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REPLY

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This article is a reply to comment by *Davies and McSaveney* [2016] doi:10.1002/2016JF003954.

Key Points:

- We reply to comment by Davies and McSaveny
- We argue that we cannot comment on the role of fragmentation
- Our work has demonstrated a friction reduction mechanis that does not involve fragmentation

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

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The crux of the comment in *Davies and McSaveney* [2016] is that their theory of dynamic fragmentation better explains the reduction of friction in long runout landslides than the acoustic fluidization hypothesis that provides the context for the analysis in *Johnson et al.* [2016]. We find this to be strange, as acoustic fluidization is essential to their theory [*Davies and McSaveney*, 2012; *Davies et al.,* 2012]; the only difference is that they assume that the source of the acoustic energy is the explosion of rocks (rock bursts) in the fragmenting process. Everything else, in particular, the reduction of normal stress and the consequent frictional weakening at contact points, are the essence of acoustic fluidization. Thus, *Davies et al.* [2012] cannot be considered an alternative to acoustic fluidization but acoustic fluidization with an alternate acoustic energy source.

Davies and McSaveney [2016] suggest that the simulations presented by *Johnson et al.* [2016] depart from reality in four significant ways. We address each point in turn.

First, *Davies and McSaveney* [2016] claim that *Johnson et al.* [2016] was not put into the proper context with previous work. Although a variety of previously suggested mechanisms for reduction of friction are discussed in *Johnson et al.* [2016], it was not meant to be an exhaustive review. We thought our intention was made clear throughout the manuscript including the abstract and 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." In addition to an apparent reduction of friction, the *Campbell et al.* [1995] model successfully describes many aspects of large landslides including the preservation of source stratigraphy.

Second, *Davies and McSaveney* [2016] then indicate the simulations of *Johnson et al.* [2016] depart from reality by ignoring the fact that rock avalanches are composed of a distribution of grain sizes including nanometer scale grains. We agree that real landslides are composed of a distribution of grain sizes. The main goal of our work, however, was to determine the mechanism responsible for the reduction of friction occurring in the simulations of *Campbell et al.* [1995]. Although many results are reported nondimensionally, we followed *Campbell et al.* [1995] focusing on landslides nominally composed of meter-scale particles. Inclusion of a broader range of particle sizes may be the subject of future work. It is, however, computationally unfeasible to use a discrete element model including very small grains to simulate an entire landslide with a volume of 10^6–10^9 m^3.

Based on the finding that the acoustic fluidization, wavelength is set by the size of particles in the slide [*Johnson et al.,* 2016], including a distribution of particle sizes that would allow a larger distribution of wavelengths to drive fluidization. Continuum modeling of landslides using the framework of acoustic fluidization suggests that although changing the acoustic fluidization wavelength alters the effective viscosity of the slide mass, it does not fundamentally affect results [*Collins and Melosh*, 2003]. Thus, we do not expect that changing the particle size or using a distribution of particle sizes would have a major effect on runout distance for slides of the same total volume.

In closing, the mere fact that the simulations studied here do not model every aspect of every landslide does not mean that the results do not apply to some aspects of some landslides. And in this section Davies and McSaveney fail to elucidate why the assumption of large particle size leads to erroneous results.

Third, *Davies and McSaveney* [2016] suggest the modeling of *Johnson et al.* [2016] is unrealistic because it does not include fragmentation and dynamic forces associated with fragmentation. Again, the main thrust of our work was to determine the mechanism responsible for the reduction of friction seen in the *Campbell et al.* [1995] landslide simulations. Thus, inclusion of fragmentation was beyond the scope of the work. Because fragmentation was not included, the work of *Johnson et al.* [2016] cannot be directly used to say anything about the effect fragmentation could have on the runout of landslides. Similarly, because no fluid was included in the 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 slide that does not involve fragmentation.

