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Lunar impact basins: Stratigraphy, sequence and ages from superposed impact crater populations measured from Lunar Orbiter Laser Altimeter (LOLA) data

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[1]   Impact basin formation is a fundamental process in the evolution of the Moon and records the history of impactors in the early solar system. In order to assess the stratigraphy, sequence, and ages of impact basins and the impactor population as a function of time, we have used topography from the Lunar Orbiter Laser Altimeter (LOLA) on the Lunar Reconnaissance Orbiter (LRO) to measure the superposed impact crater size-frequency distributions for 30 lunar basins ($D \geq 300$ km). These data generally support the widely used Wilhelms sequence of lunar basins, although we find significantly higher densities of superposed craters on many lunar basins than derived by Wilhelms (50% higher densities). Our data also provide new insight into the timing of the transition between distinct crater populations characteristic of ancient and young lunar terrains. The transition from a lunar impact flux dominated by Population 1 to Population 2 occurred before the mid-Nectarian. This is before the end of the period of rapid cratering, and potentially before the end of the hypothesized Late Heavy Bombardment. LOLA-derived crater densities also suggest that many Pre-Nectarian basins, such as South Pole-Aitken, have been cratered to saturation equilibrium. Finally, both crater counts and stratigraphic observations based on LOLA data are applicable to specific basin stratigraphic problems of interest; for example, using these data, we suggest that Serenitatis is older than Nectaris, and Humboldtianum is younger than Crisium. Sample return missions to specific basins can anchor these measurements to a Pre-Imbrian absolute chronology.

1.   Introduction

[2]   The formation of impact basins (craters ≥300 km in diameter) played a critical role in lunar evolution, and the timing and sequence of these basins is significant for understanding the stratigraphy and geology of the lunar surface [*Shoemaker and Hackman*, 1962; *Wilhelms and McCauley*, 1971; *Mutch*, 1972; *Scott et al.*, 1977; *Wilhelms and El-Baz*, 1977; *Lucchita*, 1978; *Stuart-Alexander*, 1978; *Wilhelms et al.*, 1979; *Wilhelms*, 1987]. More broadly, the impact basin record on the Moon is the best preserved in the inner solar system, so it has implications for the bombardment history of all of the terrestrial planets [e.g., *Neukum et al.*, 2001]. From this record, it has been suggested that changes in the population of impact craters occurred over time [*Whitaker and Strom*, 1976; *Wilhelms et al.*, 1978; *Strom*, 1987; *Strom et al.*, 2005; *Head et al.*, 2010]. It has also been recognized for decades that the flux of impactors has varied over time, with much higher impact rates prior to ~3.5 Gyr ago than today, although the nature of the variation during the period of 3.5–4.5 Gyr remains imperfectly known. It has been hypothesized, for example, that there was a period of Late Heavy Bombardment in the inner solar system [*Tera et al.*, 1974] perhaps caused by migration of the outer planets [e.g., *Gomes et al.*, 2005]. However, the impactor population responsible for the postulated cataclysm, its detailed timing, and the existence of a lull in cratering before this late period of impacts is uncertain [e.g., *Chapman et al.*, 2007; *Ćuk et al.*, 2010]. Thus, clarifying the nature of the early lunar impact record is of substantial interest.

[3]   The acquisition of high-resolution altimetry and topography of the Moon by the Lunar Orbiter Laser Altimeter (LOLA) [*Smith et al.*, 2010] onboard the Lunar Reconnaissance Orbiter (LRO) [*Chin et al.*, 2007] provides the ability

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to re-examine these questions. In this study, we use LOLA-derived digital terrain models to measure impact crater size-frequency distributions for 30 lunar basins that we classify as certain or probable on the basis of LOLA topography (one further basin that would fit in this category, Sikorsky-Rittenhouse, is so modified by its proximity to Schrödinger that it is not measurable). To be classified as certain or probable, we require that candidate basins have a region of low topography at least partially bounded by a circular or elliptical rim of high topography. We require that this rim be recognizable around at least 40% of the basin, although in most instances much more of the rim is intact. A number of additional, more degraded basins exist on the Moon [*Wilhelms*, 1987; *Frey*, 2011; C. A. Wood, Impact basin database, 2004, available at http://www.lpod.org/cwm/DataStuff/Lunar%20Basins.htm, hereinafter referred to as Wood, Impact basin database, 2004]. However, not all the basins that have been suggested are verifiable on the basis of LOLA topography using our criteria. This is discussed in more detail in section 3.5.

[4] In addition to determining superposed impact crater size-frequency distributions for each of these basins, we also (1) discuss the implications these results have for lunar stratigraphy and basin sequence, particularly with regard to several important individual basins and the Pre-Nectarian/Nectarian boundary, (2) use these data to examine hypothesized transitions in the impact crater populations affecting the Moon, and (3) discuss the hypothesis that saturation equilibrium was achieved on heavily cratered portions of the lunar surface.

1.1. Past Measurements of Basin Crater Statistics

[5] There have been a series of past efforts to systematically determine the relative age and superposed crater statistics for lunar basins [*Stuart-Alexander and Howard*, 1970; *Hartmann and Wood*, 1971; *Baldwin*, 1974; *Neukum*, 1983; *Wilhelms*, 1987].

[6] *Stuart-Alexander and Howard* [1970] attempted to ascertain the age of impact basins by considering their degradation state and by examining the largest craters superposed on each basin. Although essentially qualitative, their results give a first-order picture of basin age. The most comprehensive early survey to apply crater statistics to determine the age of large basins was accomplished by *Hartmann and Wood* [1971]. They report crater densities for many of lunar basins relative to the nearside lunar maria, and accounted for the effects of post-basin modification in their reported data. *Baldwin* [1974] also provided a series of crater counts on both basins and smaller craters; he divided his count results into age classes based on power law fits to the data. *Neukum* [1983] also made counts on a series of lunar basins, which have been translated into a more recent absolute chronology scheme by *Werner* [2008].

[7] Along with these important early efforts, the most widely cited stratigraphic sequence for lunar basins and analysis of broader lunar chronology was developed by *Wilhelms* [1987] in his classic The Geologic History of the Moon. Wilhelms relied on both stratigraphic inferences and crater counting to determine basin age and sequence. We compare our new results with the Wilhelms age sequence in detail.

[8] From all of these approaches and studies, there was widespread agreement that a representative sequence of basins exists, from youngest to oldest, of Orientale, Imbrium, Crisium, Nectaris, and Smythii. Most measurements also explicitly or implicitly recognize that the distinction between Imbrium and Crisium (or Imbrium and Nectaris) is far firmer than distinctions between Nectaris and many of the other basins of approximately the same age; many basins exist with superposed crater densities that are similar to Nectaris. However, disagreements existed between earlier workers about (1) the age of certain individual basins (e.g., Serenitatis, Humorum, Mendel-Rydberg, and Humboldtianum), and their position in the larger stratigraphic sequence, (2) the quantitative crater densities superposed on basins, and (3) the implications of these results for broader lunar geological history. In this study, we seek to resolve some of these differences.

1.2. Measurement Technique

[9] We derive impact crater size-frequency distributions for each basin by first mapping the preserved basin-related materials and facies, aiming to include the area that would have been unambiguously reset by the basin-forming event. In general, this is the area inside the basin not covered by later materials, and the region immediately proximal to the rim. Areas resurfaced after the basin event by volcanism or by ejecta from other basins are excluded. Along the edges of our count area, we use a buffered area correction and include craters which are superposed on the basin, but which are centered outside the count region (Figure 1). This buffered approach is similar to that of *Fassett and Head* [2008], though with a stricter buffer (no ejecta area is included and the rim of superposed craters must fall within the count area).

