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Abstract:

Observations of impact crater morphology can be used to gain insight into the geological history and evolution of a planet's surface. Image data from the Mariner 10 mission revealed the diversity of impact crater morphologies and degradational states on Mercury, leading to early studies that sought to establish a stratigraphic column for the planet, despite only acquiring image data for ~45% of the surface. In 2011, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft entered orbit around Mercury, returning a high-resolution global image dataset that enables a robust analysis of crater morphology and degradation to be completed for the entirety of Mercury's surface. In this study, we conducted a visual classification of crater degradation according to initial crater morphology, and assigned a degradation state to all craters on Mercury ≥ 40 km in diameter. In our scheme, Class 1 craters are those that are heavily degraded, and Class 5 craters are very fresh with bright ray systems. We discuss the processes involved in crater degradation and erasure, and the challenges associated with applying crater degradation to derive the timing of geological events. We found that, based on the global spatial density of craters in each class, there appears to be a dearth of Class 1 craters within the intercrater plains, likely due to several ancient basin-sized impacts effectively obliterating a considerable portion of craters ≥ 40 km in diameter in this region. The crater degradation database we present here will serve as a useful tool for future analyses of Mercury's geological evolution.

Highlights: 3-5 (max 85 characters w/ spaces per bullet point)

- Catalog of Mercurian craters ≥ 40 km in diameter classified by degradation state
- Morphological classification metrics described in detail for each class

49 • Lack of craters of the oldest morphological class near two large ancient basins

50 • LHB-induced resurfacing likely responsible for C1 and C2 crater distributions

51 **Keywords:** Mercury (planet), impact craters, degradation, crater morphology

52

1. Introduction and background

The use of crater degradation state as a tool for the relative age dating of geological units has been an important component in the correlation of geological time across multiple planetary bodies in the Solar System (McCauley et al., 1981). First developed for the Moon (Basilevsky, 1976; Pohn and Offield, 1970; Trask, 1967), a visual classification scheme of crater degradation aided in understanding the relationship between morphological characteristics associated with crater formation and modification over time. Many studies and maps of Mercury have incorporated crater degradation state as a means to understand spatial and temporal relationships among craters of various sizes and morphologies (Barnouin et al., 2012; Susorney et al., 2016), and to compare craters with other features such as hollows (Thomas et al., 2014) and optical characteristics of regolith (Braden and Robinson, 2013). However, the lack of a global database of uniformly classified craters on Mercury has necessitated that individual studies assign their own classifications based on interpretations made with varying methods and usually restricted to specific study areas or crater populations. The recent availability of global image data from the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft, however, allows for the development of a consistent classification scheme based on uniform degradation criteria that can be applied to all large impact craters and basins on the planet.

The global image dataset acquired by the Mercury Dual Imaging System (MDIS) (Hawkins et al., 2007), onboard the MESSENGER spacecraft, allows for the first systematic classification of craters across the entirety of Mercury's surface, and the reevaluation of those craters previously studied from Mariner 10 data. In this study, we standardized the degradation state classification of Mercurian craters by developing a systematic scheme based on uniform morphological criteria. We then classified all

Mercurian craters ≥ 40 kilometers in diameter with our system, thus establishing the first global dataset of crater degradation state on Mercury and providing a valuable tool for understanding the evolution of the planet's surface.

1.1. Previous classification schemes

One of the first extensive classification schemes for differentiating crater degradation state was developed by [Trask, \(1967\)](#) for the Moon. This system was based on interpretations of photographs from the Ranger VIII and Ranger IX spacecraft that divided lunar craters into four categories based on brightness and on the percent of crater interior covered in shadow. However, that study only evaluated craters from 10 to 100 meters in diameter, and focused on a small section of the lunar surface. A numeric system was later developed that used an arbitrary scale from 0.0 (oldest) to 7.0 (youngest) to assign relative ages to lunar craters ([Pohn and Offield, 1970](#)). It was hypothesized by these authors that the relative age of individual craters could be determined based on established morphological criteria (the morphological freshness of rim crest, walls, and rim deposits) and superposition relationships. As with the [Trask \(1967\)](#) system, the 1970 study was applied only to a small area, and these workers emphasized that absolute age determinations were not implied by their findings. They suggested that the erosion rate of lunar craters is “approximately exponential,” although they could not establish this view with certainty. Therefore, as [Pohn and Offield \(1970\)](#) noted, any effort to derive an absolute age from this method would yield erroneous results.

In addition to pure morphological observation, the importance of size dependence on rate of morphological change was discussed in these early papers. [Basilevsky \(1976\)](#) used a descriptive morphological 5-point classification scheme for 1–2 km-diameter craters to

enhance the study of the timing of crater evolution. That study specifically focused on craters situated on sloped terrain and the effect of slope processes on the evolution of such craters. Basilevsky (1976) found that, based on the influence of slope processes as well as superposition and size interactions for small lunar craters, the length of time a crater spends in each stage of morphological evolution increases exponentially with time. Additionally, small craters on steeper slopes tend to have shorter lifetimes than those of similar size situated on shallower slopes.

Lunar researchers therefore laid a foundation for crater classification based on degree of degradation that would later be applied to many cratered surfaces in the Solar System. The idea of crater degradation classification as a means for geological interpretation was shortly thereafter extrapolated to Mercury (McCauley et al., 1981; Wood et al., 1977) based on these previous lunar schemes, and featured five degradation classes. The first suggestion that crater classification on Mercury could be correlated with stratigraphy was made by

Figure 1. Marker impact craters and basins on Mercury denoting the onset of each geological time period. White box denotes location of Figure 3. a.) Caloris, b.) Tolstoj, c.) Mansur, d.) Kuiper.

