THE EFFECT OF PRE-IMPACT POROSITY ON THE MORPHOLOGY OF COMPLEX CRATERS ON THE MOON. C. Milbury[1], B. C. Johnson[2], H. J. Melosh[1], G. S. Collins[3], F. Nimmo[4], J. M. Soderblom[5], C. J. Bierson[4], R. J. Phillips[6], and M. T. Zuber[5]. [1]Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, 550 Stadium Mall Drive, Hampton Hall, West Lafayette, IN 47907, USA. Email: cmilbury@purdue.edu. [2]Department of Earth, Environmental and Planetary Science, Brown University, Providence, RI 02912, USA. [3]Earth Science and Engineering Department, Imperial College London, Exhibition Road, London SW7 2BP, UK. [4]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064, USA. [5]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA. [6]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA.

Introduction and Background: Complex craters on the Moon are generally deeper if they are located in the highlands than the maria. Kalynn et al. [1] quantified this relationship by calculating the morphometry of fresh complex craters. They calculated the depth (*d*), rim-to-rim diameter (*D*), and central peak height for 111 lunar craters that are relatively young (less than ~3.2 Ga) and distributed globally. Kalynn et al. [1] suggested that the difference in crater depths between the maria and highlands could be related to variations in porosity.

Milbury et al. [2] showed that porosity has a large effect on the gravity signature of complex craters, and that it can explain the observed difference between lunar [3] and terrestrial [4] craters. The Supplemental Information (SI) of [2] shows that impacts into porous targets (analogous to highlands), form craters that are deeper than nonporous targets (analogous to mare) for a 6 km diameter impactor and appropriate Acoustic Fluidization (AF) parameters. We expand this work by investigating a broad range of impactor sizes.

AF is included in most numerical modeling of impact craters and represents the behavior of fractured rock as a viscous fluid [5] that is triggered by intense, short-wavelength vibrations within the target. AF affects the final morphology of complex craters. We further the study of Milbury et al. [2] by fitting the depth/diameter (*d/D*) trends of complex craters [1] for a broad range of impactor/crater sizes.

Methodology and Modeling: We use the same iSALE impact/model parameters as Milbury et al. [2]: an impact velocity of 15 km/s, a surface gravity of 1.6249 m/s^2, a surface temperature of 300 K, and a thermal gradient of 5 K/km (consistent with current estimates, and with the age for the inventory of Eratosthenian/Copernican craters analyzed by [1]) for a 35 km thick granitic crust overlying a dunite mantle. The dilatancy model parameters used in this analysis were based on calibration of the dilatancy model with data from terrestrial craters [6, 7]. See Milbury et al. [2] and the associated SI for additional details on the modeling and input parameters.

The AF input parameters were selected on the basis that the final simulated crater shape produced by a 6 km impactor provided the best fit to the observed crater morphology [1] for crater *D*~90–95 km (cf. the SI of [2]). The parameters for the porous and nonporous targets are different because the shock wave is more strongly attenuated in more porous targets [8].

Next, we calculate *d* and *D* for each simulated crater and compare them with observations [1]. This process is repeated for simulations that vary porosity/density with depth (for more details see Milbury et al. [9]), as is observed for the Moon [10].

Results and Discussion: In Figure 1 we plot the crater depth–diameter trends for the simulations listed in Table 1 with the observed trends determined by Kalynn et al. [1]. The results show that craters formed in nonporous targets provide a good fit to maria craters, and that those formed in porous targets provide a good fit to highland craters, within the errors. The reported RMS errors for the fits to observed trends are 0.21 and 0.45 km [1] for the mare and highlands regions, respectively. The resolution for the simulations listed in Table 1 and shown in Figure 1 vary with impactor diameter and are as follows: 0.125 km for *D*=3 km, 0.25 km for *D*=6 and 8 km, and 0.5 km for *D*=10 and 12 km.

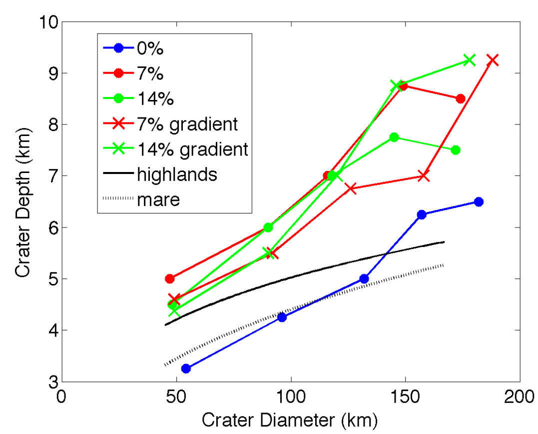

Figure 1. Plot of the modeling results (colored dots/x's) with observed trends from [1] (black/gray lines). The values listed for the porosities with a gradient are the mean value averaged over the entire depth of the crust.

