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# Rheological Properties of Mudflows Associated with the May 1980 Eruptions of Mount St. Helens Volcano, Washington

Jonathan H. Fink
*Portland State University*, jon.fink@pdx.edu

Michael C. Malin
*Arizona State University*

Richard E. D'Alli
*Arizona State University*

Ronald Greeley
*Arizona State University*



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# RHEOLOGICAL PROPERTIES OF MUDFLOWS ASSOCIATED WITH THE SPRING 1980 ERUPTIONS OF MOUNT ST. HELENS VOLCANO, WASHINGTON

Jonathan H. Fink, Michael C. Malin, Richard E. D'Alli and Ronald Greeley

Department of Geology, Arizona State University, Tempe, Arizona 85281

Abstract. Rheological properties of three recent mudflows at Mount St. Helens were estimated using techniques developed for determining the properties of debris flows based on the geometry of their deposits. Calculated yield strengths of 1100, 1000, and 400 Pa, maximum flow velocities of 10 to 31 m/s, volumetric flow rates of 300 to 3400 $m^3/s$, and plastic viscosities of 20 to 320 Pa-s all compare favorably with measured and estimated values cited in the literature. A method for determining likely sites of future mudflow initiation based on these data is outlined.

## Introduction

Recent eruptions of Mount St. Helens provided excellent conditions for studying the dynamics and properties of mudflows. Loosely consolidated deposits of ash lay on steep slopes flushed by glacial meltwater. When heated by the eruption and shaken by the associated earthquakes, the water and ash mixed to form mudflows which poured through pre-existing drainage systems picking up blocks and other debris and clogging reservoirs downstream. With the approach of the winter rainy season, attention now turns to predicting the sites and paths of future mudflows. An important step in such forecasting is determining the rheological properties of the active flows. To this end we recently (July and September, 1980) made measurements of the geometry of fresh mudflow deposits on the south side of Mount St. Helens. We applied techniques developed for debris flows by Johnson (1970 and ms.) and Johnson and Hampton (1969) and calculated densities, yield strengths, plastic viscosities, mean velocities and volumetric flow rates for three flows which shared a common channel. We present here preliminary results and suggest ways in which these data might be used to predict areas of potential hazard from mudflows.

## Description of the flow deposits

We studied deposits along a 1 km stretch of a western branch of Pine Creek. This stream flows southeastward about 6 km down Mount St. Helens' south flank, from a series of glaciers, through a field of andesite block lava flows and eventually into Pine Creek and the Swift Reservoir (Fig. 1). Several tributaries come together immediately upstream from the study area. The channel is up to 30 m deep and ranges from 10-40 m wide.

At least three overlapping mudflow deposits could be recognized within the channel (Fig. 2). Contacts between these deposits are sharp, with no sign of intermixing, suggesting that each flow had some time to dry before the next was emplaced. The outermost deposit was left by the most voluminous flow, which banked widely and overtopped the channel walls in several places. This deposit has a fine-grained (median = .165 mm), well-sorted, homogeneous matrix and contains few blocks larger than 30 cm in diameter (Fig. 3). The position of this flow deposit is marked by a dark zone along the otherwise light gray-colored, ash-covered surface (Fig. 1). Lateral deposits which were left by the flow as it went around bends indicate the original position of the flow surface. Comparison of photos taken during the first week of May and on May 19, 1980 indicate that the flow was emplaced during that period.

The middle flow deposit is restricted to the floor of the channel. This flow carried many dacite boulders up to a meter in diameter and had a coarser-grained (median = .71 mm), poorer-sorted matrix than the outer flow (Fig. 3). The deposits are up to 1.5 m thick and range up to 25 m wide. They do not appear on photos taken May 19, but are present on photos from the first week of June.

The innermost deposit closely follows the sinuous, 1-2 m wide path of the creek which cuts through all three deposits. This unit has a uniform width of about 3-4 m and a maximum observed thickness of 1 m. The poorly-sorted, coarser-grained matrix (median = .81 mm), contains dacitic lithic and pumice pebbles up to 2 cm in diameter which are uniformly distributed except for slight concentrations in lenses up to 5 cm thick. Clasts make up about 15 percent of the deposit by volume. Larger blocks up to 50 cm in diameter are less common than in the middle flow, but more so than in the outer flow. This deposit appears on photos taken after the June 12 eruption, but not before. Most of the inner flow deposit was eroded between mid-July and early September.

