WHAT ARE THE REAL CONSTRAINTS ON COMMENCEMENT OF THE LATE HEAVY BOMBARDMENT? C.R. Chapman[1], B.A. Cohen[2], and D.H. Grinspoon[1]. [1]Southwest Research Inst., #426, 1050 Walnut St., Boulder CO 80302 (cchapman@boulder.swri.edu), [2]Hawaii Inst. of Geophys. and Planetology, Univ. of Hawaii at Manoa, Honolulu HI 96822 (bcohen@higp.hawaii.edu).

Introduction: Early Apollo sample ages demonstrated an early intense bombardment by small bodies lasted until ~3.8 Ga, including a possible spike (Late Heavy Bombardment, or LHB) during a short interval just after 4.0 Gyr [1,2], which also affected other terrestrial planets [3,4]. Some data suggest the LHB affected asteroids [5] and Mars [6]. Recent dynamical models seek to explain the LHB [cf. 7,8]. Tera *et al*. [1,2] assumed that a histogram of radiometric ages directly reflected the flux of big impacts that reset rock ages. The assumption was later questioned [9,10]; it was proposed that a "stonewall" saturation of big impacts would have destroyed the pre-LHB record. Clearly, from rock ages ascribed (by geological inference) to several basins: many basin impacts happened from just ~3.90 Ga to 3.85 Ga but ended sharply with Orientale (3.82 Ga). But it is hotly debated Whether a similarly sharp rise in impact rate initiated the LHB.

Before Nectaris (probably 3.90-3.92 Ga), geological evidence is fragmentary. Impacts were so numerous during the LHB, little earlier geology remains for stratigraphy, crater counts, or to link with rock ages. The flux from crustal solidification until the LHB was much lower than during the LHB [argued by Ryder, 11], or perhaps similar or even higher. If lower, then the LHB was truly a "cataclysm"; otherwise, perhaps only a bump or inflection on a generally monotonically declining post-accretionary impact rate.

Some arguments favor a minimal pre-LHB flux. (1) A heavy flux would have pulverized and punctured the lunar crust, more than it is. However, this constrains only top-heavy size distributions, not if there were a cut-off near the sizes of the largest observed basins. (2) A heavy early flux would have contaminated the crust with more impactor signature than is found in samples. This suggestive argument is not robust, depending on the very uncertain projectile retention efficiency. (3) Most persuasively, Ryder [11] argues that the absence of old lunar impact melts, which would have been abundantly produced by early basin impacts, means that such impacts were rare; we evaluate this below.

Age Distribution of Impact Melts: Basin formation produces copious melts (~10% of involved materials); a supersaturation of such impacts would have yielded sufficient melts to be found by the astronauts [11]. Impact melts are produced more efficiently than rock ages are reset; yet, some rocks (including mare basalts) have ages (4.2-4.0 Ga) older than any melts, proving [11] that a "stonewall" can't explain lack of melts. However, >50% of all "definite" basins (and 2/3rds including "probable" and "possible") [12] occurred before Nectaris. Yet no impact melts pre-date 3.85 Ga (Imbrium) [11], though recent work [13] pushes them back to 3.92 Ga but not earlier. Why don't impact melts sample all the basins pre-dating Nectaris? We suggest that there must be a sampling bias favoring recent melts. Lack of still early impact melts would be for the same reason we don't see them from the numerous pre-Nectarian basins.

One potential bias, of course, is that Apollo and Luna samples are from the lunar front-side of the Moon, regions affected by Imbrium and other basins. Cohen *et al.* [14] dated melt clasts from lunar highland meteorites, probably lacking such bias. Within the limitations of statistics and age precision, they find no certain impact melt ages older than Nectaris, seemingly supporting Ryder's thesis. However, the Cohen data show something else: of 7 impact events sampled by lunar meteorite melt clasts, only 2 occurred during the LHB. Five occurred later (3.4-2.8 Ga), when no basins and few large craters formed. Therefore (a) despite diminished melt-production efficiency [15], smaller cratering impacts yield appreciable melts and (b) a very strong bias favors sampling of recent impact melts. Basins (more efficient melt producers) dominate volumetrically due to the "shallow" power-law size distribution. In particular, melt production should be dominated by events before 3.8 Ga because the impact rate was *hundreds* of times higher during the LHB (when a dozen basin-forming impacts happened, compared with zero). Thus we suspect that some process strongly biases against sampling older melts.

LHB and Meteorite Parent Bodies: Bogard [5] suggests a lunar-like LHB for both HED meteorites and possibly ordinary chondrites (OCs). But lunar highland rock ages (Ar-Ar and Rb-Sr) are >3.65 Ga (though a few not plotted are younger) and the vast majority (138 of 186) are 3.8-4.0 Ga (the LHB), while meteorite data are much more spread out. While 18 HEDs are 3.8-4.0 Ga, even more (27) are younger (3.0-3.7 Ga) and 16 are ≥4.1 Ga. Although old OC statistics are sparse, the 9 ages >3.1 Ga range 3.5-4.2 Ga, with less than half during the LHB (3.8-4.0 Ga). The sharp peak, <200 Myr long, in the rock ages defining the LHB "cataclysm" is just not mirrored in the meteorite data. In particular, the sharply declining lunar flux at ~3.8 Ga is not seen in the meteorite data, where ages are reset for another ~0.5 Gyr. (Age errors are typically <0.1 Ga.) Either a different LHB affected the asteroids (interasteroidal collisions following LHB-caused break-ups?) or sampling of asteroidal meteorites differs radically from lunar sampling.

