THE LUNAR CATACLYSM HYPOTHESIS: STATUS AND PROSPECTS.

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Introduction: Early studies of impact melt breccias from the near-side equatorial regions of the Moon showed a pronounced clustering of crystallization ages between 3.75 and 3.95 billion years, corresponding to an episode of intense crustal metamorphism defined by U-Pb isotopic compositions of lunar anorthosites. This was a major and unexpected discovery that produced competing hypotheses for the early impact flux to the Moon and by implication to the early Earth.

In one scenario, the impact flux increased dramatically at ~3.9 Ga, creating several of the lunar basins during a 'late heavy bombardment' (LHB) [1,2,3]. Alternatively, the impact flux may have declined more steadily with relatively minor temporal fluctuations since formation of the Moon's crust. In this scenario the apparent clustering of impact breccia ages may be due to destruction or burial of older deposits by ejecta from more recent events [4,5].

Clarifying the impact history of the Moon would have significant implications for understanding the dynamical history of the Solar System, environmental conditions on the early Earth, and for calibrating the absolute ages of planetary surfaces from crater counts.

Ages of Lunar Impact Melts: Ryder considered the lack of impact-melt crystallization ages older than ~4.0 Ga to be strong evidence supporting a late cataclysm [3]. The clustering of ages, textures, and bulk compositions in Apollo 15, 16, and 17 melt breccias [6,7] shows that several impact events sufficient in size to generate crystalline impact-melt breccias occurred within the interval 3.75 to 3.95 Ga, and that such events were relatively rare after about 3.75 Ga. Differences in ages and initial ^{87}Sr/^{86}Sr ratios of crystalline impact-melt breccias from the Apollo 14 and 16 sites [8] supports the idea that multiple events created coarse-grained melt deposits on the Moon within an interval of ~200 Myr.

Ar-Ar ages of lunar meteorites and regolith glasses confirms a general lack of melt ejecta older than 4.0 Ga in the near-surface lunar regolith [9,10,11] but the significance of this observation is mitigated by our poor understanding of regolith dynamics [5]. The predominance of relatively young ages (≤3.5 Ga) in the lunar meteorites and regolith glasses contrasts to the near-absence of hand-specimens with ages <3.75 Ga, and may suggest that the two types of sample suites are sampling different cratering regimes with meteorite clasts and regolith glasses dominated by crater populations that produced relatively modest volumes of impact melt and the hand-specimens sampling larger craters and basins.

Recently, Norman et al. [12] measured a 147Sm-143Nd isochron age of 4.20 Ga on Apollo 16 crystalline breccia 67955. Their interpretation that this dates a discrete melt-forming impact event weakens Ryder's argument somewhat, but the significance of a single sample for the lunar cratering history prior to 3.9 Ga is difficult to assess. Turner [13] presented statistical arguments that a genuine gap in lunar impact ages between 4.2 and 3.9 Ga would favor an increased cratering rate at 3.9 Ga. To the extent that the Apollo 16 breccias are a representative sampling of the lunar surface, the current distribution of impact melt breccias ages does seem consistent with such a gap, but the record is obviously sparse and the possible role of late basin-forming events on resurfacing the nearside region of the Moon needs further clarification [4,5].

Ages of Lunar Basins: The absolute ages of most lunar basins are effectively unknown. Despite the best efforts of mission planners, only Apollo 17 successfully sampled a geologically well-constrained impact-melt deposit that can be linked with confidence to a major basin. This is reflected in the relatively modest uncertainties in the age of 3.87-3.89 Ga assigned to Serenitatis by [14]. The age of Imbrium is reasonably well established at 3.77-3.85 Ga but relies more critically on interpretation of samples collected at the Apollo 14 and 15 sites whose geological context is less well established [14].

Absolute ages of older basins such as Nectaris are even more uncertain and potentially of greater importance in evaluating the LHB scenario. An age of 3.92 Ga is often cited for Nectaris [14], but this depends on the interpretation of the Apollo 16 Descartes Formation as Nectaris ejecta, and assignment of Ar ages derived from soil particles of unknown provenance to a specific basin. Alternatively, the Descartes Formation may have been emplaced as Imbrium ejecta [15], an interpretation supported by the KREEPy geochemical signatures of clasts from the Descartes breccias (implying a provenance in the Procellarum-KREEP Terrane) [16,17], and the concordance of Ar-Ar ages measured on anorthositic clasts from these breccias with the generally accepted age of Imbrium [14,18].

