New Perspectives on the Lunar Cataclysm from Pre-4 Ga Impact Melt Breccia and Cratering Density Populations

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Abstract

Crystallisation ages of impact melt breccias from the near-side equatorial regions of the Moon show a pronounced clustering between 3.75 and 3.95 billion years. This age distribution was unexpected and produced competing hypotheses for the early impact flux in the inner Solar System. In one scenario the impact flux increased dramatically at ~3.9 Ga. In this 'late heavy bombardment' scenario several of the nearside lunar basins formed within a relatively brief interval of time (200 million years). A late cataclysmic bombardment would have significant implications for Solar System dynamics perhaps involving migration of the outer planets. Alternatively, the impact flux may have declined steadily with relatively small fluctuations since formation of the Moon. In this scenario older impact deposits were destroyed and/or buried by more recent events.

Recently, Norman et al. (2007a) measured an absolute age of 4.20 $\pm$ 0.07 Ga on an Apollo 16 crystalline breccia that they interpret as an impact melt breccia. This is the first definitive evidence for a discrete melt-forming impact event older than 4.0 Ga that has been documented from the Apollo lunar sample collection, but the significance of a single sample for the lunar impact cratering history prior to 3.9 Ga is difficult to assess. A genuine gap in major impact events between 4.2 and 3.9 Ga would constitute strong evidence favouring a late cataclysm (Turner, 1979) but the effects of megaregolith evolution and burial bias on the age distribution of sampled impact melt rocks needs further clarification (Hartmann, 2003; Chapman et al., 2007).

As a complementary approach we evaluated the early lunar impact flux using crater densities preserved within large basins. This analysis provides strong evidence for a steep cratering flux early in the stratigraphic sequence of lunar basins but the implications for changes in the cratering flux through time depends on the absolute ages of lunar basins, which are not well established. A late cataclysm would be strongly supported if the South Pole Aitken (SPA) basin, stratigraphically the oldest basin on the Moon, has an absolute age not much older than the younger basins (i.e. ~ 4 Ga). Older assumed ages for SPA (e.g. 4.4 Ga or 4.2 Ga) produce cratering flux curves indicating an early heavy bombardment, and weaker evidence for a late cataclysm. The absolute age of stratigraphically intermediate basins such as Nectaris are critical for interpreting the cratering evidence for a late cataclysm, but are poorly constrained by current data.

Introduction

A better understanding of the early impact history of the terrestrial planets is one of the priority science goals for solar system exploration (Space Studies Board, 2003; Norman et al., 2007b). More specifically, ascertaining whether or not the Earth and Moon experienced a cataclysmic Late Heavy

Bombardment (LHB) of impacting planetesimals ~ 3.9 billion years ago remains an open question with significant implications for understanding the dynamical history of the inner Solar System and environmental conditions on the early Earth, and for inferring the absolute ages of planetary surfaces from crater counts.

Here we review key lines of evidence derived from the characteristics of lunar samples that tend to support the late cataclysm hypothesis, and we discuss a new interpretation that a specific type of lunar breccia may represent impact melts formed prior to the major nearside basins. If this interpretation is correct, the crystallization ages of these pre-Nectarian impact melt breccias may provide quantitative constraints on the lunar cratering record prior to 3.9 Ga. We then present a new analysis of crater density populations preserved within lunar basins that suggests previously unrecognised structure in the lunar cratering flux prior to ~ 3.9 Ga.

Was There a Late Cataclysm?

