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# Cataclysmic bombardment throughout the inner solar system 3.9–4.0 Ga

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[1] *Cohen et al.* [2000] recently confirmed the hypothesis that the Moon was resurfaced by an intense period of impact cratering ~3.9 Ga ago and, by inference, that the Earth also sustained bombardment. Analyses of lunar impact melts indicate that at least one of the projectiles that hit the Moon was a differentiated iron-rich core, implying the bombardment was caused by asteroids. Meteorite analyses indicate asteroids in the asteroid belt were also heavily cratered ~3.9 Ga and that the ancient cratered highlands of Mars suffered impacts at this time. Collectively, these data suggest there was an impact cataclysm that affected the entire inner solar system, resurfacing the terrestrial planets, and that the source of the impacting debris was the asteroid belt. Comets do not appear to have been important. *INDEX TERMS:* 1630 Global Change: Impact phenomena; 5420 Planetology: Solid Surface Planets: Impact phenomena (includes cratering); 6022 Planetology: Comets and Small Bodies: Impact phenomena; 6250 Planetology: Solar System Objects: Moon (1221); *KEYWORDS:* Impact cataclysm; impact cratering; origin of life; hydrothermal systems; Earth's crust; solar system, inner

## 1. Introduction

[2] The most intense period of impact cratering on the Earth appears to have occurred ~3.9 Ga, 500–600 million years after accretion. Evidence of this event began to accumulate when Ar-Ar isotopic analyses of Apollo and Luna samples suggested three to possibly six of the impact basins on the nearside of the Moon had been produced between 3.88 and 4.05 Ga [*Turner et al.*, 1973]. Additional analyses of Apollo samples indicated the U-Pb and Rb-Sr systems had been disturbed nearly uniformly at ~3.9 Ga, which was attributed to metamorphism of the lunar crust by a large number of asteroid and/or cometary collisions in a brief pulse of time, <200 Ma, in what was called the lunar cataclysm [*Tera et al.*, 1974].

[3] Despite a growing number of ~3.9 Ga impact melt ages from the Apollo and Luna collections [*Swindle et al.*, 1991; *Dalrymple and Ryder*, 1993, 1996], the concept of a lunar cataclysm remained controversial, in part because the Apollo and Luna samples came from a relatively small area in the equatorial nearside region of the Moon, where ages could potentially be dominated by a small number of impact events. However, recent analyses of impact melt ages in lunar meteorites, which are launched from random locations on the Moon, indicate the entire lunar surface, and, thus, Earth's surface, was affected by a cataclysmic bombardment of material ~3.9 Ga [*Cohen et al.*, 2000].

[4] The source of the impacting material remains uncertain [e.g., *Hartmann et al.*, 2000]. *Ryder* [1990] speculated that the debris was in a geocentric orbit as a byproduct of the collision that produced the Moon [e.g., *Hartmann and Davis*, 1975; *Cameron*, 2001]. However, dynamical calculations suggest all of the material that formed the Moon accreted very quickly. At least half a lunar mass accreted within a week [*Cameron*, 2001] and total accretion may have occurred within a year [*Kokubo et al.*, 2000], which are timescales orders of magnitude shorter than 600 Ma.

[5] Potential sources of debris in heliocentric orbits include rocky material remaining from the accretion process [e.g., *Wetherill*, 1975], the breakup of small bodies in the asteroid belt [e.g., *Turner et al.*, 1973; *Schmitt*, 2000], chaotic diffusion of asteroids into Earth-crossing orbits [*Morbidelli and Nesvorný*, 1999], a scattering of asteroids as Jupiter migrated inward and caused the $\nu_6$ resonance to sweep through the belt [*Hartmann et al.*, 2000], asteroids and/or comets scattered by the formation and migration of Uranus and Neptune [*Levison et al.*, 2001], comets scattered directly from the Uranus-Neptune region (most of which populated the Oort Cloud [e.g., *Hartmann et al.*, 2000]), comets perturbed from the Oort cloud, and comets from the Kuiper belt, possibly produced by the disruption of Kuiper belt objects [*Hartmann et al.*, 2000].