[10] This technique has two advantages. First, it expands our effective count area, since it takes advantage of the fact that large craters subtend more area than small ones, and second, it makes the mapping of the count area more straightforward and potentially more objective. This allows exclusion of resurfaced regions from the mapped count area without losing information about craters superposed on the edge of basin material, and there is no uncertainty about how to map the count area when craters are buried. To verify this procedure, we also compared results derived in this manner to a traditional (unbuffered) count area definition. The differences in results from these methods are below the uncertainties that arise from counting statistics, and systematic differences are negligible. Given the advantages we describe, we prefer the buffered methodology applied here to more traditional crater counting approaches for this particular problem.

[11] For our crater data, we begin with the catalog of lunar craters ≥20 km in diameter from LOLA data [*Head et al.*, 2010; *Kadish et al.*, 2011]. We then re-examine each basin using LOLA digital terrain models (DTM; updated June 2011) to systematically search for additional craters beyond the global database. In total, a modest number of additional craters were found (12%); these are predominantly small (<40 km) and degraded. We use the 64 pixel per degree (ppd) (equivalent to 473 m/px at the equator) DTM and shaded relief generated from this model. Higher resolution
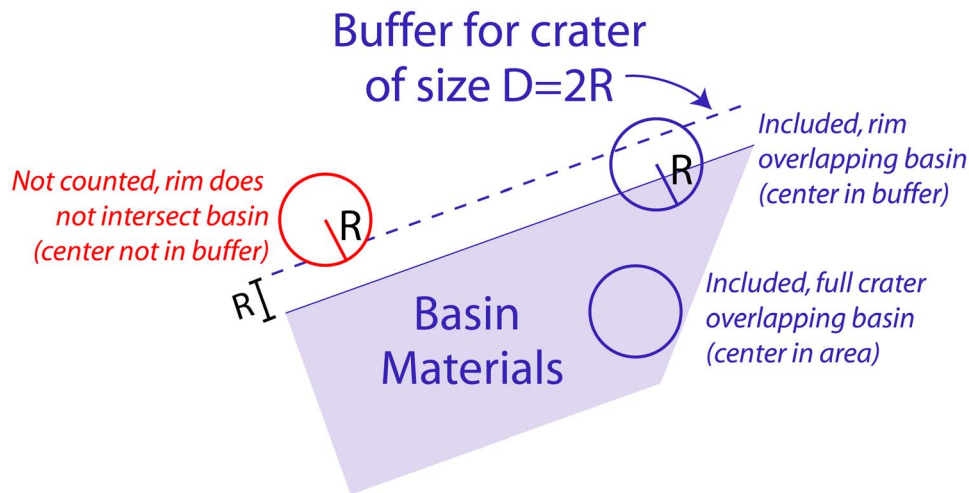
Buffer for crater of size D=2R

Figure 1. Schematic diagram illustrating the buffered crater-counting used to count craters to date basin deposits and thus ages. Areas are calculated independently for a given crater size, and craters are counted that post-date the basin and whose rims overlap basin materials [see also *Fassett and Head*, 2008, and references therein].

DTMs are available, but for our purposes (recognizing craters ≥20 km), minimizing the amount of interpolation in the DTM is desirable and the 64 ppd resolution is more than sufficient to recognize craters. For crater measurement we use the CraterTools extension to ArcMap [*Kneissl et al.*, 2011], which corrects diameter measurements to an appropriate local projection, and we compute all areas using an equal area map projection. The catalog of lunar craters reported on by *Head et al.* [2010] and *Kadish et al.* [2011] is available online at http://www.planetary.brown.edu/html_pages/LOLAcraters.html and detailed count data and areas are presented in the auxiliary material.[1]

2. Results

[12] The superposed crater densities for measured basins are given in Table 1, along with period assignments and inferred sequence. In Table 1, we provide N(20), and N(64) metrics for all the basins, as well as N(10) for these most sparsely cratered basins Schrödinger and Orientale where we made measurements to smaller crater sizes. These follow the standard convention that N(X) is the cumulative number of craters of size greater than or equal to diameter X normalized to an area of 10^6 km². This acts as a summary statistic with reference to a specific diameter, easing comparison between different measurements, although it is less detailed than the size-frequency distributions as a whole (available in the SOM). Because the measured distribution is a sparse sampling of the crater population, the N(20) density we give is extrapolated from the smallest sized crater greater than 20 km, and the N(64) density is interpolated from the density implied by the next largest and smallest craters. These corrections typically change the inferred N(X) value by less than ten percent from raw densities and are necessary

to accurately compare basins. Example crater size-frequency distributions are reproduced in Figure 2.

[13] Two major observations are evident from the crater size-frequency distributions in Figure 2, the supporting online material, and Table 1. First, despite differences in technique and improvements in data necessary to identify craters (LOLA topography), our new period assignments and basin sequence are generally consistent with those derived by *Wilhelms* [1987]. There are some minor intraperiod differences in sequence, which are expected given that counting statistics lead to overlapping error bars for some basins. It should be pointed out that a number of sequence relationships are clearly provisional (e.g., Humorum and Crisium; Freundlich-Sharonov and Nectaris), as they are indistinguishable in age on the basis of crater statistics; additionally, the sequence relationships for basins marked in the table with brackets should also be considered more uncertain for the reasons given in Table 1.

[14] Second, while there is general agreement in the basin sequence, the quantitative densities and crater size-frequency distributions that we observe on these basins differ quite appreciably from Wilhelms's measurements (Figure 3). These differences are minor for Imbrium and Orientale, but grow systematically larger for older, Nectarian and Pre-Nectarian basins. This difference is likely to be attributable to the observational advantages of using topographic data to recognize superposed degraded craters, rather than image data, which is limited by uneven illumination geometries and varying resolutions.

[15] These quantitative differences in crater frequencies have implications for the broader understanding of the stratigraphy of the Moon, particularly with regard to the Pre-Nectarian/Nectarian boundary. Period assignment based on our crater counts that used frequencies from *Wilhelms* [1987] to establish period boundaries would underestimate the portion of the Moon that is Nectarian and overestimate the amount that is Pre-Nectarian. Our data show much higher

Table 1. Derived Age Sequence of Lunar Basins From Crater Statistics[a]

Basin[b]	Period	N(20)[c]	N(64)[d]	N(10)	Wilhelms N(20)[e]	Stratigraphy/Superposition[f]	Observation Notes and Challenges
South Pole-Aitken	PN	156 ± 7^L	33 ± 3		N/A	No basin older on basis of stratigraphy	
Coulomb-Sarton	PN	271 ± 54	32 ± 14		(145 ± 22)	>Birkhoff	Size; Birkhoff Resurf.
Dirichlet-Jackson	PN	266 ± 36	33 ± 12		N/A	>Korolev	
Cruger-Sirsalis	PN	262 ± 46	39 ± 15		N/A		Orientale Ejecta
Smythii	PN	225 ± 19	28 ± 6		166 ± 19	>Crisium	
[Schiller-Zucchius]	PN	211 ± 47	41 ± 17		(112 ± 28)		Size + Mare
[Amundsen-Ganswindt]	PN	202 ± 37^L	47 ± 17		(108 ± 33)	>Schrödinger	Schrödinger Ejecta
Nubium	PN	195 ± 18	33 ± 7		N/A	>Humorum	
[Poincaré]	PN	194 ± 44	44 ± 16		(190 ± 34)		Size + Mare
Lorentz	PN	179 ± 31	32 ± 12		159 ± 28		
[Fitzgerald-Jackson]	PN	175 ± 34^L	43 ± 15		N/A	>Freundlich-Sharonov	Freundlich-Sharonov Ejecta
[Birkhoff]	PN	170 ± 33^L	46 ± 17		127 ± 18		Size
[Ingenii]	PN	167 ± 33^L	40 ± 14		162 ± 27		Furrowing; Mare
[Serenitatis]	PN?	298 ± 60	*28 ± 20*		N/A	>Nectaris (?)	Basin material poorly exposed
Apollo	PN/N	151 ± 23	*12 ± 6*		119 ± 16	>Korolev, Hertzspr.	
Freundlich-Sharonov	PN/N	140 ± 18	16 ± 6		129 ± 14	>Moscoviense	
Nectaris	Beginning of N	135 ± 14	17 ± 5		79 ± 14		
Korolev	N/PN	127 ± 22	*9 ± 5*		79 ± 8	>Hertzsprung (?)	
[Mendeleev]	N/PN	129 ± 36	*16 ± 10*		63 ± 10		Size + Mare
Hertzsprung	N/PN	129 ± 22	16 ± 6		57 ± 8		
[Grimaldi]	N/PN	126 ± 28^L	22 ± 10		(97 ± 25)	>Mendel-Rydberg	Orientale Resurfacing
Mendel-Rydberg	N/PN	125 ± 17	12 ± 5		73 ± 17		
[Planck]	N/PN	118 ± 36	*22 ± 14*		(110 ± 37)	>Schrödinger	Size, Schrö Proximity
Moscoviense	N	120 ± 17	9 ± 4		87 ± 12		
Crisium	N	113 ± 11	8 ± 3		53 ± 8	>Humboldtianum	
Humorum	N	108 ± 21	*12 ± 6*		56 ± 11		
Humboldtianum	N	93 ± 14	11 ± 4		62 ± 10		
Imbrium	Beginning of I	30 ± 5	4 ± 2		28 ± 3		
Schrödinger	I	19 ± 7		$73 \pm 1 5$	20 ± 5		
Orientale (no buff.)	I	21 ± 4	*1 ± 1*	60 ± 6	22 ± 3		

