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A post-accretionary lull in large impacts on early Mars

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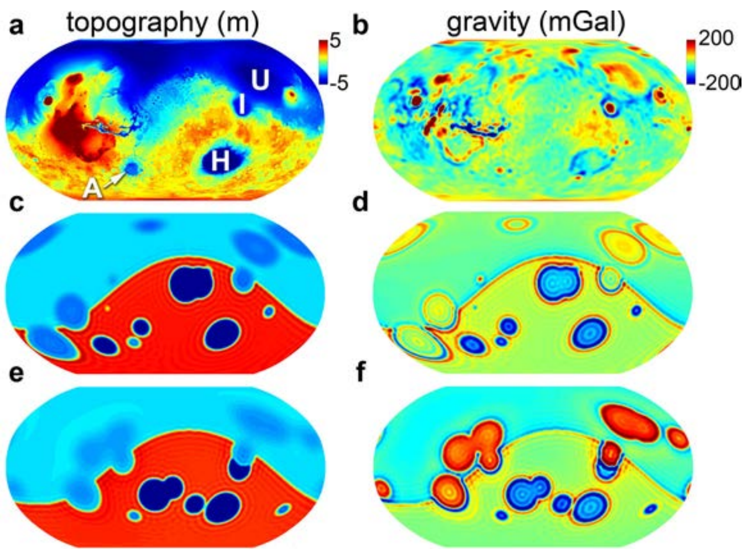


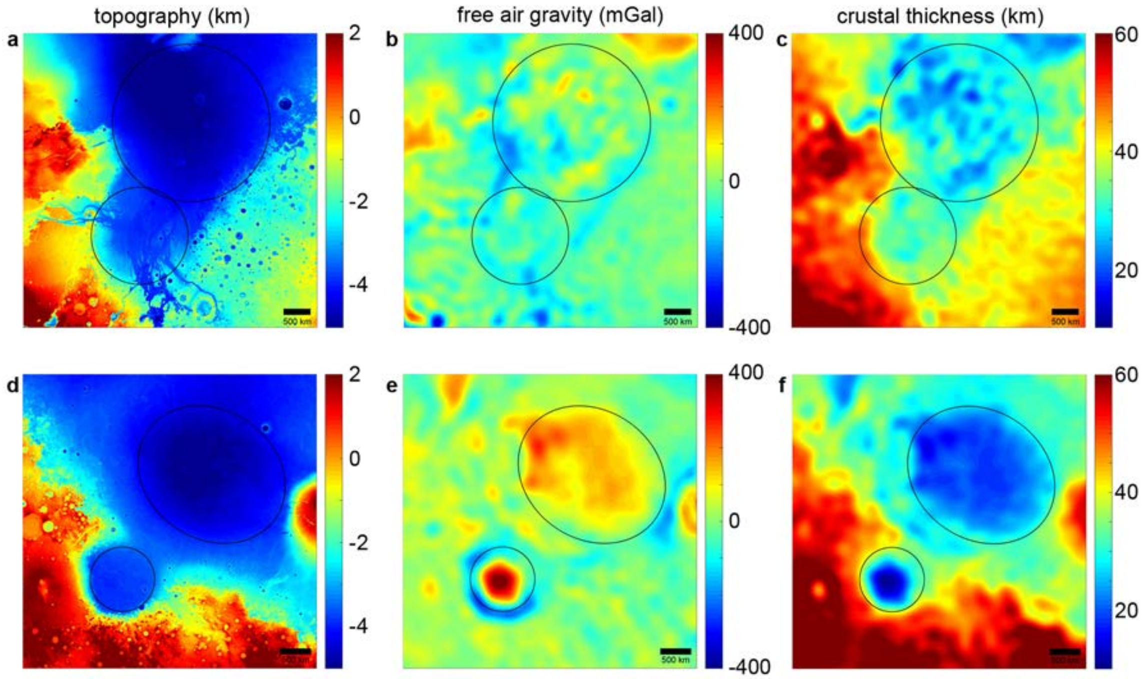
Supplemental Figure 1. Topography (left) and free air gravity (right) observed on Mars (**a,b**) and modeled from a synthetic population of 12 randomly placed basins in addition to HUIA and a hemispherical crustal dichotomy. Panels **c-d** show the same set of basins depicted in Fig.1, but modeled with a lithosphere thickness of 40 km. Panels **e-f** show an alternate realization from the Monte Carlo model, with a lithosphere thickness of 100 km.

