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Megaregolith evolution and cratering cataclysm models—Lunar cataclysm as a misconception (28 years later)

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Abstract–The hypothesis of a lunar cataclysmic cratering episode between 3.8 and 3.9 Gyr ago lacks proof. Its strongest form proposes no cratering before about 4.0 Gyr, followed by catastrophic formation of most lunar craters and basins in <200 Myr. The premise that "zero impact melts implies zero impacts" is disproved by data from asteroids, on which early collisions clearly occurred, but from which early impact melts are scarce. Plausible cataclysm models imply that any cataclysm should have affected the whole inner solar system, but among available lunar and asteroid impact melt and impact age resetting data, a narrow, strong 3.8–3.9 Gyr spike in ages is seen only in the region sampled by Apollo/Luna. Reported lunar meteorite data do not show the spike. Asteroid data show a broader, milder peak, spreading from about 4.2 to 3.5 Gyr. These data suggest either that the spike in Apollo impact melt ages is associated with unique lunar front side events, or that the lunar meteorites data represent different kinds of events than the Apollo/Luna data. Here, we develop an alternate "megaregolith evolution" hypothesis to explain these data. In this hypothesis, early impact melts are absent not because there were no impacts, but because the high rate of early impacts led to their pulverization. The model estimates survival halflives of most lunar impact melts prior to 4.1 Gyr at <100 Myr. After a certain time, $T_{critical}$ ~4.0 Gyr, impact melts began to survive to the present. The age distribution differences among impact melts and plutonic rocks are controlled by, and hold clues to, the history of regolith evolution and the relative depths of sequestration of impact melts versus plutonic rocks, both among lunar and asteroidal samples. Both the "zero cratering, then cataclysm" hypothesis and the "megaregolith evolution" hypothesis require further testing, especially with lunar meteorite impact melt studies.

BACKGROUND: CATACLYSM, IMPACT MELTS, AND CRATERING MODELS

The concept of a lunar cataclysm around 3.85 Gyr ago was first developed by Tera, Wasserberg, and co-workers when they found that Apollo samples did not contain 4.5 Gyr-old "genesis rocks," the existence of which had been predicted during preparations for Apollo missions. Instead, many lunar samples showed ages around 3.9 Gyr, with a paucity before about 4.0 Gyr (Tera et al. 1974). Hartung (1974) and Hartmann (1975) pointed out that the lack of earlier rocks did not necessarily prove the existence of a cataclysm. Cratering data combined with Apollo rock ages confirmed the pre-Apollo conclusion that the pre-mare cratering rate was much higher than the post-mare rate (see also review by Hartmann 1966; Neukum et al. 2001), and Hartung noted semi-quantitatively that high cratering before 4.0 Gyr could produce high destruction rates, with the competition between destruction and production yielding age distribution curves peaking around 4.0 to 3.8 Gyr. The subtitle of the present paper is taken from the title of Hartmann's 1975 paper.

Hartmann (1980) attempted to quantify the model of regolith development and destruction of early materials. He then emphasized that accretion theories of planet formation, including the classic pioneering work by Safronov (1972), require gradual sweep-up of planetesimals from interplanetary space, implying an impact flux declining from extremely high rates at 4.5 Gyr to lower rates by 4.0 Gyr ago. In those models, half-lives of sweep-up would gradually lengthen from a few Myr to 10–30 Myr. In that paper, he also modeled regolith evolution in terms of the diameter D and depth d of craters that saturate the surface. At any given crater density, 100% of the surface is covered by craters larger than some diameter D. In this model, regolith depths are of order of magnitude d. As crater densities increase toward the saturation equilibrium level, *D* increases and regolith depth *d* increases. The model correctly predicts the depth of regolith developed on the lunar maria (see discussion in section "Consequences for Rock Survival Lifetimes"). On the pre-4.0 Gyr moon, regolith maturation occurred to depths of hundreds of meters in 100 Myr or less, so that rocks placed in lunar near-surface layers before 4 Gyr ago would be rapidly pulverized into regolith dust on timescales <100 Myr, until the cratering rate dropped below a threshold value. (The actual model allows for finer grinding at the surface and coarser grinding at depth; see below.) Grinspoon (1989) developed the models further, concluding that the cratering rate decline was consistent with dynamical models of planetesimal sweep-up, which predict half-lives of early Earth-crossing impactors of the order ~10 Myr, probably lengthening to 20 Myr or more as nearby planetesimals were swept up (Wetherill 1975, 1977). I will refer to these ideas as the "megaregolith evolution" hypothesis.

A new round of work on early cratering and the cataclysm model was inspired by Ryder (1990), who emphasized that Apollo lunar samples show no impact melts before about 4.0 Gyr. Ryder inferred that no impact melts mean no impacts and concluded that the impact rate before 4.0 Gyr was near zero, in dramatic opposition to the dynamical models. Ryder (1990), followed by Stöffler and Ryder (2001), concluded that virtually all the large lunar basins were created between about 4.0 and 3.8 Gyr ago, probably within a time span of 100 Myr. Ryder also showed that Hartmann, Grinspoon, Hartung, and others had been somewhat cavalier in discussing the efficiency of age resetting by impacts, and confusing age resetting with destruction of materials (Ryder 1990; cf. also review by Hartmann et al. 2000).

Ryder's 1990 work produced a "strong form" of the cataclysm model, in which the cratering rate was effectively zero from near the end of planet formation until 4.0 Gyr ago, followed by a cataclysmic, basin-forming spike in cratering. We will refer to this as the "zero cratering, then cataclysm" hypothesis. Ryder (1990), Ryder et al. (2000), Cohen et al. (2000), and Stöffler and Ryder (2001) treat it as self-evident that the peak in impact melt abundances means a peak in cratering, stating (first sentence of Ryder et al. 2000) that "the Moon experienced an interval of intense bombardment peaking at 3.85 ± 0.05 Gyr..." Stöffler and Ryder (2001) treat the idea of basin formation in this very narrow interval as robustly demonstrated. As a result of such ideas, some authors also equate lack of impact melts before 4.0 Gyr as equivalent to proof of a cataclysm at 3.9 Gyr, even though this does not logically follow.

Cohen et al. (2000, 2002) made very important studies of impact melts (in lunar meteorites), choosing highland meteorites with chemistries that suggest origins outside the Apollo sampling area, possibly the far side or east limb. In a sample of 41 clasts (31 from 4 meteorites in the first paper, 10 more from 2 additional meteorites in the second), they used ideograms and error bar analysis to infer a lack of impacts before 3.92 Gyr (although they report seven melt dates between 3.92 and 4.2 Gyr), and treated this as positive confirmation of a cataclysm at 3.9 Gyr. That conclusion is questioned here because their impact melt age distribution is entirely different from that of the Apollo/Luna data set, and in fact shows no peak of impact melt ages at 3.9 Gyr.

I note that a milder form of the cataclysm hypothesis combines the two models, assuming that a high, declining cratering rate existed before 4.0 Gyr, but that it had spikes (perhaps due to breakup of planetesimals in near-Earth space), and that the event near 3.9 Gyr might be only the largest of the spikes in a declining rate, rather than an outburst following a hiatus. All these ideas are reviewed in more detail by Hartmann et al. (2000).

It is ironic and paradoxical that both a zero impact rate and an extremely high impact rate from 4.45 to 4.0 Gy are being invoked to explain the same data! In this paper, I make a case that the high impact rate in the first 600 Myr may have produced the observed effects and deserves further examination.

NUMERICAL ESTIMATES OF THE EARLY IMPACT RATE

A cratering rate that averaged higher before ~3.5 Gyr ago than afterwards was directly detected in the Earth-moon system by terrestrial cratering studies combined with lunar data (Hartmann, 1965a, 1965b, 1966), and more directly confirmed from ages of Apollo landing sites (Hartmann, 1970, 1972; Soderblom and Boyce, 1972; Neukum, 1983). The high early cratering rate can be traced back directly only to about 3.9 or 4.0 Gyr from dated landing sites and the rate is not directly measured before that time due to the lack of dated surfaces. Wetherill (1975, 1977) gave dynamical models of the depletion of planetesimal populations versus time from 4.5 to 3.9 Gyr, demonstrating the shape of the expected declining impact flux curve. The planetesimal half-life increases because near-Earth planetesimals are rapidly accreted and near encounters with growing planets scatter planetesimals into orbits of higher inclination and eccentricity, having longer half-lives. Hartmann (1972) synthesized the crater count and dynamical approaches, pointing out that the impact flux to accrete Earth in 60 Myr, at 4.55 Gyr ago, averages some 10^9 or 10^{10} times the present rate. He noted that the Wetherill-modeled decline from there, with half-life lengthening from 10 Myr to as much as 300 Myr, can dovetail with the lunar crater-versus-age data after 4.0 Gyr. Hartmann (1972) estimated from the upland crater saturation that "prior to 4.1, the cratering rate on the moon was at least 10^3 times the present rate and the number of planetesimals showed an exponential decay with a half-life about 3×10^8 years...." Neukum et al. (2001) traced crater density versus surface age back to 4.0 Gyr ago, fitted the data to a curve of impact flux versus time, and cited a rate at 4.0 Gyr of ~500 times the present cratering rate. Neukum and Ivanov (1994; Figs. 14, 16) plot various estimates of the impact flux versus time and conclude the estimates are mostly within a factor of three. To summarize, the measured, declining lunar cratering rate after 3.8–4.0 Gyr appears consistent with a smoothly declining flux before 4.0 Gyr, although it has also been interpreted as the tail end of a cataclysm.

Neukum (1983) derived a numerical model of the time behavior of the early impact rate based on fitting his lunar cratering data (crater density versus measured age of landing site) to a curve of crater density versus time. His equation (given in Neukum and Ivanov, 1994; Neukum et al., 2001) is

$$N(D > 1\text{km}) = 5.44(10^{-14})[e^{6.93T} - 1] + 8.38 \times 10^{-4}T \quad (1)$$

where *N (D >1 km)* = [craters of diameter >1 km]/km^2 produced since time *T.* Neukum, Hartmann, and others suggest that the extrapolation back before 4.0 Gyr is also approximately valid, based on the proposed behavior of planetesimals. For example, Hartmann (1980) and Hartmann et al. (2000) point out that a planetesimal flux, necessary to accrete Earth in ~50 Myr, and declining with a half-life of a few Myr lengthening to 20–30 Myr, can be fit onto the Neukum curve. In a sense, little extrapolation of the Neukum curve before 4.1 Gyr is necessary because the known high cratering rate around 3.9–4.2 Gyr is sufficient to saturate the surface, destroy surface rocks, and create powdery megaregolith (see below). This contrasts dramatically with the "strong form" of the cataclysm hypothesis, in which the curve cannot be extrapolated back before 4.0 Gyr, and the pre-4.0 Gyr cratering rate was near zero. Neukum's curve (Equation 1) is adopted here to model the consequences of intense early bombardment, partly because of the care in its derivation and numerical specificity, and partly to show that the results here do not depend only on my own curve, which I have used in past discussions.

