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Avalanche slope angles in low-gravity environments from active Martian sand dunes

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[1] The properties of granular material have an important effect on surface landforms and processes. Recently, it has been suggested that material properties called dynamic and static angle of repose vary with gravitational acceleration, which would have a significant effect on many planetary surface processes such as crater collapse and gully formation. In order to test that hypothesis, we measured lee slopes of active aeolian sand dunes on Mars using the High Resolution Imaging Experiment (HiRISE) DTMs (Digital Terrain Model). We examined dune fields in Nili Patera, Herschel Crater, and Gale Crater. Our measurements showed that the dynamic angles of repose for the sands in these areas are 33–34° in the first region and 30–31° in the other two. These results fall within the 30° to 35° window for the dynamic angles of repose for terrestrial dunes with similar flow depths and grain properties and thus show that this angle does not significantly vary with decreasing gravity. **Citation:** Atwood-Stone, C., and A. S. McEwen (2013), Avalanche slope angles in low-gravity environments from active Martian sand dunes, *Geophys. Res. Lett.*, *40*, 2929–2934, doi:10.1002/grl.50586.

1. Introduction

[2] The angles of repose of dry, cohesionless granular materials have long been of interest to the planetary science community. These measures are useful in characterization and study of a wide array of planetary surface processes including formation of impact craters, sand dunes, subaqueous deposits, granular flows, pyroclastic cones, and scree slopes. They are also of interest when planning in situ exploration that interacts with loose surface materials [*Sullivan et al*., 2011].

[3] There are two different commonly described angles of repose: static and dynamic. The static angle is the slope above which a given granular material will become unstable and begin to avalanche. The dynamic angle is the slope at which a given avalanching granular material will stabilize and come to rest; this angle is always lower than the static angle of the same material. We use the terms static and dynamic angles of repose following *Kleinhans et al*. [2011]; however, other sources use a wide variety of terms for these material properties.

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[4] Recent advances in the field of granular physics have shown that the ideas of static and dynamic angle of repose do not accurately represent the reality of granular avalanches. The newer, more physically accurate parameters are the angles θ_{start} and θ_{stop}, which respectively describe the angles at which avalanches will initiate and come to rest [*Forterre and Pouliquen*, 2008]. These quantities are both functions of the thickness of the flowing granular layer, which increase as the thickness of the flowing layer decreases [*Forterre and Pouliquen*, 2008]. Although θ_{start} and θ_{stop} are a more technically accurate way to talk about grain avalanching, the papers whose results we are examining (and most work done on grain avalanches in low-gravity environments) use the "angles of repose," and thus we frame most of our discussion in those terms.

[5] On Earth, these angles are primarily a function of grain roughness, angularity, and sorting. Moisture content and interparticle forces such as electrostatics may also play a role [*Allen*, 1969, 1970; *Carrigy*, 1970; *Cooke et al*., 1993]. It has long been assumed that the values of the angles of repose were independent of gravity. This is because when we examine the equations for the static angle of repose, the gravity term for both the shear and normal stresses is identical and thus cancels out of the equation entirely [*Melosh*, 2011, p. 328]. A similar argument, which uses kinetic as opposed to static friction, applies to the dynamic angle of repose. This assumption has previously been tested using a few different methods.

[6] One approach to studying the effects of gravity on the angle of repose is through computational numerical simulations. This has been done several times, including the fairly recent studies of *Ji and Shen* [2006] and *Nakashima et al*. [2011], which used two-dimensional discrete element methods to study this effect. Both of these studies determined that the angle of repose is basically independent of gravity, at least within the studied range of 1/6 and 1 *g*.

