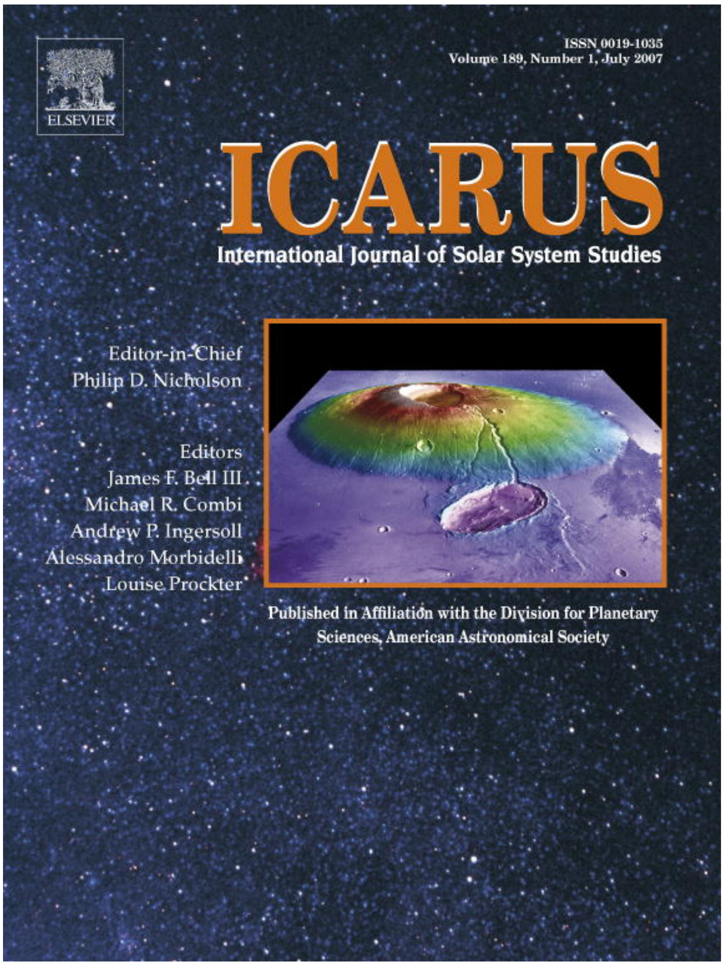
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What are the real constraints on the existence and magnitude of the late heavy bombardment?

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Abstract

Geochronological evidence for and against a late heavy bombardment (LHB) spike in impact rates on the Moon and meteorite parent bodies is re-examined. In particular, we find that the sampling of impact melts on the Moon is strongly biased against older examples, possibly due to preferential surface deposition of such melts and/or blanketing and burial by basin ejecta (arguments that the bias might be due to pulverization of old impact melts at depth are incorrect). The apparent absence of melts older than 4 Ga thus provides much weaker evidence for a pre-nectarian lull in bombardment (which would define a post-nectarian cataclysm) than has been argued, although their absence compared with other rocks from depth may remain a weak constraint. Differences in rock-age histograms between meteorite parent bodies and the Moon may imply that different sampling biases exist for bodies in the asteroid belt; otherwise, the more straightforward interpretation is that the bombardment that affected the asteroids was more long-lasting than the lunar LHB. Since the strongest constraint on the dynamics of source populations for the LHB remains the very rapid decline in rate of basin formation from 3.90 to 3.85 Ga, we must re-establish that the associations of dated samples with particular basins are robust. Further studies of processes that can bias sampling are warranted, in particular more quantitative modeling of regolith and megaregolith evolution. In summary, we find that constraints either for or against the lunar cataclysm as a spike in the bombardment rate that commenced shortly before the formation of Nectaris are very weak. There may or may not have been a lull in bombardment before 3.9 Ga. Only the rapid decline in bombardment rate after Imbrium is fairly secure and can be adopted as a constraint to be matched by various dynamical scenarios for the impact history of the Moon.

Keywords: Cosmochemistry; Cratering; Geological processes; Impact processes; Moon, surface

1. Introduction

Tera et al. (1973, 1974) first proposed, on the basis of a spike in resetting ages of Apollo samples, that a "terminal cataclysm" or late heavy bombardment (LHB) had occurred on the Moon about 4 Ga. The LHB has more recently been advocated on the basis of a spike in ages of lunar impact melts, or at least by an absence of secure impact melt ages prior to 4 Ga (Ryder, 1990, 2002; Bogard, 1995; Dalrymple et al., 2001; Cohen et al., 2000). Dates for lunar impact basins [Wilhelms (1987), updated by Stöffler and Ryder (2001); we adopt their "new set a" in their Table VI] from Nectaris (3.90 ± 0.03 Ga; conceivably as old as ∼4.1 Ga) to Imbrium (3.85 ± 0.02 Ga), indicate that bombardment ended suddenly; only Orientale formed ∼10–80 Myr later, defining an especially abrupt post-spike decline or cessation of bombardment by large projectiles (half-life <50 Myr). The basin ages are derived from resetting ages of rocks, which are inferred to have been derived from, or affected by, the particular basin-forming events (reviewed by Stöffler and Ryder, 2001). As we will discuss, the evidence concerning bombardment history prior to Nectaris is quite incomplete; there is much debate about whether the post-accretionary bombardment rate ∼4.4–4.0 Ga was light, in which case the LHB was a comparatively large spike in bombardment rate, or instead the rate was heavy, so that the most salient feature of the

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LHB is that its end marks a sudden decline after a long history of bombardment.

The LHB has played a significant role in planetary science since it was proposed to have happened on the Moon. When craters and basins were found on Mercury by Mariner 10, it was argued that many of them dated from the same epoch as the lunar LHB (Murray et al., 1975; but see Chapman, 1976). Indeed, since heliocentric impactors that strike the Moon are scattered around the inner Solar System, it has generally been presumed that all terrestrial planets—including Earth—were heavily bombarded at the same time, which has important implications for the early geological and biological evolution of Earth. The presumption also is the basis, in the absence of datable returned samples, for some commonly adopted absolute stratigraphic chronologies for both Mercury and Mars (Venus observable geology occurred much later). Indeed, when Voyager discovered the heavily cratered surfaces of many moons of Jupiter and Saturn, the LHB concept was extrapolated to the outer Solar System (cf. Smith et al., 1981) and it still underpins a minority view of Ganymede's chronology (Wagner et al., 1999). Bogard (1995), Swindle and Kring (2006), and others have argued that the LHB may be observed in some classes of meteorites and thus it affected the asteroid belt.

There were early attempts (cf. Wetherill, 1975, 1977) to provide a dynamical explanation for the LHB. Recently several new dynamical hypotheses for the LHB have been published, based on remarkable developments in dynamical simulations (cf. Morbidelli et al., 2001; Levison et al., 2001; Chambers and Lissauer, 2002; Gomes et al., 2005); all of these involve dynamical evolution or disturbance of heliocentrically orbiting populations of small bodies, whose subsequent impacts might have affected all of the terrestrial planets or even all solid-surfaced bodies in the Solar System. A very different perspective, that the LHB might have been due to a population of impactors trapped in geocentric orbits left over from the formation of the Moon (Ryder, 1990), would have very different implications: the timing of the LHB on the Moon could not then be extrapolated to other planets, except the Earth. Perhaps the new proposal of Cuk et al. (2006) that the LHB impactors were lunar trojans would result in the Earth and Moon being mainly affected, not other planets. Clearly, the existence, nature, and origin of the LHB have potentially profound implications for the early history of the Solar System generally.