Figure 1 plots a form of Equation 1, given the total accumulated cratering as a function of age; it is expressed relative to the amount accumulated on typical mare surfaces from 3.6 Gyr ago. This shows, for example, that in the 100 Myr interval between 4.1 and 4.0, the moon sustained nine times the amount of cratering that the "average" mare sustained; and between 4.2 and 4.1 Gyr ago, the moon sustained 35 times the "average mare level" of cratering. This approach allows us to compare early regolith production to the regolith and gardening produced in post-mare time.

CONSEQUENCES FOR ROCK SURVIVAL LIFETIMES

Interpretations of lunar impact melt ages need to take into account the effects of the plausible extremely high cratering

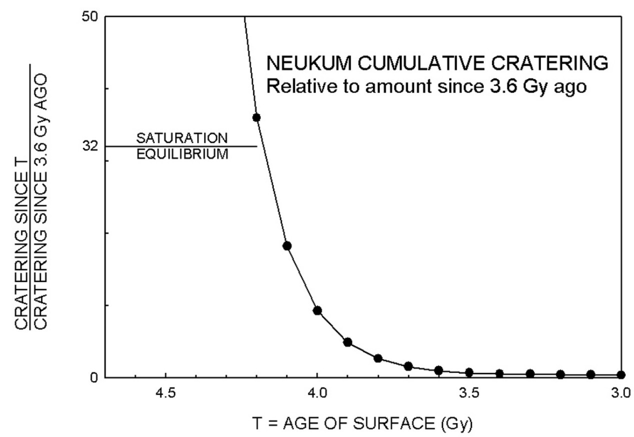

Fig. 1. Total accumulated numbers of craters as a function of surface age based on the time dependence equation derived by Neukum (see Equation 1). The author's results are similar.

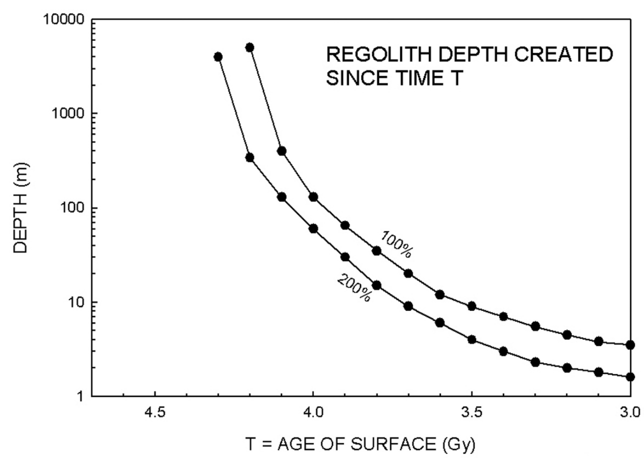

Fig. 2. Regolith depth generated on a surface of age *T,* based on the Neukum time dependence of cratering and on numerical modeling of megaregolith evolution by Hartmann (1980, Fig. 1). Upper curve refers to a criterion where 100% of area is covered by craters deeper than the specified depth; lower curve is a more conservative criterion where 200% of the area is covered by craters that excavate to the specified depth, implying more mature grinding of the surface material. These curves correctly predict roughly 5–15 m of regolith for typical mare surfaces and predict 100 m of comparable pulverization on surfaces older than 4 Gyr. See text for further discussion.

rates before 4.0 Gyr. A typical mare surface formed at 3.6 Gyr ago has about 3 to 20 m of regolith composed of very fine-grained mineral and lithic clasts, glassy agglutinates, and glass spheres (McKay et al. 1991; see also review in Hartmann 2001, pp. 38–39). If the pre-4.0 Gyr cratering followed the relations proposed by Neukum (Equation 1), Hartmann (1972, 1980), and Wetherill (1975, 1977), rather than being near zero, then it is clear that great depths of regolith and pulverization would have been created on surfaces 4.0 Gyr old and older. These depths exceed 100 m and are proposed to reach the depths excavated by the largest craters in saturation; such depths could be of the order of a few kilometers. Lunar highland experience suggests some of the resulting powders and chips were welded into coherent breccia rocks at depth after the pulverization. A concept, which is key to this paper, is that proposed high pre-mare cratering rates guarantee extreme physical damage or pulverization to rocks placed within the upper 100 m of the surface before 4 Gyr, and within the upper few hundred meters before 4.1 Gyr, and this effect tends to destroy impact melts sequestered in those layers.

To illustrate this, Fig. 2 plots estimates of the pulverization depth on a surface as a function of the age of that surface. This graph is based on material in Hartmann (1980, Table 1, Fig. 1). That work takes the observed crater size distribution on the lunar maria and tabulates the percentage area covered by all craters larger than a given size. About 50% of mare area is covered by craters >60 m, about 100% by craters >30 m, and 200% (due to crater overlap) by craters >12 m. That work assumed that fracturing and pulverization extend to a depth about 0.3 times the crater diameter, predicting immature gardening to 18 m under maria, and mature regolith to about 9 m depth, with more complete pulverization in the upper 4 m. These characteristic depths appear to be in good first-order agreement with mare observations, and are used as a tool to predict behavior under older, more cratered surfaces.

An important factor is that the highland crater density is about 32 times the mare density (Hartmann 1966) and this approximate level is believed to be the saturation equilibrium density (Hartmann 1984; Hartmann and Gaskell 1997). As discussed by Hartmann (1980), the empirical saturation crater diameter distribution has about the same slope as the crater-production-function diameter distribution for multi-kilometer craters. Therefore, as the crater density increases from mare-level densities to 32 times that amount, kilometer-scale craters and larger all go into saturation at about the same time, the crater sizes corresponding to 100% coverage jumps rapidly from D ~100 m to D >4 km, and the regolith depth "blows up" to the gardening depth (0.3 D) of the larger, multi-kilometer scale craters some thousands of meters. This is the basis of the concept of "mega-regolith" in the highlands (Short and Forman 1972; Hartmann 1973).

Based on these concepts and Hartmann (1980, Fig. 1), Fig. 2 shows the depths of regolith gardening attained as a function of surface age under two criteria, being 0.3 times the depth of craters that cover either 100% or 200% of the area (200% implying finer grinding than 100%). Since these criteria correctly predict pulverization of rocky material in the upper 3 to 20 m of lunar maria of typical age about 3.6 Gyr, I argue that they also predict roughly the depth of fine-scale fragmentation and brecciation on older, pre-mare surfaces. As seen in the diagram, the prediction for a 3.6 Gyr mare surface is 7 m of very fine pulverization to 13 m of slightly coarser pulverization (consistent with mare regolith observations); depths of comparable pulverization for surfaces 3.9, 4.0, and 4.1 Gyr old would be 30–85 m, 80–150 m, and 150–400 m, respectively. Surfaces created 4.2 Gyr ago have experienced 35 times the cratering experienced by the lunar maria, and, according to Fig. 2, these surfaces would have regolith-like conditions created to a depth of about 340 to 5000 m. Mean grain diameters in Apollo regolith samples range typically around 35 to 55 μm (McKay et al. 1991) and I conclude that what I call "pulverization" by 100% to 200% crater coverage quantitatively refers to grinding of mean particle sizes to this 50 μm scale. Cohen et al. (2000) used a micro-coring technique, producing samples of characteristic diameter around 100 μm and larger, and Ryder's (1990) samples were typically larger than that. Therefore, I conclude that most of the impact melt material that came to reside in the upper 100 m of the lunar megaregolith before 4.1 Gyr ago was physically pulverized to sizes smaller than have been dated by available techniques. This is the proposed major factor in explaining the difficulty of finding datable samples dating from before about 4.0 to 4.1 Gyr ago.

PRELIMINARY QUANTITATIVE PICTURE OF REGOLITH EVOLUTION AND SAMPLING STATISTICS

From the above, it is inferred that if the impact flux in pre-mare times behaved as in Equation 1, then impact melts created in the upper few hundred meters or so before a fairly constrained time $T_{critical}$ would have low probability of surviving until the present as datable samples. Because the craters that do most of the fine-grained, mature gardening excavate <300 m (due to the steep branch in the crater size distribution), let us define the term "surface layers" to refer to roughly the top 300 m in the following order-of-magnitude modeling. Impact melts that formed in the surface layers (or were placed into them) well before $T_{critical}$ would not survive, but the ones formed or placed into surface layers around $T_{critical}$ would survive; and because of the rapid decline in flux, impact melts created near $T_{critical}$ would outnumber later impact melts. Thus, I propose (as did Hartung 1974) that $T_{critical}$ lies in the range 4.1 to 3.8 Gyr, and that this explains the preponderance of impact melts around 4.0–3.9 Gyr. Thus, the era around 4.0–3.9 Gyr becomes an "event horizon" for observable impact melt and impact-reset lunar samples.

It is important to contrast this predicted behavior of impact melts with the predicted behavior of plutonic rocks protected under hundreds of meters of megaregolith, either as part of the primordial magma ocean crust, formed ~4.5 Gyr ago, or as dikes and sills injected somewhat later. An important principle in this paper is that if there are impact melts created at time *T*, then further cratering after time *T* acts mostly to destroy them, but the same cratering brings up fragments of primordial crust or primordial plutonic rocks from the global magma ocean crustal reservoir at the base of the megaregolith. Further cratering thus "salts" the surface regolith with ancient crustal and plutonic rocks. As the megaregolith grows deeper, new fragments of such rocks are liberated. However, few reservoirs of deep-seated impact melts exist, and hence, there is a net decline of ancient impact melts in the surface layers. In effect, according to this model, old impact melts are destroyed as cratering continues, but old plutonic rock samples are constantly re-added to the surface layers.

