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Understanding how volume affects the mobility of dry debris flows

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[1] The prediction of the runout length L of large dry debris flows has long been the subject of a considerable research effort, primarily due to the obvious concern caused by their destructive power. One seemingly well established feature is the increase of the mobility $\mathcal{M}$ of a rock avalanche, defined as the ratio of the runout distance to the fall height, with its volume V. The physical nature of this lubrication mechanism remains however controversial. In this paper, we analyse field data and discrete numerical simulations of granular flows and demonstrate the geometrical origin of the apparent enhancement of the mobility with the volume. We evidence the intertwined role of volume and topography and show the existence of two contributions in the runout, defining two flow regimes: one dominated by sliding, in which the runout is independent of V, and another dominated by spreading, in which the runout is strongly dependent on V. In the light of these results, the search of a volume dependent lubrication mechanism appears to be an ill-posed problem. **Citation:** Staron, L., and E. Lajeunesse (2009), Understanding how volume affects the mobility of dry debris flows, *Geophys. Res. Lett.*, *36*, L12402, doi:10.1029/2009GL038229.

[2] On the night of April 29, 1903, 30 million cubic meters of limestone collapsed from the east face of Turtle Mountain (Alberta, Canada) killing an estimated 70 people in the nearby town of Frank (Figure 1a). The resulting deposit covered approximately 3 km^2 of the valley floor and dammed the Crowsnest River, leading to the formation of a small lake which covered 2 km of the Canadian Pacific Railway. Such catastrophic events are not rare: hundreds of rock avalanche deposits larger than one million cubic meters in volume have been identified in the past several decades on Earth [*Hewitt et al.*, 2008], on Mars [*Quantin et al.*, 2004] and even on the moon [*Howard*, 1973]. Beside an obvious concern for hazard assessment, rock avalanches are also efficient agents of erosion in active orogens, capable of moving large masses of material over kilometre-scale distances instantaneously [*Hovius and Stark*, 2006; *Korup et al.*, 2007]. In spite of the sustained interest these dramatic natural events have raised in the scientific community, they still escape physical understanding [*Iverson*, 1997, 2003].

[3] Among the various issues raised by these flows, the prediction of their runout length L (see Figure 2a, insert) keeps a first rank position, primarily due to the obvious concern caused by their destructive power. Surprisingly, they can travel over distances several times larger than the height H of the source topography [*Dade and Huppert*, 1998]. One seemingly established feature is the increase of the mobility $\mathcal{M} = L/H$ with the volume V of rock mobilized by the avalanche (Figure 2a). This positive correlation was first noted by *Heim* [1932]. Yet, the identification of lubrication mechanisms enhanced by volume remains a persisting and challenging issue [*Legros*, 2002, and references therein]. In this paper, we analyse both field data and discrete numerical simulations of granular flows, and show that the increase of $\mathcal{M}$ with V reflects a purely geometrical correlation. In the light of these results, the search for a volume dependent lubrication mechanism appears to be an ill-posed problem.

[4] The conventional analysis of the dissipative properties of geological granular flows relies on the hypothesis, first put forward by *Heim* [1932] and prompted by an analogy with solid friction, that the whole of the initial potential energy of the mass is dissipated by the work of friction forces along the topography. Neglecting centripetal acceleration induced by the topography, and any other energy transfers in the system, we obtain:

$$mgH = \mu_e mgL \;\; \text{and therefore} \;\; \mathcal{M} = \frac{1}{\mu_e} \qquad (1)$$

where μ_e is an effective friction coefficient quantifying the average macroscopic dissipative properties of the flow. Within the frame of this analysis, $\mathcal{M}$ appears as the inverse of μ_e, and Figure 2a is interpreted as the signature of a decrease of the effective friction coefficient μ_e with the increase of the volume of the avalanche.