Spudis (1985), who formulated a stratigraphic column for Mercury to assist in the process of geological mapping of the surface. This stratigraphic column was loosely based on the lunar time periods and was similarly represented by marker impact craters Tolstoj, Caloris, Mansur, and Kuiper (FIGURE 1)—although the Mercurian stratigraphy was not suggested to be directly correlated with that of the Moon. Nonetheless, under the Spudis (1985) system, the base of each class corresponds to a crater *and* an approximate time: Pre-Tolstojan, older than ~4.0 Gyr; Tolstojan, ~3.9–4.0 Gyr; Calorian, ~3.9 Gyr; Mansurian, ~3.0–3.5 Gyr; and Kuiperian, ~1 Gyr (with these ages based on a lunar impact flux). Shortly thereafter, this first effort to develop a chronostratigraphic system for Mercury was linked with crater degradation (Spudis and Guest, 1988), i.e., specific crater morphologies were assumed to denote the time period in which a given crater formed. Absolute ages were based on areal crater density measurements for the rims of the Tolstoj and Caloris impact basins. However, because of the relatively youthful appearances and small sizes of Mansur and Kuiper, the model ages of these two time periods were derived by comparison with age-dated lunar craters of similar morphology (Spudis, 1985), as areal crater density measurements likely would not provide a statistically meaningful result.

Although useful at the time for deciphering meaningful geological relationships on a regional scale, several problems persist with the approach of tying crater degradation state to absolute formation age. First, since erosion and regolith development rates have been shown to be substantially faster on Mercury (Braden and Robinson, 2013; Denevi and Robinson, 2008; Kreslavsky et al., 2014) than on the Moon, a direct comparison of crater morphology (and, subsequently, stratigraphic age) between the two bodies is inaccurate. Both inner Solar System dynamics of small body impactors (Marchi et al., 2013) and surface roughness measurements for Mercury (Kreslavsky et al., 2014) show that these

surface modification processes likely occur about three times faster there than on the Moon. Additionally, degradation rates are not linearly connected to bombardment rates and depend on other factors as supported by recent topographic diffusion modeling of small Mercurian craters (Fassett et al., 2017). The Fassett et al. (2017) study suggested that crater degradation occurs about twice as fast on Mercury than on the Moon. Therefore, Mercurian craters of similar morphology to lunar craters are likely ~2–3 times younger than their lunar counterparts.

Secondly, by linking crater degradation with a chronostratigraphic column, the Spudis and Guest (1988) study implied that all craters of a given degradation state, regardless of size or geological context, are similar in age. Yet, given the variety of geological processes that contribute to the morphological degradation of impact craters, as we discuss in Section 1.3, and the scales at which these processes operate, such a correlation is not straightforward and can lead to incorrect interpretations of relative age. Moreover, because degradation state cannot be uniquely correlated with stratigraphic age, it is difficult to quantify the error associated with such a comparison.

Despite these issues, crater degradation classification can effectively be applied to lunar or Mercurian craters to establish relative age relations with other craters and types of landforms. Further, a global assessment of large craters and basins, such as what we report here, is less sensitive to local variations in degradation rate than an assessment of either small craters only, or an examination of a single area that might be subject to local variations in the rate of degradation. As such, a global survey can provide insight into how other geological processes, including volcanic resurfacing (Klimczak et al., 2012), tectonic deformation (Banks et al., 2015), or sublimation of surficial volatiles (Thomas et al., 2014) fit into Mercury's geological history. Additionally, because craters of various sizes do not

degrade uniformly, a database of classified craters on Mercury may improve our understanding of regional variations in the rate and mechanisms of degradation over Mercury's surface.

1.2. Degradation using Mariner 10 data

The first images of Mercury's surface were captured by the Mariner 10 spacecraft in the 1970s. The spacecraft performed three flybys of the innermost planet, returning images of approximately 45% of the surface that supported numerous studies of Mercury's geological history and several USGS-published geological quadrangle maps (Schaber and McCauley, 1980; DeHonnet al., 1981; Guest and Greeley, 1983; McGill and King, 1983; Grolier and Boyce, 1984; Spudis and Prosser, 1984; Trask and Dzurisin, 1984; King and Scott, 1990; Strom et al., 1990). These early maps included geomorphological interpretations of landforms and albedo markings to establish a regional geological sequence of events, including applying the five-class crater degradation scheme developed for Mercury (McCauley et al., 1981). However, since these maps were published over the course of ten years, there exist inconsistencies between the naming and descriptions of units, as well as the application of a consistent crater degradation scheme. For example, in most quad maps, craters greater than 30 kilometers in diameter were mapped with a corresponding degradation class. However, authors of the Victoria (H-2) (McGill and

181 [King, 1983](#)) and Bach (H-15) ([Strom et al., 1990](#)) quadrangle maps classified craters
182 greater than 20 km and 15 km in diameter, respectively.

Figure 2. Dostoevskij crater (45°S, 183°E) has been subject to multiple interpretations of degradation class in previous studies. The basin has been embayed by either impact melt or volcanic flows and heavily bombarded by subsequent impacts. (top) Mariner 10 H-12 quadrangle photomosaic (PIA02237). (bottom) MESSENGER morphology basemap.

In some cases, units were inconsistently identified and named; in others, observations of crater degradation state did not lead to uniform interpretations and classifications. Additionally, there were differing interpretations ([Spudis and Guest, 1988](#)) as to whether a major distinguishing factor between the two youngest crater classes (Mansurian and Kuiperian) should be the presence (or absence) of crater rays—that is, radial patterns of freshly excavated

197 regolith with high albedo contrast to surrounding matured regolith ([Braden and Robinson,](#)
198 [2013; Denevi and Robinson, 2008](#)).

Even with a methodical application of the five-class degradation system (McCauley et al., 1981), each of the Mariner 10 quadrangle maps emphasized different characteristics of degradation state for classification purposes. These characteristics included the presence or absence of rays; whether a continuous ejecta deposit was still present; the preservation state of the crater rim, floor, and terraces; and the presence or absence of superposed craters. One of several examples of craters to which a degradation state was not consistently assigned is Dostoevskij crater (FIGURE 2). This 430-km-diameter crater (situated at 45°S, 183° E) was historically the type example of a Calorian-aged crater (termed "Class 3" by McCauley et al., 1981), but was subsequently suggested to be one of the oldest basins on the planet (i.e., "Class 1") (Spudis and Guest, 1988) due to its number of superposed craters.