Some proposals for how an LHB spike might be produced have been effectively disproven. For example, quantitative simulations of collisional break-up of a large main-belt asteroid and evolution of its fragments to cause the LHB show that such an asteroid would have to be implausibly large to have been broken up (Ito and Malhotra, 2006; also see Levison et al., 2001). Bottke et al. (2007) argue that it is essentially impossible for long-lived inner-Solar-System planetesimals to have remained so plentiful 0.5 Gyr after Solar System formation to explain the LHB, as proposed by Morbidelli et al. (2001). We point out that none of the current dynamical models for the LHB *require* that such an event happened *at the time that it did*. The Gomes et al. (2005) scenario (the "Nice Model") may explain numerous other features of the architecture of the Solar System, but its explanation of the LHB is argument in reverse: they accept that there was an LHB spike at 3.9 Ga, and tune their simulations to be compatible with that. Other choices for parameters in their model could have an LHB-like spike occurring as early as 4.3 Ga or as late as 3.4 Ga. While the likelihood that such an event occurred at some point may be regarded as high because other features of the Solar System are explained, and while the lunar cratering record precludes it having happened later than 3.8 Ga, the available lunar evidence cannot tell us about an event as early as 4.3 Ga (or even 4.1 Ga). So a bombardment spike could have happened early on, while different cratering scenarios would have to account for whatever happened subsequently.

Our goal in this paper is not to evaluate what might have caused a cataclysm, or disprove such hypotheses. Rather, we focus on the observational and laboratory data, mainly concerning the Moon but also the asteroids and other bodies, that constrain the actual evidence for the LHB. There are some fledgling arguments involving zircons that may support a cataclysm affecting the Earth around 3.95 Ga (Trail et al., 2006), near or before the time that Nectaris formed. On the other hand, there remain long-standing arguments against an LHB. For example, Baldwin (1987, 2006) has long argued that the degradation states of lunar basins require a multi-hundred-million-year time span between the formation of Nectaris and Imbrium, much longer than is inferred from lunar sample ages. His plausible argument against a cataclysm depends on the assumption that the degradation of lunar basins was due to viscosity of the lunar crust. However, if the degradation was instead due to superimposed cratering and ejecta blankets, then his arguments are undermined.

In this paper, we critically analyze the chief sample-age evidence for the cataclysm on the Moon, which has dominated the pro-and-con debates since the hypothesis was first proposed. The evidence mainly consists of "resetting ages" of lunar rocks; these ages include crystallization ages for impact melt rocks and resetting ages for the less complete modification of other rocks due to metamorphism in hot basin ejecta blankets. We also discuss, to some extent, the evidence that the cataclysm affected meteorite parent bodies. Our goal is to determine how robust the lunar constraints are so that we may gauge the range of allowable dynamical explanations. In order to define the relevant dynamical parameters (e.g., rise times and decay times of the spike in terrestrial planet bombardment rates) that might distinguish between proposed impactor *populations* (e.g., outer Solar System planetesimals, trojans of one or more planets, main-belt asteroids, remnant planetesimal populations from the terrestrial planets, circum-terrestrial remnants of the Moon's formation) and the *dynamical processes* that might have caused such a spike (e.g., formation of Uranus/Neptune, shifts in the positions of the outer planets, ejection of a fifth terrestrial planet, collisional break-up of a large planetesimal or protoplanet), it is prudent to revisit the original lunar analyses that have defined the LHB.

At the outset of this work, we considered that the consensus in the literature is that the sharp decline in bombardment rate from the high rate between 3.90 and 3.85 Ga to the low rate more recently than 3.85 Ga is believed to be a powerful constraint on dynamical explanations for the LHB, but that evidence for the commencement of the LHB is weak, or at least controversial. While the LHB was too intense to have been simply part of a smoothly declining impact flux from the Moon's origin to the present, there is a large range of conceivable bombardment histories prior to the LHB. Perhaps the bombardment rate was much lower than during the LHB, as argued by Ryder (2002), or there may have been no impacts at all (assuming all pre-nectarian basins were formed just before Nectaris and marked the beginning of the LHB spike). Perhaps there was constant bombardment at the LHB rate from the solidification of the lunar crust at 4.45 Ga (Norman et al., 2003) until 3.85 Ga, which would involve accretion of just ~0.1% of the Moon's mass. Or the bombardment rate could have been much greater than during the LHB. If the rate was lower than during the LHB, then the LHB was truly an exceptional "cataclysm"; otherwise, perhaps it was only a bump or inflection on a generally monotonically declining post-accretionary impact rate. As we will show, the constraints on most aspects of the LHB are generally weaker than many have believed.

2. The late heavy bombardment as a "cataclysm"

Tera et al. (1974) advocated a cataclysmic spike in bombardment history as the explanation for widespread Pb loss and an associated spike in Rb–Sr and Ar–Ar resetting ages of lunar rocks. Tera et al.'s assumption was subsequently questioned by Hartmann (1975) and Grinspoon (1989), who proposed that a "stonewall" saturation of big impacts would have destroyed or hidden the pre-LHB record. What has not been strongly disputed is the sharp decline in impact rates at the end of the LHB, inferred from rock ages believed (by geological inference) to record the formation ages of several basins combined with stratigraphic relationships among these and other basins. It appears that 10–12 basin-forming impacts happened during the nectarian (Wilhelms, 1987) from just ~3.90 Ga to 3.85 Ga but that the bombardment ended sharply thereafter, with only Orientale occurring a little bit later (perhaps ~3.82 Ga). Later cratering by smaller projectiles continued to decline by another order-of-magnitude (based on crater counts) until about 3.4 Ga, after which the cratering flux has been roughly constant to within a factor of ~2 (see Fig. 1). While there remain uncertainties in exactly how sharp the decline in bombardment rate was at the end of the LHB, the hot debate concerns whether a similarly sharp rise in impact rate initiated the LHB. Prior to Nectaris (~3.90 Ga), the geological evidence is fragmentary. Impacts were so abundant during the LHB that little earlier geology remains for stratigraphic studies, crater counts, or linkages with rock ages.

Several arguments have been advanced in favor of 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; the crust would not be punctured (e.g., revealing olivine-rich mantle rocks) if there were a cut-off in the size distribution near the sizes of the largest observed basins (see Section 5 below). (2) A heavy early flux would have contaminated the crust with more siderophile-rich impactor signature than is found in lunar samples. This suggestive argument is not robust because of the very uncertain projectile retention efficiency (see Section 5 below). (3) The accreted mass cannot have exceeded some reasonable fraction of the mass of the Moon itself, or of the mass of the lunar crust. (4) The most persuasive argument (Ryder, 1990, 2002) has been 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 the evidence supporting this argument in Section 3, immediately below.

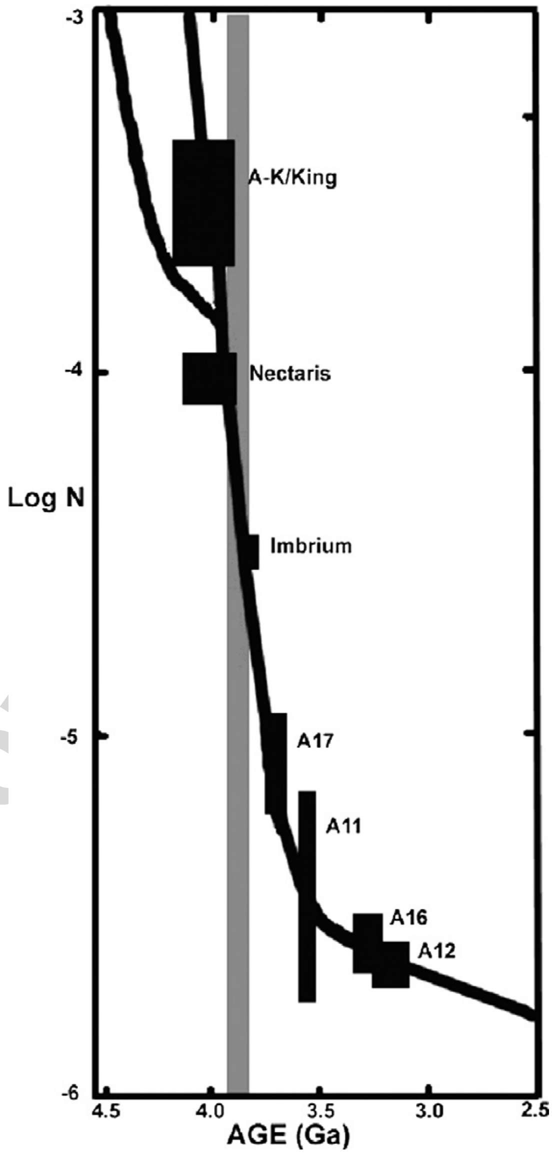

Fig. 1. Declining crater densities versus time, after Wilhelms (1987). N is the cumulative number of craters >20 km diameter per sq. km. The thin gray bar is the period of the well-defined late heavy bombardment, between the formation of Nectaris and Imbrium, when a dozen lunar basins were formed. Two extensions to the upper left indicate schematically either a lull prior to a cataclysm or a continued high bombardment rate in pre-nectarian times.

