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A post-accretionary lull in large impacts on early Mars

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The early impact bombardment of Mars has been linked to the bombardment history of the inner Solar System as a whole. However, the timing and number of basin-forming impacts on Mars are poorly constrained. The Borealis basin—thought to be the largest and oldest known Martian impact basin—forms the crustal dichotomy between the northern lowlands and southern highlands. Four unambiguous large basins post-dating Borealis have been identified, but as many as 32 additional basins larger than 1,000 km in diameter have been proposed. Here we use gravity and topography analyses to show that the crustal dichotomy boundary was excavated by only one later impact basin (Isidis), which probabilistically indicates that fewer than 12 large basins across the globe could post-date the boundary and pre-date the established younger basins. Moreover, the relatively pristine topography and crustal thickness at the dichotomy boundary indicates that younger basins should be similarly well preserved. This suggests that the post-Borealis large basin population is limited to only the four known younger basins, with estimated ages between 3.8 and 4.1 Gyr ago (Ga). We present geochemical arguments that Borealis dates to near 4.5 Ga. Combined with Monte Carlo simulations, we argue that, instead of a gradually declining impactor flux, a lull in large basin-forming impacts occurred between about 4.1 and 4.4 Ga on Mars, separating the endgame of accretion from a putative late heavy bombardment similar to that proposed for the Moon and asteroid belt.

Giant basin-forming impacts played a critical role in the early evolution of the terrestrial planets. The flux of basin-forming impacts on early Mars, however, is poorly constrained. Although the history of impacts and other processes is plausibly well constrained from the Noachian era (∼3.8–4.1 Ga) onwards, there is increasing interest in the pre-Noachian period (>4.1 Ga), for which the surface geologic record has been effectively destroyed by subsequent modification[1,2].

To explore the early bombardment history of Mars, we focus on crustal-scale impact basins, which we define as those basins that excavated a significant fraction (>25%) of the crust, resulting in a pronounced signature in topography and/or gravity data. Mars exhibits three such basins in the southern highlands (Hellas, Isidis, and Argyre, with central topographic depression diameters[3] of 1940, 1500, and 780 km; Fig. 1a,b) and one unambiguous basin in the northern lowlands (the buried Utopia basin, which is 2,200 km across). Based on the observed crustal-scale basins, we limit our analysis to basins >780 km in diameter. In addition, geophysical evidence supports the notion that the northern lowlands of Mars are an ancient impact basin with dimensions of 10,600 × 8,500 km, surrounded by a well-preserved elliptical rim[4]. Previous studies have also identified large numbers of candidate basins on the basis of more subtle signatures in topography or crustal thickness models[5–7]. In these works, up to 42 basins >1,000 km in diameter were identified, with 32 of these regarded more confidently[7] and interpreted to have formed between Borealis and Hellas, Utopia, Isidis, and Argyre (hereafter referred to as HUIA)[8]. However, these basins have very subtle signatures in gravity and topography data. The existence of these or other similar ancient basins would increase the impact-induced perturbations to the surface, atmosphere, and interior of early Mars by an order of magnitude relative to HUIA alone, with important consequences for Mars' evolution.

Preservation of the dichotomy boundary

The crustal dichotomy boundary, interpreted as the Borealis basin rim[4,9], can be used to probe the abundance and timing of a putative population of early basins. Consider that the exposed dichotomy boundary is crossed by only one crustal-scale basin, Isidis. The preservation of the exposed boundary[10] and lack of any prominent deviations from the elliptical rim of the Borealis basin[4] rules out the existence of any additional superposed crustal-scale basins. Furthermore, geophysical inversions revealed the path of the dichotomy boundary where it has been buried beneath the Tharsis volcanic rise[4], and no evidence can be found for superposed impact basins along this boundary segment.

The existence of only one dichotomy-boundary-excavating basin can be used to place statistical limits on the total post-Borealis population of basins, allowing for the possibility that basins away from the boundary may have been subsequently modified so as to have little expression. For simplicity, we represent the dichotomy boundary as a great circle around Mars, which is within 1% of the length of the best-fit ellipse to the boundary. The probability of a randomly located basin crossing the dichotomy boundary is $\sin(R_b/R_M)$, where R_b is the basin radius and R_M is the radius of Mars. For the HUIA basins, we find a 67% probability that at least one will cross the boundary, in keeping with the observation that Isidis does cross it.