Additional candidate impact basins

In this work, we predicate our conclusions on the interpretation that the only crustal-scale impact basins formed after the crustal dichotomy are those with unambiguous topographic and crustal signatures: Hellas, Utopia, Isidis, and Argyre (HUIA). Although a number of additional basins have been proposed, we note a clear distinction between the preservation and morphology of HUIA and these other proposed basins as discussed in the text. We here discuss a few previously proposed basins in greater detail.

While Chryse Planitia is often cited as an impact basin[6,63], it is not characterized by either a thinner crust[51,52] or lower topography[47] than the adjacent lowlands to the north, nor does it possess a gravity mascon indicative of infilling of an impact basin (Supplemental Figure 2). The crust within the proposed basin is 1.8±7.1 km thicker than that outside the basin in the lowlands to the north. The southeast portion of the proposed rim is coincident with the crustal dichotomy boundary, and does not impart any deviation from the path of the best-fit ellipse to this boundary[4]. The northwest portion of the proposed rim is coincident with the edge of Lunae Planum and Tempe Terra. The edge of Tempe Terra continues on this trajectory to the north with no detectable change where it departs from the proposed basin rim. Thus, the impact interpretation of Chryse Planitia requires a coincidental alignment of the basin rim with the edges of preexisting structures on both sides. In each of these ways, Chryse is in stark contrast to the Isidis basin, which clearly cuts the dichotomy boundary and is characterized by thinned crust and a striking positive gravity anomaly. The crust within Isidis is 19.6±4.7 km thinner than that in the lowlands to the north, and 43.6±2.7 km thinner than that in the highlands to the south.

Similarly, to the north of Chryse, Acidalia Planitia has also been proposed as a possible impact basin[6]. Although Acidalia is somewhat lower in elevation than the surrounding lowlands, the crust within the proposed basin deviates from that in the lowlands to the north by only -3.7±4.7 km, and thus is not statistically distinguishable from its surroundings (Supplemental Figure 2). This proposed basin does not show the dramatic crustal thinning and positive gravity anomaly of the similarly sized Utopia Basin[15], which is also located in the thin crust of the northern lowlands. Although Utopia has been filled by ~20 km of material[15], the crust within the basin today is nevertheless 13.6±3.9 km thinner than that in the surroundings. Despite the muted signatures in topography and reduced crustal thickness contrasts of the Isidis and Utopia basins



Supplemental Figure 2. Topography (left), free air gravity (center), and crustal thickness (right) for the proposed Chryse and Acidalia basins (**a-c**) and the confirmed Isidis and Utopia basins (**d-f**). Approximate basin rims are identified by circles, using proposed basin center and diameter from ref. 8 for Chryse and Acidalia.

relative to the highland basins, geophysical analyses of the strong positive gravity anomalies reveal well-preserved basins beneath the thick volcanic and sedimentary fill[15,16].

Although a number of proposed ancient basins may possess subtle topographic depressions or crustal thinning within quasi-circular regions, they contrast starkly with the clear geophysical signatures of the Hellas, Utopia, Isidis, and Argyre basins. We do not argue either for or against the existence of proposed ancient basins with very subtle geophysical signatures, but rather draw a clear contrast between the proposed basins and the unambiguous Noachian basins, as well as between the state of preservation of the proposed basin rims and the preservation of the dichotomy boundary.