Some of these arguments can be, and have been, enhanced since they were first published. We have better understandings of how rock ages are reset and of the cratering process generally, more measurements have been made of lunar samples, and so on. Here, we discuss some of the major remaining uncertainties concerning the most relevant arguments for and against a uniquely cataclysmic LHB. The dynamical requirements to explain pulses of various durations differ from those that might explain a sharp cessation of an enduring bombardment. In either case, the timescales for the pulse or cessation (whether a few tens of Myr or several hundred Myr) may implicate very different populations and processes as being responsible for the LHB.

3. Age distribution of impact melts

One of the strongest arguments favoring a cataclysmic LHB is that advanced by Ryder (1990, 2002) that the virtual absence of impact melts older than ∼4.0 Ga in the lunar sample collection rules out extensive basin formation during earlier times. The argument is that formation of basins is expected to efficiently produce copious impact melts, perhaps as much as tens of percent of the lunar materials involved, and that a supersaturation of basin-forming impacts would have produced a substantial volume of such melts, some of which should have remained to be collected by the Apollo astronauts. Ryder argued that the dominant materials with impact-reset ages are melt rocks, not other kinds of rocks; yet, he noted, occasional lunar rocks (including mare basalts) have been found with ages of 4.2 to 4.0 Ga, older than the melts, proving that not all older materials are necessarily hidden or destroyed by whatever processes might cause the hypothesized "stonewall." [The possibility has been raised that impact melts might be preferentially easier to destroy than other lunar rocks, but this is viewed as unlikely (Swindle and Kring, 2006).]

We find that there are potential problems with Ryder's argument. More than half of all "definite" basins enumerated by Wilhelms (1987) occurred prior to formation of Nectaris, which is generally believed to date from 3.90 ± 0.03 Ga. [A minority perspective (Wetherill, 1981; Warren, 2003) holds that Nectaris is appreciably older, ∼4.1 Ga, which would lengthen the duration of the LHB by at least a factor of 3 and lessen the peak impact rate.] Indeed, if one includes Wilhelms' "probable" and "possible" basins, two-thirds of all recognized basins predate Nectaris. (Still more basins presumably formed earlier than those tabulated by Wilhelms and were wholly obscured by overlapping subsequent basins; otherwise it would be a coincidence that the duration of processes that degrade basins to the point of invisibility corresponds exactly to the duration since the beginning of basin formation.) Yet, Ryder (1990) emphasized that no impact melts pre-date 3.85 Ga (the age of Imbrium); subsequent work has pushed a few impact melt ages back closer to 4.0 Ga but not earlier [except, see Norman and Taylor (2005), Norman et al. (2005), who claim to have found an older one, but interpret its existence as somehow *favoring* a cataclysm]. Why is there such a dearth in representation of all the impact melts that must have been created during formation of all of those pre-nectarian basins? Clearly, for some reason, there must be a sampling bias strongly favoring collection of impact melts formed by the most recent basins. Whatever factors have caused undersampling of all of Wilhelms' pre-nectarian basins—which we *know* were formed and must have made abundant impact melts—could also be responsible for the absence of impact melts from still more ancient times. In other words, the same argument cataclysm supporters use to say that there were few basin impacts prior to the cataclysm (dearth of impact melts) would say that the pre-Nectaris basins should not exist ... but they do!

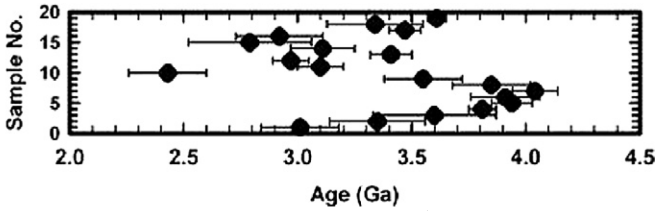

Fig. 2. Ages of small impact melts from lunar meteorites (Cohen et al., 2000). Only data having 1σ errors <0.3 Gyr are shown. There are no ages surely older than 3.9 Ga but many ages are younger than the LHB, down to less than 3 Ga.

One potential sampling bias, of course, is that Apollo and Luna samples are from the front side of the Moon and preferentially from regions prominently affected by Imbrium. The dominance of Imbrium in the geologic record of regions studied by Apollo astronauts was emphasized in a series of papers by Haskin and his associates (cf. Rockow and Haskin, 1996; Haskin et al., 1998, 2002a). In an effort to study a less geographically restricted region, Cohen et al. (2000) dated impact melt clasts from lunar meteorites (highlands breccias), which would not be likely to show an Imbrium- or front-side-bias. Within the limitations of small statistics and limited age precision, they find no certain impact melt ages older than Nectaris, qualitatively similar to age histograms of front-side impact melts.

However, when looked at closely, the Cohen et al. data (Fig. 2) show something else that is remarkable: only one-quarter of the impact events sampled by the lunar meteorite melt clasts have ages during the LHB. The majority have ages hundreds of Myr later, to as recently as 2.8 Ga, a period when no basins—and few large craters—formed on the Moon! It must be that (a) cratering events smaller than basin-forming events generate appreciable impact melt and (b) that there is a very strong bias favoring the sampling of recent impact melts. Of course, smaller impact craters do produce impact melts, but there are convincing reasons for expecting that the formation of impact melts is dominated by basins: (a) the efficiency of impact melt production is a function of crater size (cf. Pierrazo et al., 1997; Cintala and Grieve, 1998; Cushing et al., 1999; also see discussion on pp. 504–505 of Hartmann et al., 2000) with efficiency probably down by a factor of a few for large craters compared with basins, and (b) the cumulative volume of material affected by basins greatly exceeds the volume affected by smaller impacts because of the relatively "shallow" power-law approximation to the lunar impactor size distribution at these sizes. Of course, the overwhelming factor that should result in dominance of impact melt production prior to 3.8 Ga is that the impact rate was *hundreds* of times higher during the LHB than at ∼3.5 Ga—resulting, of course, in about a dozen basin-forming impacts compared with zero. Yet LHB impact melt

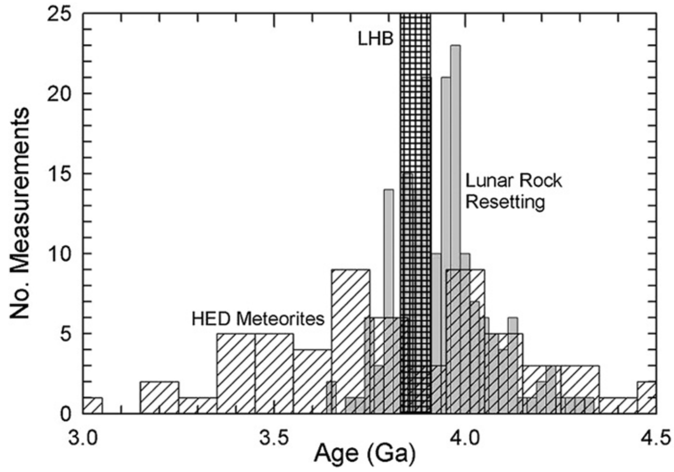

Fig. 3. Comparison of Ar–Ar and Rb–Sr resetting ages for lunar rocks (gray bars, from Apollo 14, 15, 16, and 17 samples) and for HED meteorites (broader hatched bars, including a few measurements by different chronometers) from Bogard (1995). The region inside the single tall bar spanning the graph defines the Nectaris-to-Orientale LHB shown by the gray bar in Fig. 1.

clasts are no more numerous than those that evidently were created during a low-flux period by smaller craters that produce melts inefficiently. Thus the work of Cohen et al. amplifies our suspicion that there is a strong sampling bias favoring recent impact melts and against older ones.