[6] While the source of the debris is not yet constrained by dynamical models, in this note we will utilize trace element compositions of lunar impact melts to argue that the cataclysm was produced by asteroids rather than comets. Following *Bogard* [1995], we will also use shock metamorphic ages in a large number of meteorites to argue that asteroids between Mars and Jupiter were involved in the cataclysm at the same time. This leads us to propose that the Earth-Moon cataclysm was an event that resurfaced terrestrial planets throughout the inner solar system, producing most of the impact craters on Mercury, the Moon, and the ancient cratered highlands of Mars within a brief and intense period of bombardment. Venus was also affected, but more recent geologic activity has erased its impact-cratered surface [e.g., *Strom et al.*, 1994] in the same way the record has been masked on Earth by other types of geologic activity.

## 2. Evidence That Lunar Impact Melts Were Produced by Asteroids Rather Than Comets

[7] Chemical and isotopic traces of impacting projectiles are often found in impact melts generated by the collisions. This was

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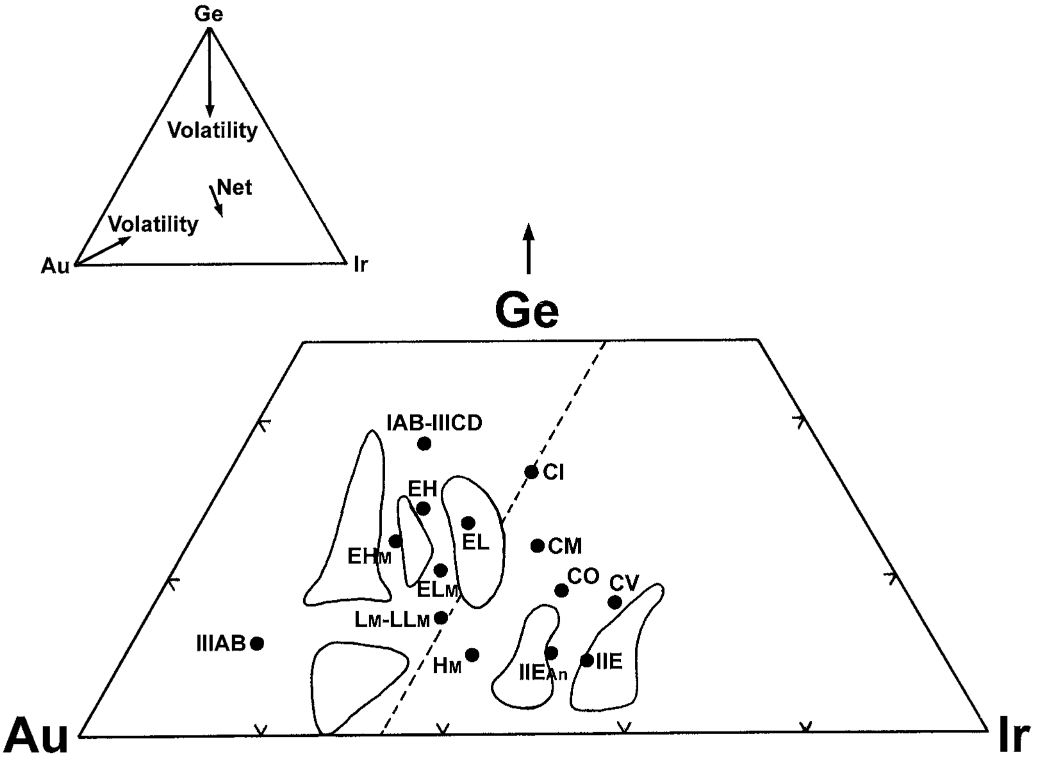