Although our simulations do not include fragmentation, we can consider fragmentation in light of the results of *Johnson et al.* [2016] and the acoustic fluidization model [*Melosh*, 1979]. First, consider that all of the energy in a landslide ultimately comes from its initial gravitational potential. While one may argue about the relative magnitude of the energy loss, fragmentation is an energy sink that abstracts energy from the moving mass and may not contribute directly to its mobility. The GHz frequencies proposed by *Davies and McSaveney* [2016] would be rapidly dissipated in a material with particle sizes larger than the acoustic wavelength and would not contribute to mobility except with respect to their contribution to fluidizing small grains. The mismatch of short wavelengths from breaking fragments and the size of the other fragments likely make this a marginal source of mobility.

Furthermore, *Davies and McSaveney* [2016] incorrectly suggest that the model of *Johnson et al.* [2016] assumes a loose granular flow. Soft-particle codes like that used by *Johnson et al.* [2016] make no assumption about the granular flow regime and can simultaneously model both dense and loose granular flows [*Campbell et al.,* 1995], and the snapshots in that paper clearly show dense flows. In fact, the acoustic fluidization hypothesis assumes the existence of a dense contact network through which the acoustic signals propagate. Finally, a quick survey of *Johnson et al.* [2016] shows that the word “loose” appears exactly once in the paper, in estimating the order of magnitude of the sound speed in a granular material. In that context, loose means “dense” (by the Davies and McSaveney usage) but lightly loaded, (although the value suggested of 100 m/s is of the correct order of magnitude for heavily loaded materials). However, the loose sound speed (measured for static beds) is likely applicable to a more heavily loaded shearing material as the shear motion disrupts the internal contact network, reducing the coordination number and thus the elastic modulus [*Bathurst and Rothenburg*, 1988] and, with it, the sound speed. In any case, the sound speed estimate appears only in discussion and is not central to any analysis of the results.

Fourth and finally, *Davies and McSaveney* [2016] argue that acoustic fluidization is much less capable of reducing friction in landslides and explaining long runouts when compared to fragmentation. *Davies and McSaveney* [2016] point to an analysis of the acoustic fluidization model for reduction of friction on faults during earthquakes [*Sornette and Sornette*, 2000]. But we believe Davies and McSaveney are incorrect in saying that Sornette and Sornette disprove the acoustic fluidization hypothesis. In fact, the final sentence in their abstract ends with “…the relevance of acoustic fluidization remains an open question.” In their analysis, *Sornette and Sornette* [2000] do outline possible inconsistencies in an application of the acoustic fluidization model to earthquakes but specific to the analysis and assumptions in *Melosh* [1996]. They then make suggestions on how these discrepancies could be remedied simply by altering some of those assumptions or changing some of the parameters in that specific model. We suggest that in addition to experiments [*Melosh and Gaffney,* 1983], numerical models of granular flows [*Giacco et al.,* 2015; *Johnson et al.,* 2016] may help to further refine the assumptions and various parameters that the acoustic fluidization model depends on [*Melosh*, 1979]. Our simulations, for example, suggest that the wavelength-driving acoustic fluidization is determined by the size of fragments present in the landslide [*Johnson et al.,* 2016].

It is important to note that our modeling does not make any a priori assumptions about the validity of the acoustic fluidization hypothesis nor is an acoustic fluidization model directly implemented in our simulations. The acoustic fluidization model of *Melosh* [1979] is a continuum model. *Johnson et al.* [2016] used the same discrete element model or “soft-particle” code used by *Campbell et al.* [1995] to simulate landslides. These simulations do not include an explicit friction reduction mechanism and essentially simulate the slides from the first principles of the mechanics of interacting particles. In the simulations of *Johnson et al.* [2016] and *Campbell et al.* [1995] the mechanism responsible for the apparent reduction of friction and long runout emerges from a multitude of simple particle-particle interactions. The primary finding of *Johnson et al.*

[2016] is that the effective friction of voluminous landslides ($>10^6$ m^3) is reduced because sliding preferentially occurs when overburden is relieved by pressure variations or acoustic waves. This mechanism is reminiscent of the acoustic fluidization hypothesis [*Melosh*, 1979].

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