[5] Many mechanisms have been invoked to account for this volume-induced lubrication. High pressure at the base of the flow can lead to a local melting and a drop of resistance to shear [*Erismann*, 1979]. Ground vibrations can restitute energy to the spreading flow [*Melosh*, 1979]. Trapped air may minimize energy dissipation at the base of the flow [*Kent*, 1966; *Shreve*, 1968]. Yet none of these scenari has so far established its universality. Beside, as argued by *Davies* [1982], it is enough to suppose that the spreading of the flow controls its runout to give the volume a first order role. In other words, Heim's correlation could be purely geometrical.

[6] Misgivings concerning the physical meaning of $\mathcal{M}$ arise from the fact that L varies over a much wider range than H, so that the latter could possibly add nothing more than scattering to the dependence of L on V [*Davies*, 1982].

[7] In the case of the data sets plotted in Figure 2a, V varies over 7 orders of magnitude, L over 4 orders of magnitude, and H covers only 1 order of magnitude. While Figure 2a demonstrates a positive correlation between $\mathcal{M}$ and V (though different for terrestrial and Martian slides) a much better correlation is achieved when simply plotting

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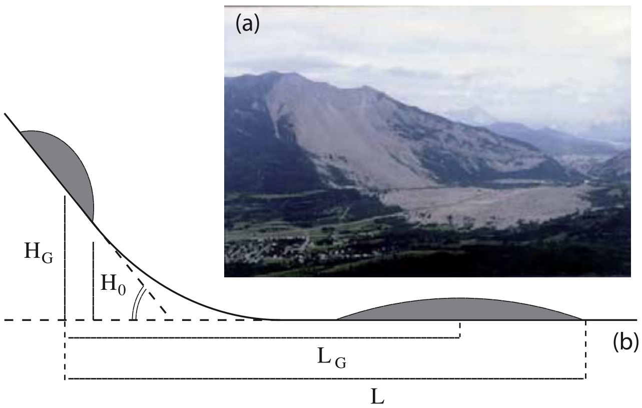

Figure 1. (a) Frank slide deposit (Photo 2002-581 by Réjean Couture reproduced with permission of Natural Resources Canada, courtesy of the Geological Survey of Canada). (b) Scheme of the numerical setup: the topography is composed of an inclined of slope θ_0 and height H_0, followed by a circular ramp connecting eventually with the horizontal plane. The initial vertical position of the center of mass is H_G, its final horizontal position is L_G, and L is the runout distance.

the runout distance L as a function of the volume, as in Figure 2b. In particular, the gap between the terrestrial and the martian data is considerably reduced. Interestingly, a purely geometrical power-law relation $L \propto V^{1/3}$ matches the trend shown by the data. Similarly, a fit of L as a function of the inundated area A reveals that $L \propto A^{1/2}$ (Figure 2b, insert) [*Iverson et al.*, 1998; *Dade and Huppert*, 1998]. These two power-laws are easily derived from a straightforward dimensional analysis. We conclude that the positive correlation observed in Figure 2a reflects the fact that landslide deposits have a common shape. In other words, field data strongly suggest that the correlation between mobility and volume of landslide is purely geometrical, and does not contain any information about the dynamics of the flow.

[8] In order to assess the generality of this conclusion, we have performed discrete numerical simulations of granular flows. Despite their apparent simplicity, granular materials, such as sand or glass beads, exhibit non-trivial behaviors bringing new insights in the problem of debris flows dynamics [*Savage*, 1989; *Campbell*, 1990; *Straub*, 1997; *Davies and McSaveney*, 1999; *Lube et al.*, 2004; *Lajeunesse et al.*, 2004, 2005, 2006]. Discrete numerical simulations of ideally simple granular flows have proven able to reproduce a realistic ability to flow, deform and spread, with a minimum number of assumptions on the flow rheology [*Cleary and Campbell*, 1993; *Campbell et al.*, 1995; *Linares-Guerrero et al.*, 2007; *Staron*, 2008].