4. LHB correlation between meteorite parent bodies, Mars, and the Moon?

In addition to the discrepancies between lunar basin ages and lunar melt rock ages, there is also clearly a discrepancy between lunar basin ages and all lunar sample resetting ages. Fig. 3 illustrates data assembled by Bogard (1995) for the Moon and for the HED parent body (from basaltic achondritic meteorites). The vertical bar spanning the graph corresponds to an approximately 0.08 Gyr period that encompasses all of the basin impacts from Nectaris to Orientale; most of the dated basins formed during an even shorter 0.05 Gyr duration. Yet lunar sample degassing ages spread over a much wider range, from >4.1 to ∼3.7 Ga. Once again, the resettings that post-date Orientale—the very last lunar basin—must have been caused by smaller impacts.

Nevertheless, to the degree that the resetting age histograms somehow reflect the lunar LHB and can be used as surrogates for the actual bombardment rate (an assumption we discuss further in Section 7), they can be compared with equivalent data for meteorites (Bogard, 1995) and one martian meteorite (ALH84001; Ash et al., 1996). At first blush it appears that there is evidence for a lunar-like LHB in the impact ages for the HED meteorites and, less securely, for the ordinary chondrites. But when Bogard's histograms for the Moon and HEDs (summarized in Fig. 3) are examined more closely, questions arise. For example, all of the lunar highland rock ages (Ar–Ar and Rb–Sr) plotted by Bogard are older than 3.65 Ga and the vast majority (138 of 186) are between 3.8 and 4.0 Ga. The HED meteorite data are much more spread out. While 18 HED ages are between 3.8 and 4.0 Ga, 27 are younger (between 3.0 and 3.7 Ga) and 14 are 4.1 Ga and older. The moderately sharp peak in lunar rock resetting ages, only 200 Myr long (itself much longer than the LHB as defined by basin ages), is simply not mirrored in the meteorite data. In particular, the sharply declining cratering rate on the Moon at the end of the LHB, around 3.8 Ga, is not reproduced in the HED data, where reset ages persist for at least another ∼0.5 Gyr, perhaps even to 3.2 Ga. (Errors in the measured ages are typically <0.1 Gyr.)

The same story holds true for other meteorite types. Although Bogard's statistics on old ordinary chondrite (OC) ages are sparse, the 9 ages older than 3.1 Ga range from 3.5 to 4.2 Ga, with less than half between 3.8 and 4.0 Ga. The same picture is seen in a slightly larger sampling of OCs, as well as for HEDs and mesosiderites, reported by Kring and Cohen (2002). For all meteorite types, the histogram widths greatly exceed the width of the LHB, as defined by basin ages, and for the HEDs and OCs they exceed the already distended spread of lunar rock resetting ages. The conclusion is clear: the characteristics of impact age *data* differ radically between lunar basin ages, lunar rock resetting ages, and meteorite resetting ages.

Perhaps a different LHB affected the asteroids, such as (a) interasteroidal collisions following break-ups caused by the more sharply peaked LHB bombardment, or (b) there was some different impactor population affecting asteroids, with a longer dynamical/collisional timescale for depletion than for the population that affected the Earth/Moon system (perhaps with the LHB superimposed on the spread-out bombardment). Alternatively, sampling of asteroidal meteorites (by the processes that deliver meteorites to the Earth) have radically different biases from those that affect lunar sampling.

There is a well-founded presumption that the impact flux history of the Moon (including any LHB) should have happened as well on the Earth. That it should map, as well, onto the other terrestrial planets is more problematical, depending on the actual dynamics of the responsible impactor populations. For example, Chapman (1976) and Leake et al. (1987) described ways in which the expressed cratering history of Mercury might have post-dated the LHB if there are/were longer-lived "vulcanoids" orbiting inside Mercury's orbit. The possibility that there were long-lived vulcanoids is dynamically possible (Vokrouhlický et al., 2000) although searches have so far failed to find large vulcanoids. No meteorite has yet been robustly ascribed to Mercury. However, famed martian meteorite ALH84001, with a resetting age of ∼4.0 Ga, has been advocated (Ash et al., 1996)—despite statistics of one—as indicating that the LHB affected Mars. While such a conclusion is plausible, it is hardly robust, as can be seen from examination of Fig. 3.

5. The role of size distributions in crustal damage and contamination

Seeking evidence about the impact history of the Moon prior to Nectaris is challenging. Little primary geological evidence about such early history remains due to subsequent impacts and mare volcanism. Two chief constraints are basically indirect arguments, which we mentioned earlier and comment on in more detail here.

It has been argued that the amount of pre-nectarian bombardment is strongly constrained by the fact that the lunar crust is largely intact. Apparently impacts have hardly ever, or only marginally, penetrated to the lunar mantle. Spectral evidence (Pieters et al., 1997) suggests that even the largest of the well-defined lunar basins, South Pole–Aitken, marginally penetrated to the mantle if it did at all, and there is minimal spectral evidence for other penetrations. What must be remembered, however, is that we simply have no evidence about whether the size distribution of impactors during pre-nectarian times (a) was "top heavy" (dominated by enormous impactors), in which case it is indeed unlikely that cumulative basin formation subsequent to crustal solidification could have exceeded the visible record by much, or (b) had a "cut-off" near the sizes of the impactors that formed the largest visible basins, in which case the crust could have been stirred repeatedly by basin-forming impacts without excavating deep mantle materials. As we examine plausible dynamical scenarios for early bombardment of terrestrial planets, we must remain aware of this constraint on the size distribution of hypothesized impactor populations.

Another argument for minimal early bombardment is that the lunar crust does not show major contamination (beyond several percent) by exogenous material. The issue of contamination is similarly fraught with uncertainties (cf. review by Levison et al., 2001). The Moon is very roughly in balance between net accretion and net erosion (Shuvalov and Artemieva, 2006). The exogenous projectile material is preferentially ejected at the highest velocities. Depending on the impact velocities, which may well have been higher for certain hypothesized early impactor populations (e.g., outer Solar System planetesimals) than they are now, an even larger fraction of projectile material may have been lost. While one can assume that there is significant retention of projectile material and develop a constraint on the cumulative mass that has bombarded the lunar crust, the argument can hardly be robust, quite apart from issues about how well the volume of the crust has been sampled or the degree of contamination of the regolith by modern meteoritic infall.

We conclude that any conclusions about the pre-LHB lunar impact flux based on crustal damage and contamination are speculative, at best.

6. A new look at the "stonewall"

Hartmann (1975) originally proposed that a "stonewall effect" might cause an apparent spike in the lunar rock age distribution, even if the impact flux had been declining slowly and monotonically (with no cataclysm). He suggested that the integrated effects of repeated saturation of the megaregolith by major impacts would have pulverized and destroyed any rocks dating from epochs before saturation, resulting in an apparent spike in impact ages. Grinspoon's (1989) quantitative model of this stonewall effect verifies that—within the 2-D limits of his model—such a spike is produced. But these arguments' limitations potentially invalidate them. While saturation by basins certainly destroys pre-existing topography, older rocks do not thereby automatically vanish. While the crust is fractured and comminuted, it remains composed of rocks, Hartmann's critics argued; because of the inefficiency of rock-age resetting, rocks with measurable ages should, therefore, stretch back through multiple generations of saturation. As Hartmann et al. (2000) (presumably one of his co-authors and not Hartmann himself) put it, "it is patently not the case" that all rocks would have been reset or "pulverized to fine powder" so that no rocks or clasts remain to be sampled and measured in the laboratory. Indeed, because of the (somewhat uncommon) existence of older, pre-nectarian rocks (though not impact melts), one would have to unrealistically imagine that impact melts are preferentially subject to being pulverized compared with other kinds of lunar rocks. We amplify on these issues in this section.