Figure 1 shows that the observed difference between the *d/D* ratio trends reported by Kalynn et al. [1] for craters in the maria versus highlands is less pronounced at large *D*. This is likely due to the fact that larger impactors affect deeper layers of the crust, so the effect of the mare layer is less important for larger impactors. The nonporous simulations have zero porosity throughout the entire depth of the crust, and the mare layer on the Moon is only ~several kilometers thick. Our simulations, however, still provide a reasonable fit to the observations for small *D*, probably due to the fact that the impactors (and therefore final craters) are relatively small.

Craters larger than ~150 km in diameter deviate from the observed trends. This size range, however, coincides with the size range for proto-basins (*D*=137–170 km [11]) and peak-ring basin (*D*>207 km [11]). Milbury et al. [2] showed that there is a transition in the gravity signature from the porosity-dominated regime to mantle uplift-dominated regime for craters in this diameter range. We show that the *d/D* trend for complex craters is different than for basin-scale impact craters, and that it transitions at diameters > 150 km, which may be the diameter at which post-impact uplift becomes important. It may also be that large basins formed at a time when the thermal gradient was higher. Johnson et al. [12] showed that the thermal structure has the most significant effect on the formation of multi-ring basins.

Simulations that include a vertical gradient in the porosity do not affect the *d/D* trends of the craters as significantly as the difference from porous/nonporous targets. The difference in crater depth for porous/nonporous targets is typically more than 1 km, whereas this difference is typically less than 1 km for simulations with constant porosity verses those with porosity gradients. This trend, however, is not observed for larger craters, i.e., those in the size range where there is a transition from complex crater to proto/peak-ring basin morphology, for the reasons discussed above.

Conclusions and Future Work: The observed difference in the *d/D* trends for craters formed in the highlands versus maria [1] can be explained by a variation in crustal porosity; our simulations show that impacts into porous targets (analogous to highlands craters) produce craters that are deeper than those into nonporous targets (analogous to mare craters) over the entire size range modeled. We predict that the post-impact isostatic compensation becomes important for impact structures that are larger than ~150 km in diameter.

Future work will include simulations that have a vertical porosity gradient with a mare layer at the surface. We will investigate variations in the thickness of the mare layer, and include more realistic porosity values (~5%) for the mare basalt layer [13].

References: [1] Kalynn J. et al. (2013), *GRL*, doi:10.1029/2012GL053608. [2] Milbury C. et al. (2015), *GRL*, doi:10.1002/2015GL066198. [3] Soderblom, J. M., et al. (2015), *GRL*, doi:10.1002/2015GL065022. [4] Pilkington, M., and R. A. F. Grieve (1992*), Rev. Geophys.,* 30, 161–181. [5] Melosh, H. J. (1989), Oxford Univ. Press, New York. [6] Wünnemann, K. et al. (2006), *Icarus*, 180, 514–527. [7] Collins, G. S. (2014), *JGR*, doi:10.1002/ 2014JE004708. [8] Milbury, C. et al. (2014) LPSC Conference, XLV: #2270. [9] Milbury et al. (2015), LPI Contribution No. 1861, p.1085. [10] Besserer, J. et al. (2014) GRL, doi:10.1002/2014GL060240. [11] Baker D. M. H. et al. (2012) *JGR*, doi:10.1029/2011JE004021. [12] Johnson B. C. et al. (2015) LPSC 46, #1362. [13] Kiefer W. S. et al (2012) *GRL*, doi:10.1029/2012GL051319.

impactor D (km)	porosity (%)	d (km)	D (km)
3	0	3.25	54
	7	5	47
	7*	4.6	49
	14	4.5	48
	14*	4.375	49
6	0	4.25	96
	7	6	90
	7*	5.5	92
	14	6	90
	14*	5.5	90
8	0	5	132
	7	7	116
	7*	6.75	126
	14	7	118
	14*	7	120
10	0	6.25	157
	7	8.75	149
	7*	7	158
	14	7.75	145
	14*	8.75	146
12	0	6.5	182
	7	8.5	174
	7*	9.25	188
	14	7.5	172
	14*	9.25	178

Table 1. The impactor D, porosity, crater depth, and crater diameter for the simulations. The star next to the porosity indicates that this is for the simulations that vary porosity with depth, so these are the mean values averaged over the entire depth of the crust.