The debris-flow rheology myth

Richard M. Iverson
U.S. Geological Survey, Vancouver, Washington USA

Keywords: debris flow, rheology, dynamics, pore pressure, feedback, mixture theory

ABSTRACT: Models that employ a fixed rheology cannot yield accurate interpretations or predictions of debris-flow motion, because the evolving behavior of debris flows is too complex to be represented by any rheological equation that uniquely relates stress and strain rate. Field observations and experimental data indicate that debris behavior can vary from nearly rigid to highly fluid as a consequence of temporal and spatial variations in pore-fluid pressure and mixture agitation. Moreover, behavior can vary if debris composition changes as a result of grain-size segregation and gain or loss of solid and fluid constituents in transit. An alternative to fixed-rheology models is provided by a Coulomb mixture theory model, which can represent variable interactions of solid and fluid constituents in heterogeneous debris-flow surges with high-friction, coarse-grained heads and low-friction, liquefied tails.

1 INTRODUCTION

Identification of an appropriate rheology has long been regarded as the key to successful interpretation, modeling, and prediction of debris-flow behavior, and debates about the most suitable rheological formula have persisted for several decades. At the same time, field observations and video recordings of debris flows have provided clear evidence that no unique rheology is likely to describe the range of mechanical behaviors exhibited by poorly sorted, water-saturated debris. Instead, apparent rheologies appear to vary with time, position, and feedbacks that depend on evolving debris-flow dynamics. Quantitative data from replicable, large-scale experiments at the U.S. Geological Survey (USGS) debris-flow flume reinforce this view.

In this paper I first summarize field observations and experimental data that illustrate the heterogeneous composition and evolving behavior of debris flows. I then review some general aspects of rheology to explain why it provides an inadequate framework for understanding and predicting this behavior. In particular, I suggest that rheometric measurements of yield strength and rate-dependent shear resistance have limited relevance to debris-flow mechanics. Finally, I argue that Coulomb mixture theory provides a better framework for analyzing debris-flow mechanics, because this theory can represent time- and space-dependent interactions of solid and fluid constituents that produce diverse apparent rheologies. The mixture-theory approach is compatible with the observation that debris-flow motion can exhibit dynamical feedback, wherein the local behavior of the solid-fluid debris is contingent on the evolving behavior of the debris flow as a whole. Understanding and predicting this behavior is principally a problem in dynamics, not rheology.

2 OBSERVATIONS OF DEBRIS FLOWS

Field observations and video recordings (e.g., Costa & Williams, 1984) reveal that debris flows behave as unsteady, nonuniform flows with distinct starting and ending points in space and time, and that most have the following attributes:

(1) Debris flows originate from discrete or distributed source areas composed of static regolith that mobilizes through introduction of surface or ground water. The *in situ* regolith may be nearly rigid, but it liquefies during frictional failure and begins to flow and commonly to mix with additional water or debris.

(2) Abrupt, steep, surge fronts form at the heads of moving debris flows and may also form at the heads of secondary surges that develop spontaneously behind the leading front. Coarse debris accumulates at surge fronts as a result of grain-size segregation and migration within debris flows, but it can also be entrained at surge fronts. Cobbles, boulders and logs at surge fronts move forward mostly by sliding and tumbling rather than by fluid-like flow.

(3) Water-saturated debris in the body behind debris-flow surge fronts is, on average, finer grained than debris within the fronts, and the fine-grained debris appears to flow more fluidly, as a liquefied mass. Thus, surge fronts commonly behave as a "bouldery dam... pushed along by the finer, more fluid debris impounded behind..." (Sharp & Nobles, 1953).

(4) Lateral levees form where liquefied debris-flow bodies shoulder aside coarse-grained, high-friction debris at surge fronts. Levees form most commonly where debris flows escape lateral confinement by overtopping channels or by discharging onto alluvial fans or plains.

(5) Depositional lobes form where the frictional resistance imposed by coarse-grained flow fronts and margins is sufficient to halt motion of the trailing, liquefied debris.

(6) Bodies of fresh debris-flow deposits generally are too weak for humans to traverse on foot, although the coarse-grained lateral levees and distal margins of freshly deposited lobes commonly afford solid footing. If coarse-grained debris is pried away from the margins of fresh deposits, finer-grained, liquefied debris tends to discharge through the opening and form thinner deposits (e.g., Pierson, 1985).

(7) Following emplacement, bodies of debris-flow deposits gradually consolidate to a degree that allows secure passage on foot. As dessication proceeds, deposits become nearly rigid.

These field observations attest to the multiphase composition and variable apparent rheology of debris, and to the complex, heterogeneous, evolving character of debris flows.

2.1 *Flume experiments*

All of the phenomena described above have been reproduced in tens of large-scale experiments conducted during the past decade at the USGS debris-flow flume (e.g., Iverson et al., 1992; Iverson, 1997a,b; Iverson et al., 1997; Major & Iverson, 1999; Iverson et al., 2000; Denlinger & Iverson, 2001). The experiments yield high-resolution data that help constrain interpretation of field observations. Here I focus on results of a flume experiment conducted 13 September 2001, which differed from experiments described in the publications cited above because it utilized a flume bed roughened with bumps similar in size to the largest grains (coarse gravel) in the debris flow.

Figures 1-3 illustrate motion of the 13 September experimental debris flow. The flow was initiated by suddenly releasing from a vertical headgate a static mass of 9.4 m^3 of unsorted, water-saturated, loosely packed sandy loam and gravel with a silt and clay content of $\sim 6\%$ by dry weight. Figure 1 depicts the debris-flow front passing a measurement cross section 66 m downslope from the headgate, and Fig. 2 shows measurements of debris-flow thickness, basal total normal stress, and basal pore-fluid pressure at this cross section and at similar cross sections upslope and downslope. The downslope cross section (90 m from the headgate) was on a planar, nearly horizontal runout surface at the base of the flume, where a deposit accumulated. Figure 3 depicts a sequence of aerial photographs of the debris flow discharging from the flume mouth and crossing this runout surface.