1.3. The crater degradation process

Several studies have sought to quantify the crater degradation process (e.g., Fassett et al., 2017; Fassett and Thomson, 2014; Mahanti et al., 2014; Trang et al., 2015), and have provided insight into the manner by which empirical methods that assess crater depth/diameter (d/D) relationships and model time-dependent morphologic change can be used to characterize crater degradation states. It is extremely challenging, however, to incorporate external factors (e.g., the continuous process of impact gardening, "topographic diffusion," etc.) that modify the crater shape independently of the intrinsic processes that alter the crater form (Fassett and Thomson, 2014). Wood et al. (1977) provided a comprehensive review of these external processes that include, but are not limited to, volcanic resurfacing, tectonic deformation, seismic shaking, and proximity weathering. This latter mechanism, in particular, can cause craters to appear older than they

Figure 3. Set of three craters (38°N, 175°E) superposed on top of the Caloris interior plains (see box in Figure 1). Due to their stratigraphic position on top of the Caloris interior, they must be younger than the basin. However, due to the influence of superposed crater ejecta, the crater referenced by the white arrow displays characteristics of a C2, degraded crater. Though the stratigraphic relationship with Caloris can be used to more accurately determine this crater's age, there are many craters that exhibit these same characteristics that cannot be tied to a stratigraphic marker and, therefore, cannot be assumed to be of a specific age (e.g., craters that lie within Mercury's intercrater plains).

actually are due to modification by ejected material from a younger crater nearby (Figure 3), and was described by [Head \(1975\)](#) with respect to large lunar basin formation during “Period I” (which roughly corresponds to the Late Heavy Bombardment (LHB)). Proximity weathering would have had a greater role in crater modification during the LHB than later in the planet's history, due to the differing size distribution of impactors.

Recent studies ([Kalynn et al., 2013](#); [Susorney et al., 2016](#)) explored the influence of target properties on d/D relationships for lunar and Mercurian craters. [Kalynn et al., 2013](#) found that complex craters (i.e., those that are large enough to have features such as wall terraces and central peaks) located within the lunar mare tend to be shallower than those located within highlands regions, suggesting that a porous megaregolith comprising the lunar highlands may be more conducive to the formation of deep craters compared with layered mare deposits. [Susorney et al., 2016](#) sought to identify a similar target property influence on crater depths on Mercury. However, more craters were selected in the Mercury study for measurement in the smooth plains than in other areas because of the limitations

of available topographic data. No statistically significant variation in the depths of craters between the Mercurian smooth plains and cratered terrains was found, potentially due to the small sample size. It is therefore possible that a difference in depth *does* exist among craters emplaced on different terrains on Mercury, but has yet to be detected. Nevertheless, it is still unclear to what degree these target material differences also affect the morphology of emplaced ejecta. The lack of comprehensive studies on the effects of target properties in relation to the extent and morphology of ejecta deposits means that substantial uncertainty remains in interpreting a crater's degradation state and deriving an associated relative (or absolute model) age.

2. Global classification of crater degradation

2.1. Description of data

Datasets that were used in this study consisted of products produced by the MESSENGER science team prior to the final Planetary Data System (PDS) data release. These datasets include four monochrome global image mosaics at moderate, low, and high-angle (east)/high-angle (west) incidence (~166 meters per pixel (m/px)), three color global image mosaics (8-color, 3-color, and 5-color at ~332 m/px, ~332 m/px, and ~665 m/px, respectively), and an enhanced-color global image mosaic compiled with principal components analysis (and with a resolution of ~655 m/px) (Chabot et al., 2016). These mosaics, along with a global digital elevation model (DEM) derived from stereophotoclinometry (Gaskell et al., 2011), were used to determine and assign a degradation class for each analyzed crater. Individual images were also used as necessary (e.g., where the mosaics did not display ideal illumination conditions) to aid in the identification of key morphological features. For our analysis, we included all craters ≥ 40

km in diameter, taken from a global database of large craters on Mercury (Fassett et al., 2011).

2.2. Classification metrics

Our classification scheme, where Class 1 (C1) is “very degraded” and Class 5 (C5) is “fresh,” is an updated approach that still maintains the temporal sequence of crater morphology associated with the chronostratigraphic column established earlier (McCauley et al., 1981). From a comprehensive evaluation of previous class descriptions for Mercurian craters (McCauley et al., 1981; Spudis and Guest, 1988), and a review of all crater descriptions on the Mariner 10 quadrangle maps, we identified the most useful diagnostic morphological features for each class. These features include the presence or absence of crater rays, the condition of the crater rim, evidence of wall terracing, the presence of ejecta facies, the presence and type of central peak features, and the presence and abundance of interior smooth plains. Table 1 was then compiled to distinguish the primary morphological characteristics of crater shape by degradation class. Whereas previous descriptions of the crater classification scheme highlighted only one or two features (e.g., presence of crater rays, evidence for wall terracing, etc.) for each class (often inconsistently), the system we describe here addresses *all* features for *every* class. Previously classified craters were also reviewed to establish a consistent set of interpretations.

<i>Crater Features</i>	<i>Class 5</i>	<i>Class 4</i>	<i>Class 3</i>	<i>Class 2</i>	<i>Class 1</i>
Rays	Bright rays extending at least several radii from crater rim	No rays	No rays	No rays	No rays
Rim	Fresh, crisp rims	Crisp rim crests	Generally continuous, rounded rims with a degraded appearance	Continuous to discontinuous rims with a rounded, degraded appearance	Discontinuous, degraded rims rising only slightly above surrounding terrain

<i>Terraces*</i>	Crisp wall terraces	Slightly degraded wall terraces	Generally slumped wall terraces	No wall terraces, remnant terraces in larger craters	No terraces or wall structure
<i>Floor-wall Boundary*</i>	Distinct contact between wall and floor	Distinct contact between wall and floor	Floor-wall boundary somewhat indistinct but still separable	Floor-wall boundary generally indistinct unless clearly embayed	No floor-wall boundary
<i>Floor*</i>	Fully or partially covered with plains materials and/or containing hummocky deposits	Fully or partially covered with plains materials and/or containing modified hummocky deposits	Fully or partially covered, or partially filled with plains, and/or containing modified hummocky deposits	Filled or partially filled with plains material; no hummocky deposits visible	Filled with plains material; no hummocky deposits visible
<i>Ejecta</i>	Radially textured continuous ejecta blanket	Radially textured continuous ejecta blanket	Continuous to discontinuous ejecta blanket	Ejecta blanket discontinuous to completely absent; largest craters may still show evidence of radial texture in remaining ejecta	No ejecta deposits
<i>Secondary Craters</i>	Well-defined continuous field of relatively crisp secondary craters	Well defined field of secondary craters	Some chains/clusters of secondary craters but not a continuous field	No secondary craters	No secondary craters
<i>Central Peaks*</i>	Crisp central peak/ring	Crisp central peak/ring	Most have subdued central peaks/rings	Rare central peaks/rings, those present are heavily degraded	No central peaks/rings
<i>Superposed Craters</i>	None	Low density	Low to moderate density	Moderate density	Moderate to high density

