Topographic characterization of lunar complex craters

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[1] We use Lunar Orbiter Laser Altimeter topography data to revisit the depth (d)-diameter (D), and central peak height (h_{cp})-diameter relationships for fresh complex lunar craters. We assembled a data set of young craters with $D \geq 15$ km and ensured the craters were unmodified and fresh using Lunar Reconnaissance Orbiter Wide-Angle Camera images. We used Lunar Orbiter Laser Altimeter gridded data to determine the rim-to-floor crater depths, as well as the height of the central peak above the crater floor. We established power-law d-D and h_{cp}-D relationships for complex craters on mare and highlands terrain. Our results indicate that craters on highland terrain are, on average, deeper and have higher central peaks than craters on mare terrain. Furthermore, we find that the crater depths for both mare and highlands craters are significantly deeper than previously reported. This likely reflects the inclusion of transitional craters and/or older and/or modified craters in previous work, as well as the limitations of the stereophotogrammetric and shadow-length data sets used in those studies. There is substantial variability in the depths and the central peak heights for craters in a given diameter range. We suggest that the differences in mean d and h_{cp} as a function of crater diameter for highlands and mare craters result from differences in bulk physical properties of the terrain types, whereas the variability in d and h_{cp} at a given diameter may reflect variations in impactor properties and impact parameters. **Citation:** Kalynn, J., C. L. Johnson, G. R. Osinski, and O. Barnouin (2013), Topographic characterization of lunar complex craters, *Geophys. Res. Lett.*, *40*, 38–42, doi:10.1029/2012GL053608.

1. Introduction

[2] The morphometry of fresh complex impact craters is important for understanding the impact cratering process and provides constraints that viable analytical or numerical models for crater formation must match [e.g., *Holsapple*, 1993; *Melosh and Ivanov*, 1999]. Early investigations of lunar crater morphometry related crater depth (d) to diameter (D) for simple and complex craters using shadow lengths from Earth-based telescopes and Lunar Orbiter IV images, and stereophotogrammetry from Apollo metric images [*Baldwin* 1963, 1965; *Pike*, 1974, 1980, 1981]. These studies yielded three main results. First, depth increases with diameter and is described by a power law relationship, $d = AD^B$, where A and B are constants determined by a linear least squares fit of log(d) versus log(D). Second, a change in the d-D relationship is seen at diameters of ~15 km, roughly coincident with the morphological transition from simple to complex craters. Third, craters in the highlands are typically deeper than those formed in the mare at a given diameter. At larger spatial scales, Clementine [*Williams and Zuber*, 1998] and more recently, Lunar Orbiter Laser Altimeter (LOLA) [*Baker et al.*, 2012] topography data indicate that the depths of lunar basins increase more slowly with diameter than the corresponding relationship for complex craters [*Pike*, 1974].

[3] Other aspects of complex craters have been investigated including the morphology of the central peak, its height (h_{cp}), diameter, area and volume, and how these quantities scale with crater diameter [*Wood*, 1973; *Wood and Head*, 1976; *Pike*, 1977; *Wood and Andersson*, 1978; *Hale and Head*, 1979; *Hale and Grieve*, 1982]. Central peak height has been found to increase with crater size up to a diameter of ~80 km [*Hale and Grieve*, 1982], but no significant differences for craters on the mare versus the highlands have been reported.

[4] With the exception of one earlier study of lunar basins and large complex craters [*Williams and Zuber*, 1998], and a recent study using LOLA data of peak ring basins and protobasins [*Baker et al.*, 2012], previous analyses have been image-based due to the lack of absolute altimetric data of sufficient resolution to characterize crater topography. LOLA data allow, for the first time, investigations of the absolute topography of lunar complex craters. The LOLA gridded data have a maximum spatial resolution of 1024 pixels per degree (ppd) or ~30 m, close to the along-track resolution of the actual orbit tracks, permitting the study of craters with diameters tens of kilometers and less. In particular, the orders of magnitude improvement in vertical precision, accuracy, and spatial resolution compared with Clementine [*Smith et al.*, 1997] or Kaguya [*Araki et al.*, 2009] topography data, are critical for the correct assessment of crater floor and rim elevations and are required to resolve the topography of central peaks.

