New morphometric measurements of craters and basins on Mercury and the Moon from MESSENGER and LRO altimetry and image data: An observational framework for evaluating models of peak-ring basin formation

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ABSTRACT

Peak-ring basins are important in understanding the formation of large impact basins on planetary bodies; however, debate still exists as to how peak rings form. Using altimetry and image data from the MESSENGER and LRO spacecraft in orbit around Mercury and the Moon, respectively, we measured the morphometric properties of impact structures in the transition from complex craters with central peaks to peak-ring basins. This work provides a comprehensive morphometric framework for craters and basins in this morphological transition that may be used to further develop and refine various models for peak-ring formation. First, we updated catalogs of craters and basins ≥ 50 km in diameter possessing interior peaks on Mercury and the Moon. Crater degradation states were assessed and morphometric measurements were made on the freshest examples, including depths to the crater floor, areas contained within the outlines of the rim crest and floor, crater volumes, and rim-crest and floor circularity. There is an abrupt decrease in crater depth in the crater to basin transition on both Mercury and the Moon. Peak-ring basins have larger floor area/interior area ratios than complex craters; this ratio is larger in craters on Mercury than on the Moon. The dimensions of central peaks (heights, areas, and volumes exposed above the surface) increase continuously up to the transition to basins. Compared with central peaks, peak rings have reduced heights; however, all interior peaks are typically > 1 km below the rim-crest elevations. Topographic profiles of peak-ring basins on Mercury and the Moon are distinct from complex craters and exhibit interior cavities or depressions that are bounded by the peak ring with outer annuli that are at higher elevations. We interpret the trends in floor and interior area to be largely due to differences in impact melt production and retention, although variations in types and thicknesses of impactites, including proximal ejecta, could also contribute to the observed trends. Our trends illustrate that the transition from craters to basins is characterized by an abrupt change in morphology, implying a change in process for the formation of peak rings. Refinement of models for peak-ring formation through improved quantitative predictions of crater morphometry and cross-validation with our morphometric framework are needed to better constrain the processes that form peak rings on the terrestrial planets.

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1. Introduction

Morphological analyses of impact craters play a key role in the study of planetary bodies. Numerous studies have focused on understanding how the geometries of crater-interior landforms evolve with increasing magnitude of the impact event, and hence diameter of the final impact crater. Craters on the Moon and many other planetary bodies show a size-dependent morphological progression of interior landforms (Hartmann and Wood, 1971; Wood and Head, 1976; Pike and Spudis, 1987); at the smallest diameters, craters start as simple bowl-shaped craters with relatively featureless interiors and increase in complexity with increasing diameter to form complex craters, which exhibit rim-wall terraces, flat floors, and central peaks. In this work, we are concerned with the poorly understood transition from complex craters to impact basins. While there has been debate in defining when a “crater” becomes a “basin” (Hartmann and Kuiper, 1962; Hartmann and Wood, 1971; Wood and Head, 1976; Pike, 1988; Alexopoulos and McKinnon, 1994), here we define basins as impact structures exhibiting at least one sizeable interior ring of peaks in addition to the rim crest (“sizeable” implies a ring diameter approximately one-half of the rim-crest diameter; e.g.,
Pike, 1988). As such, the transition from complex craters, exhibiting central peaks, to basins occurs with the formation of a sizeable interior ring of peaks: these basins are called peak-ring basins (or “two-ring basins”; Pike, 1988). Basins intermediate between complex craters and peak-ring basins, called protobasins (Pike, 1988), can exhibit both a central peak and peak ring. As a result of the largest impact events, multiple rings may form exterior or interior to the rim crest, producing multi-ring basins with three or more topographic rings and so complete the size–morphology progression of impact crater landforms. Due to their unique double–ring morphology and intermediate sizes, peak-ring basins are an integral component of the morphological transition from craters to basins and to the development of larger multi-ring basins.

Despite the importance of peak-ring basins, their morphometric properties have been poorly studied due to their topographic complexity and to limitations in data quality. To help constrain the processes controlling the formation of peak rings, we present in this work an observational framework of the morphometric properties of craters and basins spanning the transition to peak-ring basins on the Moon and Mercury. Many of the problems associated with data limitations are addressed by using recent orbital images and altimetry data from the MESSENGER Surface, Space Environment, Geochemistry, and Ranging (MSSSENGER) spacecraft in orbit at Mercury (Solomon et al., 2001) and the Lunar Reconnaissance Orbiter (LRO) spacecraft orbiting the Moon (Vondrak et al., 2010). Mercury is particularly useful for analyzing peak-ring basins due the planet’s high density of such basins (Baker et al., 2011b). First, building on the work of Baker et al. (2011a, 2011b), we present updated crater and basin catalogs of complex craters, protobasins, and peak-ring basins ≥50 km in diameter on Mercury and the Moon, including their degradation states. Second, we present new morphometric measurements of complex craters, protobasins, and peak-ring basins along with their trends with increasing rim-crest diameter on Mercury; we compare these results with updated morphometric measurements of lunar craters and basins (Baker et al., 2012). Third, we summarize our morphometric observations and discuss the implications for current models of peak-ring formation.

2. Methods

2.1. Updated crater catalogs

We build upon the recently updated catalogs of protobasins and peak-ring basins from Baker et al. (2011b) for Mercury and Baker et al. (2011a) for the Moon. These catalogs were compiled using recent flyby image data from the MESSENGER Mercury Dual Imaging System (MDIS) instrument (Hawkins et al., 2007) for Mercury and orbital altimetry and image data from the Lunar Orbiter Laser Altimeter (LOLA) (Smith et al., 2010) and Lunar Reconnaissance Orbiter Camera (LROC) (Robinson et al., 2010) instruments, respectively, for the Moon. These data were used to re-evaluate previous basin catalogs and add to them based on improved data quality or coverage. These catalogs were constructed by creating visual fits of circles to the rim crests of basins using the CraterTools extension for ArchMap (Kneissl et al., 2010). A total of 32 protobasins and 74 peak-ring basins were cataloged on Mercury (Baker et al., 2011b) and 3 protobasins and 17 peak-ring basins were cataloged on the Moon (Baker et al., 2011a). The addition of orbital monochrome images data from the MESSENGER MDIS instrument at Mercury, which now covers nearly 100% of the surface of Mercury with improved resolution and illumination conditions, provides the basis for updating the basin catalogs of Baker et al. (2011b). Here, we have added an additional 38 protobasins and 36 peak-ring basins to the catalogs of Baker et al. (2011b) for Mercury, bringing their totals to 70 and 110, respectively (Table 1). The catalogs for the Moon remain unchanged.

We have also completed catalogs of complex craters with rim-crest diameters ≥50 km on the Moon and Mercury. Previous catalogs of craters within this diameter range exist (e.g., Pike, 1976, 1988; Smith and Hartnell, 1978), but they could not benefit from the improved data quality and greater image coverage provided by the LRO and MESSENGER spacecraft. We used recent catalogs of all craters ≥20 km in diameter on the Moon (Head et al., 2010) and on Mercury (Fassett et al., 2011, 2012) in a systematic survey of all craters ≥50 km in diameter for central peaks. Before our survey was conducted, the Mercury crater catalog of Fassett et al. (2011) was updated by Fassett et al. (2012) using a mosaic of orbital MDIS Narrow Angle Camera (NAC) and Wide Angle Camera (WAC) images at 250 m/pixel resolution. The orbital image mosaic provides improved incidence angles and emission angles, such that the majority of the surface of Mercury is now imaged at favorable illumination conditions for crater recognition.

Central peaks occur with a range of morphologies, including single massifs, clusters, and dispersed types (see Section 5.1) (Hale and Head, 1979, 1980; Pike, 1988). Central peaks can also occur as arcs and with ring-shaped morphologies (Pike, 1988). The rim-crest diameters of some craters with well-formed, ring-shaped central-peak complexes on Mercury overlap in rim-crest diameter range with protobasins and peak-ring basins, and were termed “ringed peak-cluster basins” by Baker et al. (2011b). From MESSENGER flyby images, Baker et al. (2011b) interpreted these crater

<table>
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<tr>
<th>Table 1</th>
<th>Comparisons of statistics calculated from catalogs of complex craters &gt;50 km in diameter, protobasins, and peak-ring basins on Mercury and the Moon.</th>
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<td></td>
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<td>Mean impact velocity (km/s)</td>
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<td>Maximum diameter (km)</td>
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- a Data from this study and updated from Baker et al. (2011b).
- b Peak-ring basin and protobasin data from Baker et al. (2011a), Complex crater data are from this study.
- c Mean impact velocity from Le Feuvre and Wieczorek (2008).
- d After Baker et al. (2011a,b). Peak-ring basin onset diameters determined by first identifying the range of diameters over which examples of two or more crater morphological forms can both be found; the onset diameter is defined as the geometric mean of the rim-crest diameters of all craters or basins within this range. Uncertainties are one standard deviation about the geometric mean, calculated by multiplying and dividing the geometric mean by the geometric, or multiplicative, standard deviation. Peak-ring basin and protobasin data used for the calculations are from this study and from the data in Baker et al. (2011a,b). The diameters of complex craters and peak-ring basin diameters on the Moon do not overlap, so the onset diameter is calculated by taking the average of the largest complex crater (205 km) and smallest peak-ring basin (207 km).
- e After Baker et al. (2011a,b). Peak-ring basin onset diameters calculated by taking the fifth percentile of the peak-ring basin population data.
Fig. 1. Examples of complex craters (a), protobasins (b), and peak-ring basins (c) on Mercury (top panels) and the Moon (bottom panels), illustrating the morphological variations in degradation classes described in Appendix A. The least degraded craters and basins are assigned to Class I and the most degraded to Class IV. Class V craters or basins are not pictured, as only one Class V peak-ring basin has been identified. Images are from a MESSENGER MDIS NAC and WAC image mosaic (250 m/pixel) for Mercury and an LROC WAC image mosaic (100 m/pixel) for the Moon. (a) Complex craters exhibit central peaks that become less prominent with increasing degradation. From left to right, craters on Mercury are Balzac (68 km; 10.62°N, 144.62°W), an unnamed crater (77 km; 23.45°N, 129.87°W), an unnamed crater (117 km; 41.06°N, 44.85°W), and an unnamed crater (70 km; 60.54°N, 129.88°E). On the Moon: Copernicus (95 km; 9.59°N, 20.06°W), Poynting (128 km; 176°3′N, 133.38°W), Mach (180 km; 18.21°N, 149.27°W), and Amici U (96 km; 8.70°S, 175.50°W). (b) Protobasins possess both a central peak and peak ring and also exhibit a range of degradation states. From left to right, protobasins on Mercury are Zeami (128 km; 2.95°S, 147.31°W), van Gogh (99 km; 76.80°S, 138.19°W), and an unnamed protobasin (71 km; 0.21°S, 13.00°E). On the Moon: Antoniadis (137 km; 69.35°S, 172.96°W) and Compton (166 km; 55.92°N, 103.96°E). (c) Peak-ring basins have a single interior ring of peaks that become increasingly dissected with increasing degradation. From left to right, peak-ring basins on Mercury are Rachmaninoff (292 km; 27.66°N, 135.52°E), Strindberg (187 km; 53.22°N, 136.64°W), Renoir (214 km; 18.36°S, 157.47°W), and an unnamed peak-ring basin (225 km; 10.67°S, 103.36°E). On the Moon: Schrödinger (326 km; 74.90°S, 133.53°E), Korolev (417 km; 4.44°S, 157.47°W), and Poincaré (312 km; 57.32°S, 183.15°E).
types on Mercury to be transitional forms between complex craters and peak-ring basins, due to their well-developed diminutive rings and overlap in rim-crest diameter with peak-ring basins and protobasins. However, the occurrences of similar ring-like central-peak complexes at diameters (~50 km) much smaller than the onset diameter of peak-ring basins on the Moon (Smith and Hartnell, 1978; Schultz, 1976, 1988; Baker et al., 2011a) and now Mercury (Section 5.1), suggest that these central peaks may not be uniquely transitional in form but are rather a product of more complex processes related to the impact event (e.g., Schultz, 1988). Due to this uncertainty in the nature of ring-like central peaks and to facilitate discussion, we include arcuate and ring-like central peaks in our catalog of complex craters. Our final catalogs include 430 craters with central peaks for the Moon and 682 craters with central peaks for Mercury.

Supplementary online materials (Appendix C) to this manuscript include catalogs of all complex craters, protobasins, and peak-ring basins on Mercury and the Moon used in our analysis. These catalogs also include degradation classes (Section 2.2, Appendix A) and morphometric parameters calculated according to the methods described in Section 2.3 and Appendix B.

2.2. Degradation classes

As craters and basins are found in a variety of degradation states, and since we are concerned with only well-preserved craters and basins for our morphometric analyses, we assigned qualitative degradation classes to all craters and basins in our catalogs (Fig. 1, Appendix A). Craters and basins were assigned classes of I (freshest) to V (most degraded), based on morphological indicators of degradation (Appendix A). Except for peak-ring basins on the Moon, only those craters and basins with degradation classes of I to II were used for morphometric measurements.

Those peak-ring basins on the Moon measured by Baker et al. (2012) were re-assigned degradation classes here for comparisons with the larger populations of complex craters (see Appendix A). As a result, our sample size of Class I and II lunar peak-ring basins was dramatically reduced to three in number from those measured by Baker et al. (2012), who assigned relative degradation classes within the peak-ring basin population only. For a more complete basis in describing the morphometric trends in the transition between complex craters and peak-ring basins, we chose to also measure and present morphometric measurements for Class III peak-ring basins on the Moon. Because we are incorporating relatively more degraded peak-ring basins in our lunar measurements, we caution that care must be taken in interpreting the trends in the peak-ring basin data for the Moon as having resulted from primary processes. The difficulties in interpreting the trends in peak-ring basin morphology on the Moon can be overcome, however, should similar trends be observed in the peak-ring population on Mercury.