Earlier models of regolith evolution (generally considering shallower regolith depths as seen in 3.5-Gyr-old lunar maria), such as work by McKay et al. (1974) and Gault et al. (1974), very early recognized these properties, in which pulverization is fastest at the surface, and only the largest impacts bring up samples from the layer below the regolith. But the models need further quantitative development so that the distributions of ages can be tied to the distributions of different-aged materials with depth.

From the principle stated above, it is clear that the history of rocks' sequestration at depth is key to their observed age distribution in samples picked up on the lunar surface or launched toward Earth by impacts. (Note that current models imply that rocks launched by impact processes come from a very near-surface layer (Melosh 1989). Impact melts and impact age-reset rocks behave very differently. By definition, impacts occur only on the surface and so some impact melts, impact-reset materials, and glasses are distributed in ejecta blankets and in lenses on crater floors. Impact blankets are rarely more than a few hundred meters thick, and therefore, those dating from before about 4.1 Gyr would be mostly pulverized by later cratering, grinding ancient impact melts into particle sizes too small to be measured. As an extreme example of this, impact glasses splashed around the upper 1-meter-thick surface layer by 100 m scale craters 4.1 Gyr ago would clearly not be expected to survive until the present because more than 100 m of regolith has been pulverized to mean particle size around 60 μm.

Impact melt lenses sequestered beneath crater floors are thus the only plausible source of significant volumes of impact melts from before 4.1 Gyr. Since how far back in time have they survived? Pierazzo et al. (1997) discuss impact melt volumes provided by craters of different size. Volumes increase very rapidly with crater size, and impact melts from the largest basins dominate the total volume of impact produced. What is important in determining the age distribution of recovered impact melts is their sequestration at depth, which protects them from pulverization, according to the present model. One can estimate the depths of impact lenses under craters, using the following technique. Pick a crater diameter D, read the corresponding transient cavity diameter D_{tc} from the data in Pierazzo et al. (1997, Table V), then read off the total impact melt volume V_{melt} for that D_{tc} from their Fig. 12, which plots D_{tr} versus V_{melt}. The original impact melt lenses are deposited essentially on the crater floor with the top near the surface (Melosh and Pierazzo 2002, personal communication), and extending to some depth d_{melt}. If the total volume of impact melt were distributed in a cylinder of radius 80% the crater radius, its depth Z_{melt} will thus be $V_{melt}/\pi(0.4D)^2$. Following this formulation, we estimate that the depth of impact melt under craters of $D = 32$ km, 100 km, and 200 km, is Z_{melt} ~90 m, 400 m, and 800 m, respectively. Comparing these numbers with Fig. 2, we conclude that impact melt lenses under all craters of $D \leq 200$ km formed before 4.1 to 4.2 Gyr ago would be pulverized into megaregolith, to the extent that measurable samples would be rare. "Craters" of diameter 400 km, 600 km, and 800 km, i.e., multi-ring impact basins, would have impact melt lenses extending to about 1.6 km, 2.3 km, and 3 km, according to this formulation. For multi-ring basins of this scale the survival lifetime at depth is more problematic because the lenses are thicker, the interpretation of "crater diameter" is harder to estimate (given the several rings), and it is hard to estimate exactly the depth to which megaregolith has penetrated. Nectaris basin should have a lens of about 1.5 to 2.8 km depth, and Imbrium should have a lens of about 2.6 to 5 km depth, according to this model. The megaregolith evolution model, as expressed in Fig. 2, predicts a blow-up of regolith depth before about 4.2 to 4.3 Gyr, such that an impact melt from a Nectaris scale basin should not survive if it formed before about 4.25 to 4.3 Gyr, and impact melt from even an Imbrium scale basin would not survive if it formed before about 4.3 Gyr.

The upshot of this model, then, is that large impacts after about 3.9 Gyr bring up fragments of the 4.5-Gyr-old global magma ocean crust and buried plutons, and salt them into surface layers where they can survive into our sample collections. In contrast, no impact melts from even the largest basins should be found from before about 4.3 Gyr. At around 4.1 to 4.2 Gyr, we might begin to pick up a few impact melts brought to the surface layers from the last remnants of the impact melt lenses under the floors of a few, scattered ancient basins. But since these cover much less than 100% of the area of the moon, they are much less common than the crustal and plutonic fragments, which are probably global. By around 4.1 Gyr, we begin to pick up fragments that survive from more common craters that are 100–200 km in size. By around 4.0 Gyr, craters as small as 32 km begin to contribute surviving impact melts. Since 3.8 Gyr, according to Fig. 2, the cratering has been enough to pulverize only the top 20–40 m, and many impact melts begin to survive.

It could be claimed that, to first order, this is just what is seen in the sample collections from the moon. The numerical details are not as important as the overall behavior. In particular, note that in the megaregolith evolution model, the paucity of early impact melts has nothing to do with whether there was a cataclysmic spike in cratering at 3.9 Gyr, but is caused entirely by the extremely high cratering rates before 4.1 Gyr. Furthermore, the relative age distributions of crustal,

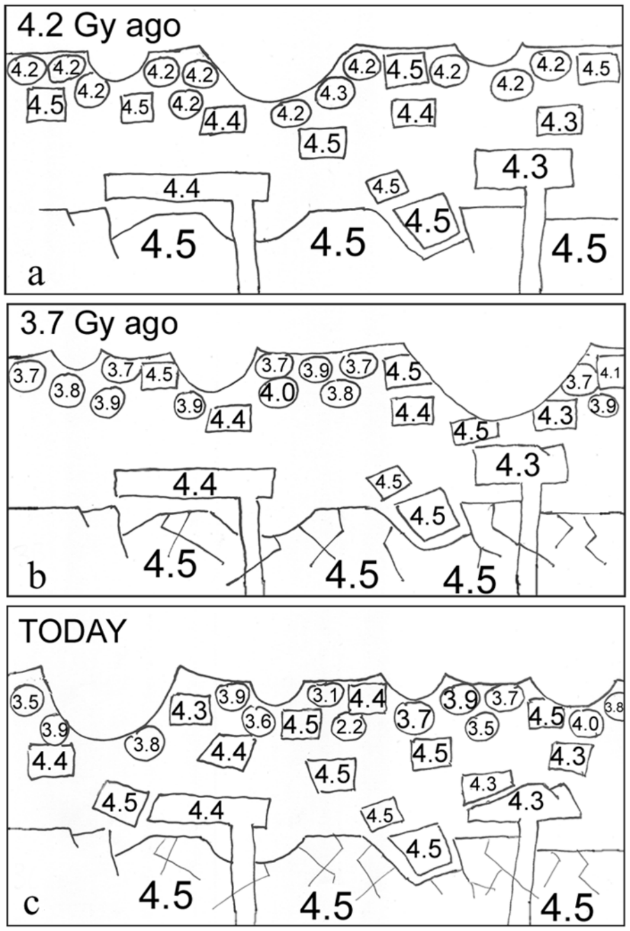

Fig. 3. Highly schematic view of lunar megaregolith evolution. Squares represent igneous plutonic and primordial crustal rock; ovals represent impact melts. Crust at the base of the megaregolith, along with deep plutons, acts as reservoirs of rocks with the earliest crystallization ages: a) at 4.2 Gyr ago, surface is dominated by impact melts created at that time; earlier impact melts have mostly been destroyed within 100 Myr by intense cratering; b) at 3.7 Gyr, cratering rate has declined to a point where survival half-life of impact melts has increased; surface layer begins to accumulate mixture of impact melt ages back to about 4.0 Gyr; c) today, cratering rate is still lower, so that impact melt on the surface is dominated by the tail end of intense bombardment back to about 4.0 Gyr; impact gardening has also continued to seed the regolith with fragments of 4.5 Gyr crust and early plutonic igneous rocks.

plutonic, and impact melts give clues to their depth distributions and creation rates as a function of time.

A simplified and schematic pictorial example, shown in Fig. 3, makes this clearer. Suppose that by 4.3 Gyr ago, a 3 km-deep megaregolith is underlain by several kilometers of 4.55–4.5 Gyr old magma crust, labeled "4.5" for convenience. (In reality, the megaregolith has eaten into the crust so that its upper surface of the crustal reservoir is highly broken and ill-defined.) Suppose there are also a few younger plutons at depth (labeled with ages 4.4 and 4.3 Gyr in Fig. 3). To add to this example, assume $T_{critical}$ ~4 Gyr ago. Then at 4.2 Gyr ago, as seen in Fig. 3a, the surface layer would have impact melts (ovals) created at that time (labeled 4.2) but few older ones, because the older ones would mostly have been destroyed on a timescale of <100 Myr. The regolith would also contain scattered chips and breccia fragments of 4.5 crust and 4.4 or 4.3 plutons (boxes), brought up shortly before by the biggest impacts during the ongoing intense early bombardment. Most of these would have been incorporated at depth into polymict breccias. After $T_{critical}$ ~4 Gyr, say at 3.7 Gyr ago, as seen in Fig. 3b, the surface layer would have impact melts dating back to the 4.0–3.9 era, indeed being dominated by impact melts from that time because of the still-declining cratering rate. The surface layer would also contain rare bits of the 4.5 crust and 4.4 or 4.3 plutons, due to continued gardening of the older layers. The relative frequency of plutonic igneous fragments in the 4.5, 4.4, and 4.3 Gyr age bins would depend on (and give clues about) the relative volumes and depths of the primordial crust and plutons. Even today, as shown in Fig. 3c, the deepest craters would salt the regolith with rare new bits of the primordial crust and plutons. The modern surface would be dominated by impact melts produced around 4.0–3.9 Gyr, along with fewer melts from later impacts (since the impact rate declined), and would also contain bits of the 4.5, 4.4, and 4.3 plutonic igneous rocks. Thus, astronauts today find intact rocks formed since 4.0 Gyr, an impact melt peak around 3.9 Gyr, and rare bits of the primordial crust and plutons.