[5] In this study, we revisit the d-D and h_{cp}-D relationships for fresh lunar complex craters using LOLA data. New d-D and h_{cp}-D relationships for mare and highland craters are reported and the implications of the results discussed.

2. Methods

2.1. Dataset of Fresh Complex Craters

[6] We used as our starting point a database of 8680 craters [*Losiak et al.*, 2009]. We selected craters with reported ages that are Eratosthenian (3.2–1.1 Ga) or Copernican

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Table 1. Coefficients A and B From Power Law Fits ($d = AD^B$) for the Depth-Diameter and Central Peak Height-Diameter ($h_{cp} = AD^B$) Relationships for Young, Fresh Complex Craters[a]

		$d = AD^B$			$h_{cp} = AD^B$		
	N	A (± 2 SE)	B (± 2 SE)	RMS (km)	A (± 2 SE)	B (± 2 SE)	RMS (km)
Highlands	49	1.558 (0.029)	0.254 (0.011)	0.45	0.034 (0.018)	0.883 (0.036)	0.44
Mare	14	0.870 (0.012)	0.352 (0.025)	0.21	0.075 (0.107)	0.614 (0.144)	0.28
All	80	-	-	-	0.034 (0.010)	0.876 (0.022)	0.42

[a]Numbers in parentheses give the 95% confidence limits (± 2 standard errors, 2 SE) on each coefficient. The number of craters (N), and the root-mean-square misfits (RMS) for each fit are also shown.

(1.1 Ga to present), where the ages are taken from *Wilhelms* [1987]. We used a minimum crater diameter of 15 km; this excludes simple craters and includes some, but not all craters that have morphologies transitional between those of simple and complex craters. These criteria resulted in a dataset of 140 craters with diameters in the range 15–167 km; craters with diameters greater than 167 km are all pre-Eratosthenian in age.

[7] We used Wide-Angle Camera (WAC) monochromatic images from the Lunar Reconnaissance Orbiter Camera (LROC) to check that our selected craters are fresh. A crater was considered fresh if one or more of the following were observed: (1) impact melt on the crater floor and ejecta facies, (2) a well-defined crisp crater rim, (3) well-defined fault scarps on the crater walls, and/or (4) rays in the ejecta blanket. In addition, fresh craters needed to show no evidence for any of the following: (1) subsequent impacts in the interior or on the rim, (2) superposed ejecta from a nearby, younger crater, (3) an irregular shape, (4) post-impact volcanic fill, or (5) post-impact tectonic deformation. Twenty-two craters that are not fresh were removed from our data set. For seven additional craters, the WAC images contained significant shadowing. Because we were unable to verify that these craters meet our freshness criteria above, we did not include them in our data set. The resulting 111 craters span the diameter range 15–167 km and are well-distributed geographically. We used the WAC images to classify each crater as complex or transitional. Both types exhibit terraced walls, but complex (or central peak) craters also exhibit a clear central peak protruding through the melt sheet. A total of 31 craters were classified as transitional because they were without a clear central peak. We identified the terrain impacted by each crater as mare (M), highland (H), mare-highland border (B), or South Pole Aitken Basin (SPA). This allowed investigations of any systematic variations in crater morphology that might be attributable to differences in the impacted terrain.

2.2. Topography Analyses

[8] We characterized crater topography using the 512 ppd (~60 m/pixel) LOLA gridded topography, obtained from the Planetary Data System Geosciences Node. We confirmed via checks of selected craters that the 512 ppd (versus the 1024 ppd) data set has sufficient resolution for our analyses. More importantly, we verified that using the gridded topography data (GDR), which is smoothed relative to the individual LOLA tracks, did not bias our measurements, in particular our estimates of central peak heights. This was done, by identifying individual LOLA Reduced Data Records (RDR) using a Java-based tool across a representative subset of the craters investigated. Measurements of central peaks using the individual RDRs were compared with the GDR data. Differences between the RDR and GDR measurements were less than 100 m, which is less than the uncertainties in our crater depths and much less than the crater-to-crater variability in central peak height at a given diameter. Given that GDRs are significantly less time consuming to investigate than locating individual tracks across all our measured craters, with no consequent effect on our measurements, we used the GDRs in our analyses.

