EMPIRICAL STUDIES OF LUNAR BOMBARDMENT AROUND 3.6-4 GY AGO. W. K. Hartmann, Planetary Science Institute, 1700 E Ft Lowell Rd, Ste 106, Tucson, AZ 85719-2395, USA, hartmann@psi.edu

Neither lunar nor asteroidal meteorite data, published to date (1-3), shows the sharp, narrow spike in impact-related materials, that Ryder (4) presented from Apollo impact-melts as proof of a sharp (150-My long) cataclysm at 3.9 Gy ago (and that was incorporated into an early version of the Nice model). What appears to be common to most lunar data sets is the difficulty of finding samples older than about 4.0 Gy – an observation which was cited along with Imbrium impact effects in the original 1970s papers that proposed the cataclysm (5). Figure 1 demonstrates these points.

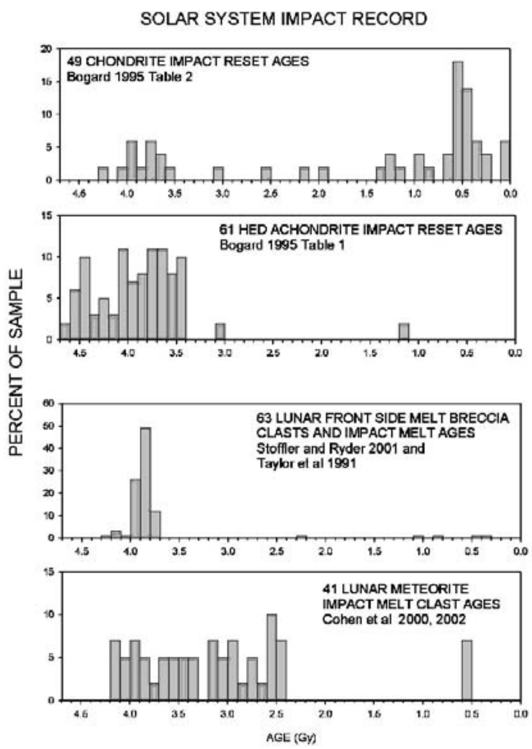

Figure 1. Age distributions for various impact-related samples. Asteroids (top two graphs) show a broad peak of impact ages from roughly 4.3 to 3.5 Gy, with chondrite samples dominated by a recent catastrophic breakup event at ~0.5 Gy. Lunar front-side Apollo impact melt rocks show a peak at about 3.8-3.9 Gy (the time of the Imbrium impact), but non-KREEP lunar meteorite impact-related clasts do not show show that peak. All lunar impact-related samples show a dearth of material pre-dating ~4.0-4.1 Gy ago.

Cratering data do show a decline in cratering rate from about 3.8 Gy to 3.5 or 3.0 Gy ago, from values at least a couple of orders of magnitude higher than today, as noted even in pre-Apollo data, when the phrase "intense early bombardment" or "EIB," was coined (6). An example of the effect of such a curve is shown in Fig. 2.

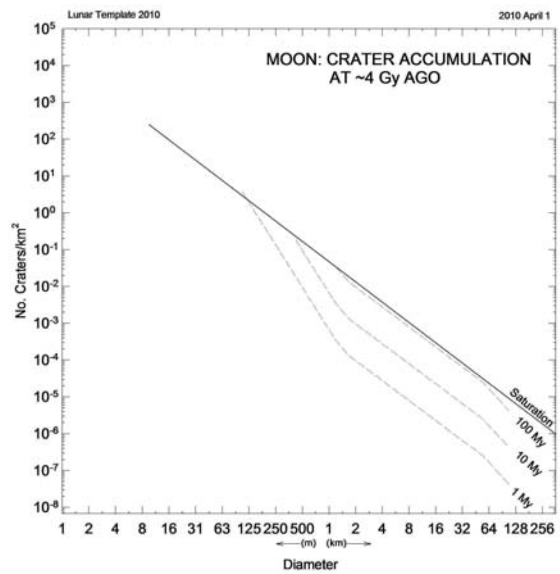

Figure 2. This crater size-distribution diagram uses an estimated cratering rate at about 4 Gy, extrapolated from observed cratering rates at 3.4-3.8 Gy ago. It shows that such a rate, crater densities would simultaneously approach saturation at crater diameters 2 km-60 km in geologically short intervals of order 100 My. The approach to saturation produces a catastrophic gardening and mega-regolith within ~100 My intervals, around 4 Gy. This means that samples on or near the surface, around 4 Gy ago, would be pulverized to regolith-like properties within 100 My, even without a Wasserburg/Ryder-type or Nice-type cataclysmic bombardment at that time. This effect may help explain the paucity of impact melt samples from before that time (cf. reference 3).