2.3. Morphometric measurements

A number of morphometric parameters were measured for the freshest craters and basins in our catalogs (Fig. 2, Appendix B). We first mapped the rim crest, base of the crater wall, and base of the interior peaks for each Class I and II crater or basin. Elevations for each feature were sampled using their outlines and LRO LOLA gridded elevation data for the Moon and MESSENGER Mercury Laser Altimeter (MLA) track data for Mercury. From these sampled elevations, we calculated a number of crater or basin parameters, including depth, height of the central peak or peak ring, and peak-to-rim-crest distance (Fig. 2, Appendix B). In addition, we measured the areas of the crater interior, floor, and peaks. The crater floor is defined as all points inward from the base of the wall,
which also include the area interior to the peak ring (Appendix B). Area measurements were also combined with elevation data for lunar craters to measure the volumes of the crater interior and peaks. Crater interior volumes were measured above all morphometric features interior to the rim-crest and relative to a plane fit to the rim-crest elevations (Appendix B). Peak volumes were calculated above a plane fit to the peak’s base, and thus only represent the portions of the peak exposed above the surface. Measurements of peak-ring and central-peak diameters (see Baker et al., 2011b) were also updated for all additions to our peak-ring basin and protobasin catalogs for Mercury. Central peak diameters for complex craters were not remeasured here, due to comprehensive measurements of this parameter made by Hale and Head (1979, 1980) and Pike (1988). Comprehensive methods of how these morphometric measurements were made are found in Appendix B.

3. The crater and basin catalog

From the updated crater and basin catalogs of Fassett et al. (2011, 2012) and Head et al. (2010), we find 2071 and 1542 craters ≥50 km in diameter on Mercury and on the Moon, respectively. On Mercury, 682 (32.9%) of these craters have central peaks only, 70 (3.4%) have central peaks plus peak rings, and 110 (5.3%) have peak rings only. The Moon has a smaller percentage of its population ≥50 km in diameter with interior structures, with 430 (27.9%) of craters ≥50 km in diameter having central peaks, 3 (0.2%) having central peaks plus peak rings, and 17 (1.1%) having peak rings only. The general statistics of craters and basins on Mercury and the Moon are given in Table 1.

While the data remain the same as those in Baker et al. (2011a) for lunar peak-ring basins and protobasins, we now update the catalog to include craters with central peaks ≥50 km in diameter, whose range extends to 205 km. The Mercury basin catalogs of Baker et al. (2011b) have been updated here to include 70 protobasins (~88% increase) and 110 peak-ring basins (~49% increase). These increases in number are due to the improved illumination geometries and resolutions provided by orbital images. Our updated peak-ring basin catalog lowers the geometric mean diameter for peak-ring basins from 180 km to 172 km but retains the range of diameters at 84 km to 320 km. Our updated protobasin catalog lowers the geometric mean diameter from 102 km to 92 km and extends the diameter range from 50 km to 195 km. The range of complex craters ≥50 km in diameter with central peaks on Mercury extends to a diameter of 168 km. These updated catalogs reinforce the conclusion from Baker et al. (2011b) (also suggested by previous work (e.g., Wood and Head, 1976; Pike, 1988)), that Mercury has the highest surface density of peak-ring basins and protobasins of any planetary body in the inner solar system. We also revised the onset diameter for peak-ring basins on Mercury from 126 (+33, –17) km to 104 (+24, –21) km using a method of overlapping crater diameters, and from 116 km to 103 km using the fifth percentile diameter of the entire peak-ring basin population. These methods for calculating onset diameter are described more fully in Baker et al. (2011a, 2011b) and Table 1.

In Fig. 3, we plot the number of crater or basin types as a fraction of the entire population of craters in 50 km diameter bins. Several differences between Mercury and the Moon are apparent from the histograms. First, there is much more overlap in diameter between different morphological crater types on Mercury than on the Moon. The reason for this overlap is likely related to the broader distribution of impact velocities at Mercury compared to the Moon. On Mercury, the mean impact velocity is around 40 km/s but there is about an equal probability of an impactor having an impact velocity from 20 km/s to 60 km/s (Le Feuvre and Wieczorek, 2008, 2011). On the Moon, the mean impact velocity is near 20 km/s but the distribution is much narrower from about 5 km/s to 40 km/s (Le Feuvre and Wieczorek, 2008, 2011). If the type of central structure is dependent on impact velocity (e.g., Baker et al., 2011a), then the broad distribution of impact velocities on Mercury predicts much more variation in peak morphology at a given rim-crest diameter, as observed in Fig. 3. For example, central peaks may be produced at lower impact velocities, while peak rings may be produced at higher impact velocities due to differences in energy and impact melting controlling the formation of these features (e.g., Cintala and Grieve, 1998). Impact angle variations will also affect parameters such as impact melt volume (e.g., Pierazzo and Melosh, 2000), which may control peak development in large craters (Cintala and Grieve, 1998) and could also be contributing to the observed overlap in peak morphology. Peak-ring basins on Mercury also have a smaller onset diameter (~103 km) and a more restricted range of diameters (236 km) compared to the Moon (onset diameter of 206 or 226 km and a rim-crest diameter range of 375 km). Assuming that all craters or basins ≥50 km in diameter should have produced an interior structure (central peak or peak ring) on Mercury and the...
Moon, about 10% to as much as 40% more craters on Mercury preserve evidence of an interior structure compared with the Moon in any given 50-km diameter bin (Fig. 3). A larger fraction of craters exhibiting interior structures on Mercury suggests that these features have been better preserved, in general, on Mercury compared with the Moon, an interpretation consistent with previous work by Wood et al. (1977). This improved preservation of interior features on Mercury is probably related to several factors, including the prevalence of peak rings, which increases the mass of the interior structure that must be removed or resurfaced, more limited areal distribution of ejecta from large impact events (number ties for the freshest craters and basins on the two bodies (Fassett et al., 2011). We also compared the percentages for each crater or basin type within a particular degradation class on Mercury and the Moon (Fig. 4). Similar distributions of degradation classes for complex craters with central peaks occur on both Mercury and the Moon, with 42% and 36%, respectively, of complex craters being Class I or II (Fig. 4). With the small population of protobasins on the Moon (number = 3) it is difficult to make direct comparisons with Mercury. A larger fraction of protobasins on Mercury are Class I or II (71%) compared with complex craters on the planet (42%). Fewer peak-ring basins are of Class I or II (24%) on Mercury compared with other crater types, and the Moon has no Class I peak-ring basins (although 18% are Class II). The higher percentage of fresh (Class I and II) peak-ring basins and complex craters with central peaks on Mercury is consistent with our observation of better preservation of interior structures on that planet (Fig. 3).

4. General crater morphometry

Using our updated catalogs for craters and basins on Mercury and the Moon, we calculated a number of morphometric properties for the freshest craters and basins on the two bodies (Section 2.3, Appendix B). In this section, we first describe the general morphometric properties of crater and basin structures on Mercury and the Moon. Measurements that we include here (Fig. 5) are depth (d), area of the floor ($A_{floor}$) and of the interior ($A_{int}$), interior volume ($V_{int}$), and the circularity of the rim crest ($f_{rim}$) and of the floor ($f_{floor}$) (Table B.2). These parameters help to constrain how the general crater shape is evolving with increasing diameter and in the transition from complex craters to peak-ring basins. With an understanding of these morphometric trends in general crater shape, in Section 5 we discuss the morphometric properties of the interior central peaks and peak rings, including their heights ($h_{pk}$), areas ($A_{pk}$), and volumes ($V_{pk}$), and ratios of these parameters to the general crater morphometric parameters. These observations are important to understand how the peaks evolve with increasing rim-crest diameter, in addition to how peaks behave in the transition to complex craters, which could give insight into the processes forming peak rings. In Section 6 we examine topographic profiles of peak-ring basins on Mercury and the Moon to gain an insight into the final shape of basins, and then compare these profiles with model predictions for crater morphology in Section 8.

All plots discussed in Sections 4 and 5 (Figs. 5, 6, 8, and 9) are presented in log–log space and given as functions of rim-crest diameter ($D_{c}$), except where indicated. We use this type of plot for consistency with previous work focused on the morphometric properties of craters (Baldwin, 1949; Pike, 1977; Hale and Grieve, 1982; Pike, 1988; Williams and Zuber, 1998; Baker et al., 2012) and to observe how these properties scale with the magnitude of the impact event. Due to the small sample-size of peak-ring basins that could be measured using MLA data (n = 12), together with the incomplete range of complex-crater diameters measured here (i.e., diameters < 50 km were not measured), we do not attempt to construct statistical fits to the data. Rather, we describe qualitative trends that we observe from the plots. These are satisfactory for addressing our initial goals, which were to describe the basic morphometric trends of craters and basins in the transition from complex craters to peak-ring basins, and to develop a morphometric framework for use in testing the models of peak-ring formation. A more statistically rigorous treatment of the data, especially for Mercury, awaits improvements in the topographic

![Degradation classes as percentages of the total number of complex craters, protobasins, and peak-ring basins on Mercury (top) and the Moon (bottom). Class I craters or basins are the freshest, with Class V being the most degraded (see Fig. 1). The numbers in parentheses give the total number for each class. Colors highlight Class I and II craters, which were used for morphometric analyses (except for lunar peak-ring basins, see Section 2.2 and Appendix A).](image-url)
Fig. 5. Log–log plots of trends with rim-crest diameter ($D_r$) for a number of morphometric parameters (Table B.2) of the overall shapes of complex craters (dark gray circles), protobasins (cyan squares), and peak-ring basins (red hexagons) on Mercury (top panels in each set) and the Moon (bottom panels in each set). Errors bars in the abscissa are root mean-squared errors from non-linear least-squares fits of circles to the outlines of the rim crest. Error bars in the ordinate are only given for depth measurements due to the calculation of interquartile range values for this parameter. See Appendix B for uncertainty estimates for additional parameters. (a) and (b) Depth ($d$). Mercury: The light-gray boxes give the trends with uncertainties determined by Pike (1988) (P88) for his defined classes of immature and mature complex craters. Moon: The solid line gives the trend determined by Pike (1974) (P74) for complex craters and the dashed line gives the trend determined by Williams and Zuber (1998) (WZ98) for peak-ring and multi-ring basins. (c) and (d) Ratio of depth to rim-crest diameter ($d/D_r$). Mercury: The light-gray boxes give the trends with uncertainties determined by Pike (1988) (P88) for immature and mature complex craters. Moon: The dashed line gives the trend determined by Pike (1974) (P74) for complex craters. (e) and (f) Area of the floor ($A_{floor}$). (g) and (h) Area of the floor to the area of the interior ($A_{floor}/A_{int}$). (i) and (j) Circularity of the rim crest ($\Gamma_{rim}$) plotted with semi-log axes. Values of 1.0 are perfectly circular, with smaller values indicating deviations from a circle. (k) and (l) Circularity of the floor (i.e., wall-base outline) ($\Gamma_{floor}$) plotted with semi-log axes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
Fig. 6. Log–log plots of total interior volumes (a) and central-peak and peak-ring volumes (b) as functions of rim-crest diameter for complex craters (gray circles), protobasins (cyan squares), and peak-ring basins (red hexagons) on the Moon. Volumes were not calculated on Mercury due to the low spatial coverage of MLA tracks over many craters and basins. (a) Interior volumes were calculated from the surface within the rim-crest outline to a plane fit to the rim-crest elevations. Shown are the trends determined by Hale and Grieve (1982) for complex craters (dashed line) and the volumes calculated using geophysical estimates of basin excavation-cavity geometries determined by Wieczorek and Phillips (1999). (b) Volumes for central peaks and peak rings were calculated for those portions above the surface, referenced to a plane fit to elevation points falling within 1 km of the outlines of the base of the peaks. Shown are the trends determined by Hale and Grieve (1982) for complex craters (dashed lines). Two separate trends were determined for complex craters by Hale and Grieve (1982), as they observed a decrease in central-peak volume between 50 km and 80 km in rim-crest diameter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Rim-crest diameters of craters exhibiting various types of uplift structures on Mercury (a) and the Moon (b). The uplift structures are arranged in order of increasing complexity from bottom to top, with rim-crest diameter plotted on a log scale. Central peaks are found to occur as a range of morphologies from single to double peaks, to clustered and dispersed peaks, and to arcuate and ring-like peaks. No trend in increasing complexity with rim-crest diameter is observed for Mercury or the Moon. Also shown are the occurrences of peak-ring plus central-peak combinations (i.e., protobasins) and single peak rings (i.e., peak-ring basins). There is much overlap in the morphology of uplift structures on Mercury between diameters of 84 and 168 km. On the Moon, there is much overlap in rim-crest diameter between central-peak types, but not between central peaks and peak rings. The dashed lines give the calculated onset diameters of peak-ring basins, determined using “Method 1” described in Table 1. The gray box in (a) gives the uncertainties in the onset diameter calculation using “Method 1.”
characterization of Mercury (more altimetry measurements and/or stereo reconstruction), with a broader analyzed range of diameters for complex craters with central peaks.

