Long-runout rockfalls

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ABSTRACT

Large rockfalls and debris avalanches constitute spectacular geologic hazards. A physical basis for the prediction of the extent of runout of such transport events has remained elusive. We consider the simplest case in which a mass *M* of debris and loose rock, having fallen from a height *H*, is subjected to a constant, overall resisting shear stress τ during runout. A prediction for such behavior is that the area overrun by an avalanche is proportional to $(gMH/\tau)^{2/3}$, where the coefficient of proportionality is near unity and a function of the geometry of the "footprint" of the avalanche deposit. This scaling results in a good collapse of the data for a wide range of terrestrial and extraterrestrial phenomena and implies a value of τ in the range 10–100 kPa. Such shear stress values are comparable to measures of the yield strength of unconfined, dry debris obtained by other means. The approach developed here does not give a detailed description of rockfall motion, but provides new insight for attempts to delineate the mechanisms that contribute to the mobility of rockfalls and other densely concentrated flows of geophysical interest.

INTRODUCTION

In the span of 3 min during April 1974, one of the largest mass movements of loose rock in recent history took place in the Peruvian Andes (Kojan and Hutchinson, 1978). Approximately 1 km^3 of debris fell 1.9 km, traveled a total of 8 km, and claimed an estimated 450 lives. Some of the debris evolved into a flow of wet mud, traveling on to wreak greater havoc. Smaller avalanches in other localities have individually resulted in a far greater number of fatalities (Plafker and Ericksen, 1978), and considerably larger events are known from the geologic record on Earth (e.g., Siebert et al., 1987) and on Mars (e.g., McEwen, 1989).

An understanding of the factors that contribute to the runout of mass movements of dry debris and rock represents an important milestone in the ability to predict related hazards. Cataclysmic rockfalls and debris avalanches exhibit a horizontal runout distance *L* that can be 5–20 times the vertical fall height *H* and that is dependent on the magnitude of the event (Fig. 1). The ratio *L*/*H* is termed the "relative runout" and is a measure of the efficiency of rockfall movement. For a rigid mass, it corresponds to the inverse of the coefficient of sliding friction, which is independent of scale (e.g., Hsü, 1975, 1978; Pariseau and Voight, 1978; Middleton and Wilcock, 1994; Iverson, 1997). The predictions from such an approach are clearly inconsistent with the data and, as a result, several explanations for the scale dependence of *L*/*H* exhibited in Figure 1 have been offered. Such explanations include the presence of lubricating fluids in the form of trapped air (Shreve, 1968), molten material (Erismann, 1979), or heat-generated pore pressure (Goguel, 1978). Melosh (1979) suggested that long-lived acoustic energy in a mass of debris intermittently reduces the severity of frictional contacts between component particles. Some of these explanations have been offered solely in the context of a site-specific event (Voight, 1978; Voight et al., 1985). None provides a universally accepted basis for the prediction of the runout behavior illustrated in Figure 1.

In this paper we consider a constant-stress resistance law for long-runout rockfalls. This approach serves as a distinct contrast to the notion of Coulomb friction, which is familiar to all who have pondered the problem posed by the phenomena illustrated in Figure 1. Constant-stress resistance is related, under certain conditions, to purely plastic deformation (see, e.g., Middleton and Wilcock, 1994, for a review of different models of deformation and resistance). Such behavior is common in metals and water-saturated clays but is, in general, not believed to be applicable to dry, granular materials. Constant stress or plastic behavior has been invoked, however, to explain the morphology of lunar impact craters following side-wall collapse (Melosh, 1977, 1989). It is likewise consistent with the area vs. energy relationship observed with large earthquakes typically associated with mechanisms of brittle failure (Kanamori and Anderson, 1975; Kanamori, 1979; see also Scholz, 1990). As we report here, the long runout of large volumes of loose rock and debris in terrestrial and extraterrestrial settings is also well described by friction associated with a resisting shear stress that is approximately constant.

The view we adopt is an extension of an idea originally advanced by Davies (1982) regarding the flow-like behavior of large volumes of debris in catastrophic transport (see also Hungr, 1990; Iverson et al., 1998). Here, however, we accommodate the geometry of the radial spread of debris during runout and quantify a key dynamic parameter that limits the areal extent of a large mass-flow deposit. The resulting, quantitative description of the runout of large volumes of debris provides a constraint for the ongoing analysis of complicated constitutive equations used to describe mass-flow phenomena in general (see, e.g., the review by Iverson, 1997). Our findings thus contribute to an understanding of other densely concentrated flows of geophysical interest, including flows of volcanic ejecta, debris flows, and some snow avalanches.