Using the same method, we can test the possibility of an additional population of putative randomly located post-Borealis basins that do not cross the boundary. For an additional population three times that of HUIA, there is a 96% chance that at least one basin will cross the dichotomy boundary, and this putative basin population can be rejected at the 2-σ confidence level. For comparison, adding 2, 4, 8, 12, and 20 HUIA basins in a Monte Carlo model destroyed a median of 0%, 4% (850 km), 12% (2,600 km), 16% (3,400 km), and 30% (6,400 km) of the Borealis rim, respectively;

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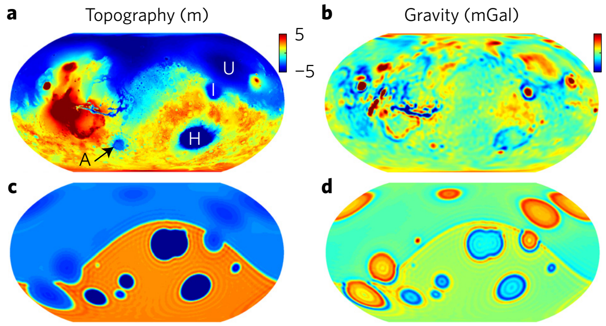

Figure 1 | Geophysical signatures of known and simulated of basins. **a**–**d**, Topography (**a**,**c**) and free air gravity (**b**,**d**) observed on Mars (top) and modelled from a synthetic population of 12 randomly placed basins in addition to HUIA and a hemispherical crustal dichotomy. The synthetic basins in **c**,**d** are taken from a single realization of the Monte Carlo model that matches the median number of dichotomy crossing basins (2) and the median fraction of the boundary destroyed by those basins (16%). Results show that >12 pre-HUIA basins assure impact modification of the dichotomy boundary in conflict with observations, and any pre-HUIA crustal-scale basins are incompatible with observed topography and gravity.

even a few basins result in a strong likelihood of obvious damage to the boundary. Alternatively, we can use HUIA to define a production function from which putative basins can be drawn randomly within a Monte Carlo simulation. For basins >500 km in diameter, we can reject the possibility that no basins will cross the boundary when $\geq$12 basins are formed (for example, Fig. 1c,d), in agreement with the previous approach. Note that tests where the Tharsis region is excluded from our runs yield comparable results.

Using the basin diameters from a proposed population of 32 basins[7] and assuming a random and isotropic distribution, the probability that none would cross the dichotomy boundary is 0.0039%. The most likely number of crossers would be 6–7. We note that we are not testing this particular population of proposed basins, but rather evaluating whether a similar population of post-dichotomy impacts, when randomly placed, would be expected to excavate the dichotomy boundary.

Geophysical signatures of impact basins

A more stringent argument against additional HUIA-sized basins post-dating the dichotomy can be made using the well-preserved signature of the dichotomy boundary in topography, gravity, and crustal thickness models. Modelled cross-sections through the crust (Fig. 2a–e) reveal that the transition in topography and crustal thickness across the dichotomy boundary is similar to that across the rims of Hellas, Isidis, and Argyre, with the more complicated transition across the Arabia Terra portion of the dichotomy boundary explained as a partial ring structure around the Borealis basin[4]. Similarly, localized power spectra of the Bouguer gravity (that portion of the gravity field arising from the subsurface) of the basin rims reveal the gravitational signature of the dichotomy boundary to be nearly indistinguishable from the rims of Hellas, Isidis, and Argyre (Fig. 2f). In contrast, a proposed 3,000-km-diameter ancient basin in Terra Sirenum[7] shows no clear signature of crustal thinning, and exhibits Bouguer power spectrum amplitudes reduced by a factor of ~10 relative to the other basins. Similarly, the buried Isidis and Utopia basins show significant reductions in crustal thickness relative to the adjacent northern lowlands (-13.6 ± 3.9 km and -19.6 ± 4.7 km, respectively), whereas the proposed Chryse and Acidalia basins do not (1.8 ± 7.1 km and -3.7 ± 4.7 km, respectively; see Supplementary Information).

