Martian landslides in Valles Marineris: Wet or dry?

Veronika Soukhovitskaya a,*, Michael Manga b

a Department of Earth and Planetary Sciences, Harvard University, 20 Oxford St., Cambridge, MA 02138, USA
b Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA

Received 12 June 2005; revised 12 September 2005
Available online 21 November 2005

Abstract

The objective of this paper is to determine whether martian landslides in Valles Marineris were wet or dry and place constraints on the availability of liquid water in Valles Marineris during the Amazonian, when the landslides occurred. We, thus, statistically compare the power-law relationship between the volume and runout distance of landslides on Earth with those in Valles Marineris, Mars. The exponent of the power-law for martian landslides is similar to that for dry landslides and volcanic flows on Earth, and differs significantly from wet debris flows on Earth. The constant of proportionality in the observed power-law relationship for martian flows is linearly proportional to gravity, as predicted from physical modeling of dry flows in which the dissipation occurs in a layer of uniform thickness. Conversion of gravitational potential energy to heat is insufficient to generate more than a few weight percent of liquid water in the landslide. We thus conclude that water did not significantly influence the dynamics of landslides in Valles Marineris. This implies predominantly dry conditions in Valles Marineris during the Amazonian.

© 2005 Elsevier Inc. All rights reserved.

Keywords: Landslide mobility; Water on Mars

1. Introduction

On Earth, water plays a significant role in both initiating landslides and their subsequent flow and emplacement. Martian landslides in Valles Marineris provide an opportunity to learn about the physical processes that govern the landslides on Mars and specifically whether liquid water played a significant role in their formation (e.g., Lucchitta, 1978; McEwen, 1989; Legros, 2002; Quantin et al., 2004a). The question whether Valles Marineris landslides were wet or dry is important because of its implications for existence of liquid water near the martian surface during late Hesperian and Amazonian when the landslides occurred (Quantin et al., 2004b). The physics of long-runout landslides has been studied extensively and several models have been developed for the motion of granular masses in a gravity field (e.g., Iverson, 1997). Measurements of geometric parameters of the numerous Valles Marineris landslides (e.g., McEwen, 1989; Quantin et al., 2004a) and Earth’s landslides enable us to test these theories in different environments.

In this study we statistically compare the power-law relationship between the volume and runout distance of landslides on Earth with those in Valles Marineris, Mars and place constraints on the availability of liquid water in Valles Marineris at the time of the formation of martian landslides. We also compare the observational data on Earth with analytical models for dry and dilute turbulent flows in order to test models for landslide dynamics. Furthermore, from data we establish runout distance–gravity scaling law for dry landslides and show that it is consistent with the physical models of dry granular flows that agree with observations on Earth. We conclude, in agreement with several previous studies (e.g., McEwen, 1989; Coleman, 2002; Barnouin-Jha and Baloga, 2003), that water did not play a significant role in the dynamics of martian landslides. This conclusion differs, however, from that of other studies (e.g., Lucchitta, 1978; Shaller, 1991; Harrison and Grimm, 2003; Quantin et al., 2004a).
2. Geometry of landslides

We use variables runout distance \((L)\) and volume \((V)\) to compare martian and terrestrial landslides. \(L\) can be defined as the maximum distance traveled or can be measured from the center-of-mass of the landslide when it first starts moving to the center-of-mass of the deposit. The two definitions are shown in Fig. 1. In this study we use maximum \(L\) as Quantin et al. (2004a) give maximum \(L\) for martian landslides and Hayashi and Self (1992) give maximum \(L\) for terrestrial landslides. We assume that the other terrestrial data sources also give maximum \(L\), but many studies are ambiguous about what is reported.

Volumes of landslides are defined as initial or final. In this study we assume that terrestrial data use final volumes because the distinction between initial and final volume is rarely made. For martian landslides, Quantin et al. (2004a) give both initial and final volumes.

