GEOPHYSICAL EVIDENCE SUPPORTING AN EARLY AS WELL AS LATE HEAVY BOMBARDMENT ON THE MOON
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Summary: Evidence supporting an intense early bombardment on the Moon in addition to the traditional Late Heavy Bombardment at ~ 4 BY ago include the distribution of N(50) Crater Retention Ages (CRAs) for candidate basins, a variety of absolute age scenarios for both a "young" and an "old" Nectaris age, and the decreasing contrasts in both topographic relief and Bouguer gravity with increasing CRA.

Crater Retention Ages: N(50) Crater Retention Ages (CRAs) for an expanded inventory of large lunar basins [1-3] based on Quasi-Circular Depressions (QCDs) in LOLA data [2,3] and Circular Thin Areas (CTAs) from model crustal thickness [4,5] show two peaks, even when weaker candidates are eliminated [6] (Figure 1). The break between older and younger impact basins is pre-Nectarian [6], as others suggested based on a smaller number of basins [7], shown in Figure 2. This two peak distribution suggests the possibility of both an Early Heavy Bombardment [6] as well as the generally recognized Late Heavy Bombardment [8-10].

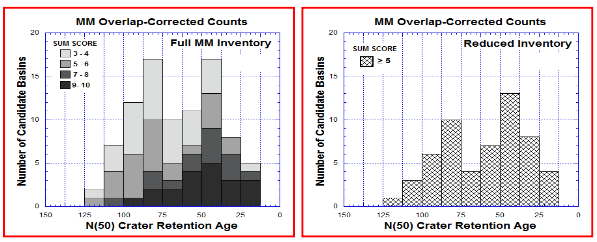


Figure 1. Distribution of Overlap-Corrected N(50) CRAs for an inventory of 90 candidate basins [11] (left), and for a much reduced inventory of 56 basins (right). Full inventory also shows distribution of summary scores (sum of topographic expression and crustal thickness expression scores) in grayscale. Weaker candidates shown in lighter shades. Reduced inventory eliminates new candidates [11] and all candidates with summary scores <5 out of a possible 10. Both inventories show an obvious two-peak distribution.

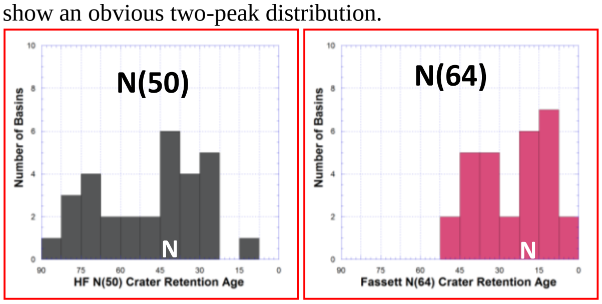


Figure 2. Distribution of N(50) CRAs (left) from Frey [1] (83 candidate basins) and N(64) CRAs (right) from Fassett et al. [7] (30 basins). Histograms have the same scale and bin size. Both show two peaks. The break between them is pre-Nectaris, the CRA for which is shown by the white N. This may suggest an Early as well as a Late Heavy Bombardment.

Absolute Age Scenarios: Absolute ages for most large lunar basin candidates are not known. Frey and McBride [12] presented scenarios for Model Absolute Ages (MAAs) using the few "known" absolute ages based on returned Apollo samples [13, references therein]. It was necessary to assume an age for the oldest inter-basin crust, several small areas of which were found to have N(50)~155, substantially older than the basin CRAs (Figure 1). An Assumed Oldest Age (AOA) of 4.5 BY was initially assumed, though cases with 4.4 BY were also considered. Results for full and reduced inventories were generally similar, but the MAAs depend greatly on the assumed age for Nectaris. If Nectaris is young (3.9 BY), the AA vs CRA relationship is a simple straight line and the two-peak distribution found in Overlap-Corrected N(50) CRAs is preserved, with peaks at ~3.9 BY and ~4.1 BY.

If Nectaris is 4.2 BY old, i.e. the source of the Apollo 16 impact breccia described by [14], the situation is more complex (Figure 3). The 4 basin points and the AOA point cannot be fit by a single straight line. A variety of scenarios were considered as shown in Figure 3. Results are shown in Figure 4.