[a]Some basins have overlapping error bars, so their order should be considered provisional.
[b]Brackets, uncertain due to observational challenges.
[c]Superscript L, value may be low.
[d]Italics, ≤4 craters.
[e]Parentheses, poor sampling.
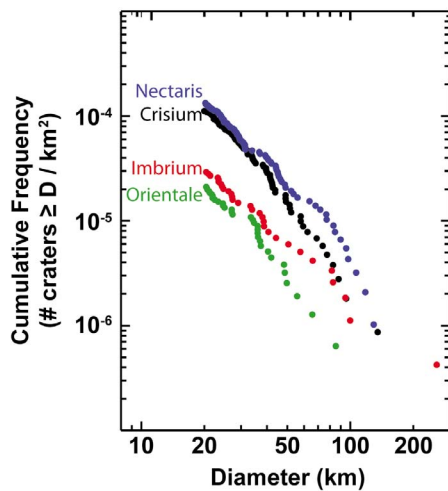[f]>X, pre-dates X based on stratigraphy.

Figure 2. Example cumulative crater size-frequency distributions for Orientale, Imbrium, Crisium, and Nectaris. Cumulative and R-plots for each basin are available in the supporting online material; see *Crater Analysis Techniques Working Group* [1978] for a description of these plotting methods.

densities of craters ≥20 km superposed on Nectaris (a factor of ~50% higher) than reported by *Wilhelms* [1987]. Putting this into perspective for the whole Moon, *Wilhelms* [1976] reported that there were ~1700 primary craters of ≥20 km between the Nectaris and Imbrium impacts, and the later data of *Wilhelms* [1987] suggests that this number should be
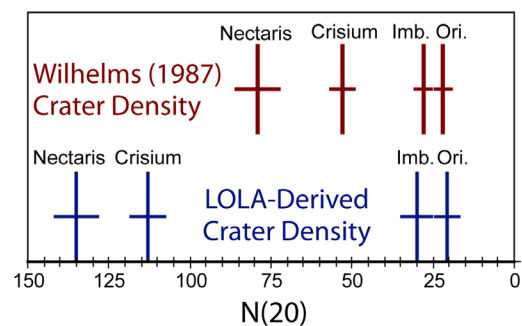

Figure 3. Comparison of N(20) densities derived for Orientale, Imbrium, Crisium, and Nectaris in this work and by *Wilhelms* [1987]. For basins older than Imbrium, we find systematically higher superposed crater densities than Wilhelms.
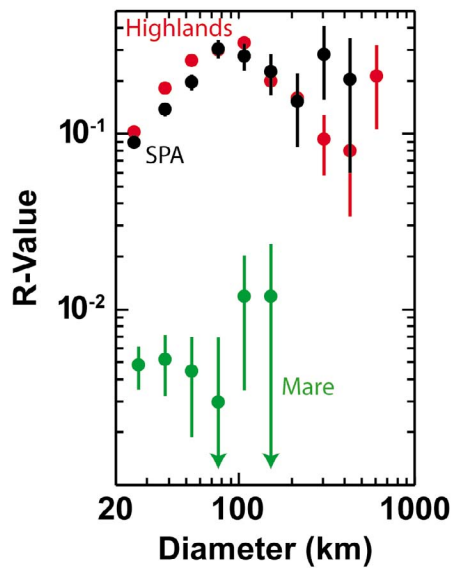
Figure 4. R-Plot showing South Pole-Aitken (SPA) basin, as well as the highlands (excluding SPA, Orientale, and regions covered by mare), and the mare from *Head et al.* [2010]. These data illustrate the difference in population that affected the lunar highlands and SPA compared to the lunar mare. Note that we follow the convention of *Strom et al.* [2005], who term the crater size-frequency distribution of the highlands 'Population 1' and that of younger units like the mare 'Population 2'.

~1900. Our data indicate ~4000 craters of all types between these two events, the vast majority of which we interpret as primary in origin (see section 3.1).

3. Discussion

3.1. Secondary Cratering

[16] The contribution of basin secondary cratering has the potential to affect the crater size-frequency distribution of individual basins [e.g., *Wilhelms*, 1976; *Wilhelms et al.*, 1978]. However, most secondary craters are smaller than 20 km, even for the largest basins such as Imbrium and Orientale, because of the steep size-frequency distribution of secondary craters [*Wilhelms et al.*, 1978]. Thus, measured crater densities are much less contaminated by secondaries at the scales we consider here (craters ≥20 km in diameter) than would be the case if we included smaller craters.

[17] There are also apparently substantial differences in the number of large secondaries produced from a given large basin. *Wilhelms et al.* [1978] classified 58 craters ≥20 km as secondaries from the Imbrium basin in an area of $4.165 \times 10^6 \text{ km}^2$ (equivalent to N(20) = 14 ± 2 in their count region), but only one crater ≥20 km as a secondary from the smaller Orientale basin in an area of $1.751 \times 10^6 \text{ km}^2$ (equivalent to N(20) = 0.6 ± 0.6). The inferred contribution of secondaries from Imbrium is likely a maximum estimate for the density of secondaries that a D ~ 1000 km basin will typically produce, since this measurement was taken where the density of secondaries was highest, and Imbrium produced far more secondaries than Orientale. The contributions of secondaries from later basins to the crater statistics of earlier basins such

as Nectaris is likely to be less than 20%, although the precise contribution of secondaries is dependent on the age of the basin and its proximity to later large basins.

[18] Given these factors, we interpret the superposed crater size-frequency distributions of lunar basins as being generally controlled by primary cratering for ≥20 km craters. This view is bolstered by (1) the lack of detection of abundant secondaries ≥20 km surrounding large young basins at appropriate ranges based on LOLA data [*Head et al.*, 2010], (2) the consistency of stratigraphic and crater counting sequence determinations, which suggests that secondary cratering does not significantly contaminate and affect these measurements, and (3) the reasonable agreement of the basin sequence based on craters of larger size (≥64 km) with what is found at N(20); secondary craters ≥64 km in diameter are unlikely to exist.

3.2. Evolution of the Lunar Crater Population and Implications for the Late Heavy Bombardment

[19] A major question in lunar science is whether the crater population or size distribution of impacting bodies that impacted the Moon was stable over time, even though the flux was changing. A long-standing and important hypothesis is that the lunar highlands were impacted by a distinct, early population of impactors that differs from what has affected the Moon since the time of the emplacement of the lunar maria [e.g., *Whitaker and Strom*, 1976; *Wilhelms et al.*, 1978; *Strom*, 1987; *Strom et al.*, 2005; *Head et al.*, 2010]. This idea has been disputed by workers who have argued that the entire visible crater record can be explained by a single impactor population, [e.g., *Neukum and Ivanov*, 1994; *Hartmann*, 1995; *Neukum et al.*, 2001], and that any observed differences in the crater record can be attributed to geological resurfacing and difficulty in finding a terrain that is an unmodified sample of the early impact record.