The data plotted in Fig. 2 quantify some important aspects of flow dynamics. The debris flow accelerated and elongated as it descended the 31-degree flume, and it decelerated, shortened and

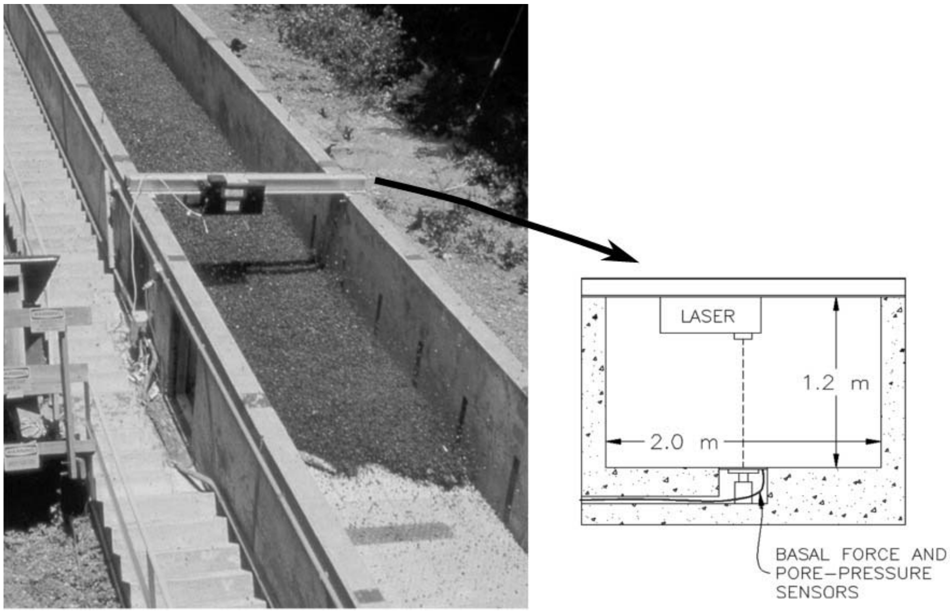

Figure 1. Photograph of a debris flow passing the instrumented cross section 66 m downslope from the flume headgate, 13 September 2001. Schematic at right shows configuration of the cross section.

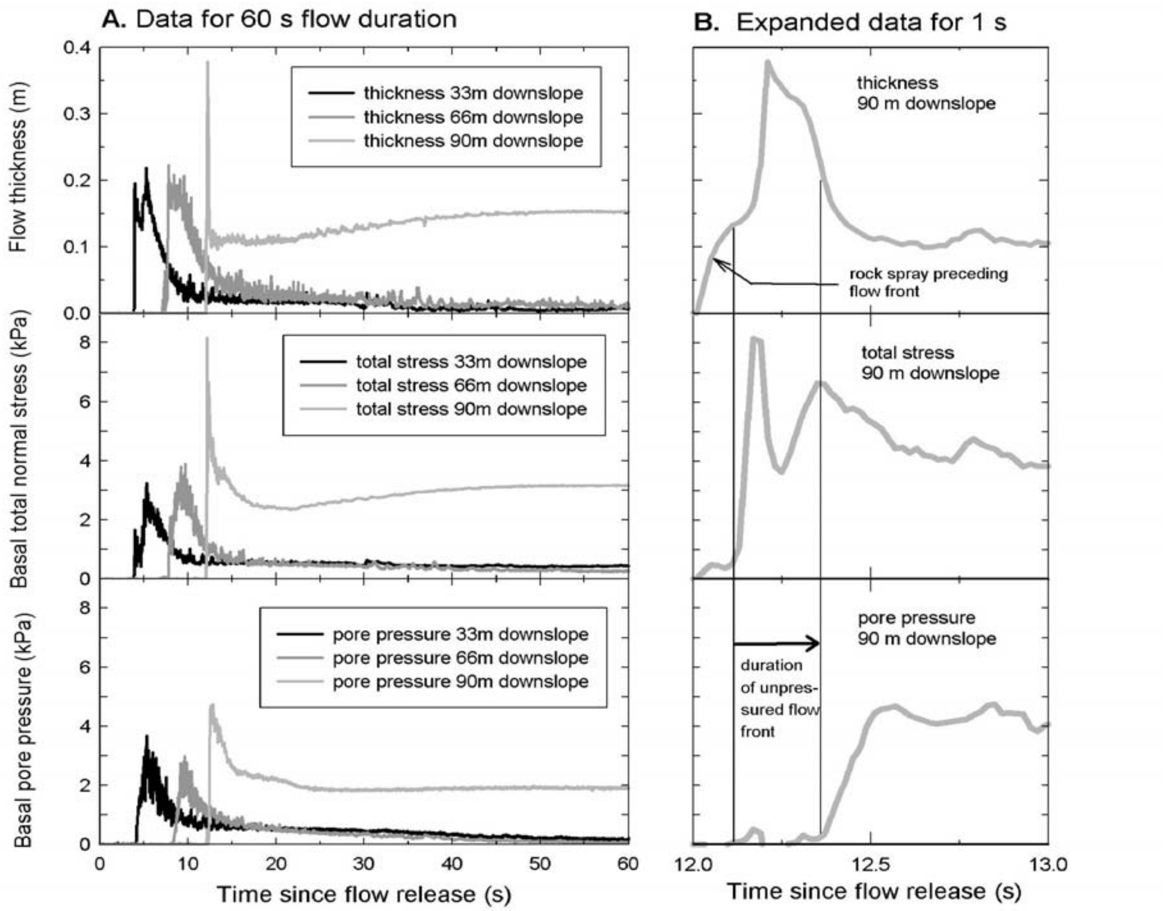

Figure 2. Time-series measurements of debris-flow thickness, basal total normal stress, and basal pore-fluid pressure at three cross sections (like that shown in Figure 1) for the flume experiment of 13 September, 2001.