4.1. Crater and basin depth ($d$)

Many studies on crater morphometry have focused on the depth versus diameter relationships of craters on all the terrestrial planets, moons, and asteroids. This fundamental parameter of crater shape is well known for simple and complex craters (Pike, 1974, 1988); however, it is less well known for larger-scale structures such as protobasins and peak-ring basins (Williams and Zuber, 1998). Our plot of depth versus rim-crest diameter for mercurian craters and basins (Fig. 5a) shows a generally increasing trend, which is expected based on crater scaling and previous morphometric studies (Pike, 1988). The depths of craters and basins on Mercury are generally at the lower depth range of the trend with uncertainties derived from shadow measurements of craters in Mariner 10 images by Pike (1988). Our generally smaller depths calculated from MLA measurements are consistent with similar measurements made by other workers for smaller craters (Barnouin et al., 2012; Talpe et al., 2012), and are likely to reflect differences with Pike (1988) in methodologies and the datasets used for calculations. On Mercury, we also observe a general decrease in the depth-to-diameter ratio ($d/D_c$) with rim-crest diameter (Fig. 5c), from an arithmetic mean $d/D_c$ of 0.034 for complex craters, to 0.027 for protobasins, and 0.017 for peak-ring basins. This general decrease in $d/D_c$ follows from the power-law relationship in Fig. 5a and has been observed in prior work for Mercury, but we are now able to extend this trend to protobasins and peak-ring basins at larger diameters.

The transition from complex craters to protobasins and peak-ring basins is marked by a rapid decrease in depth (Fig. 5c). Baker et al. (2012) suggested that the transition to peak-ring basins on the Moon could be associated with a similar discontinuous decrease in $d$ (Fig. 5b), although the small sample size precluded a confident result. Several reasons for this decrease in depth on the Moon were explored by Baker et al. (2012) (e.g., effects of post-impact modification, such as resurfacing and intrusions by volcanic material, erosion and infilling by proximal ejecta, and to the effects of impactor or target properties). It is possible that the decrease in depth observed in the transition from complex craters to peak-ring basins could be related to the effects of volcanic resurfacing. Our depths for peak-ring basins on Mercury include six peak-ring basins that show small amounts of volcanic resurfacing (see Appendix A); however, those basins without evidence of volcanic infill follow the same depth trend as these basins. This indicates that volcanic resurfacing in these peak-ring basins was limited in thickness, and that the shallowness of peak-ring basins is more likely to be related to factors other than volcanic infilling. Degradation states could also be affecting these trends, as all but three peak-ring basins in Fig. 5a are Class II. However, for complex craters in which we plot both Class I and II craters, we find no increased likelihood for Class II craters being shallower. Rather, variations in depths are more likely related to the characteristics of the target and pre-impact topography. For example, craters formed by impacts into the rims of pre-existing basins can disrupt the rim slumping process, producing asymmetrical rim heights, wall widths and floor geometries. Impact melt distribution and retention will also be affected due to asymmetrical wall slumping (Hawke and Head, 1977), leading to differences in the measured depths of these craters. Further, target strength plays a role in the late stages of crater growth (e.g., Holsapple, 1993), which may influence the depth of the crater depending on target composition. Furthermore, we do not observe thick additions of superposed crater ejecta that could be contributing to the decreased depth of peak-ring basins, nor do we observe evidence of the effects of volcanic intrusions that could produce doming of floors, as in floor-fractured craters on the Moon (Schultz, 1976). Taken together, these observations suggest that the decrease in depths from complex craters to peak-ring basins observed on Mercury and the Moon is likely to be related to primary effects of the peak-ring basin forming process.

We also observe that complex craters are shallower on Mercury than on the Moon (Fig. 5a and b). This trend was observed by Pike (1988), and confirmed here with our new catalogs and measurements. Complex craters on Mercury have a mean depth to diameter ratio of 0.034 ± 0.010, while complex craters on the Moon have a mean depth to diameter ratio of 0.055 ± 0.15 (where uncertainties are one standard deviation). However, peak-ring
Fig. 9. Log-log plots of trends with rim-crest diameter ($D_r$) for a number of morphometric parameters of central peaks and peak rings in complex craters (dark gray circles), protobasins (cyan squares and white triangles), and peak-ring basins (red hexagons) on Mercury (top panels in each set) and the Moon (bottom panels in each set). Error bars in the abscissa are root mean-squared errors from non-linear least-squares fits of circles to the outlines of the rim crest. Error bars in the ordinate are only given for those measurements using rim-crest elevations due to the calculation of interquartile range values for this parameter. See Appendix B for uncertainty estimates of additional parameters. (a) and (b) Central-peak or peak-ring height ($h_{pk}$). Mercury: The light gray box gives the trend with uncertainties determined by Malin and Dzurisin (1978) (MD78) for central peaks in complex craters. Moon: The dot-dashed line gives the trend determined by Hale and Grieve (1982) (HG82) for central peaks in small complex craters and the dashed line gives the trend determined by Pike (1977) for central peaks in the largest complex craters. (c) and (d) Ratio of height of the central peak or peak ring to the crater or basin depth ($h_{pk}/d$). (e) and (f) Distance from the top of the central peak or peak ring to the rim-crest elevation ($h_{pkr}$). (g) and (h) Area of the central peak or peak ring ($A_{pk}$), where the areas of the central peak and peak ring are plotted separately for protobasins. (i) and (j) Area of the central peak or peak ring ($A_{pk}$), where the areas of the central peak and peak ring are combined for protobasins. (k) and (l) Ratio of the area of the central peak or peak ring to the area of the interior of the crater or basin ($A_{pk}/A_{int}$). The areas of the central peak and peak ring are combined for protobasins in this plot. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
basins and protobasins have nearly the same depth-diameter ratios on Mercury and the Moon. The mean depth to diameter ratio for peak-ring basins on Mercury is 0.017 ± 0.006 compared to on the Moon, where the ratio is 0.015 ± 0.003. Protobasins on Mercury and the Moon have mean ratios of 0.027 ± 0.007 and 0.027 ± 0.010, respectively.

4.2. Interior area (Aint) and floor area (Afloor)

The areas of the crater or basin interior (the area contained within the outline of the rim crest) and of the floor (the area contained within the outline of the wall base, including points inward and outward from the peak ring) are measurements that no previous investigations have reported. As expected from the diameter dependence of area, floor areas on Mercury and the Moon increase with rim-crest diameter (Fig. 5e and f). While this increase is linear in log–log space for Mercury, the trend is more curvilinear for complex craters on the Moon. Peak-ring basins, however, have slightly greater values than protobasins and complex craters for a given rim-crest diameter (Fig. 5e and f). This difference is reflected in the ratios of floor area to interior area (Afloor/Aint) on both Mercury and the Moon (Fig. 5g and h), which show a general increase from complex craters to peak-ring basins. From this trend, it is shown that the area of the floor is making up a greater fraction of the total interior area with increasing rim-crest diameter and is the greatest for peak-ring basins. In other words, while the absolute width of the walls (i.e., exposed terraces) of craters and basins increase with crater diameter (Baker et al., 2012), the wall width becomes smaller relative to the overall diameter of the crater or basin. By comparing the Afloor/Aint ratios for diameters where central peaks and peak rings overlap on Mercury, excluding the three smallest peak-ring basins (128 km to 173 km), we calculated an arithmetic mean ratio of 0.55 ± 0.079 and 0.43 ± 0.053 for complex craters (where uncertainties are one standard deviation). The medians of the distributions of Afloor/Aint ratios for complex craters and peak-ring basins are also different at 95% confidence with a p-value of 0.0015 using a standard Mann Whitney U-test. A similar statistical test between Afloor/Aint Ratios for peak-ring basins and protobasins over the diameter range of 128 km to 181 km also suggest different populations with a p-value of 0.0005 with arithmetic means of 0.41 ± 0.098 and 0.55 ± 0.078 for protobasins and peak-ring basins. The Afloor/Aint ratios between complex craters and protobasins over the 57 km to 173 km diameter range where they overlap in diameter are not statistically different at the 95% level.

The above observations are consistent with those of Baker et al. (2012), who showed that the radius of the basin floor increased relative to its rim-crest radius in progressively larger basins. The authors suggested that this may reflect increased impact-melt production, retention, and redistribution of this melt to cover detached slump blocks or toes of listric faults. We similarly interpret the observed trends in floor area on Mercury and the Moon to be largely associated with a non-proportional increase in impact-melt production with increasing crater diameter (Grieve and Cintala, 1992). The amount of melt retained in large craters is also enhanced by the back-flow of ejected impact melt inside the crater during collapse of the transient cavity. For example, recent numerical simulations showed that only 2% of the total impact melt is ejected beyond the final rim-crest diameter for South Pole-Aitken basin (Potter et al., 2012). Furthermore, the discernible difference in the Afloor/Aint ratio between complex craters and peak-ring basins within the diameter range where they overlap on Mercury (Fig. 5g) suggests that the formation of peak-ring basins is marked by a substantially increase in impact-melt production and retention relative to complex craters with the same diameters. Also covering wall slump blocks are proximal ejecta deposits that loaded the rim of the transient cavity before slumping downward and inward with more coherent target rock and impact melt during collapse of the transient cavity. It is possible that the substantial thicknesses of proximal ejecta deposits expected for large impact basins may help to more completely bury detached slump blocks or toes of listric faults comprising the most inward portions of the collapsed transient cavity walls. Further, the absolute magnitude of wall collapse with increasing crater size may be non-proportional such that the width of the terraced zone decreases relative to the diameter of the crater or basin. Further numerical modeling of the scaling of wall collapse, proximal ejecta, and impact melting in the annular zone between the rim crest and peak ring of basins, which is beyond the scope of this paper, will be important for understanding their relative contributions in affecting such morphometric parameters as wall width and the floor area in basin-sized events.

There are also distinct differences in floor area between Mercury and the Moon, which are again likely to be due to differences in impact-melt production or a combination of other materials comprising the floor of craters, such as proximal ejecta. For a given diameter, craters on Mercury tend to have larger Afloor/Aint ratios than on the Moon (Fig. 5g and h). This is shown for complex craters, which have a larger arithmetic mean Afloor/Aint ratio on Mercury (0.37) compared with the Moon (0.27). This is also illustrated in Fig. 5g and h, which show that the smallest complex craters on the Moon have much smaller ratios than similarly sized complex craters on Mercury. Peak-ring basins on both Mercury and the Moon have the same mean ratios of 0.56, even though peak-ring basins occur at smaller rim-crest diameters on Mercury. By considering only the diameters where peak-ring basins overlap on the Moon and Mercury (236 km to 316 km), we calculated mean ratios of 0.55 for the Moon and 0.61 for Mercury, which indicate that peak-ring basins on Mercury have slightly larger Afloor/Aint ratios than on the Moon.

Taken together, comparisons of trends in the ratio of floor area to interior area suggest that this ratio is greater on Mercury than on the Moon. This observation can plausibly be explained by differences in impact-melt production between the two planetary bodies, although differences in the thickness of other impact crater floor materials such as proximal ejecta and ground surge deposits emplaced prior to transient cavity wall collapse could also be contributing factors. Due to the higher mean impact velocity at Mercury (Le Feuvre and Wieczorek, 2008), a crater of a given size will produce approximately double the amount of impact melt than on the Moon (Cintala, 1992; Cintala and Grieve, 1998). As mentioned above, this increase in impact-melt production is likely to be manifested in the floor-area measurements, with craters on Mercury exhibiting much larger floor areas for a given crater diameter than on the Moon due to redistribution and enhanced burial of slumped material by this melt. These observations are also consistent with a recent study by Ostrach et al. (2012), who used the area of smooth floor deposits as a proxy for volume of impact melt to highlight the differences in impact-melt production between Mercury and the Moon.

It is important to note that impact melt deposits are heterogeneous on the floor of craters and basins. Within peak-ring basins, impact melt layers are likely to be thinner in the annulus outward from the peak ring and thicker in the center of the basin inward from the peak ring where it probably occurs as a coherent impact melt sheet (e.g., Spray and Thompson, 2008). Studies from the terrestrial peak-ring basin, Chicxulub, (see review by Gulick et al., 2013) show that impact melt-rich lithologies are patchy in the annular region between the wall and peak ring, and that proximal ejecta and surge deposits are also important components to the basin floor stratigraphy in these regions. Thus, while the
importance of impact melt lining the floor of the basin likely increases with its size, breccias with a range of clast and melt fractions are likely to be present at depth below and outward from more coherent melt layers; higher clast fractions will be more pervasive where impact melt deposits are thinnest.

4.3. Circularity of the rim crest ($\Gamma_{\text{rim}}$) and floor ($\Gamma_{\text{floor}}$)

We also measured the circularity ($\Gamma$) of the rim crest and floor for craters and basins on Mercury and the Moon. This parameter is defined as the ratio of the circumference of a circle ($C$) with an area equal to the feature of interest ($A$) to the measured perimeter of the feature of interest ($P$). On a planar surface, circularity is given by:

$$\Gamma_{\text{planar}} = \frac{C}{P} = \frac{2(A\pi)^{0.5}}{P}$$

(1)

On a spherical surface, circularity is given by:

$$\Gamma_{\text{spherical}} = \frac{2\pi(A/\pi - A^2/4\pi R^2)^{0.5}}{P}$$

(2)

where $R$ is the radius of the planetary body. Thus, for a perfectly circular feature, $\Gamma = 1$, with irregular features having fractional values $< 1$. There is only a very small difference between the planar and spherical calculations of circularity for the sized craters in our study. We chose to report the spherical calculation for consistency with our perimeter and area measurements, which are also calculated on a sphere.