There is one other reservoir in the solar system from which we have many samples of ancient igneous "plutonic" rocks and impact melts, and that is the asteroid belt. Here there are interesting analogs and marked differences from the lunar case, as diagramed schematically in Fig. 4. The analog to samples collected by astronauts are the meteorites, which are delivered from near-resonance positions in the belt. The analog to the primordial crustal reservoir of 4.5-Gyr-old lunar rock is the large reservoir of 4.5-Gyr-old primordial chondritic material sequestered in certain taxonomic types of asteroids. Analogs to lunar igneous plutons and mare basalts are various achondrites, some of which may have been produced in interiors, and some of which may have been produced as lavas on or near surfaces of asteroids such as 4 Vesta. Many asteroids may lack well-developed regoliths because of their low gravity, but the analogy to the pulverization of early lunar surface impact melts in regoliths is that small fragments of age-reset asteroidal materials in the belt may be rapidly destroyed by collisional grinding.

I have argued that lunar impact melts reside mostly in the upper few kilometers, and therefore, cannot survive from before 4.1 to 4.3 Gyr ago. However, this effect is not so dramatic for the asteroids because whole asteroids can be broken up and reassembled, and broken up again. This means that some volumes of impact melts can be temporarily sequestered into deep interiors of asteroids, only to be released much later. When asteroids are turned into rubble

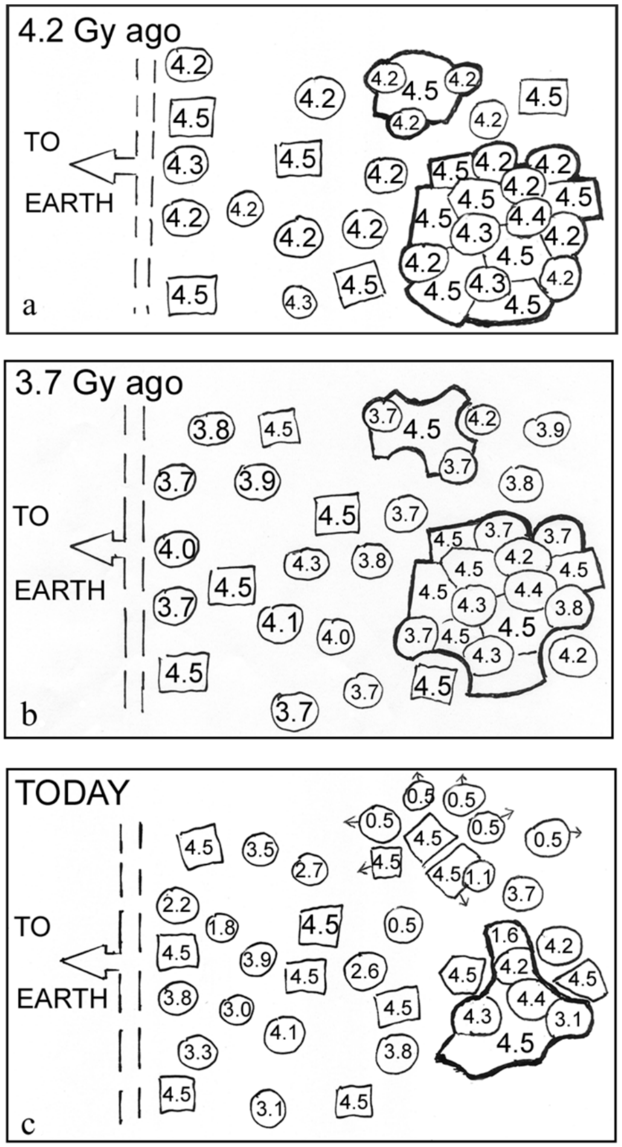

Fig. 4. Highly schematic view of asteroidal sample evolution showing similarities and differences from lunar case. Squares represent primordial rock (chondrites) and ovals represent samples with impact-reset ages. Interiors of larger asteroids act as reservoirs of 4.5 Gyr primordial rocks (basaltic achondrites are ignored for simplicity, but are analogs of lunar plutonic rocks). Dashed lines represent resonance zone where samples rapidly are delivered to Earth, analogous to lunar surface: a) at 4.2 Gyr ago, belt is dominated by an impact rate high enough to cause rapid resetting and erosion of smaller fragments and also to cause catastrophic fragmentations that create rubble piles. Rubble piles sequestered early impact melts and age-reset rocks; b) by 3.7 Gyr ago, impact rates have declined and older samples survive longer. In addition, the fragment mix is seeded by impact-reset debris of various ages, coming from breakup and cratering of rubble piles; c) today, the resonances receive a mix of debris, including recent impact debris, older reset debris broken from rubble pile asteroids, primordial 4.5 Gyr material from asteroid interior reservoirs, and debris from a breakup 0.5 Gyr ago that reset ages of many H and L chondrites (top).

piles, the most common process is not an ultra-high-energy impact that melts most of the volume or resets ages in most target material, but a smaller impact in which fractures propagate to the far side of the body at modest energy density, so that the asteroid is broken up and reassembled. This allows impact melts that would have been concentrated only in surface layers to be repositioned and sequestered into deeper positions where they can be preserved until another breakup event. If this sequestration process is efficient, the peak in asteroidal meteorite impact melt ages should be smeared out, relative to the lunar 3.8–4.0 peak, and should show more impact ages surviving from before 4.2 Gyr ago, whether the peak is due to cataclysm or regolith evolution, because more early asteroid impact melts will be sampled by breakup of rubble pile asteroids. On the other hand, if the sequestering process and asteroid breakup process is inefficient, and if a solar-system-wide cataclysm at 3.9 Gyr dominated all cratering, then asteroid impact melts should show the same peak at 3.9 as found among lunar samples.

PLANETARY ROCK AGE DATA AND THEIR INTERPRETATIONS

In this section we survey published age distributions of lunar and asteroid rocks, to compare with the model results above, and to contrast the evidence for the "megaregolith evolution" and "zero cratering, then cataclysm" hypotheses. We will present these data in the form of histograms showing age distributions of various rock sample sets. Each histogram divides the data into 100 Myr bins, and shows the percent of the specimens per bin from the sample described. For clarity, most of the histograms show just the time interval from 4.5 to 3.0 Gyr ago. These data are not new, but here we perform the useful exercise of reducing them to the same format, and presenting multiple examples in each category, showing the degree of repeatability in data tabulations of somewhat different sample groups by different authors. In each histogram, if multiple and reasonably consistent dates were reported for a clast or rock, these were averaged in order to plot one age per sample.

We will contrast data for three broad classes of rocks: 1) "Genesis rocks," or rocks that date back to the period near 4.5 Gyr; 2) "evolved igneous rocks," or rocks with formation ages well after 4.5 Gyr; and 3) impact melts.

One of the primary factors cited by Tera et al. (1974) in the original hypothesis of a lunar cataclysm was (before the detailed discussion of impact melts) the absence of "genesis rocks," for which the Apollo astronauts had been trained to look. The absence of these came to be used as an argument for an all-destroying cataclysm at 3.9 Gyr. The frequency of "genesis rocks" in the solar system remains an important clue to initial planetary histories and evolution of materials.

As shown in Fig. 5a, the asteroids give us an example of "genesis rocks" in the form of never-melted chondrites with a

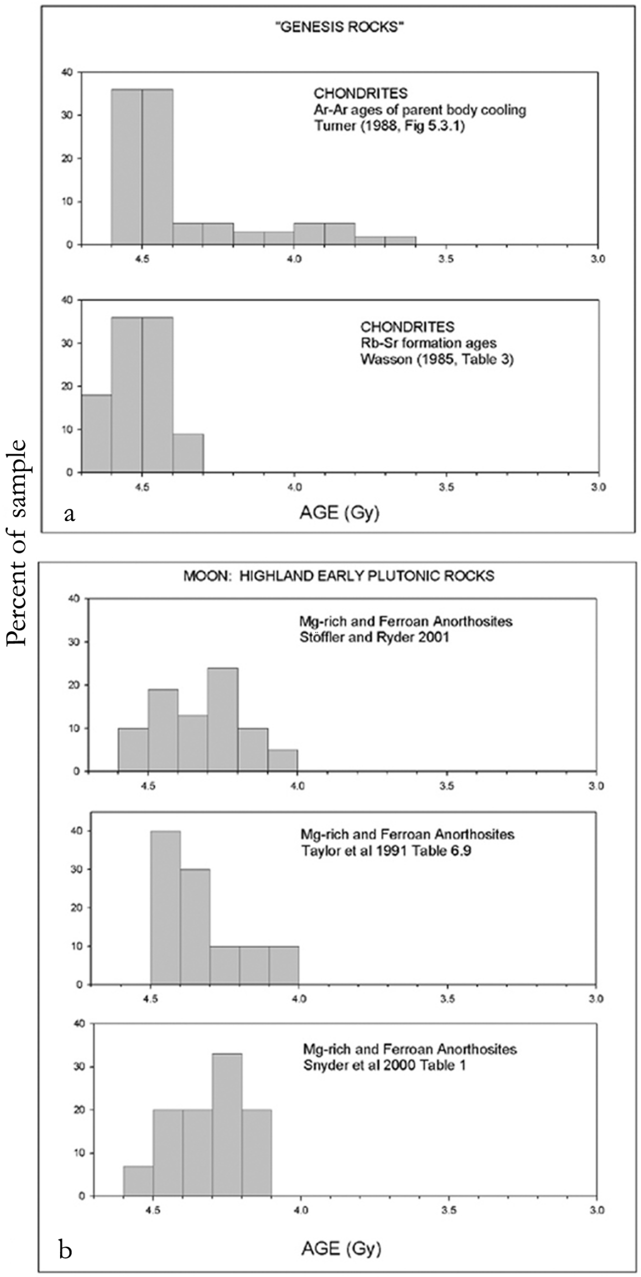

Fig. 5. Histograms showing age distribution of "genesis" rocks. This and other histograms are plotted so that the total sample adds up to 100%. Ordinate gives percent of samples falling in each 100 Myr time bin: a) strong peak at 4.5 Gyr for chondrites indicates existence of a reservoir of primordial asteroid material providing samples to us; b) age distribution for very early Mg-rich materials and ferroan anorthosites. These have been grouped by various investigators as remnants of the original magma ocean crust and show a peak in ages around 4.5–4.2 Gyr. They are interpreted here as early crustal material churned up by the largest impacts in the continuing megaregolith evolution process.

strong peak in ages around 4.5 Gyr ago, marking the formation of initial reservoirs of chondritic material. The reservoirs could be located in deep interiors of asteroids if melting happened from outside in, as can happen in electrical induction heating models such as that of Herbert (1989); in this case they would be released into the belt during catastrophic asteroid collisions. Alternatively, the reservoirs of primitive material could be in outer layers of asteroids, if melting happened from inside out, as by short-lived radioisotopes. In these cases, fragments of intact 4.5 Gyr chondritic material could be released during many cratering events in the asteroid belt. Thus, there is a relation between the sequestering models and the age distribution of fragments that will be produced. Meteorite age data are from tabulations by Turner (1988) and Wasson (1985), and show a strong peak at 4.5 Gyr. The closest lunar analogs of asteroidal genesis rocks are magnesium-rich plutonic rocks and ferroan anorthosites, with a peak in ages around 4.5 to 4.2 Gyr (Fig. 5b). These are generally seen only as clasts, interpreted as remnants of the initial lunar crust's formation (Stöffler and Ryder 2001; Snyder et al. 2000; Taylor et al. 1991). They are interpreted as being brought up from the deep megaregolith by ongoing cratering, thus proving the existence of a deep reservoir of very early material.

