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# Impact bombardment of the terrestrial planets and the early history of the Solar System

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**During the first billion years of Solar System evolution, following planetary accretion, the rate of impact cratering was substantially higher than over the past 3.5 Gyr. However, the causes, magnitude and evolution of the early impact flux remain unknown. In particular, uncertainty persists about whether the largest impact basins on the Moon and the other terrestrial planets formed from a cataclysmic bombardment in a narrow window of time about 3.9 Gyr ago, as initially suggested by the lunar sample collection, or over a more extended period. Recent observations relating to this so-called Late Heavy Bombardment imply that the window of bombardment was not as narrow and intense as originally envisaged. Nevertheless, numerical simulations suggest that the rocky bodies left behind after planetary accretion are insufficient in number to form the youngest large impact basins 4.0 to 3.7 Gyr ago. One viable hypothesis for the formation of these basins is the delivery of impactors to the inner Solar System following the migration of the giant planets, but this scenario also faces challenges. Clarifying the magnitude and length of the Late Heavy Bombardment has implications across the full range of planetary geosciences, from understanding the dynamical evolution of the Solar System to surface conditions on the terrestrial planets early in their history.**

Based on ages from Apollo and Luna samples of the maria where crater densities have been measured, the lunar impact flux >3.5 Gyr ago must have been at least two orders of magnitude higher than in the past 3.5 Gyr[1]. These data have been used to develop a widely applied model for the lunar impact flux over time[2,3]. Along with demonstrating a higher early impact flux, however, careful analysis of the Apollo samples resulted in an additional, more surprising discovery. There were very few samples dating impacts before 4.0 Gyr ago[4–6] and a widespread signature of isotopic disturbance in the samples of ~3.9 Gyr ago[5]. These findings led to the interpretation that the impact rate must have been radically enhanced in a short period between 4.0 and 3.8 Gyr ago on the Moon. Three scenarios[5] for the nature of this cataclysm are: (1) many, or most, of the main impacts on the Moon date to this very short period of time; (2) several of the chief impacts date to this period of time, but other large basins formed in the 500 Myr before 4.0 Gyr ago; or (3) the samples were universally affected by the formation of the Imbrium Basin ~3.9 Gyr ago and were radically altered by this last large event near the landing sites.

There were objections raised against the cataclysm (or Late Heavy Bombardment) interpretation almost immediately[7–9], especially in its most catastrophic form. First, the degradation state of lunar basins varies substantially, as does the number of younger craters superposed on these basins[8]. Second, there are clear reasons to suspect that the sample collection is biased towards the youngest basins, particularly Imbrium, which could have buried earlier basin materials[8–10]. Third, a suggested reason for the lack of an extensive rock record on the Moon earlier than 4.0 Gyr ago was rapid impact destruction of rocks during this period, rather than a lull in cratering[7,11]. In this case, 4.0 Gyr ago might be the first point in time (a 'stone wall'[7,11]) where numerous datable samples survived, rather than the beginning of a cataclysmic event. Fourth, for 20 yr after the cataclysm was first proposed, the dynamical scenarios invoked to explain it were *ad hoc* — it was not clear where in the Solar System the putative cataclysmic impactors could have originated or how they were delivered to the Moon in an impulsive wave several hundred million years after the birth of the Solar System.

## Basin sequence and ages from samples

The magnitude of the Late Heavy Bombardment is directly related to the period of time over which the largest lunar impact basins formed, so constraining the age of these features is important. The relative sequence of many basins is known with reasonable confidence from stratigraphic mapping and crater statistics. There is widespread agreement, for example, that Orientale, Imbrium, Nectaris, Smythii and South Pole–Aitken are in sequence from youngest to oldest (Fig. 1). Linking this sequence to an absolute chronology requires accurately determining the connection of a sample to a particular basin and accurately measuring its age. This type of analysis has been presented as an additional strong line of evidence for an intense cataclysm[2,12]. However, the confident assignment of absolute ages to particular basins has proved to be fiendishly difficult. This is primarily owing to uncertainty in sample provenance, although the interpretation of different isotopic systems provides a further challenge. The result is that there is debate about virtually every basin age assignment[13].