For the Moon, we observe a general decrease in rim-crest circularity ($\Gamma_{\text{rim}}$) with increasing rim-crest diameter (Fig. 5j; note the change to semi-log axes for consistency with Pike, 1977). This observation is consistent with the observation of Pike (1977), who used a different metric for complex craters ($r = 10$ km). We attribute this decrease in rim-crest circularity on the Moon to heterogeneous target structure and irregularities in the surface topography, which have been shown or suggested to have a large control on crater shape during crater excavation and collapse (Hawke and Head, 1977; Gifford and Maxwell, 1978; Eppler et al., 1983; Gulick et al., 2008; Poelchau et al., 2009; Ohman et al., 2010). Crustal fractures, joints, and lineaments may affect the evolving excavation flow (Poelchau et al., 2009) and may be zones of enhanced weakness and wall slumping during transient cavity collapse (Eppler et al., 1983; Ohman et al., 2010). There is also a size dependence on the effects of pre-impact topography. For example, larger craters and basins incorporate more pre-existing topography into their rim structures due to their increased areal dimensions. This irregular topography can lead to uneven rim-wall collapse (Gifford and Maxwell, 1979; Gulick et al., 2008), especially for impacts into older craters and basins, leading to more irregular rim-crest outlines. Interestingly, however, craters and basins on Mercury do not show the same decrease in rim-crest circularity as observed on the Moon (Fig. 5i). Peak-ring basins taken alone show a slight decreasing trend (Fig. 5i), but taken together, craters and basins on Mercury show no clear trend in rim-crest circularity with increasing rim-crest diameter. It is not clear why this is the case, but differences in target structure and composition may be influencing the observed difference.

Superposed impact craters could also affect the measurements of circularity, as we had to interpolate across these regions in order to complete the rim-crest outline. We minimized the need for such interpolation by analyzing only the freshest craters in the populations; however, the occurrence of large superposed craters in Class II peak-ring basins could contribute to at least some of the unusually low circularity values (Fig. 5i and j).

The outline of the floor is much less circular than the rim crest for both the Moon and Mercury (Fig. 5k and l), and there is no obvious trend in floor circularity with rim-crest diameter. The outlines of floors track the base of the wall, and are therefore expected to be highly irregular features, controlled by the collapse process and the interaction among the slumped material (also affected by target heterogeneities), impact melt and breccias, and the uplifting floor during the modification stage of the cratering event. Interestingly, the floors on Mercury tend to be more circular than on the Moon (Fig. 5k and l). It is possible that this could also be due to differences in impact-melt production and redistribution, which would tend to smooth irregularities in the wall-base outline by flooding and covering portions of the wall slump blocks. This would be enhanced on Mercury due to larger amounts of impact melting, leading to more circular floors (see Section 4.2).

4.4. Interior volume ($V_{\text{int}}$)

The volumes calculated for craters and basins on the Moon are plotted in Fig. 6a. Again, volumes for Mercury were not calculated due to the current large spacing of MLA tracks (Appendix B). All volumes of the crater or basin interior were calculated as the region bounded by the present surface topography within the rim-crest and a plane fit to the rim-crest elevation points. These revised volumes for peak-ring basins and protobasins based on the methods outlined in Appendix B have an average difference of 8% from volumes calculated by Baker et al. (2012), who used slightly different methods of calculating volumes. The volumes calculated here, however, are well within the uncertainties of the measurements by Baker et al. (2012). As also observed by Baker et al. (2012), there is an expected general increase in crater and basin volume with increasing rim-crest diameter (Fig. 6a). Our measurements of complex crater volumes are generally greater than those determined by Hale and Grieve (1982) for lunar complex craters, although uncertainties for this trend were not given by these authors. This disagreement in measured volumes is likely due to differences in methodologies and our use of LOLA gridded topography, which is much improved in spatial resolution and coverage over Lunar Topographic Orthophotomaps (LTO) used by Hale and Grieve (1982). As in Baker et al. (2012), we plotted the trend in excavation-cavity volume estimated by Wieczorek and Phillips (1999), scaled to reflect final crater rim-crest diameter (Croft, 1985). We re-state the observation of Baker et al. (2012) that about a 40% decrease in volume from the excavation cavity estimates to the final basin cavity is needed in order to produce the current measured volumes. This required change in volume may result from a number of processes, including vertical floor uplift due to a combination of gravitational collapse of the transient cavity, elastic rebound of the cavity floor, and perhaps some contribution from mantle flow processes (Melosh and McKinnon, 1978). These processes must be considered in any model for basin formation.

5. Peak morphometry

5.1. Central-peak and peak-ring morphology

As part of our catalog of complex craters on Mercury and the Moon, we include classifications of central-peak types for all Class I and II craters. There are five major types of central peaks identified: in increasing degree of complexity they are single, double, clustered, dispersed, and arcuate or ring-like. These central-peak classifications follow those developed by Smith and Hartnell (1978) and those used by Pike (1988), except that we combined the “single peaks” and “single segmented peaks” (an intact, single peak but jointed into multiple segments) classifications, and refer to peaks of the “multiple elements” type as “clustered.” We also include a type for those craters with two major central peaks (“double peak”) and those with arcuate or
ring-like central peaks. We plot all rim-crest diameters exhibiting a particular peak type, as well as those craters exhibiting both a central peak and peak ring (protobasins) and a peak ring only (peak-ring basins), in Fig. 7. We observe no increase in complexity of central structures with increasing rim-crest diameter on both Mercury (Fig. 7a) and the Moon (Fig. 7b). This observation is consistent with the analyses of lunar craters by Smith and Hartnell (1978) and Hale and Head (1979) and mercurian craters by Hale and Head (1980), which showed that central-peak complexity has no strong dependency on the size of the impact crater. This contrasts with a re-analysis of the Smith and Hartnell (1978) data by Pike (1988), who interpreted a subtle increase in complexity of central peaks with rim-crest diameter for craters on Mercury. With our updated catalog of central structures on Mercury, we favor the former interpretation, that central-peak complexity is not dependent on crater size.

In addition, Fig. 7a shows that there is substantial overlap in the rim-crest diameters at which complex craters transition to peak-ring basins on Mercury. Indeed, all five central-peak types occur within our calculated onset diameter range for peak-ring basins on Mercury (Table 1, onset diameter, method 1). On the Moon, no overlap occurs with central-peak craters. As discussed in Section 3, these differences may plausibly be explained by the differences in impact velocity distributions on the Moon and Mercury (Le Feuvre and Wieczorek, 2011). If the interior morphology of a crater is largely affected by its impact velocity (Cintala and Grieve, 1998), then craters on Mercury should exhibit a greater diversity of central structures over a given diameter range owing to the planet’s broader distribution of impact velocities, which is consistent with observations (Figs. 3 and 7). We hypothesize that central peaks may form at lower impact velocities, while peak rings may form at higher velocities due to impact velocity’s control over such things as impact melting (e.g., Cintala and Grieve, 1998). The absence of a trend of central-peak complexity with diameter was suggested to indicate that the transition to peak-ring basins cannot be described as a simple, gradual transition, but is rather defined by a sharper, stepwise transition (Hale and Head, 1979, 1980). This trend in transition is best illustrated in plots of peak-ring or central-peak diameter versus rim-crest diameter, which show an abrupt, discontinuous transition from complex craters to peak rings (Hale and Head, 1980; Hale and Grieve, 1982; Pike, 1988; Baker et al., 2011a, 2011b) (Fig. 8, Section 5.2). The substantial overlap in central-structure morphology on Mercury suggests that the process forming peak rings, while causing an abrupt transition from central peaks, is variable enough so that it can produce multiple peak morphologies for a given crater size.

5.2 Central-peak and peak-ring diameter (Dpk)

We have updated the peak-ring versus rim-crest diameter trends for Mercury from those of Pike (1988) and Baker et al. (2011b) using our new catalogs of peak-ring basins and protobasins (Fig. 8a). The unchanged lunar data from Baker et al. (2011a) are plotted in Fig. 8b for comparison. Central-peak diameters were not measured for complex craters here, but we plot trends determined by prior workers for comparison, including Pike (1988) for Mercury and Hale and Head (1979) and Hale and Grieve (1982) for the Moon (see Baker et al. (2011b) for a discussion of these trends). On both Mercury and the Moon, peak rings in protobasins and peak-ring basins are observed to follow ring versus rim diameter trends that are distinct from the central-peak versus rim diameter trends observed for complex craters. Our updated data for Mercury reveals, for the first time, that the peak rings of protobasins intersect the trend of central peaks in complex craters at a diameter of about 50 km (Fig. 8a). From these plots, the transition from complex craters to peak-ring basins appears to be abrupt, marked by a substantial divergence in the trends of peak diameter to rim-crest diameter (Pike, 1988; Baker et al., 2011a, 2011b). The process of forming peak rings must therefore also be abrupt, resulting from a fundamental change in the way target material is collapsed, uplifted and deformed during the modification stage of basin formation. Further, peak rings cannot be formed by the simple expansion of a central peak, or else peak-ring diameters would continue along the trends for central peaks in Fig. 8. This inference is consistent with the abrupt transitions observed in our other morphometric measurements, including peak complexity (Section 5.1), and peak height, area, and volume (Sections 5.3–5.5). Furthermore, we observe that the diameters of central peaks in protobasins are generally smaller and much more scattered than the trend of central peaks in complex craters on Mercury and the Moon. However, sizeable central peaks comparable to those in complex craters are still observed in the largest protobasins. Therefore, although peak-ring diameters in protobasins follow a similar trend to peak-ring basins (Fig. 8), protobasin central peaks are much more varied in their diameter, with no regular trends identified.

5.3 Central-peak and peak-ring height (hpk)

Central-peak height has also been an important but difficult parameter to measure on Mercury, the Moon, and other planetary bodies. The current altimetry data from MLA and LOLA greatly facilitate this analysis. Calculations from MLA data, however, provide less reliable results due to uneven coverage of tracks over central structures (Appendix B, Fig. B.1), and therefore represent only an estimate of central-peak and peak-ring height. There is a general increase in both as a function of rim-crest diameter on both Mercury and the Moon (Fig. 9a and b). This increase was also observed on Mercury by Malin and Dzurisin (1978) using shadow measurements of central peaks and on the Moon by Hale and Grieve (1982) and Pike (1988) using Lunar Topographic Orthophotomaps (LTOs). Our observations include more craters than did previous workers and extend the trend out to basins. Our central-peak height data for complex craters generally overlap with the larger uncertainties of the Malin and Dzurisin (1978) trend for central peaks on Mercury and are generally smaller than those determined by Pike (1977) and Hale and Grieve (1982) for the Moon. At the transition from complex craters to peak-ring basins, there is a decrease in the height of the peaks, that is, central-peak heights are larger than peak-ring heights at diameters where the two morphologies overlap. This difference in peak height is consistent with the observation by Hale and Grieve (1982) and Baker et al. (2012), who suggested that lateral redistribution of peak material may be contributing to the reduction in peak heights in the transition to peak rings. Unlike Hale and Grieve (1982), however, who suggested that the transition to peak rings might start at diameters between about 50 km and 80 km on the Moon, we find that the heights of central peaks increase continuously to the onset diameter of peak-ring basins (~206 or 226 km, see Table 1) on the Moon; Mercury shows a similar trend. Furthermore, we observe that, while central peaks are generally higher than their associated peak rings in protobasins on both the Moon and Mercury, both central-peak height and peak-ring height increase with rim-crest diameter for protobasins (Fig. 9a and b). In contrast, the trend in central-peak diameter for protobasins by Pike (1988) predicts that central peaks should diminish in size relative to their peak ring with increasing rim-crest diameter for protobasins, an expected result if central peaks are giving way to peak rings in the transition to peak-ring basins. Most models for peak-ring formation suggest that central peaks should decrease in size with increasing rim-crest diameter in protobasins (see Section 8).
Our contrasting data indicate that large central peaks are still maintained in proto-basins and that proto-basins may result from more complex formation processes in the transition to peak-ring basins than has been previously predicted.

As also described by Baker et al. (2012) for lunar basins, the ratio of the height of the central peak or peak ring to the depth of the crater or basin (hpkr/d) increases with increasing rim-crest diameter (Fig. 9c and d). Values of this ratio increase from below 0.1 at the smallest complex craters to 0.8–0.9 for the largest complex craters and for peak-ring basins. The transition from complex craters to peak-ring basins is again marked by a decrease in hpkr/d. This decrease in hpkr/d is due to the reduction in peak height observed in the trends in Fig. 9a and b. The general increase in hpkr/d with rim-crest diameter for complex craters and peak-ring basins is largely due to the trend of decreasing depth-to-diameter ratios (Fig. 5c and d), without a comparable decrease in the ratio of the peak height to diameter (i.e., hpkr/d = (hpkr/Dc)(Dc/d)).

5.4. Central-peak and peak-ring to rim-crest distance (hpkr)

While the height of the peak ring has been traditionally measured from the floor (as in Fig. 9a and b), we also present measurements of the distance from the top of the central peak or peak ring to the rim crest (Fig. 2 and Fig. 9e and f). This distance should be less affected by infilling of the crater by lava or ejecta material. No apparent trend in this parameter is observed on Mercury or the Moon (Fig. 9e and f), which is related to the increasing depth trends observed for craters and basins (Fig. 5a and b), acting to keep hpkr near a constant value. In both Fig. 9e and f, a “height ceiling” is observed at 3 km on Mercury and about 5 km on the Moon, beyond which values for hpkr do not occur. This “height ceiling” is related to the maximum depths observed for craters and basins, which are greater on the Moon than on Mercury (Fig. 5a and b) due largely to differences in relative gravity. Some of the smallest values of hpkr in complex craters occur at about 0.3 km on Mercury and about 0.7 km on the Moon. In general, the hpkr values are > 1 km for complex craters, indicating that even in the largest craters, the elevations of central peaks are well below those of the rim crest.

5.5. Central-peak and peak-ring area (Apk)

The diameter of central peaks has been a traditional measure of their areal dimensions or spread of multiple peak elements (Head, 1977; Hale and Head, 1979, 1980; Pike, 1988), and is a measurement of a best-fit circle enclosing all of the mass of the central peak (Hale and Head, 1979). While this may closely approximate the size of single peak elements, diameters become increasingly difficult to measure accurately with increasing peak complexity and segmentation. Measurements of area (Fig. 2c), in contrast, are more direct indicators of the planar dimensions of central structures regardless of complexity, and can be readily compared with similar measurements for the peak elements of peak rings. However, measurements of diameters are still useful for analysis of the lateral spread of peak materials, which can help to understand how the zone of central-peak uplift grows laterally with increasing crater diameter or size.

