Title: A thick crustal block revealed by reconstructions of early Mars highlands

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Abstract (215 words):

The global-scale crustal structure of Mars is shaped by impact basins, volcanic provinces, and a hemispheric dichotomy with a thin crust beneath the northern lowlands and a thick crust beneath the southern highlands. The southern highlands are commonly treated as a coherent terrain of ancient crust with a common origin and shared geologic history, plausibly originating from a giant impact(s) or a hemispheric-scale mantle upwelling. Previous studies have quantified the contribution of volcanism to this crustal structure, however the influence of large impacts remains unclear. Here we present reconstructions of the past crustal thickness of Mars (about 4.2 Ga ago) where the four largest impact basins (Hellas, Argyre, Isidis and Utopia) are removed, assuming mass conservation, as well as the main volcanic provinces of Tharsis and Elysium. Our reconstruction shows more subdued crustal thickness variations than at present, although the crustal dichotomy persists. However, our reconstruction reveals a region of discontinuous patches of thick crust in the southern highlands associated with magnetic and geochemical anomalies. This region, corresponding to Terra Cimmeria–Sirenum, is interpreted as a discrete crustal block. Our findings suggest that the southern highlands are composed of several crustal blocks with different geological histories. Such a complex architecture of the southern highlands is not explained by existing scenarios for crustal formation and evolution.

Main Text: 1743 words, 4 figures and 32 references

The crust of Mars has been shaped by 4.5 Gyr of meteorite impacts, volcanism, tectonism, and surface processes (Fig. 1a–b). Its most prominent crustal features are the hemispheric dichotomy,

the Tharsis volcanic province, and several large impact basins. The hemispheric dichotomy describes Mars's north-south asymmetry, where the northern lowlands have roughly half the crustal thickness of the southern highlands. The Tharsis volcanic province represents the thickest region of the crust and is associated with a prominent topographic rise responsible for deformation of the lithosphere at a planetary scale¹. Whereas the crustal thickness of Tharsis is considered to be the result of magmatic intrusions and volcanic eruptions, the origin of the hemispheric dichotomy is more enigmatic. Past studies have suggested that the hemispheric crustal dichotomy is the result of either giant impact(s)^{2,3} or hemispheric-scale mantle upwelling^{4,5}.

While previous studies have quantified the contribution of Tharsis to Mars's gravity field¹, crustal thickness⁶, and topography⁷, the contribution of impact basins to the crustal structure has never been quantified. Mars has four giant (diameters > 1,000 km) unequivocal impact basins with unambiguous gravity field anomalies and expressions in crustal thickness maps (Hellas, Argyre, Utopia, and Isidis), but only three of them have a significant topographic expression (Hellas, Argyre, and Isidis). Utopia has a muted topographic signature, due to its early formation and possible crustal relaxation⁸. The four impacts (Hellas, Argyre, Isidis and Utopia) predate Tharsis, and extensively modified Mars's crustal structure. For example, Hellas is surrounded by an annulus of high-standing topography and thickened crust, which has been interpreted to be the consequence of ejecta deposits and crustal thickening during crater excavation and collapse⁹⁻¹¹ (Extended Data Fig. 1). Several outcrops in Terra Cimmeria and Terra Sirenum are interpreted as a veneer of Hellas ejecta over older crust—roughly four crater radii away from the centre of the basin¹². Investigations of lunar gravity and topography, coupled with hydrocode impact simulations, have suggested that the Moon's hemispheric dichotomy (where the farside crust is about twice as thick as the nearside crust) may be partially explained by the deposition of a thick

ejecta blanket around the giant South Pole–Aitken impact basin^{13,14}. Extrapolating these results to Mars, it appears necessary to determine the contribution of large impact basins to its present crustal structure.