Table 1. Aspects of crater morphology used to define each class of degradation. Feature descriptions were derived from previous studies of lunar and Mercurian impact crater morphology (McCauley et al., 1981; Spudis and Guest, 1988) and the Mariner 10 geological quadrangle maps. *Descriptions only valid for crater morphologies that have these features. †Note that the approximate number of superposed craters here is based on visual interpretation of the ~166m/p monochrome image basemap.

280 We further developed a second matrix (Figure 4) to display type examples of crater
281 degradation over all crater sizes and morphologies (Baker et al., 2011; Pike, 1988). The
282 consideration of initial crater type was a key component to our analysis, as crater size was
283 not incorporated in previous classification systems even though it has been recognized that,
284 in general, crater size contributes to the overall appearance of crater features at varying
285 degrees of degradation (McCauley et al., 1981; Pohn and Offield, 1970). Of course, not all
286 sizes of craters within one class are inherently of the same age. Nonetheless, Figure 4
287 characterizes the morphological criteria we used to define degradation states as applied
288 globally to craters of various sizes.

289 Because smaller craters degrade faster than their larger counterparts (Basilevsky, 1976;
 290 Wood et al., 1977), we chose a crater diameter threshold of 40 km, below which craters
 291 were not classified. Moreover, at smaller diameters, our ability to discern ejecta deposits
 292 and other fine-scale features of even the freshest craters (an important component of our
 293 analysis) was reduced because of image resolution limitations. In addition to Classes 1

Figure 4. Crater degradation broken down by initial crater morphology (Baker et al., 2011; Pike, 1988). Different crater features will be more prominent depending on crater diameter (e.g., plains units are more pronounced in basins than in simple craters). Selected craters are centered in each image with diameters approximately one third the width of the image. No C1 Ringed Peak-cluster basins or Protobasins were identified. A characteristic of C1 craters is a lack of inner crater features (i.e., central peak/peak ring). Due to the overlapping of rim diameters between Ringed Peak-cluster basins and Peak-ring basins (75–172 km in diameter), C1 craters cannot be separated by type based on image data alone.

through 5, we also included a “ghost” class based on previous descriptions of ghost craters (craters entirely buried by subsequent lava flows) (Strom et al., 1975). These remnant craters are commonly seen expressed as sets of circular wrinkle ridges within Borealis Planitia (the vast expanse of flood lavas also known as the northern smooth plains (NSP)) (e.g., Klimczak et al., 2012).

2.3. Spatial and temporal distribution of degraded craters on Mercury

Although we discuss above the problems associated with tying crater degradation directly to crater model age, we can still obtain useful information from observing the global distributions of craters of different degradation states. Figure 5 shows the planet-wide distribution of each degradation class. The full dataset of classified craters is provided in the Supplementary Materials. There is an increase in the number of craters in each

Figure 5. Global distribution of craters in each degradational class. a) Class 1, “degraded,” b). Class 2, c) Class 3, d) Class 4, e) Class 5, “fresh.” Grey units are smooth plains as mapped by Denevi et al. (2013).

sequentially more degraded morphological class, which may in part reflect the heuristic nature of this classification scheme. However, it may be that this observation is rooted in

N(D)	Class 5	Class 4	Class 3	Class 2	Class 1	
N(40-100)	20	174	441	1077	799	nature. Due to the
N(40-200)	22	215	515	1271	987	relatively constant impact
N(40)	22	219	521	1300	1048	rate over the last ~3.3 Ga
N(100)	2	45	80	223	249	(Le Feuvre and
N(200)	0	4	6	29	61	
N(400)	0	0	2	4	131	

Table 2. Number, $N(D)$, of craters $\geq D$ diameter (km) in each class on Mercury. Note the substantial decrease in proportion of mid-sized (40-200 km) Class 1 craters relative to Class 2 compared to the increase in larger craters (>200 km) from Class 2 to Class 1. (Le Feuvre and Wieczorek, 2011), the active degradation rate, or

the instantaneous effects of each impact, has remained essentially constant. In spite of this constant degradation rate, since each

successive impact has the capacity to contribute to the degradation of a subset of previously emplaced impact craters, the crater degradation rate *slows* for the aggregate population through time, with smaller craters experiencing this additive effect to a greater degree. Additionally, the size and number of impactors has decreased since the LHB, therefore

increasing this effect when considering Mercury's crater population in total.

Previous work has put the timing of the formation of the Tolstoj basin (Class 2) at 3.7 Ga (Le Feuvre and Wieczorek, 2011). Since craters that formed prior to the Tolstojan time period would therefore have formed prior to and through the end of the LHB (~3.55–3.8 Ga), smaller craters created during this time would have been more effectively obliterated by large basins and widespread impact-induced volcanism (Marchi et al., 2013) than similarly sized craters emplaced after the end of the LHB. Further evidence for this LHB-induced increase in degradation is the noticeable lack of large impact basins that we classify as C2 ($N(200) = 29$), compared with the greater number of large basins and lack of mid-

size (40–200 km diameter) craters that have been classified as C1. This is seen in both the global class distributions (Figure 5) and the crater class size–frequency distributions (SFDs) (Figure 6). Raw $N(D)$ values for each class are also shown in Table 2.

Note that in Figure 6 there is a large gap in cumulative crater frequency between the C4 and C5 crater distributions compared with the other class distributions. Banks et al. (2017) classified a subset of fresh craters ≥ 20 km in diameter in the low- to mid-latitudes as Mansurian (C4) and Kuiperian (C5) in a study that revised the approximate ages for the base of each stratigraphic period. The distributions of craters classified in the Banks et al.