We present the areas of central peaks and peak rings as a function of rim-crest diameter in Fig. 9g and h, in which we separate the central peaks of protobasins from their peak rings; the areas of central peaks and peaks rings in protobasins are summed in Fig. 9i and j. There is a well-defined increase in the area of the central peaks and peak rings as a function of rim-crest diameter for both Mercury and the Moon. At the transition to peak-ring basins, we do not observe any deviation in this trend among central peaks, suggesting that central peaks continue to grow in size up to the transition to peak-ring basins. This is consistent with the trend of increasing central-peak height observed in Fig. 9a and b. Taken together, these observations predict a similar trend of increasing volumes of central structures with rim-crest diameter, which is supported by Fig. 6b and discussed in more detail below. Unlike the decrease in height of peak rings in the transition to peak-ring basins, the area of the peak ring continues to increase along a trend similar to that of central peaks. The ratio of peak area to interior area (Apk/Aint) of the crater on Mercury (Fig. 9k), however, suggests that protobasins and peak-ring basins have slightly larger ratios than complex craters, and thus peak rings constitute larger fractions of the basin's total interior area than do central peaks. Similar ratios are observed for craters and basins on the Moon, although with sparser samples sizes (Fig. 9l). Reasons for this higher Apk/Aint ratio for peak-ring basins and protobasins on Mercury could be due to the geometric differences between central peaks and peak rings, as peak rings require more spatially extensive geometries than do central peaks. However, impact-melt production and retention are greater for the largest impact events (Cintala and Grieve, 1998), which would tend to mask more of the interior peaks. The fact that such masking does not occur on Mercury suggests that processes such as enhanced uplift or contributions from collapse processes are dominant and so maintain the prominence of peak rings in peak-ring basins. The fact that craters and basins on the Moon do not show a similar trend in Apk/Aint ratios may be related to the greater degradation of lunar peak-ring basins (Fig. 4 and Appendix A), which generally have more eroded and obscured peak rings (Fig. 1).

5.6. Central-peak and peak-ring volume (Vpk)

As predicted by the trends of increasing central-peak height and area (Fig. 9a–d), the volumes of central peaks on the Moon increase continuously up to the transition to peak-ring basins (Fig. 6b). To reiterate, the volumes of peaks were measured for the portions exposed above the surface only (Appendix B). Hale and Grieve (1982) also made volume measurements of central peaks on the Moon, observing two trends in central-peak volume from a sample size of 20 craters (dashed lines in Fig. 6b). Six craters showed a reduction in relative central-peak volume starting at diameters of 50 to 80 km, which Hale and Grieve (1982) attributed to the initiation of peak-ring development at a much smaller diameter than previously thought. While our volume measurements do not include craters < 50 km in diameter, we do not see a distinct decrease in the volume of central peaks in the 50 to 80 km diameter range (although some craters do have lower than average central-peak volumes). We do see some scatter in the volume of central peaks for a given rim-crest diameter, which is probably related to variations in impactor conditions and pre-impact topography. Furthermore, our new crater and basin catalogs for the Moon (Baker et al., 2011b) indicate that the onset of peak-ring basins occurs at much larger diameters (of around 200 km) or around 130 km in the case of the onset of protobasins. In the transition to peak-ring basins, we observe a slight reduction in the volumes of peak rings compared with the trend of central-peak volumes. This could be influenced by the incomplete preservation of peak rings in the smallest lunar peak-ring basins (see Appendix A), as the peak rings of the largest peak-ring basins appear to follow the trend of central-peak volumes (Fig. 6b).

6. Shape of the basin interior

In addition to the morphometric properties of peak-ring basins (Figs. 5, 6, 8, and 9), profiles traversing their interiors can provide
a qualitative assessment of their present topography, which could be used to constrain the final states of dynamic models that simulate cavity collapse in the formation of peak rings. MLA profiles that traverse near the centers of eight peak-ring basins of varying size on Mercury share many common characteristics (Fig. 10). In contrast with the generally flat floors of complex craters (Fig. B.1a), the interior topographies of peak-ring basins are largely affected by the presence of the peak ring. In all cases, the annulus (a) surrounding the peak ring (pr) is at a higher elevation than the interior of the peak ring (c) (Fig. 10a–h). Moving outward along a typical radial transect shows that the peak ring rises above the surrounding floor material with a distinct asymmetric profile, which features a steeper inward-facing wall and a more gradually sloping outward-facing wall. Together, the peak ring’s inner wall helps to form a cavity-like depression within the interior of peak-ring basins. This shape is most prominent in Dürer (Fig. 10d) on Mercury, in which the floor inward from the peak ring is located 1.5 km below the annulus surrounding the ring. The peak ring is also very prominent in Dürer, and there is less than 1 km difference in elevation between the ring and the basin’s rim crest. The largest and youngest peak-ring basins (e.g., Rachmaninoff and Raditladi, Fig. 10a and b) also show prominent depressed centers. This prominence also appears to decrease in magnitude with decreasing size of the peak-ring basin. We also observe a distinctive cavity-like shape in MLA profiles of peak-ring basins on the Moon (Fig. 11). In Fig. 11, we present averaged radial MLA profiles of lunar peak-ring basins. For most of these basins, a similar profile as observed on Mercury is apparent (Fig. 10), where annuli surrounding the peak rings are at higher elevations than the interior of the peak ring, forming a central cavity bounded by the peak ring.

The cavity-like shape and asymmetry in the profile of peak rings was also recognized on Mercury by Schultz (1988), who observed from Mariner 10 images that peak rings possessed a distinctive inward-facing scarp. Later morphological analysis by
Collins et al. (2008b). Over-heightened central peak after 600 s of simulation time. Drawn and vertically exaggerated. (Fig. 10), many protobasins and complex craters where these craters and basins overlap in diameter.

3. Interior volumes: The volumes of the present basin interiors on the Moon are reduced by ~40% compared with the volumes of the scaled excavation cavities estimated for such craters by Wieczorek and Phillips (1999) (Fig. 6a).

4. Peak complexity: Central structures do not systematically increase in morphological complexity with increasing rim-crest diameter (Fig. 7). Multiple central-peak morphologies of varying complexity are observed at the onset of peak-ring basins (Fig. 7).

5. Peak diameter: Plots of updated peak-ring diameters on Mercury emphasize the abrupt, divergent transition from trends in central-peak diameters to peak-ring diameters on both Mercury and the Moon (Fig. 8), as observed by prior workers (e.g., Pike, 1988; Baker et al., 2011a, 2011b). Central peaks in protobasins are generally smaller than those in complex craters and have no regular trend with rim-crest diameter.

6. Peak heights: Heights of the central peaks in complex craters increase continuously up to the transition to peak-ring basins (Fig. 9a and b). At the onset of peak-ring basins, the height of the peak ring itself is smaller compared to central peaks at the same rim-crest diameter (Fig. 9a and b). No apparent reduction in the height of the central peaks of protobasins is observed with increasing rim-crest diameter.

7. Peak-to-rim distance: The distances from the tops of central peaks or peak rings to the rim-crest elevation (h_{pkr}) are typically greater than 1 km and are independent of rim-crest diameter on the Moon or Mercury (Fig. 9e and f).

8. Peak areas: The areas of the central peaks also increase up to the transition to peak-ring basins (Fig. 9g–l). There is a slight increase in the ratio of total peak area to total interior area for peak-ring basins, but in general there is no strong deviation from the increasing peak-area trend from complex craters to peak-ring basins (Fig. 9k and l).

9. Peak volumes: In line with the height and area measurements, the volumes of central peaks increase continuously up to the transition to peak-ring basins (Fig. 6b). There is a slight reduction in total peak volume at the onset of peak rings, but this may be an artifact of incomplete preservation of small peak rings on the Moon, as the volumes increase again to become more in line with the trend of complex craters (Fig. 6b). Incomplete preservation is due our inclusion of more degraded basins in our analyses (see Appendix A).
Table 2
Obsessional framework of morphometric trends in the transition from complex craters to peak-ring basins on Mercury and the Moon. Indicated for the two major models of peak-ring formation (dynamic collapse model, DCM, and nested melt-cavity model, NMCM) are consistencies (y), inconsistencies (n), uncertainties (“maybe”, m) and no specific prediction or specific application (?). See Section 8 for additional discussion.

<table>
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<tr>
<th>Parameter</th>
<th>Figure/Table</th>
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<td>Fig. 5a-d</td>
<td>There is a discontinuous shallowning of crater depth from complex craters to peak-ring basins. Peak-ring basins increase in depth with rim-crest diameter along a trend separate from that of complex craters, but with decreasing depth/diameter ratios</td>
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<td>A&lt;sub&gt;hoc&lt;/sub&gt;</td>
<td>Fig. 5e-h</td>
<td>The area of the floor becomes an increasingly larger fraction of the total interior area with increasing rim-crest diameter. Peak-ring basins have statistically larger floor-area to interior-area ratios compared with protobasins and complex craters in the diameter range where these craters and basins overlap</td>
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<tr>
<td>V&lt;sub&gt;int&lt;/sub&gt;</td>
<td>Fig. 6a</td>
<td>The volumes of the present basin interiors on the Moon are reduced by ~40% compared with the volumes of the scaled excavation cavities estimated by Wiesneck and Phillips (1999) for the Moon</td>
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<tr>
<td>D&lt;sub&gt;pk&lt;/sub&gt;</td>
<td>Fig. 8</td>
<td>There is an abrupt transition from trends in central-peak diameters to peak-ring diameters. The trend for peak-ring diameters in protobasins intersects the central-peak diameter trend at a rim-crest diameter of ~50 km on Mercury. Central peaks in protobasins are generally smaller in diameter than those in complex craters and have no regular trend with rim-crest diameter</td>
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<td>h&lt;sub&gt;pk&lt;/sub&gt;</td>
<td>Fig. 9a and b</td>
<td>Heights of the central peaks in complex craters increase continuously up to the transition to peak-ring basins. At the onset of peak rings, the height of the peak ring is smaller compared to central peaks at the same rim-crest diameter. No apparent reduction in the height of the central peaks of protobasins is observed with increasing rim-crest diameter</td>
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<td>h&lt;sub&gt;int&lt;/sub&gt;</td>
<td>Fig. 9e and f</td>
<td>The distances from the tops of central peaks or peak rings to rim crests are typically greater than 1 km and are independent of rim-crest diameter on the Moon and Mercury</td>
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<td>A&lt;sub&gt;pk&lt;/sub&gt;</td>
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<td>The areas of the central peaks increase up to the transition to peak-ring basins. There is a slight increase in the ratio of total peak area to total interior area for peak-ring basins, but in general there is no strong deviation from the increasing peak area trend from complex craters to peak-ring basins</td>
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<td>V&lt;sub&gt;pk&lt;/sub&gt;</td>
<td>Fig. 6b</td>
<td>The volumes of central peaks increase continuously up to the peak-ring transition. There is a slight reduction in total peak volume at the onset of peak rings, but this may be an artifact of incomplete preservation of small peak rings on the Moon, as the volumes increase again to become more in line with the trend of complex craters</td>
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<td>Central-peak Complexity</td>
<td>Fig. 7</td>
<td>Central peaks do not systematically increase in morphological complexity with increasing rim-crest diameter. Multiple central-peak morphologies of varying complexity are observed at the onset of peak-ring basins</td>
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<td>Topographic Profiles</td>
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<td>The topographic profiles of peak-ring basins exhibit a cavity-like depression bounded by a peak ring, with a steeper inward-facing wall, which describe a center that is lower in elevation compared to the annulus surrounding the peak ring</td>
</tr>
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</table>

Mercy and Moon comparisons

| Number of basins | Table 1 | The number of peak-ring basins and protobasins per unit area is higher on Mercury than on the Moon |
| Density of basins | 300 km in diameter | There is a deficit of basins ≥300 km in diameter (including peak-ring basins) on Mercury relative to the Moon |
| Peak-ring Basin Onset Diameter | Table 1 | The onset diameter of peak-ring basins is smaller on Mercury than on the Moon |
| Overlap in Morphology | Table 1 | The onset diameter of peak-ring basins is smaller on Mercury than on the Moon |
| d | Fig. 9a-d | Complex craters are much shallower on Mercury compared with the Moon, as shown by their significantly different depth-to-diameter ratios. Peak-ring basins on Mercury have similar depth-to-diameter ratios as peak-ring basins on the Moon; protobasins also have similar ratios between Mercury and the Moon |
| A<sub>hoc</sub> | Fig. 5e-h | Areas of central peaks are similar over the same rim-crest diameter range on Mercury and on the Moon, Mercury peak-ring basins have slightly greater peak ring areas than the Moon |

10. Topographic profiles: The topographic profiles of peak-ring basins exhibit a cavity-like depression bounded by a peak ring, with a shallow outward-facing wall and a steeper inward-facing wall, which describe a center that is lower in elevation compared to the annulus surrounding the peak ring (Figs. 10 and 11).

Further, there are differences between Mercury and the Moon that are also important to consider and may reveal important clues to the formation of peak rings:

1. The number of peak-ring basins and protobasins per unit area is higher on Mercury than on the Moon (Table 1).
2. There is a deficit in the spatial density of basins ≥300 km in diameter on Mercury compared with the Moon (Fassett et al., 2012).
3. The onset diameter of peak-ring basins is smaller on Mercury than on the Moon (Table 1).
4. There is much more overlap in diameter between complex craters and peak-ring basins on Mercury compared with those on the Moon (Figs. 3 and 7). The Moon has no craters with central peaks that overlap in diameter with peak-ring basins.
5. Complex craters are much shallower on Mercury compared with the Moon, as shown by their significantly different depth-to-diameter ratios (Fig. 5c and d). Peak-ring basins on Mercury and the Moon have similar depth-to-diameter ratios, as do protobasins (Fig. 5c and d).
6. Floor-area to interior-area ratios are larger on Mercury than on the Moon (Fig. 5g and h).
7. Areas of central peaks are similar over the same range of rim-crest diameters on Mercury and the Moon (Fig. 9i-j). Mercurian peak-ring basins have slightly greater peak ring areas than those on the Moon (Fig. 9i-j).