There are many methods for isolating, characterizing, and removing the contribution of impact basins and volcanoes from the gravity field and topography of planets—each with varying degrees of complexity^{1,6,15,16}. In this work we develop a method for removing these features using crustal thickness maps^{17,18} (Fig. 1c–d). These maps—which are derived from topography and gravity data (Methods)—can be used for reconstruction of the early crustal structure with conservation of mass arguments. The present crustal thickness model (Model B, ref. 18) accounts for higher crustal densities in volcanic complexes (2900 kg/m³), lower crustal densities elsewhere (2582 kg/m³) and a mantle density of 3500 kg/m³. To simplify calculations, the crustal thickness was rescaled at every location to the same crustal density (i.e., we increase (decrease) the crustal thickness in regions of high (low) density until the crustal density is globally uniform). This lets us use crustal mass and crustal volume conservation interchangeably.

We assume that impacts and volcanoes modify the crustal structure symmetrically about their centres, and that impact basins reshape the crust in a manner that approximately conserves crustal mass. Figure 2 shows an example of our fitting process for the Hellas basin. To remove the feature of interest, we first calculate the azimuthally-averaged crustal thickness as a function of distance from the centre of the feature (Fig. 2a). Next, we define an annulus outside of the feature (the “transition zone” Fig. 2a-b), which we take to represent the background crustal thickness. We calculate the mean crustal thickness in the transition zone, and then calculate the mass of crustal material above and below that datum within the “fitting zone.” If the mass above the datum (the mass excess) equals the mass below the datum (the mass deficit), then we deem

the background crustal thickness to be a mass-conserving solution. We include a cosine-taper to prevent discontinuities in the corrected crustal thickness map. For each feature of interest, we performed a parameter space search for mass-conserving crustal structure corrections—testing a range of possible transition zone radii and widths (Extended Data Figure 3). In cases where multiple mass-conserving solutions are found, we select the solution that makes the smallest change to the crustal structure. In cases where no mass-conserving solution is found, we select the solution that comes closest to conserving mass. While the formation of impact basins should conserve crustal mass, the same cannot be assumed for large volcanic edifices (as the erupted mass may be derived from the mantle and not the crust). Thus, for removing volcanoes, we prescribe a nominal angular radius of the feature based on the slope break at its edge that is identified on the azimuthally-averaged crustal thickness profiles. We then remove the crustal mass above the background, defined from an average value in an annulus surrounding the volcanic province (Extended Data Figure 4).

Using this technique, we sequentially isolated and removed the axisymmetric crustal thickness structures associated with the four largest impact basins (Hellas (Fig. 2), Argyre, Isidis, Utopia), Elysium Mons, and the Tharsis rise plus the five largest individual volcanoes: Olympus Mons, Arsia Mons, Pavonis Mons, Ascraeus Mons, Alba Patera. This method is iterative and nonlinear. That is, starting with the present crustal thickness of Mars, we remove one feature, and then use that iterated crustal thickness as the starting point for removing the next feature, and so on (Extended Data Fig. 5). This means that the resulting corrected crustal structure depends *a priori* on the order in which we remove features, though the effect of the order is minimal if the features are distant enough from each other, which is the case here. To evaluate this dependence, we repeated this analysis using randomized removal sequences. We find that the solution is only weakly dependent on the order of removal (Methods). With this precaution taken, our nominal

solution uses a removal sequence based on our current knowledge of the relative chronology of basins and volcanoes⁸, from youngest to oldest: Elysium, Olympus and Tharsis Montes, Tharsis rise, Argyre, Isidis, Hellas and Utopia.

Removing impact basins and volcanic constructs reveals more subdued crustal thickness variations (Fig. 1e–f, Fig. 3). The hemispheric dichotomy persists in the reconstruction. Hellas contributes to the southern highlands, but excavation of the basin and emplacement of ejecta are unable to explain the entire dichotomy; the mass excess in the southern highlands is about four times larger than the mass deficit within the Hellas basin.

However, after removing all the large impact basins and volcanic features, the crustal thickness map highlights a crustal block characterized by discontinuous, thick (>50 km) regions corresponding to Terra Cimmeria–Sirenum (Fig. 1e and 1f). We delineated the boundary of this block such that it includes all the neighboring >50 km thick crustal segments (Extended figure 6). We excluded the Thaumasia region, even though it has comparable thickness, because it may have a different tectonic (orogenic) history¹⁹. The relation between the most eastern part of Terra Cimmeria–Sirenum crustal block and Thaumasia is unclear (Fig. 1e and 1f).