[7] A second way to look at this problem is with physical experimentation, although this presents some issues, as it requires simulation of different gravity environments. One way this has been done is by measuring the angles of repose in high-gravity environments created in a centrifuge [*Brucks et al*., 2007]. This generally showed that the effect of gravity higher than the terrestrial value is negligible on the angles of repose. However, all of the solar system bodies with solid surfaces have lower gravity than Earth. One possible way to directly experiment with lower gravity is to use parabolic flights to produce brief periods of low gravity. This has been done several times, most recently by *Kleinhans et al*. [2011], using rotating drums of material to study these angles. In their study, they measured a number of different materials at gravities roughly approximating those of the Earth, Mars, and the Moon. *Kleinhans et al*. [2011] determined that for approximately lunar gravity (they used 0.1 *g* instead of 0.165 *g*), the static angle increased by roughly 5°, and the

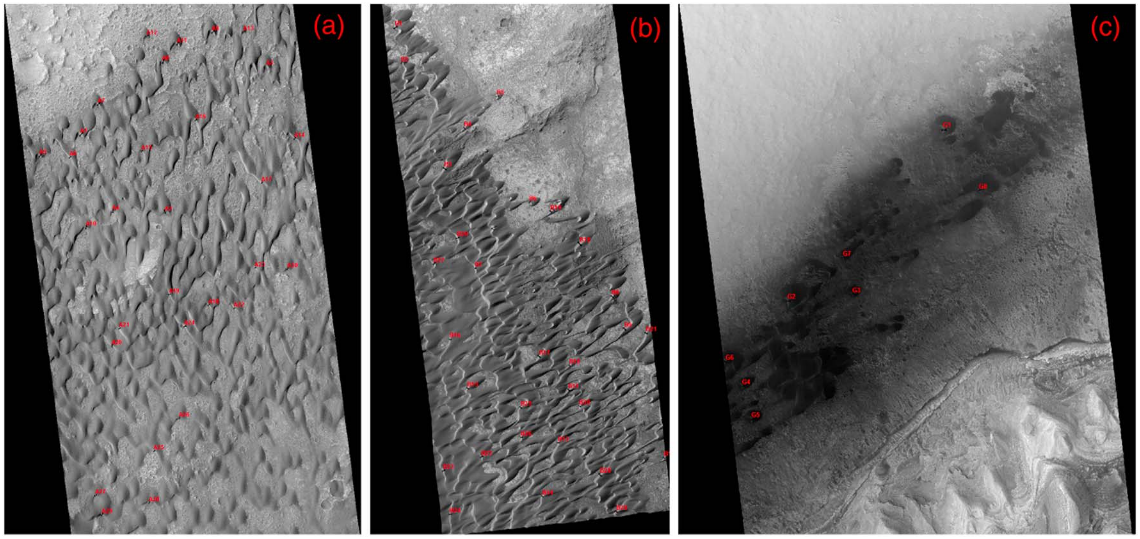

Figure 1. HiRISE orthoimages of (a) the Herschel Crater dune field DTM [DTEEC_002860_1650_003572_1650_U01], (b) the Nili Patera dune field DTM [DTEEC_017762_1890_018039_1890_A01], and (c) the Gale Crater dune field DTM [DTEEC_012551_1750_012841_1750_U01]. The red alphanumeric codes on the orthoimages show the approximate locations of the different dunes measured for this project.

dynamic angle decreased by roughly 10° with respect to their values at Earth gravity. In contrast, a study by *Nakashima et al.* [2011], which measured the angle of repose using sand dropped from a hopper during parabolic flights, showed negligible variation due to gravity. A third study by *Hofmeister et al.* [2009] measured the dynamic angle of repose using a combination of drop tower and centrifuge, which showed the dynamic angle of repose increasing with decreasing gravity.

[8] If either the *Kleinhans et al.* [2011] or the *Hofmeister et al.* [2009] values do prove to be accurate, they would have a significant effect on our interpretation of planetary surfaces. For instance, the activity of high-latitude Martian gullies is observed to correspond to the presence of seasonal CO_2, so processes involving this volatile may drive the activity, thus allowing for their low observed slopes [*Diniega et al.*, 2010; *Hansen et al.*, 2011; *Dundas et al.*, 2012]. However, *Horgan and Bell* [2012] proposed that gully formation on the northern hemisphere dunes occurs in the summer when CO_2 is absent and speculate that the unusual morphology of dunes slip faces (i.e., gullies) is due to the higher static and lower dynamic angles of repose reported by *Kleinhans et al.* [2011]. The *Kleinhans et al.* [2011] results would also have significant impact on the study of other planetary surface features whose geometries depend on the angles of repose, such as impact craters, aeolian dunes, pyroclastic cones, scree slopes, and subaqueous dunes and deltas. Another area of study that would be called into question by this result is the equilibrium shape of critically spinning rubble pile asteroids, which is controlled by the dynamic angle of repose [*Harris et al.*, 2009].