A major, unexpected discovery obtained from geochronological studies of lunar impact melt breccias was the predominance of ages between 3.8 and 4.0 Ga. The strong clustering of impact melt crystallization ages defined by ^{40}Ar-^{39}Ar incremental-heating plateaus and isochrons (Turner and Cadogan, 1975; Swindle et al., 1991; Dalrymple and Ryder, 1993, 1996; Cohen et al 2000; Norman et al., 2006) and Rb-Sr mineral isochrons (Papanastassiou and Wasserburg, 1971, 1972) from the Apollo 14, 16, 17, and Luna 20 sites and lunar meteorites corresponds to an episode of intense crustal metamorphism defined by U-Pb isotopic compositions of lunar anorthosites (Tera and Wasserburg, 1974; Tera et al., 1974). Based on the isotopic data, Tera *et al*. (1974) proposed that "highland samples from widely separated areas bear the imprint of an event or series of events in a narrow time interval which can be identified with a cataclysmic impacting rate of the Moon at ~3.9 Ga". Subsequent studies by Grenville Turner, Graham Ryder and colleagues (Turner and Cadogan, 1975; Turner, 1979; Stöffler and Ryder, 2001; Ryder, 2002; Ryder et al., 2002) developed the idea of a late cataclysmic bombardment of the Moon in greater detail, arguing for a spike in the mass flux to the Moon (and by analogy the Earth) at ~3.8-4.0 Ga, with at least 15 of the ~ 44 recognised lunar basins (diameters ≥300 km; Wood 2004) forming within a relatively brief interval of 100-200 million years.

The idea of a late heavy bombardment of the Moon is controversial. Hartmann (2003) proposed that the age distribution of lunar impact melts is also consistent with a steadily declining impact flux, with the record of older impacts being erased by younger events either through physical destruction of the older impact breccias or burial by younger impact deposits. Arguing against the 'megaregolith reworking' model are geological, petrological, and geochemical observations which show that large regions of the lunar crust preserve a primary structure likely established early in lunar history, and that the ancient lunar crust was not comminuted and mixed to great depth by a continuously declining post-accretionary bombardment. For example, thick layers of pure anorthosite, probably formed during initial lunar differentiation, are exposed in the rings of some lunar basins (Hawke et al., 2003), and the global geochemical and geophysical data obtained by the Clementine and Prospector spacecraft missions demonstrate significant vertical and lateral heterogeneity within the lunar crust rather than a well-mixed megaregolith (Jolliff et al., 2000; Wieczorek and Zuber, 2001; Petro and Pieters, 2004). Examples of cm-size clasts of lunar basalt and anorthositic igneous rocks with ages of 4.2 to 4.5 Ga and textures indicating they formed within ~0.5 km of the lunar surface (Taylor et al., 1983; Dasch et al.; 1987; Norman et al., 2003) show that some fraction of the ancient lunar crust that formed near the surface must have survived the early bombardment, but the implications of this observation for the early impact history will require significant advances in our understanding of regolith dynamics on the Moon (Chapman et al., 2007; Hartmann, 2003, pers. comm.)

Haskin et al. (1998) raised several objections to the notion of a LHB and argued that most of the mafic, KREEP-rich lunar impact-melt breccias were created by the Imbrium event, the largest and one of the youngest lunar basins. They suggested that the narrow range of $^{40}Ar/^{39}Ar$ ages of the mafic melt breccias is due to their formation in a single large event, probably the Imbrium basin-forming impact, with the apparent spread of ages from 3.8 to 4.0 Ga reflecting complexities in the breccias (e.g. incomplete degassing, inherited clasts) that introduce artefacts or biases in the measured ages (Haskin et al., 1998). It is, however, implausible that a single event could have produced the entire range of textures, compositions, and clast populations observed in lunar impact-melt breccias with ages of 3.8-4.0 Ga. Especially informative is the correlation of ages, textures, and compositions that has been documented recently in Apollo 16 melt breccias (Norman et al. 2006). This clustering shows that several impact events sufficient in size to generate crystalline impact-melt breccias occurred within the interval 3.75 to 3.95 Ga. The range in crystallization ages (3.84-3.95 Ga) and initial $^{87}Sr/^{86}Sr$ ratios (0.69920-0.70035) defined by Rb-Sr mineral isochrons on crystalline impact-melt breccias from the Apollo 14 and 16 sites (Papanastassiou and Wasserburg, 1971, 1972) also supports the idea that multiple impact events occurred on the Moon within ~ 100 Myr.