The fundamental question is whether melt rocks that would be representative of early bombardment would be expected to find their way to the lunar surface and survive in sufficient numbers to be sampled by astronauts and by lunar-meteorite-producing impacts many aeons later. That depends on where they were originally emplaced, what their subsequent history (transport, comminution, etc.) has been, and whether there are any additional biases in collection. In order to answer such questions, we must turn to models of the evolution of the lunar megaregolith as well as of the surficial regolith. We first consider and refute the idea that impact melts are somehow destroyed at depth. Then we consider whether their subsequent history would have permitted them to have been sampled by the Apollo astronauts.

Impact melts are commonly considered to be deposited in thin veneers that line the interiors and rims of craters, and may even form pools outside the rims. This perception of impact melt "sheets" is shaped by two facts: (a) the surficial distribution of impact melts is most relevant to geological fieldwork and collection of samples (any deeply buried melts are more difficult to access and less studied) and (b) most research has concerned craters of modest sizes for which the fraction of melts in the excavated material is modest, most of the melt is ejected from the crater to land on the exterior surface, and what remains within the crater is, indeed, a thin veneer. However, in the case of large impact basins, the volume of melt produced exceeds the volume of the excavated material, the melted volume may extend beneath even the depth of the transient cavity, and the majority of the melt remains within the final basin (Cintala and Grieve, 1998). That which remains near the bottom of the crater, and which is subsequently covered over by ejecta blankets from later basins may be crudely thought of as massive buried lenses of impact melt. In what follows, we will evaluate what happens to impact melts that are deeply buried as well as what happens to surficial veneers of impact melts; reality falls somewhere between these two cases, or perhaps includes both.

Hartmann (2003) has tried to rebut his presumed co-author's criticism (in Hartmann et al., 2000) by arguing that impact melts produced by early basins would, indeed, have been subsequently "destroyed" (specifically by being pulverized by later large-crater-forming impacts to particle sizes <60 μm, like particle sizes characteristic of the modern, surficial lunar regolith). Hartmann further argues that deeper basement rocks would have escaped such pulverization and might have occasionally been excavated by unusually large later impacts, thus explaining their rare but robust representation among the Apollo samples. Unfortunately, his argument is flawed, in addition to depending on a couple of questionable assumptions. The first questionable assumption is that the saturating large impact craters would excavate down to the levels of impact melt lenses sequestered under giant basins, which cannot be the case unless the saturating "large craters" were actually basin-sized, which is not Hartmann's view. The second assumption, which is partly explicit and partly implicit, is that the lunar crater size distribution has not changed with time and, for that matter, has been the same in the asteroid belt [this is a position long advocated by Neukum (see Neukum et al., 2001)]. Most researchers agree that this is not true for craters smaller than some tens of km in diameter, which clearly differ between the lunar maria and the older highlands. On the other hand, there remains good correspondence between the size distributions of the lunar highland craters and the modern main-belt asteroids (Strom et al., 2005). It is plausible that collisional evolution proceeds rapidly enough to quasi-equilibrium so that the larger impactors, which could have deeply penetrated the lunar regolith, had an asteroid-belt-like size distribution from early in the Moon's history, but that depends on how much more massive the initial asteroid belt was than it is today (Bottke et al., 2005).

A more serious issue is that Hartmann (2003) errs in arguing that the fine particulates characteristic of the uppermost layers of the lunar regolith sampled by Apollo astronauts would be expected to be produced throughout the 340 to 5000 m of megaregolith, which he argues would have been created by 100 to 200% areal coverage of multi-km-diameter and larger craters and basins [dominated areally by craters 30–100 km diameter according to Neukum's standard production function (Neukum et al., 2001), see Fig. 4]. This would be true only if the same kind of repetitive impact churning that processes the uppermost regolith could process the entire volume of megaregolith so produced. But it obviously cannot. Just as *areal* dominance is measured by comparing differential power-law index b with the horizontal "-3" line on the standard R-plot (Crater Analysis Techniques Working Group, 1979), *volumetric* dominance is measured with respect to a "-4" line. Clearly, from Neukum's standard curve, craters and basins larger than 2 km diameter increasingly dominate processed volume or mass (including crushed and excavated material, ejecta blankets, etc.); craters over the short diameter interval of 100 m to 2 km (the only size range over which small impactors volumetrically dominate larger ones) fall 1 to 3 orders of magnitude short in competing with giant craters and basins (not even counting the fact that the same near-surface volume is buffered and repeatedly processed: the small-scale impacts do not churn down into the lunar crust). So even if Hartmann's assumption were true (as it might be) that the steep, small-crater branch of the production function existed in primordial times, the churning of the surficial regolith would grow from the upper few meters of the current lunar regolith to only a couple tens of meters before enormous ejecta blankets and excavations by the huge basins and the area-saturating 30–100 km diameter craters would bury and/or disperse the

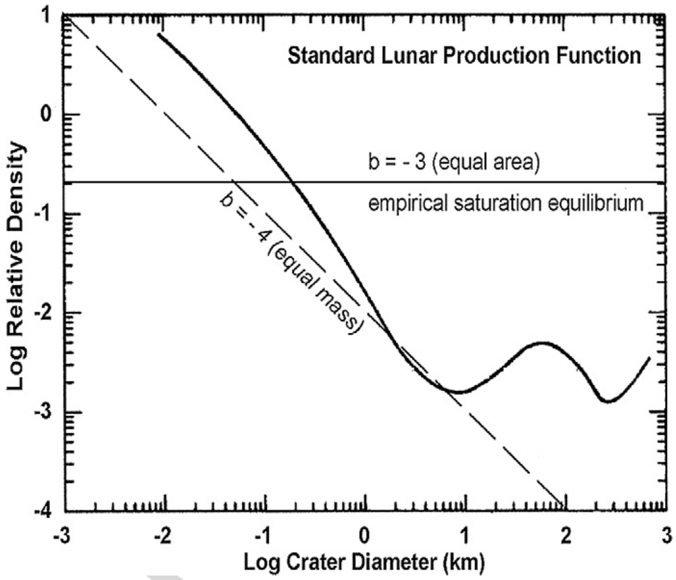

Fig. 4. Neukum's standard lunar production function (SPF) approximates the relative numbers of craters of different sizes formed on the Moon (Neukum and Ivanov, 1994); this is shown as an R-plot (Crater Analysis Techniques Working Group, 1979) in which a differential size distribution with $b = -3$ plots horizontally (which also corresponds to a distribution in which equal logarithmic size ranges of craters cover equal areas). The spatial densities shown approximately represent post-mare cratering. At sizes smaller than where the SPF intersects the empirical saturation line ($b = -3$), the observed crater population bends over and follows the saturation line; below 10 m, tens of generations of craters have formed and been erased, and even more generations of still smaller impacts have contributed to thorough comminution of the upper few meters of the regolith. Hartmann (2003) argues that around the time Nectaris formed (when the cumulative crater density was about 30 times higher than today, see Fig. 1), the "bump" in the SPF would be near the saturation level; thus 30–100 km craters would have processed the megaregolith down to depths of many km, perhaps destroying pre-existing impact melts formed by early basins. However, as measured with respect to the equal-volumetric reference line (dashed line, $b = -4$), such craters and the still larger basins completely dominate the processing of materials compared with the cumulative effects of comminution by small impacts. It is difficult to believe that one or just a few generations of such craters could comminute the megaregolith so thoroughly, especially given the relative dearth of smaller craters 2–30 km in size. Whatever processing of the megaregolith is accomplished by craters, it is dwarfed by excavation of basement rocks from still greater depths by the largest basins (rightmost end of the SPF), which extend even farther above the equal volume reference line.

surficial regolith; then the blocky, newly ejecta-blanketed surface would begin to be processed again. [The role of the steep branch of the impactor size distribution in churning the surficial regolith should be the same whether or not the impactors are predominantly secondary ejecta from larger craters, as is advocated by McEwen and Bierhaus (2006), or are part of the heliocentric population.]