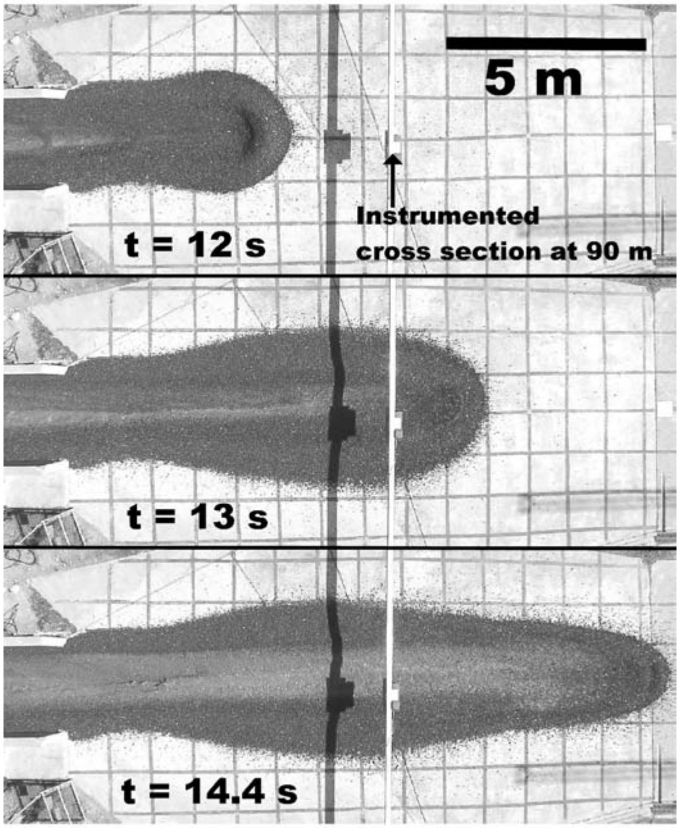

Figure 3. Sequence of aerial photographs of the 13 September 2001 experimental debris flow discharging from the flume mouth and crossing the unconfined, nearly horizontal runout surface. The dark-toned material around the perimeter of the flow is predominantly gravel, and the light-toned material in the center of the flow is predominantly liquefied mud. A shadow is cast on the flow by an I-beam, which suspends a laser normal to the flow path at the instrumented cross section 90 m downslope from the head of the flume.

thickened when it reached the runout surface. In the sloping flume, the flow front reached a maximum speed of about 11 m/s, and attained a relatively constant height of about 0.2 m. Throughout much of the debris-flow body, basal pore-fluid pressure nearly equal to the basal total normal stress persisted during motion and deposition, indicating that the body was largely liquefied. (Previous experiments demonstrated that liquefaction commences as a result of rapid contraction of water-filled pores during debris-flow initiation (Iverson et al., 1997; Iverson et al., 2000).) However, grain-size segregation during debris-flow motion led to development of a debris-flow head consisting chiefly of gravel, and the high permeability of this gravel promoted rapid dissipation of pore pressure therein. Thus, in the flow head basal pore-fluid pressure was close to zero, much smaller than the pressure necessary for liquefaction (Fig. 2B; see also Iverson, 1997a, and Major & Iverson, 1999). Self-organization of the debris flow into a liquefied body and unliquefied, high-friction head precludes accurate characterization of the debris by any specific rheology.

Interaction of the high-resistance, coarse-grained debris-flow head and low-resistance trailing body became quite visible as the flow crossed the runout surface at the base of the flume (Fig. 3). As the mud-rich, liquefied flow body pushed against the gravel-rich, high-resistance flow head, it shouldered aside some of the gravel-rich debris, which consequently formed lateral levees that confined the ensuing flow, retarded lateral spreading, and increased the distance of runout.

Runout of the 13 September 2001 experimental debris flow contrasts with that of flows containing less fine sediment. Figure 4 compares the extent and topography of the 13 September 2001 debris-flow deposit with that of an experimental debris flow that was identical except for its dearth of silt and clay-sized sediment (~ 1 % by dry weight). The conspicuous runout difference visible in Fig. 4 was replicated in several other pairs of experiments with and without significant silt and clay

