Channel-bed mobility response to extreme sediment loading at Mount Pinatubo

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ABSTRACT

Since the 1991 eruption of Mount Pinatubo, the specific sediment yields from watersheds draining its slopes have been the highest ever recorded. In spite of this overwhelming sediment load, rivers inundated by pyroclastic-flow deposits delivered almost half of the initial deposits to downslope alluvial and/or debris fans by 1996. Although most of this transport occurred by hyperconcentrated flows and debris flows (lahars), very high sediment transport rates also characterize low flow. Measured flow velocities and depths, channel properties, and the size of both mobile and stable clasts in the Sacobia and Pasig-Potrero Rivers indicate median bed-surface grain sizes of 2 to 8 mm, grain-size-independent dimensionless critical shear stresses (τ^*_c) of 0.016 to 0.041 and Manning's *n* values of 0.017 to 0.024, values well below those previously reported for steep mountain channels. The dramatic bed-surface fining, bed mobility, and selective transport in these extremely sediment-rich channels indicate that changes in grain size, τ^*_c values, and bed roughness can increase transport capacity in response to high sediment supply. Our observations also suggest viewing the apparently contradictory concepts of an equal threshold of bed mobility and grain-size–dependent selective transport as end-member concepts that apply to channels with low (or intermittent) and high (or continuous) sediment supply, respectively.

INTRODUCTION

River-channel morphology reflects both the transport capacity of the flow and the volume and size of the sediment supply (Schumm, 1971). Recent research has shown that decreased sediment loading leads to bed-surface coarsening (Andrews and Parker, 1987; Dietrich et al., 1989), which decreases sediment-transport rates. It is less clear what the effect of increased sediment load is on sediment-transport rates, in part, because most of the relevant data come from flume experiments or from natural channels with relatively low sediment supply. In addition, the bed morphology of mountain channels has been hypothesized to reflect relative sediment supply, although few direct observations are available to test such predictions (Montgomery and Buffington, 1997). Nonetheless, understanding the response of bed mobility and morphology to high sediment loads is important for predicting sediment routing through mountain drainage basins affected by land use or catastrophic disturbance.

Channels draining the slopes of Mount Pinatubo, Philippines, provide an unusual opportunity to study channel response to extreme sediment loading. High-flow events in the form of lahars dominate the overall sediment yield at Pinatubo, but continuous transport of very high sediment loads also occurs at low flow. Here we report on channel response to these low flows and, in particular, the mobility of grains over the bed surface. Our observations document that the channels have a very low bed roughness and that large clasts are selectively transported with low dimensionless critical shear stress (τ^*_c) values. We show that these factors combine to enhance bed mobility and are a mechanism of channel adjustment to extreme sediment loads.

THEORY: EQUAL MOBILITY AND SELECTIVE TRANSPORT

Bedload transport rates are generally considered to be a nonlinear function of the difference between the effective basal shear stress, τ', and the critical shear stress, τ_c, required to initiate transport:

$$Q_s = k\,(\tau' - \tau_c)^\lambda, \qquad (1)$$

where Q_s is the sediment flux, k is an empirical constant, and λ is an empirically derived exponent generally greater than 1 (Gomez and Church, 1989). A force balance for the moments acting about a downstream contact point for spherical grains of diameter D shows that the critical shear stress, τ_c, required to mobilize a stream bed is proportional to both D and the friction angle (ϕ) of the bed material and inversely proportional to grain protrusion (P). In part because P and ϕ distributions are difficult to quantify in natural channels, researchers introduced an empirical τ^*_c to account for these factors where τ_c is generally modeled by the Shields (1936) equation

$$\tau_c = \tau^*_c\,(\rho_s - \rho)\,g\,D, \qquad (2)$$

where ρ_s and ρ are the density of sediment and water, respectively, and g is gravitational acceleration. From inspection of equation 2, it is apparent that a uniform fining of the bed surface (i.e., smaller D) would decrease τ_c, which by inspection of equation 1 should lead to increased sediment transport. Similarly, equation 1 shows that an increase in τ'—through, for example, decreased bed roughness—should also increase sediment transport.

