The Hadean Eon on the Moon

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The Moon incorporates the record of asteroid and cometary impact activity in the inner solar system during the Hadean Eon on Earth. Any definition of the details of the Hadean should recognize this record and provide for correlation of related impact activity on Earth.

The Moon, Earth and other terrestrial planets originated through "impact accretion" of material in the inner portion of the solar nebula within a few tens of millions of years of the 4.567 b.y. birth of that nebula (T_0) [1]. This model continues to be supported by observations of young stars with observable accretionary disks surrounding them [2]. Consensus also exists that about 30 million of years after T_0 the Moon belatedly came into existence as a result of a giant impact between the very young Earth and a chondritic asteroid [3] that was eleven to fourteen percent the mass of the Earth [4]. This consensus holds that at the time of that collision, both the Earth and the impactor would have been at least partially differentiated from their chondritic parent material by the separation of core-forming iron-rich liquid. Some additional chemical differentiation probably also had taken place by partial crystallization of magma oceans created during the earlier accretion of the two bodies [5]. This hypothetical lunar origin by giant impact primarily offers an explanation for the unusually high angular momentum of the Earth-Moon system [6], and allows many of the lunar geochemical characteristics to be attributed to those of the original, at least partially differentiated, impactor. For example, the fifty percent higher iron content of the Moon relative to the Earth's mantle requires that at least eighty to ninety percent of the Moon be derived from the impactor rather than the core-depleted mantle of the Earth [7].

Major consequences of such a Moon-forming giant impact are presumed to be as follows: Most core-forming material in both bodies remained with or was quickly re-acquired by the Earth. The Moon formed through the rapid orbital re-aggregation of some of the material ejected by the giant impact. According to Canup's recent computer simulations, that material would have reached temperatures between 3000 and 5000 K. Thus, according to this proposed origin, the bulk of material that formed the Moon vaporized during ejection and passed through a molten stage during condensation and re-aggregation into a coherent body, erasing many primordial isotopic and volatile element signatures of the chondritic parents. Soon after or during lunar aggregation, the lunar core formed [8] and a magma ocean existed above this core [9].

Strong arguments exist, however, against the "giant impact hypothesis" for the origin of the Moon [10]. The geophysics and geochemistry of the upper mantle of the Moon are inconsistent with the implications of such a hypothesis. Geophysics strongly suggests that the lower mantle of the Moon, that is the portion below about 550 km [11], has remained largely unmelted, a conclusion that appears incompatible with giant impact [12]. Similarly, the non-glass component of the Apollo 15 and 17 orange and green pyroclastic glasses indicates that this lower mantle is volatile-rich relative to the upper mantle [13]. Further, chondritic isotopic and elemental systems exist in this non-glass component for tungsten [14], lead [15], samarium-neodymium [16], rhenium-osmium [17], and the siderophile and chalcophile elements [18]. These geochemical characteristics also appear incompatible with a giant impact origin for the Moon.

Unfortunately, "giant impact" has permeated the thinking of the planetary geology community and currently is accepted widely as fact. The alternative of the capture of an independently accreted Moon [19], possibly at one of the two the co-orbiting Sun-Earth libration points [20], does not appear to have been seriously considered by the modeling community. This is in spite of the consensus that no more than about 10% of the Moon can be from the core-depleted mantle of the Earth thus making the giant impact hypothesis an "impact assisted capture" hypothesis. Can near impacts also result in capture? It does not appear that this question has been addressed in a comprehensive way.

The Hadean

Whatever was the origin of the Moon, an original solid crust was apparently present on the Moon by 4.52 billion years as the extinct isotope ^{182}Hf system (decays to ^{182}W) indicates the lunar magma ocean was largely crystallized and fractionated within 40-50 million years of the beginning of the evolution of the solar nebula [21]. The ^{182}Hf-^{182}W isotopic system also indicates that the separation of core forming materials from the magma oceans of the Earth and Moon occurred at about 25-30 million years and for Mars at about 13 million years [22]. (Most workers still assume that "separation" is equivalent to core formation.) Actual core formation, however, appears to have been delayed in the Moon by 700 million years[23] and may have been delayed on Mars by as much as 400 million years and on Earth by as much as 100 million years [24]. As crust and core formation would be dependent on the size of the planets, such events cannot be correlated in time between planets.

Fractional crystallization of the magma ocean initially left the ultramafic upper mantle extending down to ~550 km, an iron-rich anothosite crust ~60 km thick and, in between, a zone of residual silicate liquid relatively rich in iron and potassium, rare earth elements, phosphorous (urKREEP), and thorium [25]. Interesting and complex as it is, the history [26] of solidification of the lunar mantle, and its future partial melting, does not relate to Hadean events on Earth. After the lunar crust had solidified sufficiently to record continued impacts (about 40 million years after T_0), the lunar surface was saturated with craters 60-70 km in diameter [27]. This created a mega-regolith at least 25 km deep.

The saturation cratering recorded in the lunar crust probably represents the sweep up of the last of pre-planetary accretion debris in the inner solar system and/or material ejected from the asteroid belt by its earliest interactions with Jupiter. On Earth, the effects of this intense cratering period probably dominated the first 300 million years of the Hadean. The development of a terrestrial mega-regolith, rich in glass and pulverized mineral debris, would have made clays the dominant mineral species in the water-rich environments at the surfaces of Earth [28]. This may have been the ideal environment for the development of complex organic molecules as precursors to replicating life. Such life, as discussed below, would have to wait to at least 3.8 billion years ago and the end of catastrophic cratering before such life could be assured of survival.