Where Nectaris, Serenitatis and Imbrium fit into this picture is of particular interest. At least six, but perhaps as many as 17, basins were formed between Orientale and Nectaris (inclusive)[14,15]. If Nectaris is 3.92 Gyr old, as has been interpreted on the basis of Apollo 16 samples[16], an intense cataclysm is required (Fig. 2). But an older age of 4.1–4.2 Gyr for Nectaris is also possible[9,17], consistent with a more extended, more modest bombardment. The ~3.9 Gyr ages that are indeed widespread in the Apollo 16 sample collection may be a result of the Imbrium Basin[8–10,18].

In the case of Serenitatis, geologic mapping, stratigraphy and crater counting led most early workers to conclude that it pre-dated Nectaris[19], although the proximity of Serenitatis to Imbrium makes it a particularly challenging feature to understand (Fig. 1d). Dating of Apollo 17 samples suggested to some authors that Serenitatis

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had an age of 3.89 Gyr[20], which is inconsistent with it being pre-Nectarian. However, two recent studies have supported a return to the interpretation that Serenitatis is older than Nectaris. One study used the Lunar Reconnaissance Orbiter camera to re-examine the Sculptured Hills material surrounding the Apollo 17 site[21]. They make a strong case that this highlands material is of Imbrium origin, casting doubt on the provenance of the Apollo 17 samples. Analysis of Lunar Orbiter Laser Altimeter topography also suggests that sculptured ejecta from Nectaris is superposed on Serenitatis[15]. These two observations require that Serenitatis is pre-Nectarian; the simplest explanation of these data is that Imbrium is the source of ~3.9 Gyr ages at the Apollo 17 site.

These reinterpretations, if correct, clearly demonstrate the widespread influence of Imbrium at the Apollo sites. Zircons[22,23] in impact melt breccias rich in potassium, rare earth elements and phosphorus from the Apollo 12 mission and the lunar meteorite Sayh al Uhaymir 169 have recently been dated and provide precise Pb/Pb ages that imply Imbrium is ~3.90–3.93 Gyr old. An age this old would imply that many other sample or basin age assignments in the era around ~3.9 Gyr ago may reflect Imbrium instead.

A possible pathway for avoiding a bias towards Imbrium is analysis of lunar meteorites, which provide a more random sampling of the lunar crust[24,25]. These data, like the Apollo sample collection, show a dearth of impact melts with Ar/Ar ages >4.0 Gyr. This has been interpreted as favouring, or at least being consistent with, a cataclysm hypothesis. What is most surprising about these data, however, is the number of impact melt samples that have ages <3.5 Gyr[11,24–26]. Current models for the impact flux suggest approximately an order of magnitude fewer craters formed in the interval from 3.5 to 2.5 Gyr ago than from 3.9 to 3.5 Gyr ago[3]. As most impact events inferred from these samples date to the period from 3.5 to 2.5 Gyr ago, the impact melt ages derived from the lunar meteorites seem to be biased towards younger impacts that post-date the era of heavy bombardment.

The arguments over the lunar sample collection, although important, do not radically affect the interpretation of the chronology of the youngest large basins (Imbrium and Orientale). Samples, stratigraphy and crater statistics suggest that Imbrium and Orientale formed between 3.93 and 3.72 Gyr ago[2,13]; the much smaller Schrödinger Basin seems to date to this era as well[15]. A reasonable assumption is that the source population of these late basin impactors was not impacting only the Moon, but possibly elsewhere in the inner Solar System too. On Mercury, the two best-preserved large basins, Caloris and Rembrandt, have superposed crater densities that imply that they formed in this time frame, as do Hellas, Isidis and Argyre on Mars. The extrapolation of the lunar cratering record to Mars and Mercury is uncertain, especially during their early history. Nonetheless, the lunar record suggests that all of the inner planets were subjected to a period of large-basin-forming impacts >500 Myr into Solar System history.

