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Key Points:
- We explore the striking difference between the mobility of long-runout landslides on the Earth and Mars
- We simulate long-runout landslides as granular flow using a soft-particle code
- Differences in drop height explain the difference in volume mobility trends of Martian and terrestrial landslides

Correspondence to:
B. C. Johnson,
brandon_johnson@brown.edu

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Drop Height and Volume Control the Mobility of Long-Runout Landslides on the Earth and Mars

Brandon C. Johnson[1] and Charles S. Campbell[2]

[1]Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, [2]Department of Aerospace and Mechanical Engineering, University of Southern California, Los Angeles, CA, USA

Abstract Long-runout landslides are landslides with volumes of 10^5 m^3 or more, which move much farther from their source than expected. The observation that Martian landslides are generally less mobile than terrestrial landslides offers important evidence regarding the mechanism responsible for the high mobility of long-runout landslides. Here we simulate landslides as granular flow using a soft-particle discrete element model. We show that while surface gravity plays a negligible role, observed differences in fall height naturally reproduce the observed differences in mobility of Martian and terrestrial landslides. We also demonstrate that landslides on Iapetus may fit this trend. Our simulations do not include any fluid and indicate that a mechanism similar to acoustic fluidization can explain the high mobility of long-runout landslides. This implies that long-runout landslides on Mars should not be considered as evidence for ice, saturated clays, or liquid water.

1. Introduction

Long-runout landslides are among the most spectacular and catastrophic geologic processes. They are characterized by their high mobility (usually expressed as *L*/*H*, where *L* is runout distance and *H* is fall height) and an observed increase in mobility with slide volume (Legros, 2002). Assuming that the rheology of landslides is well described by a dry Coulomb friction law with an effective friction, μ_{eff}, landslides from the laboratory scale to volumes of 10^5 m^3 are well described by $\mu_{\text{eff}} \approx 0.5 - 0.7$ (Lucas et al., 2014). This is in agreement with typical friction coefficients of rocks as measured in the laboratory (Jaeger et al., 2009). As the volume of a landslide increases from 10^5 m^3, μ_{eff} decreases and above 10^9 m^3 $\mu_{\text{eff}} < 0.1$ are possible.

Many mechanisms have been proposed to explain this unexpected increase in mobility with slide volume (Cleary & Campbell, 1993; Collins & Melosh, 2003; Davies et al., 2012; Erismann, 1979; Lucchitta, 1987; Shreve, 1968; Singer et al., 2012). The observation of long-runout landslides on the Moon (Howard, 1973), Venus (Malin, 1992), Io (Schenk & Bulmer, 1998), Iapetus (Singer et al., 2012), Callisto (Chuang & Greeley, 2000), Phobos (Shingareva & Kuzmin, 2001), and Ceres (Schmidt et al., 2017) indicate that long-runout landslides can occur on bodies without liquid water and, with the exception of Venus, without an atmosphere. Mechanisms that require the presence of fluids, other than frictional melts, are at odds with these observations. Long-runout landslides on the Earth and Mars appear to be relatively dry and are distinguished from saturated terrestrial debris flows (Legros, 2002; McEwen, 1989; Soukhovitskaya & Manga, 2006). Other authors, however, argue that water or ice plays an important role in the reduction of friction of these landslides (De Blasio, 2011; Harrison & Grimm, 2003; Iverson, 2016; Lucchitta, 1987; Quantin et al., 2004; Watkins et al., 2015).

Terrestrial and Martian landslides exhibit a clear difference in their volume mobility trends (Figure 1). These volume trends are often reported as *H*/*L* versus slide volume as more accurate determination of μ_{eff} requires detailed reconstructions of the initial slide mass (note that this is the inverse of the mobility *L*/*H*, referred to above, which of course is larger for more mobile slides). For landslides with volumes exceeding 10^5 m^3, *H*/*L* acts as a reasonable proxy for determining the slides' effective friction where lower *H*/*L* corresponds to more mobile slides with lower effective friction (Lucas et al., 2014). Martian landslides are on average less mobile than terrestrial landslides of the same volume and may need to be 100 times more voluminous than their terrestrial counterparts to reach the same mobility (Figure 1) (McEwen, 1989). However, Martian landslides with smaller drop heights (blue to green-colored symbols in Figure 1) have mobilities similar to terrestrial slides (Figure 1). Note that many of the largest slides, with volumes exceeding 10^{11} m^3, are confined by