(2017) study indicate that the rate of degradation from C5 to C4 of craters above 20 km in diameter does not change as crater size increases, as these authors noted that such a phenomenon would result in a break in slope of the SFD. Though we do see slight differences in the slopes of the two youngest classes highlighted in the R -plot (Figure 6b,d), our results show slope variations for craters ≥ 40 km in diameter for those same classes comparable to the Banks et al. (2017) study. Since the only differentiating feature between these two classes is the presence of rays, then, assuming a standard chronology model (Le Feuvre and Wieczorek, 2011), the larger gap between the distributions of C4 and C5 craters compared with other classes is evidence that the optical maturation of fresh crater ejecta occurs at a faster rate than other indicators of crater age. This finding demonstrates that the transition from C5 to C4 takes place relatively soon after crater formation. Since rays are a surficial deposit, characterized by grain size (centimeter- to decimeter-sized clasts (Neish et al., 2013)) and lacking a topographic expression, it follows that rays should degrade at a similar rate regardless of crater size. However, further investigation into the composition and nature of crater rays is necessary to confirm whether this is indeed the case.

Figure 6. Cumulative size-frequency distributions (left) and R-plot (right) for each degradation class. The upper two plots (a,b) show the *raw* distributions for each individual class (open circles). The bottom two plots (c,d) show the traditional *additive* distributions where each, more degraded class distribution contains the craters in that class and every less degraded class (closed circles). The total area used to calculate the cumulative crater frequency is $5.55 \times 10^7 \text{ km}^2$ for C1 and C2 (without the largest smooth plains regions), and $7.48 \times 10^7 \text{ km}^2$ for C3, C4, and C5 (the entirety of Mercury's surface area). Note that the purple closed-circle distribution in (a) and (b) is identical to the Class 1 distribution in (c) and (d) respectively. All plots utilize standard root-2 binning (Arvidson et al., 1979).

354 Conversely, as crater size increases, the cumulative number and magnitude of events that

degrade craters after the depletion of ray systems (e.g., local seismic shaking, proximity weathering, and superposed impact events) is expected to also increase in order to completely erase the topographic signature of the crater.

Figure 7 shows crater spatial density of each degradation class. Spatial density of craters in each class was calculated using the ArcGIS 10.6 geodesic kernel density tool based on an adaptive kernel. The Standard Distance, or the measure of the dispersion of the datapoints, is first calculated as:

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n} + \frac{\sum_{i=1}^n (y_i - \bar{Y})^2}{n}} \quad (1)$$

where x_i and y_i are the coordinates for feature i , $\{\bar{X}, \bar{Y}\}$ represents the Mean Center for the features, and n is the number of data points (craters in this instance). The search radius (bandwidth) was then calculated as:

$$SearchRadius = 0.9 * \min \left(SD, \sqrt{\frac{1}{\ln(2)}} * D_m \right) * n^{-0.2} \quad (2)$$

where D_m is the median distance, taking into account the curvature of the input spheroid.

Spatial density is then calculated using the following 2-dimensional quartic kernel function

(Silverman, 1998):

$$K_2(x) = \begin{cases} 3\pi^{-1}(1 - x^T x)^2, & \text{if } x^T x < 1 \\ 0, & \text{otherwise} \end{cases} \quad (3)$$

Several unconfirmed basins (specifically those labeled “B30” and “B56”) that were identified by Fassett et al. (2012) are situated in a region with a relatively lower spatial density of mid-size craters classified as C1 (Denevi et al., 2016). The largest continuous

gaps in the spatial density of C1 craters reside proximal to the annular deposits of the B30 and B56 basins. The low spatial density of craters in this region supports the existence of these putative basins. Similar gaps are present in maps of the spatial density of small craters in the annular deposits of the Caloris and Rembrandt basins, which would also reduce the number of mid-size craters that could be identified as being older than these basins.

Additionally, it is possible that the similar SFDs of mid-size C1 and C2 craters reflect instances where crater degradation state was misclassified. Specifically, at smaller crater diameters, our ability to robustly and reliably differentiate between the two classes on a visual basis alone is increasingly challenged. Although the resolution of the image mosaics we employed are more than sufficient to investigate craters down to 40 km in diameter, the morphological indicators we use for degradation classification are fewer in number for the smallest craters we classified. Additionally, it should be noted that the error bars associated with the SFDs presented in Figure 6 represent the traditional error for SFDs (i.e., $\pm\sqrt{N}$, with N the number of craters counted), and do not include error associated with classification. Further, as discussed in Section 2.2, due to the variations in degradation rate as a function of crater size, the interpretation of class distributions in Figure 6 is not straightforward. It is likely that smaller diameter craters are younger than large diameter craters of the same class. Therefore, though they are subsets of the overall crater distribution on Mercury, the class distributions should not be interpreted as production functions for each time period of Mercury's history.

3. Discussion and conclusions

With every prior study that has evaluated crater morphology on a variety of Solar System bodies, the method used to classify craters based on degradation state has had a

401 slightly different interpretation. Many previous examples of the use of degradation classes
402 compared craters of vastly different sizes, and so were unable to address the differences in
403 formation mechanisms of craters at different diameters (that lead to differences in post-
404 formation morphology) or the rate of the degradation process with respect to crater size.
405 Further, it is known that smaller craters lack more complex interior features (e.g., central
406 peaks, wall terraces) (Pike, 1988) and therefore should not be directly compared with
407 larger, more complex craters and basins. Though the entire range and magnitude of crater
408 degradation mechanisms were not addressed within the limits of this study, it is important
409 to highlight these inconsistencies.

410 The degradation classification scheme cannot be applied to all crater diameters equally
411 with the expectation that the ages of said craters can be fully correlated with the established
412 Mercurian stratigraphic column. For example, the degradation state of Dostoevskij crater
413 (Section 1.2; Figure 2) is C2 according to our classification scheme, purely on the basis of
414 morphology due to similarities to other C2 craters of its size (i.e., lack of continuous ejecta
415 deposits but still somewhat defined rim and radial texture of ejecta). However, updated
416 crater counts using recent MESSENGER images is warranted to confirm superposed crater
417 areal densities on Dostoevskij's rim deposits to determine if the basin falls within the
418 Tolstojan time period.

