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[1] Analogy with lab-scale dry granular flow experiments demonstrates that runouts and deposits heights of Valles-Marineris (VM) landslides can be scaled on a curve varying primarily with the initial aspect ratio of the mobilized rock mass (before slope failure). This results suggests both that any interstitial fluid played a negligible part in the VM landslides dynamics and that mobility is not an appropriate tool to characterize their dynamics. **Citation:** Lajeunesse, E., C. Quantin, P. Allemand, and C. Delacourt (2006), New insights on the runout of large landslides in the Valles-Marineris canyons, Mars, *Geophys. Res. Lett.*, *33*, L04403, doi:10.1029/2005GL025168.

1. Introduction

[2] Since the first pictures returned from Viking Orbiters, the numerous landslides identified along the canyons of Valles-Marineris (VM) have been the subject of considerable controversy as potential clues of the presence of liquid water on Mars in the past. *Luchitta* [1979] interpreted VM landslides as wet debris flows whereas *McEwen* [1989] concluded that they are analogous to dry terrestrial rock avalanches. Numerical simulations [*Harrison and Grimm*, 2003] indicate that neither Bingham rheology, nor acoustic fluidization nor frictional rheology satisfactorily reproduces VM deposits. More recently *Bulmer and Zimmerman* [2005] proposed to interpret the VM landslides morphology as the result of a slow deep-seated gravitational creep of the rock mass. The mechanisms controlling the runout of VM landslides remain therefore a subject of debate.

[3] Following the model of [*Heim*, 1882] for terrestrial landslides, the efficiency of landslides in the VM is usually estimated by their mobility (ratio of runout length ΔL to vertical drop ΔH). Mobility is commonly considered to increase with volume V. VM landslides however do not conform well to this size and mobility relationship: There is in fact a considerable scatter of the data particularly along the volume axis (see Figure 1).

[4] In this context, laboratory granular flows experiments allow new insights into the VM landslides. *Lube et al.* [2004], *Balmforth and Kerswell* [2005] and *Lajeunesse et al.* [2004, 2005] have recently investigated the transient flow occurring when a column of dry granular material is suddenly released on a horizontal surface. They all drew the same striking conclusion: the runout of the flow can be collapsed in a quantitative way independent of the released volume V but varying primarily with the aspect ratio of the initial granular column.

[5] In this paper we show that these results can be extrapolated to VM landslides, resulting in a much better merging of the data than the usual mobility/volume hypothesis. This result suggests both that the interstitial fluid played a negligible part in the VM landslides dynamics and that mobility is not an appropriate tool to characterize their dynamics.

2. Summary of the Laboratory Experimental Studies

[6] Granular column collapses were investigated in two different configurations. The first one [*Lube et al.*, 2004; *Lajeunesse et al.*, 2004] consisted of partially filling a tube reposing on an horizontal surface with a volume V of granular material resulting in a cylindrical column of initial radius L_i and height H_i (Figure 2). The tube was then quickly lifted to release the granular mass which spread over the surface. The second configuration [*Lajeunesse et al.*, 2005; *Balmforth and Kerswell*, 2005] consisted to release a rectangular granular column of initial length L_i and height H_i inside a linear channel of width W. In this section, we briefly summarize the main experimental results. Details about the experimental procedures can be found in the references cited above.

[7] Typical experiments are illustrated by the two sequences of images displayed on Figure 2. Upon release the granular mass collapses and spreads until it comes to rest and forms a deposit of final height H_f and length L_f. The flow is initiated by a Coulomb-like failure mobilizing an important fraction of the granular mass [*Lajeunesse et al.*, 2005]. However grains at the base of the flow progressively accrete in a static layer while the flow concentrates in a surface layer which gets progressively thinner as illustrated by the image differences of Figure 2b.