[20] The basis for the idea that impact populations on the Moon have changed over time is that the observed crater size-frequency distributions of ancient highland terrains are distinct from those that are observed on the maria (e.g., Figure 4) [see also *Strom et al.*, 2005; *Head et al.*, 2010]. This is manifested by a having a lower ratio of ~20–40 km craters to ~80–100 km craters in the highlands than in the mare (in other words, there is an excess of these larger craters in the highlands). That the maria and highland have differently shaped crater size-frequency distributions is statistically significant when applying the two-sample Kolmogorov-Smirnov test to their empirical cumulative densities (Figure 5a). *Ćuk et al.* [2010, 2011] also demonstrated that the size-frequency distribution of Imbrian craters on the Moon are statistically distinguishable from the highlands curve, using data from both *Wilhelms et al.* [1978] and the fresh crater distribution (of class 1 craters) from *Strom et al.* [2005].

[21] As noted above, this observation does not guarantee that the difference in observed crater size-frequency distribution is a direct result of a shift in the impactor population that affected the Moon in its early history relative to more recent times. A viable alternative hypothesis is that early surfaces were bombarded by a crater population similar to the population that impacted the maria, but that geologic processes such as volcanism or repeated cratering preferentially removed small craters and thus resulted in the observed
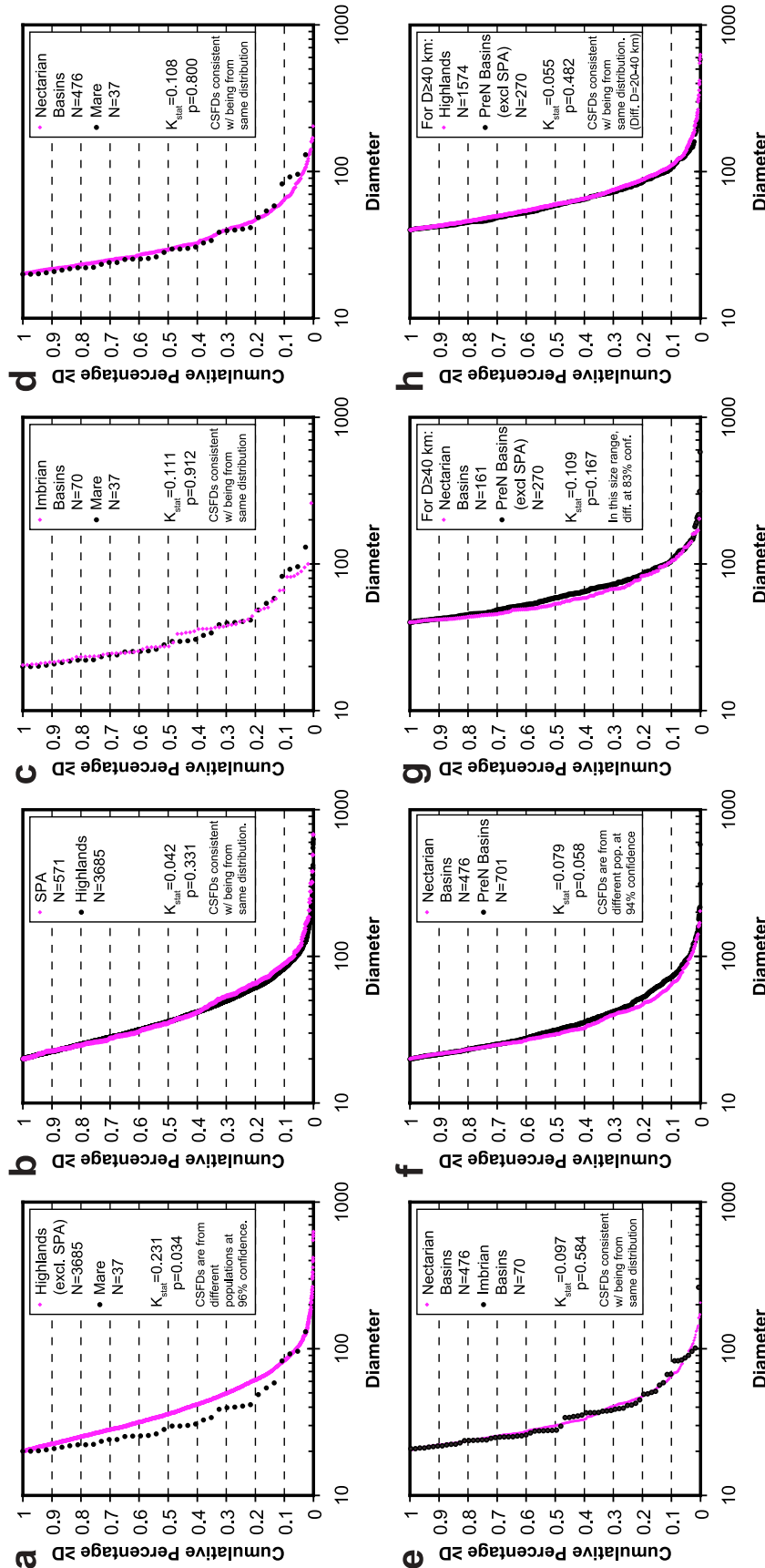
Figure 5. Empirical cumulative density functions (cdfs) for a variety of different terrains on the Moon along with the relevant Kolmogorov-Smirnov statistic (K_{stat}) for two distributions. K_{stat} is a statistical metric based on the maximum difference between two cdfs and provides a test of whether two populations are different. (a) Comparison of the mare and highlands excluding SPA [see also *Strom et al.*, 2005; *Ćuk et al.*, 2010, 2011; *Head et al.*, 2010]. These terrains (Figure 4) are from statistically significant different populations of craters. (b) Comparison of SPA and the highlands excluding SPA (Figure 4); these distributions are consistent with being from the same population (not significantly different), though SPA has a modestly fewer craters in the D = 20–64 km size range. (c) Comparison of Imbrian basins and the mare, which are not significantly different. (d) Comparison of Nectarian basins and the mare, which are not significantly different. (e) Comparison of Imbrian and Nectarian basins (see also Figure 6), which are not significantly different. (f) Comparison of Nectarian and Pre-Nectarian basins (see also Figure 6). These are different at 94% confidence. (g) Comparison of Nectarian and Pre-Nectarian basins for craters larger than 40 km; these are different at 83% confidence. (h) Comparison of Pre-Nectarian basins and the highlands excluding SPA for craters larger than 40 km. These are not distinguishable in this size range. At smaller sizes, the 'average' highlands excluding SPA have fewer craters than these Pre-Nectarian basins (compare Figures 4 and 6). This difference at small sizes may be a result of moderate deficiency in 20–40 km craters in the highlands curve (due to crater removal and modest incompleteness) (see section 3.2).
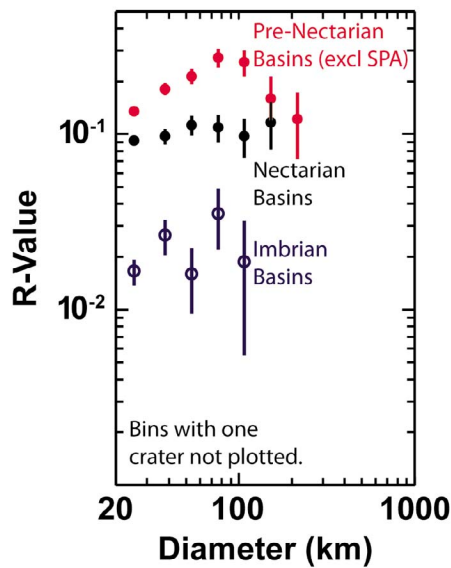
Figure 6. R-Plot showing the integrated crater size-frequency distributions for Pre-Nectarian-aged basins (excluding SPA), Nectarian-aged basins (including Nectaris), and Imbrian-aged basins (including Imbrium). Nectarian basins have a flat distribution on an R-Plot, consistent with the mare-like Population 2 crater distribution. The Pre-Nectarian basins are more similar to Population 1. This suggests that the transition from terrains with highlands-like Population 1 to Population 2 happened by the mid-Nectarian, as the Nectarian basins primarily accumulated craters from Population 2.

change [*Hartmann*, 1984, 1995]. This is plausible because both later impacts and volcanic infilling affect smaller craters more easily than larger craters, which extend across more area and have greater initial relief.

