either the experiments described herein or the geotechnical soils literature. The elevation of experimental work in geomorphology to its natural place alongside theory (e.g., Paola et al., 2009) cannot occur if experimental results are dismissed without adequate justification.

6.2. Sedimentary products: implications

Understanding of the dynamics of the shear zone at the beds of sliding glaciers is improved by knowledge of its kinematics. Studies of motion at the beds of modern glaciers through boreholes yield only local kinematic information, and remotely sensed geophysical data are commonly subject to a liberal degree of interpretation. The third approach—studying well-exposed basal tills of the geologic record—also unfortunately involves considerable interpretation. Experimental results can complement field studies by improving interpretations of basal till characteristics.

Experiments on till grain comminution and mixing, although they provide insight into the mechanics of these processes, need to be interpreted cautiously as indicators of bed deformation. Comminution experiments indeed help clarify the relationship between grain size evolution and the changing character of stress concentrations and comminution mechanisms with progressive bed deformation (Fig. 8). However, despite the attainment of a steady fractal dimension for the grain size distribution ($m \sim 2.85$, Eq. 1), Iverson et al. (1996) emphasized that a fractal dimension ‘greater than 2.6 in no way demonstrates that a till has undergone large strains.’ Fractal dimensions > 2.6 , simulated by Benn and Gemmell (2002) by mixing tills of different

textures, indeed bear this out. The different resistances to comminution of centric and pennate diatoms provide a more solid basis for inferring subglacial deformation (Scherer et al., 2004), although this criterion has obvious geographic limitations. The diffusivity associated with shear-induced mixing between till layers varied through a factor of ~50 in experiments, which together with the unknown initial roughnesses of till contacts in the sedimentary record prior to shear allowed only a gross upper bound on shear strain to be determined from field contacts (Hooyer and Iverson, 2000a). These mixing experiments do indicate, however, that sharp till contacts with no resolvable mixing across layers cannot have been subjected to significant shear strain that spanned the contact, owing to vertical particle motions that inevitably occur during shear. This conclusion is consistent with some interpretations of bedded tills as indicators of minimal bed deformation (e.g., Piotrowski and Tulaczyk, 1999).

More encouraging for inferring shear-strain magnitude is the prevalence of microshears (Fig. 9), as given by the index, I_L (Eq. 2). Larsen et al. (2006) used values measured from Quaternary basal tills in Denmark, Poland, and Svalbard, to infer shear strains of ~10, too small to have contributed significantly to glacier motion. Inferred strains, in that case, were uncertain because the index was applied to tills not studied experimentally, highlighting the best practice of working experimentally with the specific tills that require field interpretation. An inherent limitation of using this index is the subjectivity involved in identifying and measuring the combined lengths of microshears, which are commonly not well defined optically. Applying consistent scale and visibility thresholds for measurements is thus difficult.

Most helpful for inferring bed-deformation kinematics are preferred orientations of particles and of principal magnetic susceptibilities. Experiments provide some simple facts about fabric evolution and its relationship to shear-strain magnitude and orientation:

- 544 • Strong, steady-state, fabrics based on clast long axes and k_1 orientations develop at shear
545 strains of 7-30. These strains are low to moderate within the context of the bed-deformation
546 model of glacier flow, which requires higher strains to account for most glacier motion
547 (Thomason and Iverson, 2006). A cautionary note is that similarly strong fabrics can likely
548 also develop by lodgment of till from basal ice (e.g., Ham and Mickelson, 1994), so they
549 should be viewed as necessary but insufficient criteria for indicating unidirectional simple
550 shear in soft beds to such strains (Iverson et al., 2008).
- 551 • Steady clast long-axis and k_1 fabrics are parallel to the shearing direction and plunge
552 upglacier 5-30° (Fig. 11). For AMS fabrics, the orientation of the shear plane can be inferred
553 from the experimentally determined plunge and the orientation of k_2 , which lies in the shear
554 plane. The orientation of k_3 plunges steeply downglacier and along with k_1 lies in the
555 longitudinal flow plane (Fig. 13). Thus, in the common case of a massive basal till in the
556 geologic record without macroscopic strain indicators, the sense of shear and its orientation
557 can be inferred from orientations of principal susceptibilities.
- 558 • The Jeffery model of particle rotation, which predicts weak flow-parallel fabrics and
559 transverse fabrics at high strains, should not be used to help interpret till fabrics.
- 560 • Fabric development in till depends most sensitively on strain magnitude and orientation (Fig.
561 12). If these variables are poorly known, attributing fabric characteristics to other variables,
562 such as till thickness, water content, or the magnitude of shear or effective stress, is not
563 justified.
- 564 • AMS fabrics are both more accurate and contain more information about deformation
565 kinematics than traditional grain fabrics, although the method works best in fine-grained tills.