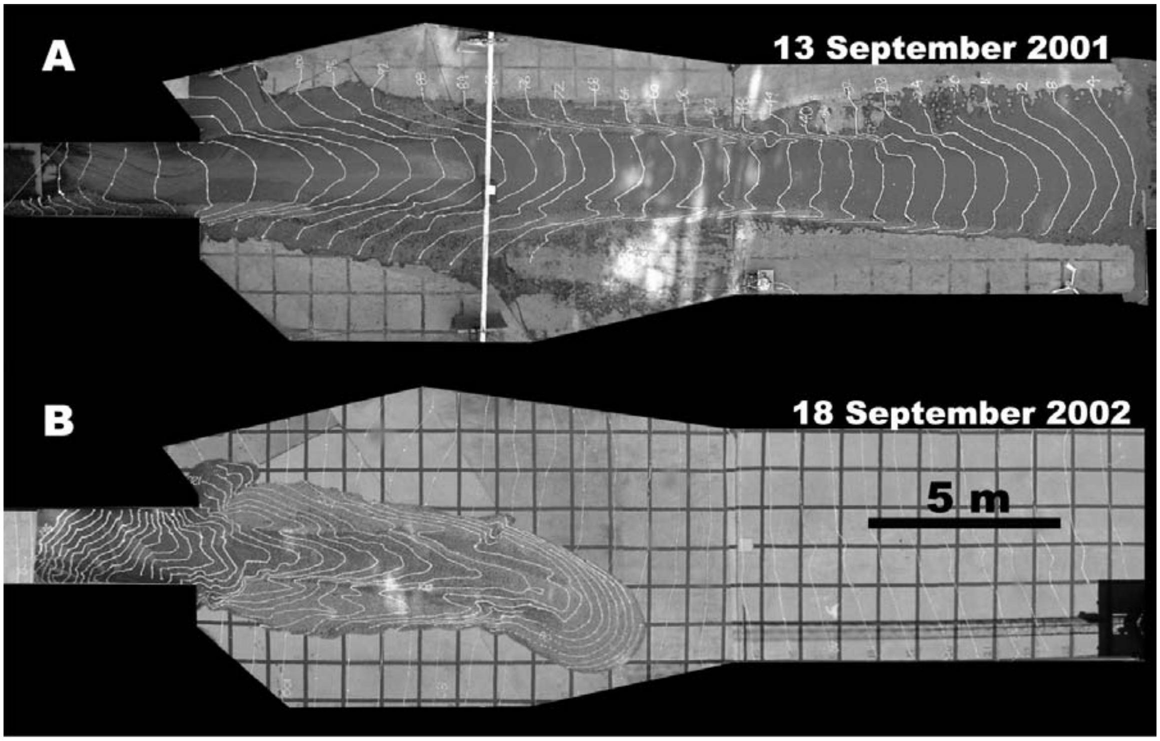

Figure 4. Rectified aerial photographs of deposits formed by experimental debris flows with nearly identical volumes, water contents, and sand-and-gravel contents, but with differing percentages of silt-and-clay-sized sediment. **A**: 13 September 2001 deposit with a silt-and-clay content of ~ 6% by dry weight. **B**: 18 September 2002 deposit with a silt-and-clay content of ~1% by dry weight. Topographic contours were placed on the deposit surfaces by laser leveling and applying white paste. Contour interval is 4 cm

contents. A logical inference is that fine sediment systematically enhances runout because it aids persistence of high pore pressures in debris-flow bodies. Deposits such as those shown in Fig. 4 also demonstrate that debris flows with little fine sediment produce thicker deposits than do flows enriched with fine sediment. Thus, if deposit thickness is a proxy for debris strength, the presence of fine sediment weakens debris and facilitates flow.

Figure 5 depicts a cross section excavated through the 13 September 2001 debris-flow deposit several hours after its emplacement near the mouth of the flume. Maintenance of open excavations through the fresh deposit was difficult, because mud-rich liquefied debris that was impounded by the gravel-rich levee tended to discharge into the opening and form a deposit much thinner than the adjacent undisturbed deposit. The disparity in behavior of the levee debris and adjacent liquefied debris illustrates the implausibility of a unique rheological representation of the debris, even in static states.

3 THE RHEOLOGY PARADIGM

To appreciate the limitations of rheology for assessing behavior of debris flows, it is useful to review the conceptual and experimental basis of rheological science. Reiner's (1960) classic rheology text begins with a description of a thought experiment in which a pencil, a ball of plasticene, and a volume of water are dropped from the same height onto a table. Reiner (1960, p. 1) notes that upon impact the three substances behave quite differently, and he states, "Of these so entirely different manners of behavior, mechanics cannot give any account, and here it is that rheology steps in." Although Reiner's point is pedagogically expedient, it is not strictly correct. Physical law indicates that mechanics accounts precisely for the observed behavior of the three substances, although it may be necessary to delve into the molecular or even quantum realm to find mechanical

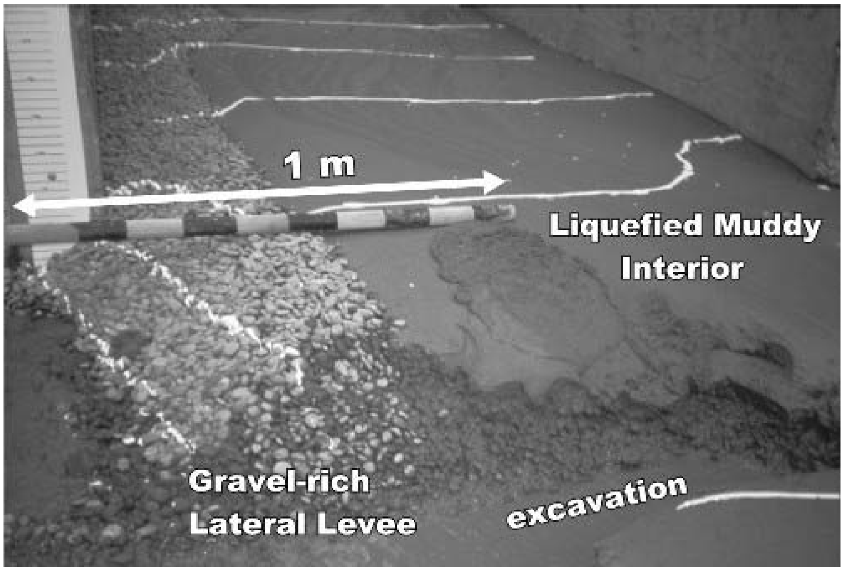

Figure 5. Photograph of transverse excavation through the margin of the debris-flow deposit on the runout surface adjacent to the flume mouth, 13 September 2001. Curved white lines on the surface of the deposit are topographic contours established by laser leveling and applied using white paste (see Fig. 4).

explanations of some macroscopic effects (e.g., Feynman, 1994). Rheology aims to summarize macroscopic effects without delving into such details, and an apt definition of rheology must, therefore, make explicit note of scale. Thus, in place of Reiner's (1960) statement quoted above, I suggest that rheology summarizes the observable mechanical effects of physical laws operating at scales too small to be resolvable at a macroscopic scale of interest. In other words, rheology summarizes mechanical effects at scales smaller than those of a representative elemental volume (REV) within a substance modeled mathematically as a continuum (cf. Malvern, 1969; Bear, 1972).