[9] The crater rim was identified using Lambert equal area projections of the topography centered on each crater. If necessary the diameter given in the *Losiak et al.* [2009] database was updated to match that inferred from the LOLA data. In general, the rim crest lies within an annulus bounded by 0.98D and 1.05D and, when present, the central peak typically lies within a circular region of diameter less than 0.2D.

[10] For each crater we estimated the rim and floor elevations and their respective uncertainties. We first identified regions of impact melt in the WAC image, and used the topography of these regions to characterize the floor elevation. To characterize the rim elevation, we used the GDR topography within an annulus bounded by 0.98D and 1.05D.

[11] For the rim and floor regions we produced histograms of elevation, binned in 10 m intervals. We took the elevation characteristic of the floor (h_{floor}) to be the average of the modal (h_{mode}) and minimum (h_{min}) elevations and assigned an uncertainty of $(h_{mode} - h_{min})/2$. Similarly, we took the elevation characteristic of the rim (h_{rim}) to be the average of the modal (h_{mode}) and maximum (h_{max}) elevations and assigned an uncertainty of $(h_{max} - h_{mode})/2$. The crater depth, d, is the difference in floor and rim elevations, with an uncertainty equal to the square root of the sum of the squared uncertainties for the rim and the floor. The 10 m histogram bin width is greater than the vertical precision of the LOLA

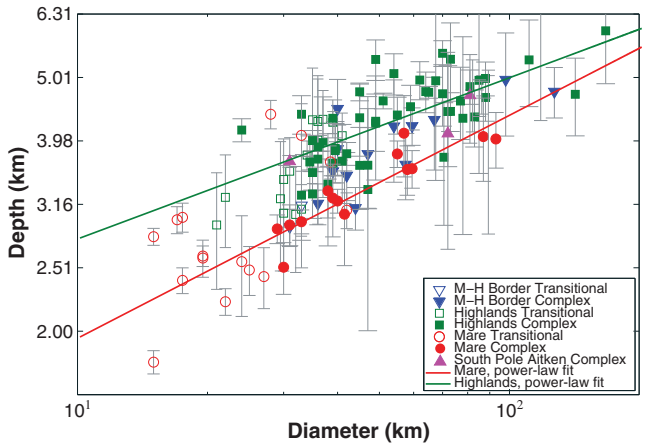

Figure 1. Log-log plot of depth (d) vs. diameter (D) for our 111 fresh, young craters (symbols described in legend). Vertical gray bars denote depth uncertainties (see section 2.2).

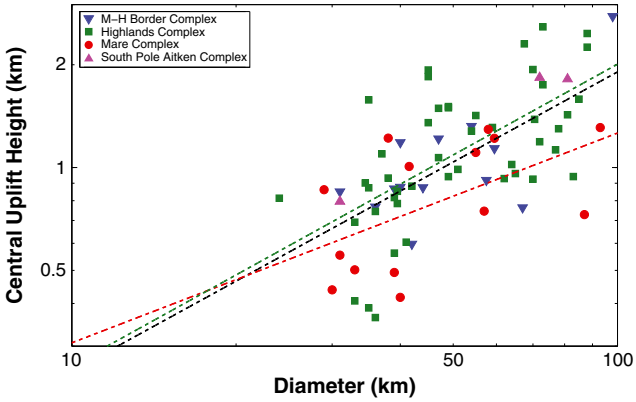

Figure 2. Log-log plot of central peak height vs. diameter for complex craters with $D < 100$ km shown (four with $D > 100$ km not shown). Symbol color and type as in Figure 1. Dashed lines show best-fit power law relationships for highlands (green), mare (red), and all (black) young, fresh complex craters.

data, such that each bin contains many measurements, but is much smaller than the resulting uncertainty in the crater depth. We confirmed that our results are insensitive to the exact choice of bin width.