These precepts are just beginning to be used to infer magnitudes and patterns of bed deformation beneath past ice sheets. For example, in a basal till of the Lake Michigan lobe of the Laurentide ice sheet, k_1 and grain fabric azimuths change progressively over depths of decimeters, indicating progressive changes in shearing direction as till accreted to the bed (Thomason and Iverson, 2009). Orientations of principal magnetic susceptibilities show that shear planes were commonly not horizontal, such that deformation deviated from bed-parallel simple shear. Significant zones within till exposures (more than 50% of the till sampled) have k_1 fabrics too weak for till to have been sheared to moderate strains of 7-30. A basal till of the ice sheet's Superior lobe displays similar fabric variability vertically and laterally, with large differences in k_1 fabric azimuths ($>45^\circ$) over lateral distances of 2-30 m and inferred shear planes that commonly dip steeply (Shumway and Iverson, 2009).

These data indicate that the bed deformed heterogeneously in isolated patches (Piotrowski et al., 2004) or in anastomosing zones (Shumway and Iverson, 2009) with local major deviations from bed-parallel simple shear. Variations in fabric azimuths with depth indicate that till layers did not shear simultaneously at all depths but that as till accumulated at the bed it sheared in temporally shifting, shallow (<1 m) zones (Fig. 14). This pattern of subglacial till deformation (see also Larsen et al., 2004) is quite different from traditional applications of the bed-deformation model, in which the bed undergoes pervasive widespread simple shear to high strains and to depths usually larger than 1 m (Alley et al., 1987; MacAyeal, 1989; Jenson et al., 1995; Boulton, 1996; Hooke and Elverhøi, 1996; Dowdeswell and Siegert, 1999). On the other hand, these deformation patterns are consistent with most direct observations beneath modern soft-bedded glaciers, which commonly indicate steep, transient lateral gradients in basal water pressure (Hubbard et al., 1995; Murray and Clarke, 1995; Engelhardt and Kamb, 1997;

Kavanaugh and Clarke, 2001) and sensitivity of strain partitioning in the bed to basal water pressure (Blake et al., 1994; Iverson et al., 1999, 2003, 2007; Fischer et al., 1999; Boulton et al., 2001; Fischer and Clarke, 2001; Kavanaugh and Clarke, 2006). Not surprisingly, models of till deformation beneath modern glaciers based on data from subglacial sensors have highlighted its transient, local character (Fischer and Clarke, 1997; Fischer et al., 1999; Kavanaugh and Clarke, 2006).

Deformation patterns like those depicted in Fig. 14 affect sediment transport and basal slip dynamics. Sediment fluxes by bed deformation are far smaller than those of models that advocate deep, pervasive deformation of the bed, and basal shear stress concentrations (i.e., sticky spots, Alley, 1993; Stokes et al., 2007) can result from hydrologic heterogeneity that promotes rigid till, rather than from bedrock bumps or hills. Such deformation patterns may also affect the development of subglacial bedforms.