3. Models for landslides

3.1. Dry granular flows

Kilburn and Sorensen (1998) derive an analytical model of sturzstroms—giant landslides—based on mechanical energy dissipation, frictional stress, and fragmentation of particles within the flow. The results of the model yield \(L \sim g V^{1/3}\) for whole-body flow, where \(g\) is gravitational acceleration. For basal boundary layer flow, in which the bulk of the energy dissipation occurs within a thin layer at the base of the flow which thickness increases with distance traveled, results are \(L \sim g^{5/6} V^{1/2}\) (Kilburn and Sorensen, 1998). Moreover, for the dry boundary layer flow of constant thickness, based on this model and the model of Iverson (1997) for oscillating grains, scaling laws are \(L \sim g V^{1/3}\), identical to the whole-body flow.

As we will see, the latter boundary layer model and the model of Kilburn and Sorensen (1998) for dry whole-body flows agree best with the observational data on Earth, so in Appendix A we provide a brief overview of the physical processes that lead to these scaling laws.

3.2. Turbulent flows

Turbulent flows are dilute flows with a high content of fines. Dade (2003) describes the main features of the analytical model of dilute, turbulent gravity currents used to model the formation of low-aspect ratio ignimbrites (Dade and Huppert, 1995). The aspect-ratio of such flow is the ratio of its average thickness to the radius of a circle over which it spreads. The model is based on depth-averaged equations for the dynamics of dilute, suspension-driven gravity flows with no more than 30% by volume of solids concentration. The flows spread radially from a source upon instantaneous volume release. The characteristic lengthscale for such gravity currents are \(L \sim g^{1/8} V^{3/8}\) (Dade, 2003).

4. Observations

4.1. Data

As a way of testing the landslide dynamics we statistically compare the data for martian and terrestrial landslides. The data analyzed here come exclusively from previously published papers (sources of data are listed in the caption of Fig. 2). Fig. 2 shows the relationship between \(L\) and \(V\) for martian and terrestrial landslides. Table 1 summarizes the observed trends.

Uncertainties in the measurements of \(V\) may be as much as 30% (Kilburn and Sorensen, 1998) but are not usually reported. Uncertainties in \(L\) are discussed in Hayashi and Self (1992). However, we do not take these uncertainties into account in the least-squares fit of the data (Table 1) because errors on individual measurements are poorly known and are assumed to be

![Fig. 1. A sketch showing schematic landslide with definitions of landslide variables: landslide volume \((V)\), slope angle \((\theta)\), and two definitions of runout distance \((L)\).](image-url)

![Fig. 2. Runout distance \((L)\) as a function of landslide volume \((V)\) for martian and terrestrial landslides. The lines show approximate trends of the data. Best fits are given in Table 1. Data for martian slides come from Quantin et al. (2004a); for Earth’s dry and volcanic landslides from Hayashi and Self (1992), Evans and DeGraff (2002), and Legros (2002); and for Earth’s wet debris flows from Iverson (1997), Wieczorek and Naeser (2000), Bulmer et al. (2002), Evans and DeGraff (2002), and Legros (2002).](image-url)
4.2 Data analysis

Here we compare the slopes for the observed $L-V$ trends for martian and terrestrial landslides and discuss the validity of the assumption that $L$ predominantly depends on $V$ and $g$.

To compare different datasets we note that, even though the value of $R^2$ (Table 1) is smaller for martian landslides than that for terrestrial landslides, the values of $t$-statistic and $P$-value (Table 1) indicate that the linear trends for all datasets are statistically significant. The equations in Table 1 suggest that martian landslides are more similar to volcanic or dry landslides than wet debris flows on Earth. We thus argue that martian flows were largely dry and not water-saturated flows.

Runout distance $L$ may also depend on other variables such as drop height ($H$), slope, material properties, and confinement of the material. To test if $L$ depends on $H$ we performed multiple regression analysis of the data. Null hypothesis testing showed that there is no power law relationship between $H$ and $L$ for martian landslides, which is consistent with the plot of $L$ vs $H$ for martian data (Table 1) suggest that martian landslides are more similar to volcanic or dry landslides than wet debris flows on Earth. We thus argue that martian flows were largely dry and not water-saturated flows.