[8] A large number of experimental runs were carried out in which the volume released was varied, a wide variety of granular material was used (glass beads of diameters ranging from 0.3 mm to 3 mm, salt, sand and even couscous, sugar or rice) and the properties of the substrate were altered (rough or smooth, erodible or rigid). The mobility of experimental collapses estimated by the ratio of the runout distance $\Delta L = L_f - L_i$ to the fall height $\Delta H = H_i - H_f$ is plotted as a function of volume in the insert of Figure 1: data exhibit a lot of scatter as in the case of VM landslides. On the other hand, scaling the runout with respect to L_i enable all the experimental data to be merged on a single curve varying primarily with the aspect ratio of the initial granular column $a = H_i/L_i$ as shown on Figure 3a [*Lube et al.*, 2004; *Lajeunesse et al.*,

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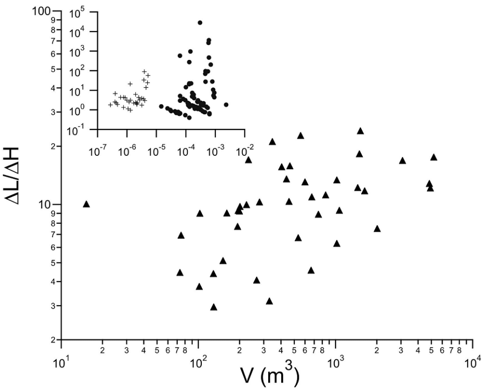

Figure 1. Mobility $\Delta L/\Delta H$ of the Valles-Marineris Landslides as a function of their volume V. Data from *Quantin et al.* [2004]. Insert: same plot for the experimental collapses. Circles and crosses correspond to experimental data obtained respectively by *Lajeunesse et al.* [2004] in the axisymmetric geometry and by *Lajeunesse et al.* [2005] in a rectangular channel.

2004, 2005; *Balmforth and Kerswell*, 2005]. Moreover, the scaled deposit height H_f/L_i also varies with a (see Figure 3b). Despite the rather complex flow dynamics, ΔL and H_f obey quite simple power laws whose exponents depend on the flow geometry (see Figure 3) [*Lajeunesse et al.*, 2005]:

[9] In the axisymmetric geometry:

$$\frac{H_f}{L_i} = \begin{cases} a & a \lesssim \lambda_1 \\ \lambda_1 & a \gtrsim \lambda_1 \end{cases} \tag{1}$$

$$\frac{\Delta L}{L_i} = \begin{cases} \lambda_2\, a & a \lesssim 3 \\ \lambda_3\, a^{\frac{1}{2}} & a \gtrsim 3, \end{cases} \tag{2}$$

[10] In the rectangular channel:

$$\frac{H_f}{L_i} = \begin{cases} \lambda_4\, a & a \lesssim \lambda_4 \\ \lambda_5\, a^{\frac{1}{3}} & a \gtrsim \lambda_4 \end{cases} \tag{3}$$

$$\frac{\Delta L}{L_i} = \begin{cases} \lambda_6\, a & a \lesssim 3 \\ \lambda_7\, a^{\frac{2}{3}} & a \gtrsim 3. \end{cases} \tag{4}$$

where the numerical constants λ_i (i = 1, 7) depend on the basal friction angle of grains contacting bed (ϕ_{bed}) and on the internal friction angle of the granular material (ϕ_{int}) [*Balmforth and Kerswell*, 2005].

[11] These results are supported by the following dimensional analysis. Listing the variables likely to influence flow dynamics, runout and deposit height leads to:

$$\left(\Delta L, H_f\right) = f(L_i, H_i, d, \phi_{bed}, \phi_{int}) \tag{5}$$

where d is the typical grain size. Gravity and granular material density only affect dynamical variables such as avalanche velocity and internal stress. This is why we omit them in the following. Straightforward dimensional analysis leads to:

$$\left(\frac{\Delta L}{L_i}, \frac{H_f}{L_i}\right) = f\left(a, \frac{d}{L_i}, \phi_{bed}, \phi_{int}\right) \tag{6}$$

d/L_i is of order 0 in all experiments. $\Delta L/L_i$ and H_f/L_i are therefore expected to vary primarily with a, ϕ_{bed}, and ϕ_{int} in agreement with experiments.