6.3. Future experiments

Lacking entirely from experimental contributions to glacial geomorphology and badly needed are experiments with ISSS (Fig. 2) that include sliding ice and a soft bed. Motivation for such experiments comes partly from the need for a constitutive rule that includes the combined effects of sliding, bed shear, and plowing. Although these processes have been studied separately (Figs. 3, 5, and 7), their relative importance likely changes as a function of sliding speed and effective pressure, perhaps leading to different constitutive rules operating over different ranges of parameter space. Given that soft-bedded basal slip gives rise to the most dynamic behavior of glaciers (Clarke, 2005), experimentally simulating this motion to the fullest extent possible should be a high priority. Also badly needed are experiments designed to study sediment

transport when glaciers move over a soft bed. Mechanisms of debris entrainment in ice (e.g., Alley et al., 1997), modification of that debris in basal transport (e.g., Dreimanis and Vagners, 1971), including fabric development in ice (Lawson, 1979; Bennett et al., 1999) and deposition of debris from sliding ice (so-called lodgment, Boulton, 1975), have been frequent sources of discussion for more than 45 years in glacial geomorphology (see Benn and Evans, 2010, for a review) but without a single experiment being conducted. Experimental results could help guide interpretations of basal ice facies (Lawson, 1979; Hubbard and Sharp, 1995) and the sedimentary record, such as distinguishing among different proposed origins of basal tills (Benn and Evans, 2010). Perhaps most importantly, this work on sediment transport would provide information for assessing till continuity (Alley, 2000; Iverson, 2010) and the fundamental processes that dictate whether a glacier bed consists of deformable sediments or rigid bedrock.

Additional hard-bedded experiments with ISSS are also warranted. The effect of different bed geometries on the relationship between drag and sliding speed needs to be explored (e.g., Gagliardini et al., 2007), as does the effect of debris in ice on frictional drag at the bed (Iverson et al., 2003; Cohen et al., 2005; Zoet et al., 2013). Abrasion and quarrying of bedrock should be studied with wavy or stepped rock beds to test bedrock erosion rules that are used widely in glacial landscape evolution models (e.g., Egholm et al., 2009; 2012; Herman et al., 2011).

Indeed, experimental work has been so limited in glacial geomorphology that pathways for making solid progress with a device such as ISSS are not difficult to identify. The more difficult challenge is ensuring—through well-designed experiments, convincing analyses, and clear exposition—that this progress is embraced by theoreticians and field workers.

Acknowledgements

Construction of ISU ring-shear device and ISSS and most of their subsequent use has been supported by grants from the National Science Foundation. We thank T. Herrman and D. Jones of the US Department of Energy Ames Laboratory for their help designing and fabricating ISSS. J. Piotrowski and an anonymous reviewer provided helpful comments on the manuscript.

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951 Figure Captions

952 Fig. 1. (A) Cross-section of the ISU ring-shear device and (B) detail of the sample chamber.

953 Solid light gray components rotate. Gear boxes (not shown) below the device are driven by an

954 electric motor in experiments in which shear rate is controlled. See Moore and Iverson (2002) for

955 a discussion of the device configured for experiments in which shear stress is controlled

956 (modified from Iverson et al., 1997).

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958 Fig. 2. (A) The Iowa State Sliding Simulator (ISSS). Two diametrically opposed gear boxes

959 rotate an annular platen, which grips the upper surface of the ice ring and drags it across a hard

960 or soft bed at either a constant speed or shear stress. A steady vertical stress is applied by a

961 servo-controlled hydraulic ram. The ice chamber resides in a tub, through which a glycol/water

962 mixture circulates and regulates the ice temperature. The temperature of the glycol/water mixture

963 is controlled to 0.01°C by an external bath and circulator (not shown). The apparatus is operated

964 in a walk-in freezer. (B) The ice ring and sinusoidal bed, with the surrounding ice chamber not

965 shown. The bed is rigid, polyoxymethylene plastic, with a low conductivity ($0.33 \text{ W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$) to

966 inhibit regelation. The ring slides over the bed and also along smooth aluminum walls that

confine the ring along its sides. The rigid bed can be replaced by a bed consisting of till or other sediment.