Figure 6 shows the crystallization age distributions from some samples of more evolved igneous asteroidal rocks and deep-seated plutonic lunar rocks and clasts. In the asteroids these exist as various basaltic achondrites including basalts on 4 Vesta, and probably as plutons; on the moon they range from plutons deep in the megaregolith to lunar pre-mare and mare basalts. ("Pre-mare basalts" refer to basalts buried under a thin veneer of high albedo plains, as evidenced by spectra of dark halo craters by Hawke and Bell 1981, 1982, 1983.) The main point of this diagram is to confirm that a broad range of crystallization ages are represented from both before and after the putative cataclysm at 3.85 Gyr, consistent with a view that asteroid collisions and lunar megaregolith evolution continually "salt" our samples with early material. In the lunar case, the age distribution is a clue to the depth distribution. The data in Fig. 6 are from Stöffler and Ryder (2001) and Snyder et al. (2000).

When we turn to impact melts, a very different pattern emerges, as emphasized by Ryder (1990). Figure 7 compares the data for asteroids and the moon. Figure 7a shows an asteroid-related tabulation by Bogard (1995, Table 2) of impact reset ages for 13 chondrite samples, mostly based on Ar-Ar degassing ages, and also shows Bogard's data (Table 1) for 33 achondrite samples, again mostly Ar-Ar ages. Most of the data are plotted as one age per rock, but in the cases of Bhalghotti, Cachari, Kapoeta, and LEW 85300, the data were interpreted to indicate two different impacts per rock. Bogard correctly points out that the interpretation of these age

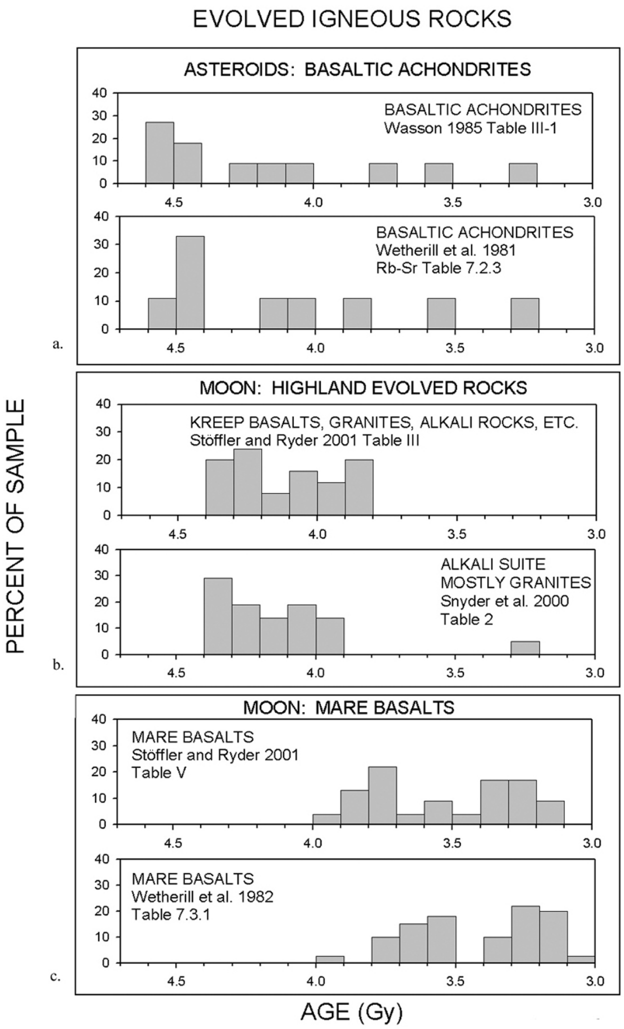

Fig. 6. Age distributions of evolved igneous asteroidal and lunar samples. There is a range of ages from before the putative cataclysm at 3.85 Gyr to 3.0 Gyr and later. The shapes of these distributions are interpreted here as containing information about the interplay between the volumes of source material created at various ages, the rate of churning them into the upper layers by megaregolith gardening, and by their survival lifetimes once in the surface layers: a) asteroidal-evolved igneous rocks (achondrites); b) lunar-evolved igneous breccia fragments brought up by megaregolith churning. The shape of this distribution involves a contest between bringing up fragments and destroying them once they are near the surface; c) lunar mare basalts—basaltic igneous surface rocks sufficiently fresh that their low albedos and volcanic surface structures are still visible. The difference between the samples in (b) and (c) implies that, by about 4.0 to 3.7 Gyr ago, cratering had declined to the point where surface structures in the upper tens of meters could be preserved (as shown also in Fig. 2).

distributions requires consideration of the history of preservation, depth of burial, and surface exposure to impacts among the asteroid parent bodies, commenting that "impacts which partially reset the Ar-Ar ages of most chondrites left the material in a buried, shielded state, and it was subsequent, less severe impacts which brought the meteorites into space..." Bogard's discussion, at some level, is analogous to Hartung's early suggestion that lunar age distributions required modeling of the regolith evolutionary competition among processes of rock creation, burial, and destruction.

Figure 7b includes the pattern observed between two different lists of Apollo/Luna lunar impact melt samples, including a list of nine crystalline melt breccias and eight clast-poor impact melts from Taylor et al. (1991), and also a list of 46 polymict highland breccias from Stöffler and Ryder (2001). Taylor et al. describe these as polymict breccias or impact melt rocks. Figure 7b shows a much tighter peak from 4.0 to 3.8 Gyr than the asteroidal sample, where the peak spreads from about 4.5 to 3.8 Gyr ago. Note that the lunar spike approaches 50%, i.e., around half these lunar samples come from the narrow, 100 Myr time interval of 3.8 to 3.9 Gyr.

Comparison of Figs. 7a and 7b would appear to disprove the "strong form" of the hypothesis of Ryder (1990) that the lack of lunar impact melts before ~4.1 to 4.3 Gyr ago requires a lack of cratering at that time. The reasoning is that both the chondrite and achondrite samples in Fig. 7a show fewer samples before ~4.1 Gyr than in the 4.0 to 3.6 time interval, and yet we can be sure there was at least as much collisional impacting in the asteroid before 4.1 Gyr than since then (Safronov 1972; Weidenschilling et al. 2001). In the asteroid belt, at least, we can be sure that the broad peak in ages around 4.0 to 3.6 Gyr ago is not associated with an absence of cratering before 4.0 Gyr, but is associated with collisional evolution and sequestering histories, as in the regolith evolution hypothesis.

The most important thing about Figs. 7a and b is that while the asteroid belt does show a broad peak bracketing 3.9 Gyr, it does not offer strong support for an overwhelming cataclysm between 4.0 and 3.8 Gyr. If such a cataclysm occurred in the belt, its effects seem to have been overwhelmed by the background of collision and cratering in the belt – an important boundary condition on its magnitude and distribution in the inner solar system.

THE LUNAR METEORITE RECORD: EVIDENCE AGAINST A CATACLYSM?

The primary evidence for a brief (<200 Myr) cataclysm at 3.85 Gyr comes from Apollo and Luna samples collected in a rather limited portion of the front side of the moon, with the majority of sites being in areas where the nearest highlands are involved with Imbrium ejecta. Citing the possibility that the ages in these collections might be dominated by front-side basin-forming events, especially Imbrium, Cohen et al. (2000) made a valuable effort to measure Ar-Ar impact ages of lunar meteorites, which presumably offer a more random sampling of the moon's surface, making some petrochemical choices to favor lunar meteorites that differed from the Apollo