Visualize the following example. Imagine standing on mare regolith, some meters deep, just before the Copernicus crater formed. If this location is one crater diameter away from the final location of Copernicus' rim, then nearly 100 m of continuous ejecta are suddenly and violently deposited at this location (cf. Rehfuss et al., 1977). Whether the initial meters of surficial regolith are scoured away or simply buried, it is the Copernican ejecta deposition that dominates not only the landscape but the vertical stratigraphy at this location. Now scale up the dimensions by an order-of-magnitude and one can appreciate the minimal volumetric processing by surficial regolith churning processes of a surface being bombarded by large craters and basins. The deep impact melts associated with ancient impact basins, which Hartmann would pulverize, typically lie many km beneath the surface and simply cannot have been affected by the physical processes that have pulverized the surficial regolith soils sampled by Apollo astronauts. The concept of complete pulverization would be relevant only if it were physically reasonable that a few generations of processing by giant craters or basins would thoroughly pulverize the affected materials. However, the mere existence of Copernicus' secondary crater field (made by large ejecta blocks) proves that a significant fraction of the affected materials remain in the tens to hundreds of meters size range; they are hardly all pulverized to <60 μm (presumably fragments have sizes throughout the range of tens of μm and smaller up to hundreds of meters). In summary, megaregolith processes at depth cannot and do not comminute materials as thoroughly as regolith at the immediate lunar surface is comminuted.

We have shown that impact melts cannot be pulverized at depth, but perhaps they can be hidden. We now consider a range of places where such melts might be deposited and evaluate how they might be subsequently processed and sampled. First, we consider the case that impact melts are preferentially deposited at the lunar surface rather than throughout the volume of the megaregolith. This case is essentially that modeled by Grinspoon (1989). In his 2-D model, the ages of rocks throughout a new crater's interior are all reset (or the rocks are melted). Since resetting and impact-melting efficiencies are low, resetting or melting the entire *volume* of crater materials does not happen; but because this is a 2-D model, it resets or melts only the surface *area* within a crater. Indeed, melts often preferentially veneer crater surfaces (Melosh, 1989; Cintala and Grieve, 1998); shocked/melted materials are also favored in higher-velocity, widespread ejecta that are deposited on or near the surface beyond the crater. [Beyond the continuous ejecta blanket, basin ejecta become increasingly diluted by country rocks due to the secondary cratering process (Oberbeck et al., 1975).] In this 2-D case, collection of rocks—whether by astronauts or by excavation by the impacts that yield lunar meteorites—would preferentially sample the most recently produced impact melts. Indeed, the surficial veneers from the most recent impacts, whose integrated ejecta blanket areas approach saturation, would overwhelmingly dominate samples; there would be little representation of earlier impact melts covered up by subsequent ejecta blankets. This attribute of the 2-D model is consistent with the observation that impact melts sample only the most recent third of observed basins (whose ejecta nearly, but did not quite, saturate the Moon's surface) as well as melts produced by smaller, more recent craters. Note that the 2/3rds of known or suspected basins that are older than Nectaris are manifested by topography, but their surfaces could well have been veneered by ejecta deposits from later basins. Although Grinspoon's model is simplistic, it amply illustrates—as he originally argued—the "stonewall" effect: whether or not earlier impacts happened, impact melts collected at the lunar surface would preferentially sample only the most recent, subsaturating impacts ... provided that impact melts are indeed originally deposited only at the surface.

A more realistic, 3-D model would consider vertical mixing within the megaregolith. Assuming that a few percent to perhaps tens of percent (varying with crater diameter) of mobilized crater materials are melted, we now consider the 3-D distributions of the melt throughout the volume of the crater. Let us consider the case that such impact melts are distributed uniformly throughout the volume of the affected materials (i.e., throughout the megaregolith). Though much impact melt may be plated out on the surface, much may also wind up in a lens of impact melt near the bottom of the crater; so uniform distribution is an intermediate case between distribution of impact melts only at the surface and only at great depth. If a megaregolith containing uniformly distributed impact melts were then thoroughly and uniformly stirred throughout its depth (like dough containing raisins), then any sampling of rocks at the top of the megaregolith (or anywhere else within it) should yield impact melts directly in proportion to their fractional production, which was Ryder's hypothesis. Then Ryder's point about the absence of impact melts before ∼3.9 Ga would rule out appreciable pre-nectarian basin-formation and the LHB cataclysm would be proved. (Of course, mixing of the megaregolith by the shallow-sloped size distribution of large impactors cannot be nearly as thorough as churning of the surficial regolith by a steep-sloped size distribution; considerable heterogeneity must remain.)

Under conditions of saturation and thorough megaregolith redistribution, even surficially deposited impact melts from all times stand some chance of being exhumed and represented on the surface, so one would not expect a complete dearth of older examples. If one had unlimited basin formation in the megaregolith (assuming a size distribution with a large-diameter cutoff so as not to excavate the lunar mantle), eventually most megaregolith materials would be converted to impact melt. Thus the observed absence of old impact melts would establish some upper limit to the number of generations of pre-nectarian impacts. But is the megaregolith mixed adequately—even if not thoroughly—so that surface sampling could be representative of what lies beneath? A definitive answer must await detailed modeling of megaregolith processes. But, qualitatively, we can turn to Hartmann's (2003) arguments and see that the answer may be "yes." If the Neukum production function were applicable in pre-nectarian times, then the numerous observed pre-nectarian impact basins (and any that were degraded to invisibility) must have been accompanied by several generations of saturation cratering by craters 30–100 km in size. While we have argued above that such cratering would not have comminuted materials to <60 μm sizes, it certainly would have excavated materials from many km depth, overturned stratigraphy in places, ejected materials to considerable distances, and generally stirred the upper kilometers of the lunar crust. It is difficult to envision how impact melts—whether initially deposited surficially or at considerable depth—could be excluded from participation in such transport.

A final question remains, however, in the chain of processes from creation of impact melts to their final residence in terrestrial laboratories: to what degree are impact melts (or other materials) derived from depth represented at the *immediate* lunar surface (e.g., the upper couple of meters sampled by astronauts)? The collection of samples by astronauts is necessarily restricted to the immediate surface, and that surface is a very special environment, quite unlike any place else farther down in the lunar megaregolith. It is only on the surface that distal ejecta blankets are deposited. Moreover, it is only at the surface that the continual impacts of small meteoroids (and secondary ejecta) repeatedly churn, comminute, and melt surface materials into the soils that comprise the bulk of the materials available to the astronauts for collection. Instead of arguing for pulverization at depth (Hartmann, 2003), Hartmann might turn to the modern lunar regolith where, indeed, most rocks and particles are efficiently comminuted to <60 μm sizes once they get near the surface. But here again, detailed regolith modeling would be necessary to determine how efficiently rocks arriving on the surface from depth are pulverized. Obviously, all rocks lying on the lunar surface are not pulverized, and returned sample collections are replete with rocks and chips—which, significantly, do not contain pre-nectarian impact melts while they do contain a few old basement rocks. Where do these surviving or unprocessed rocks and chips come from and should they be expected to include a representative fraction of old basin impact melts or should they mostly represent the latest ejecta blankets? We return in Section 8 to the question of what quantitative constraints can be placed on these issues by modeling of megaregolith and surficial regolith processes.