For hydraulically rough flow, τ^*_c is generally between 0.030 and 0.073 (Buffington and Montgomery, 1997), although it is recognized to vary as a function of grain protrusion and exposure (Fenton and Abbot, 1977), friction angle (Buffington et al., 1992), bed packing (Church, 1978), bed relief, sediment fabric (Laronne and Carson, 1976; Brayshaw, 1985; Brayshaw et al., 1983), and the definition of incipient motion (Buffington and Montgomery, 1997). Combining equation 2 with an expression for basal shear stress ($\tau = \rho g H \sin\theta$, where H is flow depth and θ is the channel slope) yields

$$\tau^*_c = [\rho/(\rho_s - \rho)]\,[H_c/D]\sin\theta, \qquad (3)$$

where H_c is the critical flow depth required to mobilize grains. Equation 3 indicates that if τ^*_c is the same for all grain sizes, then the critical flow depth is a linear function of grain size:

$$H_c = D\,\tau^*_c/\{[\rho/(\rho_s - \rho)]\sin\theta\}. \qquad (4)$$

On a natural stream bed composed of grains of various sizes, small clasts will tend to be sheltered by large grains, which are more exposed to the flow, a phenomenon known as the hiding effect. Consequently, D in equation 2 is often considered to be the median grain size in streams with rough, gravel beds composed of mixed grain sizes. In such channels, Parker et al. (1982) hypothesized that, to a first approximation, low friction angles for large clasts and high friction angles for small clasts lead to an approximately equal threshold of mobility for different grain sizes. This concept is supported by observations from gravel-bed channels (Andrews, 1983; Andrews and Erman, 1986; Wilcock and Southard, 1988) and theoretical analyses (Wiberg and Smith, 1987).

Parker et al. (1982) argued that a threshold mobility of the bed surface is maintained by a grain size dependence to τ^*_c, in which larger clasts have lower values and finer clasts have higher values. Andrews and Parker (1987) reviewed data from natural channels with relatively low sediment supply and concluded that an appropriate hiding factor is given by

$$\tau^*_{ci}/\tau^*_{c50} = (D_i/D_{50})^{-1}, \qquad (5)$$

where D_{50} is the median grain size and the subscript i denotes a grain size of interest. The equal-mobility view of initial motion holds that because of the hiding effect, grains of different size will become mobile at about the same flow stage (Fig. 1).

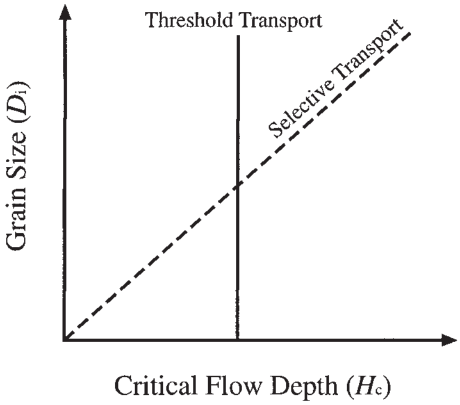

Figure 1. Relationship between grain size (*D*) and critical flow depth (H_c) for equally mobile and selective transport initiation.

Conversely, observations of some stream beds indicate that smaller clasts are more readily mobilized from the bed surface and are preferentially mobile at low flow (Baker and Ritter, 1975; Ashworth and Ferguson, 1989; Ferguson et al., 1996), resulting in selective transport. On the basis of sediment-transport data from a variety of channels, workers have reported an exponent different from –1 in equation 5, a range of –0.6 to –0.9 indicating that different size fractions become mobile at different flow stages (Komar, 1987; Ferguson et al., 1989; Kuhnle, 1992; Wathen et al., 1995). Adding complexity to the conditions of equal mobility and purely selective transport, Wilcock (1997) argued that in many channels, a partial mobility occurs in which only some of the grains of a given size are mobile at a particular flow depth. At present there is no consensus as to the particular conditions under which threshold mobility, selective transport, and partial mobility occur.