[12] Of the 111 craters, 80 display central peaks characteristic of complex craters. The central peak height was calculated by taking the difference between the maximum elevation of the central peak and h_{floor}. Uncertainties in the central peak height were assigned as the uncertainty in h_{floor}; however, because these are much smaller than the variability in h_{cp}, they were not used in our analyses. Crater diameters, depths, depth uncertainties, and central peak heights are reported in Table S1 of the auxiliary material.[1]

3. Results

[13] Previous studies have reported the transition from simple to complex craters to occur over the diameter range 15–35 km [*Pike*, 1981] or 10–20 km [*Head*, 1976]. We did not attempt to capture all transitional craters; however, Table 1 shows that all craters in the 15–20 km diameter range are transitional. In the 20–45 km diameter range there are both complex and transitional craters; craters with diameters >45 km are all complex.

[14] Our *d-D* results (Figure 1) show two trends consistent with earlier work. First, crater depth increases with increasing diameter [*Pike*, 1974, 1980, 1981; *Wood and Andersson*, 1978]. Second, complex craters on highland terrain are deeper than those on the mare terrain [*Wood and Andersson*, 1978; *Pike*, 1980, 1981, 1988]. Uncertainties in crater depths are dominated by variations in the crater rim height. The average variability in the floor and rim elevations is 40 and 440 m, respectively. The largest variations in rim height, and hence the largest uncertainties in our crater depths, are associated with craters that have impacted terrain with variations in preexisting topography (e.g., highlands/mare boundaries). These craters exhibit histograms of rim elevations that exhibit a broad spread of values, and this is captured in our estimate of crater rim uncertainty and hence depth uncertainty.

[15] We performed a linear least squares regression in log-log space, to obtain power law relationships of the form $d = AD^B$ for complex craters on the mare and on the highlands. We determined the constants A and B, their 95% confidence intervals, and the root mean square misfit of each model to the corresponding data (Table 1). Transitional craters were not included in the fits, so our models are strictly for young, fresh complex craters. The mare-highlands *d-D* difference is significant at the 95% confidence level (Table 1 and Figure 3). Although we did not include the young South Pole Aitken or mare-highland border complex craters in our fits, all of these populations are consistent overall with the fits for the highlands craters, as suggested by Figure 1.

[16] Our study shows that central peak height increases with increasing crater diameter (Figure 2). The central peak heights of mare craters are lower on average than those of highland craters over the same diameter range and this difference increases with increasing crater diameter. Central peak heights also show substantial variability at a given crater diameter. Power law fits and their 95% confidence limits for the h_{cp}-D data for mare, highlands, and all young, fresh craters are reported in Table 1.

4. Discussion

[17] Our *d-D* relationships and associated confidence limits confirm that complex craters on the lunar highlands are significantly deeper than those on the mare, but indicate deeper craters on both the highlands and mare than previously documented (Figure 3). The latter result was also suggested in a study that examined 8 highlands and 6 mare fresh, deep, complex craters [*Boyce*, 2008]. Our *d-D* relationship for the highlands is significantly deeper than that of *Pike* [1981] at the 95% confidence level and Figure 3 shows that our 95% confidence interval for mare craters only just encloses the corresponding relationship of *Pike* [1981]. We examined the data set of *Pike* [1981]: only 16 of the 57 craters in that study are young, fresh, highlands or mare craters used here, and of these 7 are transitional. For the 9 complex craters that overlap both studies, we find 2 craters with depths that are 30 to 80 m shallower than those of *Pike* [1981], and 7 craters that are 140 m to 1.2 km deeper. Many of the remaining 41 craters of *Pike* [1981] have $D < 45$ km, and may be transitional craters. We suggest that the different *d-D* relationships found here result from (1) easier, accurate identification of fresh versus modified craters in LROC images, (2) the advantages of using combined LROC and LOLA data, versus image data alone to clearly discriminate between transitional and complex craters, and (3) the use of high resolution LOLA data, versus stereophotogrammetric and shadow-length data, to accurately assess floor and rim elevations in fresh craters. In contrast, comparison of our results with a more modern study shows that our depth estimate at Hausen crater (5.94 km) is in excellent agreement with that of *Baker et al.* [2012] (5.93 km), and h_{cp} estimates in the two studies agree to within 1%, providing confidence in our results.

[18] The power law exponent in the *d-D* relationship (B in Table 1) is important for scaling crater dimensions [*Melosh*, 1989]. The values of, and 95% confidence interval in, B indicate that our mare *d-D* relationship has a power law

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL053608.