Tera et al. (1973) first mentioned, and others (e.g., Haskin et al., 1998) have later restated, the vital idea that sampling of lunar rocks is biased toward Imbrium, the last front-side impact basin. This idea conforms to the late-event biasing that we should expect if a significant portion of impact melts are surficially deposited. If Imbrium dominance was substantially true, it would be a kind of vindication of Hartmann's stonewall hypothesis. The difference from his original concept of a stonewall would be that physical, geological stratification of the lunar surface is what would saturate, thus covering up rather than actually pulverizing and destroying older rocks. By being covered over and then volumetrically mixed throughout the megaregolith by the penetration and ejecta blanketing of subsequently formed craters and basins, older impact melts would less likely be sampled on the surface than melts recently deposited by the last basins and left on the surface comparatively undisturbed thereafter. Full 3-D modeling of the relevant processes is needed to quantitatively verify our qualitative expectations.

Doubt is thus cast on past arguments concerning pre-nectarian impact rates. If one accepts the apparently sharp cessation of basin formation (ending ∼3.85–3.82 Ga) based on inferred basin ages, one might suppose that such a rapidly decaying impactor source would have commenced with similar rapidity, causing a spike. But we assert that the *observational* support for, or against, that supposition is lacking. We simply cannot know the pre-nectarian lunar bombardment rate, pending 3-D modeling of relevant processes.

7. Association between rock samples, impact events, and specific basins

Although generally considered to be a robust result, evidence for the sharp cessation of basin bombardment inferred from ages of rocks associated with basin formation deserves to be re-examined, as well. Geological and chemical associations between lunar samples and impact basins are the basis for the generally accepted ages of the major post-Nectaris basins (for a detailed discussion of these arguments, see Stöffler and Ryder, 2001). Stratigraphic relationships (including relative age-dating of different units from varying densities of small, superimposed impact craters) have extended the age constraints to other post-Nectaris basins, for which samples are not available, and to other lunar features. How robust is the evidence that identified front-side basins formed in the very short, 50 Myr, period between 3.90 Ga (Nectaris) and 3.85 Ga (Imbrium)?

Even without clear associations between specific rocks and specific basins, correlations between ages and compositions (chemical and isotopic) of lunar impact melt rocks define specific impact events and show that the preponderance of such events occurred during this brief period. Major element, trace element, and siderophile element compositions have been used to identify distinct populations of impact melt rocks. Among the Apollo 16 crystalline melt breccias (i.e., those likely to have been formed in large events), several compositional clusters or groupings are recognized based on major and trace elements. Two groups (possibly up to five subgroups) are basaltic or mafic impact melts; two other groups have feldspathic, KREEP-poor compositions (Korotev, 1997). Highly siderophile element compositions of Apollo 17 lunar impact melt breccias reveal at least two separate groups of impact melts (Norman et al., 2001), both chemically distinct from any Apollo 16 compositions (Norman, 2003). Major and trace elements have also been used to distinguish the Apollo 15 melt rocks from compositional groups in the Apollo 16 and 17 samples, and to further characterize at least four subgroups (Ryder and Spudis, 1987). Chemical composition identifies very feldspathic impact melt material, likely a product of impacts prior to formation of the KREEP terrane, in the Luna 20 soil as well as very KREEP-rich ropy glass in the Copernicus rays at Apollo 12. If, as shown in terrestrial melt sheets [e.g., Mistasin Lake (Grieve, 1975), Manicoagan (Floran et al., 1978)], impact melt sheets are homogeneous, then these distinct chemical groups must have been formed in different impact events. However, larger impact melt sheets may have differentiated [e.g., Sudbury (Grieve et al., 1991; Therriault et al., 1999)] and impact melt compositions in the ejecta may not have had time to homogenize to the composition of the total melt sheet. In the latter case, melt rocks from a single basin-forming event could vary in their chemical characteristics.

It turns out that ages for impact melt rocks or clasts (which often, but not always, can be determined unambiguously by several isotopic techniques) are correlated with their compositions,

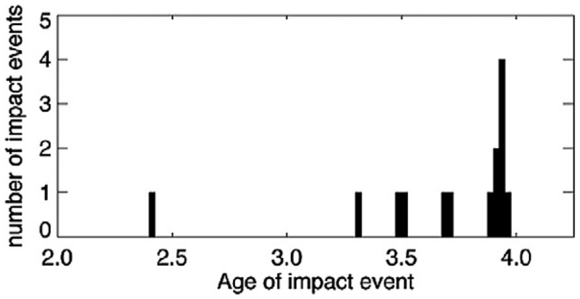

Fig. 5. Histogram of lunar impact events. Each individual event in this histogram is inferred from coherent ages of chemically distinct impact melt rocks. A peak in the histogram occurs at ∼3.9 Ga, where 8 separate impact events are inferred to have occurred based on this type of discriminator.

providing a powerful way to distinguish groups of rocks created in discrete impact events. Chemically and texturally similar groups of Apollo 16 impact melt rocks have consistent ages, implying that three to five different impact events are represented among these rocks (Duncan et al., 2004). The Apollo 17 poikilitic melt rock group has been precisely dated at 3.89 Ga (Dalrymple and Ryder, 1996). Impact melt clasts in lunar meteorites also form clear groups in major-element chemistry and age that imply they were created in several different impact events (Cohen et al., 2000). A histogram of individual sample ages does not tell the complete story, because multiple samples of the same compositional and age group probably record the same impact event, thus artificially stacking a sample histogram. If we rather examine a histogram of inferred impact events, as determined by both composition and age of sample groups as discussed above (Fig. 5), we observe that a large number of impact events occurred within the same narrow window of time, ∼3.9 Ga, and no events older than 4.0 are yet unequivocally represented.

The final step in establishing post-nectarian basin-forming history is to associate the identified impact events with formation of specific front-side basins, in order to invoke the visible stratigraphic relationships. This is more problematic. After all, no lunar sample holds a sign saying, "I was formed when the Crisium basin was formed." Association of dated samples with specific geological units or topographic formations remains an exercise in geological interpretation. Prior to the Apollo missions, Mutch (1970) wrote skeptically of how the lunar stratigraphy could be dated from rock samples collected at the surface:

> Little detailed attention has been given to the matter of obtaining a vertical sequence of samples through more than the upper few inches of the surficial fragmental layer. Yet we are told, rather simplistically, that radiometric dating of samples collected near craters will date them and will, indeed, allow us to order the individual cratering events temporally. Just how this will be accomplished is not clear.

Eventually, core samples were returned from depths greater than "a few inches," but the vertical column sampled is still thin compared with average surficial regolith depths let alone the depth of the megaregolith. As described by Grieve (1980), the associations of samples with basins through the 1970s often were made in the context of the pre-mission rationales for landing site selection. Sometimes samples were assigned to basins solely on the basis of proximity, rather than because of any substantial geological evidence.

More recently, geologic association of specific samples with known basins or craters has been revisited and arguments have been downgraded or strengthened based on renewed interest in the cataclysm arguments (James, 1981, 1996; Spudis and Ryder, 1981; Dalrymple and Ryder, 1996). The probability of a rock being of local rather than distant origin is not easily determined but rather depends on models for target composition, impact ejecta emplacement, and disturbance of the pre-existing (mega)regolith. Given that limited numbers of samples were collected, that they were not collected randomly, and that lunar surface processes manifest major heterogeneities at various scales, the sampling statistics could well be skewed. While arguments for some associations often seem to be very plausible, such as for the poikilitic impact melt formations of North and South Massifs being formed by the Serenitatis basin event, others remain more ambiguous or are even disputed decades after the samples were returned. On Earth, an unambiguous age for a structure can be obtained from samples collected by drilling into its intact melt sheet. Lunar basins whose melt sheets were quickly covered by mare basalts, such as Nectaris and Orientale, would be excellent future targets for this sort of collection strategy. Stratigraphically older lunar basins, such as the South Pole–Aitken basin, may still have abundant available melt rocks (Petro and Pieters, 2003), especially if ejecta from later far-side basins stirred up and became intermixed with SPA surficial rocks rather than simply burying them. In such a case, one may expect that SPA impact melts can be recognized by having different compositions from materials derived from afar. Nonetheless, proposed associations between samples and basins is, at present, merely suggestive rather than secure (cf. Rockow and Haskin, 1996; Haskin et al., 2002a) and they should not currently be viewed as strong constraints in the face of robust, conflicting evidence.