[9] The numerical method applied is the Contact Dynamics [*Moreau*, 1994; *Staron and Hinch*, 2005]. The grains are strictly rigid, and they interact at contacts through a Coulomb friction law and elastic restitution. Accordingly, energy is dissipated when collisions and sliding occur between grains. In what follows, friction and elastic restitution at contacts are constant; their value was set to allow the granular mass to spread following a dense flow regime. The numerical procedure consists in building a 2D rounded mass of circular grains of mean diameter d. This granular mass of volume V is released from the top of a topography over which it flows. The topography is composed of an incline of slope θ_0 and initial height H_0, followed by a circular ramp connecting eventually with the horizontal plane (see Figure 1, and *Staron* [2008] for full details). The topography is made rough by gluing grains on it. The initial height of the gravity center of the granular mass is denoted H_G. After the mass has flowed down the topography and come to a rest, the runout distance L and the distance L_G travelled by the center of mass of the avalanche are measured (Figure 1). Note that the evaluation of L takes into account the coherent mass of touching grains only: the rare particles moving independently ahead of the main flow are excluded.

[10] Series of simulations were performed varying the volume V of the flowing mass from 300 grains to 12300 grains, the initial height H_0 from 4 to 16 m (ie $80 \le H_0/d \le 320$), and the initial slope θ_0 was alternatively set to 40 or 60 degrees. A total of 64 independent runs was carried out.

[11] One obvious difference between numerical simulations and real flows is that the first are 2D. This difference of geometry is easily accounted for by redimensionalizing the volume, considering $V^{1/D}$ (m) (with D = 2 for the numerics and D = 3 for data), instead of the volume V (m^3). Implicitly, we suppose that 3D effects such as lateral spreading play a marginal role in the issue discussed here. Once the volume redimensionalized, numerical simulations exhibit the same behavior as real rock avalanches in terms

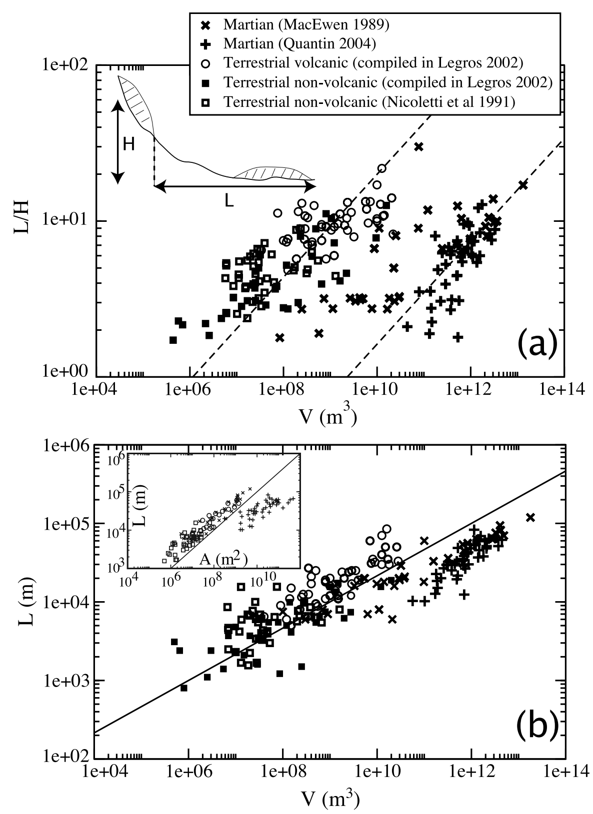

Figure 2. (a) Flow mobility $\mathcal{M} = L/H$ for series of terrestrial and martian data sets (see legend). Insert: sketch of the runout length L and the fallen height H of a dry debris flow. (b) Runout distance L as a function of V for the same data sets. Insert: Runout distance L as a function of the inundated area A.

