IMPACT FRAGMENTATION AND DEVELOPMENT OF THE LUNAR MEGAREGOLITH. S. E. Wiggins[1], B. C. Johnson[1], E. A. Silber[1], T. J. Bowling[2], and H. J. Melosh[3], [1]Department of Earth, Environmental, and Planetary Sciences, Brown University, 324 Brook Street, Providence, RI 02912, USA. (Sean_Wiggins@Brown.edu). [2]Department of the Geophysical Sciences, University of Chicago, 5734 S. Ellis Avenue, Chicago, Illinois 60637, USA. [3]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, West Lafayette, Indiana 47907, USA.

Introduction: Understanding impact fragmentation and how megaregolith develops is paramount to our understanding of the thermal, magmatic, and hydrologic evolution of ancient planetary crusts [1,2]. The Lunar megaregolith remains as a pristine example of an ancient planetary crust and is thought to be composed of a thin regolith, 2-3 km of ballistically emplaced ejecta, and ~10 km of structurally disturbed fragmented crust [1]. Recent results from the GRAIL missions suggest that the lunar crust is highly porous [3] and that this porosity extends to depths of 10-25 km [4]. Although it is generally accepted that the megaregolith is the product of impact cratering, the dynamics of impact fragmentation and the dynamics of the megaregolith production have received little attention [5]. Here we estimate the extent of fragmentation and fragment sizes produced by lunar impacts as a first step toward understanding the production of lunar megaregolith. Although we focus on *in situ* fragmentation, estimating the sizes of ejected fragments will be the focus of future work.

Methods: We simulated impacts of spherical basalt impactors with a Moonlike target at 15 km/s using the iSALE shock physics code [6,7,8]. We varied the diameter of impactors from 10 m to 10 km, while keeping a resolution of 10 cells per projectile radius. We also produced runs at resolutions of 5 and 20 cells per projectile radius and found that our results are not resolution dependent. We use the ANEOS equations of state of basalt for both the impactor and the target [9]. We estimate fragment sizes using the Grady-Kipp fragmentation model [10] recently implemented in iSALE [11]. The Grady-Kipp fragmentation model is a dynamic model that tracks the damage caused by tensile stresses. The Weibull parameters used are $k=10^{32}$ and $m=9.5$. These parameters produced the best fit to results of laboratory impact fragmentation experiments [11].

Results: An impact produces an expanding hemispherical shockwave in the target that is followed by a rarefaction wave. This rarefaction wave can produce tensile stresses in the material, causing dynamic fragmentation. Fig. 1-A and 1-B (10 and 100 m diameter impactors) show a nearly hemispherical zone where material is fragmented by this tensile pulse. The near surface shows additional structure consistent with an interference zone and spallation [12]. The size of this hemispherical zone scales nearly linearly with impactor size. As the size of the impactor increases further to 1 km (Fig. 1-C) the role of increasing overburden becomes apparent. When scaled by the size of the impactor, the region in which the rarefaction causes tensile failure becomes smaller until it can no longer be seen (Fig. 2). This zone is composed of fragments that are meter to tens of meters in scale regardless of impactor size (Fig. 1). The Grady-Kipp fragmentation model predicts that higher strain rates will produce smaller fragments [11]. Thus, the relatively constant fragment size demonstrates that strain rates in the rarefaction are independent of impactor size far from the point of impact. Although the impact by the 10 km diameter impactor causes limited fragmentation at depth relative to its size when compared to the smaller impactors (Figs. 1, 2), the near surface zone contains fragments 10 m to 1 km in size extending far away from the contact site and to a depth around 10 - 20 km.

Closer to the point of impact, especially directly beneath the point of impact (r=0), fragment size has a monotonic dependence on impactor size. This suggests that the strain rates in the rarefaction depend on impactor size in the nearfield (close to the point of impact) but that they are insensitive to changes in impactor size further from the impact point. This is consistent with recent discussion of shock rise times and dwell times experienced by the Martian meteorites [13].

The current implementation of Grady-Kipp fragmentation model only tracks accumulation of fracture area when material is in tension. In all frames of Fig. 1 and in Fig. 2 there are zones of large fragment sizes adjacent to the transient crater. This material becomes fractured predominantly through shear failure rather than tensile failure. Thus, the fragment size estimates in these regions are an upper bound and should be viewed with skepticism. An accurate fragment size calculation for this region will require estimates of how fracture area accumulates during shear failure. This may be the subject of future work.