## Calculations of yield strength

Characterizing rheological properties is essential for determining how far mudflows will travel, what types of deposits they will leave, and how much damage they may cause to structures in their paths. Defining these parameters is complicated by spatial and temporal variations within a given mudflow. For example, mudflows commonly concentrate boulders and other debris ahead of themselves so that deposits left at the snout of a flow or along its margins will tend to be coarser-grained with higher yield strengths and viscosities than deposits in the middle of the channel. Surges and waves which periodically move through the channel may also produce deposits with different properties. Nonetheless, by sampling at several different places along a flow, average properties may be calculated which can be used to distinguish one flow from another.

We initially modeled active mudflows as Coulomb-viscous materials (Johnson, 1970; Johnson and Hampton, 1969) which possess cohesive strength, internal friction and viscosity. Subsequent measurements and calculations indicated that the apparent internal friction angles of the mobilized flows were consistently small ($\lesssim 1.5°$); thus the more simple Bingham model, in which the flow can be characterized by a yield strength, $\tau$, and a plastic viscosity, $\eta_p$ (Caldwell and Babbitt, 1941) can be applied. The goal was then to estimate these parameters based upon the geometry of the deposits.

Fig. 1. Western branch of Pine Creek, with summit of Mount St. Helens in background. Creek begins amid dark ash-covered glaciers and flows between blocky andesite flows. Prominent bend in foreground is shown in Figure 2.



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Fig. 2. West Pine Creek showing three overlapping mudflow deposits. a = outer flow; b = middle flow; c = inner flow, which has already been partially eroded. Two months after this picture was taken, the inner flow deposit was completely eroded and the middle deposit was partially buried by later mudflows.

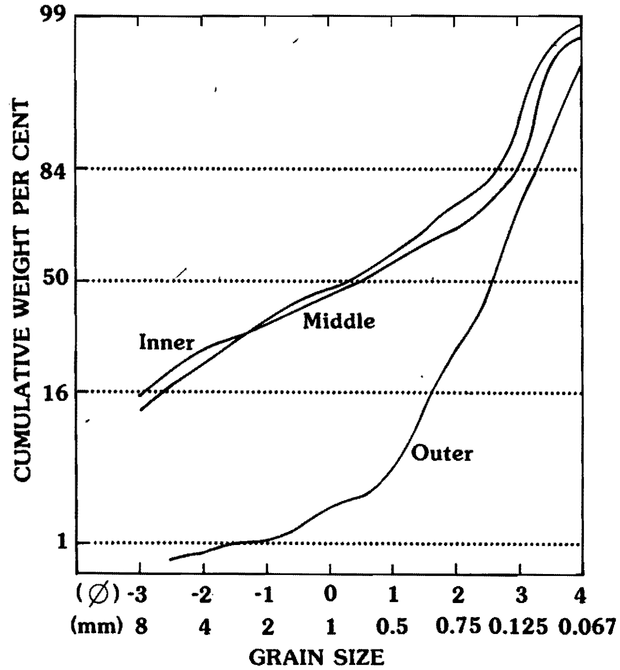


Fig. 3. Grain size distribution of three mudflow deposits in west branch of Pine Creek. Outer flow is better sorted and finer grained than middle and inner flow deposits.

The first procedure used unusually large blocks as indicators of the yield strength of the flow. The densities of both the supported block and the matrix of the flow were measured and the blocks partially excavated to calculate the ratio of their submerged to total height. We then used the formula (Johnson, 1970, p. 486):

$$\tau = m\,h\,(\gamma_b - n\,\gamma_d) \qquad (1)$$

where $\tau$ = yield strength, m = constant = 0.22 for zero internal friction (Johnson and Hampton, 1969), h = total height of block, n = ratio of submerged to total block height, $\gamma_b$ = specific weight (density x gravitational acceleration) of the block, and $\gamma_d$ = specific weight of the flow matrix. At least three blocks were measured for each of the flow deposits.