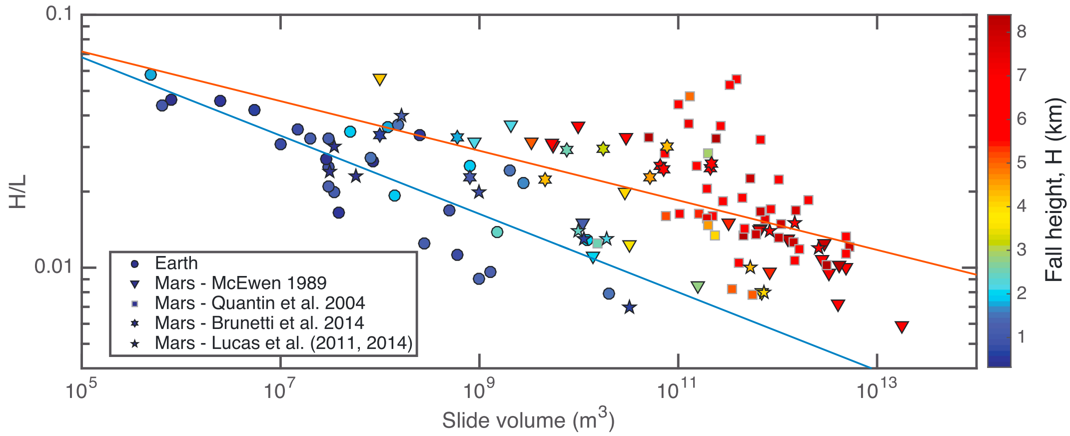

Figure 1. *H*/*L* versus slide volume of observed terrestrial and Martian landslides. Observed terrestrial (Legros, 2002) (circles) and Martian (McEwen, 1989) (triangles), (Quantin et al., 2004) (squares), (Brunetti et al., 2014) (hexagram), and (Lucas et al., 2011, 2014) (pentagram) colored by fall height *H* according to the color bar. The red and blue trend lines are based on Martian and terrestrial observations, respectively.

the canyon making runout estimates less certain (Brunetti et al., 2014). If these largest slides are ignored, the trend of lower mobility with increasing fall height is more evident (Figure 1).

Campbell et al. (1995) modeled terrestrial landslides as dry granular flows using a soft-particle code. Their simulations successfully reproduced observed terrestrial landslide volume mobility trends and the preservation of source stratigraphy in the final slide mass observed in many landslides (Erismann, 1979; Hewitt, 2002; Hsü, 1975; Shreve, 1968; Yarnold & Lombard, 2012). Johnson et al. (2016) demonstrated that the reduced friction and long runout of these simulated slides are explained by preferential slipping occurring when overburden pressures are relieved by transient pressure variations. Their results (Johnson et al., 2016) are broadly consistent with the acoustic fluidization mechanism proposed to explain the low strength and reduced friction of large deforming masses of rock (Melosh, 1979). Here we use the same code to demonstrate that the larger fall height *H* of Martian slides is a natural explanation for the observed differences between Martian and terrestrial slides. We then comment on the implications our work has for mechanism responsible for the high mobility of long-runout landslides.

2. Comparison of Terrestrial and Martian Slides

The observed difference between Martian and terrestrial landslides illustrated in Figure 1, provides a critical constraint for models of long-runout landslides. As can be seen in the figure, which plots *H*/*L* versus the slide volume, the Martian slides generally lie above the terrestrial slides. Or in other words, for the same slide volume, terrestrial slides will have a smaller effective friction than Martian slides. As with the mechanism leading to reduction of effective friction of long-runout landslides, the reason for distinct volume mobility trends for Mars and Earth remains mysterious. One obvious difference between Mars and Earth is their surface gravities ($g_{\mathrm{Earth}} \approx 9.8$ m/s^2, $g_{\mathrm{Mars}} \approx 3.7$ m/s^2). If landslides are well described by dry friction laws, we would not expect this difference to change slide mobility because the driving and resisting forces are both proportional to the surface gravity. The similar morphologies of small landslides and granular flows on Vesta, the Moon, and Mars suggest that surface gravity has a limited effect on slide mobility (Krohn et al., 2014). However, if the slides were well described by say, a Bingham rheology with a constant yield strength, a simple change in surface gravity could explain the observed difference in mobility between Martian and terrestrial slides (McEwen, 1989).