8. Models of peak-ring formation

We use our observational framework of seventeen points (Section 7 and Table 2) to discuss two major peak-ring formation models, dynamic collapse and nested melt cavity, to assess the
model predictions of the evolution of interior landform morphology with increasing size, and to outline new areas identified by our analysis that need to be addressed by these and any other peak-ring formation models.

8.1. Dynamic collapse model

Peak rings in basins on the terrestrial planets (e.g., the Chicxulub impact structure) have been interpreted in context of the “dynamic collapse model.” The dynamic collapse model explains peak-ring formation as a product of fluid-like gravitational collapse of an over-heightened central peak (Fig. 12a). This model was initially suggested qualitatively from studies of basins on the Moon, Mars, and Mercury (Murray, 1980) and terrestrial impact structures (Grieve, 1981). Further quantitative development of this hypothesis was made on the basis of theory (Melosh, 1982, 1989) and hydrocode modeling combined with geologic and geophysical studies (e.g., Morgan et al., 2000; Collins et al., 2002, 2008b; Ivanov, 2005). The principal stages in the model include substantial transient weakening and collapse of the target rock, which is brittlely deformed at all scales such that it behaves like a fluid; rebounding or inward and upward wall collapse to form an over-heightened, gravitationally unstable central uplift; downward and outward collapse of the unstable central uplift to override the collapsed transient cavity wall; and “freezing” of the collapsed, outwardly flowing central-peak material to form a peak ring (Fig. 12a).

![Fig. 12. Schematics of the formation of central peaks and peak rings as described by dynamic collapse of a gravitationally unstable central peak (a, “dynamic collapse model”) and modification of interior morphology resulting from growth of an interior melt cavity (b, “nested melt-cavity model”). The final profiles in each sequence identify the locations of the rim crest (rc), central peak (cp), and peak ring (pr). Relative diameters between craters and basins are not to scale. (a) Dynamic collapse model: Central peaks in complex craters form as brittlely deformed target material collapses in a fluid-like behavior inward and upward under the influence of gravity. The onset of peak rings occurs when the central peak reaches an elevation at which it is gravitationally unstable and collapses back downward. Protobasins may form by incomplete collapse of the central peak, which could produce a central peak plus a small ring of peaks. Single peak rings form as a very large central peak collapses downward and outward and folds over wall material that has collapsed inward and downward into the center of the crater (e.g., Collins et al., 2008b). (b) Nested melt-cavity model: The topmost sequence of figures show the evolution of the melted zone relative to the size of the transient cavity with increasing size of the crater (after Cintala and Grieve, 1998). For complex craters, the volumes and depths of melting are small enough so that they do not modify the interior of the crater during collapse of the transient cavity. At a critical volume and depth of melting, melt begins to suppress central peaks, and the uplifted region consists of a broader zone of solid material to include central peaks and peaks around the periphery of the melt zone remains as the only topographically prominent feature in the interior of the crater to form peak rings. At this stage, the volumes and depths of melting are so great that uplift and rebound processes are not sufficient to uplift a central peak of solid material. The final profiles in each sequence identify the locations of the rim crest (rc), central peak (cp), and peak ring (pr). Relative diameters between craters and basins are not to scale. The final profiles in each sequence identify the locations of the rim crest (rc), central peak (cp), and peak ring (pr). Relative diameters between craters and basins are not to scale.](image-url)
The dynamic collapse model makes several predictions regarding the behavior of central peaks and peak rings with increasing rim-crest diameter. First, central peaks should increase in dimensions until they become gravitationally unstable and begin to collapse downward and outward to form peak rings (Fig. 12a). As originally suggested by the work by Hale and Head (1979, 1980) and Hale and Grieve (1982), the lack of increasing complexity of central-peak morphology and the continued increase in central-peak dimensions with rim-crest diameter pointed toward an abrupt transition to peak rings; this was viewed by Hale and Grieve (1982) as consistent with a dynamic collapse model. Our observations support the work by Hale and Head (1979, 1980) and the observations of others to suggest that central peaks do not increase in complexity with increasing rim-crest diameter (Fig. 7). Our data also show that central peaks increase in dimensions (height, area, and volume) continuously up to the transition to peak-ring basins (Figs. 7b and 9), which is consistent with central peaks becoming more gravitationally unstable at the largest crater diameters. A recent study examining the height and volumes of central peaks and peak rings on the Moon by Bray et al. (2012) also showed a continuous increase in the dimensions of the central peak.

Transitional complex craters with reduced central-peak heights are not observed in our data, however, which may be expected for incipient collapse of a gravitationally unstable uplift, eventually leading to peak-ring formation. Unlike the work by Bray et al. (2012), we do not see a distinct decrease in the trend of central peak heights or volumes at a crater diameter of around 80 km; the authors also did not observe a decrease in height from central-peak to peak rings, which we document here in Fig. 9a and b. Some protobasins in our data do have reduced central-peak heights, but most central-peak heights for protobasins are comparable to those in complex craters and do not decrease with crater size (Fig. 9a–d). These observations could be inconsistent with the dynamic collapse model if transitional complex craters are to be predicted (e.g., Collins et al., 2008a); such models examining transitional crater morphologies on the Moon and Mercury have not been completed and should be a focus of future work. The lack of a systematic change in central-peak morphology and complexity with increasing rim-crest diameter also suggests that the transition from central peaks to peak rings is more abrupt and not gradual as early workers have suggested (Hartmann and Wood, 1971; Head, 1978; Hodges and Wilhelms, 1978). The trends in peak-ring and central-peak diameter (Fig. 8) also support this assertion.

While hydrocode models of central-peak formation within large complex craters produce central peaks below the rim-crest elevation (e.g., Wünnemann and Ivanov, 2003; Collins et al., 2008a), consistent with our morphometric observations, peak-ring formation appears to require transient central peaks that substantially overshoot the rim-crest elevation by many kilometers. Simulations of the dynamic collapse model for peak-ring formation, such as for Chicxulub on Earth (e.g., Collins et al., 2002, 2008b; Ivanov, 2005; Wünnemann et al., 2005), consistently show central peaks that overshoot the rim crests of the crater by 10 to 20 km (which is a factor of two to three times the final depths of the basins modeled) before gravitationally collapsing and freezing into place to produce the peak ring (Fig. 12a). Our measurements indicate that the tops of most central peaks are >1 km below the elevation of the rim crest (Fig. 9e and f), even near the peak-ring basin onset diameter. Only several of the largest central peaks come within several hundred meters of the rim crest, which is still far from the elevations achieved by the transient central peaks in simulations of peak-ring formation (Collins et al., 2002, 2008b; Ivanov, 2005; Wünnemann et al., 2005). Further, no reduction in central-peak height is observed within the largest complex craters and most protobasins on the Moon or Mercury (Fig. 9a–d), which would be predicted for incipient peak collapse in the transition to peak rings. The absence of transitional central peaks and the substantial change in central uplift height that are required to produce peak rings in the dynamic collapse model, suggest that the transition from crater to basin is more abrupt than current models may predict. The lack of a systematic modeling effort focusing on the evolution of morphometries of central uplifts in the transitional diameter range of ~150 to 250 km on the Moon and Mercury makes it difficult for firm comparisons between our observations and models to be made. Future work should strive to make these comparisons, with models that assume a consistent set of planetary-specific target and transient weakening parameters.

Most models of the dynamic collapse process (Collins et al., 2002, 2008b; Ivanov, 2005; Wünnemann et al., 2005), and in particular models of the Chicxulub impact (Collins et al., 2002, 2008b; Ivanov, 2005), show a distinctive topographic profile formed as a result of the outwardly collapsing central peak converging and thrusting over the inwardly collapsed rim material. Final crater shapes that typically result are marked by a peak ring with a steep, outward facing wall and a more gradually sloping inward-facing wall with an annular trough surrounding the peak ring (e.g., Collins et al., 2002, 2008b) (Fig. 10). This type of interior shape is very different from the topographic profiles of peak-ring basins on Mercury and the Moon (Figs. 10 and 11). Our observations show that peak-ring basins commonly have peak rings with steep, inward facing walls and more gradually sloping, outward-facing walls. The annulus surrounding the peak ring is typically at a much higher elevation than the floor interior to peak ring, creating a cavity-like depression within the interior. Current hydrocode models do not account for every geological process important for impact crater formation, it is not surprising that the final profiles produced from the models are quite different from observations. The discrepancies between models and observations indicate that important processes are missing or are not accurately treated in the current impact simulations. One of these processes is faulting, which will greatly affect the final surface morphometry of the crater or basin, particularly in the wall and annular region surrounding the peak ring. Faulting associated with formation and collapse of central uplifts and interaction with impact melt should also be important in large-scale impact events. Current simulations also do not account for post-impact modification to the basin. In peak-ring basins, kilometers-thick melt sheets form in their centers inward from the peak ring, and are direct results of the geometry of the melted region produced during shock-wave propagation and decay during the early stages of the impact event (e.g., Grieve and Cintala, 1992). Subsequent post-impact cooling and thermal contraction of these impact melt sheets can lead to dramatic changes in the basin shape, such as the observed presence of central depressions (Baker et al., 2012). Further, current assumptions for the target weakening parameters, or target strength, leading to peak-ring formation during the modification stage could be inappropriate for modeling impact basins on the Moon and Mercury. Our observed topographic profiles are more consistent with models in which the target material has high strength and only a small portion is transiently weakened (Morgan et al., 2011), as suggested for the Ries impact structure (Wünnemann et al., 2005; Collins et al., 2008a). This type of model, however, suggests that peak rings form as the most inward collapsed portions of the rim of the transient cavity, with only modest convergence and overtopping of an outwardly collapsed central peak. The scenario (Wünnemann et al., 2005) also requires tens of kilometers of inward displacement of rim-wall material and substantial downward, then upward, displacement to form a peak ring.

In summary, there are some consistencies between our observations and predictions of the dynamic collapse model, but uncertainties and inconsistencies with the model remain. While the trend of increasing central-peak dimensions may be consistent with the formation of increasingly unstable central uplifts, our observations show that the transition to peak rings is not marked by a reduction of central-peaks dimensions, which would be
predicted from incipient collapse of an unstable uplift. Also, central peaks in complex craters near the transition to peak-ring basins remain well below the rim-crest elevation by about 1 km, which appear at odds with the prediction of uplifts that significantly overshoot the rim-crest elevation then collapse downward to form peak rings. Further, the final basin profiles predicted by current models of the dynamic collapse process are substantially different from the observed profiles of peak-ring basins on Mercury and the Moon. This disagreement suggests that important processes such as faulting and modification of large impact melt pools during crater formation and post-impact are missing or not well-represented in current hydrocode models.

8.2. Nested melt-cavity model

In the nested melt-cavity model (Cintala and Grieve, 1998; Head, 2010; Baker et al., 2011a, 2011b), the transition from complex craters to peak-ring basins is the result of non-proportional growth in impact-melt volume with increasing basin size, together with an increase in depth of melting relative to the depth of the transient crater (Fig. 12b); this process acts to weaken the central uplifted portions of the crater interior during large impact events. In this scenario, complex craters are formed when the rebound of a focused region of solids that is experiencing the largest shock stresses within the center of the displaced zone results in the formation of a central-uptilt (Fig. 12b, “Complex Craters”). The depth of melting is generally not sufficient in complex craters to modify the uplifted morphology of the crater interior. In contrast, the rings in protobasins and peak-ring basins form due to the non-proportional increase in depth of impact melting (Fig. 12b, “Protobasins” and “Peak-ring Basins”). In this regime, the region of peak shock stress in the solid target expands to outline a broad central region of impact melt nested within the transient crater. Melted material will be displaced and streamed downward and outward during growth of the transient cavity. During rebound and collapse of the transient cavity, the region of melted material is translated upward and inward. Unlike rebound in complex craters, however, the central melt region is sufficiently deep to retard the development of an ordinary-sized central peak (Cintala and Grieve, 1998). Rather, the uplifted periphery of the central melt cavity remains as the only topographically prominent feature, resulting in the formation of a peak ring (Fig. 12b, “Peak-ring Basins”). At smaller crater sizes, and hence smaller depths of melting, it is still possible for a diminutive central peak to rise through the central melt pool, accounting for the occurrences of small central-peak and peak-ring combinations that are commonly seen in proto-basins (Fig. 12b, “Protobasins”).

The onset of peak-ring basins under the nested melt-cavity model is intimately tied to the volumes and depths of melting produced during impact events. Not only are the effects of impact melting readily apparent from our morphometric data, but there are distinct differences between complex craters and peak-ring basins that indicate that increased melt production is likely to be associated with the onset of peak-ring basins, as predicted by the nested melt-cavity model. First, our observations demonstrate a statistically significant difference between the $A_{\text{floor}}/A_{\text{out}}$ ratios of complex craters and peak-ring basins over the diameter range where these crater types overlap (Fig. 5g and h). Should this difference in ratio be the result of differences in impact-melt production, which seems to be the case (see Section 4.2), then it would indicate that the formation of peak-ring basins is marked by enhanced impact-melt production relative to complex craters occurring in the same diameter range. This observation is consistent with the nested melt-cavity model, which predicts that peak-ring basins should have much larger volumes and depths of melting compared with complex craters (Fig. 12b). The substantial diameter overlap over which central peaks and peak rings occur on Mercury (Fig. 7) may be due to the much broader distribution of impact velocities occurring at Mercury (Le Feuvre and Wieczorek, 2011), which will affect the volume of impact melt (Cintala and Grieve, 1998).