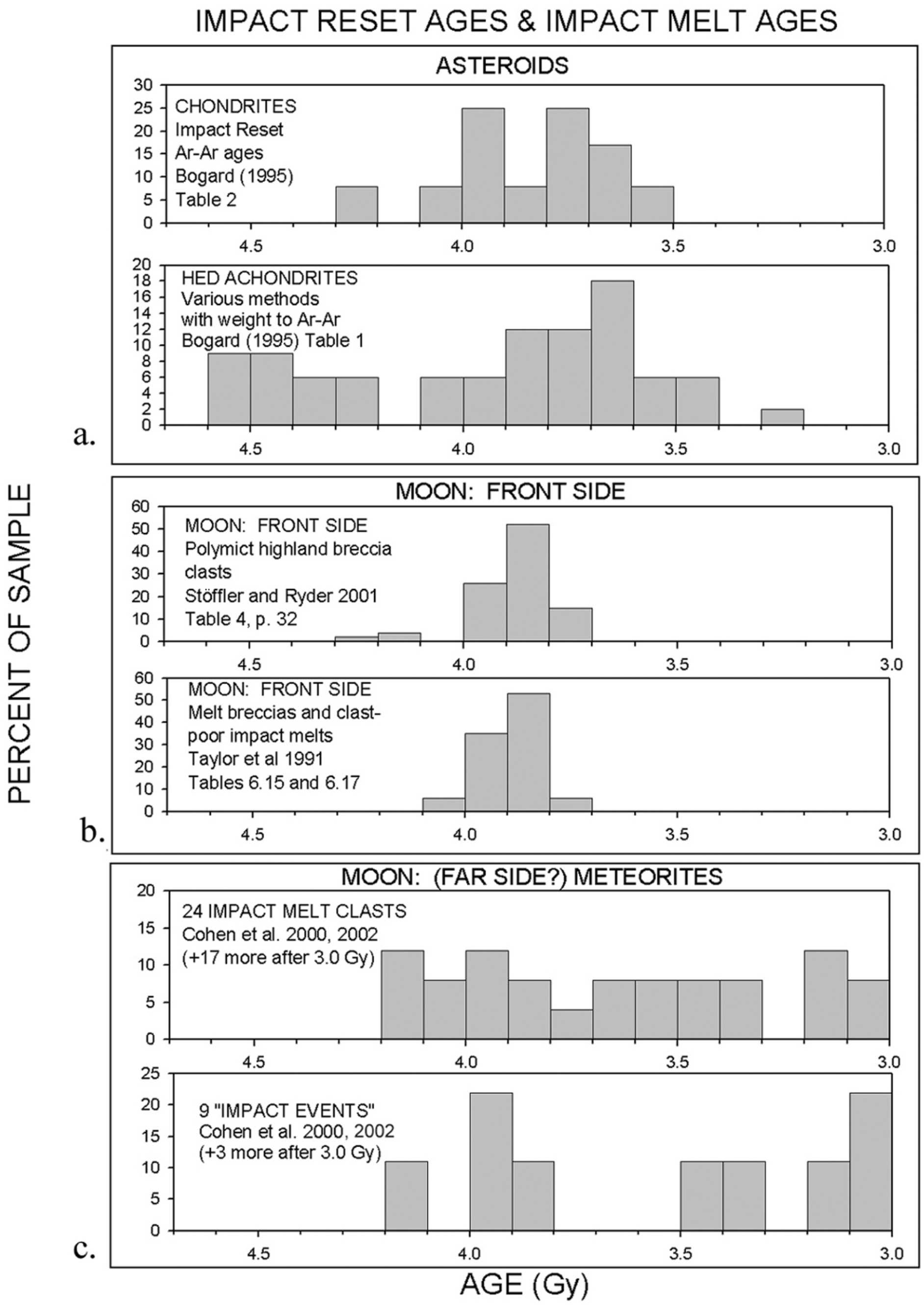

Fig. 7. Age distributions of impact melts and rocks with impact-reset ages in asteroidal and lunar materials: a) both chondrites and achondrites show a broad peak around 4.0 to 3.6 Gyr. Models show that collisions were common in the early asteroid belt (Weidenschilling et al. 2001), and so the relative dearth of impact reset ages before 4.1 (especially among chondrites) disproves that Ryder's premise that lack of impact-reset ages means lack of impacts. Thus, the asteroids' profile before 4.1 Gyr is controlled by production rates and survival lifetimes and the asteroid belt does not offer proof for a 100 Myr cataclysm at 3.85 Gyr; b) spike-like age distributions of impact melts in lunar Apollo/Luna samples are very different, with roughly half the samples dating to the 100 Myr interval of 3.9 to 3.8 Gyr ago. This is the primary evidence for a cratering cataclysm; c) impact melt clast ages and impact events identified in lunar meteorites by Cohen et al. (2000, 2002) do not show any spike at 3.9 Gyr. Top diagram shows impact melt clast ages from the 24 clasts from six meteorites. Bottom diagram shows ages of 9 impact events detected in the clasts. Cohen et al. interpreted the data in (c) as supporting a cataclysmic event at 3.9 Gyr on the grounds of lack of early melts, but the data are very different from the Apollo/Luna data (b) and are more consistent with a regolith evolution model not dominated by a cataclysm.

sample chemistries, and thus might come from other parts of the moon.

Figure 7c (top) shows data from 41 impact melt clast ages measured by Cohen et al. (2000, 2002) and (bottom) ages of 13 "impact events" identified by them, as defined by an age deduced by statistical analysis of the ages and uncertainties. Seventeen of the 41 clast ages and 4 of the 13 identified impact events are younger than 3.0 Gyr and lie off Fig. 7c to the right. Cohen et al. (2000) interpret these data as "support for the lunar cataclysm hypothesis from lunar meteorite impact ages" (the title of their paper), and concluded that "the lack of impact melt older than 3.92 Ga supports the concept of a short, intense period of bombardment in the Earth-moon system at ~3.9 Ga" (from their abstract). A similar conclusion is repeated by Kring and Cohen (2002). From the point of view of the "megaregolith evolution" hypothesis, those conclusions do not follow from the data. In the first place, contrary to their statement, the data of Cohen et al. (2000, 2002) do show impact melt ages older than 3.92 Gyr (4 of the 31 impact melt clasts in the first paper have reported ages of 3.94, 4.01, 4.04, and 4.12 Gyr, and 3 of the 10 in the second paper have reported ages of 3.95 [isochron age; 4.01 ± 0.20 plateau age on the same sample], 4.16, and 4.20 Gyr, albeit with error bars that usually overlap 3.92 within 1σ). Their statement should have referred to their interpreted impact events (not to the impact melts themselves), which show an absence of impact melts before 4.2 Gyr. In the second place, in context of the present work, one could infer from the data that, remarkably, the opposite conclusion is true, namely, that there is no sign of a strong peak in impact ages at 4.0–3.9 Gyr, and thus that the data do not particularly support the cataclysm hypothesis. The overwhelming, 50%-level spike in ages at 3.8–3.9 Gyr, seen in the front side data, is simply absent in the meteorite data of Cohen et al. (2000, 2002). The mis-application of this work as a result of its title, abstract, and conclusions, is striking. For example, Peck et al. (2001), in developing a model of a cool, early Earth, state: "recent work has documented a strong peak in impact intensity at ~3.9 Ga (Cohen et al. 2000)," when in fact, the cited paper shows no peak at all. In the third place, the present work shows that absence of impact melts before 4.2 Gyr (or 3.92 Gyr) has nothing to do with whether a cataclysm occurred at 3.85 Gyr, at least as viewed within the "megaregolith evolution" hypothesis. Indeed, if one wants to attach significance to the absence of impacts before 3.92 in the lunar meteorite collection as a measure of lunar impact history, one must accept that the data on these (far side?) meteorites at 3.8–3.9 Gyr are also significant and they show no peak, completely contradicting the Apollo/Luna front side data.

Why don't the lunar meteorite data show a clearer confirmation of the sharp, 50%-level spike observed in the lunar Apollo/Luna data of Fig. 7b? One possibility (raised in round table discussions at the 2002 LPSC following the Ryder-dedicated session on lunar meteorites) is that there may be some systematic differences between the selection criteria of Ryder and others who chose impact melts from the Apollo/Luna samples and those used by Cohen and co-workers who chose impact melts from lunar meteorites. This may have caused the latter sampling to be skewed more toward smaller impact crater events dotted down through lunar history.

This is shown more clearly in Fig. 8, which shows the entire solar system history in terms of impact melt and age-reset samples of chondrites, achondrites, lunar meteorites (with "non-front-side" chemistry), and the lunar Apollo/Luna sample from the front side. The lunar front side sample of Apollo/Luna materials appears to be dominated by the resetting events near 3.9 Gyr, while the meteorite samples might be described as picking up at around 4.1 Gyr and sampling impact events on down through later time—clearly not major basin forming events.

A different interpretation of Figs. 7 and 8 is that the tight spike in age-reset events is seen only in the lunar front side Apollo/Luna sample-collecting area and might therefore represent a unique event that affected that region—most likely the Imbrium-forming event. I consider this interpretation below.

OLD IMPACT MELTS ENTRAINED IN THE IMBRIUM EJECTA—A FACTOR IN APOLLO DATA?

An argument made by researchers such as Stöffler and Ryder (2001) in favor of the cataclysm is that front side data prove that five major impact basins—Imbrium, Orientale, Nectaris, Crisium, Serenitatis—have been dated and all formed within the interval 3.92 to 3.72 Gyr, with 3.77 ± 0.02 and 3.85 ± 0.02 Gyr being mentioned by them (their Table VI) as possible ages for Imbrium. The argument is controversial and complex, but centers around assertions that impact melts found at Apollo sites can be used to date formations that relate to the basin-forming impacts, and that the melts date basin-scale events because most melts come from the largest basins.

If we could confirm that nearly all visible basins formed in only 200 Myr around 3.9 Gyr ago, it would confirm a cataclysm. However, crater density differences among basin impact surfaces have been confirmed (Hartmann and Wood 1971; Wilhelms 1987). On the other hand, it has long been recognized that due to the rapid decline in cratering rate documented at ~4 Gyr ago, large crater density differences may reflect only small differences in ages. Confirming whether visible basins span only 100–200 Myr, or 300–500 Myr, is thus crucial in discussing cataclysms.

There may be a factor that seems not to have been adequately considered, namely that the area excavated by Imbrium, and sampled by Apollo astronauts in its ejecta blanket, may have included the impact melt lenses of several large craters that formed in that area shortly before the Imbrium impact. Fig. 1 shows that the lunar surface would have been hit by 32 times the mare crater density—i.e., the