Hydrocode models show that the observed preservation of the Borealis basin rim in the immediate aftermath of the impact is possible despite the high impact energy and large volumes of melt produced[11,12]. The observed preservation state of the boundary also reflects minimal later modification by erosion[10] and viscous relaxation[13], the latter of which can be particularly important in degrading the deep geophysical signature. The lack of relaxation of such large impact structures is in part a result of the low crustal thickness beneath the basin floors, which prevents channelized crustal flow into the basin interiors[14]. The similar preservation states of the dichotomy boundary and the rims of Hellas, Isidis, and Argyre require that any basins of Argyre-size or larger anywhere on the planet formed after the dichotomy boundary should be clearly preserved to the present day with only modest degradation by surface erosion or viscous relaxation, but such pre-HUIA structures are not observed. This argument is here based solely on observational grounds, and is thus independent of assumptions regarding rheology or heat flow[13,14].

Large basins buried in the northern lowlands may not show a clear topographic or crustal thickness signature, but should show a strong signature in gravity, as observed in the Utopia and Isidis basins[15,16]. Smaller basins still within the resolution of existing gravity data would be even more strongly expressed as a result of the wavelength dependence of flexural support by the lithosphere[17]. Models of the topographic and gravitational signatures of a random population of 12 basins in addition to HUIA not only violate the previous constraint on the preservation of the dichotomy boundary, but are also in clear conflict with the observed gravity and topography (Fig. 1c,d). Based on this reasoning, we conclude that the only crustal-scale impact basins formed subsequent to the dichotomy are the unambiguous HUIA population. These results do not rule out the possibility that ancient basins formed in the southern highlands prior to the Borealis impact may have a weak relict geophysical signature[5–7], existing as subtle palimpsests of deep-seated structures. Although previous work determined ages for proposed basins falling between the ages of Borealis and HUIA (ref. 8), the near-complete erasure of the topographic and crustal signatures of the proposed ancient basins would have also reset the crater record, making crater retention ages for such structures lower bounds only.

Basin age constraints

The implications of these results for Mars's early bombardment depend on the timing of the HUIA and Borealis impacts. The ages of Hellas, Isidis, and Argyre have been constrained using crater retention ages tied to the absolute timescale established for the Moon (see compilation in ref. 18). Using a variety of crater diameters and production functions[18], they formed 3.88–4.07 Ga or 3.78–3.99 Ga. The buried Utopia basin must be at least 3.8 Ga based on buried craters up to 20 km in diameter[19], and may be appreciably older[6]. We caution that the specific ages of the Noachian-aged basins are dependent upon several interpretations and assumptions. The similarity of the Noachian basin ages to young lunar basin ages like Imbrium, arguably well constrained by Apollo samples to be ~3.9 Ga, supports the application of the lunar chronology to these three basins (for example, ref. 19).

Geologic evidence indicates that the dichotomy is the most ancient feature on Mars[5,10]. The absolute age of the Borealis basin can be bracketed using isotopic data from the Martian meteorites. A key constraint on early Martian bombardment comes from the inferred abundance of highly siderophile elements (HSEs) within Mars's mantle. The extremely high metal-silicate partition coefficients of the HSEs imply that when Mars differentiated, the vast majority of these elements should have migrated to Mars's core, leaving behind a Martian mantle effectively cleansed of HSEs. Intriguingly, the abundance of HSEs in Mars's mantle, which are chondritic in their ratios, are much higher than expected[20]. They are also well mixed within the shergottite source reservoirs[21]. This