In addition, we see that the topographic profiles of peak-ring basins on Mercury and the Moon are marked by large interior depressions, with peak rings bounding a central area that is depressed substantially relative to the annulus surrounding the peak ring (Figs. 10 and 11). This observation strongly supports the predicted development of an interior melt cavity, which is bounded by solid target rocks at the base of the excavation cavity that are uplifted to form the peak ring (Fig. 12b, “Peak-ring basins”). Baker et al. (2012) suggested that the increase in floor height (the difference between the wall-base elevation and the center elevation) observed for lunar peak-ring basins may be related to the expulsion of impact melt and its redistribution to points outward from the central portions of the basin. It was suggested that this could help to explain the decreasing wall height to depth ratios and increasing floor radii relative to the rim-crest radii in peak-ring basins on the Moon. These lunar observations are consistent with our new morphometric data, and indicate that the formation of a large interior melt cavity and redistribution of this impact melt may have helped to substantially modify the interior morphologies of peak-ring basins. Support for late-stage impact melt transport comes from terrestrial craters, such as Ries, which indicate that momentum imparted to the melt from uplift of the crater floor can cause substantial transport and ejection of this melt in large complex craters (Osinski et al., 2011). Further post-impact modification of a central impact melt sheet through cooling and thermal contraction to form inner depressions (Wilson and Head, 2011; Vaughan et al., 2013) can also be contributing to the observed morphometric trends.

Since impact-melt production scales with crater size (Grieve and Cintala, 1992), a gradual transition to peak-ring basins would be initially expected as melt consumes more material that would otherwise form central peaks (Fig. 12b). From our morphometric measurements, the transition to peak-ring basins appears more abrupt. Central-peak complexity does not increase with crater size (Fig. 7), and central-peak dimensions continue to increase up to the transition to peak-ring basins. These observations appear to be in contrast to the more gradual transition that would be inferred if continued depth of melting continues to suppress central-peak formation. It is possible, however, that this intuition may be incorrect. The onset of peak rings may only initiate after the depth of melting, which suppresses central peaks, is able to overcome the competing effects of cavity collapse and floor uplift or rebound, which act to increase central-peak height. Only at this critical depth of melting will peak rings begin to form. This concept is consistent with suggestions by Cintala and Grieve (1991) and Baker et al. (2011a), that the onset of peak-ring basins appear to be coincident with a critical depth of melting, which is about 0.75 to 1.0 of the depth of the transient cavity (assuming that the transient cavity obeys a $d_{\text{melt}}D_{\text{c}}$ ratio of 1/3, where $d_{\text{melt}}$ is the depth of the transient cavity and $D_{\text{c}}$ is the diameter of the transient cavity). Further numerical or dynamic modeling of the competing effects of impact melting and floor uplift in producing central peaks and rings should be completed in order to test this hypothesis.

9. Conclusions

Using new image and topography data from MESSENGER in orbit around Mercury and LRO around the Moon, we determined a variety of morphometric properties of complex craters, proto-basins, and peak-ring basins, all of which were ≥50 km in diameter. We present updated catalogs of protobasins and peak-ring basins on Mercury, bringing their totals to 70 and 110, respectively. In
addition, we have cataloged 682 and 430 complex craters with central peaks on Mercury and the Moon, respectively. Degradation-class assignments (from I to V for least to most degraded landform) for each crater or basin in our catalogs permitted us to assess the freshest structures within the populations. New techniques and data allowed us to calculate a number of morphometric parameters and to evaluate trends in those parameters as a function of rim-crest diameter. A list of those trends is presented in Table 2, which may be used as an observational framework for refining current models of peak-ring formation.

Based on our comparisons with two current models for peak-ring formation (dynamic collapse and nested melt cavity), we identify future areas of focus for refining the details of these models. Trends in the dimensions of central peaks on Mercury and the Moon are generally consistent with predictions of the dynamic collapse model, although our data show that central-peak elevations are well below rim-crest elevations even at the onset of peak rings and that no reduction in central-peak dimensions are observed in the transition to peak rings, which would be predicted to result from incipient central-peak collapse. These observations suggest that the transition to peak rings may be more abrupt than current models would predict. The apparent disconnect between central-peak dimensions observed within complex craters and the large transient central-peak elevations required for peak-ring formation should be elucidated with subsequent modeling efforts. Central-peak dimensions do not gradually decrease with rim-crest diameter, as may result from increased depth of melting in the nested melt-cavity model. This apparent inconsistency suggests that central peaks may only begin to give way to peak rings after a critical depth of melting (relative to the depth of the transient cavity), as supported by previous suggestions (Grieve et al., 2010; Baker et al., 2011b). However, additional quantification of this process is needed before more robust predictions may be made. The topographic profiles of peak-ring basins on Mercury and the Moon are much different than the final profiles predicted from simulations of the dynamic collapse process (e.g., Collins et al., 2008b). Critical processes such as faulting, impact melt mobilization, and post-impact modification may help to explain this disagreement and should be evaluated with more refined numerical modeling. Observed topographic profiles appear to be consistent with the modification effects of interior pools of impact melt, along with increased impact-melt production and redistribution within the basin interiors. The increased floor area observed between complex craters and peak-ring basins also points to the large role that impact melting has in shaping the interiors of impact structures in the transition to peak-ring basins. Further, the large crater diameter overlap in peak morphology on Mercury may be explained by the planet’s much broader distribution of impact velocities, increasing the variance in impact processes such as melt production and type of central uplift produced for a given crater size. Overall, there is a critical need for improved model predictions of the evolution of the dimensions of central peaks and peak rings for impact craters in the ~100 to 300 km diameter range on the Moon and Mercury, and for improvement in aspects of models focused on the effects of impact-melt production in modifying interior morphologies near the onset of peak-ring basins (e.g., the effects on central structures and the expulsion and re-distribution of melt within the interior of the craters). Some processes important to producing the final morphology of craters and basins (e.g., faulting and modification of impact melt) should be incorporated into current models to better validate these models with the observations presented here.

Comparisons between our morphometric observations and model predictions of impact structures in the transition from complex craters to basins highlight the utility of using morphometric data in constraining the processes involved in peak-ring formation. Further quantification of current models directed toward explaining the trends presented here should be completed to help in further improving our understanding of the processes leading to peak rings on planetary bodies. Additional refinements of the observed morphometric trends should also be completed with additional altimetry data or stereo-derived topography over peak-ring basins obtained from MESSENGER in orbit at Mercury.

Acknowledgements

We thank the engineers and scientists of the MERcury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) and Lunar Reconnaissance Orbiter (LRO) missions for helping to revolutionize our understanding of Mercury and the Moon and for making this work possible. Thanks are extended to Caleb Fassett and Seth Kadish for the use of catalogs of craters on the Moon and Mercury (available online from the Brown University Planetary Geosciences Group at: http://www.planetary.brown.edu/html_pages/data.htm). Earlier drafts of this manuscript greatly benefited from detailed reviews by Caleb Fassett, Paul Byrne, and Mark Cintala. We thank Sean Gulick for a constructive review, which helped to improve the quality of the manuscript. The MESSENGER project is supported by the NASA Discovery Program under contracts NASW-00002 to the Carnegie Institution of Washington and NASA-97271 to the Johns Hopkins University Applied Physics Laboratory. We also gratefully acknowledge financial support from the NASA Lunar Reconnaissance Orbiter Lunar Orbiter Laser Altimeter (LOLA) experiment (NNX09AM54G to JWH).

Appendix A. Degradation classes

All craters were classified into one of five crater degradation classes, with Class I including the freshest craters and Class V corresponding to the most severely degraded craters (Fig. 1). This is based on the classification scheme of Arthur et al. (1963), which has been used as the basis for many subsequent crater degradation studies (e.g., Wood et al., 1977; Smith and Hartnell, 1978). Class I craters are the freshest, exhibiting sharp rim crests, terraces and well-preserved ejecta. Many Class I simple craters exhibit bright rays of ejecta, but this is less common for the complex craters and basins analyzed in this study. Class II craters are more degraded than Class I craters, commonly having several superposed impact craters and more subdued rim crests and terraces. Ejecta deposits around Class II craters have more superposed craters and are not as crisp as those around Class I structures. Class III craters are much more battered by subsequent impacts than Class II craters. Terraces are generally not preserved; rather, the walls are smoother and rim crests are rounded but still continuous compared to Class II craters. Large, superposed craters can disrupt portions of the crater rim and lead to masking of some features by emplaced ejecta (a process termed proximity degradation; Head, 1975). Class IV craters have been severely damaged by superposed impacts and proximal ejecta, which may lead to only portions of the rim being preserved. The outlines of Class IV craters are more difficult to recognize, but the crater shape is still preserved. Due to their degraded nature, central peaks are often not preserved, and therefore Class IV craters compose only a small fraction of most craters and basins with primary interior landforms (Fig. 4). Continuous ejecta are not preserved for Class IV craters but may be recognized in isolated patches. Class V craters are nearly unrecognizable as craters. Degradation processes have nearly completely removed evidence of the crater-related features but positive identification of the crater is still possible, often with the aid of topography data. Several iterations of these classifications were made as our experience with the morphologies of craters on both the Moon and Mercury improved with time.
It is important to note that there are substantial differences in the way that craters of differing sizes will degrade (Pohn and Offield, 1970; Wood et al., 1977; Ronca et al., 1981; Craddock and Howard, 2000). For example, small, simple craters will degrade much more rapidly than larger complex craters, as smaller craters, due to their size, are much more susceptible to resurfacing and proximal erosion from nearby impact events (Head, 1975; Wood et al., 1977). As a result, simple and complex craters of the same class will cover a range of absolute ages (Head, 1975). We have sought to match degradation states between complex craters and basins, and between craters on Mercury and the Moon, as much as possible to facilitate comparison between craters of differing morphologies and between the two planetary bodies. For this reason, we have updated the degradation classes for protobasins and peak-ring basins on the Moon from Baker et al. (2012), which were largely based on the observed variations in degradation state within the cataloged basin populations. An important change to these degradation assignments is that some lunar peak-ring basins are now assigned to Class III instead of Class II, which reduces the number of the freshest basins (i.e., Class I and II) to three in number. Since we are restricting our morphometric analyses to craters and basins of Classes I and II (see Appendix B), this dramatically reduces our sample size for lunar peak-ring basins from those measured by Baker et al. (2012). We choose, however, to present the morphometric measurements for Class III peak-ring basins on the Moon for a more complete basis in describing the morphometric trends in the transition between complex craters and peak-ring basins.

Our catalogs also include some craters and basins that have been partially resurfaced by volcanic materials. On the Moon, mare materials are usually easily identified by their distinctive low albedo and infilling relationships with craters. On the Moon, only 13 complex craters that we measured showed signs of low to moderate infilling (i.e. volcanic material that is volumetrically small enough to preserve interior features such as peaks and wall slump material), with 120 not displaying any evidence, and 19 showing possible evidence of mare material. Three of the eight peak-ring basins and one of the three protobasins on the Moon

Fig. B.1. Examples of how elevations were measured for complex craters (a), protobasins (b), and peak-ring basins (c) on Mercury and the Moon. The outlines of three features, the rim crest, wall base, and base of the central peak or peak ring, were first mapped (irregular black lines for each crater or basin in the left most panels). Then, elevations were selected for use in calculating a number of parameters (see Fig. 2, Tables B.1 and B.2, and discussion in Appendix B). Track data from the Mercury Laser Altimeter (MLA) instrument (north to south trending black lines and points) were used for measurements of craters and basins on Mercury (leftmost panels in a, b, and c). Selected MLA track points used for measurements are shown in yellow. Note the differences in densities of MLA track coverage between the craters and basins and lack of coverage over some peak rings and central peaks. Gridded LOLA topography data (128 pixels per degree) were used for measurements on the Moon (right image panels in a, b, and c). Selected maximum elevation points within the rim-crest buffer (dashed area) are shown in white. The rightmost panels show north to south trending profiles for lunar complex craters (a), protobasins (b), and peak-ring basins (c), highlighting typical morphologies, including the rim crest (“r”) and peak ring (“pr”). Profiles for mercurian craters are from MLA tracks; their locations are shown as red dashed lines in the left panels. Complex craters shown are Stieglitz (94 km; 72.60° N, 67.55° E) on Mercury (MLA track 1106140102) and Theophilus (98 km; 11.40° S, 26.33° E) on the Moon. Protobasins shown are Velazquez (123 km; 37.68° N, 55.61° W) on Mercury (MLA track 1110312147) and Antoniadi (137 km; 69.35° S, 172.96° W) on the Moon. Peak-ring basins shown are Ahmad Baba (124; 58.26° N, 128.52° W) on Mercury (MLA track 1109140532) and Schrödinger (326 km; 74.90° S, 133.53° E) on the Moon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
showed evidence of volcanic resurfacing (Baker et al., 2012), although, except for Moscoviense and Antoniadi, these were restricted to relatively small patches within the basins.