Identification of Lunar Impact Melts Older than 4 Ga

The lack of impact-melt breccias with crystallization ages older than ~4.0 Ga has been cited as one of the primary lines of evidence supporting a lunar cataclysm (Dalrymple and Ryder, 1993, 1996; Ryder, 2002; Ryder et al., 2002). Therefore, identification of older impact melt rocks and determination of their crystallization ages would provide an important constraint on the lunar impact cratering history. We suggest that ancient impact-melt breccias do exist in the lunar sample collection but they have not been recognised previously. Two examples of potential impact melt rocks that may be significantly older than the Imbrium basin are the crystalline anorthositic breccias 67955 and 77017, which were collected from the Apollo 16 and 17 sites, respectively (Hollister, 1973; Ashwal 1975).

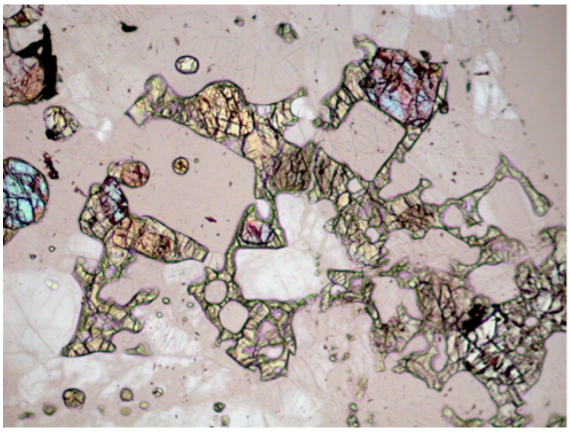

Figure 1. Photomicrograph of lunar sample 67955 illustrating the predominant melt texture of the rock as indicated by euhedral to subhedral plagioclase and olivine crystals, and poikilitic interstitial pyroxene. Field of view is ~1 mm wide.

Hollister and Ashwal interpreted these rocks as igneous cumulates but later work classified as them as ‘granulitic impactites’ (Lindstrom and Lindstrom, 1986; Cushing et al., 1999), and they have largely been ignored in discussions of lunar impact melt rocks (Vaniman and Papike, 1980; Korotev, 1994). However, the combination of well-preserved melt textures (Fig. 1) and the high concentrations of siderophile elements present within FeNi metal grains in textural equilibrium with the host melt rock (Norman et al., 2007b) suggested to us an origin of these rocks as impact melts. To test this proposal we conducted a geochemical and geochronological study of sample 67955 to define its crystallisation age.

Crystallisation age of 67955

^{147}Sm/^{144}Nd vs. ^{143}Nd/^{144}Nd isotopic compositions of plagioclase, pyroxene and whole rock splits from 67955 define an age of 4.20 $\pm$ 0.07 Ga. Norman et al. (2007a) interpreted this as the primary crystallisation age of the rock and proposed that it directly dates an impact event on the lunar surface. This would be the first discrete melt-forming impact event demonstrably older than 4.0 Ga to be recognized from a sample in the Apollo collection. This impact was probably a sizable event, as indicated by the coarse-grained, slowly cooled texture of 67955 (referred to as ‘plutonic’ in earlier descriptions; Hollister, 1973; Ashwal 1975), although we have not attempted to estimate the size of the parent crater. Rb-Sr and U-Pb isotopic compositions of minerals in 67955 are consistent with this age but these systems are more disturbed by later shock and heating events (Norman et al., 2007a). ^{40}Ar-^{39}Ar compositions have been highly disturbed by a very young, essentially zero-age diffusive loss of ^{40}Ar, demonstrating a complex post-crystallisation history of this sample on the lunar surface.