Changes to surface gravity also affect the timescale for a gravity driven flow. For a slide of a given volume and size, timescales are proportional $1/\sqrt{g}$ meaning the slide progresses faster when surface gravity is higher. It follows that all corresponding strain rates will scale as $\dot{\epsilon} \propto \sqrt{g}$. Assuming that fragments in the slide are produced by dynamic fragmentation (Grady, 1982; Grady & Kipp, 1980), which predicts that a typical fragment size should scale as $\dot{\epsilon}^{-2/3}$, then, all else being equal, the typical fragment size on Mars will be

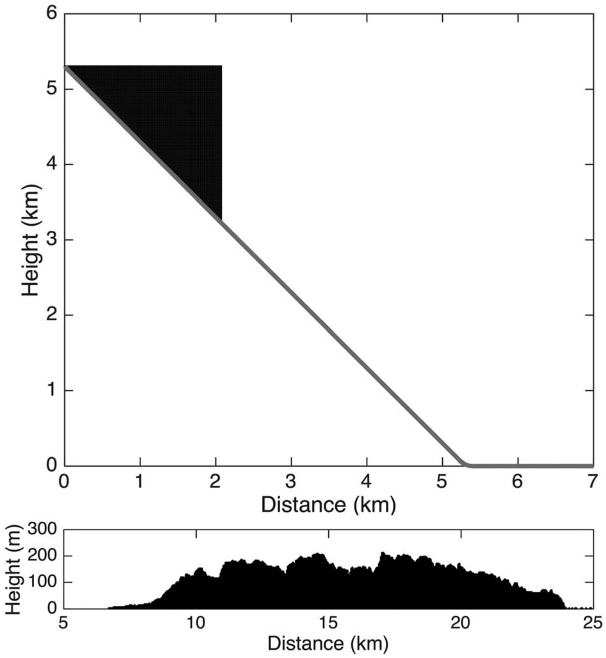

Figure 2. (top) Initial and (bottom) final slide geometry for 5.3 km fall height $D = 2$ m and Martian gravity. The black points mark the location of individual particles. The thick gray curve in the top plot shows the ground contour. Note that the bottom plot is 10 times vertically exaggerated.

$d_{\mathrm{Mars}} = d_{\mathrm{Earth}}\left(\frac{g_{\mathrm{Earth}}}{g_{\mathrm{Mars}}}\right)^{1/3} \approx 2d_{\mathrm{Earth}}$ (i.e., the typical size of fragments in a Martian slide would be approximately twice the size of those in a terrestrial slide of the same volume). Changing the typical particle size may also affect the overall mobility of the slide (Campbell et al., 1995; Johnson et al., 2016).

In addition to differences in surface gravity, Martian landslides fall from greater height, *H*, than their terrestrial counterparts (Figure 1). The average fall height of terrestrial landslides is 1.2 km where Martian landslides typically fall from 5.3 km. This may simply be the result of many of the Martian slides in Figure 1 being slides from Valles Marineris, which is up to 7 km deep (the Grand Canyon is about 1.6 km deep). The lower surface gravity of Mars means that for the same material strength Mars can support proportionally higher topography than Earth (Melosh, 2011). Thus, the greater fall heights for Martian landslides may be a common characteristic holding even for more complete global surveys of Martian slides. Although the results is somewhat counterintuitive, Campbell et al. (1995) found that simulated landslides with greater fall heights are less mobile than slides with the same volume and smaller fall heights. Here we explore the effects of fall height, particle size, volume, and surface gravity on landslide mobility by exploring parameters appropriate for the Earth and Mars.