[9] Perhaps the best way to examine the effect of gravity on the angles of repose would be to measure these angles in situ on other planetary surfaces. This has been done on the Moon and Mars for the static angle of repose or friction angle [*Mitchell et al.*, 1972; *Moore et al.*, 1982; *Sullivan et al.*, 2011]. The data from these experiments appear typical for terrestrial soil simulants, which are thought to match the properties of the in situ regoliths [*Crosby et al.*, 2009]. To our knowledge, the dynamic angle of repose has not been measured in situ anywhere but Earth. In this paper, we measure the dynamic angle of repose of sand on Mars using high-resolution (~0.3 m/pixel) images from MRO's High Resolution Imaging Experiment (HiRISE) [*McEwen et al.*, 2007].

2. Methods

[10] It has been long established that the flat slip faces of active sand dunes are found at, or somewhat lower than, the dynamic angle of repose of their constituent sand [*Carrigy*, 1970; *Allen*, 1970; *Cooke et al.*, 1993]. By measuring the slopes of the slip faces of active Martian sand dunes, we should be able to determine the dynamic angle of repose of sand under a low-gravity environment. Active sand dunes are constantly reforming their slip faces, and thus we are confident that later processes did not significantly modify these slopes. Recent work using change detection between images of dune fields taken at different times has definitively shown that many Martian sand dune fields are active [*Chojnacki et al.*, 2011; *Bridges et al.*, 2012a, 2012b; *Silvestro et al.*, 2013]. Also, by using HiRISE DTMs (digital terrain models) [*Kirk et al.*, 2008], these slopes can be measured. Two DTMs of large active fields of barchan dunes are available, one of Nili Patera [*Bridges et al.*, 2012b] and one in Herschel Crater [*Bridges et al.*, 2012a] (see Figure 1). Additionally, we used a DTM of a small set of active dunes at Gale Crater [*Silvestro et al.*, 2013], near the Curiosity landing site. These DTMs have 1 m postings and a vertical precision of ~20 cm.

[11] Using these data sets, we can measure the slopes of the slip faces, and thus the dynamic angle of repose for these conditions, to compare them to terrestrial dunes. On Earth, the dynamic angle of repose for sand, found from both dune slip faces and experimentation, ranges between approximately 30° and 35° [*Carrigy*, 1970; *Cooke et al.*, 1993, and references therein] and the static angle is on average 2.5° higher [*Cooke et al.*, 1993]. The Martian and terrestrial dynamic angle of repose measurements that we are comparing in this study are thus taken from measurements of real sand dunes; this is important as values determined from experimental setups can vary somewhat from those found in real landforms. Thus, if the dynamic

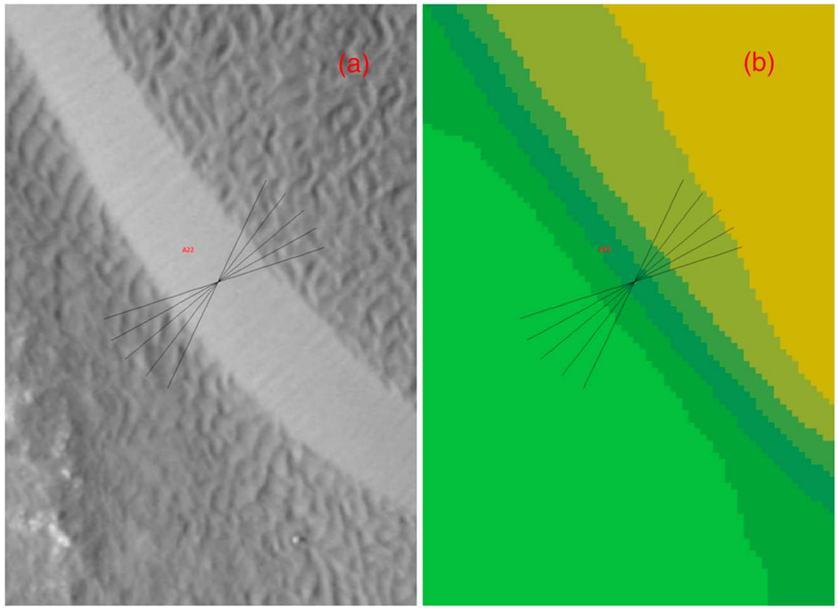

Figure 2. (a) Orthoimage and (b) DTM showing the 22nd dune slip face measured in Herschel Crater. The five lines drawn through the slip face of the dune show the positions of the five measured profiles of the slip face, where the center profile is usually the steepest profile. These figures show a good example in both image and DTM view of the kind of dune that was best for measuring.