Calculated strengths are shown in Table 1. The outer flow had a mean strength of 390 Pa (3900 dyne/cm$^2$). The middle and inner flows had significantly higher strengths (1000 and 1100 Pa respectively). These calculations are consistent with the observations that the outer flow carried fewer and smaller blocks than the middle and inner flows.

A second method for determining yield strength relies on the tendency of deposits left by flowing Bingham materials to have finite thicknesses (Johnson, 1970, p. 488). For a particular topographic slope and mudflow density, there is a critical thickness ($T_c$) below which the flow ceases to move. This is because shear stress increases with depth, and if the basal shear stress is less than the yield strength, no flow can occur. If the flow thickness, specific gravity ($\gamma_d$) and slope ($\delta$) can all be measured, then the strength may be calculated from the relation:

$$\tau = T_c\,\gamma_d \sin\delta \qquad (2)$$

Owing to the general similarity of their matrix materials, it was difficult

Table 1. Yield strength and critical thickness calculations.

| | $\rho_{mud}$ (x $10^3$kg/m$^3$) | $\rho_{block}$ | h (m) | n | $\tau$ (x $10^3$ Pa) | $\delta$ (degrees) | $T_c$ (m) |
|---|---|---|---|---|---|---|---|
| Inner Flow | 1.99 | | | | | | |
| block 1 | | 2.47 | 0.30 | 0.19 | 1.3 | 3.5 | 1.09 |
| block 2 | | 2.47 | 0.32 | 0.24 | 1.4 | 3.5 | 1.18 |
| block 3 | | 2.33 | 0.20 | 0.35 | 0.7 | 3.5 | 1.15 |
| mean | | | | | $\tau$ = 1.13±0.38 | | |
| Middle Flow | 2.03 | | | | | | |
| block 1 | | 2.38 | 0.72 | 0.71 | 1.45 | 3.5 | 1.19 |
| block 2 | | 2.37 | 0.22 | 0.18 | 0.93 | 3.5 | 1.55 |
| block 3 | | 2.28 | 0.23 | 0.47 | 0.65 | 3.5 | 1.09 |
| mean | | | | | $\tau$ = 1.01±0.41 | | |
| Outer Flow | 1.97 | | | | | | |
| block 1 | | 2.17 | 0.22 | 0.49 | 0.57 | 3.5 | 0.48 |
| block 2 | | 2.20 | 0.11 | 0.50 | 0.30 | 3.5 | 0.25 |
| block 3 | | 1.88 | 0.20 | 0.63 | 0.28 | 3.5 | 0.24 |
| block 4 | | 2.33 | 0.10 | 0.14 | 0.39 | 3.5 | 0.33 |
| mean | | | | | $\tau$ = 0.39±0.13 | | |

to locate the lower surfaces and hence determine the thicknesses of the overlapping flow deposits. However, using estimates of strength derived from the boulder method described above, the equation can be used to calculate flow thicknesses which may then be compared with maximum thicknesses determined in the field. Calculated critical thicknesses for the three mudflows in the west branch of Pine Creek are shown in Table 1, along with the corresponding slopes. The greater thickness values for the inner flows are consistent with observations of their lateral deposits.

Both of the above methods for determining yield strength require measurements of density for the flowing mud. These measurements were made by taking samples of the dry deposit and adding small amounts of water until the consistency changed from a sticky immobile substance to a flowing mud. This change occurs over a very narrow range of water contents for most samples of mudflows and debris flows (Johnson and Hampton, 1969). We thus assume that the density of this mobilized mud is the same as that of the active flows, because when water is added to ash in the field the material will flow as soon as this critical water content is reached.