3. Methods

Here we simulate Martian and terrestrial landslides using a two-dimensional soft-particle code. In this code, developed by Campbell et al. (1995), a granular flow is simulated by tracking the motions of multitudes of two-dimensional interacting disk shaped particles. The disk-shaped particles of diameter D can fall, slide, and roll down a frictional surface. The frictional surface is a slope of 45°, which transitions to a flat surface through an arc with radius of curvature equal to 250 D (this is the standard case used by Campbell et al., 1995). See Figure 2 for an example of our initial conditions. When particles overlap with each other or the underlying surface they interact. The normal force is modeled as a parallel spring and dashpot with the amount of compression equal to the amount of overlap of interacting particles. To model terrestrial slides, Campbell et al. (1995) and Johnson et al. (2016) use a nominal spring constant $kD/mg_{\mathrm{Earth}} = 12{,}250$, where *m* is the mass of the disk and $g_{\mathrm{Earth}} = 9.8$ m/s^2 is terrestrial surface gravity. To model landslides on Mars, we changed the surface gravity in our models to $g_{\mathrm{Mars}} = 3.711$ m/s^2. To ensure that the spring constant remained unchanged from the simulations of terrestrial slides (Campbell et al., 1995; Johnson et al., 2016), we set $kD/mg_{\mathrm{Mars}} = 32{,}350$. The dashpot coefficient, *d*, is given by $d/\sqrt{km} = 0.836$, making collisions quite dissipative (in a binary collision ~99% of energy is dissipated corresponding to a coefficient of restitution of 0.1) (Campbell et al., 1995). Johnson et al. (2016) show even changing *d* so that the coefficient of restitution is 0.5 only increases slide runout by ~6%. The choice of *d* has little effect on our results because long-runout landslides operate in a quasistatic granular flow regime, in which particles are locked in force chains (Campbell, 2002) and collisions are rare. While in a force chain, particles are frictionally locked with their neighbors and prevented from rolling. This limited rolling supports our choice of simple circular particles over more complicated shapes. Motivated by typical rock friction found in laboratory experiments, the force tangential to the contact of interacting particles is treated as a frictional slider with friction coefficient of 0.5 (Campbell et al., 1995).

To compare our simulated two-dimensional slides to observations, we follow Campbell et al. (1995), assuming that the slide volume is $V \approx (ND^2)^{\frac{3}{2}}$, where *N* is the number of particles in the simulation. This plausible assumption produces reasonable fits to the observed terrestrial slides when $D = 1$ m (Campbell et al., 1995) (Figure 1b, black triangles). Campbell et al. (1995) argue that this particle size is reasonable as it lies between the average clast size and largest clast size and also is computationally manageable. Johnson et al. (2016) suggest that higher *k* values and smaller *D* that are perhaps more realistic would produce slides with the same mobility. However, as *k* is increased and *D* is decreased, the computational expense of simulating a

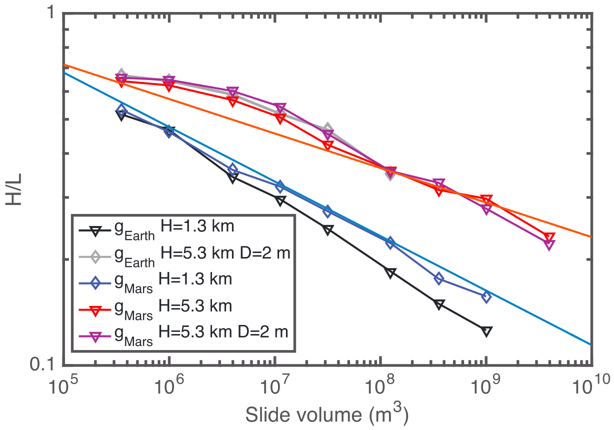

Figure 3. *H/L* versus slide volume of simulated terrestrial and Martian landslides. Simulations for different fall heights, surface gravities, and particle sizes as indicated in the legend (the black triangles were previously reported in by Johnson et al., 2016). Each point represents the result of a single simulation. Trend lines for observed terrestrial and Martian slides from Figure 1 are included for comparison.

slide of a given volume increases dramatically. Johnson et al. (2016), however, found that changing *k* by a factor 100 only changed *H*/*L* by 15%, suggesting that our results are quite insensitive to choice of *k*. Another factor that can change runout distances is the particle size distribution (Cleary & Campbell, 1993). Testing with a flat distribution of particle sizes from 1 to 5 m with an average particle size of 3 m suggests that choice of a single particle size produces longer runouts by 10–30%. Inclusion of the size frequency distribution still shows a large drop in mobility with increasing fall height (for a volume of 3.2×10^7 m^3 $H/L = 0.56$ and 0.44 for the $H = 1.3$ km and $H = 5.3$ km, respectively). Despite the difficulties of comparing two-dimensional slides to observations and uncertainties associated with our simplified models, we argue that the absolute estimates are not vital. The most important aspect of this work is demonstrating how landslide mobility changes from conditions of terrestrial slides to conditions of Martian slides. The comparisons of landslide mobility are robust and clearly demonstrate that differences in volume mobility trends of the Earth and Mars are naturally explained by differences in fall height.