Rheological formulas, such as Newton's law of viscosity and Hooke's law of elasticity, are useful only to the extent that they summarize the macroscopic effects of small-scale mechanical processes which operate consistently in every REV of a particular continuum. (No single rheological formula would be expected to describe successfully both Reiner's pencil in one REV and water in an adjacent REV, for example.) Thus, a crucial question is, "Can any rheological formula summarize observable macroscopic effects of small-scale mechanical processes in every REV within a debris flow that includes diverse granular solids and fluids?" The apparent answer is no, because the effects of small-scale mechanical processes vary greatly with time and position within debris flows as a consequence of varying interactions between solids and fluids. In debris flows, different REV's have different apparent rheologies, and an individual REV may have an apparent rheology that varies with time.

Experimental rheology depends on the existence of "rheometric" flows, defined as those in which the state of stress can be uniquely determined independent of material properties. Rheological formulae are inferred by establishing a rheometric flow and measuring material responses to known stresses. To apply this methodology, rheometric flows generally must involve a homogeneous substance, must be time-invariant, and must be one-dimensional unless only the value and not the character of a rheological property is sought. In this context, crucial questions in debris-flow mechanics are whether steady, one-dimensional, rheometric flows of realistic debris are (A) experimentally attainable, and (B) pertinent to behavior of debris flows. If non-hydrostatic pore-fluid pressures are an inherent feature of debris flows, as indicated in Fig. 2 and elsewhere (e.g., Takahashi, 1991; Iverson, 1997a,b), then relevant rheometric flows are in principle unattainable because non-hydrostatic pressures cannot exist in steady states. Likewise, if a genuinely steady rheometric flow of a debris mixture is attained, then it has questionable relevance to the mechanics of debris flows.

Theoretical rheology generally assumes the existence of a "simple" material (i.e., Malvern 1969). Although sophisticated quantitative definitions of such materials are possible, a distinguishing qualitative trait of a simple material is that stress is a local quantity that does not depend on deformation histories of regions some distance from the location of interest. Thus, if a material evolves during deformation such that regions with distinct physical properties develop and interact to redistribute stress, the material is not "simple" and is not amendable to traditional rheological analysis. It appears unlikely that debris flows are rheologically "simple," because some regions become liquefied by high pore-fluid pressures during motion, while other regions (e.g., coarse-grained debris-flow snouts and margins) develop high internal friction due to grain-to-grain contacts.

Changes in the apparent rheology of debris-flow mixtures prompt an analogy to changes of state that occur in molecularly pure substances. The rheology of pure water, for example, is greatly influenced by changes in temperature and pressure that cause transitions from solid to liquid to gas. State variables such as temperature and pressure differ fundamentally from rheological variables because they obey evolution equations – solutions of which are influenced by initial and boundary conditions – rather than fixed formulae. For debris flows one can infer that pertinent state variables include pore-fluid pressure and grain agitation (i.e., "granular temperature"), which greatly influence the apparent rheology of debris (Iverson & Vallance, 2001).

3.1 *Yield strength*

Assessment of debris-flow yield strength (i.e., shear strength) furnishes an apt example of the limitations of rheology. Debris flows clearly exhibit nonzero strength, but rheology provides an inadequate description of the phenomenon because strength depends, for example, on pore-fluid pressure, which evolves with time and position.

The concept of debris-flow yield strength appears to have been introduced quantitatively in the pioneering work of Johnson (1965) and Yano & Daido (1965). Johnson (1965) emphasized that debris yield strength is predominantly a frictional phenomenon analogous to the Coulomb strength of granular soils, and that strength consequently varies with effective normal stress. Yano & Daido (1965) emphasized that their measurements of intrinsic yield strength applied only to mud slurries, not to debris with high concentrations of gravel, cobbles, and boulders.

Rheometric measurements of shear strengths of poorly sorted debris-flow mixtures have typically employed only the readily sampled, fine-grained "matrix" component, quite similar to the mud investigated by Yano & Daido (1965). These water-saturated slurries of clay, silt and sand have exhibited strengths from about 10 to 400 Pa (e.g., Kang & Zhang, 1980; O'Brien & Julien, 1988; Phillips & Davies, 1991; Major & Pierson, 1992; Coussot & Piau, 1995; Locat, 1997; Parsons et al., 2001). To gain some intuitive grasp of the small size of these strengths, it is instructive to slide a book across a tabletop. For diverse books and tabletops, basal shear stresses that resist sliding range from about 10 to 400 Pa, comparable to the measured strengths of fine-grained slurries.

The small magnitude of measured slurry strengths is also evident in the range of deposit thicknesses inferred from these strengths. Figure 6 depicts deposit thicknesses inferred from the one-dimensional static limit-equilibrium equation, $\tau = \rho g h \sin \theta$, where τ is shear strength, h is the thickness of the debris layer, ρ is the debris density, g is the acceleration due to gravity, and θ is the angle of slope inclination. The figure indicates that debris flows with yield strengths < 400 Pa should produce deposits no thicker than about 1 m on slopes that exceed 1degree. For slopes > 5 degrees (typical of debris-flow depositional zones on mountain-front fans) deposits with strengths < 400 Pa should be no thicker than about 0.2 m. This inference conflicts with observations of debris-flow deposits, which are commonly meters in thickness even on steep, mountain-front fans.

Many investigators have noted the discrepancy between measured slurry shear strengths and debris-flow deposit thicknesses, and some have attempted to provide a rheological resolution. For example, Coussot et al. (1998) suggested that yield strength increases continually as successively coarser constituents are added to sediment-water mixtures. Although the data of Coussot et al. (1998) are pertinent, their rheological interpretation has at least three problems. First, adjustment of yield strength to accommodate the influence of ever-coarser constituents negates all hope of making relevant laboratory measurements of strengths of many debris-flow mixtures, which

