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REPLY

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This article is a reply to comment by *Iverson* [2016] doi:10.1002/2016JF003979.

Key Points:
- We reply to comment by Iverson
- Extraterrestrial landslides clearly demonstrate that dry landslides have reduced friction
- Our work demonstrates a friction reduction mechanism that does not involve fluid

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Reply to comment by Iverson on "The reduction of friction in long runout landslides as an emergent phenomenon"

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Abstract Here we address the comments by Iverson (2016) on our recent work concerning the reduction of friction in long runout landslides. Iverson (2016) questions the veracity of our models and suggests that high basal pore fluid pressure is the dominant mechanism reducing friction in long runout landslides. The main goal of our work was to elucidate the mechanism responsible for the apparent reduction of friction and long runout occurring in the landslide simulations of Campbell et al. (1995), which did not include an interstitial fluid. We found that the apparent reduction of friction in large slides could be explained by acoustic waves causing sliding to preferentially occur at pressures below the expected overburden, a mechanism reminiscent of acoustic fluidization. Such a mechanism is required to explain the long runout of dry landslides such as those on the Moon and other airless or waterless bodies. While our models provide no estimates of the effect of fluids on landslide runout, we have demonstrated a mechanism that increases runout distances that does not involve fluids.

1. Introduction

Iverson [2016] argues that high basal pore fluid pressure better explains the reduction of friction in long runout landslides than the acoustic fluidization hypothesis [*Melosh*, 1979] that *Johnson et al.* [2016] explored. Iverson's arguments are centered on the idea that fluid plays a role in nearly all landslides. This omits consideration of observations of extraterrestrial slides that occur in fluid-free environments. We agree that fluids play a role in some landslides, but clearly, a friction reduction mechanism that operates in dry landslides is required. In addition, *Iverson* [2016] takes issue with the simplicity of the models used by *Johnson et al.* [2016]. We respond to each of the sections in *Iverson* [2016] in turn. Our response to some sections has been combined into a single section for clarity.

2. *H*/*L*, H_{cm}/L_{cm}, and the Low Friction of Large Landslides

Iverson [2016] argues that small *H*/*L* values, where *H* is the vertical fall height and *L* it the horizontal runout distance of the slide, are not limited to large landslides. Although that may be true even for laboratory scale slides, *H*/*L* is not a direct measure of a slide's effective friction. As argued by *Johnson et al.* [2016] and many others, *H*/L is simply a convenient measure of the slide's mobility. A more robust measure of effective friction is the fall height and horizontal runout distance of the center of mass of the slide, $\mu_{eff} = H_{cm}/L_{cm}$. (Figure 2a of *Johnson et al.* [2016] is a plot of H_{cm}/L_{cm}.) We agree with *Iverson* [2016] that an actual friction reduction mechanism is needed to explain the high mobility of large runout landslides, and this is supported by detailed observations showing that some long runout slides have $H_{cm}/L_{cm} < 0.15$ [*Iverson*, 2016; *Iverson and George*, 2016], much lower than static rock friction of $\mu \approx 0.5 - 0.7$ [*Jaeger et al*., 2009].

Although laboratory experiments of dry granular flows may have low *H*/*L*, they do not necessarily yield low μ_{eff}. Analytical models of slides with a coulomb rheology show that μ_{eff} can be estimated using easily measured quantities regarding the initial and final geometry of the slide [*Lucas et al*., 2014]. A compilation of data from laboratory experiments of dry granular flows and terrestrial landslides shows that μ_{eff} is relatively constant for slide volumes below ~10^3 m^3 and that μ_{eff} decreases with increasing volume for larger slides [*Lucas et al*., 2014]. Model results in *Johnson et al*. [2016] are reported in both *H*/*L* and $\mu_{eff} = H_{cm}/L_{cm}$ and are consistent with the volume trend found by *Lucas et al*. [2014].

3. No Universal Explanation Needed

We agree with Iverson that a universal explanation of the low friction of landslides is not necessary. The offending sentence from *Johnson et al*. [2016] reads "Here we resurrect the *Campbell et al*. [1995] soft-particle code and implement it on modern workstations in an attempt to finally determine the underlying mechanism responsible for the apparent reduction of friction in long runout landslides." This sentence does not include a claim of unique correctness nor a promise of a universal explanation. This intention was stated in our original manuscript, including, for example, the following statement: "However, our goal for this work is to elucidate the mechanism responsible for the reduction of friction seen in the *Campbell et al*. [1995] models."