STUDY AREA

Mount Pinatubo lies about 100 km northwest of Manila in central Luzon, Philippines (Fig. 2). The flanks of the volcano are composed of steeply dissected terrain with hillslope angles that range up to >45° at elevations above 1000 m, giving way to broad, coalescing alluvial fans below 200 m elevation (Major et al., 1996). The 1991 eruption of Mount Pinatubo delivered 5 to 6 km^3 of pyroclastic flow deposits and ~0.5 km^3 of tephra-fall deposits to the flanks of the volcano (Newhall and Pungonbayan, 1996; Scott et al., 1996). These deposits covered 29% and 33% of the drainage basins of the Pasig-Potrero and Sacobia Rivers, respectively, and buried the main channels under as much as 200 m of deposits (Newhall and Pungonbayan, 1996; Major et al., 1996). Over the next 6 yr, about one-half of this material was transported and deposited on downstream lahar fans (Janda et al., 1996), maintaining extraordinarily high sediment loads in these rivers. Extensive deposition on these fans resulted in ongoing burial of entire towns (Newhall and Pungonbayan, 1996; Major et al., 1996). Estimated annual sediment yields from the Pasig-Potrero and Sacobia Rivers exceed previous record-breaking values from the rivers draining Mount St. Helens by an order of magnitude (Dinehart et al., 1981; Umbal, 1997).

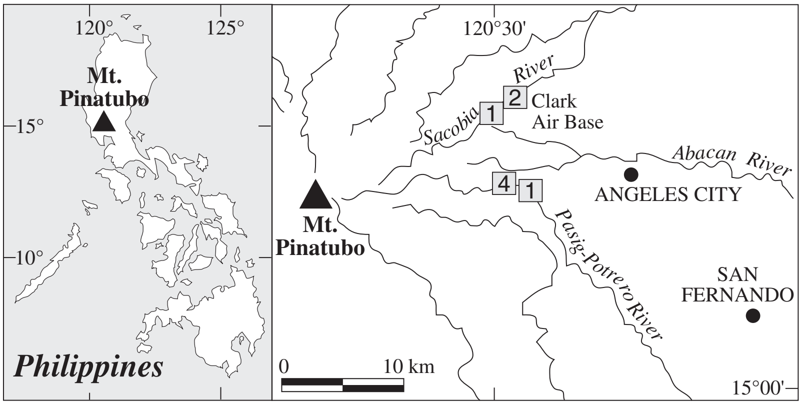

Figure 2. Location of study reaches on flanks of Mount Pinatubo, Philippines.

TABLE 1. STUDY REACH CHARACTERISTICS

Reach	Slope (m/m)	D_{50} (mm)	Flow depth (m)	Flow velocity* (m/s)	τ^*_c	*n*	Fr	Re (x10^3)
Pasig-Potrero 1	0.015	2	0.04	0.9 (0.6)	0.016–0.027	0.024	1.0	24
Sacobia 2	0.017	2–4	0.03	1.1 (0.7)	0.018–0.031	0.018	1.3	21
Sacobia 3	0.020	2–4	0.04	1.3 (0.8)	0.021–0.036	0.020	1.3	32
Pasig-Potrero 4	0.023	4–8	0.05	1.8 (1.2)	0.024–0.041	0.017	1.7	60

Note: D_{50} = median grain size; *n* = Manning's *n*; Fr = Froude number; Re = Reynolds number.
*Measured surface velocity (average velocity).

METHODS

A striking characteristic of the Sacobia and Pasig-Potrero Rivers at present is the procession of rocks that roll down river even during shallow flows. These rocks range in size from gravel to cobbles at low flow and are up to boulder size at higher flows. Many of the rolling rocks protrude through the flow, and most travel intermittently. At four representative reaches near the heads of the alluvial fans, we measured the intermediate axis of 621 clasts that were stable (i.e., not moving), rolling, or sliding down the channel. We also measured the local flow depth to the nearest centimeter at the sampling point for each clast. Our measurements spanned the full range of flow depths across each reach. At each study reach, we also surveyed a longitudinal bed-surface profile with a stadia rod, tape, and hand level; estimated surface-flow velocity by timing the passage of floating objects; and conducted a pebble count (Wolman, 1954) (Table 1). The average slope of each reach was determined from a least-squares linear regression of the surveyed longitudinal profile. A total of 22 clasts sampled for saturated-density determination indicated a range of 1100 to 2500 kg/m^3; the means were 1300 kg/m^3 for pumice, 2100 kg/m^3 for lithic material, and 1500 kg/m^3 for all of the samples.