angle is independent of gravity, we would expect to see that our measured Martian dynamic angles fall within this range. Alternately, *Kleinhans et al.*'s [2011] experiments for sand under roughly Martian gravity (0.38 *g*) suggest angles 5° to 7° lower than those found under terrestrial gravity.

[12] In order to be certain that gravity is the only free parameter, we need to know whether other controls on the dynamic angle of repose differ between Earth and Mars. Significant controls on the dynamic angle of repose are the shapes of sand grains, grain sorting, moisture content, and flow thickness. Grain shape is broken into the categories of roundness and sphericity, and on Earth aeolian sand grains are often subrounded, although this and sphericity are somewhat variable [*Livingstone and Warren*, 1996]. These variations are at least partially responsible for the 30–35° range of dynamic angle of repose in sand dunes. Measurements made of rippled aeolian sand in Gusev Crater by the Spirit rover indicate that these particular sands are largely subrounded and fairly spherical in character [*McGlynn et al.*, 2011], meaning this aeolian Martian sand is similar in shape to that on Earth. *McGlynn et al.* [2011] also show that the inclusive graphic standard deviation of the grain sizes of these aeolian sediments ranges from 0.42 to 0.80, which according to the grain sorting schema described by *Folk* [1981] indicates that they are moderately well to well sorted, which is the same amount of grain sorting seen in terrestrial aeolian dunes [*Cooke et al.*, 1993]. The moisture content of equatorial Martian dunes should be minor, making them quite similar to desert dunes on Earth. Avalanche flows on subaerial terrestrial dunes are almost always less than 2 cm thick [*Lowe*, 1976; *Cooke et al.*, 1993]. Although we have no measurements of flow thickness on Mars, the total sand fluxes are comparable [*Bridges et al.*, 2012b]. Thus, any major variations in dune slopes measured on Mars from those on Earth should be an effect of the lower gravitational acceleration.

[13] To measure a dune field, we imported the DTM into ArcMap 10, along with an orthoimage congruent to the DTM. A slope map was then created from the DTM to show the slopes of the slip faces. Noticeable artifacts affect the slope maps because the dark sand surfaces are relatively bland and featureless [*Mattson et al.*, 2012], and as such the slope for each dune could not be simply read off the map. To accurately measure the slopes, we created topographic profiles through each slip face, which would read out elevation data with horizontal distance. We were then able to create a line of best fit down the slip face to estimate the slope. The dune crest and base of the slip face are distinctive features and are well correlated in the stereo matching, so the extent of the slip face is well characterized in the DTM (when well illuminated).

[14] We chose 30 dunes each from the Nili Patera and Herschel Crater dune fields (see Figure 1) and eight dunes from Gale Crater. Dunes were selected from all over the mapped region according to certain criteria, which allow for more confident measurement. First, we wanted slopes that were not in shadow in the orthoimages. Next we tried to avoid the most heavily artifacted slopes and those where the width of the slip face in the orthoimage did not match that in the DTM. We tried to select slip faces that were mostly planar, as opposed to significantly convex or concave; these correspond to the active dunes. Finally, we looked for slopes where the top and bottom of the slip face were roughly parallel (i.e., not the curved portion of a barchan dune), although this was not always possible. Five profiles were drawn through each chosen slope, as shown in Figure 2, thus assuring that we did not undervalue the slope of the slip face by taking a profile that did not follow exactly the downhill gradient. Each of the five profiles was cut down so that it only included data from the slip face, using specified elevation values to define the top and the bottom of the slip face (see Figure 3). Each topographic profile was fit with a