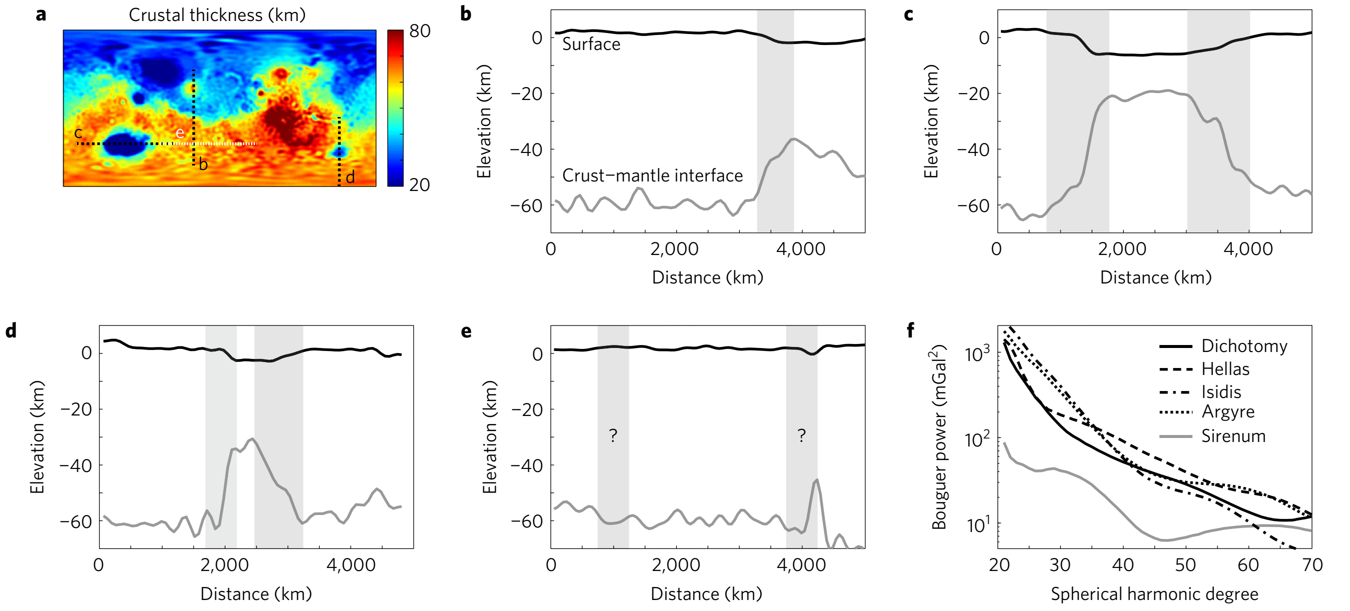

Figure 2 | Crustal thickness transitions across the dichotomy and known basins. a, Modelled crustal thickness[46,47] in map view. **b–e**, Cross-sections through the dichotomy boundary (**b**), Hellas (**c**) and Argyre (**d**) basins, and a proposed ancient basin in Terra Sirenum (**e**). The black and grey lines represent the surface and crust-mantle interface, respectively. Transitions in crustal thickness at basin rims are highlighted in grey. **f**, Power spectra of the localized Bouguer gravity anomaly on the basin rims highlight the similarity between the dichotomy and Hellas, Isidis, and Argyre basins, and the weaker expression of the Sirenum basin (note logarithmic scale).

over-abundance suggests late HSE deliveries to Mars via chondritic projectiles took place after Mars's differentiation but before the shergottite source separated into two distinct reservoirs and final magma ocean crystallization took place at ~4.47 Ga (ref. 21) or 4.504 ± 0.006 Ga (ref. 22).

The ratio of Os in the Martian mantle to the average concentration in chondrites requires the late addition of mass to be at least $\sim 2.1 \times 10^{21}$ kg, equivalent to a single projectile with a Ceres-like diameter of ~1,100 km (ref. 20). This value may be overly conservative in that it neglects the loss of HSEs either to the Martian core or to impact ejecta. If we assume net accretion of chondritic material to the Martian mantle was only 10–50% efficient, the diameter of a single projectile delivering all of Mars's HSEs would increase to 1,400–2,300 km. This value matches the preferred projectile diameters needed to produce the Borealis basin[11,12]. In contrast, the projectiles responsible for the HUIA basins would have only delivered ~8–13% of the HSEs needed, assuming a conservative ratio of 5–6 between the basin and projectile diameter[3] and that all of the projectile material was incorporated into the mantle. This implies the impactor that formed Borealis also delivered most HSEs to Mars' mantle, and therefore this impact took place >4.47–4.5 Ga. This argument supports the earlier suggestion that the Borealis impact established the shergottite source reservoir[23].

Independent constraints on the timing of the Borealis impact may also come from the oldest minerals found within Martian meteorites. Consider that the Borealis impact should have reset the age of virtually the entire Martian crust through the excavation and melting of the northern lowlands and burial of the southern highlands beneath tens of kilometres of impact ejecta. Intriguingly, the oldest Martian zircons are ~4.43 Ga, and they have been relatively unaffected by subsequent events[24]. This implies that Borealis must be at least this old, thereby corroborating its prospective age from HSEs. Moreover, the zircons were found within a set of singular Martian meteorite breccias that closely resemble the majority of Martian surface rocks analysed from various orbital and rover missions[25], and thus may be representative of a large fraction of Martian terrain.