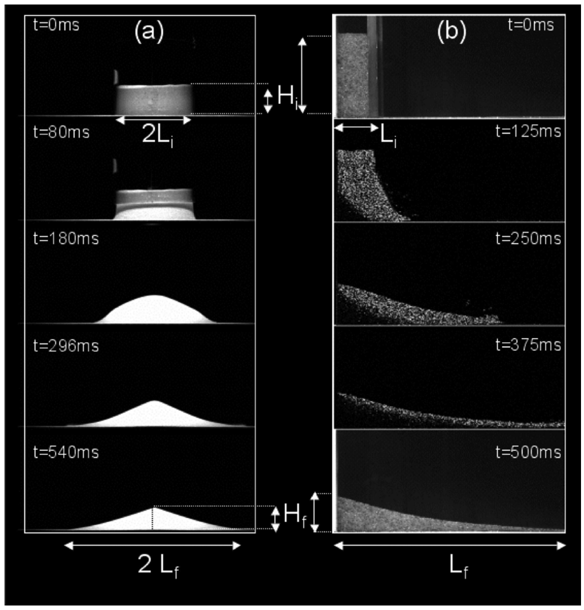

Figure 2. Sequences of side-view images showing the collapse of a granular column (a) in the axisymmetric geometry and (b) in a rectangular channel. In this latter case, images 2, 3 and 4 were obtained by calculating the difference between two consecutive snapshots. As a result, flowing regions appear in white and static zones in black.

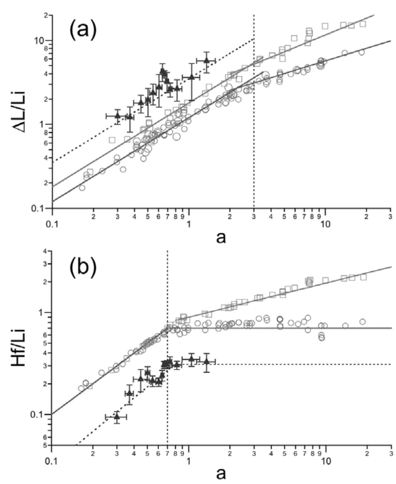

Figure 3. (a) Rescaled runout $\Delta L/L_i$ and (b) rescaled deposit height H_f/L_i as a function of a. Circles and squares correspond to experimental data obtained respectively in the axisymmetric geometry [*Lajeunesse et al.*, 2004] and in a rectangular channel [*Lajeunesse et al.*, 2005]. Triangles correspond to a run average performed over of the Valles-Marineris landslides data.

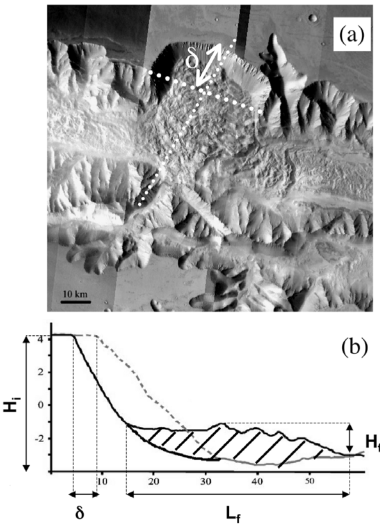

Figure 4. (a) Image of a landslides area in Valles Marineris. This image was obtained by combining several pictures taken by the Thermal Emission Imaging Spectrometer embedded in the Mars Odyssey 2001 probe (NASA). (b) Topographic profile along the dotted line of Figure 4a. Units of height and distance are *km*. The plain profile corresponds to the present post-landslide topography. The dotted profile is an estimate of the pre-landslide geometry [see *Quantin et al.*, 2004].