Other basins with clear crustal signatures do exist in the southern highlands, but they are smaller than HUIA and exhibit much less crustal thinning than that across the dichotomy boundary, which would enhance lower crustal flow and relaxation in the smaller basins[14,64]. Thus, arguments based on the preservation of the basins in comparison to the preservation of the dichotomy boundary cannot be made for these smaller basins. For example, Ladon basin (18°S, 28°E) is an ancient impact basin with clear crustal thinning in the basin interior, but the central topographic depression is only ~470 km across and exhibits a crustal thickness contrast of only ~15 km relative to the surrounding highlands. Prometheus basin is an ancient basin that is partially buried beneath the south polar layered deposits. The diameter of the well-preserved rim of this basin of ~850 km likely corresponds to an outer ring structure rather than the central topographic depression, though no evidence for a central topographic depression is seen in topography data, gravity data, or crustal thickness models. However, the geophysical signature is complicated by the infilling of the basin center by low-density ice. Scaling from lunar basins[65] suggests a central topographic depression diameter of ~425 km for this basin. A large number of smaller basins (<500 km outer diameter) exist in a range of preservation states, including Schiaparelli, Cassini, Antoniadi, and Huygens. In most cases, the topographic rims correspond to outer rings and the geophysical signatures of positive Bouguer gravity anomalies and modest crustal thinning are confined to smaller central structures, as is also observed on the Moon in higher resolution GRAIL gravity data[65]. These smaller basins retain sufficient crust in their centers to enable relaxation by lower crustal flow[14], and thus are not relevant to this analysis.

Ladon basin is particularly interesting in that the muted, yet still unambiguous, topographic signature of the basin rim and partial outer ring suggests that it may pre-date HUIA but post-date Borealis. The topographic signature of Ladon is in marked contrast to the steeper slopes and sharper structures associated with the rims and ejecta blocks of Hellas, Isidis, and Argyre. The crater retention age of the basin from an isochron fit of 4.17-4.18 Ga [ref. 18] supports its interpretation as a doldrums-era basin. Although, the crater retention age based on craters <50 km in diameter are indistinguishable from Hellas[11], possibly due to erosion and infilling, it is perhaps the best candidate for a pre-HUIA basin. The reduced impact flux during the doldrums is contrary to the bombardment history assumed in calculating its age, and thus the basin could be substantially older. Ladon also places an important constraint on the basin population during this time period. Based on a theoretical production function[35], 1.15 Ladon-sized basins should form for every one basin in all larger size categories. The lack of any HUIA-sized basins formed during the doldrums is permissive of the formation of ~1 (±1) Ladon-sized basin. Ladon is the only strong candidate for a pre-HUIA basin with a clear crustal signature in this size range, further supporting our proposed impact chronology.

Preservation of impact basins occurring before or immediately after the formation of Borealis basin

Our results do not rule out the possibility that ancient basins formed prior to the Borealis basin impact may have some relict geophysical signature. While any basins in the present-day northern lowlands would have been excavated and erased by the Borealis impact, basins in the southern highlands may have been merely buried beneath the thick ejecta blanket. Hydrocode simulations suggest that the crust in the southern highlands may have been doubled in thickness as a result of the ejecta from the Borealis impact event[11,66], suggesting ejecta thickness up to 30 km. Although burial of an ancient basin beneath ~30 km of ejecta would obscure the topographic signature, we cannot rule out the possibility of a subtle relict geophysical signature for basins whose excavation depths were of this order.

The lack of evidence for a population of crustal-scale basins formed in the same time frame as the Borealis impact either suggests that few smaller bodies remained in the leftover planetesimal population at the same time (i.e., the leftover planetesimals had a shallow power law size distribution[20]), or there was a rapid decay of the projectile population responsible for that impact. Focusing on the latter, there would be a short period of time after the Borealis impact during which the preservation of subsequent impact basins would have been made difficult by the high crustal temperatures within the basin and its surrounding thick ejecta sheet.

A rough estimate for the time during which subsequent basins would not be expected to survive in the northern lowlands can be based on the time required for the lithosphere to re-thicken after the Borealis impact. Assuming half-space cooling[67] of a solidified impact melt pond for an initial temperature at the basalt solidus of ~1000°C and a temperature at the base of the lithosphere of 600°C, the lithosphere thickness would reach the crustal thickness in the lowlands of ~25 km after only 13 Myr. Thus, there is a narrow window of ~10 Myr after the Borealis impact during which subsequent basins could have formed and relaxed away to leave little or no crustal signature. These timescales would presumably be shorter for the southern highlands, since the ejecta must be largely solid in order to explain the preservation of the Borealis basin[66,68]. The prime candidate for such a northern lowlands palimpsest is a 1100 km-diameter structure in Amazonis Planitia[69]. This structure is revealed as a strikingly circular pattern of gravity anomalies accompanied by an arcuate pattern of outcrops of ancient basement crust, and yet with no discernible contrast in crustal thickness between the center and exterior.