4. Simulation Results

First, we simulate Martian landslides by changing only surface gravity to $g_{Mars} = 3.711$ m/s^2 keeping $H = 1.3$ km $D = 1$ m appropriate for terrestrial slides (Figure 3, blue diamonds). Although these slides progress slower than their terrestrial counterparts, the overall effect on runout *L* is modest. This suggests that the lower surface gravity does not lead to significantly reduced mobility. As previously discussed, the driving and resisting forces are both proportional to the surface gravity so the net effect of changing surface gravity is small. Comparison of simulations with $H = 5.3$ km $D = 2$ m with Martian and terrestrial surface gravities further demonstrate that the surface gravity has a weak effect on slide mobility (Figure 3, gray diamonds and purple triangles).

The next parameter we change is fall height setting $H = 5.3$ km, the average fall height of the observed Martian slides plotted in Figure 1; other parameters were $g_{Mars} = 3.711$ m/s^2 and $D = 1$ m (Figure 3, red triangles). Increasing the fall height decreases mobility, significantly putting our simulations in good agreement with the Mars trend line (Figure 3, red line). As demonstrated by Campbell et al. (1995) the increased runout with slide volume and decreased mobility with increased fall height can both be explained when the shear stresses increase with shear rate, but normal stresses are independent of shear rate. For a given slide volume the shear rates and shear stresses will be lower on Mars than on Earth, but the normal stresses are also reduced. When fall heights are increased, however, shear rates and shear stresses are increased while normal stresses remain unchanged. Thus, as fall height increases, slide mobility decreases and simulations are in good agreement with the observed lower mobility of Martian slides compared to their terrestrial counterparts. We will discuss the implications of this rheology in the following section.

As we argue in the previous section we may also expect that the particle size appropriate for a Martian landslide is approximately twice the size appropriate for a terrestrial landslide when all other conditions are equal. To test the effect this would have on slide mobility, we produce a suite of landslide simulations with $H = 5.3$ km, $g_{Mars} = 3.711$ m/s^2, and $D = 2$ m (Figure 1b, purple triangles). At the smaller slide volume, increasing particle diameter leads to slightly reduced mobility. Together our simulations suggest that the observed larger fall heights of Martian landslides act as a natural explanation for the differences in the volume mobility trends of terrestrial and Martian landslides.

5. Implications for Long-Runout Mechanism

To compare with the Singer et al. (2012) observation of landslides on Iapetus, we follow their example and produce an *H*/*L* versus *L* plot (Figure 4). Here in the absence of detailed volume reconstructions, landslide runout length *L* is taken as a proxy for slide volume (Singer et al., 2012). As with *H*/*L* and slide volume (Figure 1), terrestrial and Martian slides have decreasing *H*/*L* with increasing L (Figure 4). Landslides on Iapetus, captured in pictures by the Cassini spacecraft, however, do not demonstrate this same trend.

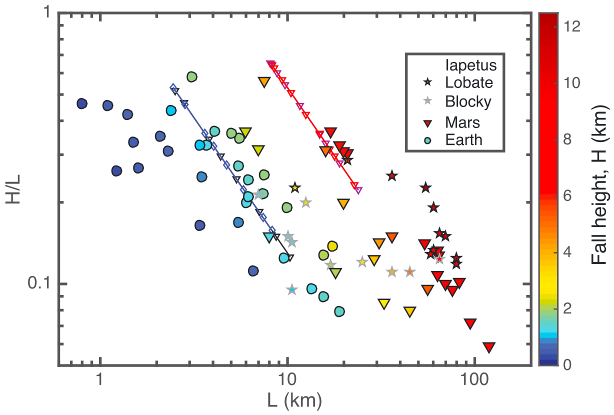

Figure 4. Comparison of *H/L* versus *L*. Observed landslides on Earth (Legros, 2002) (circles), Mars (McEwen, 1989) (triangles), and Iapetus (Singer et al., 2012) (pentagram) colored by fall height *H* according to the color bar. The lines are simulation results reported in Figure 3.

Singer et al. (2012) suggest that this is indicative of a different mechanism for the apparent reduction of friction in these slides. They suggest that localized frictional heating causes the ice surface to become slippery (Singer et al., 2012). On an *H/L* versus *L* plot, slides from a constant fall height plot along a single line, as demonstrated by our simulation results. A comparison of Figures 1 and 4 also demonstrates that *L* is not a robust proxy for slide volume. We color points on *H/L* versus *L* plot according to their fall height demonstrating that the uncertain trend for Iapetus may result from the large range of fall heights of these slides. For reference mean and one sigma deviation of fall heights for the various bodies in Figure 4 are H_{Earth} = 1.2 ± 0.56 km, H_{Mars} = 5.3 ± 2.3 km, and H_{Iapetus} = 6.0 ± 3.9 km.