8. Modeling regolith evolution and sampling of lunar rocks

One way to learn how data from impact melts might help us understand the LHB is to model the evolution of the lunar megaregolith and other processes that influence our collection and statistical analysis of lunar impact melts. This is our chief near-term hope for improved understanding, although future geological field studies and sample collections on the lunar surface will eventually be more robust. So we briefly review approaches to modeling lunar processes and sampling procedures that affect interpretations of lunar impact melt data.

There are two disjoint elements to be modeled. First is the creation and initial distribution of relevant impact melts followed by their subsequent redistribution as the lunar megaregolith evolves during later bombardment by basins and large craters. Second is modeling of how the much more modest processes of surficial regolith evolution since the end of the LHB might have affected the sampling and collection—by Apollo astronauts and by lunar-meteorite-producing impacts—

that has led to our current database on impact melt rocks. These two cratering regimes—saturated impacts by large craters and basins followed by modest impacts by a much steeper size distribution that has churned the sampled upper meters of the lunar regolith—must be distinguished and separately understood. The first determines the general distribution of impact melts throughout the upper kilometers of the megaregolith. The second determines whether such impact melts are available for collection (or incorporation in lunar meteorites) at or very near the immediate surface of the lunar regolith.

Beginning with evolution of the lunar megaregolith, there are uncertainties about the applicable size distribution of impactors, and particularly about whether or not there was a cap on the frequency of extremely large impactors, whose effects would be extreme and still observable. There are understandings, based both on hydrocode simulations and on observations of the outcomes of actual impacts (especially on the Earth), that can help us assess what happens in an individual giant impact. Megaregolith models by Haskin and his associates (cf. Moss and Haskin, 1994; Haskin et al., 2002b) are a first step. They assimilated what is known about the processes of cratering ejecta and ballistic sedimentation in order to construct a detailed model that predicts size distributions of ejecta fragments, secondary crater fields, depths of ejecta deposits, and other effects of large-scale cratering far from the crater. Haskin et al. were especially interested in applying their model to study the two largest, most recent basin impacts (Imbrium and Orientale). Their model does not, however, deal with more than a single impact and hence does not model the evolution of the megaregolith. Ultimately, we must follow individual melt rocks as they are moved or destroyed during a succession of subsequent impacts. That important step remains to be modeled.

The next regime to be modeled is evolution of the surficial regolith on the Moon, the upper several meters, which ultimately controls the practical sampling of lunar impact melts. Because of the volumetric dominance of large craters and basins in affecting the upper kilometers of the lunar crust, the concurrent lunar regolith processes are negligible in comparison during and prior to the LHB. But after the LHB, the cumulative effects of the large craters and basins until the present became negligible (there were no more basin-forming impacts, and large craters have been formed only in scattered locations). So only the processing by much smaller impactors (whether of primary or secondary origin) became relevant. And this small-scale regolith evolution alone has affected the upper meters of the lunar surface during the last ∼3.5 Gyr of lunar history, which is especially relevant to the collection of samples from the immediate surface.

Surficial regolith evolution has been studied and modeled much more than megaregolith evolution (cf. Langevin and Arnold, 1977). Qualitatively, we note that the extremely steep production function for craters smaller than a kilometer in diameter results in saturation by craters smaller than roughly a hundred meters in diameter, and super-saturation at still smaller sizes. The resulting, well-churned regolith is known [e.g., by the observations of Oberbeck and Quaide (1968) and the modeling of Oberbeck et al. (1973)] to be several meters to ∼10 m thick on the lunar maria; if a similar size distribution applied during post-Imbrium epochs until the end of maria formation, a well-churned surficial regolith might be several times thicker on the highlands. In any case, the fate of rocks left in the top layer of the megaregolith must be studied with a much finer spatial grid, which includes consideration—for example—of the smaller impacts that catastrophically comminute and destroy rocks: (a) rocks sitting on the immediate surface are destroyed by small millimeter-and-centimeter scale meteoroids and (b) rocks within the surficial regolith are destroyed by the meter-scale impactors that eventually saturate the surficial regolith with small craters many times over. Clearly, such destruction of rocks is a major feature of surficial regolith evolution during the last several Gyr, which explains the comparative absence of rocks on typical lunar surfaces compared with what is seen in the immediate vicinity of recent impact craters that have penetrated through the regolith. However, the rocks sampled by the astronauts (and by lunar meteorite production processes) are those that have *escaped* such destruction. It is not intuitively obvious to us, short of constructing and running such simulations, how *they* might—or might not—be biased with respect to the distributions of impact melts left in the top layer at the end of megaregolith modeling.

We believe that it is of high priority to pursue the approach of Haskin and others to use modern computing power to model the evolution of the lunar megaregolith and surficial regolith. Of course, beyond modeling these processes, a return to the Moon with activities directed toward investigating specific basins (e.g., Nectaris, South Pole–Aitken) would be a much more direct approach to studying these important issues.

9. Conclusions

An apparent total absence of early (pre-nectarian) impact melts was argued by Ryder to be potent evidence for a lull in average impact rates on the Moon that lasted from crustal solidification to the formation of the Nectaris basin, thus defining a post-nectarian LHB or “cataclysm,” namely a spike in the lunar impact flux around 3.9 Ga. (There are excellent reasons for believing that basins should overwhelmingly dominate production of impact melts on or within the lunar crust.) Histograms of impact melt crystallization ages (including melt clasts from lunar meteorites) and of inferred impact resetting ages for lunar rocks, are not in good accord with each other nor with the inferred sharp cessation of bombardment by basin-forming projectiles. (Nor are the lunar data in accord with analogous data for meteorites derived from the asteroid belt.) We regard these discrepancies not as tending to disprove that a cataclysm happened but rather as being the result of non-uniform, biased sampling—due mainly to poorly understood processes of megaregolith and surficial regolith evolution—of whatever lunar materials were affected by the giant impacts. A cogent observation is that while numerous, known pre-nectarian impact basins fail to be represented by any of the identified impact melts, many impact melts date from well after the formation of Orientale, the very last basin. Such enormous biases in representation of impact melts invalidate the qualitative conclusions that have frequently been expounded that absence of early impact melts implies that the early basin-formation rate was low. Issues of collection biases (e.g., by the astronauts) need to be evaluated, but we suspect that the prime sampling bias is due to megaregolith development processes, which may preferentially bury older impact melts and exaggerate the near-surface contribution of the most recent basins (e.g., Imbrium) and of later cratering. Arguments by Hartmann that absence of old basin impact melts is due solely to their complete pulverization by subsequent saturation of large craters appear to be untenable. However, Ryder's inference that the dearth of impact melts implies a low rate of early bombardment needs to be tested by quantitative comparison of the statistics of ages of samples derived from the lunar surface with predictions of physically realistic modeling of basin formation, megaregolith evolution, and surficial regolith processing of ancient materials until the present. Until such modeling is done, we believe that there can be no robust arguments either for or against a lengthy lull in impact rates before the cataclysmic LHB about 3.9 Ga. The impact rate of basin-forming projectiles was indisputably high around 3.9 Ga and it ceased altogether within ∼0.05–0.1 Gyr; that sharp decline (independent of whether it was preceded by an equally sharp rise) may help constrain the dynamical origin of the basin-forming projectiles, which almost certainly rained down on Earth, as well, just as life was attempting to gain a foothold on our planet.

Acknowledgments

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