To illustrate the implications of this uncertainty in basin ages, Fig. 1 shows three model curves for the pre-Imbrium impact flux to the lunar crust. The curves were obtained by converting crater density data for lunar basins with D > 300 km [20,21] to absolute ages pinned to three sets of plausible ages for Nectaris and South Pole-Aitken (SPA) and an age of 3.85 Ga for Imbrium [19]. Nectaris represents a stratigraphically intermediate-age basin with well-preserved geological relationships to the other central nearside basins such as Imbrium, Serenitatis, and Crisium, whereas SPA is the oldest basin on the Moon.

The ages assumed for this analysis included (1) t_{SPA} = 4.4 Ga, t_{Nec} = 4.1 Ga, (2) t_{SPA} = 4.2 Ga, t_{Nec} = 3.95, and (3) t_{SPA} = 4.0 Ga, t_{Nec} = 3.9 Ga (Fig. 1). These particular ages for Nectaris and SPA were guided by the recent result for 67955 on the assumption that larger basins are more likely to be sampled because they produce the largest volumes of impact melt, Wilhelms' [20] preference for a 4.2 Ga age of SPA, and recent proposals citing an age of 4.1 Ga for Nectaris [22,23].

For all three sets of age assumptions the crater density data apparently imply an episode of **early** heavy bombardment in which the cumulative crater diameter (flux) increases rapidly in the interval between SPA and the Keeler-Heaviside (KH) basin (Fig. 1).

The evidence for a **late** (post-Nectaris) cataclysm is model-dependent and relies critically on the assumed age of Nectaris relative to SPA and Imbrium. The case for a Late Heavy Bombardment would be strongest if SPA is quite young (~4 Ga; curve 3). In this case, all of the lunar basins would have formed in an interval of about 250 million years and the heavy bombardment between SPA and the KH basin could be part of an extended late cataclysm that would have been most intense early in the sequence of lunar basins and tapered off somewhat after the KH basin formed (Fig. 1).

If SPA and Nectaris are both relatively old (curve 1), the post-KH cratering history appears like a sequence of steps with a relatively constant and gentle slope. This scenario provides little support for a late cataclysm between 3.95 – 3.75 Ga, in which case the predominant clustering of lunar impact melt ages must reflect a near-side equatorial geographical selection effect or a bias in preservation such as the burial of older deposits by younger ejecta [4,5]. A modest post-Nectaris increase in cratering flux seems to be implied if the age of Nectaris is <4 Ga (curve 2) and would be even more apparent if ages of 4.4 Ga and 3.95 were assigned to SPA and Nectaris, respectively. This illustrates the critical necessity of accurately defining absolute ages of stratigraphically intermediate lunar basin for constraining the LHB hypothesis.

Sampling Targets for Future Missions: A better understanding of the early impact history of the terrestrial planets is one of the priority science goals for solar system exploration, so where to go on the Moon to obtain clearer tests of the LHB hypothesis will be an important consideration for science goals during the next phase of lunar exploration. SPA provides an attractive exploration target because it is the oldest recognized basin on the Moon and because the pre-Nectarian basins Australe, Ingenii, Poincare, Planck, and Apollo basins all occur within or proximal to SPA. Quantitative ages for any of these basins would vastly improve our understanding of the impact history of the lunar crust and the early Earth, and provide a test of the late heavy bombardment hypothesis.

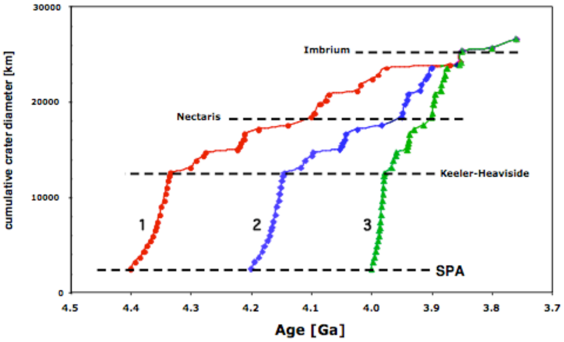

Figure 1. *Cumulative crater diameter vs. model age of lunar basins as a proxy for cumulative impact flux. After Norman and Lineweaver [19].*

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