Another significant process was unfolding simultaneously with the formation of the lunar and terrestrial mega-regoliths, the latter now recorded as "cratered highlands" relative to the lowlands plains of the lunar maria. During that same period, a few very large basins formed on the Moon and certainly also on the other terrestrial planets. The youngest and most obvious of these, the largely far-side basin South Pole-Aitken (~2500 km in diameter) [29], is recognized by the entire planetary geology community [30]; however, evidence exists for at least four other older basins of comparable or greater size [31]. The largest of these, Procellarum, is ~3200 km in diameter. The age of South Pole-Aitken is estimated to be about 4.2 billion years because its rim remains clearly definable and has not been destroyed by the saturation cratering that sculpted the cratered highlands [32]. Procellarum would have formed earlier than South Pole-Aitken, possibly about 4.3 billion years ago, as the on-going saturation cratering and subsequent large basin impacts have significantly modified its rim. The overlap of the South Pole-Aitken and Procellarum ejecta blankets produced the thickest crust on the Moon (about 100 km thick versus an average of about 60 km and minima of about 30 km) [33].

The 4.2 billion year mark identified above is not well pinned down and may be off by ±0.1 billion years. It deserves, however, to be a placeholder for the separation of two, inner solar system eras of great importance and contrast. Prior to that time, in addition to saturation cratering and the clay dominated sedimentary environment, the seeds of the first terrestrial continents could have been formed by the fractional crystallization of thick, water-rich impact melt sheets formed in the very large, continental scale impact basins comparable to South Pole-Aitken and Procellarum [34]. Crystallization dates for detrital zircon from ancient basin sediments in Australia at 4.4 billion years of age, and evidence of their formation in the presence of water, strongly support this conclusion [35].

Subsequent to ~4.2 billion years, saturation cratering and the formation of very large basins had ceased and the period of large basin forming impacts had begun or their basins began to be preserved [36]. The definable, ~50 large basins (300-1000 km in diameter) formed before the main period of eruption of lunar mare basalts that began about 3.85 billion years ago. They may represent the appearance of a new source of impactors for the inner solar system [37]. This source probably was the proto-Kuiper belt of icy bodies, many of which were injected into the inner solar system when Neptune and other giant planets interacted as they apparently migrated outward early in solar system evolution [38].

On the Moon, old large basins are distinct from young large basins [39], the younger being more crisply defined in shape and having both mass concentrations (mascons) in their interiors and mass deficiencies beneath their rims [40]. The lunar crustal strengthening "transition event" that separates young mascon basins from older non-mascon basins probably occurred gradually between 4.2 and 3.9 billion years, but this event is lunar specific in time. The transition represents the movement of potassium, rare earth element, phosphorus (KREEP), and thorium-rich residual magma ocean liquid into the crust and its gradual solidification. A similar upward movement and solidification of residual magma ocean liquid probably occurred on every planet, but its composition, timing, and effects would be largely unique to the size of the planet and the thickness of each crust.

The 3.8 billion year date for the end of the Hadean is solidly based on the well-defined end of large basin (300-1000 km diameter) formation on the Moon and therefore on all the inner solar system planets [41]. Subsequent to 3.8 billion years, the formation of impact craters larger than ~100 km in diameter has been very rare. In lunar time-stratigraphic nomenclature this would be the end of the combined “Nectarian and Imbrium Systems”. In addition, the planetary geology community has adopted this date as the approximate time of the “cataclysm” or “late bombardment” of impacts in the inner solar system [42].

Like the “giant impact” hypothesis, we should question the planetary geology community's consensus that there was a “cataclysm” of impacts in the inner solar system between 3.8 and 3.9 billion years that accounted for the vast majority of lunar basins and highland craters. Alternatively, the lunar wide distribution of ejecta and thus the sample bias created by the last 10-15 (out of about 50) large (300-1000 km) basin-forming events during the ~100 million year period around 3.8 billion years probably accounts for the concentration of argon ages around 3.85 ± 0.05 billion years [43]. These “mascon basins” make up the combined “Nectarian and Imbrium Systems” of the USGS time-stratigraphic system for the Moon [44].

In spite of the apparent consensus for a cataclysm, strong arguments can be made for a more prolonged impact history. Various lunar samples and several lines of reasoning suggest that this period of large basin-forming events, the latter part of the “Pre-Nectarian System”, began about 4.2 billion years ago [45]. This, therefore, suggests a ~400 million year “cataclysm” which, in turn, suggests that adjustments in the orbits of the outer planets took longer than implied by current computer models. This prolonged ~400 million year “cataclysm” would involve only large basin formation against a declining background of smaller crater saturation. The proponents for the shorter ~100 million year cataclysm say that it would include almost all pre-mare cratering recorded on the Moon. For the latter to be the case, the following major episodes in lunar history would need to occur in that relatively short period [46]:

1. Saturated impacts covered the lunar crust with craters 60-70 km in diameter.
2. A number (1-5) of very large craters formed.
3. Old large basins (~35) formed.
4. Magma ocean residual liquid migrated into crust and cryptomaria/KREEP basalt lavas erupted, probably represented by lunar samples dated as ~4.3 billion years old [47].
5. Young large basins (~15) formed, and
6. Cryptomaria surfaces covered by young large basin ejecta.

Clearly, 100 million years is a long time and all of the above could have occurred in such a period. To this observer, however, that would seem unlikely and worthy of much further investigation.

Summary

Currently known lunar history suggests that two major boundaries can be defined for the Hadean. The first is at about 4.2 billion years, the end of saturation cratering and very large basin formation in the inner solar system. The second boundary and the potentially definable end of the Hadean is at about 3.8 billion years, the end of large basin formation in the inner solar system. Although not yet fully confirmed, the 3.8 billion year boundary also may be the point at which the first isotopic evidence of life on earth appears [48].

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