STRATIGRAPHY, SEQUENCE, AND CRATER POPULATIONS OF LUNAR IMPACT BASINS FROM LUNAR ORBITER LASER ALTIMETER (LOLA) DATA: IMPLICATIONS FOR THE LATE HEAVY BOMBARDMENT.

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Introduction: New measurements of the topography of the Moon from the Lunar Orbiter Laser Altimeter (LOLA)[1] provide an excellent basemap for analyzing the large crater population ($D \geq 20$ km)of the lunar surface [2, 3]. We have recently used this data to calculate crater size-frequency distributions (CSFD) for 30 lunar impact basins, which have implications for their stratigraphy and sequence. These data provide an avenue for assessing the timing of the transitions between distinct crater populations characteristic of ancient and young lunar terrains, which has been linked to the late heavy bombardment (LHB). We also use LOLA data to re-examine relative stratigraphic relationships between key lunar basins.

Method: We derive the CSFD for each basin by mapping preserved basin-related materials (the region proximal to and within the basin rim that has not been resurfaced by volcanism or other processes). We use a buffered area correction and include craters which are superposed on the basin but which are centered outside the count region [e.g., 4] This technique slightly expands our effective count area, since large craters subtend more area than small ones. It also allows exclusion of resurfaced regions from the mapped count area without losing information about craters superposed on the edge of basin material.

For crater data, we start with the catalog of lunar craters ≥20 km in diameter from LOLA data [2,3]. We then re-examined each basin using the 64 ppd LOLA DTM and shaded relief to systematically search for additional craters beyond the global database. In total, a modest number of additional craters were found (12%); these are generally small (<40 km) and degraded. Crater measurement are made with CraterTools [5]; all areas and diameters are computed using equal area map projections.

Stratigraphy: Our measurements provide a test of the widely-used Wilhelms [6] sequence of lunar basins. There is strong qualitative agreement between this earlier sequence and our new measurements. However, there are substantial quantitative differences in the crater densities we observe, particularly for older basins. For example, the N(20) (# of craters ≥20 km normalized to an area of 10^6 km^2) we derive for the Nectaris basin is 135±14 compared to Wilhelms's 79±14. This difference has implications for the cratering history of the Moon and the crater frequency of the Pre-Nectarian/Nectarian boundary: Wilhelms's data [6] would imply the Moon had ~1900 impacts ≥20 km between Nectaris and Imbrium, whereas our data would suggest that ~4000 such craters formed.

Impactor Populations and the LHB: There has been a long debate in lunar science about whether heavily-cratered highlands records a distinct population of impactors from the lunar maria [7,8,9,10,11]. Measurements of the CSFDs of the highlands and mare imply that the highlands have a lower ratio of ~20-40 km craters to ~80-100 km craters than the mare [9; see also 2]. This difference is statistically significant at 96% confidence when applying the two-sample Kolmogorov-Smirnov (K-S) test to their CSFDs.

This observation does not guarantee that the difference in CSFDs is a result of a shift in the impactor populations. An alternative is geologic processes such as volcanism or repeated cratering preferentially removed small craters on ancient surfaces in a manner that resulted in the observed change [10]. Although possible, this hypothesis seems less likely given that a similar shift in CSFDs is observed on Mercury [9, 12] and Mars [9] to what is observed on the Moon. Given their distinct geologic histories, there is no reason that crater removal on each planet should be similar.

Strom et al. [9] propose that the shift in crater populations is related to the LHB. They note that the early population (Pop. 1) is similar to what would be expected from direct delivery of a collisionally-evolved population like the Main Asteroid Belt, and the younger population (Pop. 2) matches well with the Near-Earth Objects, which have a 'flatter' shape on an R-plot than Population 1 and are delivered via a more size-selective process [13].

Our measurements of basin CSFDs allows us to examine when the hypothesized transition between populations occurred. We examine this change by aggregating the statistics of basins from a given period, since counting statistics of individual basins alone are insufficient to assess population differences. We combine the crater counts and areas for the Imbrian basins (including Imbrium; aggregate N(20) of 22±3), the Nectarian basins (including Nectaris; aggregate

N(20) of 110±5), and Pre-Nectarian basins (excluding SPA to avoid it dominating the statistics; N(20)=188±7).

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 (Fig. 1). The K-S test suggests that the Pre-Nectarian and Nectarian-aged basins are distinct from each other at the 94% confidence level.

These observations are surprising, since the transition from Population 1 to 2 has previously been linked to the transition from the LHB population to the modern population [9], and the basins formed during the Nectarian are commonly assumed to be part of the Late Heavy Bombardment. 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. If Population 1 dominated at that time, we would expect to see its signature in the Nectarian basin curve. 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. These data would suggest that the transition observed in the lunar impact crater population occurred earlier than has been previously suggested. It is unknown whether the transition between the two impactor populations was gradual or abrupt, but Population 1 cannot have remained the predominant source of lunar impacts as late as Imbrium.

Relative Stratigraphy of Lunar Basins: *Crisium and Humboldtianum:* The relationship between Crisium and Humboldtianum is uncertain despite their close proximity and good preservation state. LOLA data (Fig. 2a) suggest that secondary craters and sculpture from Humboldtianum reach to, or across, the outer ring of Crisium. These stratigraphic relationships, which agree with crater statistics, support the interpretation that Humboldtianum is younger than Crisium.

Serenitatis and Nectaris: The 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. In general early crater counting preferred an interpretation where Serenitatis was Pre-Nectarian [e.g., 14], 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 [15]. LOLA topography provides support for the interpretation that Serenitatis is older than Nectaris as well: (1) crater counting, which finds a crater density in the Taurus Mountains at a factor of two times that of Crisium or Nectaris, with more than sufficient counting statistics, and (2) evidence in LOLA topography for sculpturing from Nectaris on the south-eastern rim of Serenitatis near the Apollo 17 landing site (Fig. 2b-c).

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Fig. 1. R-plot showing the CSFDs for Pre-Nectarian, Nectarian, & Imbrian basins. Nectarian basins have a distribution consistent with the mare-like, Population 2. The Pre-Nectarian basins are more similar to Population 1. This suggests the transition from predominantly Pop. 1 to 2 happened by the mid-Nectarian, as the Nectarian basins primarily accumulated craters from Population 2.

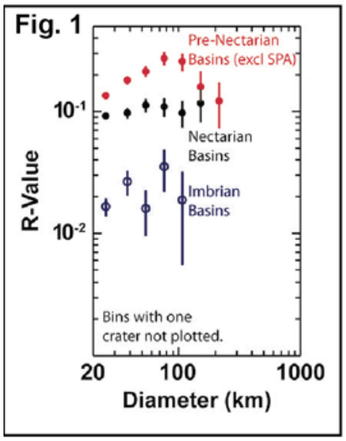

Fig. 2. (a) LOLA shaded-relief overlaid by topography, showing sculptured ejecta from Humboldtianum superposed on Crisium. (b) Context and (c) closeup views of the Serenitatis basin and Taurus mountains, showing potential sculpture from Nectaris superposed on Serenitatis.