THE HEAVY BOMBARDMENT OF THE MOON.

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Introduction: The ancient lunar crust bears testimony of an early (>3.7 Ga) period that is characterized by frequent hypervelocity impacts of 10´s to 100´s km sized projectiles that detonated ~40 basin sized (>300 km diameter) impact structures into the lunar crust [e.g., 1]. By implication, a larger number of such massive impact events affected the early Earth [2], but the traces of these events are erased by crustal recycling of our geological active planet. An important debate in lunar and planetary science relates to the period of time during which these lunar basins formed. The finding that ~3.9 Ga old impact reset rocks were collected on all 6 Apollo landing sites gave rise to the concept of a strong "Late Heavy Bombardment (LHB)" or "terminal lunar cataclysm" where most or all of the basins formed during a <200 Ma time interval centered around 3.9 Ga [3-6]. The LHB hypothesis gained popularity with dynamical models presenting celestial mechanisms for a "late" reconfiguration of the Solar System architecture that could provide abundant projectiles for such a "late" event [7, 8].

However, the interpretation that the Apollo and Luna samples and lunar meteorites bear evidence for a "terminal lunar cataclysm" is repeatedly criticized [i.e. 9- 11]. Currently the dominance of ~3.9 Ga ages in Apollo and Luna mission samples is thought to be due to either 1) the resetting of the different radiogenic chronometers (e.g. Rb/Sr, Ar/Ar) around 3.9 Ga by a large number of impacts at that time [i.e. 12], or 2) because all Apollo missions mainly sampled Imbrium ejecta [9,10].

In order to contribute to the aims of the lunar community for acquiring a more comprehensive view of the impact history of the Earth-Moon system, we briefly 1) revisit the first 800 Ma of lunar history, 2) review radiometric ages (including correction for K-decay and monitor ages as appropriate; [13-15]), 3) review petrography of Apollo and Luna samples and 4) discuss four different approaches for constraining the time interval during which the lunar basins formed.

1) Relating impact melt rocks to specific basins by geological arguments – The Nectaris case -

The age of the Nectaris basin (and it difference in age to Imbrium basin) is considered key for testing the putative LHB [16]. Proposed ages for Nectaris formation range between 4.2 Ga [17] and 3.85 Ga [18]. The assignment of a 3.9 Ga [19] and 3.85 Ga[18] age for Nectaris are based on formation age (minimum age given by the youngest clast within the breccia) of rock sized breccias collected on the rim of the North Ray Crater (NRC). Later, Norman et al. [20] reported KREEP-rich impact melt clasts of 3.85 Ga within some of the NRC breccias. They concluded that this breccias bear no information for the age of Nectaris, because the KREEP signature should be indicative of Imbrium derived ejecta.

A 4.2 Ga age was proposed for Nectaris to account for the variety of lithologies related to the Descartes formation [17]. In addition, different publications report rocks with impact reset ages up to 4.3 Ga for samples collected by Apollo 16 astronauts [21, 22], (Fig. 1). Thus, the Moon surface was impacted before 4.0 Ga ago. Moreover, a variety of impact craters, including basins Tranquilitatis, Nectaris, Serentiatis and Imbrium, delivered material to the Apollo 16 landing site. Thus, relating individual samples collected from the lunar surface with a specific impact basin will always be ambiguous. Therefore, additional information is required to constrain the heavy bombardment of the Moon.

The lunar curst: Understanding the formation, thickening and cooling of the lunar crust is essential to constrain the:

1) formation time when impacts could leave lasting marks, i.e., it provides a maximum age for lunar basins.

2) thickening time after which the crust was too thick for the delivery of meteoritic PGE´s to the mantle by even the largest impact events, i.e., the 0.02 % of lunar mass equivalent of meteoritical material required to explain the chondritic PGE signature in lunar basalts [23] had to be delivered before that time .

3) cooling time of the lunar crust which increases viscosity and by this the support for retaining the topographic relief of impact structures for the past ~4 billion years [i.e. 9. 24].

2) Time estimates based on geological independent processes:

In order to estimate the time lapse between formation of different basins Baldwin [9, 24] argued that the ages of lunar basins can be deduced by comparing the topographic relief of the impact structures (categorized from young to old correspond to class 1 to 10, respectively). The older crater structures (>161 km diameter) that formed in a less viscous (warmer) lunar crust would display a higher degree of topographic smoothing compared to younger crater structures that formed on a cooler and thus a more supportive lunar crust. At about 3.7 Ga ago, the viscosity of the lunar crust had increased to high values allowing it to support the prominent topographic relief of Imbrium and Orientale for billions of years. Baldwin [9, 24] argued that the prominent morphological differences of Orientale (class 2) and Nectaris (class 7) require that the latter basin to be older by a few 100´s Ma.