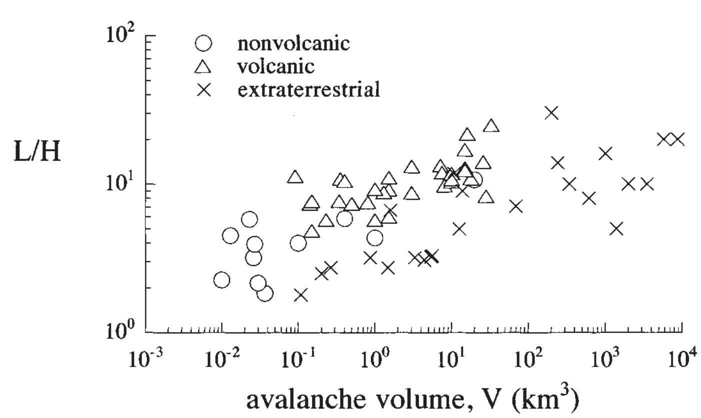

Figure 1. Relative runout *L*/*H* as function of rockfall volume *V*. Data compiled from Howard (1973), Voight (1978), Lucchitta (1978, 1979), Crandell et al. (1984), Francis et al. (1985), Siebert et al. (1987), McEwen (1989), and Stoopes and Sheridan (1992).

ANALYSIS

The overall runout of a volume of rock with mass M and bulk density ρ that is initially mobilized by one of a number of possible trigger mechanisms and that spreads under gravity g with speed U can be described in terms of the balance between changes in kinetic energy (KE), potential energy (PE), and the energy W lost to friction and internal deformation (Middleton and Wilcock, 1994; Iverson, 1997). One advantage of considering an energy balance, instead of the equations of motion, is that details of the history of an avalanche along its path of travel are not required. In such an analysis, debris that loses elevation δz over a small distance along the path of travel is subject to the overall energy balance KE gain = PE loss – incremental work extracted by friction and deformation:

$$\delta(MU^2/2) = gM\,\delta z - \delta W. \tag{1}$$

Upon integration of equation 1 over a path of length L for which the fall height is H and $U = 0$ both at the origin and at L, one obtains an expression that describes the effects of the total work W performed during runout. The expression represents a balance between total available energy and work, and is given by

$$0 = gMH - W. \tag{2}$$

The work performed by the steady motion is the product of the resisting force F and runout length L. For a cohesionless, rigid mass that exhibits simple Coulomb friction $F = \mu gM$, where μ is an empirical friction coefficient that is assumed to be constant. Note that the introduction of μ implies no constraints on the details of the physics of rockfall runout. Upon substitution of this closure for F and W into equation 2 and subsequent rearrangement, one obtains the result

$$L/H = \mu^{-1}. \tag{3}$$

For materials subjected to relatively small stress and strain, μ typically takes on a value in the range 0.5–0.8 (Scholz, 1990; Middleton and Wilcock, 1994). Under such conditions, equation 3 indicates that the total runout of an avalanche should be no more than about twice its height of fall and that the relative runout should be independent of gravity and event size. This is approximately the case for rockfalls of small volume and laboratory flows of dry, granular materials (e.g., Hutter et al., 1995). In this context, an explanation for the exceptional mobility of extremely voluminous events shown in Figure 1 is problematic.

The physics of granular media are not well understood, and the applicability of the friction law described above to a large volume of heterogeneous, unconfined debris undergoing catastrophic collapse and subsequent shear is open to examination. We consider here the simple, contrasting scenario analogous to that analyzed by Knopoff (1958) for the relaxation of stress during an earthquake. In the case of rockfalls, such an analysis yields an expression for the total work performed during runout given by

$$W = \tau AL. \tag{4}$$

In equation 4, $A = \lambda L^2$ is the total area overrun by an avalanche and 2λ is the angular extent of the assumed uniform sector through which an avalanche spreads (alternatively, λ is the ratio of the average width to the length of an avalanche deposit). The stress parameter τ represents the average shear stress in the mobile debris during runout. It is assumed to be constant and not necessarily related to the overburden stress. It is, in other words, a modulus of resistance associated with internal deformation and friction at the lower boundary of a mobile mass. Note that in proposing equation 4, we are invoking a simple, end-member closure for W that is distinctly different from that which leads to the result given in equation 3. As with the introduction of μ in the more conventional analysis, however, the introduction of the stress parameter τ implies no detailed interpretation of the physics of rockfall runout.