The implications of this new result for interpretations of the lunar LHB are not necessarily straightforward. Our new age determination of 4.2 Ga for crystalline impact melt breccia 67955 based on a ^{147}Sm-^{143}Nd mineral isochron shows that earlier discussions of the lunar impact record emphasizing the lack of events significantly older than 3.9 Ga (Ryder, 2002; Ryder et al., 2002) needs to be revised (Hartmann et al., 2007; Chapman et al., 2007). Turner (1979) presented statistical arguments that a genuine gap in lunar impact ages between 4.2 and 3.9 Ga would constitute strong evidence favouring a rise in the cratering rate at around 3.9 Ga. To the extent that the Apollo 16 breccias represent a representative sampling of the lunar surface the current distribution of impact melt breccias ages does seem consistent with such a gap, but the possible effects of resurfacing of the nearside region of the Moon by late large impacts such as the Imbrium and Serenitatis basin-forming events may introduce a sampling bias favouring exposure of younger deposits (Chapman et al., 2007). Obviously with only one documented lunar impact event at 4.2 Ga the record is sparse and far from complete. We have, however, demonstrated that it is possible to lift the veil of the late overprint and begin to see into the earlier impact history of the Moon.

Crater Density Populations

As an alternative approach and to help evaluate the implications of this 4.2 Ga date for a late heavy bombardment, we revisited lunar crater-count data. We reconsidered the cratering density data for deposits associated with large pre-Nectarian and Nectarian age lunar basins with diameters D > 300 km (Wilhelms 1987, Tables 8.2, Fig 8.6, Table 9.3 and Fig. 9.22 -- crater diameters are taken from Wood, 2004). Based on the density of craters with diameters > 20 km present within basins and a variety of age-dependent over-lap features, Wilhelms recognized 28 basins (D > 300 km) older than Nectaris and younger than South Pole-Aitken (SPA, the oldest recognisable basin on the Moon).

Wilhelms (1987) expressed more confidence in his ranking of the relative ages of his nine pre-Nectarian age groups and of his two Nectarian age groups than in an absolute sequence of basins based solely on crater densities: "ranking of groups is more certain than ranking within a group." Here we extend Wilhelm's analysis by using crater densities to estimate the time elapsed between impacts. One complication that we faced was that ~5%-10% of the basins in Wilhelms' younger groups have a higher impact density within them than some craters in Wilhelms' older groups. Assuming the relative sequence of Wilhelms' groups are correct, this must be due to factors such as statistical fluctuations, saturation effects, incomplete preservation, or secondary cratering (see Fig. 8.6 and 9.22 of Wilhelms 1987). We therefore modified these anamolous crater densities so that the use of crater densities as an age proxy would respect Wilhelms' ranking of age groups. These modifications were as small as possible and were within the Poisson uncertainties of the data (uncertainties shown by the fluctuations in the cumulative number of craters as a function of crater size, Wilhelms 1987, Figs 8.6 and 9.22).

We then performed a conversion between crater-densities (which yield fairly robust relative ages) to absolute ages assuming t_{Imb} = 3.85 Ga for the age of the Imbrium impact (Dalrymple and Ryder, 1993), and using three sets of plausible calibration ages for SPA and Nectaris: (1) an older set with t_{SPA} = 4.4 Ga and t_{Nec} = 4.1 Ga, (2) an intermediate set with t_{SPA} = 4.2 Ga and t_{Nec} = 3.95 and (3) a younger set with t_{SPA} = 4.0 Ga, t_{Nec} = 3.9 Ga. We adopted an age of 3.75 Ga for Orientale, the youngest lunar basin, but it has could be as old as 3.84 Ga (Stöffler and Ryder, 2001). Fixing the age of Nectaris was chosen for this analysis because it represents a stratigraphically intermediate-age basin with well-preserved geological relationships to the other central nearside basins such as Imbrium, Serenitatis, and Crisium. Selection of these particular sets of ages for Nectaris and SPA, which correspond to the three curves plotted in Figure 2, were guided in part by the result for 67955 on the assumption that larger basins are more likely to be sampled because the largest basins produce the largest volumes of impact melt.