Fig. 3. (A) Longitudinal profiles of cavities at the ice-ring centerline at sliding speeds of 2.6, 7.25, and 290 m y^{-1} (gray lines), under a total vertical stress of 500 kPa and atmospheric pressure in cavities. Cavity geometry at 290 m y^{-1} was measured directly (x's) and fitted (gray line) using the theory of Kamb (1987). Error bars indicate $\pm$ one standard deviation of variability based on measurements of multiple cavities. Note the vertical exaggeration. (B) Drag on the bed. Mean steady shear stress as a function of sliding speed for a sinusoidal bed and a flat bed. Error bars indicate $\pm$ one standard deviation from the mean, once a time-averaged steady stress or speed was reached. The speeds (2.6, 7.25, and 290 m y^{-1}) correspond to the cavity geometries of part (A). The solid line is the sum of the shear stress estimated using a theory of sliding in the presence of cavities (Lliboutry, 1968, 1979) and the background shear stress measured with the flat bed.

Fig. 4. Ice crystal fabric developed during sliding. (A) A horizontal thin section of ice from an experiment under cross-polarized lenses. Ice was collected from ~ 1 mm above the cavity ceiling after a total sliding displacement at the ice-ring centerline of 6.51 m. The grid squares are 10 mm. (B) C-axis orientations of 150 crystals on a lower-hemisphere, equal-area plot, with Kamb contouring and a contour interval of 20° . The C-axes are centered on the vector normal to the shear plane. Both figures are oriented with respect to the sense of shear indicated. Initial C-axis orientations, prior to sliding, were close to random.

Fig. 5. (A) Till critical-state strength normalized by effective pressure, as a function of shear strain rate, from regressions of laboratory data from tests on five basal tills using ring-shear devices. Shear-strain rates were calculated by dividing shear rate by a measured (Iverson et al., 1998) or estimated (Tika et al., 1996) shear-zone thickness. (B) Till critical-state strength as a function of effective pressure for three of the five tills of part (A). Tests on the Cowden till and Lower Cromer till were conducted at an insufficient number of effective pressures to obtain a relationship (modified from Iverson, 2010). Tests on basal tills using devices other than ring-shear devices have yielded either no dependence of till friction on strain rate (Tulaczyk et al., 2000) or relationships in which friction depends on strain rate raised to a power less than 0.017, indicating essentially plastic behavior (Kamb, 1991; Rathbun et al., 2008, Iverson, 2010).

Fig. 6. Episodic, pseudo-viscous shear of the Storglaciären basal till owing to dilatant strengthening. A constant shear stress was applied to the till, and total normal stress was reduced in small increments until the till began to shear. Pore-water pressure was measured at three locations along the till-specimen centerline and within the shear zone. Shear resistance was measured and also calculated with the average pore pressure, total normal stress, and Coulomb friction rule. Cohesion was assumed to be negligible, based on past experiments with this till (Iverson et al., 1998), and friction angle was assumed to decrease linearly with porosity (Lambe and Whitman, 1969) as pores dilated progressively during shear (from Moore and Iverson, 2002).

Fig. 7. Rate-weakening from plowing. Steady shear stresses, normalized to their mean value, on hemispheres of two diameters, d (19 and 40 mm) as they plowed through the basal till of the Des

Moines Lobe at various steady speeds in ring-shear experiments. Also plotted are pore pressures in excess of hydrostatic measured in the till about one radius *downglacier* from the hemispheres (modified from Thomason and Iverson, 2008).

Fig. 8. Evolution of grain size and stress heterogeneity with grain comminution, during shear of initially equigranular siltstone grains in ring-shear experiments. Squares indicate fractal dimensions of the grain size distribution (Eq. 1) measured in three different experiments (different shades of gray). Also shown is normal stress measured in the upper platen of the ring-shear device (Fig. 1A) over a miniature platen 18 mm in diameter, during two experiments (solid and dashed lines). The horizontal dashed line indicates the steady normal stress averaged over the full area of the device's upper platen (Fig. 1). Experiments were conducted at a centerline shearing rate of 321 m y^{-1} (modified from Iverson et al., 1996).