## Basin formation and planet migration

The terrestrial planets formed from the accretion of smaller bodies,

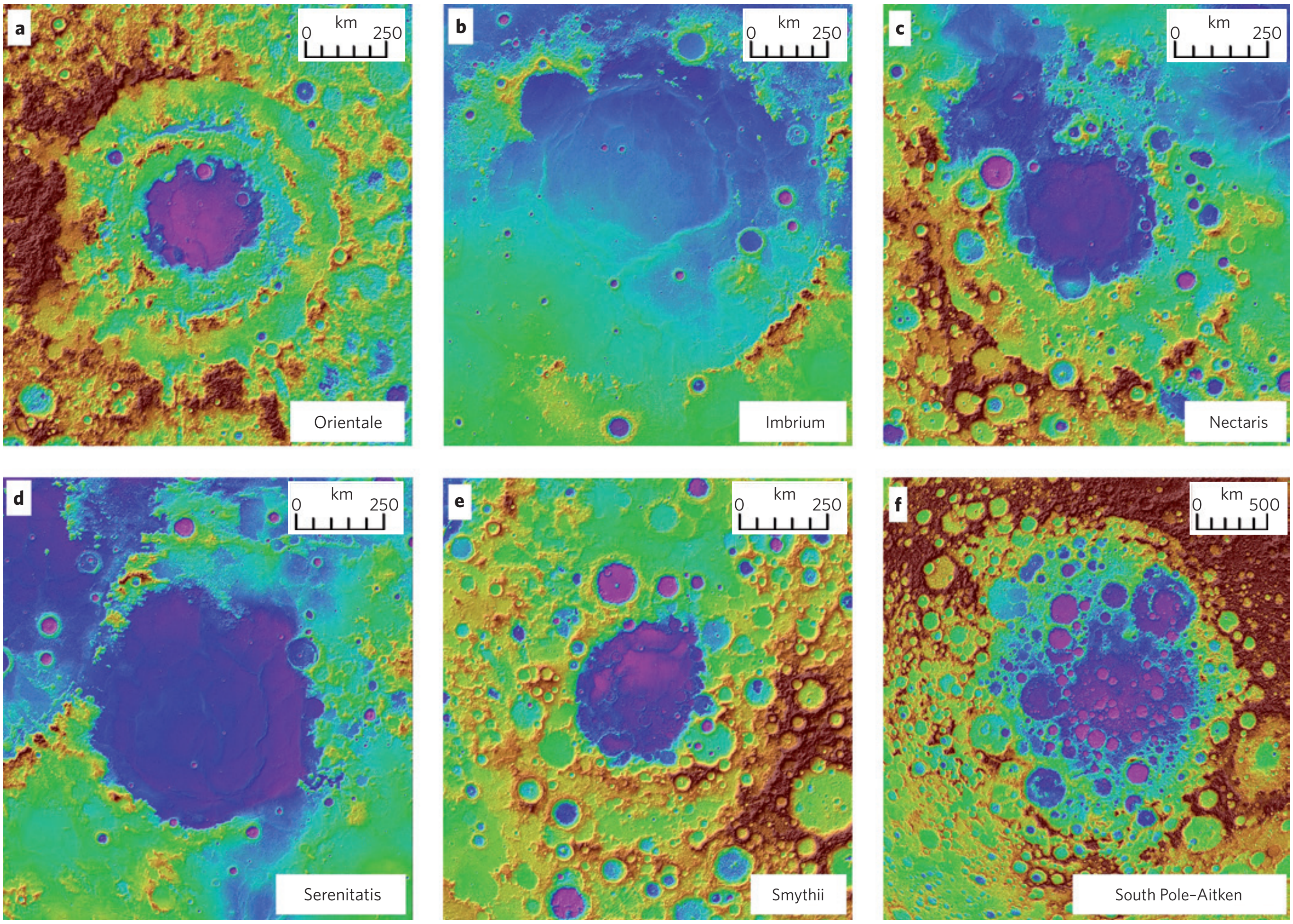

**Figure 1 | Lunar Orbiter Laser Altimeter topography of six lunar basins. a,** Orientale. **b,** Imbrium. **c,** Nectaris. **d,** Serenitatis. **e,** Smythii. **f,** South Pole–Aitken. These are in order of formation from youngest to oldest, with the most uncertainty surrounding the stratigraphic position of Serenitatis, which has been a long-standing subject of debate[15,19–21].