Substitution of equation 4 into equation 2 and rearrangement of the result indicate that the area A covered by an avalanche is given by

$$A = \lambda^{1/3}(gMH/\tau)^{2/3}. \tag{5}$$

Equation 5 reveals that the area overrun by a long-runout rockfall is proportional to the potential energy of the debris mass before failure, gMH, raised to the two-thirds power. The extent of runout is limited by the magnitude of the resisting shear stress τ and is weakly dependent on the geometry parameter λ. The relationship given by equation 5 is analogous to the scaling between the area of a fault over which displacement occurs and the seismic moment of major earthquakes (Kanamori and Anderson, 1975; Kanamori, 1979).

The average stress τ in debris that fails catastrophically and rapidly deforms can be constrained as follows. In the simplest case the initial and final stresses, τ_0 and τ_∞, respectively, are distributed uniformly over a finite area. Under such conditions, $\tau = (\tau_0 + \tau_\infty)/2$ or, equivalently $\tau = \Delta\tau/2 + \tau_\infty$, where $\Delta\tau = \tau_0 - \tau_\infty$ is the differential stress (or, equivalently, the stress drop). It is likely that the circumstances leading to the failure of loose rock and debris reduce the initial stress τ_0 to the yield strength τ_y of the unconfined material. One possibility is that the residual stress τ_∞ also corresponds to τ_y as a mass of avalanche debris comes to rest on the floor of a gently sloping valley (e.g., McEwen, 1989). Under such conditions the stress drop vanishes and $\tau \approx \tau_\infty \approx \tau_y$. This condition is analogous to the model advanced by Orowan (1960) for slip along a fault in which the average frictional stress is related to the final stress. Alternatively, if $\tau_\infty = 0$, then the stress drop is complete and $\tau = \Delta\tau/2 \approx \tau_y/2$.

In either of the simple scenarios of rockfall runout outlined here, the average resistance stress τ corresponds approximately to the plastic yield strength τ_y of the unconfined debris. Such scenarios are consistent with the view that stress within a volume of debris is reduced to its yield strength at the instant of catastrophic failure. It is thus reasonable to propose that independent estimates of τ_y can be used to constrain τ a priori. Existing estimates of τ_y that do not assume Coulomb friction (and thus which are consistent with our analysis) are based on measurements of the local thickness of an arrested flow on a sloping surface and on the strength of material required to support large blocks and boulders of known size (Shreve, 1968; Eppler et al., 1987; McEwen, 1989; McSaveny, 1978). Order of magnitude estimates of τ_y obtained in this way are in the range 10–100 kPa. Sources of variability in this material property include the lithology and size of component particles in the debris, and the presence of pore fluids.

One implication of the view of rockfall runout outlined here is that a mass of debris may catastrophically flow in a purely plastic-like state for which the approximately constant resisting shear stress τ is related to τ_y. This idea is pursued further by noting that, upon rearrangement of equation 5, one can isolate the geometric terms of rockfall volume V, A, and λ, and the dynamic terms ρgH and τ. Accordingly, we consider a friction number N_f given by

$$N_f \equiv \rho gH/\tau = A^{3/2}/\lambda^{1/2}V. \tag{6}$$

From the energy balance given in equation 1, we note that an upper bound for U^2 scales with gH. The friction number N_f given in equation 6 thus represents a likely upper limit for the ratio of inertia to constant-stress resistance. In this sense, N_f is analogous to the Hampton number invoked by Hiscott and Middleton (1979) and Middleton and Southard (1984) to describe geologic flow phenomena that exhibit Bingham-plastic behavior. In proposing this analogy, we aim only to constrain the limits to the stability of flow phenomena dominated by constant-stress resistance. Such limits are related to the Hampton number or other forms akin to equation 6 (see Iverson, 1997, for a review of the possibilities for granular flows). If a Hampton-number analogy is appropriate for rockfalls and avalanches, we observe that maximal values of N_f should be of the order of 10^3 for strictly nonturbulent transport conditions (Middleton and Southard 1984). In the case of the flows of predominantly dry, granular debris considered here, "turbulence," if it existed, would probably be characterized by interactions of highly agitated, component grains in pervasive shearing motion (Iverson, 1997).