To convert from crater density to absolute age, we assumed a constant cratering rate $R_{SPA-Nec}$, between SPA and Nectaris, and a constant cratering rate $R_{Nec-Imb}$ between Nectaris and Imbrium. Thus,

$$R_{SPA-Nec} = \Delta\rho/\Delta t = (\rho_{SPA} - \rho_{Nec}) / (t_{SPA} - t_{Nec})$$

$$R_{Nec-Imb} = \Delta\rho/\Delta t = (\rho_{Nec} - \rho_{Imb}) / (t_{Nec} - t_{Imb})$$

where $\rho_{Nec} = 79$ is the Nectaris crater-number density, i.e., the number of craters with D > 20 km, per million square km inside of Nectaris.

To obtain an absolute age t_i for a pre-Nectarian crater from the density of craters ρ_i within it, we used:

$$t_i = t_{Nec} + (\rho_i - \rho_{Nec}) / R_{SPA-Nec}$$

Similarly, to obtain an absolute age t_i for a pre-Imbrium (post-Nectarian) crater we used:

$$t_i = t_{Imb} + (\rho_i - \rho_{Imb}) / R_{Nec - Imb}$$

The crater density ρ_{SPA} of SPA was not listed in Wilhelms (1987) possibly because of saturation effects. It cannot be much lower than 215 because of the measured crater densities inside craters that are inside SPA. For this analysis we assumed that $\rho_{SPA} = 215$ and $\rho_{SPA} = 250$. This range of values does not change the implications of Figure 2 for the late cataclysm.

For all three sets of age assumptions the data strongly suggest an episode of **early** heavy bombardment in which the cumulative crater diameter (flux) increases rapidly in the interval between SPA and the Keeler-Heaviside basin (Fig. 2). In addition, Wilhelms (1987, p 157) writes: "Procellarum, South Pole Aitken, and at least 14 now-obliterated basins formed between crustal solidification and the oldest of the 28 pre-Nectarian basins of groups 2 through 9." If we were to include Procellarum and these 14 other (so far undiscovered) basins in Figure 2, the early heavy bombardment at, and subsequent to, SPA would be even more prominent. For our assumed age calibration this corresponds to period of a ~50 Myr after SPA. To the best of our knowledge, this evidence for an early heavy bombardment has not been recognised previously in the lunar data.