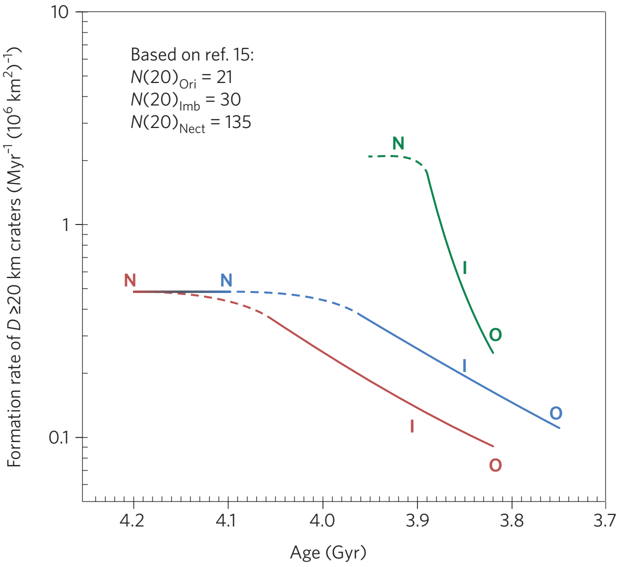

**Figure 2 | Impact flux during the period of heavy bombardment on the Moon at various points in time, assuming different ages for Orientale (O), Imbrium (I) and Nectaris (N) and specific values for their superposed crater densities[15].** The required intensity of early bombardment is critically dependent on the age of Nectaris and Imbrium. The green curve is anchored by a young age for Nectaris (3.92 Gyr) and is an intense cataclysm[2,12]. The blue and red curves are two versions of a more modest cataclysm, with Nectaris 4.1–4.2 Gyr old[9,17,49]. *D*, crater diameter. The frequency *N*(20) is the inferred number of $D \geq 20$ km craters superposed on each basin, normalized to an area of $10^6$ km$^2$.

so it is expected that the bombardment rate early in Solar System history was much higher than it is now, as the remnants of the planet-formation process were swept up by the young planets. An important question is whether these large basins can form this late in Solar System history if the only sources of impactors were these remnants of planet formation. One recent study addressed this problem on the Moon[27]. It was found that, regardless of the initial mass of the planet-formation remnant population, the likelihood of producing basins as large and young as those observed is quite low, primarily because collisional evolution of the planet-formation remnants is rapid. This is strong evidence that the late formation of Orientale and Imbrium requires a dynamical process besides slow, standard delivery of planet-formation leftovers.

Starting in the mid-1980s, studies focused on understanding the orbital architecture of the outer Solar System, and wholly unrelated to the impact history of the Moon, began to uncover evidence that the giant planets may have formed in a more compact configuration and subsequently migrated into their present orbits[28–31]. This process was seen as a potential mechanism for producing a lunar cataclysm owing to the destabilization of not only the primordial Kuiper belt, but also the main asteroid belt.

Although giant-planet migration provides a mechanism for delivering impactors into the inner Solar System in a short time interval, there was no obvious reason why the giant planets should have stayed in a compact configuration for several hundred million years after Solar System formation before migrating. One suggestion was that Uranus and Neptune simply took ~700 Myr to form[32], although whether this is plausible remains uncertain.

An alternative explanation for the late nature of planet migration was proposed in one[33] of three papers[33–35] collectively referred to as the Nice model (after the L'Obervatoire de la Côte d'Azur in Nice, France, where the authors were working). In the Nice model, the giant planets can stay in a compact configuration for an arbitrary period of time, migrating very slowly owing to angular momentum exchange with an adjacent massive icy planetesimal disk. Migration becomes rapid only after Jupiter and Saturn cross a mean motion resonance with each other. This provides a plausible way to trigger giant-planet migration and deliver impactors to the Moon as late as 3.9 Gyr ago in a relatively narrow spike. Although the exact timing of resonance crossing and the resulting bombardment was a free parameter of the original model, more recent work has better constrained its timescale to ~400–900 Myr[36]. This is consistent with a delay of ~600 Myr between planet formation and the onset of the Late Heavy Bombardment.

Observational evidence for the Nice model comes in part from the distribution of asteroids in the main asteroid belt, which is consistent with mass depletion caused by orbital excitation owing to the migration of giant-planet resonances through the belt well after its formation[31,37]. Furthermore, highland surfaces on the Moon have a distinct size–frequency distribution of impact craters from the maria, a distinction that is apparent on Mars and Mercury as well[38]. On these bodies, the oldest surfaces have a crater population consistent with impactors delivered in a size-independent manner owing to the destabilization of the main asteroid belt during planet migration, whereas younger surfaces are cratered primarily by near-Earth asteroids, delivered in a size-selective manner owing to the Yarkovsky effect[38]. The transition between these two observed crater populations is the result of a change in the impactor population before and after the Late Heavy Bombardment, though the precise nature and timing of this transition is controversial[15,39,40].