ROCKFALL RUNOUT

The data given in Figure 2 portray the areal extent of avalanches that resulted from the cataclysmic failure of volcanic and nonvolcanic slopes on Earth, the Moon, and Mars. The solid line in Figure 2 indicates a least-squares, best-fit regression of the form given by equation 5 for which the coefficient of proportionality for all data corresponds to $\tau/\lambda^{1/2} = 45 \pm 6$ kPa ($n = 65$, $R = 0.93$, and where the indicated range corresponds to ±2 [standard error] of the estimate). A best-fit regression of a power-law relationship with an unspecified exponent on the same data gives an estimate of the 95% confidence interval of the exponent as 0.58–0.68 (R = 0.95). This result also gives strong confirmation of the 2/3 power-law relationship between area and potential energy indicated by equation 5.

The deposits of cataclysmic rockfalls and debris avalanches in both terrestrial and extraterrestrial settings exhibit an aspect ratio in plan view λ for which the values, although wide ranging, are less than $\pi/3$ (which corresponds to a radial spread of 120°) and have a median value of about 0.25 (which corresponds to a radial spread of 30°) (Fig. 3). These observations

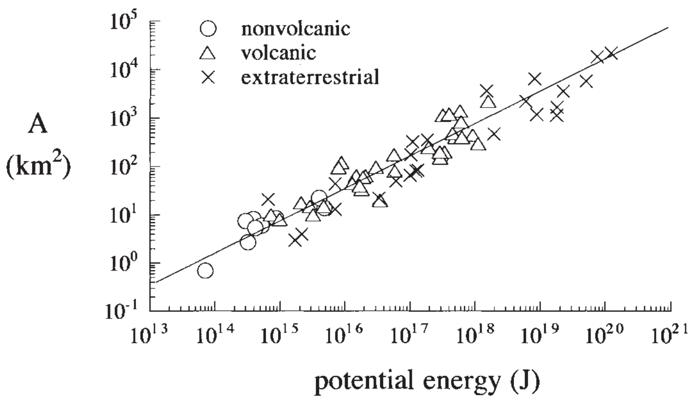

Figure 2. Area *A* overrun by avalanche or rockfall as function of potential energy *gHM* of debris before transport. Data are same as shown in Figure 1. Solid line indicates least-squares best fit of form given by text equation 5.

reflect the restricted aspect of most avalanches owing to forward inertia or the effects of existing, laterally confining topography. The plan geometry of the Peruvian debris avalanche mentioned in the opening remarks corresponds to $\lambda \approx 0.1$, for example, and even smaller values of λ are estimated for other events. As a rule, long-runout rockfalls are not radially widespread.

The value of the stress parameter τ for individual events is estimated, upon rearrangement of equation 5, as $\lambda^{1/2}\rho gHV/A^{3/2}$. The mean value of τ obtained in this way is 48 ± 15 kPa. This result represents a value inferred from the observations of avalanche runout using the analysis summarized in the previous section. It is not a value assumed a priori. No detailed, mechanistic significance is necessarily assigned here to τ, but we note that the range 10–100 kPa corresponds to the normal stress associated with an overburden of debris about 1–10 m thick. Values of τ of the order of 50 kPa are one to two orders of magnitude less than the stress drop associated with large earthquakes (Kanamori and Anderson, 1975; Kanamori, 1979) or the strength of lunar debris inferred from the morphology of lunar impact craters following sidewall collapse (Melosh, 1977, 1989). Values of about 50 kPa are, however, comparable to existing estimates of the yield strength of unconfined, dry avalanche debris obtained by other means (Shreve, 1968; McSaveny, 1978; Eppler et al., 1987; McEwen, 1989). The favorable comparison between τ and the strength of debris suggests that the resistance incurred by a large, spreading mass is dominated by the average stress that must be overcome by the unconfined and disturbed debris during flowlike deformation, runout, and deposit emplacement.