Implications for the early bombardment history of Mars

The sequence of early Martian bombardment supported by the above analysis and synthesis is that the Borealis basin formed >4.47 Ga; followed by a relative lull in impacts between 4.1–4.4 Ga; followed by the formation of the Hellas, Isidis, and Argyre basins ~3.8–4.1 Ga. We cannot yet exclude the possibility, however, that these basins formed from a single exponentially decaying but poorly sampled production population. We evaluated this scenario using a Monte Carlo model of the bombardment history of Mars (see Methods for detail). Our criteria for success were to have three of four HUIA basins formed in the age intervals 3.88–4.07 Ga or 3.78–3.99 Ga, and the fourth with an age >3.8 Ga, the lower bound on the age of Utopia basin. After testing all possible exponential decay rates, we found the largest probabilities of success were 0.7% and 0.5%, respectively, which can be excluded at the 2-σ level. Short decay rates were unlikely to produce the inferred basin ages, while longer decay rates made too many basins before and after the HUIA age constraints.

Accordingly, we infer that two distinct populations of impactors hit early Mars, separated by a relative lull in impacts that we refer to as the 'doldrums'. This bombardment history is consistent with evidence from shock degassing ages of meteorites[26–28], shock degassing ages of lunar samples[27], the ages of terrestrial zircons[29], and estimated ages of the oldest cratered terrains and basins on Mercury[30]. By extrapolation, this in turn suggests the HUIA basins on Mars may have been created during a Late Heavy Bombardment by bodies potentially liberated from the main asteroid belt in the aftermath of late giant planet migration, as has been proposed to explain the bombardment histories of other bodies[27,31,32]. Different assumptions regarding the time evolution of the impact flux since the beginning of the Noachian may change the model ages of HUIA and shorten or lengthen the doldrums, but would not affect our conclusions regarding the sequence and timing of major impacts relative to the geologic history of Mars. For example, allowing an age for Hellas of 4.2 Ga, based on uncertainty in the age of the similar aged lunar Nectaris basin[33,34], increases the probability of producing the basin ages from a single decaying population to only 6.4%.

It is likely that smaller impacts were occurring during the apparent lull in basin formation between 4.1–4.4 Ga. For an assumed production function of basins[35], the lack of HUIA-sized basins is permissive of the existence of one basin in the next smaller size interval (400–566 km, for typical root-2 scaling of diameter bins) and also permissive of a larger number of smaller impacts. These statistics are consistent with a pre-Noachian age for the Ladon basin[18,19], which has a central topographic depression diameter of ~500 km. Although the size-frequency distribution of impacts over this interval may have been different, meteorite shock degassing ages also support a lull in the number of impacts occurring in the asteroid belt during this time period[26–28].

This evidence suggests that the majority of the pre-Noachian period of Martian history was relatively quiescent in terms of large impacts in comparison with the tempestuous times at the end of accretion and during the late heavy bombardment. The reduced impact flux during this time is at odds with common assumptions used in assigning absolute ages from crater counting[36], making the dating of pre-Noachian events difficult[6,8]. The pulse of basin-forming impacts on Mars during the Noachian period has parallels in the volcanic[37], tectonic[38], and fluvial[39–41] history of the planet. The thermal consequences of the Noachian basin-forming impacts may have terminated the magnetic dynamo[42], and thus the relative lull in very large impacts during the pre-Noachian may have enabled a dynamo that could have shielded the atmosphere from loss to space. Similarly, the pre-Noachian may have been a period during which volcanic outgassing[37] outpaced losses to impact erosion[43,44], resulting in a thickening atmosphere. Alternatively, impact-induced warming of the climate has been invoked to explain evidence for warmer and wetter conditions in the Noachian[45], and thus the reduced pre-Noachian impact flux may have resulted in a more stable but potentially cooler climate. Although the details remain uncertain, it is clear that the bombardment history of Mars, including the reduced impact flux during the doldrums, profoundly affected its early evolution.

Methods

Methods, including statements of data availability and any associated accession codes and references, are available in the online version of this paper.

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Author contributions
W.F.B. performed the Monte Carlo models. J.C.A.-H. performed the geophysical analyses. Both authors contributed equally to the discussions, interpretations, and preparation of the manuscript.

Additional information
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Competing financial interests
The authors declare no competing financial interests.