3) Impact exhumation scenario: Basin-sized impacts into a warm and less viscous lunar crust [9, 24] would be consistent with an impact exhumation scenario for some lunar rocks by considering: 1) crystallization in deep and warm crustal areas with an open system behaviour for some isotopic systems, followed by impact-exhumation by large impacts, and then cooling on or near the lunar surface. This impact exhumation scenario can explain the difference between the Sm-Nd crystallization age and the K-Ar age for FAN rock 60025 with crystallization at 4.44 Ga and resetting of the K-Ar system at ~4.2 Ga [25-27]. It could also explain the 4.36 Ga Pb-Pb age, and 4.32 Ga ^{146}Sm-^{142}Nd ages reported recently for 60025 [28] within the petrological context of the standard lunar magma ocean (LMO) model. The standard LMO model [29, and refs. therein] interprets FAN rocks as flotation cumulates that formed during crystallization of the LMO. Hence, the FAN rock 60025 must have formed earlier than the 4.36 Ga Pb-Pb ages since the LMO crystallization is constrained to have been completed before 4.42 Ga ago, as given by the isotopic age of the KREEP reservoir [29]. The impact excavation model could explain the isotopic age of FAN rocks being younger than the reservoir age of the KREEP source. 60025 could have formed early (>4.42 Ga) during the LMO crystallization at deep crustal levels where temperatures remained for an extended period above the closing temperatures of the different isotopic systems. The 4.2 Ga Ar-age of FAN rock 60025 [21,22, 25-27] would then date the time of a basin sized impact.

4) Impact age frequencies for meteorites from the Moon and the asteroid belt can provide another test for an extreme intense bombardment during a putative LHB. Statistical age distribution for impact reset H and L chondrites and HED [30] and lunar [11] meteorites provide no evidence for a brief (<200 Ma) and extremely high impact rate centered around 3.9 Ga. Instead, the ages distribution shows a similar number of impact ages between 4.2 and ~3.0 Ga.

Conclusion: The currently available lunar impact record dates back to [at least] 4.3 Ga ago. The lithologic variety of impact reset rocks older than 4.0 Ga show that not all basins formed around 3.9 Ga ago. Despite that some of the large lunar basins (Imbrium and Orientale) formed “late”, it has to be seriously considered that a large number of lunar basins formed are older than 4.0Ga (see also [59], i.e., could reasonably be part of the tail end of planetary accretion [60].

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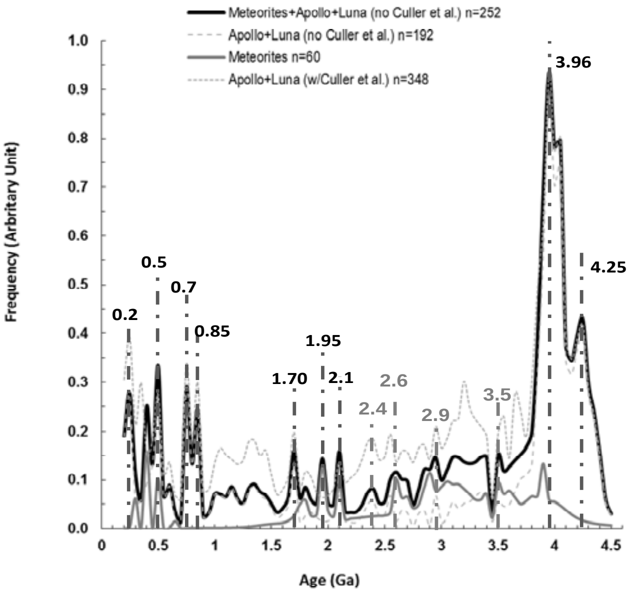

Figure 1: Gaussian probability curve calculated using published ^{40}Ar/^{39}Ar impact ages obtained for samples from Apollo 12, 14, 16 and 17 and Luna 16 and 24 missions [26, 27, 31-47] and lunar meteorites [7, 48-58]. To calculate this curve, the sample age and error were combined in bins of 0.05 Ga (50 Ma) which is representative of the average error in ^{40}Ar/^{39}Ar age determination. Where necessary, the age was corrected for monitor age and decay-constant. The thick black line is the cumulative impact ages for Apollo, Luna and meteorites and does not include the [41] due to uncertainty in the glass origin, i.e., volcanic or impact. However, for comparison, the same line with the [41] data is plotted and shown using the thin dotted line.