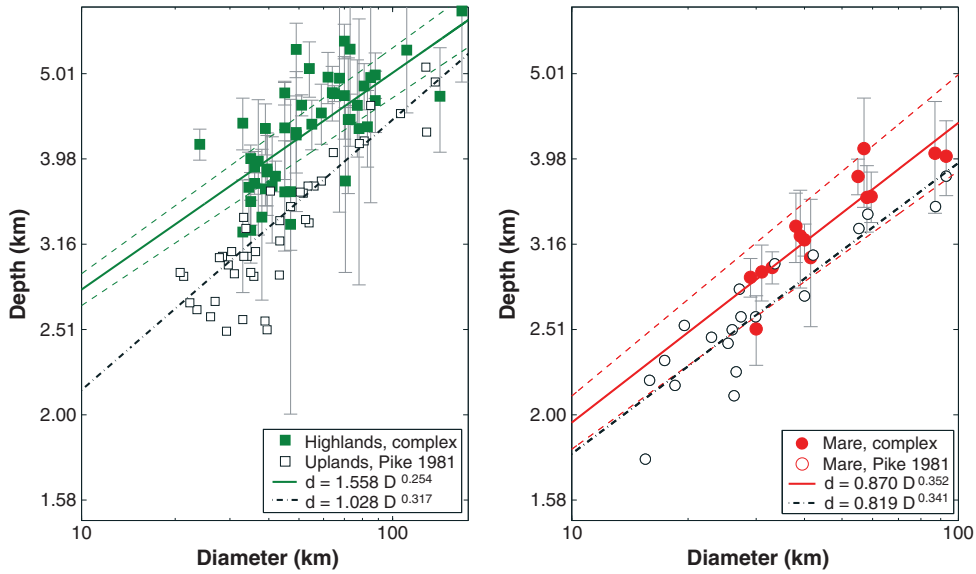

Figure 3. Best fit *d-D* relationships (solid lines) for our (a) highland (green) and (b) mare (red) complex craters, together with the data used to derive these curves (filled symbols, as in Figure 1). Dashed red and green lines show the 95% confidence limits for our best fit curves and vertical gray bars denote depth uncertainties (see section 2.2). Black dotted lines show the *d-D* relationships from *Pike* [1981], based on his data for 37 uplands/highlands craters (black open squares) and 20 mare craters (black open circles). Only 16 of the 57 craters used by *Pike* [1981] are also included in our data set; of these 9 are complex (Tycho, King, Copernicus, Aristoteles, Eratosthenes, Aristillus, Plinius, Timocharis, Lambert) and 7 are transitional (Necho, Conon, Euler, Delisle, Pytheas, Dawes, Bessel).

exponent consistent with that of *Pike* [1981], whereas our highlands *d-D* relationship has a significantly lower power-law exponent compared with that of *Pike* [1981]. In other words, we find highlands craters to be not only deeper than in *Pike* [1981], but to have depths that increase less strongly with diameter.

[19] A reduction in the *d/D* ratio of a factor of about two from large complex craters to basins has been reported [*Baker et al.*, 2012; *Williams and Zuber*, 1998], and our data are consistent with these results. Statistical tests showed that there are too few large diameter craters in our data set alone to establish a change in the *d-D* relationship at large diameters, but when combined with 7 larger basins [*Williams and Zuber*, 1998, Figure 4] our data set is consistent with an inflection in the *d-D* curve occurring in the 100–200 km diameter range as reported in *Williams and Zuber* [1998]. Five of our large young, fresh craters (King, Tycho, Aristoteles, Langrenus, and Hausen) were also used in the study of *Williams and Zuber* [1998]. Our depth estimates for four of these are up to 10% deeper than those reported in *Williams and Zuber* [1998], but the differences are less than the uncertainties in the depths.