## Remaining uncertainty of the causes of heavy bombardment

The migration of the giant planets provides a dynamical explanation for why the Moon and other terrestrial planets experienced a period of heavy bombardment well after their formation; however, uncertainties remain. Here we will address some of the most significant existing challenges to the hypothesis that giant-planet migration was the proximate cause of the Late Heavy Bombardment.

The consequences of giant-planet migration for the orbits of the terrestrial planets were not directly addressed in the Nice model or in earlier migration models for reasons of computational expediency. Recent work has revealed that late giant-planet migration has the potential to destabilize the terrestrial planets[41,42]. This is caused by the sweeping of a so-called secular resonance (the $\nu_5$ resonance) across the terrestrial planet region. The location of this secular resonance is set by the orbital positions of Jupiter and Saturn and, as the giant planets migrated away from each other, the location of the $\nu_5$ would have swept across the inner Solar System, exciting terrestrial planet eccentricities above their present values and potentially causing them to collide with one another. The fact that the terrestrial planets exist is an indication that something is amiss with the Nice model in its original form.

Another strong constraint on giant-planet migration models is the orbital element distribution of the main asteroid belt itself. During planet migration, two powerful secular resonances are thought to have swept across the main asteroid belt, the $\nu_6$, which excites eccentricities and the $\nu_{16}$, which excites inclinations. Under reasonable assumptions, the magnitude of the excitation in these orbital parameters is most strongly controlled by the speed at which Jupiter and Saturn were moving apart from each other. Therefore the present eccentricity and inclination distributions of the main belt may be used to as a tool to uncover the migration rate of the giant planets. Numerical simulations show that migration rates consistent with giant-planet migration by means of planetesimal scattering should have left the main belt with a significant high-inclination population, which is not observed[43]. An analytical study of the eccentricity distribution of the main belt tells a similar story and limits the migration rate of the giant planet to speeds much higher than typically seen in planetesimal scattering models[44]. The semimajor axis distribution of the main belt is also well reproduced by a very rapid migration speed[37].

Taken together, the constraints on the dynamical state (and existence) of the terrestrial planets and main asteroid belt all point towards a migration history of the giant planets that was far more rapid than expected from planetesimal scattering models, far earlier than would be expected to cause a late cataclysm. A solution has recently been proposed. In these simulations, dubbed the 'jumping Jupiter scenario', most of the migration history of Jupiter and Saturn occurs owing to close encounters with Uranus and Neptune[41,42] in a process known to exoplanet researchers as planet–planet scattering. Planet–planet scattering occurs when planets approach each other so closely that their orbital motion is dominated by their mutual gravitational influence rather than that of the central star. A scattering event can lead to very large changes in the orbits of the planets and may result in the ejection of a planet out of the system entirely. However, the fraction of these simulations that undergo the kind of violent evolution needed to preserve the terrestrial planets is <10% (ref. 42). This probability may be increased if there had been an extra ice giant (or two) with a mass comparable to Uranus that was ejected from the Solar System by Jupiter[45–47]. The survival of the terrestrial planets against the sweeping of the $\nu_5$ resonance is one of the most limiting constraints on jumping Jupiter scenarios. It has been noted that this constraint is significantly relaxed if the Nice model scenario occurred in the first 30–100 Myr of Solar System formation, before the time when terrestrial planet accretion had mostly completed[42]. If so, giant-planet migration, although an important aspect of the early history of the Solar System, is not the explanation for the Late Heavy Bombardment.

A second challenge to the Nice model follows directly from the need for giant-planet migration to have been very rapid. Such a rapid evolution does not destabilize as many asteroids from the main belt as was originally estimated, such that only about 50% of the main belt is lost owing to resonance sweeping[44] as opposed to >90% (ref. 33), which reduces the total number of impactors available to make basins by at least a factor of five. This would not produce the number of lunar basins that the cataclysm would require. One recent suggestion to address this problem is that the asteroid belt might have once extended farther inwards towards Mars in what has been termed the E-belt[48]. This region is now mostly dynamically unstable owing to the presence of the powerful $\nu_6$ resonance, though an island of stability at high inclination is occupied by a population of asteroids called the Hungarias. However, before giant-planet migration this region would have been much more stable because of the absence of the $\nu_6$. The E-belt's proximity to the inner planets would give this population a higher impact probability than the main belt and requires less mass depletion to produce a given amount of cratering. The impact flux from this region has a slow decay, consistent with the decline in lunar cratering[49], and may also reproduce an increase in the impactor velocity that has been hypothesized based on analysis of crater-size distributions of the lunar highlands[40]. This model predicts the formation of nine lunar basins from 4.1 to 3.7 Gyr ago (a few additional basins formed during this time might come from the primordial main belt[49]). This is a modest cataclysm, as there are at least 31 basins on the Moon[14,15] and may be many more[14]. These unaccounted-for lunar basins would have to come from a different process or source, yet retain the main-belt-size distribution.

