NUMERICAL MODELLING OF THE EFFECT OF IMPACTOR SIZE AND VELOCITY ON MORPHOLOGICAL DIVERSITY OF SIMPLE-TO-COMPLEX LUNAR CRATERS. E. A. Silber[1,2], G. R. Osinski[2,3], B. C. Johnson[1] and R. A. F. Grieve[3], [1]Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI, USA, 06912, [2]Centre for Planetary Science & Exploration / Department of Physics and Astronomy, University of Western Ontario, London, ON, N6A 3K7, Canada, [3]Department of Earth Science, University of Western Ontario, London, ON, N6A 5B7, Canada (elizabeth_silber@brown.edu).

Introduction: Impact craters, produced by hypervelocity cosmic collisions, are one of the most ubiquitous geological features on solid planetary surfaces. Impact craters are typically classified into simple and complex [1]. However, another sub-group of craters, dubbed "transitional", is intermediate to simple and complex structures. Such craters exhibit flat floors, completely or partly covered with impactites, and no visible central uplift [2,3]. On the Moon, the transition from simple to complex structures occurs at an average diameter of ~19 km [3]; however, there is considerable variation [4]. The morphological properties of impact craters, and their variation as a function of depth and diameter, are vital for understanding the impact cratering processes and for providing insight into target and impactor characteristics, as well as important constraints for numerical models.

Several weakening process models have been proposed [5,6,7], one of which is acoustic fluidization [8]. According to the "block-model" [9] of acoustic fluidization, a system of large, discrete blocks (comprised of shattered target rock), each of characteristic size h, oscillate at some frequency (T) within a matrix of smaller fragments. The two parameters that control the weakening process are the kinematic viscosity of the fluidized region (η_{lim}) and the decay time of the block vibrations (T_{dec}).

According to [10], the block size should remain relatively invariant for a given transient crater diameter (D_{tr}), then the oscillation decay time (T_{dec}) should remain constant regardless of the impactor size and velocity. On the other hand, [11], proposed that if impact velocity is held constant, the block size will scale directly with impactor size such that $\eta_{lim} = \gamma_\eta c_b R_i \rho$ (1) and $T_{dec} = \gamma_\beta (R_i/c_b)$ (2), where γ_η and γ_β are the viscosity and time decay acoustic fluidization constants, and R_i, c_b and ρ are the impactor radius, and target sound speed and density, respectively.

The concept of the point source coupling parameter [12] builds upon the "late-stage equivalence" principle [13], which indicates that at some point in time (or space), the information about the projectile will no longer influence the terminal effects of the impact and therefore can be considered as a point source of energy. The coupling parameter (C) characterizes the coupling of impactor energy and momentum into the target material, and is a function of the impactor diameter (D_i), velocity (u_i) and density (ρ):

$$C = D_i u_i^{\mu} \rho^{\nu} \quad (3),$$

where ν=1/3 and μ= 0.55 for most geological materials [14]. Hence, it follows that all impacts with equal C (where D_i and u_i take some realistic value) are expected to produce a transient crater of the same size.

In this study, we employ the two commonly accepted acoustic fluidization scaling assumptions in order to quantify and contrast their effect on crater morphology and progression from simple to complex structures.

Methodology: We ran a series of simulations using iSALE-2D, a multi-material, multi-rheology shock physics hydrocode [15,16]. Due to the axial symmetry of the 2D model, only vertical impacts were considered. We used the ANEOS equation of state for granite [17] to represent the lunar crust, and dunite [18], as it is a good approximation for typical asteroidal material (ordinary chondrite), to represent the impactor, with the grid resolution of 10 cells per projectile radius. The two parameters varied throughout all simulations were the u_i and D_i. To account for a wide range of lunar impact velocities [19], we model vertical impacts with u_i = 6, 10, 15, and 20 km/s.

The impactor size was determined through the coupling parameter (eq. (3)), such that the final crater diameters (D_f) produced by the combinations of u_i and D_i are 10, 13, 20 and 26 km (D_{tr} = 7–17 km). Each set of simulations consisted of two subsets, featuring the acoustic fluidization scaling according to either the impactor size [11] (γ_β = 300, γ_η = 0.015) or the coupling parameter [10] (γ_β = 180, γ_η = 0.00897 (6 km/s); γ_β = 239, γ_η = 0.0119 (10 km/s); γ_β = 300, γ_η = 0.015 (15 km/s), and γ_β = 352, γ_η = 0.0176 (20 km/s)).