RESULTS

Substantial sediment transport occurred even at the low-flow conditions that we sampled; the flow was brown and opaque where deep. The channel bed in each surveyed reach was braided, with low-amplitude bars and a relatively smooth bed. In areas of deeper flow, a continuous moving carpet of coarse sand to gravel (composed of waterlogged pumice and lithic fragments) extended across the entire wetted width. In areas of shallow flow, smaller clasts moved around individual stable clasts. Low-flow bedload transport rates measured with a pressure-difference sampler ranged from 0.1 kg$\cdot$m$^{-1}\cdot$s^{-1} in the smallest braids to 1.6 kg$\cdot$m$^{-1}\cdot$s^{-1} in larger braids. Many of the largest clasts (i.e., those >0.1 m in diameter) protruded through the flow while rolling through areas of deeper flow, but stopped when transported from deep to shallow points in the flow. In contrast, periodic surges deeper than the average flow swept through the study reaches and consistently destabilized many of the previously stable large clasts. Slight flow diversions also could induce stable clasts to roll. These observations indicate that most of the larger clasts were near the condition for incipient motion even at the low-flow conditions that we measured.

Comparison of the size of stable and mobile clasts reveals a distinct grain-size dependence to the critical flow depth. Plots of flow depth, H, vs. grain size reveal distinct fields for stable and mobile clasts, with a strong grain size dependence to the flow depth that separates stable and mobile clasts (Fig. 3). Moreover, in each of the study reaches the onset of initial motion is well approximated by $H_c = 0.5D$. Given ρ, ρ_s, and $\sin\theta$, inspection of equation 4 indicates that τ^*_c can be calculated from the slope of the boundary between the data fields defined by stable and mobile clasts in Figure 3, by setting the slope of the boundary (H_c/D) equal to

$$H_c/D = \tau^*_c/\{[\rho/(\rho_s - \rho)] \sin\theta\}. \qquad (6)$$

Incorporating a sediment density of 1300 to 1500 kg/m^3, a fluid density of 1016 kg/m^3 calculated from the average suspended-sediment concentration at the time of our measurements, $H_c/D = 0.5$, and the reach-average slope for each reach into equation 3 yields τ^*_c values of 0.016 to 0.041 (Table 1). Assuming that the kinematic viscosity, ν, of the flow is 10^{-6} m^2/s and that the average flow velocity is two-thirds of the estimated surface-flow velocity (Chow, 1959), calculated Reynolds numbers (Re = $u\,H/\nu$, where u is flow velocity) indicate fully turbulent flow characteristic of mountain channels (Table 1).

A striking characteristic of the Sacobia and Pasig-Patrero Rivers is their very smooth bed surface. The hydraulic bores that swept down the channel at both the low-flow conditions that we sampled and high-flow events that we observed resemble the periodic surges or pulsating flow described by Chow (1959) as flow instabilities that form in flow over steep, smooth beds at supercritical flow with Froude numbers (Fr) greater than 1 [Fr = $u/(gH)^{0.5}$]. Hence, these regularly periodic surges and the calculated Fr of 1.0 to 1.7 for the surveyed channels indicate formation of a smooth channel bed. Grant (1997) also found Fr ≥ 1.0 for the Pasig-Potrero River and argued that such supercritical flow could only be sustained over long distances and time periods with a very smooth bed. Back-calculated Manning's n values ($n = H^{0.67}S^{0.5}u^{-1}$) of 0.017 to 0.024 confirm that the low-flow beds of these channels have very low roughness in comparison to typical mountain channels with comparable slopes (Fig. 4).

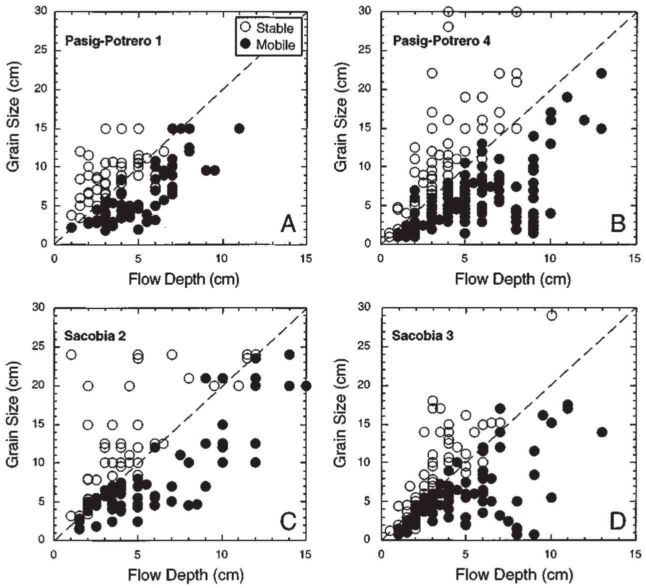

Figure 3. Plots of local flow depth vs. grain size for mobile (solid symbols) and stable (open symbols) clasts sampled from reaches of Pasig-Potrero River (A and B) and Sacobia River (C and D). Note that data are all for cases where measured grains are greater than median grain size [(D_i/D_{50}) > 1].