[12] Despite several attempts to model theoretically granular column collapse [*Denlinger and Iverson*, 2004; *Kerswell*, 2005; *Mangeney-Castelnau et al.*, 2005], no model yet has achieved a full comprehension of the power laws (1) to (4) which remains an active subject of research out of the scope of the present paper. Let us only mention that equations (2) and (4) can be understood dimensionally on the basis of a balance between inertia, pressure gradient and friction forces provided that both flow localization in a surface layer and vertical momentum transfers are taken into account [*Lajeunesse et al.*, 2005].

3. Test of the Experimental Scaling Laws on the VM Landslides

[13] The 3D geometry of 45 landslides deposits located along the walls of the VM canyons was recently analyzed by *Quantin et al.* [2004] from topographic data acquired by the Mars Orbiter Laser Altimeter and remote sensing images taken by Viking, the Thermal Emission Imaging Spectrometer and the Mars Orbiter Camera. VM landslides are characterized by large circular depletion zone where the slide mass originated (Figure 4a). Landslides scarps are curved and cut into the canyon rim allowing to identify the site of origin failure. The presence of numerous aprons at several landslide sites shown by images and topography data raises the question as to wether these aprons are the result from one or several successive landslides. In this paper, we use measurements performed by *Quantin et al.* [2004], who estimated VM landslides dimensions by considering all aprons as resulting from one single landslide event. Given this assumption, deposit volumes and thicknesses are large, ranging respectively from tens to thousands of cubic kilometers and from 0.1 to 2 km. Runout distances can be as large as 80 km and vertical drops reach 8 km.

[14] Several mechanisms such as weathering, change in pore pressure or Mars quakes have been invoked as triggers of VM slope failures. Modeling of VM slope stability by *Schultz* [2002] shows that seismic accelerations allow to initiate collapse of a dry weathered basaltic canyon wall along a single deep-seated shear surface. This is consistent with spectral observation of VM canyons walls from the Thermal Emission Spectrometer which suggests basaltic composition [*Bandfield et al.*, 2000]. In the following, we therefore consider VM landslides as resulting from a single deep-seated failure.

[15] The experimental granular column collapses are not meant to capture the whole complexity of natural landslides and they exhibit several obvious differences with VM landslides. First, the experiments involved volumes of the order of 10^{-3} m^3 whereas they reach 10^{12} m^3 on Mars. Secondly the experimental collapses were performed using a dry monodisperse granular material. On the other hand, VM landslides granulometric distribution probably resembles that of terrestrial debris flows usually ranging from clay size to boulder size [*Iverson*, 1997]. Interstitial water might also have affected VM landslides dynamics, although this matter is still a subject of debate. Third, VM topography is somewhat different from the experimental configuration. In particular, the average slope of the VM canyons wall before failure is of the order of 30° whereas the experimental granular column are vertical. Finally failure mechanism is likely to be the major difference between experiments and VM landslides. Experimental collapses are triggered by releasing a granular material. On the other hand, VM landslides granular material is likely to result from fragmentation of the rock wall during the early stages of collapses, as usually observed on Earth [*Kilburn and Sørensen*, 1998].

[16] Despite these differences, both experiments and VM landslides involve the spreading of a granular mass along a quasi-horizontal surface. Dimensional arguments also indicate that miniature dry granular flow experiments can be used to model aspects of rock avalanches for which the effects of intergranular fluid and cohesion are negligible [*Iverson et al.*, 2004]. These considerations were the motivation for testing the experimental scaling laws on VM landslides to determine if they might lead to a better result than the usual mobility/volume curve.

[17] To do so, we need to estimate H_i, L_i, H_f and L_f for each VM landslide. The easiest quantity to measure is L_i that we choose to estimate from the scarp thickness δ as shown on Figures 4a and 4b. Measurements of the other quantities are not so straightforward as the pre-landslide topography is unknown. This latter was reconstructed by measuring two reference profiles across intact wallslope on both sides of each landslide. Assuming that these intact wallslopes were similar to the geometry of the area before failure, the pre-landslide geometry was reconstructed by a linear interpolation between these two side profiles [*Quantin et al.*, 2004]. Initial height H_i and final deposit height and length H_f and L_f were then easily measured from the comparison between pre and post-landslide topographic profiles (see Figure 4b), allowing us to estimate the initial aspect ratio of each landslide: $a = H_i/\delta$.