**Figure 1.** Compositional envelopes in the Ge-Au-Ir ternary system of the projectiles that produced large lunar impact craters, in a CI-normalized projection. For comparison, the compositions of several meteoritic fragments of asteroids are shown, including those of primitive carbonaceous (CI, CM, CO, CV) and enstatite (EH, EL) chondritic bodies and differentiated bodies with concentrated masses of iron (IAB-IIICD, IIIAB, IIE, and IIEAn). Ordinary chondrites are represented by their metal fraction (Lm-LLm, Hm), because Ge in whole rock samples have not been measured. These compositions are slightly displaced from where bulk analyses likely plot, as illustrated by comparing the metal fraction in enstatite chondrites (EHm, ELm) with bulk analyses (EH, EL). To assess the effects of volatility, qualitative effects are illustrated in the inset and, for reference, a dashed line of constant Ir/(Au + Ge) has been drawn through the CI composition (see text). The fields that define projectile compositions from the Apollo sites are from *Morgan et al.* [1974]. The field with the lowest Ge and highest Au abundances may represent a projectile composition that does not exist in our inventory of modern falls and finds, suggesting our inventory is incomplete and/or the compositions of asteroids hitting the Earth-Moon system have changed with time. Alternatively, *Ganapathy et al.* [1974] suggested the field is spurious and was produced by selective volatilization of Ge from projectiles that define fields with higher Ge abundances. The field near IIEAn was partly defined by two glass spheres and a glass coating (60095,5; 65016,7; 64455,25) rather than impact breccias, which have subsequently been found to have formed 2 Ma rather than 3.9 Ga [*Hertogen et al.*, 1977]. It is unclear if the remaining components in that field were involved in the cataclysm. The meteorite compositions are compiled from *Kallemeyn and Wasson* [1981, 1986], *Wasson and Wang* [1986], *Anders and Grevesse* [1989], *Choi et al.* [1995], *Kong and Ebihara* [1997], *Kong et al.* [1997], *Wasson and Canut de Bon* [1998], and *Wasson et al.* [1998].

quickly realized when Apollo samples were being analyzed [e.g., *Anders et al.*, 1973] and has been used on Earth to identify the projectiles that produced over a dozen impact craters [e.g., *Morgan et al.*, 1975; *Palme et al.*, 1978; *Wolf et al.*, 1980; *Schmidt et al.*, 1997]. Siderophile elements from the projectile are the best trace elements for identification, because these elements are depleted in the crust of a differentiated planet like the Earth or Moon.

[8] Siderophile element signatures of projectiles incorporated into impact melts produced by large basin-forming impact events were determined at each of the Apollo landing sites [*Morgan et al.*, 1972, 1974; *Ganapathy et al.*, 1974]. The siderophile element signatures of six projectiles that produced large volumes of impact melt at Apollo 12, 14, 15, 16, and 17 are shown in Figure 1. For comparison, the compositions of various types of meteorites are shown. Meteorites represent asteroid compositions, including both those that are primitive and those that are differentiated. In addition, the CI and CM compositions are good proxies for comets, because porous interplanetary dust particles collected in the stratosphere have nearly CI compositions [*Schramm et al.*, 1989] and cosmic spherules have CM compositions [*Brownlee et al.*, 1997].

[9] There are two important features of this diagram. First, none of the projectile compositions are similar to carbonaceous chondrite compositions. Rather, several of the projectile compositions are similar to those of some iron meteorites and enstatite chondrites. This means that comets were not responsible for the impact melt compositions.

[10] Second, volatility-driven fractionation of siderophile elements during the impact events could not alter this conclusion. To help illustrate the effect of volatility, a line of constant Ir/(Au + Ge) has been drawn through the CI composition in Figure 1. Germa-

nium is the least refractory element, followed by Au, so any loss as a result of volatility will enrich Ir. Consequently, projectile compositions to the left of the constant Ir/(Au + Ge) line could be fractionated so that they appear to be from comets, but one cannot fractionate a comet composition so that it appears to be a IAB-IIICD or enstatite chondrite composition. Consequently, at least three of the projectile compositions (those on the left side of the constant Ir/(Au + Ge) line) could not have been produced by comets and possibly all six projectile compositions.