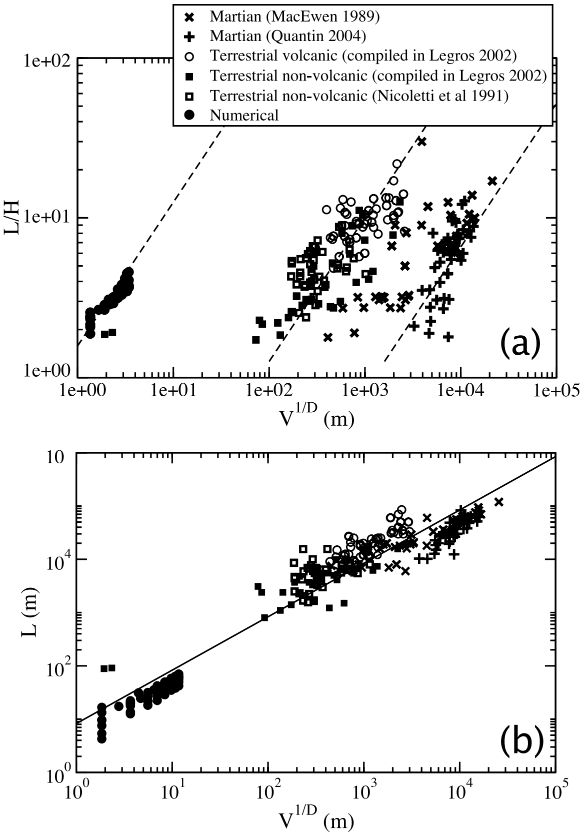

Figure 3. (a) Flow mobility $\mathcal{M} = L/H$ and (b) runout distance L as a function of $V^{1/D}$ for real flow data and numerical simulations.

of mobility: L/H, plotted against $V^{1/D}$, follows a power-law like trend similar to that shown by terrestrial and martian data (Figure 3a).

[12] Importantly, a plot of L as a function of $V^{1/D}$ shows a remarkable correlation merging along one single trend the numerical data and the natural data (Figure 3b). This suggests that the same mechanism works in both simulations and real flows, and stresses the first order role of geometrical spreading in the apparent volume-induced lubrication of large rock flows.

[13] This issue can be clarified in more general terms. The runout of a gravity-driven granular flow can be decomposed in two contributions: sliding along the topography and spreading of the unconsolidated mass:

$$L = L_{sliding} + L_{spreading}.$$

By analogy with solid friction, the sliding contribution is expected to be independent of the volume V involved (as expressed in equation (1)). By contrast, the spreading contribution should grow at first order as $V^{1/D}$, where D is the space dimension. The role of volume in the flow dynamics and runout should be posed in terms of a competition between these two contributions. Intuitively, one understands that when the volume of the flow is small compared to the size of the topography, sliding will dominate in the final runout. By contrast if the volume is large compared to the topography, then spreading will

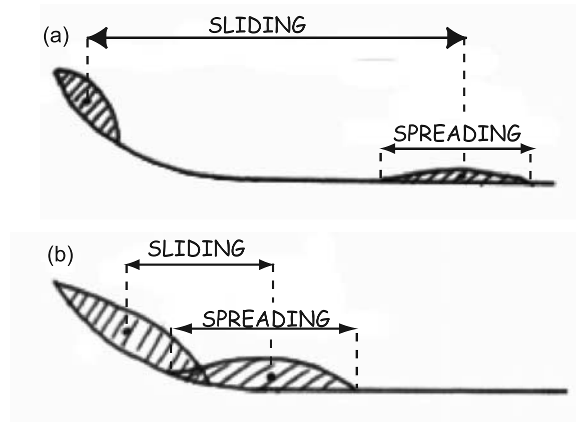

Figure 4. Respective contribution of sliding and spreading to the final runout depending on the volume of the flowing material with respect to the topography.

dominate (Figure 4). Hence, it seems that a relevant description should involve the volume of the mass and the topography geometry rather than the volume alone.