Alternatively, subtle quasi-circular geophysical signatures in both the lowlands and highlands may instead be the result of non-impact processes such as mantle plumes, as is commonly interpreted for corona and other structures on Venus[70,71]. A variety of geophysical processes are capable of producing arcuate and circular patterns when operating in a spherical planet.

Comparison to the lunar cratering record

If the terrestrial planets experienced a similar bombardment history, our inferred impact chronology for Mars should be compatible with the record of lunar impacts. The pre-Noachian period of martian history potentially corresponds with the pre-Nectarian period of lunar history. Of the 22 basins classified as either pre-Nectarian or Nectarian/pre-Nectarian in age[72,73], only the South Pole-Aitken basin is in the size range of HUIA basins, being comparable to Hellas and Utopia in size. The diameters of the positive Bouguer anomalies associated with lunar basins are equivalent to the diameters of the excavated crustal cavities[65]. The next largest possibly pre-Nectarian basin on the Moon is Serenitatis, with a positive Bouguer anomaly diameter of 556 km, somewhat larger than Ladon basin but smaller than Argyre. Even if Serenitatis is pre-Nectarian in age, we cannot rule out the possibility that it formed as part of the LHB, particularly since its preservation state is similar to the Nectarian-age basins. The largest unambiguous pre-Nectarian basin after South Pole-Aitken is Smythii, with a positive Bouguer anomaly diameter of 438 km. Given the uncertainties in the lunar impact chronology and the scaling of impacts from the Moon to Mars, a martian chronology with no HUIA-sized basins between ~4.4 and ~4.1 Ga is entirely consistent with the lunar record.

Discussion of ancient Martian meteorite samples

The most ancient zircons found in martian meteorites to date come from the group of associated meteorites from northwest Africa (NWA 7034-7475-7533-7906-7907-8114-8171) that are regolith breccias. The zircons analyzed within NWA 7533 and 7034 show numerous ages at 4.43-4.44 Ga, 1.44 Ga, and 1.71 Ga, though one zircon in 7533 has an age of 4.1 Ga and another in 7034 has an age of 4.35 Ga (refs. 24,74). The survival of these minerals, as well as co-existing baddeleyite in basaltic-composition breccia as crystal clasts, indicates these phases likely persist in Mars's mafic crustal record[75]. Wittmann et al.[76] argue that the clast assemblage in NWA 7475 provides a record of at least three impact events, one that formed an impact melt sheet on Mars >4.4 Ga ago, a second that assembled NWA 7475 from impactites associated with the impact melt sheet at 1.7–1.4 Ga, and a third that launched NWA 7475 from Mars ~5 Ma ago. This chronology places the age of the Borealis basin at >4.43-4.44 Ga.

The geologic context of these rocks could explain the paucity of major disturbances found after 4.43-4.44 Ga. Using the Mars Odyssey gamma-ray spectrometer data and the Fe and Th abundances of NWA 7475, Wittmann et al. (ref. 76) suggest this breccia may have come from the 6.9 km diameter Gratteri crater in the ancient southern highlands. This location is close to the periphery of Borealis basin and far from any other major basins, implying that (i) the zircons were not hidden at depth from the global effects of a Borealis basin formation event, and (ii) they were not strongly affected by the most dramatic events of the martian late heavy bombardment (e.g., ref. 75).

Martian meteorite ALH84001 is the oldest known igneous rock from Mars, and thus it must either post-date or have formed contemporaneously with the Borealis impact. However, its crystallization age has been controversial. Interpreted to have formed by crystal accumulation in a large body of magma, the first estimate of its age was ~4.5 Ga based on the Rb-Sr and Sm-Nd isotopic dating systems (ref. 77; see also ref. 78). This age was called into question based on the possibility that the Rb-Sr and Sm-Nd systems were affected by impact heating and water alteration[79]. Using the Lu-Hf system, that study argued a better crystallization age was 4.091 Ga. This led Nyquist and Shih[80] to reanalyze their ALH84001 data to avoid possible disturbances in the Sm-Nd system. They argued that their revised age of 4.47 ± 0.035 Ga is likely the magmatic age, with a strong thermal event at ~4.1 Ga resetting the Lu-Hf system and producing the disturbed Sm-Nd data. Regardless, neither age conflicts with our interpretation of Borealis formation >4.47 Ga and a proposed impact lull between ~4.1-4.4 Ga.