[11] The siderophile element signatures of the projectiles suggest some had compositions similar to those of iron meteorites and enstatite chondrites, although not necessarily identical to those of the meteorites falling today. Assessments of siderophile element data, including discrete metal particles, have led others to also suggest projectiles were similar to iron meteorites and enstatite chondrites [*Ganapathy et al.*, 1972; *James*, 1994, 1995, 1996; *Korotev*, 1994; *Norman et al.*, 2001]. In the case of iron meteorites this would suggest a source involving large, once hot, differentiated bodies, implying an asteroid source for the projectiles rather than a cometary source. In a different approach, *Gros et al.* [1976] used discriminant and cluster analysis of siderophile element abundances and concluded that three of the projectile groups resemble ordinary chondrites and three resemble enstatite chondrites. Significantly, none of them resemble CI and CM chondrites, implying that asteroids with CI and CM compositions or comets did not produce the impact melts.

[12] Collectively, analyses of impact melts from several Apollo sites indicate that some of the projectile compositions were asteroids, not comets. Since it is likely the cataclysmic event that affected the Moon was dominated by impactors from a single dynamical reservoir, the signatures of a few non-carbonaceous chondrite projectiles implies that most (if not all) of the impactors involved in the cataclysm were asteroids, not comets.

## 3. Evidence of an Impact Cataclysm in the Asteroid Belt

[13] If asteroids produced the Earth-Moon cataclysm, then their source could be the asteroid belt between the orbits of Mars and Jupiter. If so, then many of the planetesimals and asteroid fragments in that region should have recorded the collisional event. Figure 2 is a compilation of impact-induced shock-degassing ages in three groups of meteorites: ordinary chondrites (LL, L, and H), which comprise 82% of the meteorites that fall to Earth [*Grady*, 2000]; howardites, eucrites, and diogenites (HED), silicate-rich crustal and regolith rocks from a differentiated planetesimal, the remnants of which are possibly Vesta [*McCord et al.*, 1970; *Consolmagno and Drake*, 1977; *Binzel and Xu*, 1993]; and mesosiderites, which are stony-iron mixtures from an incompletely melted and differentiated planetesimal.

[14] Several events formed the spectrum of ages in ordinary chondrites, including one at ~500 Ma, which is believed to represent the disruption of an L-chondrite planetesimal [e.g., *Anders*, 1964]. There is also a peak in the spectrum of ages centered at ~3.9 Ga, coincident with the events recorded on the Moon [*Turner*, 1988; *Bogard*, 1995]. The HED population also suffered impact degassing ~3.9 Ga, although some basalts (eucrites) have older ages, remnants of the brief period of volcanic activity that formed the original crust of the planetesimal ~4.5 Ga, and some younger ages, which indicate additional impact events. The spectrum of degassing ages among mesosiderites is sharply peaked at ~3.9 Ga. We interpret this as being the result of the same bombardment event. There are a few ages down to ~3.5 Ga, similar to impact ages on the Moon [*Cohen et al.*, 2000]. While the largest impact basins on the Moon occurred within a brief 20–200 Ma period [*Tera et al.*, 1974; *Ryder*, 1990], several smaller impact events may have continued to occur as the last of the debris associated with the cataclysm was swept up.