[22] There are several reasons, however, to question this resurfacing explanation: (1) A variety of ancient terrains with distinct crater density and geological histories, such as inside South Pole-Aitken (SPA) and in the heavily cratered highlands, have similar shapes to their crater size-frequency distributions [*Head et al.*, 2010] (Figure 4 and 5b). Despite these different histories, both distributions are statistically distinguishable from the mare and indistinguishable from each other. (2) A similar distinction exists between old and young terrains on Mercury and Mars as well as the Moon [*Strom et al.*, 2005; *Fassett et al.*, 2011a]. There is no reason that crater removal processes on each planet should be manifested in a similar manner in their crater statistics, while an inner solar system-wide change in the impactor population can readily explain the same change directly. (3) A process-oriented explanation [*Strom et al.*, 2005] exists for such a change in impactor population, since the early population (what Strom and colleagues call 'Population 1') has a shape that matches well with a collisionally evolved population like the Main Asteroid Belt, and the younger population ('Population 2') may be a result of size-selective processes that preferentially transport smaller asteroids to the inner solar system [e.g., *Morbidelli and Vokrouhlický*, 2003]. Because of this size-selection, the resulting population has a 'flatter' shape on an R-plot (Figure 4). The Population 2 shape also matches well with the inferred crater population

that would be expected to be produced from the present Near Earth Object distribution [*Strom et al.*, 2005].

[23] Using our new database of the global crater population $\geq$20 km from LOLA data, we found support for the presence of the two populations proposed by *Strom et al.* [2005] [*Head et al.*, 2010; *Kadish et al.*, 2011], and the results of our new analysis continue to support this interpretation. We thus provisionally accept the hypothesis that different impactor populations affected the Moon, and hence basins on its surface, as a function of time. With our new data, we can examine when the hypothesized transition between populations occurred. In practice, it is difficult to address this question on a basin by basin basis, because counting statistics are insufficient to demonstrate significant changes over these short time intervals, particularly when relying on the large craters that we consider most reliable for assessing basin ages. This challenge is demonstrated by the ongoing arguments about whether Orientale has a crater size-frequency distribution reflecting Population 1 or 2 [*Strom*, 1977; *Woronow et al.*, 1982; *Hartmann*, 1984; *Head et al.*, 2010; *Ćuk et al.*, 2010, 2011]. Orientale's $\geq$20 km crater population cannot be statistically distinguished from either population with confidence.

[24] We choose to address this counting statistics problem by aggregating the statistics from individual basins into average crater size-frequency distributions for basins of a given period (Figures 5 and 6). We combine the crater counts and areas for the Imbrian basins (including Imbrium), the Nectarian basins (including Nectaris), and the Pre-Nectarian basins (excluding South Pole-Aitken to avoid it dominating the statistics).

[25] No single basin unduly influences any of these aggregate crater size-frequency distributions. For the Pre-Nectarian, with aggregate N(20) = 188 $\pm$ 7, no basin represent more than ~20% of the aggregated data; the largest two contributors are Smythii (20%) and Nubium (16%), and the other 13 basins each have less than a 10% influence on the sum total. Crisium and Nectaris each represent ~20% of the Nectarian curve, and the other 9 basins represent the remaining ~60%. The aggregate N(20) for the Nectarian average is 110 $\pm$ 5. In the Imbrian, with few basins, Imbrium and Orientale contribute 43% and 47% of the craters respectively, and Schrodinger represents the other 10%. The aggregate N(20) for the Imbrium data is 22 $\pm$ 3. In total, the Imbrian, Nectarian, and Pre-Nectarian basin distributions are a sample of 8%, 10%, and 9% of the lunar surface area.

[26] These aggregated data imply that both the Imbrian-aged basins and the Nectarian-aged basins are consistent with the flatter Population 2 (more mare-like) shapes (see Figures 4, 5c, 5d, and 6). The Pre-Nectarian and Nectarian-aged basins are distinct from each other at the 94% confidence level (Figure 5f and 6); the Nectarian-aged basins also differ significantly from the highlands population (Population 1), assuming that the non-SPA highlands data set from *Head et al.* [2010] are representative of this population.

[27] These observations are surprising, since the transition from Population 1 to Population 2 has previously been linked to the transition away from the Late Heavy Bombardment population of impactors to the modern population [*Strom et al.*, 2005], and the basins formed during the Nectarian are commonly assumed to be part of the Late Heavy Bombardment. For this reason, we might expect that

these Nectarian basins were witness to the putative Late Heavy Bombardment population of impactors (Pop. 1) and would have a superposed crater population different from that of the maria. Moreover, because of the high crater flux during this time period, 65–75% of the craters that we measure on the Nectarian basins actually formed during the Nectarian period (Table 1; compare the N(20) of Nectarian basins with Imbrium). So if Population 1 dominated the impactors during this period, we would expect to see its signature in the Nectarian basin curve.

[28] Instead, our data show a difference between the crater size-frequency distributions of the Nectarian-aged and the Pre-Nectarian-aged basins (Figure 5f and 5g), and a close similarity between the Nectarian-aged basin population and the population of impactors recorded on the maria or Imbrian basins (Pop. 2) (Figures 5d and 5e). These observations are not consistent with a mid-Nectarian-to-Imbrian Late Heavy Bombardment dominated by a size-independent delivery of impactors from a collisionally evolved, Main Asteroid Belt-like population of impactors (Population 1) [Gomes et al., 2005; Strom et al., 2005]. Based on different data, Ćuk et al. [2010, 2011] reached a similar interpretation that later, Imbrian-aged impactors that may have been part of the Late Heavy Bombardment also lack a Population 1 shape. Instead, the impactor size-frequency distribution by the mid-Nectarian is consistent with that of the lunar mare, despite the high flux during this period, rather than with the size-frequency distribution characteristic of the lunar highlands or SPA.

[29] The Pre-Nectarian-aged basins have a size-frequency distribution of superposed craters that is qualitatively closer in shape to the highlands than Nectarian-aged basins (Figure 4, 5f, and 6), although there is still some observed difference in these distributions between D = 20 and 40 km. (This difference may arise from the fact that the pre-Nectarian basins size-frequency distribution is more representative of the original impactor population than the lunar highlands curve. The highlands data may be a modest underestimate of the crater frequency characteristic of this population between 20 and 40 km because of removal of craters at these size ranges [e.g., Hartmann, 1995]. It is also likely that there is modest incompleteness in the highlands data set in this size range (estimated to be <20%)).

[30] If craters D < 40 km are excluded, the Pre-Nectarian-aged basins and highlands are similar (Figure 5h), but Nectarian-aged and Pre-Nectarian-aged basins are different with 83% confidence (Figure 5g; see also Figure 5f). Taken at face value, these data are consistent with a scenario in which the population of impactors was evolving over time, starting with Population 1 primarily recorded on the ancient cratered highlands and Pre-Nectarian-aged basin surfaces, with a transition to predominantly Population 2 impactors by the mid-Nectarian.