We agree that fluids can act as a major driver of the reduction of friction in terrestrial landslides, but we do not attempt to discuss collectively such physically disparate systems as dry granular rock avalanches, viscous-like mud flows, and slurry-like debris flows as if they are a single phenomenon, even though they may all show long runout behavior. We adopt a similar philosophy to that outlined by *Legros* [2002]: instead of a clear distinction there is likely a continuum from completely saturated debris flows to the waterless landsides on the Moon, Mercury, Venus, Io, and Phobos [*Legros*, 2002; *Howard*, 1973; *Brunetti et al*., 2015; *Malin*, 1992; *Schenk and Bulmer*, 1998; *Shingareva and Kuzmin*, 2001], and we only address the corner of that phenomena that we can address with the means available, that of dry rock avalanches. Although no universal mechanism is needed to explain the reduction of friction in large landslides, some mechanism not involving fluid is required to explain the long runout of dry slides. Because no fluid was included in our models, the simulations do not directly determine the effect of introducing fluid to a landslide. However, our work has demonstrated a mechanism that reduces the effective friction of the modeled slides which do not involve fluids.

4. Modern Slides Have Diverse Composition

Iverson [2016] argues that modern landslides have diverse compositions and a variety of stratigraphic and structural relationships. Our models [*Johnson et al*., 2016] only include a single basal topography, are two dimensional, and model landslides as a multitude of interacting disks. There is no question that these models are simple and do not capture the full diversity of modern slides. Exploring the effect of composition through inclusion of different grain shapes, size distributions, and grain surface friction may be the subject of future work.

The implication of Iverson's arguments seems to be that a basal friction reduction mechanism is sufficient to explain the reduction of friction in long runout landslides. Observations of many landslide deposits show that source stratigraphy is preserved. (Iverson is incorrect in stating that the preservation of stratigraphy is only seen in the Blackhawk landslide [*Shreve*, 1968]. Such observations go back all the way to Heim's survey of the 1881 Elm slide [*Heim*, 1882, 1932; *Hsü*, 1978]. Other examples are the Karakoram slides [*Hewitt*, 1988, 2002; *Hewitt et al*., 2008], the Socompa slide [*Wadge et al*., 1995], the Köfels slide [*Erismann*, 1979], Madison Canyon [*Hadley*, 1964], Black Canyon, and El Capitan and Split Mountain slides [*Yarnold and Lombard*, 1989].) *Campbell et al*. [1995] demonstrated that stratigraphy preservation is the result of a folding process during which the entire landslide is shearing, requiring a friction reduction mechanism that acts globally, not just in a basal layer. Only very near the end of sliding did these authors observe shear localized at the base. We note that landslide observations occur after the slide has come to rest. Thus, the observational relationships indicating low basal friction [e.g., *Coe et al*., 2016] are consistent with the late time behavior of the slides simulated by *Campbell et al*. [1995].

Another line of evidence supporting the interpretation that friction is reduced throughout the slide mass comes from recent landslide models of *Lucas et al*. [2014]. By including a phenomenological friction weakening rheology, *Lucas et al*. [2014] were able to reproduce the morphology of landslide deposits from the laboratory scale up to the largest long runout landslides. This friction weakening rheology acts globally and is consistent with initial shearing of the entire landslide mass.

5. Modern Long Runout Landslides Involved Water

Water is pervasive on Earth, and it may be impossible to rule out the possibility that water is driving the reduction of friction in at least some terrestrial slides. As previously stated, there is likely a continuum from saturated debris flows, where the role of water is dominant, to completely dry landslides, where water cannot play a role. Extraterrestrial slides offer us a valuable look at landslide dynamics under conditions that may never occur on Earth. Most notably, long runout landslides on the Moon, Mercury, Venus, Io, and Phobos clearly demonstrate that some friction reduction mechanism must operate even in completely dry slides [*Legros*, 2002; *Howard*, 1973; *Brunetti et al.*, 2015; *Malin*, 1992; *Schenk and Bulmer*, 1998; *Shingareva and Kuzmin*, 2001]. Moreover, the mobility of lunar slides is comparable to that of terrestrial slides of similar volume [*Lucas et al.*, 2014]. This suggests that the presence of water in relatively dry terrestrial slides may not significantly contribute to the reduction of friction. Currently, our models cannot be used to say anything directly about the effect of fluids on landslide dynamics. Future modeling work, including fluids, could help determine how saturated a voluminous long runout slide must be for fluids to play a significant role in reducing friction.