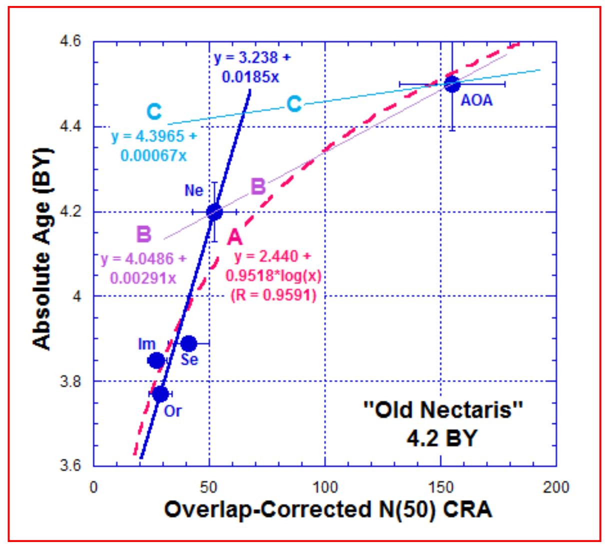


Figure 3. AA vs N(50) CRAs for Nectaris = 4.2 BY old. A = log(x) type fit to the 4 basins with known AAs and the Assumed Oldest Age (AOA) of 4.5 BY. B = two branch linear fit through Nectaris. C = two branch linear fit through the AA value on the younger branch at N(50) = 65 (the trough in the two-peak distribution of CRAs in Figure 1).

The **Case A** log(x) fit produces a most prominent peak at ~4.25 +/- 0.15 BY which is stronger than the secondary peak at 4.0 +/- 0.1 BY (Figure 4A). The **Case B** two branch, straightline fits through Nectaris push more basins to older ages (Figure 4B). A peak occurs at ~4.3 BY but is much more prominent than in A (the vertical scale is the same for all plots in Figure 4). There is a very much weaker peak at ~4.0 to 4.1 and a peak half this high at ~3.7 BY. The **Case C** two branch straightline fit through the AA on the younger branch at N(50) = 65 (the trough in the distribution of CRAs in Figure 1) results in a very large number of candidate basins with MAAs of 4.4-4.5 BY. The younger portion of the distribution is the same as in Case B, because the curve used over this CRA range is the same. Case C emphasizes the likely two population nature of the N(50) CRAs, but, like Case A and B, does NOT have a prominent and narrow peak at 3.9 BY. In all cases the older peak is more prominent.

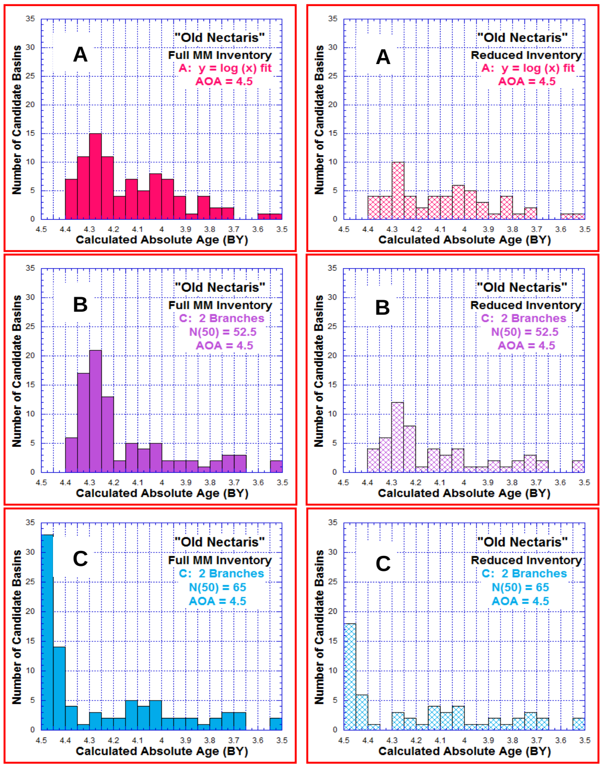


Figure 4. MAA distributions for the full inventory (left) and the reduced inventory (right) for the three "Old Nectaris" scenarios shown in Figure 3. See text for details. All three scenarios make the oldest peak the most prominent, and spread out the ages of basins younger than the 4.2 age for Nectaris into two weak peaks at ~ 4.1 and 3.7 BY.

Geophysical Contrasts. Contrasts in topographic relief and Bouguer gravity were derived from profiles through the candidate basins. Contrasts plotted versus Overlap-Corrected N(50) CRAs are shown in Figure 5. In both cases there is a general increase in contrast with decreasing CRA, as might be expected if earlier basins formed during a time when compensatsion of impact topography happened more easily.