Recognition of volcanic plains materials within craters and basins is more difficult on Mercury because their albedos are very similar to those of other crustal materials. To determine which craters and basins have been modified by volcanism on Mercury, we examined their detailed morphology and their spectral characteristics using an MDIS color mosaic in the 1000 nm, 750 nm, and 430 nm bands. We used three criteria to distinguish between volcanic infilling and impact melt, including evidence of superposed craters embayed by smooth plains material, the presence of wrinkle ridges, and unambiguous spectral contrasts between interior fill and basin materials (e.g., Prockter et al., 2012). Of the 163 Class I and II complex craters that we mapped (Appendix B), 28 contained volcanic material, 89 had none, and 46 showed possible evidence of volcanics. Only five complex craters had volcanic material of the 59 that we measured with MESSENGER Mercury Laser Altimeter (MLA) topographic data. None of the 50 protobasins we examined showed definitive evidence of volcanic resurfacing, with 14 showing possible evidence. Of the 12 peak-ring basins measured with MLA data, six had low to moderate degrees of volcanic resurfacing, while four had none and two showed possible signs of volcanics. Of the 27 peak-ring basins we measured for interior areas, ten were volcanically infilled, nine were not, and seven had possible evidence for volcanic infilling. The majority of those with evidence of resurfacing showed spectral contrasts confined mostly interior to the peak ring. This suggests that while resurfacing may have some effect on our measured depths, resurfacing probably has a more limited effect on floor-area measurements due to its general confinement to the interior of peak rings. However, the preservation of prominent peak rings in most of these basins, together with similar depth trends for peak-ring basins with and without volcanic material (Section 4.1) suggests that volcanism was limited in these basins.

Appendix B. Morphometric measurements

Mapping feature outlines

Morphometric measurements of craters and basins on the Moon and Mercury were restricted to Class I and II craters (except for lunar peak-ring basins, see above), determined using the criteria in Appendix A. We restricted our measurements to Class I and II craters as these craters have been least affected by post-impact modification processes and therefore provide the most reliable morphometric data. All morphometric measurements were made by first mapping the outlines of three major crater features: the rim crest, the base of the wall (”wall base”), and the bases of central peaks or peak rings (Fig. 2 and Fig. B.1). Mapping was completed in the ESRI ArcMap environment using local projections for each crater and a 2440 km datum for Mercury and 1737.4 km for the Moon. Our basemap for the mapping work for Mercury was a 250 m/pixel global mosaic of MDIS NAC and WAC orbital images. We supplemented gaps or unfavorable illumination conditions in the mosaic with individual orbital MDIS NAC or WAC images and mosaics from MESSENGER flyby and Mariner 10 images. For the Moon, we used a 100 m/pixel LROC Wide Angle Camera (WAC) mosaic overlay by 128 ppd (pixel per degree) gridded colored topography data from LOLA. Combining the image mosaic with the gridded topography provided unique cross-validation for identifying these morphological features.

Crate rim crests were identified in the basemaps as the highest points on each crater’s rim. The wall base was defined topographically by a sharp break in slope between the terraced wall and the flatter floor material. The wall base was more difficult to map due to its irregularity and to the continuation of slump blocks into the interior of the crater and onto the crater floor. It is common for portions of the rims and walls of craters to have been disrupted by superposed craters of various diameters, although this modification to our mapping of the wall-base perimeter was minimized by only analyzing the freshest craters and basins in our catalogs. We connected discontinuous portions of the crater features by interpolating across any disrupted segments of the feature with straight lines. The bases of the central peaks and peak rings were defined as a topographic break in slope between steeply sloping peak walls and the flatter floor material. At the smallest complex crater diameters, the toes of slumped material often merged with the central structures. This was manifested as distinct terraces abutting the walls of the peaks or as floor roughening associated with slump material that continued into dispersed, higher relief central peaks toward the center of the crater. For these occurrences, the bases of the peaks were mapped as the contact between rough slump material and higher-sloping central peaks. Many central peaks and peak rings are not continuous, instead existing as clusters or separated peak elements (Section 5.1); therefore, multiple outlines of peaks were often required for a given crater or basin.

Extraction of elevation points

The mapped outlines of the rim crest, wall base, and base of peaks were then used as locations for extracting and calculating feature elevations (Fig. B.1 and Table B.1). To extract individual elevation points, we employed two methods based on the characteristics of the topography dataset. We followed the method of Baker et al. (2012) for the Moon, in which maximum elevation points from LOLA 128-pdp data are extracted along profiles radial to the basin center, separated by 1° of azimuth and within buffer zones for the rim crest and wall base. Individual radial measurements from LOLA are accurate to 1–2 m with respect to the center of mass on the Moon (Smith et al., 2010). Unlike the method

<table>
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<th>Full name</th>
<th>Mercury measurement</th>
<th>Moon measurement</th>
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<td>$e_{rc}$</td>
<td>Rim-crest elevation</td>
<td>Median and interquartile range of all MLA data within a 1 km buffer surrounding the rim-crest outline</td>
<td>Median and interquartile range of all maximum elevation points extracted along radial profiles and falling within a buffer surrounding the rim-crest outline</td>
</tr>
<tr>
<td>$e_{wb}$</td>
<td>Wall-base elevation</td>
<td>Median and interquartile range of all MLA data within a 1 km buffer surrounding the wall-base outline</td>
<td>Median and interquartile range of all maximum elevation points extracted along radial profiles and falling on the wall-base outline</td>
</tr>
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<td>$e_{floor}$</td>
<td>Floor elevation</td>
<td>10th percentile of all MLA data contained within the wall-base outline, exclusive of points within the peak outlines</td>
<td>10th percentile of all profile elevation points contained within the wall-base outline, exclusive of points within the peak outlines</td>
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<tr>
<td>$e_{pk}$</td>
<td>Peak elevation</td>
<td>95th percentile of all MLA points contained within the central-peak or peak-ring outlines</td>
<td>95th percentile of all LOLA gridded elevation points contained within the central-peak or peak-ring outlines</td>
</tr>
</tbody>
</table>

Table B.1

Descriptions of feature elevations calculated for each crater and basin on Mercury and the Moon. These were used to determine the morphometric parameters listed and described in Table B.2.
employed by Baker et al. (2012), who used buffer zones around a fixed crater radius, we used buffers here that surround our mapped outlines of the crater features. Buffers were set to equal a fixed value of 5% of the crater radius around the rim-crest outline for the extraction of rim elevations. Mapped outlines of the rim crest more closely follow the true rim crest of the crater or basin, as this feature can be highly irregular and can be missed when a circular geometry is assumed. All extracted points within the rim-crest buffer were used to calculate a median value and interquartile range for the rim-crest elevation.

The elevations of peak rings and central peaks were defined as the 95th percentile of all LOLA gridded elevation points contained within the outlines of the ring or peak features. This means that the calculated elevation value is greater than 95% of all elevation points contained within the peak outline. This differs from the method in Baker et al. (2012), who calculated the median value and interquartile range from all maximum elevation points falling within the ring buffer. We chose the 95th percentile statistic here for a more realistic comparison between the elevations of central peaks and peak rings and to facilitate comparison of peak features with Mercury. The 95th percentile statistic also avoids the use of extreme elevation points to define a maximum value for peak elevations.

The elevation of the floor was calculated as the 10th percentile of all elevation points falling within the outline of the wall base, exclusive of those points within the ring or peak outlines. The crater floor elevation is thus calculated from elevation points in the annulus between the base of the wall and the peak ring and also those points inward from the peak ring. This method also differs from the method in Baker et al. (2012) who used median values of all elevation points on the floor bounded by the peak ring. We use the 10th percentile statistic here to facilitate comparison between peak-ring basins, complex craters, and protobasins. The 10th percentile statistic also reduces biases introduced by small to medium-sized superposed craters that may pepper the floor of some analyzed craters and minimizes the effects of extrema resulting from higher floor elevations that occur near the walls of the craters.

We used our mapped outlines of the mercurian crater features to extract elevation points from individual Mercury Laser Altimeter (MLA) (Cavanaugh et al., 2007) shot data (Fig. B.1). MLA pulse widths range from an average of 15 to 100 m, with radial precision of <1 m and an accuracy with respect to Mercury’s center of mass of better than 20 m (Cavanaugh et al., 2007; Zuber et al., 2012). We used only channel 1, “high” threshold pulse MLA returns to avoid incorporation of spurious returns in the analysis. MLA tracks used are selected from those obtained from March 2011 to December 2011. For some MLA tracks, using only channel 1, high-threshold returns resulted in a dramatic increase of along-track point spacing, with some gaps extending for several kilometers, especially over terrain with steep slopes. In general, however, point-to-point spacing was around 400 m, varying by about ±50–100 m from track to track. Due to the large MLA track-to-track spacing that can occur and which increases equatorward due to the elliptical orbit of MESSENGER, we chose not to use gridded topography data to avoid the effects of large inter-track interpolations. The highly elliptical orbit of MESSENGER also prevents MLA valid returns for most of the southern hemisphere. As a result, the morphometric analysis of craters and basins using MLA data were restricted to the northern hemisphere. Near the equator, many craters and basins do not have adequate MLA track coverage to be included in the analysis. As a rule, we included only those craters and basins with at least two tracks traversing the entire impact structure, with at least one passing close to the center. Due to the non-uniform crossings of MLA tracks, our calculated elevations will be biased based on where the MLA points are located along the feature outline. Bias increases with a smaller number of track crossings and hence smaller sampling size. All tracks were manually filtered by removing any remaining noisy points and those falling within large superposed craters that could affect elevation calculations.

Elevations were extracted from individual MLA points within a ±1 km buffer surrounding the outlines of the rim crest and wall base (Fig. B.1, Table B.1). Median and interquartile range values for each feature were then calculated from all extracted points. For the central peaks and peak rings, we extracted all MLA points contained within the outline(s) of the peak(s). As for the Moon, the elevation of the central peak or peak ring was then calculated as the 95th percentile of all of these points. Use of this statistic avoided the inclusion of outliers and compensates for the uneven coverage of MLA tracks over the peaks. As for the Moon, the elevation of the floor for complex craters, protobasins, and peak-ring basins was calculated as the 10th percentile of all the elevation points extracted within the wall-base outline, exclusive of points falling within the outline of the peaks.

### Calculation of basin and peak parameters

From the calculated elevations for the rim crest, wall base, floor, and central peak or peak ring (Table B.1), a number of crater or basin parameters (depth, height of the central peak or peak ring, and peak-to-rim-crest distance) were calculated, shown schematically in Fig. 2 and listed and described in Table B.2. The rim-crest diameter for each crater or basin was also calculated as a non-linear least-squares circle fit to the mapped outline of the rim crest. Least-squares fits were calculated in equidistant azimuthal

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<tr>
<td>Dc</td>
<td>Rim-crest diameter</td>
<td>Non-linear least squares circle fit to the rim-crest outline</td>
</tr>
<tr>
<td>d</td>
<td>Depth</td>
<td>( e_{r} - e_{floor} )</td>
</tr>
<tr>
<td>Ao</td>
<td>Interior area</td>
<td>Integration of spherical triangles within the rim-crest outline</td>
</tr>
<tr>
<td>Afl</td>
<td>Floor area</td>
<td>Integration of spherical triangles within the wall-base outline</td>
</tr>
<tr>
<td>Voi</td>
<td>Interior volume</td>
<td>Delaunay triangulation of gridded elevation points within the rim-crest outline. Referenced to a plane fit to rim-crest elevation points</td>
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<td>Rim-crest circularity</td>
<td>See Eq. (2), Section 4.3</td>
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<td>( \Gamma_{flo} )</td>
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<tr>
<td>( h_{pk} )</td>
<td>Central-peak or peak-ring height</td>
<td>( e_{pk} - e_{floor} )</td>
</tr>
<tr>
<td>( h_{pk} )</td>
<td>Central-peak or peak-ring to rim-crest distance</td>
<td>( e_{pk} - e_{pk} )</td>
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<tr>
<td>A</td>
<td>Peak area</td>
<td>Integration of spherical triangles within the peak outlines</td>
</tr>
<tr>
<td>Vpk</td>
<td>Peak volume</td>
<td>Delaunay triangulation of gridded elevation points within the peak outlines. Referenced to a plane fit to points 1 km from the peak outline</td>
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planar coordinates centered on the crater or basin of interest. In general, we find an average of about 4% difference between our visual circle fits from cataloging (Baker et al., 2011a, 2011b; this work) and our least squares circle fits. The calculated diameters were systematically larger than our visual circle fits, most of which fall at distances exceeding our previous visual fits.

Areas and perimeters of the rim crest, floor, and ring or peak outlines were calculated by using the Tools for Graphics and Shapes extension for ArcMap (Jenness, 2011). Based on repeat measurements of the outlines of a sample of craters and basins, we estimated that the uncertainties in the area measurements are 5% for the rim crest and floor and ~15% for central peaks and peak rings. The larger estimated uncertainties for central peaks and peak rings are due to their often irregular outlines and complex topography and relationships with adjacent floor material, making precise measurements of these features difficult. Estimated uncertainties in perimeter measurements of the rim crest and floor are about 5%.

Volumes were calculated for crater interiors and central structures on the Moon only. Similar measurements on Mercury were not made due to the current lack of gridded topography of sufficient resolution to perform these measurements. To calculate the volumes of features, we first extracted all LOLA gridded elevation values falling within the outline of the feature. We then used Delaunay triangulation (e.g., Lee and Schachter, 1980) to approximate a continuous surface of the extracted pixels and calculated the integrated volume of all truncated prisms produced by the triangulation procedure. All of the nodes of the triangulated mesh were referenced to a plane fit by least squares to elevation points falling within a 1 km buffer surrounding the feature outline. Use of this reference plane accounts for sloping floors or uneven rim-crest elevations. As many central peaks and peak rings consist of multiple peak elements, we fit planes to each peak element for use in the volume calculation. It is possible that errors could result from the plane-fitting procedure when peaks are directly adjacent to each other or near other high-standing topography, which would lead to erroneously sloping planes and reduced volumes. Also, the volumes for the interior of craters and basins incorporated superposed craters, which increase the calculated interior volumes; this increase is likely due to the small size of using only Class I and II craters and basins. Based on our estimates of the uncertainties in feature area, as well as the uncertainties associated with calculation of the fitted reference planes, we estimate the total error in our volume calculations to be on the order of 15–20%. This is consistent with those uncertainties determined from similar measurements of volume by Baker et al. (2012).

Appendix C. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.pss.2013.07.003.

References