Our preliminary results suggest that impacts could efficiently fracture the lunar crust to depths of ~20 km and the crust would be broken into blocks a few meters in scale. Future work will explore how variations of the Weibull parameters and impact velocity change these results.

References: [1] Hiesinger, H. and Head, J. W. (2006) *Rev. in Mineralogy & Geochem., 60,* 1-80. [2] Zhang, N. et al. (2013) *GRL, 40,* 5019-5023. [3]

Wieczorek, M. A. et al. (2013) *Science, 339*, 671-675. [4] Besserer, J. et al. (2014) *GRL*, *41*, 5771-5777. [5] Hartmann, W. K. (2003) *MAPS*, *38*, 579-593. [6] Amsden, A. et al. (1980) *LANL Report*, LA-8095. [7] Collins, G. S. et al. (2004) *MAPS, 38,* 217-231. [8] Wünnemann, K. et al. (2006) *Icarus*, *180*, 514-527. [9] Pierazzo, E. et al. (2005) *Geological Soc. Of America*, Special Report 384. [10] Melosh, H. J. et al. (1992) *JGR*, *97*, 735-759. [11] Johnson, B. C. et al. (2016) *LPS XLVII*, Abstract #1492. [12] Melosh, H. J. (1984) *Icarus*, *59*, 234-260. [13] Bowling, T. J. et al. (2015) *LPS XLVI*, Abstract #2289

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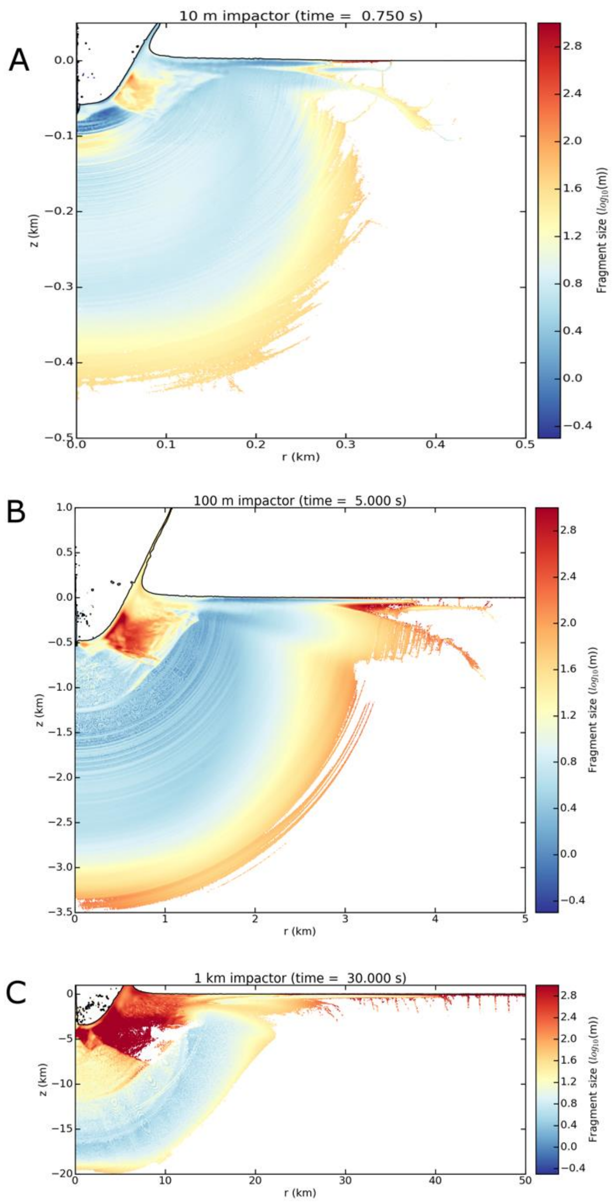

Figure 1 (Left). Material colored according to average fragment size. The 10 m, 100 m, and 1 km impactor diameter simulations are given in A, B, and C, respectively. The plots only show fragments for material that was at least 99% damaged. Therefore, the white spaces in the fractured field represent material that is less than 99% damaged.

Figure 2 (Below). Material colored according to average fragment size for the 10 km diameter impactor simulation. The larger overburden pressure at great depths leads to a markedly different fracture field shape when compared to the smaller impact in Fig. 1. Note that the scale bar here is quite different than those of Fig. 1, going to fragment sizes up to 10^4 m. The fragment sizes do exceed this level, but only in the shear damage zone.