Runout distance $L$ may also depend on other variables such as drop height ($H$), slope, material properties, and confinement of the material. To test if $L$ depends on $H$ we performed multiple regression analysis of the data. Null hypothesis testing showed that there is no power law relationship between $H$ and $L$ for martian landslides, which is consistent with the plot of $L$ vs $H$ for martian data (Table 1) suggest that martian landslides are more similar to volcanic or dry landslides than wet debris flows on Earth. We thus argue that martian flows were largely dry and not water-saturated flows.

4.3 Assessment of analytical models for landslides

Here we compare the observed terrestrial $L-V$ trends to analytical models of landslides and assess the validity of the models.

Comparing observational data on Earth to analytical models shows that the dry whole-body flow model of Kilburn and Sorensen (1998) and the dry boundary layer flow model of Iverson (1997) accurately predict the trends of volcanic and dry terrestrial flows to within errors.

In contrast, the dry boundary layer flow model of Kilburn and Sorensen (1998) and the dilute flow model are not consistent with observations of the dynamics of natural dry and wet landslides, respectively. The fact that the boundary layer flow model of Kilburn and Sorensen (1998) describes the dynamics of wet landslides may be due to the fact that derived $L-V$ scaling law is based on the concept of boundary layer flow in continuum fluid mechanics [Eq. (A.5)].

5 Runout distance–gravity relationship

The empirical relationships between runout distance and volume for Earth’s and martian flows can be used to learn about the role of gravity in the flow movement as has been suggested by previous authors (e.g., Quantin et al., 2004a). For example, McEwen (1989) estimates an offset of 2.0 between the trends for martian and terrestrial landslides from $H/L$ vs $V$ plot, but attributes the offset to the yield strength of materials rather than gravity. Also Kilburn and Sorensen (1998) note that their derived runout distance–gravity relation for dry boundary layer flow, $L \sim g^{5/6}$, is consistent with observations. However, the $L-g$ scaling law has not been established quantitatively from data.

For this analysis we adopt the power law for the combined dataset of terrestrial volcanic and dry landslides (Table 1) be-
cause the observed trends show that martian landslides are more similar to volcanic or dry landslides. We include both dry and volcanic landslides data in this analysis because both dry and volcanic landslides do not contain significant amounts of liquid water and also because their observed trends have similar slopes to within the errors (Table 1) implying that they have similar emplacement mechanisms as suggested by Hayashi and Self (1992).

We assume that the empirical power laws for Earth’s and martian landslides can be written as $L \sim CV^b$. We also assume that the value of the power $b$ is the same on Mars and Earth (0.30: in agreement with the prediction of the model for constant thickness boundary layer dry flows and within the errors for both martian and terrestrial datasets), in order to compare the trends for the same exponent. Assuming a power law relationship $L \sim g^\delta$ we thus obtain:

$$C_{Earth}/C_{Mars} = (g_{Earth}/g_{Mars})^{\delta},$$

(1)

where $C_{Earth} = 13.1 \pm 0.1$ and $C_{Mars} = 5 \pm 1$ for $g_{Earth} = 9.8 \text{ m s}^{-2}$ and $g_{Mars} = 3.7 \text{ m s}^{-2}$. The values for $C_{Earth}$ and $C_{Mars}$ come from rescaling the proportionality constants for terrestrial and martian landslides (Table 1), respectively, according to the assumed power law $L \sim CV^{0.30}$. (For the rescaling factors we use the average values for log $V$ from martian and combined terrestrial datasets, respectively, to minimize the residuals in the new equations.) Then from Eq. (1) $\delta = 1.0 \pm 0.1$, and the empirical power law becomes $L \sim g^{1.0}V^{0.30}$, that is, the runout distance scales approximately linearly with gravity. The result of $L \sim g$, for a given volume, is consistent with physical models of dry granular flows that agree with observations on Earth, and supports the hypothesis that martian flows are best modeled as dry flows.