Calculations of velocity, volumetric flow rate and plastic viscosity

Figure 1 shows that the outer flow banked as it passed around bends in the channel, leaving deposits which are higher on the outside of the bends. This relation is common in debris flow deposits (Sharp and Noble, 1941), and can be used to estimate velocities of the formerly active flows (Johnson and Hampton, 1969). Tilting of the flow surface was caused by radial acceleration of the mudflow. By measuring the tilt angle ($\beta$), the channel slope ($\delta$) and the radius of curvature of the bend ($\psi$), we can estimate the mean flow velocity (u):

$$u = (g \ \psi \ \cos\delta \ \tan\beta)^{1/2} \tag{3}$$

or if the channel slope is small ($\lesssim 15^{\circ}$):

$$u = (g \ \psi \ \tan\beta)^{1/2} \tag{4}$$

These equations assume that the flows behaved as perfect (inviscid) fluids. For low volume channels or flows with high yield strengths, this assumption may lead to overly large estimates of velocity.

Velocities were calculated by this method at four sites, two in the outer flow deposit (sites 1 and 2) and two in the middle flow (3 and 4) (Table 2). The innermost flow did not show any measurable banking, due to either its low volume or high strength. At site 2, the outer flow was moving at a calculated 15 m/s. The cross sectional area (A) of the flow at this point was about 230 $m^2$ so that the volumetric flow rate (Q) was a high 3400 $m^3/s$. At site 1 (about 400 m upstream from site 2), the calculated velocity of the outer flow was more than twice as high (31 m/s). Here the flow splashed 30 m up on the west bank of the channel, but the cross sectional area was less than at site 2 owing to the steep banking angle (30°); thus the volumetric flow rates are comparable. Sites 3 and 4 were used to calculate velocities of the middle flow. The velocities varied from 10-15 m/s but again the volumetric flow rates were similar, at about 300 $m^3/s$. Owing to the higher strength and lower volume of the middle flow, we suspect that the estimates of its velocity and flow rate are too large, but we cannot presently determine the degree of inaccuracy.

Pierson (1980) presents a summary of the physical characteristics of fluid debris reported from different areas. Most have velocities of 1 to 5 m/s, well below those calculated for the mudflows in the present study. However, the observations were made primarily in the low gradient portions of the drainage systems, not in steep ravines like those where our measurements were made. Niyazov and Degovets (1975) report a surface velocity of 9.4 m/s for an 8.5 m thick mudflow on a slope of 7.9 degrees; values similar to those for the outer flow in west Pine Creek (Table 2). We can conclude that compared to other reported mudflows, the one associated with the May 18 eruption of Mount St. Helens had an extremely large volume and high speed.

If the strength and volumetric flow rate can both be measured at a single locality, then an upper bound on the value of the plastic viscosity, $\eta_p$, can be set as follows (Johnson, ms.). We first assume that the channel is semi-circular with a radius, $R_c = (2A/\pi)^{1/2}$. Next we calculate the greatest depth, $d_m$, of a flow which would clog the channel:

$$d_m = (2\tau/(\gamma_d \sin\delta)) \tag{5}$$

These values are substituted into:

$$\eta_p \lesssim (\pi/48)\,(\gamma_d/Q)\,\sin\delta\,(R_c)^4((d_m/R_c)^4 - 4(d_m/R_c) + 3) \tag{6}$$

which can be derived from the Buckingham-Reiner equation for flow of a Bingham fluid in a circular pipe (Bird et al., 1960, p. 48-50). Upper bounds on the plastic viscosities of the outer and middle flows are listed in Table 2. The calculated maximum viscosity values of 20-320 Pa-s (200-3200 poises) are lower than values calculated for debris flows (100-500 Pa-s; Johnson and Hampton, 1969) and are comparable to apparent viscosity values measured for clay slurries (8-200 Pa-s; Greeley et al., 1980).

These calculations of plastic viscosity depend upon previously derived values for yield strength, density, velocity, surface slope and cross sectional areas of the channels. Errors arising from individual computations of these parameters may have been compounded when the viscosities were calculated. Additional errors may have arisen from the assumptions that the flows had zero strength when they banked around bends and that they moved in a semi-circular channel. Furthermore, velocities and volumetric flow rates calculated from the banked channel deposits were probably much higher than those at the time the boulders used to compute yield strengths were deposited. These higher rates would cause the computed viscosity values to be too low.