DISCUSSION

In our study reaches, the combination of low roughness, dramatic bed-surface fining, and low τ^*_c values leads to high excess shear stresses (i.e., $\tau' - \tau_c$) and, therefore, substantial bedload transport even at low flow. Although it is well known that channel beds dynamically adjust to changes in sediment loading, the low τ^*_c and Manning's n values for high Reynolds number flow in the relatively steep Pinatubo rivers document enhanced bed mobility in these channels with extreme sediment loads. The increased mobility of the stream bed, in turn, increases the transport efficiency of the channel, thereby providing a mechanism for positive feedback between high sediment loading and high sediment-transport rates. This enhanced bed mobility occurs both by decreasing τ_c and by increasing τ' through lower roughness.

The linear boundary between data for stable and mobile clasts for each reach in Figure 2 documents a grain-size–dependent threshold for incipient motion that indicates strongly selective transport (equivalent to an exponent of 0 in equation 5). Moreover, the linear nature of this threshold shows that a constant τ^*_c reasonably characterizes the condition for incipient mobility in the Sacobia and Pasig-Potrero Rivers for grain sizes larger than the median grain size. In contrast to predictions of the equal-mobility concept, and the relatively thresholdlike bed mobility typically observed in mountain-channel networks (Montgomery and Buffington, 1997), it appears that these extremely sediment-laden rivers present examples of strongly selective transport in which a single τ^*_c value reasonably characterizes the mobility of a wide range of grain sizes. Furthermore, τ^*_c values for these channels are below or at the low end of the range of values reported for comparably high Reynolds number flow (Buffington and Montgomery, 1997). The low τ^*_c values for these channels, however, are comparable to those reported for overriding grains (Fenton and Abbot, 1977), such as gravel moving over a sand bed (Ferguson et al., 1989).

We interpret the dramatic selective mobility at our study reaches to reflect that high sediment supply leads to selective transport, in addition to enhanced bed mobility. Sustained selective transport without a supply of sediment from upstream leads to the development of a stable armored surface (Sutherland, 1987) through progressive win-

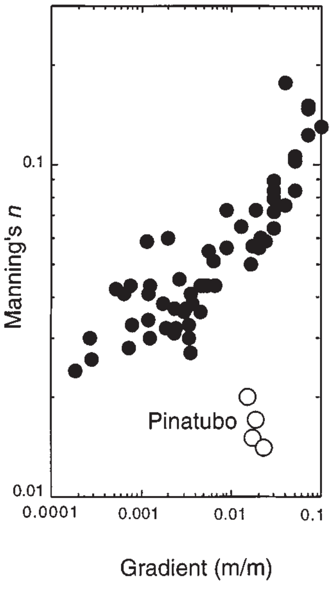

Figure 4. Plot of Manning's *n* vs. reach slope for data from Sacobia and Pasig-Potrero Rivers (this study) and values from mountain drainage basins reported by Barnes (1967) and Marcus et al. (1992).

nowing of finer material from the bed surface. With a reduction in sediment supply relative to transport capacity, selective transport can begin to stabilize a mixed-grain-size bed surface through greater interparticle interference and progressive development of higher friction angles. Given sufficient time, development of an armor layer with a wide range of friction angles leads to a commensurately narrow range of critical discharges that approximates an equal-mobility threshold. In contrast, a channel with a relatively continuous high sediment supply, like the Pinatubo channels, can maintain selective transport until the sediment supply is ultimately reduced. Perhaps the "partially selective transport" described by Wilcock (1997) reflects the wide range of intermediate and episodic sediment loading that characterizes natural stream channels. As selective transport represents high or continuous sediment loading (Sutherland, 1987), we suggest that threshold mobility (Parker et al., 1982) characterizes channels with relatively low or intermittent sediment supply. Our conclusion is consistent with the general observation of selective transport in experiments in recirculating flumes, which can be considered to represent a high or continuous sediment supply case, whereas experiments in sediment-feed flumes generally report results more consistent with equal mobility and represent cases in which a low sediment supply is common.

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