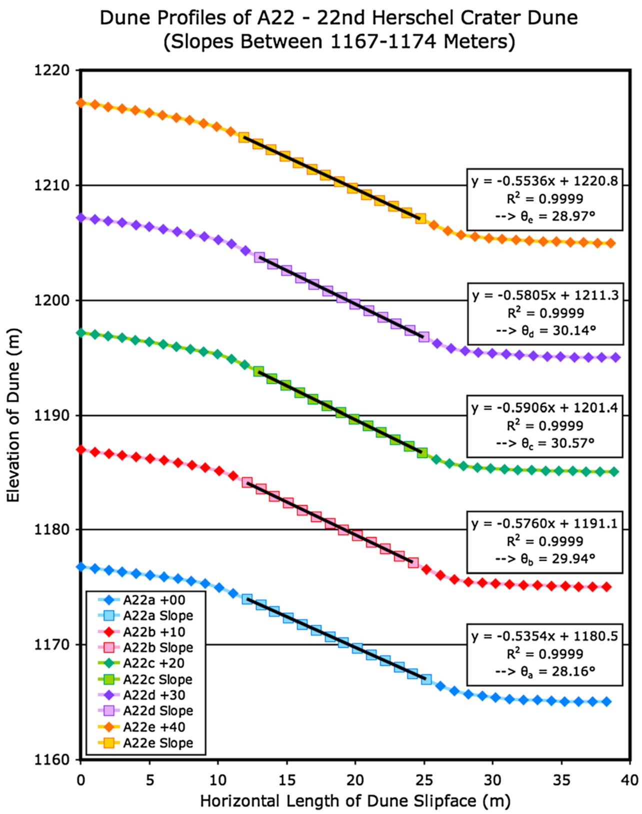

Figure 3. This graph shows the five profiles from the 22nd dune slip face measured in Herschel Crater, each vertically offset from the others by 10 m for clarity (the bottom profile is at the correct elevation). The long profiles (with diamond markers) show the original profiles through the dune, the shorter overlaid profiles (with square markers) show the profiles cut down to just the slip face. The top and bottom elevations of the slip face in each profile are taken to be the same for consistency, in this case 1174 and 1167 m, respectively. Then the black lines of best fit are calculated from the shorter profiles and their equations displayed on the right-hand side of the graph. The slope angle for each profile is calculated from these equations and displayed below them. The center (green) profile is clearly the steepest here with slope 30.57°. A similar graph is used to calculate the slope of each of the measured dunes.

line, the steepest of which was taken to be the slope of the slip face. In cases where two adjacent profiles had roughly equal (and highest) slope, a sixth profile was taken between those two profiles and was used to calculate the slope of the dune slip face.

3. Results and Discussion

[15] The slopes of the Herschel Crater dunes (barring a few outliers) range between 28° and 31°, weighted somewhat toward the top of that range (see Figure 4). Recalling that slip faces of sand dunes are found at or somewhat below the dynamic angle of repose [*Carrigy*, 1970; *Cooke et al*., 1993], we posit that the dynamic angle for the sand in the Herschel Crater dune field is ~30–31°. In Nili Patera, the slip face slopes (again barring a few outliers) range between 31° and 34°; thus, we posit that the dynamic angle of repose for this sand is ~33–34°. Finally, for the dunes near Gale Crater, the slopes range between 28° and 31°, strongly weighted toward the top of this range, suggesting a dynamic angle of repose of ~30–31°; however, the data for the Gale Crater dunes are both sparser and of lower quality than the other two regions, and so this value is less certain. Our measurements in Gale crater agree with those of *Silvestro et al*. [2013] based on the same HiRISE DTMs.

[16] These measured values of dynamic angle of repose of ~30–31° and ~33–34° match the expected range of 30° to 35° found both from laboratory experiments and measurements of terrestrial dunes [*Cooke et al*., 1993, and references therein] and are certainly not 5° to 7° lower than terrestrial values as predicted by *Kleinhans et al*. [2011]. These results support the hypothesis that the dynamic angle of repose is independent of gravity. It is possible that some other factor, such as static charge between grains, could be counteracting a real decrease in the dynamic angle of repose due to low gravity. However, we believe this is improbable both because such a counteracting force would be unlikely to produce results this congruent with our expectations of the angle being independent of gravity and because the requisite interparticle forces would strongly inhibit the saltation required to produce the observed dune migration.