6. Landslide Experiments

Landslide experiments are critically important for understanding landslide dynamics. Laboratory scale experiments are especially valuable in understanding saturated debris flows [*Iverson*, 2015]. However, experiments are currently unable to reproduce long runout behavior for dry slides. *Lucas et al.* [2014] showed that the effective friction of slides is relatively constant for slide volumes below ~10^3 m^3 and that μ_{eff} decreases with increasing volume for larger slides. This volume dependence indicates that the reduction of friction of dry slides is an emergent phenomenon. Somehow, when the slide becomes voluminous enough, the simple interaction of particles produces a collective behavior that reduces the friction of the slide. Although they are conceivable, experiments involving well over 10^3 m^3 of rock will likely never be performed. Without such experiments, we must rely on landslide observations and models to explore how friction is reduced in dry slides.

7. Landslide Dynamics, Testing Models, and Diverse Data

Section 8 of *Iverson* [2016] is devoted to questioning the veracity of our models. *Iverson* [2016] suggests that our models were not tested at the laboratory scale. This is simply untrue. The soft-particle discrete element technique has been tested against numerous laboratory experiments [e.g., *Mead and Cleary*, 2015]. (And while Iverson seems to have a high opinion of the Mead and Cleary simulations, their results merely show that discrete element model simulations can closely match one of Iverson's experiments; they reveal nothing about mechanics of long runout landslides.) *Iverson* [2016] suggests that the slides modeled in *Johnson et al.* [2016] start out in a highly unbalanced stress state with a "dam" removed at time zero. This again is incorrect. The modeled slide mass begins in a hexagonal close packed configuration with zero prestress (as clearly demonstrated by Figure 4 in *Johnson et al.* [2016]).

We did not mean to suggest that experiments and terrestrial observation of landslides are unimportant. Of course, experiments, modeling, and observation of modern slides are paramount to understanding landslide dynamics. We agree that each of these modes of study has its unique advantages and a deeper understanding of landslides requires synthesis of ideas from all of these fields. However, we argue that the study of extraterrestrial landslides and prehistoric landslides should be seriously considered as important contributors to the study of landslides. Although the fidelity of observations is lacking when compared to terrestrial observation, (dry) extraterrestrial landslides allow us control the influence of fluids on landslide behavior and require full consideration.

Much of sections 8 and 9 of *Iverson* [2016] are devoted to suggesting that the models in *Johnson et al.* [2016] are oversimplified. We argue that the simplicity of our models is the key to their effectiveness. The interactions of individual grains are simple, yet somehow the collective effect of many simple interactions leads to a reduction of friction. Without this simplicity, we may not have identified the mechanism responsible for reduction of friction in these models. Future works including the added complexities suggested by Iverson (e.g., realistic basal topography, three dimensional models, variations in grain shape, variations in grain friction, and variation in grain sizes) are certainly warranted, but stripping a problem down to its simplest form also has its merits and can help advance landslide science.

References

Brunetti, M. T., Z. Xiao, G. Komatsu, S. Peruccacci, and F. Guzzetti (2015), Large rock slides in impact craters on the Moon and Mercury, *Icarus*, *260*, 289–300.

Campbell, C. S., P. W. Cleary, and M. Hopkins (1995), Large-scale landslide simulations: Global deformation, velocities and basal friction, *J. Geophys. Res.*, *100*(B5), 8267–8283, doi:10.1029/94JB00937.

Coe, J. A., R. L. Baum, K. E. Allstadt, B. F. Kochevar Jr., R. G. Schmitt, M. L. Morgan, J. L. White, B. T. Stratton, T. A. Hayashi, and J. W. Kean (2016), Rock-avalanche dynamics revealed by large-scale field mapping and seismic signals at a highly mobile avalanche in the West Salt Creek valley, western Colorado, *Geosphere*, *12*, 607–631, doi:10.1130/GES01265.1.

Erismann, T. H. (1979), Mechanisms of large landslides, *Rock Mech.*, *12*, 15–46.s.

Hadley, J. B. (1964), Landslides and related phenomena accompanying the Hebgen Lake earthquake of August 17, 1959. U.S, *Geol. Surv. Prof. Pap.*, *435-K*, 107–138.

Heim, A. (1882), Der Bergstürz von Elm, *Z. Deutschen Geologie Gesellschaft*, *34*, 74–115.