As an aside, we point out that the carbonates found in ALH84001 were dated to be 3.9 Ga to 4.04 Ga (ref. 78,81). These ages are coincident with the era of basin formation defined by HUIA, consistent with the expectation of widespread impact-induced hydrothermal circulation at this time[82].

Finally, there have also been arguments made using the Pb-Pb system that the martian shergottite meteorites may have formed ~4.1-4.3 Ga, rather than ~0.15-0.6 Ga as previously argued[83]. This interpretation, however, has been challenged by many groups (e.g., refs. 84–87). Those studies argue that a more likely explanation for the old ages is either terrestrial or martian

Pb contamination, or the signature of the early differentiation of the depleted source reservoir. Given the highly controversial nature of these data, we do not use these ages as evidence for or against our scenario.

Additional discussion of highly siderophile elements and martian bombardment

A key constraint on early Martian bombardment comes from the inferred abundance of highly siderophile elements (HSEs) within Mars's mantle. The HSE class of metals, which include Re, Os, Ir, Ru, Pt, Rh, Pd, and Au, has extremely high low-pressure metal-silicate partition coefficients ($>10^4$). This implies that when Mars differentiated early in its history, probably 5-30 Ma after CAIs[21], the vast majority of these elements should have migrated to Mars's core, leaving behind a Martian mantle effectively cleansed of HSEs. Intriguingly, the inferred abundances of HSEs in Mars's mantle, as well as those inferred to exist in the mantles of large differentiated bodies like Earth, Moon, and certain asteroids, are much higher than expected from low-pressure metal-silicate partitioning. Moreover, the HSE signatures of these worlds are broadly chondritic, even though the HSEs themselves often have a huge range of partition coefficients. A reasonable interpretation of these data, therefore, is that HSE abundances derived from derivative mantle melts provide a record of so-called late accretion events. Here it is assumed that broadly chondritic projectiles striking after planetary differentiation delivered HSEs to the mantles of Mars and several other worlds. This could potentially explain the elevated absolute and chondritic relative HSE abundances found for Mars, ~0.007 × carbonaceous chondrite Ivuna (CI) composition, as well as that for Earth (0.009 × CI) and the Moon (~0.0002), respectively[88].

For worlds lacking in plate tectonics like Mars and the Moon, however, HSE data can also be used to interpret the nature and timing of late accretion impacts. By definition, late accretion projectiles had to be large enough on these worlds to breach the crust and reach the mantle. This effectively rules out HSE delivery by numerous tiny impactors, particularly because neither world shows any evidence for an extraordinary high abundance of HSEs within their crust (e.g., refs. 88,89). The projectiles must also reach the mantle in time for HSEs to become well-mixed into the source reservoirs of mantle-derived melts. In considering late accretion on Mars, isotopic characteristics of the shergottites indicate that Martian HSEs were well mixed within their enriched and depleted source reservoirs prior to their closure times[21], which occurred at either 4.47 Ga (ref. 90) or 4.504 Ga (ref. 22).

In the main text, we infer that the projectile diameters needed to make Borealis basin range from 1100 km (minimum) to 1400-2300 km (mantle accretion efficiencies of HSEs of 10-50%). These values are intriguing because they are a reasonably good match to the preferred projectile diameters needed to produce the enormous Borealis basin on Mars. For example, Marinova et al. (refs. 4, 62) used SPH simulations to explore a wide range of possible impact energies (2×10^{27} J to 6×10^{29} J), impact velocities (6-50 km/s), and impact angles (0°-75°) in an attempt to match Borealis basin characteristics (e.g., basin size and shape; crustal thickness; relative paucity of impact melt, preservation of the basin rim). Their best-fit results came from projectiles striking near 6 km/s at a 45° angle, with a net impact energy of $\sim 3 \times 10^{29}$ J. This impact may also be capable of reproducing the current rotation of Mars; the current Martian spin period is 1.03 days, while their favored impact yielded 1.3 days. Comparable Borealis formation results were found by Nimmo et al. using an alternative eulerian numerical hydrocode approach[23]. They found vertical impacts at energies between 3×10^{28} J to 1×10^{29} J were capable of producing the appropriate Borealis crater cavity without producing too much melt.