Modern interpretation of lunar samples, relative to cataclysm and basin formation, needs to involve more study of the relation between cratering rates, regolith evolution, and sample survival.

A new attempt is made here to measure the impact flux in the 200-300 My period between Imbrium impact and the tail-off of Imbrium mare emplacement. Note that the possibility has not been ruled out that the Orientale impactor was a satellite of the earth-crossing Imbrium impactor; if it missed the moon during the Imbrium impact event, it could have hit a few years later. It is thus not a firm parameter for claiming a very short period or sharp rate of decline for independent basin-forming impacts (though it has been so used).

The distinctive feature of the 3.8-4.1 Gy period of lunar history (in addition to the Imbrium impact) may be not a 150-My wide cataclysmic spike in cratering, but rather that the cratering rate across the whole size spectrum, before and/or during that time, was so high that rocks *placed on lunar surface* before then had much reduced chance of surviving intact to be collected or ejected to Earth today. Thus, the 4.0 Gy period is notable for marking the beginning of the easily-acquired sample record. This effect is shown in Fig. 3. In that view, the Nice-type scattering event may have been more smeared out in time, and may have been ending about 3.8 Gy ago. This is more consistent with the asteroidal record (3), and is also consistent with suggestions in 1987-90 that an "early intense flux" of scattered, black, outer solar system asteroids account for the number of black, probably-captured satellites, such as Phobos and Phoebe (7, 8), and also with new work on the Nice model, presented by Bottke in 2011 (9).

References: (1) Cohen B. A., Swindle T. D. and Kring D.A. (2000) Science 290, 1754-1756. (2) Cohen B. A., Swindle, T. D. and Kring D. A. (2005) Meteorit. Planet. Sci. 40, 755-777. (3) Hartmann W. K. (2003) Meteorit. Planet. Sci. 38, 579-593. (4) Ryder G. (1990) EOS 71, 313. (5) Tera F., Papanastassiou D. A., and Wasserburg G. J. (1974) Earth Planet. Sci. Lett. 22, 1-21. (6) Hartmann W. K. (1966) Icarus 5, 406-418. (7) Hartmann W. K. (1987) Icarus 71, 57-68. (8) Hartmann W. K. (1990) Icarus 87, 236. (9) Bottke W. F. (2011) DPS abstract #1884.

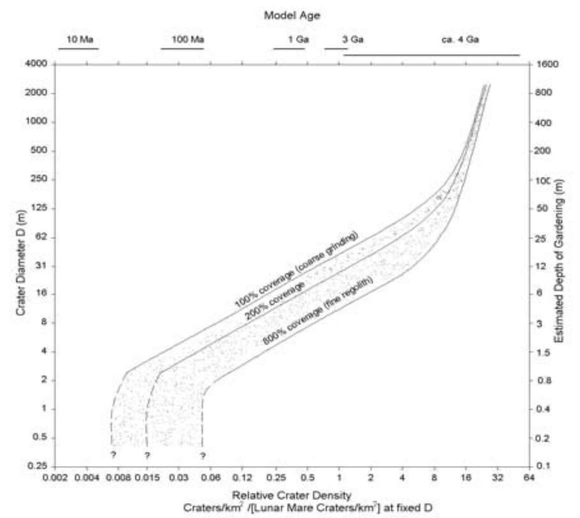

Figure 3. This diagram shows the explosive growth of mega-regolith as crater densities (abscissa, bottom) approach saturation values (about 32 × lunar mare crater densities, as observed in lunar highlands). At such crater densities (or higher), 100% of the area has high probability of having experienced formation of a multi-kilometer crater. (Curves for 200% and 800% represent high probability of multiple impacts of given crater size at a given site.) Right-hand ordinate scale indicates depths of expected regolith pulverization. These effects suggest why pre-4.0 Gy materials are found more often as clasts in impact melt breccias than as intact rocks.