[17] To be more technically accurate, this discussion should be framed in terms of θ_{stop} as was mentioned earlier. In this case, we still observe that Martian and terrestrial dunes exhibit the same range of angles on their lee slopes. Assuming similar thicknesses of granular flow in both cases, which seems reasonable given that the granular materials should be basically similar, that the overall landform morphology is the same, and that the sand fluxes are comparable [*Bridges et al*., 2012b], it would seem that the parameter θ_{stop} is mostly independent of gravity.

[18] The results of *Kleinhans et al*. [2011] were used by *Horgan and Bell* [2012] to argue against the role of CO_2 frost in forming dune gullies in the north polar sand sea of Mars [*Hansen et al*., 2011]. However, our results show that these slope angles should not be altered by the low-gravity environment, and we also note that Martian dune gullies have been directly observed to form only when there is CO_2 frost on the ground, at least in the southern hemisphere [*Diniega et al*., 2010; *Dundas et al*., 2012]. Preliminary results of monitoring the northern dunes through the most recent summer also do not show gully formation (C. Hansen, personal communication, 2012).

[19] Another interesting result comes from the observation that the dynamic angle appears to be ~3° lower in Herschel and Gale Craters than it is at Nili Patera. If this difference is due primarily to grain shape, it suggests that the sand grains at Herschel and Gale Craters are more rounded and smoother than those in Nili Patera. This difference could suggest that the sand was sourced further away and had to saltate farther to get to the dune field and thus become more rounded. The Nili Patera dunes appear to emanate from the well-exposed, high-albedo, actively eroding area of bedrock on the caldera floor where sand may have been scoured away by the wind [*Michaels*, 2011], whereas dunes at Herschel and Gale do not have an obvious local sand source. However, we do not know for certain the origin of the sands in any of these locations. Alternately, the higher degree of erosion on the Herschel and Gale sand grains could be a result of a longer weathering history in that area, perhaps due to sand being trapped. Nili Patera is a volcanic caldera at the summit of a broad shield volcano, so sand from distance sources might

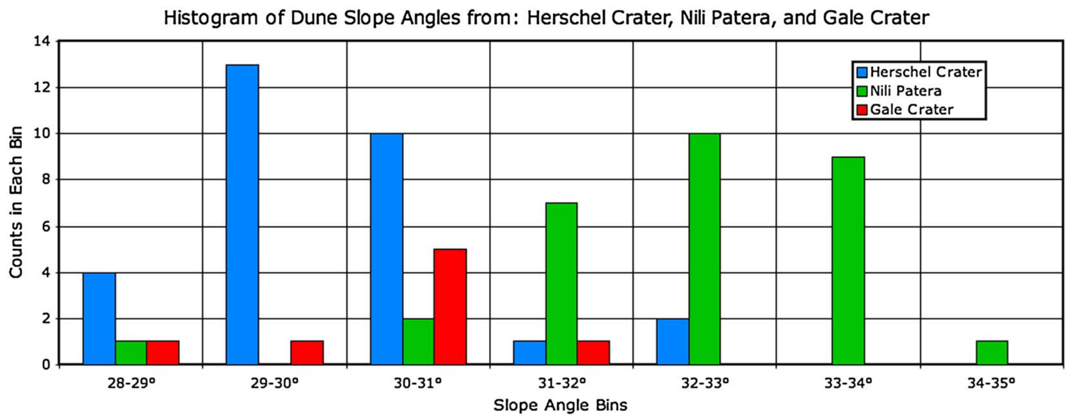

Figure 4. Histogram of measured slope angles from Herschel Crater, Nili Patera, and Gale Crater binned into 1° increments. The steepest bin filled by each dune field (excluding obvious outliers) is taken to be the angle of repose for the sand of that region. Thus, Herschel Crater and Gale Crater have dynamic angles of repose of approximately 30–31° each, and Nili Patera has a dynamic angle of repose of approximately 33–34°.

be less likely to be trapped here than in Herschel or Gale craters. Thus, measuring dune slip faces in this manner may present an interesting method for estimating sand grain textures from orbital imagery. These measurements could also provide ideas about the distance between a dune and its source of sand.