Results: The crater temporal evolution and morphology are highly sensitive to the choice of acoustic fluidization scaling, as well as the impactor u_i and D_i combination, especially in the transitional crater regime. A direct, step-by-step comparison between the simulations with two acoustic fluidization scaling modes shows that in the impactor size scaling, the acoustic fluidization induced by large/slow impactors will continue to drive the change in crater morphology long after the effect of acoustic fluidization has ceased for small/fast impactors.

Figure 1 shows a set of simulations corresponding to D_f = 20 km. Using the impactor size scaling implementation and starting off with the approximately same transient crater diameter, large/slow impactors will tend to produce early transition from simple to complex crater morphologies as compared to their small/fast counterparts. The depth difference between large/slow and small/fast at t = 160 s is ~1.9 km (impactor size scaling) and ~1 km (coupling parameter scaling).

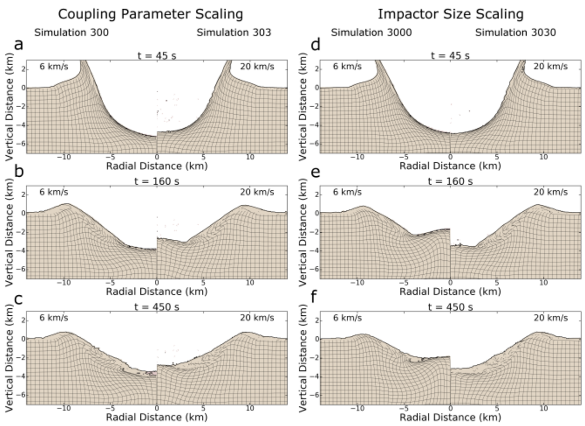

Figure 1: The comparison between large/slow and small/fast impactors. The left (a-c) and right (d-e) columns show the comparison between the coupling parameter scaling and the impactor size scaling, respectively.

In particular, relative to the far ends of the transitional regime spectrum, the largest transitional craters would be those formed by small/fast impactors. The coupling parameter scaling leads to the opposite outcome – small/fast impactors are more likely to lead to the early onset of complex structures. Therefore, the largest transitional craters would be the result of large/slow projectiles. The coupling parameter is a good first approximation, but it does not adequately describe the crater temporal evolution and the resulting morphological differences for the simple-to-complex transition regime.

Our simulated crater depth to diameter ratios are in excellent agreement with observed lunar craters [4], with the impactor size scaling implementation being well in line with the lunar mare and the highlands. Compared to Mars, the onset of complex structures on Mercury occurs at larger diameters than expected. Although there are differences in target strength, this alone cannot account for the observed trend. However, the average impact velocity on Mercury is far greater, ~42 km/s as opposed to ~13 km/s on Mars. Our study suggests that in order to account for the observed trend of later onset of complex structures on Mercury [20], the scaling by impactor size would be more appropriate.

Conclusions: The effect of acoustic fluidization on simple-to-complex lunar craters is substantial, especially on the crater depth and morphology in the transitional crater regime. The exception is simple craters (D_f = 10 km). The lateral crater growth is relatively insensitive to the choice of the acoustic fluidization scaling, within the limit boundaries for γ_η and γ_β investigated in this study. The combination of the impactor size and velocity plays a greater role than previously thought in crater morphology progression from simple to complex structures. Our study suggests that the scaling by impactor size is an appropriate choice for modeling simple-to-complex craters on planetary surfaces including both varying and constant impact velocities, as the modeling results are consistent with the observations of crater simple-to-complex transition on Mercury.

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Acknowledgements: We gratefully acknowledge the developers of iSALE-2D (www.isale-code.de), the simulation code used in our research, including Gareth Collins, Kai Wünnermann, Dirk Elbeshausen, Boris Ivanov and Jay Melosh. EAS gratefully acknowledges the Natural Sciences and Engineering Research Council of Canada (NSERC) Postdoctoral Fellowship program for partly funding this project.