Putting all results together, it is plausible that the Borealis basin-forming event was formed by projectiles striking at impact energies near $\sim 1 \times 10^{29}$ J to $\sim 3 \times 10^{29}$ J. If true, the impact energy and velocity results above yield an approximate projectile diameter of 1500-2200 km (0.009-0.026 Mars masses), assuming the projectile had a bulk density of 3000 kg m^{-3}. Alternatively, if we assume 100% accretion of the projectile into the martian mantle, our lower bound 1100 km diameter impactor yields $\sim 3 \times 10^{28}$ J, which is within the acceptable energy range provided by Nimmo et al. New work will be needed to determine which one of these impact scenarios is most likely to reproduce Borealis basin and HSE constraints.

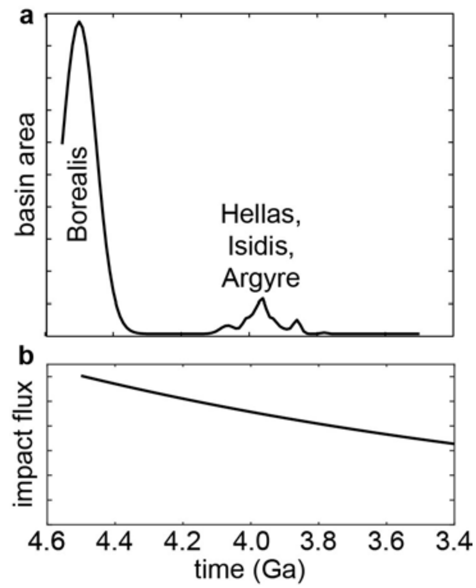
Delivering nearly all Martian HSEs by the Borealis impactor alone is also consistent with the predicted shallow size distribution of late accretion projectiles, which likely to have a differential power law index $q < 2$ (ref. 20; see also ref. 91). In other words, most of the mass of late accretion impactors was likely to be in the largest objects.

Could the majority of Mars's HSEs have been delivered by impacts striking prior to Borealis basin formation? This question is difficult to answer definitively, but we suspect not. To deliver meaningful HSE abundances to Mars by non-Borealis impactors after Mars differentiated, one almost certainly needs to employ impactors that rival the size deduced for the Borealis impactor. The signatures of such colossal collisions, however, would then need to be completely erased in gravity and topography before or during the Borealis basin formation event. Given the prominence of Borealis basin in existing data sets, and the lack of evidence for any previous Borealis-like events, we favor the simplest solution, namely that Borealis dominated HSE delivery to Mars. Similarly, the Borealis impact may have delivered the majority of Mars' angular momentum[92].

Early martian bombardment rates

Given that early Martian bombardment models are still uncertain, we do not attempt to link our work to any quantitative impact flux simulations at this time. Still, for the use of the general reader, we have prepared a schematic diagram of what early bombardment on Mars might have been like. Note that we purposely do not put values on the y-axis to avoid misinterpretation (Supplemental Figure 3).

Limiting our consideration to the large (>780 km diameter) crustal scale basins, the formation of at least three basins (Hellas, Isidis, and Argyre) between 3.88-4.07 Ga and at most one basin (Utopia) during the period from 4.1-4.4 Ga implies an impact flux during the doldrums that was less than ~20% of that during the following Late Heavy Bombardment. However, we emphasize that this simple calculation does not take into account the fact that the flux during both the LHB and the doldrums likely varied greatly with time in a manner that remains poorly constrained.



Supplemental Figure 3. **a** Area-weighted basin ages of the Borealis, Hellas, Isidis, and Argyre basins based on the isochron fits[18]. **b** The best-fit impact decay curve from a Monte Carlo model assuming a single population decaying from 4.47 Ga, attempting to reproduce the age constraints for Hellas, Utopis, Isidis, and Argyre,. From this best-fit decay curve, 99% of trials failed to satisfy the age constraints, ruling out a single decaying population at the 2-σ level, and showing that two distinct populations of projectiles are required to explain the observed timing of major basin-forming impacts on Mars.

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