The mean value of N_f for the rockfalls and avalanches considered here is 1500 ± 600. To the degree to which N_f is analogous to the Hampton number, as discussed in the previous section, the calculated values of this parameter imply that long-runout rockfalls are typically near the upper limit of a regime of nonturbulent flow. Thus the strong correlation of area with potential energy shown in Figure 2 probably represents a general upper limit for the extent of the runout of a densely concentrated mass of debris in a state of non-agitated granular flow. Such conditions are independently implied by the general preservation in an avalanche deposit of the original arrangement of rocks in the source region (Hsü, 1975). This interpretation is open to discussion, but we note in any event that the range of observed values of N_f of large rockfalls is relatively limited. As a result, there is a strong correlation between area raised to the power 3/2 and the volume of an avalanche (Fig. 4). This geometrical correspondence has been observed independently by others for long-runout rockfalls and debris avalanches (Hungr, 1990; Vallance and Scott, 1997), and debris flows and lahars (Iverson et al., 1998). Our analysis provides a physical basis for this relationship.

The relationships illustrated in Figures 2 and 4 place important constraints on the interpretation of mass-flow deposits and hazards associated with their parent flows. For example, a deposit which, when plotted in Fig-

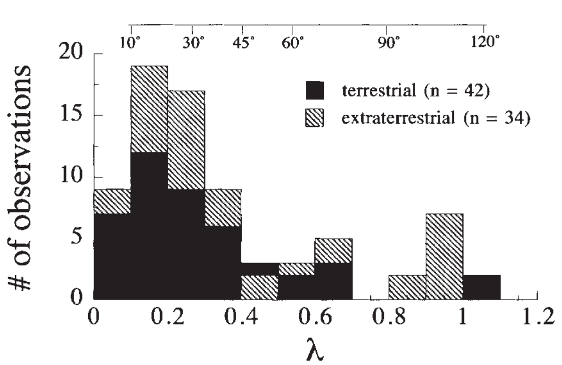

Figure 3. Distribution of values of aspect ratio λ, calculated as area/(length)^2, of deposits of rockfalls and avalanches depicted in Figure 2. Corresponding values of 2λ are indicated in degrees on upper horizontal axis. See text for discussion.

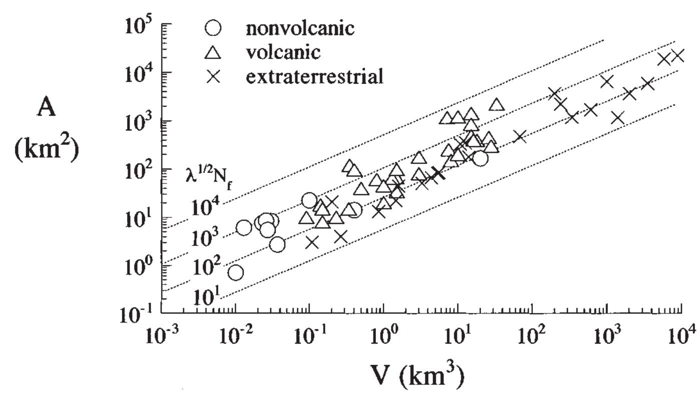

Figure 4. Area *A* overrun by avalanche or rockfall as function of its volume *V*. Data are same as in Figure 2. Dashed lines show relationship predicted from equations 5 and 6 for indicated values of $\lambda^{1/2}N_f$. See text for discussion.

ure 4, indicates a value of $\lambda^{1/2}N_f$ in significant excess of 10^3 should be considered to have resulted from a parent flow that represents a transport regime distinctly different from that of long-runout rockfalls.

CONCLUSION

Our new scaling arguments for the runout behavior of large rockfalls and debris avalanches are based on an energy balance associated with large-scale dislocation. Comparison of the predictions from our analysis with observations of the areal extent of large volumes of avalanche debris of volcanic and nonvolcanic origins in terrestrial and extraterrestrial settings indicates that the runout of individual parent flows is limited by an approximately constant shear stress that resists deformation and transport. A more sophisticated approach is required to delineate the mechanisms that contribute to such behavior and to predict the details of flow histories for complicated paths of travel. The analysis outlined here does not obviously preclude any of the previous explanations for the enhanced mobility of some rockfalls. Our analysis does indicate clearly, however, that any mechanism that is proposed to explain the mobility of rockfalls and avalanches in general must accommodate an approximately constant stress of resistance and the geometry of the spreading mass of debris during runout and deposit emplacement.

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