Another way to constrain the viscosity values is by consideration of the flow regime at the time of deposition of the large blocks. As discussed earlier, mechanical properties of the flows may vary widely during the course of emplacement; the flow regime may similarly vary between laminar and turbulent. If the blocks were deposited during or preceding a turbulent phase, then they should have been rolled and coated in mud. However, most of the blocks appear to have been carried passively along in a non-deforming, laminar plug flow. Hence calculated values of the "modified Reynolds number", $R_m$, appropriate for Bingham fluids:

$$R_m = 2/((\eta_p/\rho\, u\, R_c) + (\tau/2\, \rho\, u^2)) \tag{7}$$

should be less than 2100, which is assumed to be the transition value between laminar and turbulent flow (Moore and Schaber, 1975). Substituting data from Tables 1 and 2 into the above equation, we find that study sites 2, 3, and 4 all had $R_m$ values less than 2100, whereas site 1 had an $R_m$ of 5500. In order to reduce this value below 2100, the viscosity would have to increase three-fold, from the earlier calculated 120 Pa-s to 390 Pa-s. We further recall that deposition probably occurred when the velocities were less than the peak values already calculated from channel geometry. If we reduce the velocity values substituted into equation (7) by

Table 2. Velocity, flow rate and viscosity calculations.

| Site | $\beta$ (deg) | $\delta$ (deg) | $\psi$ (m) | (u) (m/s) | Area ($m^2$) | Q ($m^3/s$) | $\tau$ (x $10^3$ Pa) | $\gamma_d$ ($10^4 kg/m^2$-$s^2$) | $d_m$ (m) | $R_c$ (m) | $R_m$ | $\eta_p$(max) (x $10^2$ Pa-s) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 30 | 18 | 180 | 31.1 | ~90 | ~2800 | 0.39 | 1.97 | 0.13 | 7.4 | 5500 | 1.2 |
| 2 | 17 | 8 | 168 | 14.9 | 230 | 3400 | 0.39 | 1.97 | 0.29 | 12.1 | 1512 | 3.2 |
| 3 | 14 | 14 | 96 | 15.2 | 18 | 275 | 1.01 | 1.99 | 0.42 | 3.4 | 119 | 0.4 |
| 4 | 8 | 4 | 72 | 10.0 | 32 | 320 | 1.01 | 1.99 | 1.46 | 4.5 | 79 | 0.2 |

a factor of two, then all four study sites would show laminar flow, even for the velocities calculated originally from equation (6).

## Discussion and conclusions

One of the main goals of this study was to determine whether methods used to calculate rheological properties of debris flows based on the geometry of their deposits could be applied to mudflows as well. Estimates of yield strength, plastic viscosity, mean flow velocity, and volumetric flow rate for three fresh mudflows (less than 2 months old) on Mount St. Helens all appear compatible with observations of active debris flows and with laboratory measurements of the rheology of mud slurries. The Bingham rheological model explains most of the observed structures of these low to medium volume mudflows. Extrapolation of these results to the large mudflows which choked the Cowlitz and North and South Toutle Rivers may require modification of the rheological model to account for the higher clay content of material eroded from the bottoms of these rivers.

Although mudflow development after the major eruption of May 18 has been restricted to areas near the summit and areas possibly inundated by water splashed out of Spirit Lake, we can expect that mudflows will become abundant this winter and next spring when the ash-covered slopes begin to receive substantial precipitation. Currently the volcano and its vicinity are blanketed by up to 10 cm of dry ash. Additions of fresh ash from future eruptions may cause some oversteepening of slopes and subsequent landsliding, but mudflows are the main concern. As we have seen in our study, addition of water to the dry ash will eventually lead to a sudden drop in strength, at which point deposits on slopes of a certain gradient will become mobilized as mudflows. The calculation of yield strength can lead to estimates of this potential for slope failure on different areas of the volcano. Using computer-generated map overlays which show ash isopachs, rainfall data and topographic gradients, we are presently constructing a composite map that will show the most likely areas for mudflow initiation. Through more extensive field measurements and concurrent laboratory tests of yield strengths of dry and wet ash, as well as calculations of the areas of the available mudflow sources, we will be able to estimate the likey distance and velocity with which a given predicted mudflow will travel.

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