Figure 7. Spatial density map of each crater class in magnitude per km using a kernel function. a) Class 1 crater spatial density. Note the low density of Class 1 craters proximal to the approximate continuous ejecta deposits (i.e., extending to one crater radius from the rim (dashed white)) of B30 and B56 basins (dashed red). The estimated extent of the continuous ejecta deposits of several additional large basins is also displayed (dashed white). b) Class 2 crater spatial density. c) Class 3 crater spatial density. d) Class 4 crater spatial density. Since so few Class 5 craters were identified ≥ 40 km, a spatial density map of craters of this class is not included. Note the relatively uniform distribution within the intercrater plains of all other crater classes besides Class 1, the oldest and most degraded class. Grey units are smooth plains as mapped by [Denevi et al. \(2013\)](#).

419 Even within the constraints applied to those images included in the final MESSENGER

global monochrome image mosaic—low emission and moderate incidence angles near 68° (Chabot et al., 2016) (see Section 2.1)—that we used for our visual assigning of degradation states, the viewing geometries of those component images nonetheless varies considerably across Mercury’s surface. As a result, the observed textures and shapes of ejecta deposits are not always consistent across all craters of a given size that we interpret to be of a similar degradation state. For instance, some “fresher” (C4 and C5) craters feature ejecta deposits that display a clear radial texture, whereas others show seemingly smoother continuous deposits, even when all such craters possess other morphologically crisp and undisturbed features (such as rays) that indicate their young age. Although this variation in the observed morphology of fresh craters could be an artifact of inconsistent illumination conditions, it is possible that these variations in observed texture are due in part to real geological differences in ejecta between craters of similar sizes and ages. Investigating these differences is beyond the scope of this study, but is a natural next step in understanding impact physics, crater morphology, and target material properties on Mercury. These methods will be more easily applied with improved image, topographic, and compositional datasets for Mercury with global coverage to be acquired by the BepiColombo spacecraft within the next decade.

Previous investigations of Mercury’s cratering and arguably *geological* history have been limited by the lack of a consistent scheme for the global classification of crater degradation. The database we present here, with morphological metrics applied consistently across the planet, is a useful tool for understanding the relative relationships of geological landforms. Importantly, by considering the global population of craters on Mercury with these metrics, we were able to classify these landforms with a consistency not previously possible.

444

445 *3.1. Craters of the oldest morphological classes*

446 The differences between C2 and C3 craters are mostly defined by the transition of
447 interior crater characteristics, such as the destruction of wall terraces and the preservation
448 state of the floor–wall boundary. Additionally, by definition, older craters have had a
449 longer time to accumulate superposed craters and deposits from other geological events
450 than younger craters. As a result, the vast majority of the oldest craters on Mercury retain
451 little to no evidence of their original ejecta deposits, and indeed are identified by the lack
452 of preservation of this feature. Further, craters situated within the intercrater plains have
453 the greatest amount of uncertainty in terms of their degradation class due to the high spatial
454 density of impact-related features and lack of established stratigraphic markers in this
455 terrain type. Craters and basins that formed within the bounds of the present-day smooth
456 plains prior to the emplacement of those plains present an unresolved challenge to the
457 morphological classification system. Though these impact structures have been clearly
458 embayed by smooth plains deposits and likely would display C1 or C2 morphology had
459 the smooth plains not been emplaced, it is very difficult to determine which of these two
460 classes each should be categorized as. As stated in Section 2.2, rather than assigning a class
461 to these craters, they were identified as ghost craters in our study.

462 Both the crater SFDs (Figure 6) and the areal crater density plots (Figure 7) indicate a
463 dearth of craters 40–150 km in diameter of the most degraded morphological class, termed
464 here as C1. Several mechanisms could possibly explain this observation, such as the
465 potential for smaller craters having a higher probability of transitioning from a C2
466 morphology to being completely obliterated, or the shift in impactor populations from early
467 in the Solar System’s history to post-LHB conditions (proposed as Populations 1 and 2 by

[Strom et al., 2005](#)). The presence of two substantial, ancient basins and their ejecta deposits in the region of greatest paucity of C1 craters (B30 and B56) suggests that the formation of these two basins effectively obliterated many C1 craters when they formed. This finding is consistent with other geological observations that indicate the early portion of Mercurian history is no longer preserved on the planet surface, likely due to both impact bombardment and widespread volcanism (e.g., [Marchi et al., 2013](#)).

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References:

- Arvidson, R.E., Boyce, J.M., Chapman, C.R., Cintala, M.J., Fulchignoni, M., Moore, H., Soderblom, L.A., Neukum, G., Schultz, P.H., Strom, R.G., 1979. Standard techniques for presentation and analysis of crater size-frequency data. *Icarus* 474, 467–474. [https://doi.org/10.1016/0019-1035\(79\)90009-5](https://doi.org/10.1016/0019-1035(79)90009-5)
- Baker, D.M.H., Head, J.W., Schon, S.C., Ernst, C.M., Prockter, L.M., Murchie, S.L., Denevi, B.W., Solomon, S.C., Strom, R.G., 2011. The transition from complex crater to peak-ring basin on Mercury: New observations from MESSENGER flyby data and constraints on basin formation models. *Planet. Space Sci.* 59, 1932–1948. <https://doi.org/10.1016/j.pss.2011.05.010>
- Banks, M.E., Xiao, Z., Braden, S.E., Barlow, N.G., Chapman, C.R., Fassett, C.I., Marchi, S.S., 2017. Revised constraints on absolute age limits for Mercury’s Kuiperian and Mansurian stratigraphic systems. *J. Geophys. Res. Planets* 122, 1010–1020. <https://doi.org/10.1002/2016JE005254>
- Banks, M.E., Xiao, Z., Watters, T.R., Strom, R.G., Braden, S.E., Chapman, C.R., Solomon, S.C., Klimczak, C., Byrne, P.K., 2015. Duration of activity on lobate-scarp thrust faults on Mercury. *J. Geophys. Res. E Planets* 120, 1751–1762. <https://doi.org/10.1002/2015JE004828>
- Barnouin, O.S., Zuber, M.T., Smith, D.E., Neumann, G.A., Herrick, R.R., Chappelow, J.E., Murchie, S.L., Prockter, L.M., 2012. The morphology of craters on Mercury: Results from MESSENGER flybys. *Icarus* 219, 414–427. <https://doi.org/10.1016/j.icarus.2012.02.029>
- Basilevsky, A.T., 1976. On the evolution rate of small lunar craters. *Lunar Planet. Sci. Conf.* 7, 1005–1020.
- Braden, S.E., Robinson, M.S., 2013. Relative rates of optical maturation of regolith on Mercury and the Moon. *J. Geophys. Res. Planets* 118, 1–12. <https://doi.org/10.1002/jgre.20143>
- Chabot, N.L., Denevi, B.W., Murchie, S.L., Hash, C.D., Ernst, C.M., Blewett, D.T., Nair, H., Laslo, N.R., Solomon, S.C., 2016. Mapping Mercury: Global Imaging Strategy and Products from the MESSENGER Mission. *Lunar Planet. Sci. Conf. XLVII* 46–47.
- DeHon, R.A., Scott, D.H., Underwood, J.R. (1981) Geologic map of the Kuiper (H-6) quadrangle of Mercury. *United States Geological Survey, Miscellaneous Investigations Series, Map I-1233*.
- Denevi, B.W., Ernst, C.M., Meyer, H.M., Robinson, M.S., Murchie, S.L., Whitten, J.L., Head, J.W., Watters, T.R., Solomon, S.C., Ostrach, L.R., Chapman, C.R., Byrne, P.K., Klimczak, C., Peplowski, P.N., 2013. The distribution and origin of smooth plains on Mercury. *J. Geophys. Res. E Planets* 118,

891–907. <https://doi.org/10.1002/jgre.20075>

Denevi, B.W., Ernst, C.M., Prockter, L.M., Robinson, M.S., Spudis, P.D., Klima, R.L., Murchie, S.L., Solomon, S.C., Whitten, J.L., Povilaitis, R.Z., Kinczyk, M.J., 2016. The origin of Mercury's oldest surfaces and the nature of intercrater plains resurfacing. 47th Lunar Planet. Sci. Conf.

Denevi, B.W., Robinson, M.S., 2008. Mercury's albedo from Mariner 10: Implications for the presence of ferrous iron. *Icarus* 197, 239–246. <https://doi.org/10.1016/j.icarus.2008.04.021>

Fassett, C.I., Crowley, M.C., Leight, C., Dyar, M.D., Minton, D.A., Hirabayashi, M., Thomson, B.J., Watters, W.A., 2017. Evidence for rapid topographic evolution and crater degradation on Mercury from simple crater morphometry. *Geophys. Res. Lett.* 44, 5326–5335. <https://doi.org/10.1002/2017GL073769>

Fassett, C.I., Head, J.W., Baker, D.M.H., Zuber, M.T., Smith, D.E., Neumann, G.A., Solomon, S.C., Klimczak, C., Strom, R.G., Chapman, C.R., Prockter, L.M., Phillips, R.J., Oberst, J., Preusker, F., 2012. Large impact basins on Mercury: Global distribution, characteristics, and modification history from MESSENGER orbital data. *J. Geophys. Res. E Planets* 117, 1–15. <https://doi.org/10.1029/2012JE004154>

Fassett, C.I., Kadish, S.J., Head, J.W., Solomon, S.C., Strom, R.G., 2011. The global population of large craters on Mercury and comparison with the Moon. *Geophys. Res. Lett.* 38, 1–6. <https://doi.org/10.1029/2011GL047294>

Fassett, C.I., Thomson, B.J., 2014. Crater degradation on the lunar maria: Topographic diffusion and the rate of erosion on the Moon. *J. Geophys. Res. Planets* 119, 2255–2271. <https://doi.org/10.1002/2014JE004698>.Received

Gaskell, R.W., Palmer, E.E., Mastrodemos, N., Barnouin-Jha, O.S., Jorda, L., Taylor, A.H., 2011. Mercury and Vesta - Preliminary shape and topography, in: P41A-1576. San Francisco.

Grolier, M. J., & Boyce, J. M. (1984). Geologic map of the Borealis region (H-1) of Mercury. *United States Geological Survey, Miscellaneous Investigations Series, Map I-1660*.

Guest, J. E., & Greeley, R. (1983). Geologic map of the Shakespeare (H-3) quadrangle of Mercury. *United States Geological Survey, Miscellaneous Investigations Series, Map I-1408*.