Finally, all giant-planet migration models imply a large flux of icy cometary impactors to the Moon, yet the signature of this population is curiously absent both in the cratering record and geochemistry[38]. The absence of a non-asteroidal impactor population in the lunar cratering record is especially challenging for jumping-Jupiter-type rapid migration models that can produce, at most, only about one-third of the observed ancient lunar basins. In such a model, cometary impactors should have dominated the pre-Nectarian cratering record[43], unless a substantial number disintegrated before they reached the inner Solar System[48,49].

## Synthesis

There is no question that the terrestrial planets were cratered much more intensively during their first billion years[1–3] (Fig. 3). The hypothesis dating back to analysis of the Apollo samples that most of the large basins on the Moon formed in a short period of time (100–200 Myr) remains possible, but some of the lines of evidence that motivated its original suggestion now seem less strong. In particular, the Apollo sample collection is plausibly dominated by the formation of the Imbrium Basin ~3.9 Gyr ago[8–10].

Nevertheless, a dynamical event is probably necessary[27] to allow the relatively late formation of large basins such as Imbrium and Orientale on the Moon, Caloris and Rembrandt on Mercury, and Argyre, Hellas and Isidis on Mars. A giant-planet-migration scenario is the best current hypothesis for how this might occur. The Late Heavy Bombardment that results may not be as cataclysmic or as short as once thought: it is plausible that only a third of lunar basins are attributed to the bombardment and it may have extended for >400 Myr[11,48,49], rather than including all pre-Nectarian basins and lasting only 50–200 Myr as was once proposed[4–6,12] (Fig. 2). The additional impact flux that results has a long tail, extending to later times for smaller impactors and effectively persisting for longer on planets with a higher impact probability, such as Earth[48,50].

Further evaluation of both the timing and magnitude of the Late Heavy Bombardment will require additional lunar samples. Despite disagreements about ages determined from the existing sample collection, lunar sample return is a worthwhile endeavour. Future sampling strategies will be able to take advantage of the lessons learnt during the Apollo missions and of advances in robotic exploration and tools for remote and *in situ* characterization. The total time on the lunar surface during the Apollo missions was only 80 hr; it is unlikely that any equivalent amount of geologic fieldwork has answered more fundamental questions about the history of the Solar System. Obtaining additional dates for lunar basins will build on this legacy and help anchor our understanding of the Late Heavy Bombardment.

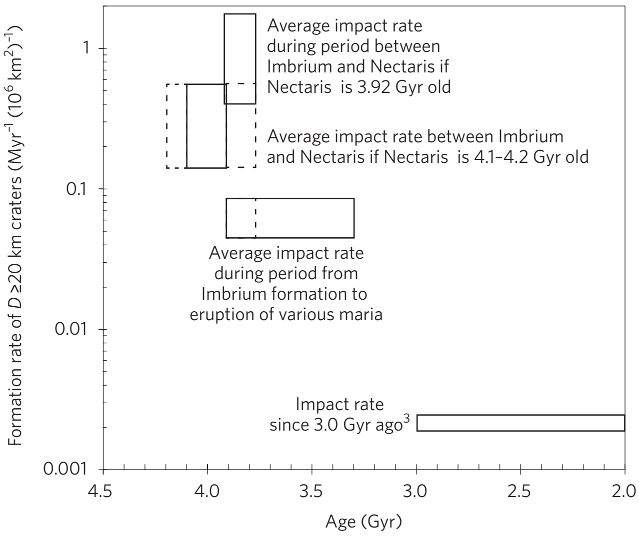

**Figure 3 | Rectangles showing the range of impact flux required on the Moon at various points in time, assuming different ages and superposed crater densities for Orientale (O), Imbrium (I) and Nectaris (N) and various maria[3,13].** Regardless of the form of the early bombardment history, the impact flux in the past 3.0 Gyr was a factor of ~50–100 times lower than at the time of the Imbrium impact.

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## Additional information

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## Competing financial interests

The authors declare no competing financial interests.