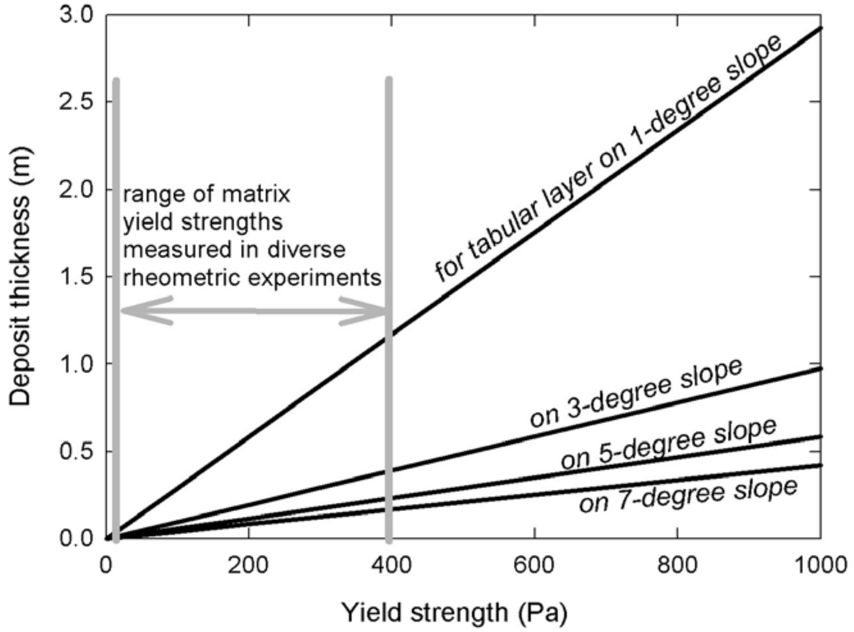

Figure 6. Effect of intrinsic yield strength on debris-flow deposit thicknesses inferred form a one-dimensional static limit-equilibrium equation. A debris bulk density of 2000 kg/m^3 is assumed.

include large boulders and logs. Second, if grain-size segregation occurs during debris-flow motion, yield strengths must be adjusted spatially and temporally to simulate the effects of changing size distributions. Treatment of yield strengths as adjustable coefficients, rather than as measured properties, greatly diminishes their value in formulating predictive models. Third, and most important, the rheological interpretation of Coussot et al. (1998) neglects an obvious alternative interpretation: poorly sorted debris-flow mixtures attain most of their strength from intergranular friction proportional to intergranular normal stress, rather than from yield strength that is an intrinsic rheological property. In this interpretation, increased strength due to increased grain size is a logical consequence of the greater weight of larger grains. Friction implies that the potential maximum strength of a debris-flow mixture is roughly proportional to its maximum thickness. As a consequence, strength is a phenomenon that evolves as debris-flow motion evolves, and is not a rheological property.

As an important adjunct to the concept of frictional strength, increased pore-fluid pressure causes strength reduction. Coulomb's friction rule can be combined with Terzaghi's effective-stress principle to form the shear-strength equation generally used in soil mechanics, $\tau = (\sigma - p) \tan \phi + c$, where σ is the normal stress on a shear surface, p is the pore-fluid pressure on the surface, ϕ is the angle of internal friction, and c is the cohesion or intrinsic shear strength (e.g., Lambe & Whitman, 1979). A key feature of this well-known equation is the dependence of shear strength on normal stress and pore pressure. In granular soils, sediments, and debris-flow slurries with $\phi \sim$ 30E and $\sigma \sim 10$ kPa (typical of a debris flow 1 m thick), strength due to $(\sigma - p) \tan \phi$ greatly exceeds that due to c unless p nearly equals σ and the mixture is essentially liquefied (cf. Major et al., 1997). Thus, a fixed yield strength c might be relevant if debris flows consisted wholly of liquefied sediment mixtures. However, field and experimental evidence points to variable pore pressure, variable liquefaction, and variable strength as fundamental features of debris-flow behavior.

3.2 *Rate dependence*

Frictional behavior implies no explicit dependence of shear resistance on shear rate, whereas rheological formulas commonly used to model debris flows generally include a viscous component that specifies a fixed functional relationship between shear resistance and shear rate. Although rate-dependent shear resistance is almost certainly present in debris flows, its magnitude and origin indicate that it is of ancillary rather than essential importance.

The simplest quantitative assessment of rate dependence assumes a linear relation between shear stress and shear rate, as in the Bingham model. (Although rheometric data indicate that rate dependence might actually be somewhat nonlinear, a linear model suffices to draw conclusions about the order of magnitude of apparent viscosities.) Fitting a Bingham model to rheometric data for diverse clay-silt-sand slurries yields viscosity values from about 0.1 to 50 Pa-s, hundreds to tens of thousands of times larger than the viscosity of pure water. (e.g., Kang & Zhang, 1980; O'Brien & Julien, 1988; Major & Pierson, 1992; Coussot & Piau, 1995; Locat, 1997; Parsons et al., 2001). Although such viscosities seem large, their relatively modest effects on debris-flow dynamics become evident if viscosity is multiplied by typical debris-flow shear rates (generally no larger than 10 s^{-1}), which lead to estimates of rate-dependent resisting stresses no larger than 500 Pa. Therefore, measured slurry viscosities imply that rate-dependent resisting stresses are roughly comparable in size to the slurry yield strengths described above. Shear resistance of this magnitude is very small in comparison to the ~ 10 kPa shear resistance due to Coulomb friction in a 1-m thick debris-flow snout lacking positive pore pressure.

Interpretation of rheometric data on slurry viscosities is complicated by the possibility of variable liquefaction that causes variable intergranular friction, and this complication grows more severe as larger grain sizes are included in sediment-water mixtures. Unless full liquefaction is assured at all shear rates in rheometric experiments, it is difficult to ascertain whether viscosity or variable Coulomb friction is the true source of observed rate-dependent resistance. For example, in the relatively coarse-grained debris mixtures tested by Phillips & Davies (1991), Major & Pierson (1992), and Conteras & Davies (2000), fluctuating and hysteretic shear resistance provided strong evidence of variable frictional effects. Moreover, in rheometric experiments with mixtures of liquids and solids sheared under controlled normal stresses, Deganutti & Scotton (1997) found that Coulomb frictional resistance clearly surpassed viscous resistance. Most rheometric experiments do not reveal this effect because normal stress is not varied or controlled systematically.