Using dry landslides trend instead of combined dataset trend in this analysis will affect the results. However, because the proportionality constants in the derived trends also depend on the material properties [as suggested by Hayashi and Self (1992) to explain the difference in the proportionality constants between dry and volcanic landslides on Earth], the reason that the dry landslides do not produce the $L \sim g$ scaling law, while volcanic landslides do, may be due to the possibility that martian landslides in Valles Marineris are better represented by volcanic materials. However, because Valles Marineris landslides’ materials are not well constrained, we assume that they are of mixed type, in which case the combined dataset is the most valid approximation to use in the derivation of the $L \sim g$ power law.

Landslides on other planetary bodies can provide an additional check on $L \sim g$ scaling for dry granular flows. For example, Eq. (1) predicts 10 km runout distance for the landslide on lapetus (image PIA06171, $V \sim 5.3 \times 10^4 \text{ km}^3$), which traveled about 60 km. The discrepancy factor of 6 corresponds approximately to four standard deviations (Table 1), assuming that the landslide on lapetus was dry. Otherwise, the greater runout distance may also indicate that liquid water enhanced the mobility. However, for two landslides on Callisto (image PIA01095, $V \sim 9 \text{ km}^3$), which traveled about 3 km each, Eq. (1) accurately predicts a travel distance of 3 km.

6. Melting of surface ice

It is possible that massive landslides in Valles Marineris melted frozen water in pore spaces as the potential energy of falling landslides was converted into thermal energy and energy of fusion (e.g., Harrison and Grimm, 2003). In order to obtain an upper bound on the volume of melt-water generated, we assume that all the dissipated potential energy ($E_{pot}$) goes into the latent heat of fusion ($Q$) and neglect the energy contribution to warming the rock, ice, or liquid water. Then, using $E_{pot} = Q$, where $E_{pot} = \rho gVH$, $\rho$ is the average density of landslides ($\sim 2000 \text{ kg m}^{-3}$), $H \sim 6000 \text{ m}$ (e.g., Harrison and Grimm, 2003), $Q = V_{melt}\rho_{ice}L_{f}$, $V_{melt}$ is the volume of melted ice, $\rho_{ice}$ is the density of ice, and $L_{f} = 334 \times 10^3 \text{ J kg}^{-1}$ is the latent heat of fusion of ice at normal atmospheric pressure, gives:

$$V_{melt}/V \approx H\rho_{Mars}/L_{f}\rho_{ice} \approx 0.1.$$  

(2)

Thus, on average, martian landslides could melt a volume of ice less than 10% of their total volume by the time the landslide stops advancing. This calculation is an upper bound and shows that during the runout landslides would at most produce a few percent by volume of liquid water. For comparison, wet debris flows on Earth contain more than 15–20% water by volume (e.g., Costa, 1984; Johnson and Rodine, 1984). This is consistent with our inference that the Valles Marineris landslides were largely dry. However, some melted ice at the time of deposition could influence the morphology and final stage emplacement of the deposit. This would reconcile the findings of this study that the landslides were largely dry with those of previous studies that the topography of landslide deposits in Valles Marineris is consistent with the presence of fluidization mechanism or liquid water (e.g., Harrison and Grimm, 2003; Quantin et al., 2004a).

7. Conclusion

We conclude that martian landslides in Valles Marineris are more similar to dry or volcanic landslides, than wet debris flows, on Earth. Runout distances of martian landslides are not as large as runout distances of dry landslides of comparable volume on Earth and are much smaller than runout distances of wet landslides on Earth. Thus, it is not necessary to appeal to any unusual fluidization mechanisms. Analysis of the runout distance of martian landslides is consistent with landslides being governed by whole-body or constant thickness boundary layer dry granular flow. Consequently, liquid water probably did not contribute significantly to the dynamics of martian landslides except perhaps during the final stages of emplacement.