4. Conclusions

[20] By measuring the dynamic angle of repose of sand on Mars using the slip faces of active Martian sand dunes in Nili Patera, Herschel Crater, and Gale Crater, we are able to conclude that the dynamic angle of repose of dry granular material is, as was long suspected, independent of gravity. Since grain flows on dune slip faces are likely similar on the Earth and Mars, the more technically accurate parameter θ_{stop} is also shown to be independent of gravity. Our data do not allow us to directly examine the relationship between the static angle of repose and decreasing gravity; however, previous results from landers and rovers have been interpreted as indicating that the static angle is also independent of gravity. Finally, our results showing that the slip faces in Nili Patera are on average 3° steeper than those in Herschel and Gale craters indicate that the sand grains at Nili Patera are likely rougher than those at Herschel and Gale. This is interesting as we are thus able to learn about grain textures from orbital imagery.

[21] **Acknowledgment.** We would like to thank Serina Diniega for her thoughtful and helpful comments.

[22] The Editor thanks Jim McElwaine for his assistance in evaluating this paper.

References

Allen, J. R. L. (1969), The maximum slope-angle attainable by surfaces underlain by bulked equal spheroids with variable dimensional ordering, *Geol. Soc. Am. Bull.*, *80*, 1923–1930.

Allen, J. R. L. (1970), The avalanching of granular solids on dune and similar slopes, *J. Geol.*, *78*, 326–351.

Bridges, N. T., F. Ayoub, J. P. Avouac, S. Leprince, A. Lucas, and S. Mattson (2012a), Earth-like sand fluxes on Mars, *Nature*, *485*, 339–342, doi:10.1038/nature11022.

Bridges, N. T. et al. (2012b), Planet-wide sand motion on Mars, *Geology*, *40*, 31–34, doi:10.1130/G32373.1.

Brucks, A., T. Arndt, J. Ottino, and R. Lueptow (2007), Behavior of flowing granular materials under variable *g*, *Phys. Rev. E*, *75*, 032301, doi:10.1103/PhysRevE.75.032301.

Carrigy, M. A. (1970), Experiments on the angles of repose of granular materials, *Sedimentology*, *14*, 147–158.

Chojnacki, M., D. M. Burr, J. E. Moersch, and T. I. Michaels (2011), Orbital observations of contemporary dune activity in Endeavour Crater, Meridiani Planum, Mars, *J. Geophys. Res.*, *116*, E00F19, doi:10.1029/2010JE003675.

Cooke, R., A. Warren, and A. Goudie (1993), Dune processes, in *Desert Geomorphology*, UCL Press Limited, London, pp. 321–345.

Crosby, K. M., I. Fritz, S. Kreppel, E. Martin, C. Pennington, B. Frye, and J. Agui (2009), Scaling relations for repose angles of lunar mare simulants, paper presented at 2009 Annual Meeting of Lunar Exploration Analysis Group (LEAG), Houston, Texas.

Diniega, S., S. Byrne, N. T. Bridges, C. M. Dundas, and A. S. McEwen (2010), Seasonality of present-day Martian dune-gully activity, *Geology*, *38*, 1047–1050, doi:10.1130/G31287.1.

Dundas, C. M., S. Diniega, C. J. Hansen, S. Byrne, and A. S. McEwen (2012), Seasonal activity and morphological changes in Martian gullies, *Icarus*, *220*, 124–143, doi:10.1016/j.icarus.2012.04.005.

Folk, R. L. (1981), *Petrology of Sedimentary Rocks*, Hemphill, Austin, Tex.

Forterre, Y., and O. Pouliquen (2008), Flows of dense granular media, *Annu. Rev. Fluid Mech.*, *40*, 1–24, doi:10.1146/annurev.fluid.40.111406.102142.

Hansen, C. J. et al. (2011), Seasonal erosion and restoration of Mars' northern polar dunes, *Science*, *331*, 575–578, doi:10.1126/science.1197636.

Harris, A. W., E. G. Fahnestock, and P. Pravec (2009), On the shapes and spins of "rubble pile" asteroids, *Icarus*, *199*, 310–318, doi:10.1016/j.icarus.2008.09.012.

Hofmeister, P. G., J. Blum, and D. Heiβelmann (2009), The flow of granular matter under reduced gravity conditions, *AIP Conf. Proc., 1145*, 71-74, doi:10.1063/1.3180028.