A New Look at the "Stonewall": Repeated saturation of the megaregolith would have pulverized/destroyed rocks dating from epochs before saturation (integrating back in time), creating an apparent spike in the rock ages even if the flux had been declining monotonically [9]. Grinspoon's quantitative models [10] of this stonewall effect verify such a spike -- within the 2-D limits of his model . But these arguments' limitations potentially invalidate them. While saturation by basins certainly destroys pre-existing topography, older rocks do not thereby vanish. While the crust is fractured and comminuted, it remains composed of rocks. Because of the inefficiency of rock-age resetting, rocks with measurable ages should stretch back through multiple generations of saturation. As Hartmann *et al.* [16] put it, "it is patently not the case" that all rocks would have been reset or "pulverized to fine powder" so as to be unmeasurable.

Is Grinspoon's model unrealistically simplistic? It is a 2-D model in which all of a crater's interior is reset. Since impact-melting and resetting efficiencies are low, resetting the entire volume of crater materials would be wrong. But a 2-D model involves area not volume, so we must consider a 3-D model in which only a few percent (varying with crater diameter) of crater materials are reset. Sampling vitally depends on where melts and other re-set rocks are emplaced by the impact event and on how they are subsequent "churned" in the megaregolith. At one extreme, if melts were located uniformly throughout such a megaregolith, then sampling at the surface should yield melts in proportion to their formation rate; the melt age histogram would thus rule out much pre-Nectarian basin-formation, proving the cataclysm.

At the other extreme, deposition of melts only on the surface would resemble Grinspoon's 2-D model. Indeed, melts often preferentially veneer crater surfaces [17, 15]; shocked/melted materials are favored in higher-velocity, widespread surface-deposited ejecta. If 3-D modelling confirms this surface-deposition case, then surface sampling -- whether by astronauts or by lunar meteorite excavation -- would tend to sample recently produced melts since earlier ones are blanketed. Of course, under saturation and churning, such earlier melts stand some chance of being exhumed, so a complete dearth of old examples is not expected. Unlimited basin impacts would eventually convert all megaregolith to melt (a scenario not yet modelled quantitatively). In the extreme surficial deposition case, all melt-surface-veneering events would be represented back to when the integrated ejecta blanket area approaches saturation; this might explain why melts sample only the most recent third of observed basins (whose ejecta did not quite saturate the surface, or else we wouldn't see the 2/3rds of basins that are older). (Tera *et al.* [1] first mentioned and others [e.g. 18] restated the essential idea that sampling of rocks is biased toward Imbrium, an element of the late-event biasing we expect in the surficial deposition case.)

The surficial deposition case might vindicate the stonewall hypothesis. The difference is that physical, geological stratification of the lunar surface, not pulverization/destruction, that saturates and covers up older samples. Older samples are covered by basin ejecta and volumetrically mixed into the megaregolith; hence they are less likely to be sampled on the surface than melts deposited and left on the surface. The basic math of Grinspoon's model would thus apply. Still, super-saturation by basins would eventually build up sufficient melts to be found; thus the lack of ancient melts still contrains, although less restrictively than has been argued, the pre-LHB impact flux. Full 3-D modelling of the relevant processes is needed.

Doubt is thus cast on past arguments concerning pre-Nectarian impact rates. The sharp cessation of basin formation (3.85-3.80 Ga) cannot be doubted, however, and still strongly constrains any dynamical processes proposed to deliver the LHB impactors. Perhaps a rapidly decaying impactor source would have commenced with similar rapidity, causing a spike; but we assert that observational support for (or against) that supposition is lacking. We simply cannot know the pre-Nectarian lunar bombardment rate, pending 3-D modelling of relevant processes.

References: [1] Tera F. et al. (1973) *LS IV*, 723-725. [2] Tera F. et al. (1974) *EPSL, 22*, 1-21. [3] Wetherill G.W. (1974) *Proc. Soviet-American Conf. on Cosmochemistry of Moon & Planets* (LSI, Houston). [4] Wetherill G.W. (1975) *Proc. LSC 6*, 1539-1561. [5] Bogard D.D. (1995) *Meteoritics, 30*, 244-268. [6] Ash R.D. et al. (1996) *Nature, 380*, 57-59. [7] Morbidelli A. et al. (2001) *MAPS, 36*, 371-380. [8] Levison H.F. et al. (2001) *Icarus, 151*, 286-306. [9] Hartmann W.K. (1975) *Icarus, 24*, 181-187. [10] Grinspoon D.H. (1989). Sect. 2, Ph.D. thesis, UA, Tucson. [11] Ryder G. (1990) *Eos, 71*, 313 & 322-3. [12] Wilhelms D.E. (1987) *USGS Prof. Paper* 1348, 302 pp. [13] Dalrymple G.B. et al. (2001) *LPS XXXII*, #1225. [14] Cohen B.A. et al. (2000) *Science, 290*, 1754-1756. [15] Cintala M.J. and Grieve R.A.F. (1998) *MAPS, 33*, 889-912. [16] Hartmann W.K. et al. (2000) In "Origin of the Earth and Moon" [UA Press, Tucson] 493-512. [17] Melosh H.J. (1989) "Impact Cratering: a Geologic Process." (Oxford Univ. Press, N.Y.) 345 pp. [18] Haskin L.A. et al. (1998) *MAPS, 33*, 959-975.