Elimination of frictional effects through use of neutrally buoyant grains was the stroke of genius in the oft-cited rheometric experiments of Bagnold (1954). However, it is important to note that fluid pressure conditions mimicking neutral buoyancy exist in debris-flow mixtures only if they are completely and uniformly liquefied. Furthermore, Hunt et al. (2002) indicate that Bagnold's (1954) data interpretation was flawed owing to his neglect of geometric effects of his shear cell, and they suggest that the rate-dependent shear resistance evident in Bagnold's data can be explained by a linear model with viscosity dependent on grain concentration. Hunt et al. (2002) use Bagnold's data to infer viscosities between 10 and 50 Pa-s for mixtures of water and small spheres at concentrations (~ 0.6) like those of debris flows. Thus, Bagnold's (1954) data appear entirely consistent with other rheometric data on shear resistance of concentrated suspensions of small grains in water.

The rate-dependence of normal stresses measured by Bagnold (1954) remains difficult to assess (Hunt et al., 2002). However, Bagnold's own opinion, expressed late in life, was that, "The most important result of this experiment was that... the coefficient of solid to solid friction for a sheared dispersion of granular solids is virtually the same as that for the same solids in continuous contact" (Bagnold, 1990). In other words, the ratio of shear to normal stresses in rapidly sheared liquefied mixtures may differ negligibly from the ratio in slowly shearing Coulomb granular solids (cf. Savage & Hutter, 1989; Iverson & Denlinger, 2001). Shear stresses in liquefied mixtures are much smaller, however, than in a deforming Coulomb granular solid that has no pore-fluid pressure and a thickness (>1 m) similar to that of many debris flows. Thus, the normal-stress effect observed by Bagnold (1954) was quite modest in comparison to gravitational normal stresses that affect friction in unliquefied parts of debris flows.

4 CONCLUSION: THE NEED FOR A NEW PARADIGM

By combining evidence from field observations, experimental debris flows, and rheometric studies, I infer that the mechanical behavior of debris-flow mixtures can be summarized as follows:

(1) The muddy slurry matrix becomes and remains essentially liquefied through the duration of most debris flows because the time scale for pore-pressure equilibration is relatively long in mixtures that consist mostly of clay, silt, sand and water (Iverson & Denlinger, 2001). Shear resistance of the liquefied, fine-grained matrix can be characterized adequately by relatively simple rheological models, such as those of Newton, Bingham, or Herschel and Bulkley.

(2) Grain-to-grain contacts dominate shear resistance in unliquefied parts of debris flows, and are especially prevalent where there are concentrations of coarse clasts. The Coulomb friction equation provides a suitable description of this shear resistance.

(3) Shear resistance due to the intrinsic strength and viscosity of liquefied, fine-grained debris-flow slurries is tens to hundreds of times smaller than the frictional shear resistance of granular solids with thicknesses (~ 1 m) relevant to field-scale debris flows.

(4) A gradational transition exists between debris behavior dominated by grain-contact friction and behavior dominated by the intrinsic strength and viscosity of liquefied slurries. Evolving distributions of pore-fluid pressure govern this transition, and persistence of high pore pressure is aided by the presence of silt and clay in debris-flow mixtures.

(5) A disparity in the shear resistance of friction-dominated portions and liquefied portions gives most debris flows their characteristic behavior and morphology. This same disparity renders rheological representations of flow resistance difficult if not impossible.

As an alternative to rheological approaches, Hutter et al. (1996) and Iverson (1997a) described the rationale for using mixture theory to model debris flows, and Iverson (1997a,b) computed one-dimensional flow dynamics based on this approach. Subsequent extensions of this work have considered multidimensional flow (Iverson & Denlinger, 2001; Denlinger & Iverson, 2001) and explicit coupling that accounts for feedback between mixture motion and pore-pressure evolution (Savage & Iverson, this volume).

The distinguishing element of mixture theory (as applied to debris flows) is use of separate momentum-conservation equations for the solid and fluid constituents, with coupling terms that make the momentum equations interdependent. In this way, mixture theory eliminates the need to specify a rheological formula for the solid-fluid composite, and instead specifies distinct constitutive equations for the solid phase, the liquid phase, and phase interaction forces. Specification of these constitutive equations is a much more tractable task than is specification of debris-flow rheology.

The version of mixture theory employed by Iverson (1997a) and Iverson & Denlinger (2001) assumes that granular solids in debris flows behave as Coulomb frictional materials and that intergranular fluids (with clay and silt carried in suspension) behave as Newtonian viscous fluids; coupling between solid and fluid motion obeys Terzaghi's effective-stress principle and Darcy's law for drag due to relative motion of the solid and fluid phases. Pore-fluid pressure is the critical "state variable" in this formulation, as behavior of the mixture reduces to that a Coulomb solid when pore pressure is absent and to that of a viscous fluid when the pore pressure is sufficient for complete liquefaction. Pore pressure evolution obeys a forced diffusion equation, which reduces to a standard soil consolidation equation for cases in which the mixture is quasi-static (e.g., Savage & Iverson, this volume). A key advantage of Coulomb mixture theory is that it describes the behavior of debris-flow mixtures from the onset of motion through deposition and post-depositional consolidation. As a consequence, the entire debris-flow process can be modeled in a consistent manner, with no redefinition of rheological parameters.

ACKNOWLEDGMENTS

Successful experiments at the USGS debris-flow flume would be impossible without the skilled assistance of several people, especially Richard LaHusen and Matthew Logan. Joseph Walder and Roger Denlinger provided thoughtful reviews of the manuscript.

REFERENCES

Bagnold, R.A. 1954. Experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear. *Proceedings of the Royal Society of London* A 225: 49-63.

Bagnold, R.A. 1990. *Sand, Wind and War: Memoirs of a Desert Explorer*. Tucson: University of Arizona Press.