Methods

Geophysical analyses. Bouguer gravity was calculated from the gravity field *JGMRO110c* derived from tracking of the Mars Reconnaissance Orbiter (MRO) spacecraft[48] and topography from the Mars Orbiter Laser Altimeter (MOLA)[49], assuming a crustal density of 2,900 kg m^{-3} (ref. 50) and taking into account the finite amplitude of relief at the surface[51]. Bouguer power spectra were calculated using spatio-spectral localization[52] to isolate circular caps centred on the dichotomy boundary (5.1° S, 137.8° E) and the rims of the Hellas (28° S, 70° E), Isidis (3° N, 83° E), Argyre (57° S, 320° E), and the proposed Sirenum basin (34.5° S, 140° E). A taper bandwidth of $L_w = 20$ was used, such that a circular cap with a radius of 17° had one nearly perfectly localized taper. Localized gravity can be analysed between degrees $L_w + 1$ and $L_{max}–L_w$. The global gravity model begins to show signs of ringing beyond degree 90, so we plot our power spectra between degrees 21 and 70. Crustal thickness analyses use a model[46,47] derived from MRO gravity and MOLA topography, with a low-pass cosine-shaped filter applied between degrees 70 and 80. Gravity analyses made use of the *SHTOOLS* software package[53].

The gravity and topography from a synthetic set of basins were modelled by taking into account the membrane-flexural deformation of the lithosphere in response to the load[54], with corrections as described by ref. 55. Basin diameters and locations were taken from one realization of the Monte Carlo model adding 12 pre-HUIA basins to Mars, selecting a model that matched both the median number of boundary-crossing basins (2) and the median fraction of the dichotomy boundary destroyed by those basins (16%). For comparison to the observed data, we modelled synthetic representations of the HUIA basins in addition to this randomly generated population. The crustal dichotomy was represented as a hemispheric step function in crustal thickness from 60 km in the highlands to 30 km in the lowlands. Basins were generated as isostatically compensated hemispherical cavities with excavation depth to diameter ratios of 0.05, and with a minimum crustal thickness of 10 km to reflect the new crust generated from the impact melt for basins that do excavate the entire crustal column. Basins intersecting the northern lowlands were subjected to five successive infill events, in which they were flooded with lava to reach the level of the surrounding plains and then allowed to come into flexural equilibrium. A lithosphere thickness of 100 km was assumed, consistent with global lithosphere thickness estimates required to support Tharsis[37,56] as well as the fill within the Utopia[15] and Isidis[16] basins. Reducing the lithosphere thickness to 40 km to represent basins that were both formed and filled earlier in Mars history increases the topographic expression of the filled basins while reducing the gravitational signature (Supplementary Fig. 1).

The HUIA basin diameters used in this study are the diameters of the central topographic depressions[3], and thus are smaller than diameters based on the outermost identifiable ring structures. For the Orientale basin on the Moon, the equivalent diameter would be that of the Inner Rook ring, within which the crust has been thinned by the impact[57]. The diameter of the central topographic depression is more relevant to our discussion of the existence and preservation of ancient basins. It is not clear whether the diameters of proposed ancient basins[5–7] correspond to the outer ring or central topographic depressions, although the stated diameters of HUIA in those studies correspond to the central topographic depression. If we assume that diameters of the proposed ancient basins represent outer ring structures that are scaled by a factor of $2^{0.5}$ relative to the central topographic depression[58] the probability that none of the central topographic depressions of a randomly placed population of 32 basins would excavate into the dichotomy boundary is increased to 0.1%, and can still be confidently rejected.

Monte Carlo code results of early Martian bombardment. Other than using the analytical description of early Martian bombardment as described in the main text, we also employed numerical Monte Carlo bombardment simulations to supplement our results. Both approaches produced similar outcomes.

Here we assumed Borealis was the oldest observed surface structure on Mars, comprising a great circle with a perimeter of 21,300 km and a centre located at 67° N, 208° E. New basins formed after Borealis were defined as circles with radius *R*. They were placed at random and isotropic locations on a Martian globe, with an algorithm checking to see if any portion of the basin crossed an undamaged portion of the Borealis' boundary. If so, the destroyed portion of the Borealis boundary was computed and recorded for later use.

Over 100,000 trial runs, our simulations were found to readily reproduce the analytical results discussed above; when 12 basins were added to Mars, with diameters equal to Hellas, Utopia, Isidis, and Argyre, we found a 96% probability that a noticeable portion of the Borealis margin would be destroyed. The median number of basins crossing the margin in this example were two, with the mean and median portions erased being 17 ± 9% (3,600 ± 1,900 km) and 16% (3,400 km), respectively. As discussed in the main text, adding 2, 4, 8, and 20 basins destroyed a median of 0%, 4% (850 km), 12% (2,600 km), and 30% (6,400 km) of the Borealis periphery, respectively. Thus, even when only a few basins are added, the likelihood of obvious damage to the Borealis rim was substantial.