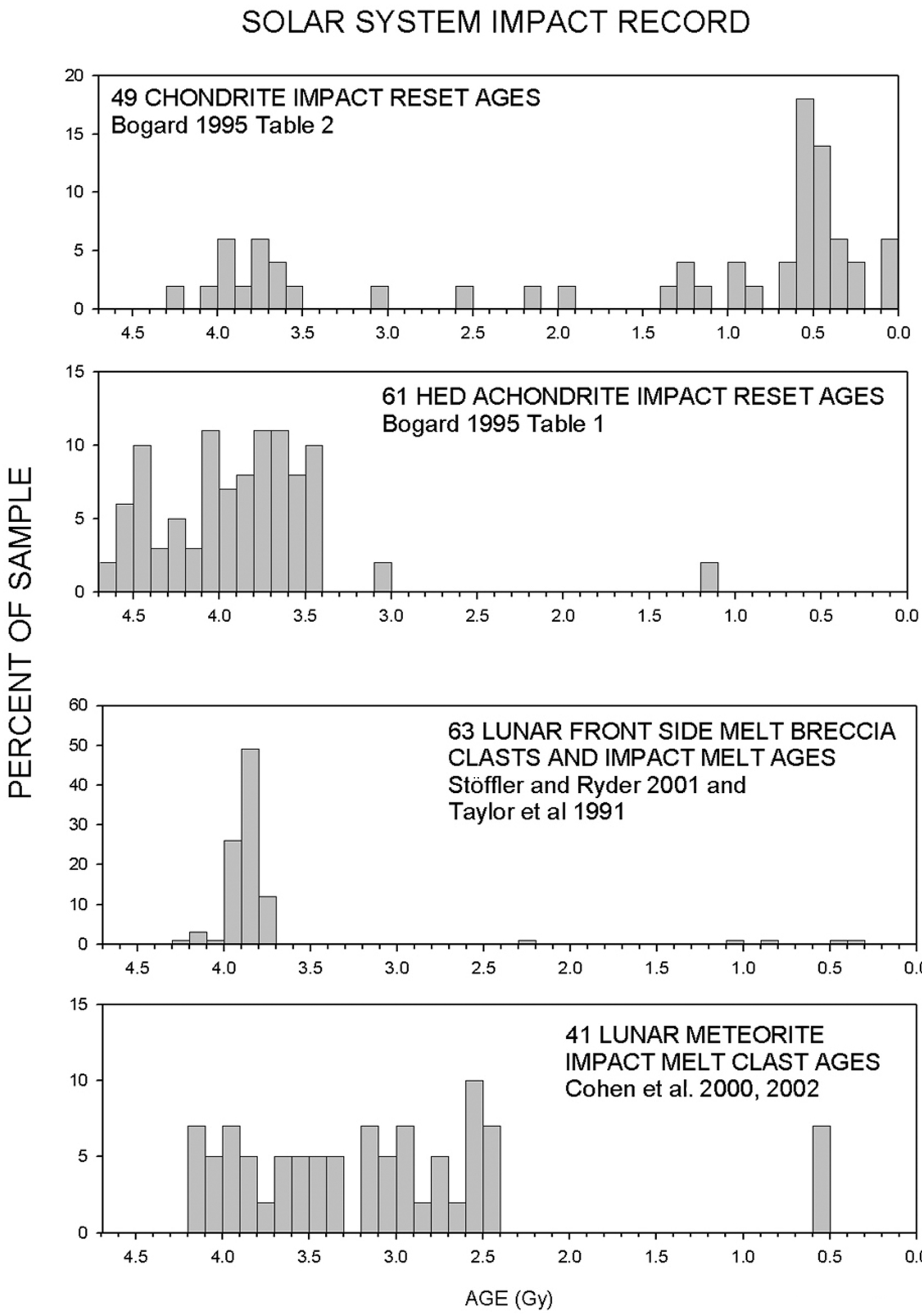

Fig. 8. Summary of the inner solar system's entire history in terms of impact melt and age resetting statistics for asteroids, lunar front side, and lunar meteorites. The asteroids and the moon show a scattering of impacts after the 3.0 Gyr cutoff used in the earlier figures. Lunar data from Fig. 7 are combined into one graph. The difference between the lunar "front side" and lunar meteorite sampling of impact melts is pronounced, in that the lunar meteorite data suggest a long sampling of impacts back to 4.1 or 4.2 Gyr ago, with no peak at 3.9 Gyr. The 3.9 Gyr peak may relate to a front side event. The asteroidal collision breakup event that produced the chondrites ~0.5 Gyr ago may be detected in the lunar meteorite record as well—in terms of an increased number of lunar hits. The overall data appear consistent with more intense cratering in the early solar system, with survival probability impact melts in surface layers high only after $T_{critical}$~4.0 Gyr ago.

density needed for saturation—between ~4.3–4.2 Gyr ago and the time of the Imbrium impact ~3.8 Gyr ago. From Fig. 2, the depth finely gardened into regolith in that interval is roughly 250 m, with more coarse gardening to a few km. Based on our early discussion, craters larger than 100 km to 200 km formed after 4.3–4.2 Gyr could thus have had impact lenses that might at least partially survive the megaregolith gardening that occurred by the time of the Imbrium impact. Using the saturation densities derived by Hartmann (1984) and Hartmann and Gaskell (1997), I find that if the ejecta blanket was derived from an Imbrium area 1000 km across, the ejecta would entrain debris from eleven such craters larger than 100 km across, including three larger than 200 km. If the blanket came from a transient cavity area of about 400 km diameter, the figures are 3 craters and 1 crater, respectively. Therefore, it appears plausible the area of ejection of Imbrium debris could have contained several impact melt lenses and ejecta blankets of now-lost, pre-Imbrian small basins or large craters that covered appreciable areas compared to the Imbrium ejecta area itself. Those impact melt fragments might play a role in confusing the issue of using small-scale impact melt clasts brought back from Apollo landing sites to date distant basin systems.

THE TERRESTRIAL RECORD: UNCERTAIN EVIDENCE FOR A CATACLYSM

Ryder et al. (2000) pointed out that if the putative lunar cataclysm occurred, it should be manifested among the oldest terrestrial rocks by shocked minerals. They undertook a search for these among Archean sediments of age >3.7 Gyr, including rocks from West Greenland interpreted to be at least 3.8 Gyr in age. They found no evidence of unusual abundance of shocked minerals, and concluded that "no direct...evidence of a late heavy bombardment on Earth can as yet be confirmed." They inferred that the bombardment declined so fast after 3.85 Gyr that slightly later rocks do not show it, but their evidence is also consistent with the idea that the cataclysm never happened. More recently, Schoenberg et al. (2002) suggested that the terrestrial evidence seems to be equivocal.

MARTIAN METEORITES AND A CLUE ABOUT 4.5 GYR RESERVOIRS

Because astronauts could find no "genesis rocks" on the lunar surface (the samples in Fig. 5b being mostly small breccia clasts and chips), it is all the more remarkable one of the first 20 rocks from four to eight sampled impact sites on Mars is "a fragment from the ancient Martian crust," essentially a "genesis rock." It is the coarse-grained, brecciated orthopyroxenite Allan Hills 84001, which has a crystallization age of around 4.50–4.56 Gyr (Nyquist et al. 2001). Other currently known Martian meteorites are younger than 1.3 Gyr, far too young to have a bearing on the cataclysm issue.

This important difference between Mars and the moon is instructive. The lunar 4.5 Gyr magma ocean crust is buried under perhaps several kilometers of megaregolith, and thus highly brecciated samples are exposed only by cratering and megaregolith churning. On Mars, parts of the primordial crust must be near the surface, because rocks can probably be launched into space only from the upper layers (100 m?; see review by Nyquist et al. 2001). The primordial Martian crust has thus apparently been exposed at the surface by vigorous Martian erosion processes, across a non-negligible fraction of the surface. This has several implications discussed further by Hartmann and Neukum (2001), but, in particular, Mars may give us our only chance to sample primordial magma ocean crust (which is buried on the moon and was destroyed by plate tectonics on Earth).

CONCLUSIONS

The hypothesis that a lunar or inner-solar-system-wide cratering cataclysm occurred ~3.9 Gyr ago is not established, and comparison of Apollo/Luna samples, lunar meteorites, and asteroidal meteorites does not give compelling support for it.

Arguments that the cataclysm has been confirmed in lunar (far side?) meteorites, expressed by Cohen et al. (2000, 2002), and Kring and Cohen (2002), appear inconclusive because their data do not show the spike at 3.9 Gyr that contains nearly half the impact melts found in Apollo/Luna samples, and their finding of a lack of impact melts before ~4.2 Gyr does not prove a cataclysm at 3.9 Gyr. In a related issue, the argument that a dearth of impact melts before 4.2 Gyr proves a dearth of impacts at that time (Ryder 1990) is disproved by data from the asteroids, where such a relative dearth of pre-4.2 Gyr impact-reset ages also appears, in spite of near certainty that impact rates were not lower at that time.

The widely cited assertion that at least five major basins formed in a 200 Myr interval centered around 3.82 Gyr ago (e.g., Stöffler and Ryder 2001) appears not fully confirmed because of issues about correlating specific small-scale samples at Apollo sites with specific distant basins. This issue may be complicated by the fact that the Imbrium ejecta blanket may contain impact melts from a few pre-Imbrian basins or large craters that occupied the Imbrium impact site and were destroyed by the Imbrium impact.

A plausible alternative "regolith evolution hypothesis," dating back to the work of Hartung (1974)—namely that impact melts from that period were destroyed by intense cratering at that time needs continued testing. A key fact, considered here, is that impact melts on average spend more time near the surface than early crustal and plutonic rocks and hence are destroyed more efficiently by cratering after their formation. The crude modeling presented here appears to confirm that most impact melts created before about 4.1–4.2 Gyr ago would be physically pulverized by subsequent cratering on timescales <100 Myr, reducing them to mean particle sizes <60 μm. Thus they would not appear among datable samples. The hypothesized very high early cratering rates, suggested by accretion models as well as by backward extrapolation of measured cratering rates, would not only destroy most old impact melts but would also constantly re-seed the megaregolith with early crustal and igneous fragments dredged up from depth by the largest craters. Only after a certain time $T_{critical}$ would the impact flux decline to a point where survival lifetime of impact melts exceeds the time available; $T_{critical}$ is suggested to be about 4.0 Gyr.

If the impact flux rate was still declining at that time, the peak in asteroidal and lunar front side impact melts at about 4.0 to 3.8 Gyr may be caused by the combination of destruction before that time and the declining creation of them after that time. Furthermore, the lunar meteorite data so far do not confirm the sharp "50%-level" peak. Its absence outside the front-side Apollo/Luna collecting area would rule out the classic cataclysm models and suggest that the front side spike in impact melt ages may be associated with the Imbrium event.

The valuable lunar meteorite impact melt data of Cohen et al. (2000, 2002) appear consistent with the "megaregolith evolution" hypothesis of a declining impact flux and a $T_{critical}$ cutoff date around 4.0 Gyr. Following the lead of Cohen et al., more complete studies of impact melts in the growing lunar meteorite collection are thus extremely important to test the "megaregolith evolution" model versus the "zero cratering, then cataclysm" model. The two hypotheses mentioned are deliberately chosen as end members and it should be remembered that the truth could lie between, involving an intense early declining bombardment associated with accretion, with superimposed spikes (including a large one at 3.85 Gyr?) caused by breakup of a large Earth-crosser, which could occur by collision at aphelion in the belt, producing an increased flux of modest-sized impactors for timescales on the order of 10–20 Myr.

Several important tests would help clarify the situation.