Bear, J. 1972. *Dynamics of Fluids in Porous Media*. New York: Dover.

Conteras, S.M. & Davies, T.R.H. 2000. Coarse-grained debris flows: hysteresis and time-dependent rheology. *Journal of Hydraulic Engineering* 126: 938-941.

Costa, J.E. & Williams, G. 1984. Debris flow dynamics. *U.S. Geological Survey Open-file Report 84-606* (videotape).

Coussot, P., Laigle, D., Arattano, M., Deganutti, A. & Marchi, L. 1998. Direct determination of rheological characteristics of debris flow. *Journal of Hydraulic Engineering* 124: 865-868.

Coussot, P. and Piau, J-M. 1995. A large-scale field coaxial cylinder rheometer for the study of the rheology of natural coarse suspensions. *Journal of Rheology* 39: 105-124.

Deganutti, A.M. & Scotton, P. 1997. Yield stress of granular material. *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment*. New York: American Society of Civil Engineers. 270-278.

Denlinger, R.P. & Iverson, R.M. 2001. Flow of variably fluidized granular masses across three-dimensional terrain: 2. numerical predictions and experimental tests. *Journal of Geophysical Research* 106 (B1): 553-566.

Feynman, R.P. 1994. *The Character of Physical Law*. New York: The Modern Library.

Hunt, M.L., Zenit, R., Campbell, C.S. & Brennen, C.E. 2002. Revisiting the 1954 suspension experiments of R.A. Bagnold. *Journal of Fluid Mechanics* 452: 1-24.

Hutter, K., Svendsen, B. & Rickenmann, D. 1996. Debris-flow modeling: a review. *Continuum Mechanics and Thermodynamics* 8: 1-35.

Iverson, R.M. 1997a. The physics of debris flows. *Reviews of Geophysics* 35: 245-296.

Iverson, R.M. 1997b. Hydraulic modeling of unsteady debris-flow surges with solid-fluid interactions. *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment*. New York: American Society of Civil Engineers. 550-560.

Iverson, R.M., Costa, J.E. & LaHusen.R.G. 1992, Debris-flow flume at H.J. Andrews Experimental Forest, Oregon. *U.S. Geological Survey Open-file Report 92-483*.

Iverson, R.M., & Denlinger, R.P. 2001. Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory. *Journal of Geophysical Research* 106 (B1): 537-552.

Iverson, R.M., Reid, M.E., Iverson, N.R., LaHusen, R.G., Logan, M., Mann, J.E. & Brien, D.L. 2000. Acute sensitivity of landslide rates to initial soil porosity. *Science* 290: 513-516.

Iverson, R.M., Reid, M.E. & LaHusen, R.G. 1997. Debris-flow mobilization from landslides. *Annual Review of Earth and Planetary Sciences* 25: 85-138.

Iverson, R.M. & Vallance, J.W. 2001. New views of granular mass flows. *Geology* 29(2): 115-118.

Johnson, A.M. 1965. *A model for debris flow*. Ph.D. dissertation, The Pennsylvania State University.

Kang, Z. & Zhang, S. 1980. A preliminary analysis of the characteristics of debris flow. *Proceedings of the International Symposium on River Sedimentation*. Chinese Society for Hydraulic Engineering: Beijing. 225-226.

Lambe, T.W. & Whitman, R.V. 1979. *Soil Mechanics, SI Version*. New York: Wiley.

Locat, J. 1997. Normalized rheological behavior of fine muds and their properties in a pseudoplastic regime. *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment*. New York: American Society of Civil Engineers. 260-269.

Major, J.J. and Iverson, R.M. 1999. Debris-flow deposition — effects of pore-fluid pressure and friction concentrated at flow margins. *Geological Society of America Bulletin* 111: 1424-1434.

Major, J.J., Iverson, R.M., McTigue, D.F., Macias, S. & Fiedorowicz, B.K. 1997. Geotechnical properties of debris-flow sediments and slurries. *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment*. New York: American Society of Civil Engineers. 249-259.

Major, J.J., & Pierson, T.C. 1992. Debris flow rheology: experimental analysis of fine-grained slurries. *Water Resources Research* 28: 841-857.

Malvern, L.E. 1969. *Introduction to the Mechanics of a Continuous Medium*. Englewood Cliffs: Prentice-Hall.

O'Brien, J.S. & Julien, P.Y. 1989. Laboratory analysis of mudflow properties. *Journal of Hydraulic Engineering* 114: 877-887.

Parsons, J.D., Whipple, K.X. & Simioni, A. 2001. Experimental study of the grain-flow, fluid-mud transition in debris flows. *Journal of Geology* 109: 427-447.

Phillips, C.J. & Davies, T.R.H. 1991. Determining rheological parameters of debris flow material. *Geomorphology* 4: 101-110.

Pierson, T.C. 1985. Effects of slurry composition on debris flow dynamics. Rudd Canyon, Utah. *Delineation of Landslide, Flash Flood, and Debris Flow Hazards in Utah* (Proceedings of a specialty conference at Utah State University, Logan, Utah, June 14-15, 1984). 132-152.

Reiner, M. 1960. *Deformation, Strain and Flow: An Elementary Introduction to Rheology*. New York: Interscience Publishers.

Savage, S.B. & Hutter, K. 1989. The motion of a finite mass of granular material down a rough incline. *Journal of Fluid Mechanics* 199: 177-215.

Savage, S.B. & Iverson, R.M. 2003. Surge dynamics coupled to pore-pressure evolution in debris flows. *This volume.*

Sharp, R.P. & Nobles, L.H. 1953. Mudflow of 1941at Wrightwood, southern California. *Geological Society of America Bulletin* 64: 547-560.

Takahashi, T. 1991. *Debris Flow*. Rotterdam: Balkema..

Yano, K. & Daido, A. 1965. Fundamental study on mud-flow. *Bulletin of the Disaster Prevention Research Institute* (Japan) 14 part 2: 69-83.