[31] These data would suggest that the transition observed in the lunar impact crater population occurred earlier than has been previously suggested. Although it is difficult to ascertain whether the transition between the two impactor populations was gradual or abrupt., Population 1 cannot have remained the predominant source of lunar impacts as late as Imbrium. If this were the case the majority of craters on the Nectarian basins would be expected to be from Population 1, which would have resulted in a size-frequency distribution

distinct from younger surfaces, unlike what we observe. Given the high impactor flux during the Nectarian, this shift in population also appears to have occurred before the flux of impactors rapidly declined; this transition may be before the end of the hypothesized Late Heavy Bombardment. The lunar impactor population then appears not to have varied significantly over the last ~3.9–4 Gyr, as all younger surfaces have a Population 2-like crater size-frequency distribution.

3.3. Individual Basins and Basin Relationships

3.3.1. Crisium and Humboldtianum Basins

[32] The stratigraphic relationship between Crisium and Humboldtianum basins has been uncertain, despite their close proximity and good preservation state. Based on crater statistics, Hartmann and Wood [1971] argued that Humboldtianum ('relative age' of 15 ± 2) appears younger than Crisium ('relative age' of 17 ± 4). (Note that Hartmann and Wood's basin relative ages can be compared to N(20) densities that we report for all basin by multiplying their data by a factor of ~8.5). This interpretation that Humboldtianum was younger than Crisium was supported by the mapping of Wilhelms and El-Baz [1977]. However, Stuart-Alexander and Howard [1970], Baldwin [1974], and Wilhelms [1987] ($N_{Humbo}(20) = 62 \pm 10$, $N_{Cris}(20) = 53 \pm 8$) all favored the interpretation that Humboldtianum was older than Crisium.

[33] Figure 7 shows a LOLA DTM and shaded relief portrayal, as well as a detrended version of the DTM with long wavelength trends removed by subtracting out the median elevation in 100 km neighborhoods. These data show the presence of secondary crater chains and sculpture from Humboldtianum that reach to or across the outer ring of Crisium, and are thus superposed on Crisium. Both these stratigraphic relationships, as well as crater statistics (Table 1), support the interpretation that Humboldtianum is younger than Crisium.

3.3.2. Serenitatis Basin

[34] The stratigraphic relationship of Serenitatis to its surrounding basins is a long-standing problem in lunar science and is closely tied to the interpretation of samples from Apollo 17 [e.g., Head, 1974, 1979; Spudis et al., 2011]. Most early workers interpreted Serenitatis as Pre-Nectarian [Stuart-Alexander and Howard, 1970; Hartmann and Wood, 1971; Wilhelms and McCauley, 1971; Head, 1974; Baldwin, 1974], a view that has been advocated anew based on analyses of the sculptured hills of the Taurus-Littrow region with Lunar Reconnaissance Orbiter camera data [Spudis et al., 2011]. However, for much of the past 30 years, Serenitatis has been accepted as post-Crisium in age [Wilhelms, 1976, 1987], based on the comparatively young age of Apollo 17 samples that were interpreted as Serenitatis melt and ejecta [e.g., Dalrymple and Ryder, 1996, and references therein], as well as re-evaluation of stratigraphic relationships.

[35] Wilhelms [1987] presents six arguments for this relatively young age (p. 173): (1) the lack of obvious large craters that are clearly younger than Serenitatis and older than Imbrium; (2) the destruction or degradation of Serenitatis (particularly its western sector) is primarily a result of proximity to Imbrium and not an indicator of relative age; (3) the presence of craters interpreted as Serenitatis secondaries superposed on Crisium materials; (4) lack of Crisium ejecta apparent near the Taurus-Littrow massifs (although
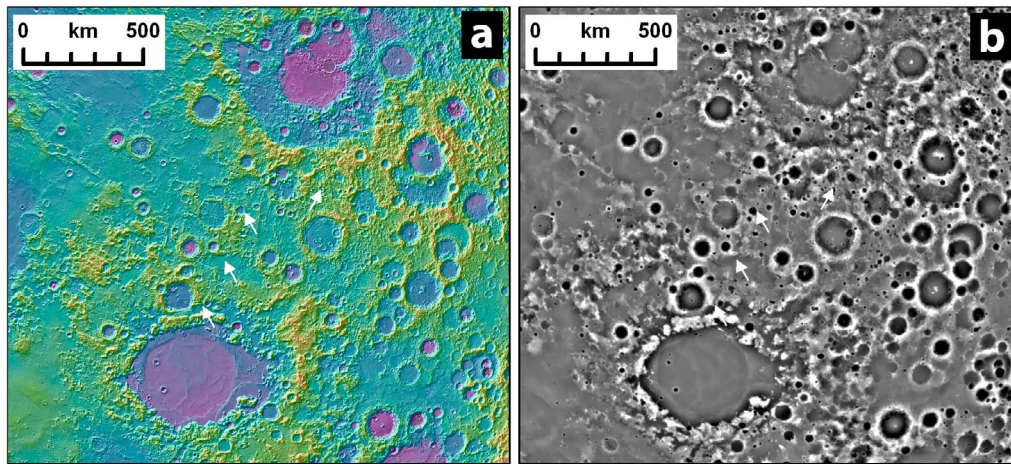
Figure 7. The region of Crisium and Humboldtianum in LOLA data. (a) A shaded relief map overlaid by topography. (b) Regionally detrended topographic data set, which highlights local topography. These data suggest to us that ejecta or sculpture from Humboldtianum is superposed on Crisium and Crisium ejecta, and that Humboldtianum post-dates Crisium, consistent with crater counting results as well, though they overlap in density at 1σ.

Wilhelms notes that an alternative explanation for this observation is asymmetry in the Crisium ejecta distribution); (5) the thick mare in Serenitatis suggests that it was a deep basin when volcanism began; and (6) Apollo 17 Command Module pilot Ronald Evans described the Serenitatis massifs as fresher looking and more boulder strewn than those of Crisium.

[36] LOLA topography can shed light on these stratigraphic arguments. These data reveal a number of very degraded craters that are near to the rim of Serenitatis that are filled with Imbrium ejecta, some of which are quite large (20–80 km) (see Serenitatis image in SOM). Moreover, evidence for sculpturing from Nectaris exists on the southeastern rim of Serenitatis near the Apollo 17 landing site (Figure 8).
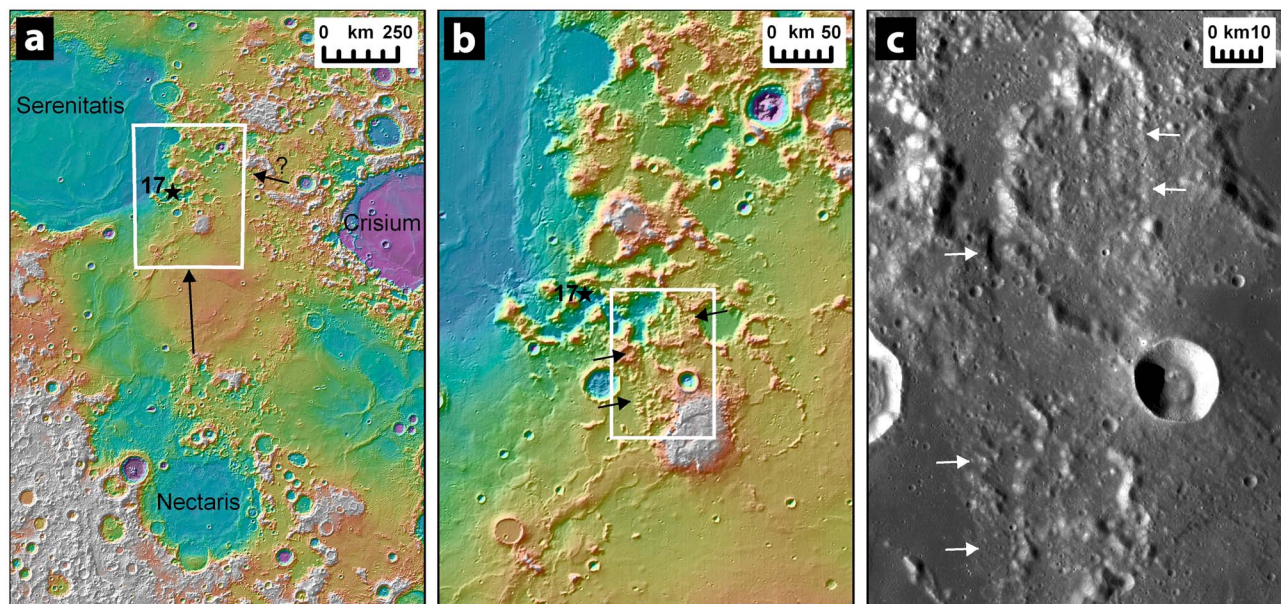

Figure 8. (a) A regional view of SE Serenitatis basin (top left), Nectaris basin (bottom), and Crisium basin (top right); LOLA shaded relief overlaid by topography (box is location of inset b; arrow shows direction from Nectaris ejecta to affect the eastern rim of Serenitatis). (b) Lineated terrain on the southeastern rim of Serenitatis near the landing site of Apollo 17 that appears to be sculptured ejecta from Nectaris. These relationships suggest that Serenitatis pre-dates Nectaris, consistent with very high crater densities in the Taurus mountains that make up the eastern rim of Serenitatis, part of which are seen here. (c) Detail of lineated terrain in LROC WAC mosaic, showing muted morphology of lineations, which appear superposed by Imbrium ejecta.