538 Hawkins, S.E., Boldt, J.D., Darlington, E.H., Espiritu, R., Gold, R.E., Gotwols, B., Grey, M.P., Hash, C.D.,
 539 Hayes, J.R., Jaskulek, S.E., Kardian, C.J., Keller, M.R., Malaret, E.R., Murchie, S.L., Murphy, P.K.,
 540 Peacock, K., Prockter, L.M., Reiter, R.A., Robinson, M.S., Schaefer, E.D., Shelton, R.G., Sterner,
 541 R.E., Taylor, H.W., Watters, T.R., Williams, B.D., 2007. The mercury dual imaging system on the
 542 MESSENGER spacecraft. *Space Sci. Rev.* 131, 247–338. <https://doi.org/10.1007/s11214-007-9266-3>
 543 Head, J.W., 1975. Process of Lunar Crater Degradation: Changes in Style with Geologic Time. *Moon* 12,
 544 299–329. <https://doi.org/10.1007/bf02629699>
 545 Kalynn, J., Johnson, C.L., Osinski, G.R., Barnouin, O.S., 2013. Topographic characterization of lunar
 546 complex craters. *Geophys. Res. Lett.* 40, 38–42. <https://doi.org/10.1029/2012GL053608>
 547 King, J. S., & Scott, D. H. (1990). Geologic map of the Beethoven (H-7) quadrangle of Mercury. *United*
 548 *States Geological Survey, Miscellaneous Investigations Series, Map I-2048.*
 549 Klimczak, C., Watters, T.R., Ernst, C.M., Freed, A.M., Byrne, P.K., Solomon, S.C., Blair, D.M., Head,
 550 J.W., 2012. Deformation associated with ghost craters and basins in volcanic smooth plains on
 551 Mercury: Strain analysis and implications for plains evolution. *J. Geophys. Res. E Planets.*
 552 <https://doi.org/10.1029/2012JE004100>
 553 Kreslavsky, M.A., Head, J.W., Neumann, G.A., Zuber, M.T., Smith, D.E., 2014. Kilometer-scale
 554 topographic roughness of Mercury: Correlation with geologic features and units. *Geophys. Res. Lett.*
 555 41, 8245–8251. <https://doi.org/10.1002/2014GL062162>
 556 Le Feuvre, M., Wieczorek, M.A., 2011. Nonuniform cratering of the Moon and a revised crater chronology
 557 of the inner Solar System. *Icarus* 214, 1–20. <https://doi.org/10.1016/j.icarus.2011.03.010>
 558 Mahanti, P., Robinson, M.S., Humm, D.C., Stopar, J.D., 2014. A standardized approach for quantitative
 559 characterization of impact crater topography. *Icarus* 241, 114–129.
 560 <https://doi.org/10.1016/j.icarus.2014.06.023>
 561 Marchi, S.S., Chapman, C.R., Fassett, C.I., Head, J.W., Bottke, W.F., Strom, R.G., 2013. Global
 562 resurfacing of Mercury 4.0–4.1 billion years ago by heavy bombardment and volcanism. *Nature* 499,
 563 59–61. <https://doi.org/10.1038/nature12280>
 564 McCauley, J.F., Guest, J.E., Schaber, G.G., Trask, N.J., Greeley, R., 1981. Stratigraphy of the Caloris
 565 basin, Mercury. *Icarus* 47, 184–202. [https://doi.org/10.1016/0019-1035\(81\)90166-4](https://doi.org/10.1016/0019-1035(81)90166-4)

566 McGill, G. E., & King, E. A. (1983). Geologic map of the Victoria (H-2) quadrangle of Mercury. *United*
 567 *States Geological Survey, Miscellaneous Investigations Series, Map I-1409.*
 568 Michael, G.G., Neukum, G., 2010. Planetary surface dating from crater size-frequency distribution
 569 measurements: Partial resurfacing events and statistical age uncertainty. *Earth Planet. Sci. Lett.* 294,
 570 223–229. <https://doi.org/10.1016/j.epsl.2009.12.041>
 571 Neish, C.D., Blewett, D.T., Harmon, J.K., Coman, E.I., Cahill, J.T.S., Ernst, C.M., 2013. A comparison of
 572 rayed craters on the moon and mercury. *J. Geophys. Res. E Planets* 118, 2247–2261.
 573 <https://doi.org/10.1002/jgre.20166>
 574 Pike, R.J., 1988. Geomorphology of impact craters on Mercury, in: *Mercury*. pp. 165–273.
 575 Pohn, H.A., Offield, T.W., 1970. Lunar crater morphology and relative-age determination of Lunar
 576 geologic units: Part 1. classification. *Geol. Surv. Res.* 700–C.
 577 Schaber, G. G., & McCauley, J. F. (1980). Geologic map of the Tolstoj (H-8) quadrangle of
 578 Mercury. *United States Geological Survey, Miscellaneous Investigations Series, Map I-1199.*
 579 Silverman, B.W., 1998. *Density Estimation for Statistics and Data Analysis*. New York: Routledge.
 580 Spudis, P. D., & Prosser, J. G. (1984). Geologic map of the Michaelangelo (H-12) quadrangle of
 581 Mercury. *United States Geological Survey, Miscellaneous Investigations Series, Map I-1659.*
 582 Spudis, P.D., 1985. A Mercurian chronostratigraphic classification. *Reports Planet. Geol. Geophys.*
 583 *Program*; 1984. 87563, 595–597.
 584 Spudis, P.D., Guest, J.E., 1988. Stratigraphy and geologic history of Mercury, in: *Mercury*. pp. 118–164.
 585 Strom, R.G., Malhotra, R., Ito, T., Yoshida, F., Kring, D.A., 2005. The Origin of Planetary Impactors in the
 586 Inner Solar System. *Science* (80-.). 309, 1847–1850. <https://doi.org/10.1126/science.1113544>
 587 Strom, R.G., Trask, N.J., Guest, J.E., 1975. Tectonism and volcanism on Mercury. *J. Geophys. Res.* 80,
 588 2478. <https://doi.org/10.1029/JB080i017p02478>
 589 Strom, R. G., Malin, M. C., & Leake, M. A. (1990) Geologic map of the Bach (H-15) region of Mercury.
 590 *United States Geological Survey, Miscellaneous Investigations Series, Map I-2015.*
 591 Susorney, H.C.M., Barnouin, O.S., Ernst, C.M., Johnson, C.L., 2016. Morphometry of impact craters on
 592 Mercury from MESSENGER altimetry and imaging. *Icarus* 271, 180–193.
 593 <https://doi.org/10.1016/j.icarus.2016.01.022>

594 Thomas, R.J., Rothery, D. a., Conway, S.J., Anand, M., 2014. Hollows on Mercury: Materials and
595 mechanisms involved in their formation. *Icarus* 229, 221–235.
596 <https://doi.org/10.1016/j.icarus.2013.11.018>
597 Trang, D., Gillis-davis, J.J., Boyce, J.M., 2015. Absolute model ages from lunar crater morphology. *J.*
598 *Geophys. Res. Planets.* <https://doi.org/10.1002/2014JE004639>.Received
599 Trask, N.J., 1967. Distribution of Lunar craters according to morphology from Ranger VIII and IX
600 photographs. *Icarus* 6, 270–276. [https://doi.org/10.1016/0019-1035\(67\)90023-1](https://doi.org/10.1016/0019-1035(67)90023-1)
601 Trask, N. J., & Dzurisin, D. (1984). Geologic map of the Discovery (H-11) quadrangle of Mercury. *United*
602 *States Geological Survey, Miscellaneous Investigations Series, Map I-1658.*
603 Wood, C.A., Head, J.W., Cintala, M.J., 1977. Crater degradation on Mercury and the moon - Clues to
604 surface evolution 3503–3520.