Possible triggering-mechanisms for landsliding may be volcanic activity or Marsquakes, but, given that the landslides were probably dry, not rainfall or melting of surface ice. This implies predominantly dry conditions in Valles Marineris during the Amazonian.
Acknowledgments

Supported by the UC, Berkeley SROP program, the NASA astrobiology institute and NSF. We thank D. Baratoux, H. Gonnemann, K. Harrison, L. Hsu, and T. Perron for suggestions.

Appendix A

Here we provide a brief overview of the derivation of the model for dry landslides (Kilburn and Sorensen, 1998) because we find that martian landslides behave similarly to dry landslides on Earth.

Assuming an energy balance between the potential energy ($E_{\text{pot}}$) and the energy dissipated ($E_d$) during the runout due to grain collisions, it is possible to write a relation between the potential energy and frictional stress ($\tau$):

$$E_{\text{pot}} \sim E_d \sim \tau AL.$$  \hspace{1cm} (A.1)

Solving Eq. (A.1) for $z$ we obtain:

$$L \sim \rho V g z / \tau,$$  \hspace{1cm} (A.2)

where $z$ is vertical extent of the landslide in the zone of collapse and $A$ is the cross-sectional area. Kilburn and Sorensen (1998) assume that geometrically $z \sim V^{1/3}$, $A \sim V^{2/3}$, and $Ah \sim V$, where $h$ is the average thickness of the landslide. Since $\tau = (\text{momentum loss per collision}) \times (\text{frequency of collisions per fragment}) \times (\text{number of fragments per unit area})$, we obtain for a concentrated layer of fragments ($D/S > 1$):

$$\tau \sim (\rho D^3 U)(U/S)(\Delta /SD^2) \sim \rho U^2 (D/S)^2(\Delta /D),$$  \hspace{1cm} (A.3)

where $D$ is the typical grain size, $S$ is the average spacing between the fragments, $U$ is the average velocity of the landslide ($\sim (gz)^{1/2}$), and $\Delta$ is the thickness of the collision zone. For the whole-body flow:

$$\Delta \sim h.$$  \hspace{1cm} (A.4)

For the boundary layer flow:

$$\Delta \sim (vt)^{1/2} \sim (vL/U)^{1/2},$$  \hspace{1cm} (A.5)

where $t$ is time and $v$ is the diffusivity of momentum. Furthermore, potential energy per unit volume consumed due to stretching of the material before fragmentation is equal to $G(\delta V/V)^2$, where $G$ is the modulus of rigidity and $\delta V$ is the incremental change in the volume of the landslide (Jaeger, 1969). For small $\delta V/V$ and $S/D$, we have $\delta V/V \sim S/D$. Therefore:

$$S/D \sim (\rho g z / G)^{1/2}.$$  \hspace{1cm} (A.6)

Substituting the appropriate relations for $z$, $A$, $\tau$, $S/D$, $\Delta$, and $U$ into the expression for $L$ [Eq. (A.2)], we obtain for the whole-body flow $L \sim g V^{1/3}$, and for the boundary layer flow $L \sim g^{5/6} V^{1/2}$.

Building upon this model and the agitated basal layer model of Iverson (1997), it is possible to derive a scaling law for the dry flow with boundary layer of constant thickness. Iverson (1997) gives a solution for the mean free path or amplitude of oscillation of the lower agitated boundary layer of oscillating dry grains, according to which the boundary layer thickness scales as:

$$\Delta \sim U^2 / g.$$  \hspace{1cm} (A.7)

Substituting this into the expression for $\Delta$ [Eq. (A.5)] gives $L \sim g V^{1/3}$, identical to dry whole-body flow. This result is expected because assuming a flow of constant velocity leads to a constant boundary-layer thickness $\Delta$ [Eq. (A.7)].

References