Singer et al. (2012) also classified slides as lobate or blocky. Blocky slides have a noticeably rough surface indicating that they contain surface clasts that are larger than the resolution limit of Cassini's camera. Lobate slides have smooth surface where no individual clast can be resolved, indicating that they are more finely broken. The majority of the lobate slides are from large fall heights (Singer et al., 2012), which would account for the finer breakage. Furthermore, the mobilities of the lobate slides were more Mars-like and the blocky slides were more earthlike. In light of our results for Martian and terrestrial slides (Figure 3), the higher fall heights and speeds of the lobate slides account for their Mars-like behavior and the lower fall heights and speeds of the blocky slides account for their earthlike behavior. This indicates that fall heights are more important than clast sizes, a conclusion consistent with our model results. From this point of view, there is little need for a distinct friction reduction mechanism operating at Iapetus.

The initial conditions of our simulations of a vertical cliff face fragmented into equal-sized particles (Figure 2a) clearly do not include the complexities of actual Martian landslides. For example, many Martian landslides exhibit large unbroken toreva blocks (e.g., Quantin et al., 2004), which we cannot simulate with our models. In Martian landslides that include toreva blocks, a large mass of the slide does not runout long distances. This may indicate that our simulated slides are more representative of Martian slides with even larger volumes. Although our simulations are not capable of simulating breakage, we can consider whether fragmentation is a major sink of energy. Comparing the gravitational potential energy to surface energy density given by $\Gamma = \frac{3K^2}{\rho c^2 d}$, according to Grady (1982), where fracture toughness of $K \approx 2$ MPa m$^{1/2}$, density $\rho \approx 2800$ kg/m^3, and sound speed $c \approx 5000$ m/s are appropriate for intact basalt (Jian-An & Sijing, 1985), and d is a typical fragment size. Falling from a height of 1 km, the slide mass would have to break up into millimeter-scale fragments to dissipate ~1% of the slides' initial potential energy. Thus, we do not expect fragmentation to play a major role in the energy budget of the slide.

Many other variables could affect landslide mobility including particle size distribution, particle shapes, material composition, local geology, local topography, and the slope of the ground contour. Variations in these parameters may explain some of the variations seen in Figure 1 that are not readily explained by differences in fall height. Our simulations are not meant to accurately reproduce all details of observed landslides, but rather act a simplified system to isolate and test the effects of various parameters on the runout of these enigmatic long-runout slides. In addition to the agreement between observed slides and our simulations, the fact that our smallest simulated slides have mobility consistent with expectations from laboratory measurements indicates that our simulations include the relevant physical mechanisms that control the mobility of long-runout slides. Another test of these models comes from estimates of Martian slide velocities that indicate long-runout slides traveled at speeds exceeding 100 m/s (Mazzanti et al., 2016). Our largest simulated slides reached a peak velocity of 125 m/s (when the slide transition to a flat ground contour), broadly consistent with the finding of Mazzanti et al. (2016).

Remember that our simulations essentially model dry granular flow from first principles and do not include the effect of ground ice, water, frictional heating, frictional melting, or particle fragmentation. Although we cannot comment on the possible role of these various proposed mechanisms for increasing slide mobility, we demonstrate that some process naturally occurring in dry granular flows can explain the distinct volume mobility trends of landslides on the Earth, Mars, and perhaps Iapetus under ordinary conditions. Thus, caution should be exercised when considering long-runout landslides on Mars as potential evidence of saturated clays, ice, or liquid water. It follows that these landslides do not offer robust constraints on past Martian climate.

Although the interactions of single particles in these simulations are simple, Johnson et al. (2016) showed that collective effects result in a reduction of friction. They found sliding preferentially occurred when overburden pressures were relieved by transient pressure variations consistent with the main arguments of acoustic fluidization (Melosh, 1979). We consider the rheology occurring in our simulated slides where shear stresses increase with increasing shear rate faster than normal stresses increase. In addition to explaining general increases in mobility with increasing slide volume, this rheology also explains the observed decrease in mobility with increasing fall height, also consistent with the predictions of acoustic fluidization (Collins & Melosh, 2003; Johnson et al., 2016; Melosh, 1979). Furthermore, acoustic fluidization or something similar to it may be important for understanding the movement of large rock masses during earthquakes or the collapse of impact craters (Giacco et al., 2015; Melosh, 1979).

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