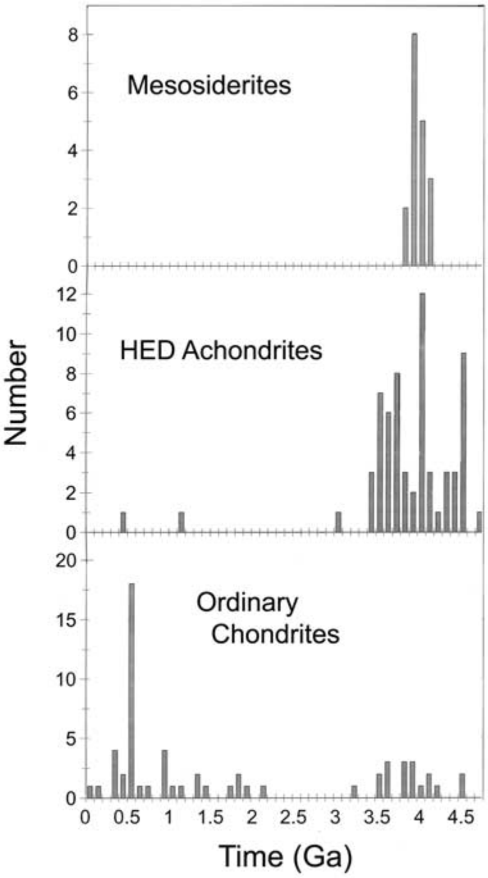

**Figure 2.** The distribution of impact-degassing ages in three groups of meteorites: ordinary chondrites (LL, L, and H); HED achondrites (howardites, eucrites, and diogenites); and mesosiderites. The data are compiled from *Bogard* [1995], *Bogard and Garrison* [1995], *Kring et al.* [1996b, 2000], *Grier et al.* [1997], *Nyquist et al.* [1997], and *Kunz et al.* [1997].

## 4. Evidence of an Impact Cataclysm on Mars

[15] If a cataclysm affected the Earth, Moon, and multiple bodies in the asteroid belt, it likely affected the entire inner solar system. If so, Mercury, Venus, and Mars should all have been resurfaced by impact cratering processes at ~3.9 Ga. We have a single sample of early crust from one of those planets, Mars, in Martian meteorite Allan Hills 84001 (ALH 84001). Sm-Nd isotopic analyses indicate ALH 84001 crystallized 4.50 ± 0.13 Ga [*Nyquist et al.*, 1995], forming part of the original crust on Mars <100 Ma after planetary differentiation. The rock was subsequently altered by fluid and shock-metamorphic processes. Carbonates deposited from the fluid system have a Rb-Sr age of 3.90 ± 0.04 Ga and a Pb-Pb age of 4.04 ± 0.10 Ga [*Borg et al.*, 1999], coincident with the Ar-Ar shock-degassing age of 3.92 ± 0.04 Ga [*Turner et al.*, 1997], which we interpret to represent the effects of the cataclysm. If Mars was affected by the same bombardment, then most of the craters in the ancient highlands of the southern hemisphere may have been produced in a brief period of time ~3.9 Ga. The Northern Hemisphere would have

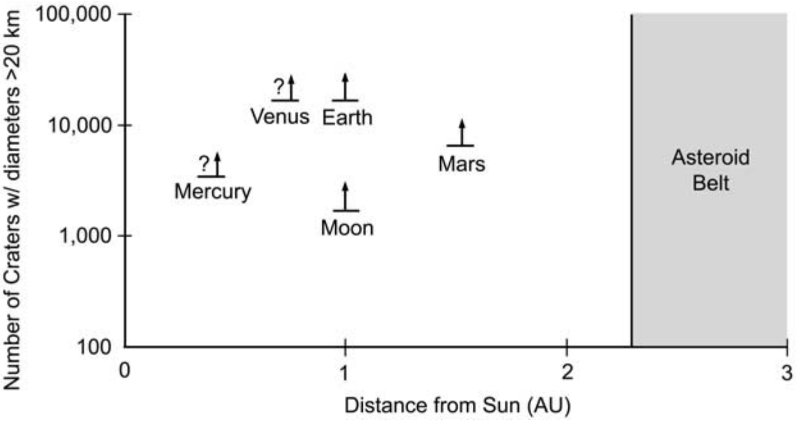

**Figure 3.** Lower limits of the number of impact craters with diameters ≥20 km that were produced during the cataclysm on the Earth, Moon, and Mars. The scaling factor for the relative impact rates on Venus and Mercury are unknown, so estimates of the number of craters on those two planets are more uncertain.

similarly been battered but has subsequently been resurfaced by other geologic processes.

