A COMBINED MODELING AND OBSERVATIONAL STUDY OF THE EFFECT OF IMPACT VELOCITY ON PRODUCTION OF MELT IN SIMPLE-TO-COMPLEX LUNAR CRATERS. E. A. Silber[1], M. Zanetti[2], G. R. Osinski[2,3], B. C. Johnson[1] and R. A. F. Grieve[3], [1]Dept. of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI, USA, 06912 (Elizabeth_Silber@Brown.edu) [2]Centre for Planetary Science & Exploration / Dept. of Physics and Astronomy, University of Western Ontario, London, ON, N6A 3K7, Canada, [3]Dept. of Earth Science, University of Western Ontario, London, ON, N6A 5B7, Canada.

Introduction: Impact craters, produced by hypervelocity cosmic collisions, are one of the most ubiquitous geological features on solid planetary surfaces. Impact craters are generally classified into two main categories; simple and complex [1]. However, as craters transition from simple to complex structures [2], another sub-group, dubbed "transitional" craters, appears. Transitional craters cannot be classified as either simple or complex because of the differing morphology (e.g., flat crater floors, but no visible central uplift) [2]. On the Moon, the transition from simple to complex structures occurs at D ~19 km [2]; although there is considerable variation [3]. While target properties are generally considered as the primary factor in the observed differences [2], the role of the impactor properties, velocity in particular, is non-negligible [4].

A recent study by Silber et al. [4] focused on numerical simulations of crater formation in the simple-to-complex regime, and investigated the effect of acoustic fluidization [5] and impact velocity on crater morphology and the onset of complex structures. In principle, craters of the same size can be produced by impactors having different combinations of diameters (D_i) and impact velocities (v_i); however, the resulting crater depth and morphology will be affected. The conclusions reported by [4] suggest that the impact velocity might account for the apparent difference in the transition diameters on Mercury and Mars (the average impact velocity on Mercury is ~42 km/s, and ~13 km/s on Mars) [6]. If that is the case, then some population of the largest transitional and largest simple craters are likely produced by fast impactors, and this population may be identified through observational evidence of larger volumes of melt [7]. This also implies that the irregularities in crater morphology of sub-group end members (i.e. largest simple vs smallest transitional and largest transitional vs smallest complex) might be explained by impactor velocity.

To further investigate this assertion, we expand on the study of [4] by placing the emphasis on melt production in craters within the simple-to-complex regime. We use iSALE-2D [8,9] shock physics code to model formation of craters by impactors with combinations of D_i and v_i as reported by [4]. We also compare our modeling results to the observed melt volumes in lunar craters for which such data is possible to obtain. Since target porosity also has a notable effect on the amount of melt produced during an impact, we take advantage of the surface porosity distribution map [10] based on the data collected by the Gravity Recovery and Interior Laboratory (GRAIL) [11]. Thus, to account for and minimize the contribution of lithology and the melt produced by virtue of a higher porosity target, we only make a comparison to observed lunar craters that come from a target with approximately the same surface porosity.

Our aim is to investigate: (1) whether craters produced by fast impactors are morphologically and/or morphometrically distinguishable from those produced by low velocity impactors; (2) if the contrast in transition diameters observed on Mars and Mercury can be attributed to the factor of ~3 difference in the average impact velocity.

Methodology: We model formation of impact craters using iSALE-2D shock physics code [8,9]. Due to the axial symmetry of the 2D model, only vertical impacts are considered. Following [4], we use the ANEOS equation of state for granite [7] to represent the lunar crust, and dunite [12] to represent the impactor. The two parameters varied throughout all simulations are the impact velocity (v_i = 6 – 20 km/s) and the impactor diameter (D_i = ~0.4 - ~2.4 km). The combinations of v_i and D_i, and other inputs are identical to those listed in [4, see Tables 1 and 2]. To estimate the volume of melt (V_m), we employ high resolution simulations (80 cells per projectile radius) with cell tracers turned on, and in post-processing, implement the peak shock pressure method [14].

To validate our modeling results, we make a comparison to observational data for lunar craters. We select the craters from a region bearing approximately the same surface porosity [10] to minimize the bias in melt contribution from lithology. For simple lunar craters, we compare the simulated V_m to those measured by Plescia et al. [15]. For transitional and complex craters, it is difficult to accurately estimate V_m due to the unknown geometry of the crater floor and melt body thickness. In these cases we use the surface area of melt as a proxy and assume a reasonable range in possible melt volumes based on the surface area/volume ratio of simple craters (with added margin). Although these estimates are poorly constrained, they are the best that can be estimated using remote sensing. Another alternative, complementary to the aforementioned, is to establish the V_m-D relation for simple craters and extrapolate to larger sizes, but within the limit of the simple-to-complex regime.

Preliminary Results: In general, the melt production during cratering process is highly sensitive to both porosity [8,14] and impact velocity [13]. High porosity and/or high impact velocity result in higher V_m. To differentiate between these two effects, we utilize the surface density map by [10] to plot the observed V_m-D [15] such that the points are color-coded according to target density (Figs. 1, 2). The measured V_m-D data for lunar craters are from Plescia et al. [15]. Our modeling results are overplotted, showing V_m-D for four impact velocities. The difference in V_m produced by the slowest/largest and fastest/smallest impactors is two orders of magnitude, consistent with the results of [13].