For the previously proposed case[7] described in the main text, in which 32 large basins were added to Mars after Borealis, we found a 99.996% likelihood that the Borealis rim would be hit. The most likely number of basins crossing the Borealis boundary was six to seven.

Modelling the decay rates for post-Borealis basin-forming impactors. Our work from above, as well as the inferred ages of the large observed basins Borealis, Hellas, Isidis, and Argyre, seemingly implies that very few basins formed between ~4.1–4.4 Ga. It is also possible, however, that these basins formed from a single slowly decaying but poorly sampled production population. To evaluate this scenario, we used a Monte Carlo code to test whether any single production function describing projectiles hitting Mars at time t after Borealis formation (>4.47 Ga) could produce the observed basins. Using estimates of Hellas–Isidis–Argyre formation ages from the literature, we evaluated basin formation intervals of 3.88–4.07 Ga and 3.78–3.99 Ga (ref. 18), 3.83–3.99 Ga (ref. 19) and 3.93–4.03 Ga (ref. 59). For the latter, the time span was derived from the mean of the basin ages found using Neukum and Hartmann crater chronologies, and the two different age ranges from ref. 18 are based on the chronologies of ref. 35 and ref. 60 (see Table 2 in Robbins *et al.* 2013).

The probability of a basin-forming event at time t was set proportional to $e^{-\lambda t}$, with λ an input decay constant and a start time of 4.47 Ga. Older start times always yielded lower probabilities of success. For each Monte Carlo trial, random deviates were used to select four values of t from the probability distribution; one each for Utopia, Hellas, Isidis, and Argyre. Here Utopia was included, even though its age is unknown, because its t value could conceivably help fill the bombardment gap between ~4.1–4.4 Ga. Our criteria for success was to have three of four basins (representing Hellas, Isidis, and Argyre) with t in the age intervals above and the fourth basin (representing Utopia) with an age >3.8 Ga.

Over 30,000 trials for all possible λ values, we found the largest probabilities of success for the intervals 3.88–4.07 Ga and 3.78–3.99 Ga, were 0.7% ($\lambda = 2.1$ Gyr^{-1}) and 0.47% ($\lambda = 2.0$ Gyr^{-1}), respectively. Considering basin ages from ref. 19 and ref. 59 of 3.83–3.99 Ga, and 3.93–4.03 Ga, we found probabilities of success of 0.3% ($\lambda = 2.1$ Gyr^{-1}) and 0.57% ($\lambda = 2.4$ Gyr^{-1}), respectively. These values allow us to reject a single decay model making the HUIA basins at the ~2-σ level.

However, we acknowledge the great uncertainty in absolute ages derived from crater counts for features on Mars, which are based on the still controversial lunar chronology[34]. In particular, the proposed age of the lunar Nectaris basin from Apollo 16 samples of 3.92 Ga (for example, ref. 61) is in dispute, with some studies favouring an age of ~4.2 Ga (ref. 33) and others suggesting that the age of the basin is not represented in any returned samples[62]. This basin is particularly important in that it defines the end of the Nectarian era on the Moon, and has a nearly identical crater retention age to the Martian Hellas basin[19]. Although there is no established Martian chronology accounting for the possibility of an older Nectaris age, we approximate such a scenario by assuming that three of the four basins formed in the interval 3.8–4.2 Ga, and the fourth formed >3.8 Ga. We find a maximum probability that these basins could have formed from a single decaying population of projectiles of 6.4% ($\lambda = 2.3$ Ga^{-1}). Although the probability for this more generous age range exceeds the 2-σ threshold, it is still an unlikely scenario.

Code availability. The gravity analyses in this study used the publicly available code SHTOOLS (available on-line at https://shtools.oca.eu/shtools). The codes used to produce the Monte Carlo results were created using IDL and are available from the corresponding author upon request.

Data availability. Gravity and topography data for Mars is publicly available at the Geosciences Node of NASA's Planetary Data System (PDS) archives (http://geo.pds.nasa.gov). Any additional modelling data that support the findings of this study are available from the corresponding author upon request.

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