## 5. Implications of an Impact Cataclysm Throughout the Inner Solar System, Including Earth

[16] Fifteen impact basins with diameters ranging from 300 to 1200 km were produced on the Moon during the Nectarian and Early Imbrian periods that represent the bombardment [*Wilhelms*, 1984]. At least 1700 impact craters with diameters larger than 20 km were excavated (Figure 3). The mass of asteroids needed to produce the impact basins is $6.5 \times 10^{21}$ g, assuming median density asteroids (3.3 g/cm$^3$), $7.3 \times 10^{21}$ g, assuming low-density asteroids (2.2 g/cm$^3$), and $8.7 \times 10^{21}$g, assuming very low density asteroids (1.2 g/cm$^3$), corresponding to the densities of Vesta, Ceres, and the average for C asteroids, respectively [*Britt and Consolmagno*, 2001].

[17] Depending on the size distribution among impactors, the Earth is hit by 13–500 times more mass than the Moon [*Zahnle and Sleep*, 1997; *Hartmann et al.*, 2000], implying $8.7 \times 10^{22}$ to $4.4 \times 10^{24}$ g, with a median of $3 \times 10^{23}$ g, hit the Earth during the bombardment. The lower factor of 13 is simply scaling to Earth's larger surface area. Using this conservative value, it is clear that over 22,000 impact craters with diameters larger than 20 km were produced on the Earth, including ~40 impact basins ~1000 km in diameter (the approximate size of the Moon's Orientale, Imbrium, and Crisium basins), and several with diameters of ~5000 km, each one exceeding the dimensions of Australia, Europe, Antarctica, or South America. At least $10^{28}$ J ($3 \times 10^{12}$ MT) of energy were delivered to the surface of the Earth.

[18] The relative impact flux between the Moon and Mars is unity when scaled for surface area [*Ivanov*, 2001], implying at least 6400 craters with diameters ≥20 km were produced on Mars. This is comparable to the 9278 craters with those dimensions that have been mapped on Mars (R. Strom, personal communication, 2001). A slightly smaller number of impact craters was probably produced on Venus, since it only has 90% of Earth's surface area, assuming dynamical issues do not affect the interplanetary flux. Mercury's surface area is slightly larger than the Moon's surface area and suggests at least 3300 craters with diameters larger than 20 km were produced.

[19] Most of the Moon was resurfaced by the cataclysmic bombardment [*Wilhelms*, 1984; *Kring*, 2000a], and it is likely the same happened to Earth, which would explain why the oldest crustal rocks have similar 3.8–4.0 Ga ages [e.g., *Bowring et al.*, 1989; *Bowring and Williams*, 1999; *Mojzsis and Harrison*, 2000] and only a few mineral relics of older crustal rocks survive [*Froude et al.*, 1983; *Wilde et al.*, 2001; *Mojzsis et al.*, 2001].

[20] The impact cataclysm is also nearly coincident with the earliest isotopic evidence of life, 3.85 Ga [*Mojzsis and Harrison*, 2000], suggesting the bombarding asteroids may have affected the biologic evolution of Earth. The Chicxulub impact event 65 million years ago illustrates how a single impact event can dramatically alter the environment and biologic evolution of Earth [e.g., *Kring*, 2000a]. In the case of the cataclysm, tens of thousands of impact events would have been altering the environment. If the bombardment was concentrated in a 20–200 Ma period [*Tera et al.*, 1974; *Ryder*, 2000], then impact events producing craters ≥20 km diameter were occurring at an average rate of once per $10^2 - 10^4$ years using the conservative or median mass influx estimates above. If the highest possible influx rate occurred, craters with diameters ≥20 km would have been produced at an average rate of once per 20 years. All of these impact events were large enough to have produced global environmental effects [*Kring et al.*, 1996a; *Kring*, 2000a]. The largest impact events, producing >1000 km diameter craters, may have vaporized the Earth's oceans [e.g., *Zahnle and Sleep*, 1997] and have previously been implicated in the possible demise of any extant life [*Maher and Stevenson*, 1988; *Chyba*, 1993].