Fig. 9. Microshear development during till shear, as indicated by I_L (Eq. 2), from experiments on different basal tills using different ring-shear devices. Grain size distributions were 54% silt and clay, 44% sand, 2% gravel (Larsen et al., 2006) and 23% silt and clay, 72% sand, and 5% gravel (Thomason and Iverson, 2006). Effective normal stresses were 85 and 65 kPa, respectively. Also shown are logarithmic best fits to the data (modified from Larsen et al., 2006).

Fig. 10. Rotation of long axes of gravel-sized ellipsoidal clasts (aspect ratio = 2.0) observed in transparent viscous putty and in the Storglaciären till (see Iverson et al., 1997, for a description of the till). Prediction of Jeffery (1922) is also shown. Clasts were initially vertical (0°). Putty results are the average orientations of five clasts observed directly through the transparent walls

of the sample chamber. Till results are based on the average orientation of 25 clasts in experiments terminated at the indicated strains. Most clasts in till plunged upglacier ($<90^\circ$ as plotted). Error bars for the till data show ± 1 standard deviation. Standard deviations for the putty data are smaller than the symbol diameter (modified from Hooyer and Iverson, 2000b).

Fig. 11. Steady-state clast fabrics developed in ring-shear experiments carried out to high shear strains ($229 < \gamma < 475$). Long-axis orientations of clasts of various shapes in the Stoglaciären till with long-axis lengths of 6-16 mm and various aspect ratios (A.R.). Fabric strength is proportional to the value of the eigenvalue, S_I . Prior to consolidation and shearing, clasts were placed individually in the till, so that their orientation distributions were random. From those initial orientation distributions, the fabrics predicted by the Jeffery model at the indicated strain are also shown. They are weaker than experimental fabrics because the theory predicts grains rotate continuously, although more slowly when oriented near the shear plane. Plunges of V_I , the orientation of maximum clustering, are shown for the experimental fabrics and are *upglacier* (u.g.) (modified from Hooyer and Iverson, 2000b).

Fig. 12. AMS fabric strength, based on k_1 orientations, as a function of shear strain for the (A) Douglas till and (B) Batestown till (see Hooyer et al., 2008, for till descriptions), as determined in ring-shear experiments carried out to the indicated shear strains. Lines of the form $y = y_0 + a(1 - e^{bx})$ were fitted to the data. Standard errors were 0.063 and 0.067 for the Douglas and Batestown tills, respectively. Lower-hemisphere stereonet accompany each data point showing orientations of the maximum (squares), intermediate (triangles), and minimum (circles) principal susceptibilities. The direction of shearing is along the x axis, and the sense of shearing in the

stereonet is bottom north and top south. Stereonet labels indicate experiment number and the number, n , of AMS samples (from Hooyer et al., 2008).

Fig. 13. AMS ellipsoid showing steady-state average orientations of principal susceptibilities in simple shear, attained at shear strains of 7-30 in ring-shear experiments (Hooyer et al., 2008; Iverson et al., 2008). Sufficiently clustered AMS data, therefore, by indicating the shearing azimuth and shear-plane orientation, provide a complete description of shear orientation in till (modified from Shumway and Iverson, 2009).

Fig. 14. Schematic depiction of shallow, heterogeneous deformation in the Douglas till as it progressively accreted to the bed beneath the Lake Superior Lobe (Lakeview advance, Clayton, 1984) of the Laurentide ice sheet in northwestern Wisconsin. The resultant till is a composite of accreted layers that have been subjected to shear deformation of variable magnitude and orientation (modified from Shumway and Iverson, 2009).

Figure 4 color

Figure 5 color

Figure 6 color

Figure 1 revised

Figure 2 revised

Figure 3 revised

Figure 4 revised B&W

Figure 5 revised B&W

Figure 6 B&W

Figure 7 revised

Figure 8 revised

Figure 9

Figure 10

Figure 12 revised

Figure 11

Figure 13

Figure 14