[20] Relationships between central peak height and diameter were previously established for 45 craters with 5 km $< D <$ 170 km [*Wood and Andersson*, 1978] and 10 fresh craters with 15 km $< D <$ 80 km [*Hale and Grieve*, 1982]. The latter study noted that four additional craters with $D >$ 80 km showed relatively reduced and more variable central peak heights. *Bray et al.* [2012] find that central peak heights increase more slowly for $D >$ 60 km. We calculated a running mean and standard deviation in 10 km diameter bins for the larger data set available here. For both the highlands data alone, and the data from all terrain types combined, the average central peak height increases with diameter at least up to $D = 100$ km. Overall, the central peak height increases beyond $D = 100$ km, although at these diameters there is only one data point in each bin. Central peaks of mare craters are lower on average than those of highland craters, although a larger mare data set is required to examine this rigorously. We report h_{cp}-*D* relationships for mare and highland craters separately as well as all craters combined (Table 1). At all diameters there is a large range in h_{cp}, and the variability increases at diameters above 60 km, as expected from Figure 2.

[21] In summary, our data indicate that both the average crater depth and central peak height at a given crater diameter are different for craters on the highlands and on the mare, with those on the highlands being deeper and exhibiting larger central peaks. Although terrain differences have been noted previously [*Wood and Andersson*, 1978; *Pike*, 1980, 1981, 1988], these have received less attention than the terrain-averaged *d-D* relationships [*Pike*, 1974; *Melosh*, 1989]. Crater depths and central peak heights show considerable variability at any given diameter, in particular for highland craters; however, the current data set contains too few mare craters to be able to determine whether there are also terrain-type differences in variability in *d* and h_{cp} as a function of crater diameter. The dominant physical processes that determine how terrain type affects the final crater morphology are not well understood, but may include differences in strength of the target material [e.g., *Cintala et al.*, 1977; *Senft and Stewart*, 2007], or in the depth-dependence of shock impedance. We suggest that the differences in average *d* and h_{cp} values between mare and highlands reflect terrain properties, but that the variability at a given diameter in *d* and h_{cp} (for either mare or highlands craters) may reflect variations in impact parameters (e.g., size, speed, obliquity, and density of the impactor). We suggest that the more fragmented and porous highland megaregolith may allow the formation of deeper transient craters [*Housen and Holsapple*, 2003; *Schultz et al.*, 2007] and correspondingly larger

central peaks due to greater isosastic rebound, relative to those for craters that formed in stronger, denser mare targets. Although the more fragmented highlands target can result in greater collapse of the transient crater relative to mare craters [*Barnouin-Jha et al*., 2007], the original deeper transient crater signature and correspondingly larger central peak may be preserved [*Barnouin et al*., 2011]. In terrestrial craters, central peaks are found to be more subdued in layered sedimentary terrains than in crystalline targets [*Osinski and Spray*, 2005]. By analogy, layering observed in LROC images of the mare may contribute to lower central peaks in mare versus highlands craters, although differences in the lunar and terrestrial environments (in particular the role of erosion) indicate that such an analogy should be tested via laboratory and numerical experiments.

5. Conclusions

[22] We established a data set of 80 fresh, lunar, complex craters that are Eratosthenian or Copernican in age. We find that highland and mare complex craters have depth-diameter relationships given by $d = 1.558D^{0.254}$ and $d = 0.870D^{0.352}$, respectively. Craters on the lunar highlands are on average significantly deeper than those on the mare, and craters that straddle mare/highlands terrains have depths compatible with the *d-D* relationship for highlands craters. Importantly, complex craters on both the mare and the highlands are significantly deeper than previously reported for each terrain type [*Pike*, 1981], and the *d-D* power law exponent for highlands craters is also significantly less than previously published. We infer that the differences result from the inclusion of transitional and older and/or modified craters in previous work and/or limitations of the stereophotogrammetric and shadow-length data sets used in previous studies. We find central peak heights that are on average larger for craters in the highlands than in the mare. However, central peak heights show substantial variability at any given diameter, and this, combined with the small number of mare craters, means that a larger data set is needed to confirm terrain-type differences in the mean h_{cp}-*D* relationship.

[23] We suggest that the differences in mean *d* and h_{cp} as a function of crater diameter for highlands and mare craters result from differences in bulk physical properties of the terrain types. In particular, the more fragmented and porous megaregolith may allow the formation of deeper craters with larger central peaks in the highlands compared with those in the mare. Differences in layering in the target terrain may also contribute to differences in final crater morphology. We suggest that variations in depth and central peak height at any given diameter for either mare or highlands terrain may reflect the effects of variations in impact parameters.

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