There are reasons to eliminate points in the two plots. Figure 5A makes no correction for basins with significant mare fill or which occur in mare regions, where true basin relief may be underestimated. Figure 5B includes basins formed in extremely thin crust (e.g., SPA) and also unusually thick crust (Korolev, Dirichlet-Jackson, Hertzsprung, Fitzgerald-Jackson). Bouguer contrasts for these are are likely anomalous, as is that for SPA. Bouguer contrasts for the smallest basins (D<400 km) have low values and show no trend with age, suggesting they may have been too small to produce much contrast when formed. Both plots include cases where finding values from profiles is difficult and compromised by basin overlap. These are shown by smaller interior symbols in both plots. Removing these (and SPA, anomalous in both plots) produces the stronger trends in Figures 5C and 5D. Note some of the low contrast values at young ages in 5C are relatively weak candidates, so the actual trend in topographic relief may be even stronger than shown.

The older population has overall weaker contrasts than the younger population, consistent with the older basins forming early in lunar history when compensation of basin topography happened more quickly and thoroughly.

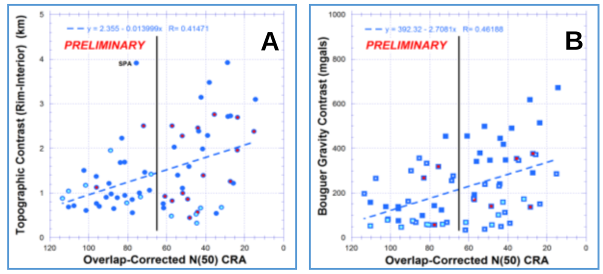
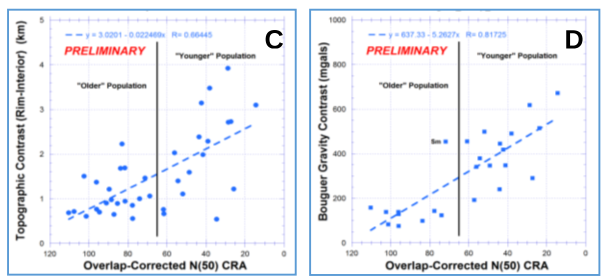


Figure 5. Above: Topographic (rim minus interior) contrast (A) and Bouguer gravity contrast (B) vs Overlap-Corrected N(50) CRA. Black vertical line shows separation between an older and younger population of large candidate impact basins, defined by the trough in Figure 1 and occurring at N(50) ~ 65. Linear fits to all the points shown; in both cases R ~ 0.4. Many of the points can be reasonably eliminated: these are marked with the interior symbols. Below: Without these likely anomalous points the trend toward increasing contrast with decreasing age is much stronger, with R ~ 0.6 for Topographic Relief (C) and ~0.8 for Bouguer Gravity (D).



Summary: The distribution of N(50) Crater Retention Ages (CRAs) for candidate basins, a variety of absolute age scenarios for both a "young" and an "old" Nectaris age, and the decreasing contrasts in both topographic relief and Bouguer gravity with increasing CRA are all consistent with an Early as well as a Late Heavy Bombardment, perhaps by two different populations of large diameter impactors.

References. [1] Frey, H.V. (2012) LPSC 43, abstract #1852. [2] Romine, G. and H. Frey (2011) LPSC 42, abstract #1188. [3]] Frey, H. V., H. M. Meyer and G. C. Romine (2012a) *Early Solar System Impact Bombardment II,* Abstract #4005. [4]] Wieczorek, M.A. (private communication). [5] Meyer, H.M. and H.V. Frey (2012) LPSC 43, abstreact #1936. [6] Frey, H.V. and E.E. Burgess (2013) LPSC 44 abstract #1606. [7] Fassett, C.I. et al., JGR (Planets) LRO special issue. [8] Tera, F. et al. (1974) Earth Planet. Sci. Lett. 22, 1-22. [9] Ryder, G. et al. (2002) in R.M. Canup and K. Righter (eds) Origin of the Earth and Moon, 475-492, Un. AZ Press, Tucson. [10] Ryder, G. (2002) JGR 107, 5022, doi: 10.1029/2001JE001583. [11] McBride, M.J. and H.V. Frey (2014) LPSC 45, abstract # 2150. [12] Frey, H.V. and McBride, M.J., LPSC 45, abstract # 1101. [13] Stoffler, D. et al. (2006) Chapter 5 in New views of the Moon, Rev. Mineralogy and Geochem., vol. 60. [14] Norman, M.D. and A.A. Nemchin (2104) Earth. Planet. Sci. Lett. 388, 387-398.