Heim, A. (1932), *Bergstürz und Menschenleben*, 218 pp., Fretz and Wasmuth, Zürich.

Hewitt, K. (1988), Catastrophic landslide deposits in the Karakoram Himalaya, *Science*, *242*, 64–67.

Hewitt, K. (2002), Styles of rock avalanche depositional complexes conditioned by very rugged terrain, Karakoram Himalaya, Pakistan, *Rev. Eng. Geol.*, *15*, 345–377.

Hewitt, K., J. J. Clague, and J. F. Orwin (2008), Legacies of catastrophic rock slope failures in mountain landscapes, *Earth Sci. Rev.*, *87*, 1–38.

Howard, K. A. (1973), Avalanche mode of motion: Implications from lunar examples, *Science*, *180*(4), 1052–1055, doi:10.1126/science.180.4090.1052.

Hsü, K. J. (1978), Albert Heim: Observations on landslides and relevance to modern interpretations, in *Rockslides and Avalanches: 1. Natural Phenomena*, edited by B. Voight, pp. 71–93, Elsevier, Amsterdam.

Iverson, R. M. (2015), Scaling and design of landslide and debris-flow experiments, *Geomorphology*, *244*, 9–20, doi:10.1016/j.geomorph.2015.02.033.

Iverson, R. M., and D. L. George (2016), Modeling landslide liquefaction, mobility bifurcation and the dynamics of the 2014 Oso disaster, *Geotechnique*, *66*, 175–187, doi:10.1680/jgeot.15.LM.004.

Iverson, R. M. (2016), Comment on "The reduction of friction in long-runout landslides as an emergent phenomenon" by Brandon C. Johnson et al., *J. Geophys. Res. Earth Surf.*, *121*, doi:10.1002/2016JF003979.

Jaeger, J. C., N. G. W. Cook, and R. Zimmerman (2009), *Fundamentals of Rock Mechanics*, John Wiley, New York.

Johnson, B. C., C. S. Campbell, and H. J. Melosh (2016), The reduction of friction in long runout landslides as an emergent phenomenon, *J. Geophys. Res. Earth Surf.*, *121*, 881–889, doi:10.1002/2015JF003751.

Legros, F. (2002), The mobility of long-runout landslides, *Eng. Geol.*, *63*(3–4), 301–331, doi:10.1016/s0013-7952(01)00090-4.

Lucas, A., A. Mangeney, and J. P. Ampuero (2014), Frictional velocity-weakening in landslides on Earth and on other planetary bodies, *Nat. Commun.*, *5*, 3417, doi:10.1038/ncomms4417.

Malin, M. C. (1992), Mass movements on Venus: Preliminary results from Magellan cycle 1 observations, *J. Geophys. Res.*, *97*, 16,337–16,352, doi:10.1029/92JE01343.

Mead, S. R., and P. W. Cleary (2015), Validation of DEM prediction for granular avalanches on irregular terrain, *J. Geophys. Res. Earth Surf.*, *120*, 1724–1742, doi:10.1002/2014JF003331.

Melosh, H. J. (1979), Acoustic fluidization—A new geologic process, *J. Geophys. Res.*, *84*(B13), 7513–7520, doi:10.1029/JB084iB13p07513.1.

Schenk, P. M., and M. H. Bulmer (1998), Origin of mountains on Io by thrust faulting and large-scale mass movements, *Science*, *279*(5356), 1514–1517, doi:10.1126/science.279.5356.1514.

Shingareva, T. V., and R. O. Kuzmin (2001), Mass-wasting processes on the surface of Phobos, *Sol. Syst. Res.*, *35*(6), 431–443, doi:10.1023/A:1013082711274.

Shreve, R. L. (1968), The Blackhawk landslide, *Geol. Soc. Am. Spec. Pap.*, *108*, 1–48, doi:10.1130/SPE108-p1.

Wadge, G., P. W. Francis, and C. F. Ramirez (1995), The Socompa collapse and avalanche event, *J. Volcanol. Geotherm. Res.*, *66*, 309–336.

Yarnold, J. C., and J. P. Lombard (1989), A facies model for large rock-avalanche deposits formed in dry climates, in *Conglomerates in Basin Analysis: A Symposium Dedicated to A. O. Woodford*, edited by I. P. Colburn, P. L. Abbott, and J. Minch, pp. 9–31, Pac. Sect. Soc. of Econ. Paleontol. and Mineral., Los Angeles, Calif.