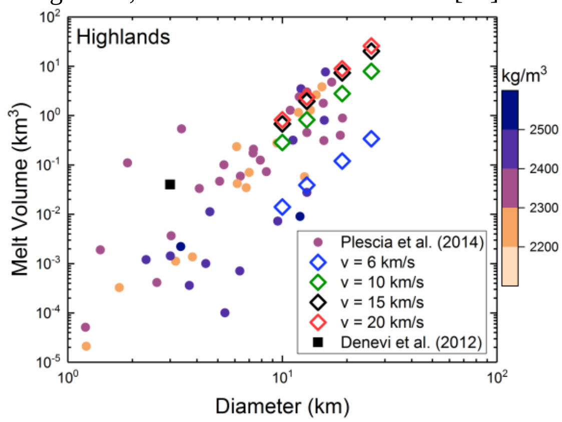

Figure 1: The melt volume (V_m) versus crater diameter (D). Circles represent the dataset from Plescia et al. [15] for the highlands terrain, color coded according to surface density [10] (pale orange is the least dense and hence most porous surface, and dark blue is the most dense and least porous target). The square represents the data point from [16].

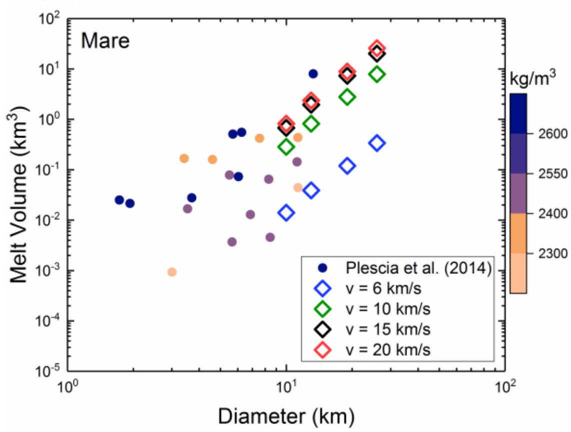

Figure 2: V_m–D. Circles represent the dataset from Plescia et al. [15] for the mare terrain, color coded according to surface density [10]. Note that the color bar scale here is different from that in Fig. 1.

The preliminary results show that, when the effect of lithology is excluded, some craters still exhibit larger than expected volumes of melt (order of magnitude). We attribute this melt volume increase to the effect of impact velocity (at least in some of these craters), which is consistent with the finding of [13]. This assertion could also explain why some observed simple craters exhibit unusually large volumes of melt [15,16]. However, to establish whether there is a link between the impact velocity and onset of transitional and complex craters, it is necessary to determine if some craters in this size range exhibit larger than expected volumes of melt. This work is ongoing.

Summary: Previous studies suggested that in theory, it should be possible to distinguish between craters produced by fast/small and slow/large impactors [17]; however, this has never been directly validated due to challenges to establish the melt volume with certainty. Thus far, no study has investigated the effect of impact velocity in transitional lunar craters in conjunction with observational data, whilst eliminating bias stemming from target porosity. While it is challenging to precisely quantify to what degree impactor velocity plays the role in the final crater characteristics, the aftermath of slow vs fast impactor (for a given crater size) suggest a rather large contrast in terms of volume of melt, and therefore projectile survivability, mineralogical composition, and potential hydrothermal activity. The latter is an especially important factor when planning space missions and searching for possible ancient life on other planetary bodies (e.g., Mars).

References: [1] Stöffler D. et al. (2006) *Rev. Min. Geoche.*, 60, 519-596. [2] Pike R. J. (1980) *Proc. LPSC. 11th*, 2159-2189 [3] Kalynn J. et al. (2013) *JGR*, *40*, 38-42. [4] Silber E. A. et al. (2017) *JGR-Planets*, 122, 800–821. [5] Melosh H. J. (1979) *JGR*, *84(B13)*, 7513-7520. [6] Le Feuvre M. and Wieczorek M. A. (2011) *Icarus*, 214(1), 1-20. [7] Pierazzo E. et al. (1997) *Icarus*, *127*, 408-423. [8] Wünnemann K. et al. (2006) *Icarus*, *180*, 514–527. [9] Collins G. S. et al. (2004) *Meteorit. Planet. Sci.*, *39*, 217–231. [10] Bessserer, J. et al. (2014) *GRL*, 41(16), 5771-5777. [11] Zuber M. T. et al. (2013) *Science*, 339. [12] Benz W. et al. (1989) *Icarus*, *81*, 113-131. [13] Pierazzo E. et al. (1997) *Icarus*, *127*, 408-423. [14] Wünnemann K. et al. (2008) *EPSL*, 269(3), 530-539. [15] Plescia J. B. et al. (2014) *LPSC XLV*, 2141. [16] Denevi B.W. et al. (2012) *Icarus*, 219(2), 665-675. [17] Grieve, R. A. F. and Cintala, M. J. (1981) *LPSC*, XII, 1607-1621.

Acknowledgements: We thank J. Plescia and J. Stopar for kindly providing the dataset with crater locations, diameters and melt volumes (Fig. 3 in [15]). We gratefully acknowledge the developers of iSALE (www.isale-code.de), the simulation code used in our research, including G. Collins, K. Wünnemann, D. Elbeshausen, B. Ivanov and J. Melosh.