[18] The resulting data exhibit statistical dispersion due to differences of local topography, scarp shape and pre-landslide slope from one landslide to the other one. To obtain statistically valid relationships, measurements were averaged by ranges of initial aspect ratios. The resulting average scaled runout and deposit height, $\langle \Delta L/L_i \rangle$ and $\langle H_f/L_i \rangle$, are plotted as a function of the averaged aspect ratio $\langle a \rangle$ in Figure 3. Error bars correspond to the root mean square associated to the run average process. Results exhibits good collapse of the data (as opposed to the plot of mobility vs volume) indicating that both the scaled runout and deposit height depend primarily on a. Moreover, although VM data do not fall on the experimental curves, they follow a similar trend: VM landslides runout increases linearly with the canyon wall height as observed for experimental data in the corresponding range of a (between 0.2 and 1.5). VM deposit heights also seem to follow a trend analogous to experiments performed in the axisymmetric geometry.

[19] Beside the difference of initial geometry, the systematic shift between VM and experimental data is likely to be due to differences of failure mechanism and granulometric composition. E. Linares et al. (New insight on the understanding of long runout avalanches: Geometric lubrication, submitted to *Physical Review Letters*, 2005) have recently shown that the runout length of a granular mixture varies slightly with its grain size distribution. This effect is not taken into account in our experiments but is likely to play a part in the case of VM landslides which result from deep failure of the rockwall and are therefore likely to involve a large range of grain size with large intact slabs.

4. Conclusions

[20] Analogy with lab-scale dry granular flow experiments demonstrates that the runout and deposit height of VM landslides can be scaled on a curve varying primarily with the initial aspect ratio of the mobilized rock mass (before slope failure). The resulting curve leads to a good collapse of the data as opposed to the usual mobility vs volume hypothesis. These results, which can be understood on the basis of a dimensional analysis analogous to the one developed above for laboratory experiments, suggests that interstitial fluid probably played a negligible part in VM landslides dynamics in agreement with the analysis of *McEwen* [1989].

[21] Four hypothesis have been proposed to account for the runout of large landslides [see *Legros*, 2002, and references within]: (1) sliding on an air cushion, (2) presence of a basal layer of melted ice, (3) fluidization due to effects of low amounts of water in unsaturated landslides or (4) acoustic fluidization. None of these mechanisms is consistent with what is observed in experimental collapses where the initial deep seated failure is followed by progressive flow localization in a surface layer which gets thinner and thinner. Assuming the same mechanism holds for VM landslides might explain the origin of large runout: the flow did not involve a thick layer propagating on an horizontal surface (large friction and small gravity component) but a thinner surface layer flowing along an inclined grain/grain interface (small friction and large gravity component).

[22] The above analysis suggests that mobility is not an appropriate tool to characterize VM landslides dynamics and casts doubt on its validity for terrestrial events as already proposed by *Savage* [1989] and *Legros* [2002]. In fact, careful examination of terrestrial landslides data reveal that V varies between 10^6 m^3 and 10^{13} m^3, ΔL between 10^2 m and 10^5 m and ΔH between 10^2 m and 10^3 m. Plotting $\Delta L/\Delta H$ vs V is therefore equivalent to plot ΔL (covering 3 orders of magnitude) vs V (covering 7 orders of magnitude) with scatter added by ΔH (covering less than one order of magnitude). We therefore believe that increase of mobility with volume is a simple consequence of volume conservation. To prove this statement, we need to perform the same analysis on terrestrial landslides as on VM landslides. This work which is in progress is however rather difficult: VM is rather unique in offering a set of landslides with similar topography and lithology. On the other hand, topography and lithology vary a lot from one terrestrial landslide to the other one making life difficult when attempting to extract the effect of one single parameter such as volume or initial aspect ratio.

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