Sculptured ejecta from Crisium may also be present but it is difficult to distinguish from Imbrium-related sculpture which is similarly oriented. Additionally, secondary craters that have been suggested to be from Serenitatis and superposed on Crisium [*Wilhelms*, 1987, Figure 9.15] are likely to be from Imbrium: they are oriented along great circle paths that trace back to Imbrium as well as Serenitatis, and the size of the largest such secondary (D = 22 km) suggests that an Imbrium origin is more likely. This is larger than any secondaries that *Wilhelms et al.* [1978] mapped from Orientale, which is a larger basin than Serenitatis.

[37] Our crater counting in the Taurus Mountains also provides strong evidence that Serenitatis is older than Crisium or Nectaris. The density of ≥20 km craters within the Taurus Mountains is at least a factor of 2 times that of Crisium materials, with more than sufficient counting statistics to be certain that the Mountains are more heavily cratered than Crisium materials. Two possible explanations might be invoked to explain this observation besides a comparatively old age for Serenitatis: (1) many of these craters could be Imbrium secondaries, or, alternatively (2) many of these craters could pre-date the Serenitatis basin. Neither of these explanations appears to be satisfactory. For example, if ≥20 km secondary craters from Imbrium were a major contributor to the crater population of this region, there is no reason to believe that Crisium materials immediately to the east would not have been similarly polluted by secondaries. Many of these craters are obviously degraded and modified by Imbrium ejecta, and they lack morphological characteristics suggesting a secondary origin.

[38] The second of these two explanations, that many of these craters could pre-date the Serenitatis basin, appears to have been favored by *Wilhelms* [1987], who placed the Serenitatis basin rim within Mare Serenitatis. However, the observed topography of the basin with LOLA casts doubt on this interpretation, as the basin deepens rapidly inward of the Taurus mountains (see also *Head* [1979], who placed the inner edge of the Taurus mountains as the Outer Rook-equivalent ring for Serenitatis). If these craters were pre-existing craters, recent measurements of the effects of impact ejecta on crater burial [*Head et al.*, 2010; *Fassett et al.*, 2011b] suggest that they should have been far more deeply degraded by Serenitatis ejecta than is observed; around Orientale, more than 50% of pre-existing craters were removed within one-half of a basin radius from the Cordillera ring [*Head et al.*, 2010], and the pre-existing craters that survived are deeply filled by Orientale ejecta [*Fassett et al.*, 2011b]. Thus, we interpret the crater population of the Taurus Mountain region as primarily being post-Serenitatis, and its high density to be a result of a relatively ancient age for Serenitatis.

3.3.3. South Pole-Aitken Basin

[39] On the basis of stratigraphy, the South Pole-Aitken basin has been interpreted as the oldest detectable basin in the lunar cratering record [*Wilhelms*, 1987]. The SPA basin has a comparable to slightly higher density of superposed large craters (>60–80 km) than the highlands outside the basin (Figure 4). However, at smaller sizes (D ≤ ~60–80 km), there is a divergence between the crater density of the area outside SPA and within the basin [*Kadish et al.*, 2011]. The interior of SPA has a density that is lower in this size range than highlands outside the basin (Figure 4),

and it has fewer craters in this size range than a number of other Pre-Nectarian-aged basins (Table 1). Despite this fact, basins that have higher N(20) densities than SPA (e.g., Smythii) should be assumed to post-date SPA on the basis of stratigraphy; if they were preexisting, they would have been deeply modified by SPA ejecta upon its formation.

[40] We interpret the deficit of craters in SPA between 20 km and ~60–80 km as having resulted from moderately more resurfacing than typical highlands regions. As with all of our basin measurements, we excluded obvious plains and mare on the SPA basin floor from the assessment of its superposed crater population, so other resurfacing needs to be considered. Two possibilities are an unusual allotment of young basins within and close to SPA, which may have erased craters (e.g., by ejecta emplacement), or early volcanic plains that are less apparent and not fully mapped. Both explanations are plausible. Recent work by *Petro et al.* [2011] suggests that the extent of volcanism inside SPA is greater than has been previously recognized. Alternatively, deviations of the small portion of the cratering curve as a result of ongoing cratering in saturation are observed in models [*Chapman and McKinnon*, 1986; *Richardson*, 2009] (see section 3.4). More work is needed to assess the relative importance of these resurfacing mechanisms, but the magnitude of erasure had to have been substantial enough to affect the observed density of 20–80 km craters.

3.4. Saturation Equilibrium and the Basin Impact Crater Record

[41] The lunar highlands have crater densities for craters with a diameter D ≥20km that are close to, and likely to be at, the densities expected for saturation equilibrium, the condition where the formation of a new crater on average erases enough pre-existing craters that the overall density of crater ceases to increase with time [*Gault*, 1970; *Marcus*, 1970, *Hartmann*, 1984; *Chapman and McKinnon*, 1986; *Richardson*, 2009; *Head et al.*, 2010].

[42] Modeling by *Chapman and McKinnon* [1986] and more recently by *Richardson* [2009] reveals two important elements concerning the way surfaces behave when shallow-sloped impact crater size-frequency distributions approach saturation. First, for these distributions, there is no single 'saturation' value or characteristic distribution; instead, crater densities oscillate in a range that depends on how recently the infrequent formation of a large crater erased previous craters over a large area. An approximate estimate for the R-values where this commonly occurs is ~0.1 to 0.3, although this is dependent on model parameters. Second, these models indicate that the shape of the production population can be preserved even on saturated surfaces. This helps bolster the argument that the transition between Population 1 and 2 that we describe above is a robust determination and not simply a result of some currently not well-understood saturation behavior.

[43] Are any of the basins that we observe cratered to saturation? If the lunar highlands are in fact saturated, it is very likely that SPA is also saturated given that it is characterized by higher crater densities at large crater sizes than the highlands (Figure 4). Indeed, the deviation of its N(20) value from the highlands may result from a saturation phenomenon where it was affected by an unusual concentration of large late basins (presumably as a function of chance).

[44] Many other Pre-Nectarian basins, perhaps excepting Apollo and Freundlich-Sharonov, are characterized by densities that likely imply that they also reached saturation. This means that their age and sequence may be imperfectly tied to the density of craters that are superposed on their surface (Table 1). Most Pre-Nectarian basins are clustered at N(20)~165 to 265 and N(64)~30 to 48; equivalent to R_{20}~0.1–0.15 and R_{64}~0.25–0.4 with a highlands-like crater size-frequency distribution. If all of these basins are saturated, differences in degradation state and topography hint at how long the basin has been in this condition, although this relationship should be size-dependent. For basins the size of SPA, later cratering is almost certainly ineffective as a process to completely erase basin topographic signatures. However, for small 300–500 km diameter basins, this is potentially a far more efficient process.