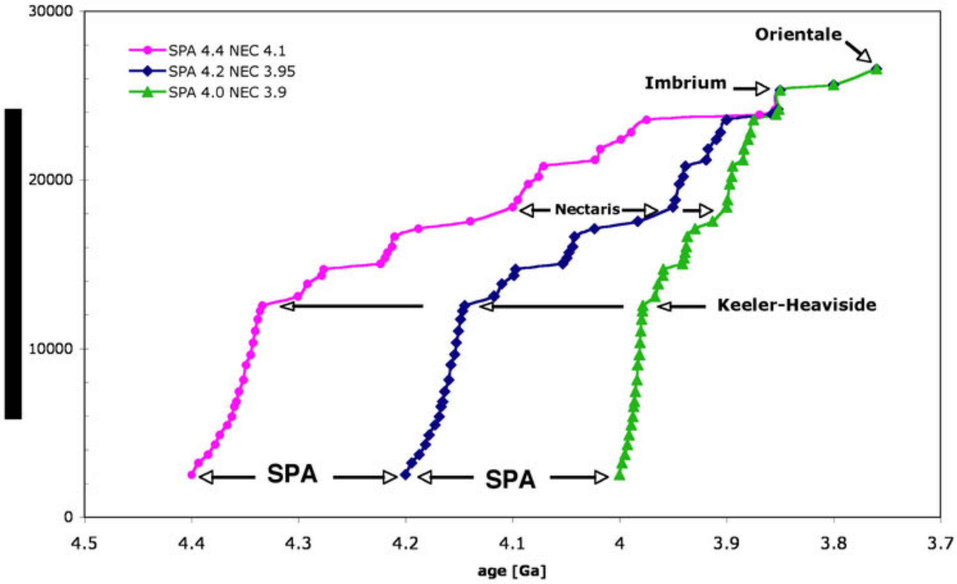

Figure 2 Cumulative crater diameter is a useful proxy for cumulative impact flux. The density of smaller craters (D>20 km) within the larger basins (D > 300 km) have been used to convert relative ages to absolute age estimates for three different plausible assumptions about the absolute ages of SPA and Nectaris. The steeper the slopes of the curves, the heavier the bombardment. The evidence for a late cataclysm is strongest if SPA is young (~ 4 Ga) and part of the late cataclysm. If SPA is older (either 4.2 or 4.4 Ga), the data suggest an early heavy bombardment between SPA and the Keeler-Heaviside basin. Inference of a late cataclysm depends critically on the assumed age of Nectaris.

The evidence for a **late** (post-Nectaris) cataclysm is more model-dependent and relies critically on the assumed age of Nectaris relative to SPA and Imbrium. The evidence for a late heavy bombardment is strongest if SPA is quite young (~4 Ga; age set #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 Keeler-Heaviside 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 Keeler-Heaviside basin formed (Fig. 2). While such an episode of intense cratering would certainly have been catastrophic, there may be problems delivering such a large amount of material to the inner Solar System in such a narrow interval of time (Bottke, et al., 2007).

If SPA and Nectaris are both relatively old (4.4 and 4.2 Ga, respectively; age set #1), the high-flux episode between SPA and Keeler-Heaviside basins remains as a robust result and the post-Keeler-Heaviside cratering history appears like a sequence of steps with a relatively 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 (Chapman et al., 2007).

A post-Nectaris increase in cratering flux also seems to be implied if the age of Nectaris is <4 Ga (Fig. 2; age set #2). This is shown by the increased flux immediately after Nectaris relative to the time between Nectaris and the Keeler-Heaviside basin, and would be even more apparent if ages of 4.4 Ga were assigned to SPA and 3.95 Ga to Nectaris. Recent reviews of lunar geology have assigned an age of ~3.95 Ga to Nectaris based on radiometric ages obtained from some Apollo 16 samples (the landing site closest to Nectaris) and interpretation of Apollo 16 site geology (Stöffler and Ryder, 2001) but recent work has questioned this, proposing both older ages for Nectaris (~4.1 Ga; Korotev et al., 2002; Warren, 2003) and reinterpretations of Apollo 16 site geology (Norman et al., 2007a). This illustrates both the current uncertainty in the age of Nectaris, and the critical necessity of accurately defining the absolute age of a stratigraphically intermediate lunar basin for constraining the LHB hypothesis.

Sampling targets for future missions

New manned and robotic missions to the Moon over the coming decades will provide opportunities for returning suites of lunar samples from previously unexplored terranes, and for conducting in-situ experiments that will better define the impact history of the Earth and Moon. 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. The South Pole-Aitken basin (SPA) provides an attractive exploration target for many reasons. SPA is stratigraphically the oldest basin on the Moon, and our lunar crater analysis suggests that the age of SPA will provide strong evidence for the LHB hypothesis if it is very young (~4 Ga). Ages of 4.2-4.4 Ga will provide useful constraints on the integrated cratering curve but will provide a less-definitive test of the LHB hypothesis.

Alternatively, the age of a stratigraphically intermediate basin such as Nectaris may provide a more diagnostic test of the cataclysm. The Australe, Ingenii, Poincare, Planck, and Apollo basins are all pre-Nectarian in age and they occur within or proximal to SPA. These basins may provide attractive exploration targets if a south pole lunar outpost proceeds. 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 better test of the late heavy bombardment hypothesis.

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