[21] However, the impact events would have also created new habitats in the form of vast hydrothermal systems in the Earth's crust [*Kring*, 2000b; *Daubar and Kring*, 2001]. These were likely important for life, because the larger impact events may have completely vaporized Earth's oceans and removed surface water for periods of ~1000 years [*Zahnle and Sleep*, 1997]. Thus the only suitable habitats were in subsurface systems, which would have been good incubators for prebiotic chemistry and the early evolution of life. This is supported by phylogenies that suggest Archaea, Bacteria, and Eucarya have a common ancestor (or genetic reservoir) comparable to present-day thermophilic or hypthermophilic organisms [*Woese et al.*, 1990; *Pace*, 1991, 1997], which should have thrived in impact-generated systems. These systems may have spanned the diameter of each crater, penetrated the crust down to depths of several kilometers, and have life times up to $10^6$ years [*Kring*, 2000b; *Daubar and Kring*, 2001].

[22] One consequence of the conclusions here is that organic-rich comets were not seeding the surface of the Earth as much as has been proposed [cf. *Chyba*, 1993; *Pierazzo and Chyba*, 1999]. Nonetheless, asteroidal material still would have delivered a large mass of biogenic materials. If the projectiles are represented by the compositions of enstatite chondrites [*Kring et al.*, 1996a], then a minimum of $3.4 \times 10^{21}$ g of S, $3.2 \times 10^{20}$ g of C, $9.4 \times 10^{20}$ g of

$H_2O$ were delivered to the Earth's biozone. This amount of carbon, for example, is 160 times larger than that in the total land biomass today [*de Baar and Suess*, 1993]. This material was also delivered in a relatively short 20–200 Ma period, rather than the extended 500–600 Ma considered previously.

## 6. Conclusion

[23] The cataclysmic bombardment that occurred throughout the inner solar system $\sim$3.9 Ga dwarfs the Chicxulub impact event at the K/T boundary and its environmental consequences. Its coincidence with the oldest surviving rocks on Earth is due to the destruction or metamorphism of preexisting crust. Because of the destruction of the rock record, it is not yet clear whether the coincidence of the bombardment with the earliest isotopic evidence of life on Earth implies the event was an environmental bottleneck through which life survived or whether the bombardment was intimately associated with the origin of life.

[24] In this note, we argue the projectiles that dramatically altered surface conditions in the Earth-Moon system were asteroids. Previously, *Ryder* [1990] suggested the cataclysm was restricted to the Earth-Moon system, envisioning additional moons in geocentric orbit which collided to form a swarm of projectiles that then hit the Earth and Moon, leaving Venus, Mercury, and Mars unaffected. However, a large number of $\sim$3.9 Ga impact degassing ages among meteorites from the asteroid belt and an impact age in our single sample of the ancient crust of Mars suggests the cataclysm affected the entire inner solar system. Thus the dynamical source of the material was likely in heliocentric orbit in the asteroid belt. Potential sources of debris in this type of orbit include rocky material remaining from the accretion process, the breakup of small bodies in the asteroid belt, chaotic diffusion of asteroids into Earth-crossing orbits, and a scattering of asteroids as the Jupiter migrated inward and caused the $\nu_6$ resonance to sweep through the belt.

[25] The impacts affected the environment and likely affected the early evolution of life on Earth, both by causing devastation at the surface of the planet and, in contrast, producing habitable conditions in subsurface environments. The impactors likely delivered biogenic materials, although it is not clear if these were essential for life's origins. Comets were not important during this time.

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