[14] Plotting the final position of the center of mass (normalised by H_0) against the normalised volume $V^{1/2}/(H_G \sin\theta_0)$ for the 64 independent simulations with varying V, H_0 and θ_0 allows for a collapse of the points on a single master curve (Figure 5). In other words, the relevant variable is the ratio of the two following quantities: the projection of the length scale related to the mass involved following the vertical direction $V^{1/2}/\sin\theta_0$, and its initial height H_G. If this ratio is small compared to 1, sliding dominates, whereas if it is large compared to 1, spreading dominates. Two regimes emerge: one in which L_g/H_0 remains constant irrespective of $V^{1/2}/(H_G \sin\theta_0)$ and dominated by sliding, and another in which L_g/H_0 rapidly increases with $V/(H_G \sin\theta_0)$ and dominated by spreading. The fact that Coulomb-like models fails for flows of volume greater than 10^6 m^3 is in favor of this analysis [*Iverson*, 2003].

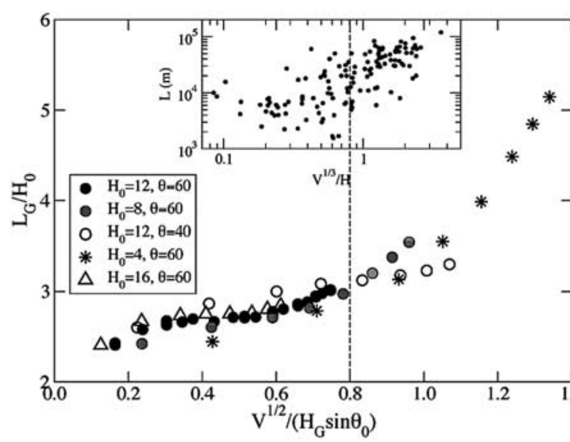

Figure 5. Normalized final position of the center of mass L_G/H_0 as a function of the normalized volume $V^{1/2}/(H_G \sin\theta_0)$ for all simulation series. Inset graph shows runout L as a function of normalized volume $V^{1/3}/H$ for terrestrial and Martian data.

[15] Hence, it appears that addressing the issue of volume-induced lubrication of flows on the basis of the volume alone is irrelevant. Rather, two regimes accounting for both volume and topography are evidenced. The similarity of behaviors of numerical and natural data on Figure 3 makes it likely that our conclusion applies to natural flows. The challenge now is to determine to which regime they belong. This is made difficult by the fact that no data on the position of the center of mass are available. Nevertheless, for the terrestrial and Martian data sets discussed in this paper, we can estimate $V^{1/3}/(H_G \sin\theta_0)$ assuming (arbitrarily) $\theta_0 = 45°$, and $H_G = H$: data seem to span the two regimes (Figure 5, insert).

[16] From these results, we conclude that understanding the physics and dynamics of dry natural flows implies the understanding of the intertwined role of volume and topography, and the way both control the respective contribution of sliding, as modeled by Heim, and spreading, of which friction models fail to give account. Particularly, the existence of two regimes demonstrated by the simulations, one dominated by sliding and the other dominated by spreading, open new prospects in our apprehension of debris flows behavior. Creating a reliable corpus of topographic features as a systematic description of flow deposits seems an essential step towards these improvements, as suggested by *Lajeunesse et al.* [2006] and *Staron* [2008]. By all means, considering the role of the volume of the flow as an isolated factor appears to be irrelevant. In the same way, our results show that invoking complex physical mechanisms (such as melting, acoustic energy exchanges, trapped air pressure…) is unnecessary to tackle the effect of large volumes. From both data and simulations analysis, geometry emerges as the first order factor, and the only universal candidate to explain the apparent volume-induced lubrication exhibited by dry debris flows.

[17] **Acknowledgments.** We thank Niels Hovius for interesting comments and critical reading of this paper.

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