[45] The apparent saturation of early surfaces on the Moon that our measurements support weakens the evidence for forms of the Late Heavy Bombardment hypothesis that postulate a lower impact flux before Nectaris, because the cratering record of the Pre-Nectarian must be incomplete [see also *Hartmann*, 1975; *Chapman et al.*, 2007]. Since this early impact record is missing, the large number of Nectarian and younger basins (at least 13; Table 1) need not require an anomalously high basin-forming flux compared to the preceding pre-Nectarian period, although the impact flux in early periods was far higher than that during later times.

3.5. Degraded and Uncertain Basins

[46] In addition to the basins documented and discussed here, there are numerous less well-defined basins [e.g., *Wilhelms*, 1987; *Frey*, 2011; Wood, Impact basin database, 2004] that have been suggested to exist on the Moon. A number of these suggested basins do not appear to have a clear signature in LOLA altimetry data. In other instances, some evidence exists for basins that are now simply too ambiguous to be confidently identified using our criteria. The list we provide here (Table 1) is conservative in the sense that we are confident that all of the basins that we measure have a very high probability of being impact basins. The vast majority of the remaining highly degraded, ambiguous and uncertain basins are Pre-Nectarian in age, as discussed further below, and thus do not affect the observations and conclusions discussed above.

[47] *Frey* [2011] evaluated the basins compiled by *Wilhelms* [1987] using the Unified Lunar Control Network topography of *Archinal et al.* [2006]. Additional efforts to analyze the degraded basins with LOLA topography are ongoing, so we do not dwell on this issue here and address only a few points. First, there is significant agreement between the *Frey* [2011] judgments of the *Wilhelms* [1987] basin list and our independent evaluations, although we additionally exclude as doubtful Keeler-Heaviside, Fecunditatis, Mutus-Vlacq, Lomonosov-Fleming, and Tsiolkovsky-Stark (as well as Balmer-Kapteyn and Bailly, which we assess as having smaller main ring diameters than our size cutoff).

[48] We also examined the additional suggested topographic basins of both Wood (Impact basin database, 2004) and *Frey* [2011]. A few of these meet our criteria as probable-to-certain basins; in the *Frey* [2011] naming scheme these are TOPO-30 (Cruger-Sirsalis) [*Spudis et al.*, 1994; *Cook et al.*, 2002], TOPO-24 (Dirichlet-Jackson) [*Cook et al.*, 2000], and

TOPO-41 (Fitzgerald-Jackson) [*Cook et al.*, 2000]. Conversely, in a few instances, we think 'positive evidence' exists against some suggest candidates being actual impact basins, such as TOPO-38, which is entirely inside Imbrium and demarcated by wrinkle ridge ring. We interpret this as an inner ring of the Imbrium basin rather than a separate basin. Again, most of the suggested basins that we do not include here are ambiguous; some evidence would argue for their existence and some against.

[49] What do we know about the age and crater statistics of these ambiguous basins? In general, the vast majority must be Pre-Nectarian in age. We have made measurements which support this view in regions that have traditionally been suggested to have one or more basins by various authors, such as Australe, Lomonosov-Fleming, and Werner-Airy. All have superposed crater densities of N(20) > 180 and N(64) > 35, indicative of Pre-Nectarian ages (see Table 1). As discussed above, these densities are at levels consistent with saturation equilibrium, which also would explain the very highly degraded state of the purported basins.

[50] Younger impact basins also should obviously not have high crater densities or saturated surfaces, nor have subtle basin topographic signatures (excepting any that were erased by direct superposition of later, larger basins). For these reasons, the Nectarian and younger basins in Table 1 are likely to be a nearly complete representation of the basins that actually formed on the Moon during this period.

3.6. Calibrating Ages and Sampling Suggestions

[51] Better understanding of the absolute ages of various basins on the Moon is important for understanding lunar geology as well as for understanding the impact record across the inner solar system. This problem is highly convolved with the provenance of the lunar samples, and making progress in this area may require additional in situ fieldwork and/or robotic sample return.

[52] When considering how to calibrate the translation of measured crater size-frequency distributions into absolute ages, one issue is that the most commonly applied models for lunar crater statistics [e.g., *Neukum et al.*, 2001] do not yet account for the fact that the impactor population on the Moon appears to have evolved with time [*Strom et al.*, 2005]. Recent work by *Marchi et al.* [2009] has made some progress in considering this problem, but the detailed nature of the transition between the two populations has been uncertain, which complicates any attempt at incorporating this into absolute age models. Our work supports the conclusion that basins from the mid-Nectarian onwards were dominated by Population 2 impactors. The radiogenic dates derived for the relatively late basins and the mare, and their associated crater frequencies, represent only the younger population and no confident calibration of a surface with the earlier population presently exists.

[53] At present, suggested ages exist for Imbrium, Orientale, Crisium, Nectaris and Serenitatis [see *Stöffler et al.*, 2006], although the youthful ages that have been interpreted to represent Serenitatis are certainly inconsistent with our preferred interpretation of its stratigraphy (see section 3.3.2 [see also *Spudis et al.*, 2011]). It remains plausible that many of the absolute ages for basins that have been assigned on the basis of samples actually relate to Imbrium because of its potential for having played a dominant role in

the sample collection [*Haskin et al.*, 1998]. In general, it is highly desirable to have further measurement of pre-Imbrian basins on the Moon to allow firmer translation of the relative frequencies that we derive (e.g., Table 1).

[54] What sample return sites would be best to visit to get additional calibration of the absolute timescale for the lunar surface? Although more samples are undoubtedly better, one candidate of interest for future sampling is the Freundlich-Sharonov basin. It is one of the oldest basins with a well-preserved topographic signature and only moderate resurfacing, and it does not appear to have been cratered to saturation equilibrium. It also has crater statistics that are quite similar to Nectaris, so it would potentially provide a 'second check' on ages derived on the lunar nearside. Along with clarifying the ages of nearside basins, future lunar exploration should seek to expand the sample collection to the lunar farside and deep into the impact basin record. Samples from within South Pole-Aitken that could address its absolute age, as well as potentially provide dates for other basins that superpose it, would also provide new calibration of the early lunar cratering record [see also *Norman*, 2009; *Joliff et al.*, 2010].

4. Summary

[55] We derive impact crater size-frequency distributions for 30 certain or probable D > 300 km lunar impact basins, which provide insight into the sequence, timing, and history of the Moon. Major findings are as follows:

[56] 1. The sequence for lunar basins compiled by *Wilhelms* [1987] remains supported by newly measured crater statistics (Table 1). However, this agreement is qualitative, not quantitative, and we measure systematically higher crater densities than found by Wilhelms (e.g., Figure 3).

[57] 2. The superposed population of impact craters on ancient lunar surfaces (i.e., the lunar highlands, Pre-Nectarian-aged basins) and later terrains (mare, Imbrian-aged and Nectarian-aged basins) are different (Figures 4–6). The shift in the dominant impactor population between these two eras took place by the mid-Nectarian, before the end of the period of rapid cratering.

[58] 3. Many Pre-Nectarian basins, including SPA, have crater densities consistent with saturation equilibrium. In this condition, crater densities become decoupled from the basin's relative and absolute age. In the case of SPA, stratigraphy suggests that it is the oldest observed basin, and it has a higher density of large craters than the broader highlands, but for craters in the ~20 km-64 km diameter range, it has a lower density than a variety of other basins. This is likely to be due to a combination of more abundant early volcanic resurfacing within SPA than previously suspected, and an unusually large number of superposed impact basins.

[59] 4. Crater statistics and observational stratigraphy using the new LOLA data suggest that Humboldtianum may be younger than Crisium, and that Serenitatis may be older than Nectaris (Figures 7 and 8). If this interpretation of the relative stratigraphy of Serenitatis is correct [see also *Spudis et al.*, 2011], then assigned absolute ages for these nearside basins need to be re-evaluated. Additional sample return of lunar basins would be very valuable to provide additional calibration of the absolute ages of lunar basins and test our current understanding of its impact history.

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