Horgan, B. H. N., and J. F. Bell III (2012), Seasonally active slipface avalanches in the north polar sand sea of Mars: Evidence for a wind related origin, *Geophys. Res. Lett.*, *39*, L09201, doi:10.1029/2012GL041329.

Ji, S., and H. H. Shen (2006), Contrasting terrestrial and lunar gravity: Angle of repose and incline flows, paper presented at 10th International Conference on Engineering, Construction, and Operations in Challenging Environments, *Aerosp. Div., Am. Soc. of Civ. Eng.*, Houston, Tex.

Kirk, R. L., et al. (2008), Ultrahigh resolution topographic mapping of Mars with MRO HiRISE stereo images: Meter-scale slopes of candidate Phoenix landing sites, *J. Geophys. Res.*, *113*, E00A24, doi:10.1029/2007JE003000.

Kleinhans, M. G., H. Markies, S. J. de Vet, A. C. in 't Veld, and F. N. Postema (2011), Static and dynamic angles of repose in loose granular materials under reduced gravity, *J. Geophys. Res.*, *116*, E11004, doi:10.1029/2011JE003865.

Livingstone, I., and A. Warren (1996), *Aeolian Geomorphology*, Longman, Essex, U. K.

Lowe, D. R. (1976), Grain flow and grain flow deposits, *J. Sediment. Petrol.*, *46*, 188–199.

Mattson, S., N. T. Bridges, R. L. Kirk, E. Howington-Kraus, N. Mogk, L. Ojha, and the HiRISE Team (2012), Studying Martian dune changes with HiRISE DTMs and orthoimages, paper presented at Third International Planetary Dunes Workshop, Lunar and Planetary Institute Flagstaff, Ariz.

McEwen, A. S. et al. (2007), Mars Reconnaissance Orbiter's High Resolution Imaging Science Experiment (HiRISE), *J. Geophys. Res.*, *112*, E05S02, doi:10.1029/2005JE002605.
McGlynn, I. O., C. M. Fedo, and H. Y. McSween Jr. (2011), Origin of basaltic soils at Gusev crater, Mars, by aeolian modification of impact-generated sediment, *J. Geophys. Res.*, *116*, E00F22, doi:10.1029/2010JE003712.
Melosh, H. J. (2011), *Planetary Surface Processes*, Cambridge Univ. Press, Cambridge, U. K.
Michaels, T. (2011), Modeling aeolian surface interaction phenomena at Nili and Meroe Patera, paper presented at EPSC-DPS Joint Meeting 2011, Nantes, France.
Mitchell, J. K., W. N. Houston, R. F. Scott, N. C. Costes, W. D. IIICarrier, and L. G. Bromwell (1972), Mechanical properties of lunar soil: Density, porosity, cohesion, and angle of internal friction, *Proc. Third Lunar Sci. Conf.*, *3*, 3235–3253.
Moore, H. J., G. D. Clow, and R. E. Hutton (1982), A summary of Viking sample-trench analyses for angles of internal friction and cohesions, *J. Geophys. Res.*, *87*, 10,043–10,050.
Nakashima, H., Y. Shioji, T. Kobayashi, S. Aoki, H. Shimizu, J. Miyasaka, and K. Ohdoi (2011), Determining the angle of repose of sand under low gravity conditions using discrete element method, *J. Terramech.*, *48*, 17–26, doi:10.1016/j.jterra.2010.09.002.
Silvestro, S., D. A. Vaz, R. C. Ewing, A. P. Rossi, L. K. Fenton, T. I. Michaels, J. Flahaut, and P. E. Geissler (2013), Pervasive aeolian activity along rover Curiosity's traverse in Gale Crater, Mars, *Geology*, *41*, 483–486, doi:10.1130/G34126.1.
Sullivan, R., R. Anderson, J. Biesiadecki, T. Bond, and H. Stewart (2011), Cohesions, friction angles, and other physical properties of Martian regolith from Mars Exploration Rover wheel trenches and wheel scuffs, *J. Geophys. Res.*, *116*, E02006, doi:10.1029/2010JE003625.

The angle of repose is the maximum angle/slope at which a material can be stable and does not slide or fall. This angle is independent of gravitational acceleration g, so whether it is on Earth, Mars, or the Moon this angle is about 35^0