1. We need to establish if selection criteria for identifying impact melt samples, such as the Cohen et al. criteria for meteorites versus the Ryder criteria for Apollo samples, are giving different results. If the Cohen impact melt selection criteria are used on Apollo samples, do they produce an age distribution that looks like the Cohen et al. (2000, 2002) lunar meteorite distributions, or like the sharply spiked front side Apollo impact melt distribution? If Cohen's technique applied to Apollo samples does not confirm the spike in ages, it would suggest that two different selection criteria are being used for choosing impact melt samples.
2. Given the Cohen et al. attempt to sample lunar meteorites with chemistry unlike that on the front side, then is it possible to pick other lunar meteorites that appear to have chemistry like the Apollo front side samples and determine if they show a spike in impact melt ages at 3.9 Gyr? If so, this result would imply that the spike is restricted to a phenomenon that happened on the lunar front side, so that the lack of a spike in the remaining sample would more definitively argue against an inner-solar-system-wide cratering cataclysm.
3. A dedicated lunar sample return mission to definitively establish the age of the Nectaris multi-ring basin system (or other similar basins) would help resolve the basin-dating issues.
4. The present model implies that impact melts of older ages, before 4.1 Gyr, may be concentrated among particles smaller than 50–100 μm.

Editorial Handling—Dr. Stuart Ross Taylor

REFERENCES

Bogard D. 1995. Impact ages of meteorites: A synthesis. *Meteoritics* 30:244–268.
Cohen B. A. 2002. Geochemical and geochronological constraints on early lunar bombardment history (abstract #1984). 32nd Lunar and Planetary Science Conference. CD-ROM.
Cohen B. A., Swindle T. D., and Kring D. A. 2000. Support for the lunar cataclysm hypothesis from lunar meteorite impact melt ages. *Science* 290:1754–1756.
Gault D. E., Hörz F., Brownlee D. E., and Hartung J. B. 1974. Mixing of the lunar regolith. Proceedings, 5th Lunar and Planetary Science Conference. pp. 260–262.
Grinspoon D. H. 1989. Large impact events and atmospheric evolution on the terrestrial planets. Ph.D. thesis, University of Arizona, Tucson, Arizona, USA. 209 p.
Hartmann W. K. 1965a. Terrestrial and lunar flux of large meteorites in the last two billion years. *Icarus* 4:157–165.
Hartmann W. K. 1965b. Secular changes in meteoritic flux through the history of the solar system. *Icarus* 4:207–213.
Hartmann W. K. 1966. Early lunar cratering. *Icarus* 5:406–418.
Hartmann W. K. 1970. Preliminary note on lunar cratering rates and absolute timescales. *Icarus* 12:131–133.
Hartmann W. K. 1972. Paleocratering of the moon: Review of post-Apollo data. *Astrophysics and Space Science* 12:48–64.
Hartmann W. K. 1973. Ancient lunar mega-regolith and subsurface structure. *Icarus* 18:634–636.
Hartmann W. K. 1975. Lunar "cataclysm:" A misconception? *Icarus* 24:181–187.
Hartmann W. K. 1980. Dropping stones in magma oceans: Effects of early cratering. Proceedings, Conference on Lunar Highlands Crust. pp. 155–171.
Hartmann W. K. 1984. Does crater "saturation equilibrium" occur in the solar system? *Icarus* 60:56–74.
Hartmann W. K. 2001. Martian cratering 7: The role of impact gardening. *Icarus* 149:37–53.
Hartmann W. K. and Gaskell R. W. 1997. Planetary cratering 2: Studies of saturation equilibrium. *Meteoritics & Planetary Science* 32:109–121.
Hartmann W. K. and Neukum G. 2001. Cratering chronology and the evolution of Mars. In *Chronology and evolution of Mars,* edited by Kallenbach R., Geiss J., and Hartmann W. K. Bern, Switzerland: International Space Science Institute. pp. 165–194.
Hartmann W. K. and Wood C. A. 1971. Moon: Origin and evolution of multi-ring basins. *The Moon* 3:3.
Hartmann W. K., Ryder G., Dones L., and Grinspoon D. 2000. The time-dependent intense bombardment of the primordial Earth/moon system. In *Origin of the Earth and Moon,* edited by Canup R. and Righter K. Tucson, Arizona: University of Arizona Press. pp. 493–512.
Hartung J. B. 1974. Can random impacts cause the observed 39Av/40Av age distribution for lunar highland rocks? *Meteoritics* 9: 349.
Hawke B. R. and Bell J. F. 1981. Remote sensing studies of lunar dark-halo impact craters: Preliminary results and implications of

early volcanism. Proceedings, 12th Lunar and Planetary Science Conference. pp. 665–678.
Hawke B. R. and Bell J. F. 1983. Spectral reflectance studies of dark-haloed impact craters: Implications for the composition and distribution of ancient lunar basalts. Proceedings, 16th Lunar and Planetary Science Conference. pp. 287–288.
Herbert F. 1989. Primordial electrical induction heating of asteroids. *Icarus* 78:402–410.
Kring D. A. and Cohen B. A. 2002. Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga. *Journal of Geophysical Research* 107(E2):4.1–4.6.
McKay D. S., Fruland R. M., and Heiken G. H. 1974. Grain size and evolution of lunar soils. Proceedings, 5th Lunar and Planetary Science Conference. pp. 887–906.
McKay D. S., Heiken G., Basu A., Blanford G., Simon S., Reedy R., French B. M., and Papike J. 1991. The lunar regolith. In *Lunar sourcebook,* edited by Heiken G., Vaniman D., and French B. Cambridge, Massachusetts: Cambridge University Press. pp. 285–356.
Melosh H. J. 1989. *Impact cratering, a geologic process.* New York: Oxford University Press. 245 p.
Neukum G. 1983. Meteoritenbombardement und Datierung planetarer Oberflachen. Habilitation. Dissertation for Faculty Membership, Ludwig-Maximillians-University of Munich. 186 p.
Neukum G. and Ivanov B.A. 1994. Crater size distributions and impact probabilities on Earth from lunar, terrestrial-planet, and asteroid cratering data. In *Hazards due to comets and asteroids,* edited by Gehrels T. Tucson, Arizona: University of Arizona Press. pp. 359–416.
Neukum G., Ivanov B. A., and Hartmann W. K. 2001. Cratering records in the inner solar system in relation to the lunar reference system. In *Chronology and evolution of Mars,* edited by Kallenbach R., Geiss J., and Hartmann W. K. Bern, Switzerland: International Space Science Institute. pp. 55–86. (also in *Space Science Reviews* 96:55–86).
Nyquist K., Bogard D., Shih C. Y., Greshake A., Stöffler D., and Eugster O. 2001. Ages of martian meteorites. In *Chronology and evolution of Mars,* edited by Kallenbach R., Geiss J., and Hartmann W. K. Bern, Switzerland: International Space Science Institute. pp. 105–164.
Peck W. H., Valley J. W., Wilde S. A., and Graham C. M. 2001. Oxygen isotope ratios and rare earth elements in 3.3 to 4.3 Ga zircons: Ion microprobe evidence for high ^{18}O continental crust and oceans in the early Archean. *Geochimica et Cosmochimica Acta* 65:4215–4229.
Pierazzo E., Vickery A. M. and Melosh H. J. 1997. A reevaluation of impact melt production. *Icarus* 127:408–423.
Ryder G. 1990. Lunar samples, lunar accretion, and the early bombardment of the Moon. *Eos* 71:313, 322–323.
Ryder G., Koeberl C., and Mojzsis S. J. 2000. Heavy bombardement of the Earth as 3.85 Ga: The search for petrographic and geochemical evidence. In *Origin of the Earth and Moon,* edited by Canup R. and Righter K. Tucson, Arizona: University of Arizona Press. pp. 475–492.
Safronov V.S. 1972. *Evolution of the protoplanetary cloud and formation of the Earth and the planets.* Jerusalem: Israel Program for Scientific Translations. 206 p.
Schoenberg R., Kamber B. S., and Collerson K. D. 2002. Evidence for ~3.8 Ga meteorite bombardment of the Earth (abstract). 12th Annual V. M. Goldschmidt Conference. p. A684.
Short N. and Forman M. 1972. Thickness of impact crater ejecta on the lunar surface. *Modern Geology* 3:69.
Snyder G. A., Borg L. E., Nyquist L. E., and Taylor L. A. 2000. Chronology and isotopic constraints on lunar evolution. In *Origin of the Earth and Moon,* edited by Canup R. and Righter K. Tucson, Arizona: University of Arizona Press. pp. 361–396.
Soderblom L. A. and Boyce J. M. 1972. Relative ages of some near-side and far-side terra plains based on Apollo 16 metric photography. In *Apollo 16 preliminary science report.* NASA Special Paper-315. Washington, D. C.: NASA. pp. 29.3–29.6.6.
Stöffler D. and Ryder G. 2001. Stratigraphy and isotope ages of lunar geologic units: Chronological standard for the inner solar system. In *Chronology and evolution of Mars,* edited by Kallenbach R., Geiss J., and Hartmann W. K. Bern, Switzerland: International Space Science Institute. pp. 9–54.
Taylor G. J., Warren P., Ryder G., Delano J., Pieters C., and Lofgren G. 1991. Lunar rocks. In *Lunar sourcebook,* edited by Heiken G., Vaniman D., and French B. Cambridge, Massachusetts: Cambridge University Press. pp. 181–284.
Tera F. D., Papanastassiou A. and Wasserburg G. J. 1974. Isotopic evidence for a terminal lunar cataclysm. *Earth and Planetary Science Letters* 22:1–21.
Turner G. 1988. Dating of secondary events. In *Meteorites and the early solar system,* edited by Kerridge J. F. and Matthews M. S. Tucson, Arizona: University of Arizona Press. pp. 276–288.
Wasson J. T. 1985. *Meteorites: Their record of early solar system history.* New York: W. H. Freeman. 274 p.
Weidenschilling S. J., Davis D. R., and Marzari F. 2001. Very early collisional evolution in the asteroid belt. *Earth Planets Space* 53: 1093–1097.
Wetherill G. W. 1975. Late heavy bombardment of the moon and terrestrial planets. Proceedings, 6th Lunar and Planetary Science Conference. pp. 1539–1561.
Wetherill G. W. 1977. Pre-mare cratering and early solar system history. In *The Soviet-American Conference on Cosmochemistry of the Moon and Planets.* NASA Special Paper-370. Washington, D. C.: NASA. pp. 553–567.
Wilhelms D. 1987. The geologic history of the moon. U. S. Geological Survey Professional Paper 1348. Washington, D. C.: U. S. Government Printing Office. 302 p.