The distribution of crustal thicknesses suggests that the early Martian crust can be divided into three main crustal domains having characteristic thickness ranges which partially overlap (Fig. 3b): (1) the northern lowlands with a thickness between 20 and 38 km (centered at 33 km), (2) the southern highlands—including Arabia Terra, Hellas, and Argyre—with an intermediate thickness between 30 and 55 km (centered at 46 km), and (3) the Terra Cimmeria–Sirenum block with a thickness between 42 and 60 km (centered at 50 km).

The Cimmeria–Sirenum crustal block is also noticeable because it shares many of the characteristics of terrestrial continental crust. On Earth, continental crust is derived via differentiation and re-melting of pre-existing basaltic crust. It possesses an intermediate composition between felsic and mafic, is enriched in incompatible elements, and is associated with thicker crust and elevated topography. Terra Cimmeria–Sirenum region is associated with anomalously elevated pre-Tharsis topography²⁰ (Extended Data Fig. 7) and includes the strongest crustal magnetic anomalies^{21–24} (Fig. 4a), which, by comparison with the Earth, could correspond to the accretion of terranes²⁵. Terra Cimmeria–Sirenum is also associated with some of the highest surface (down to the first meter) abundances of potassium (K) and thorium (Th) (Fig. 4b–c)²⁶. This region is the only place in the southern terrains where K and Th are correlated. Within this region, lower concentrations of K and Th are noted in the region near the south pole, where ground ice may mask the true (ice-free) K and Th²⁶. Only the most eastern part of the crustal block (~10% of its surface area) is not associated with these geochemical and magnetic anomalies. Possible fragments of continental crust have been found with in-situ observations by the Curiosity rover at Gale crater²⁷ on the northern edge of the Cimmeria–Sirenum block (Fig. 1a). While this interpretation appears inconsistent with the vast amount of spectroscopic observations suggesting that the surface of this region is dominated by basaltic rock²⁸, it is plausible that these basalts are surficial deposits overlying a geochemically distinct crust. This would explain why exposed continental components are rare in the southern hemisphere²⁹.

The existence of (at least) one crustal block on Mars makes the pre-Noachian geologic history of Mars—and the origin of the hemispheric dichotomy—much more complex than previously recognized. While continental crust-like material on Mars has been identified in specific outcrops³⁰, or inferred from meteoritic samples containing zircons^{27,31,32}, this study clearly identifies a regional-scale crustal block, covering 10% of Mars, with geophysical and

geochemical affinities with the terrestrial continental crust. Since this terrain is overprinted by Hellas and Argyre basins, it is likely the oldest part of the crust. Subsequent large impacts significantly altered Mars's crustal structure and contributed to the observed hemispheric dichotomy. Therefore, the southern highlands should not be considered as a single, homogeneous unit (requiring a single formation mechanism), but rather a collection of crustal blocks with plausibly different origins, variably affected by magmatic, tectonic and impact processes. The formation mechanism of several crustal blocks during the pre-Noachian (before 4.1 Ga) remains to be deciphered and has important implications for the planet's evolution, including its climate, the surface environment and the mantle dynamics.

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Author Contributions: S.B first identified the anomalous crustal structure of Cimmeria–Sirenum. S.B. and D.B. developed the hypothesis and its implications, guided the research effort. J.T.K. created and executed the crustal thickness correction method and created all figures. The manuscript was collectively written by J.T.K., S.B. and D.B. (in order of the importance of the contribution). I.M. performed preliminary calculations of Mars without Tharsis. B.L. provided the Martian magnetic field model. All authors provided input on the manuscript and the broader implications of this work.

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Figures:

Figure 1 | Global view of the crustal structure of Mars. **a–b**, MOLA topography of Mars with features of interest labelled⁹. **c–d**, crustal thickness of Mars based on crustal model B (ref. 18, Methods). **e–f**, the crustal thickness of Mars after removing all the large impact basins and volcanic features. The Cimmeria–Sirenum crustal block is enclosed by a dash-dot line. The question mark to the east of the block indicates the unclear boundary between the Thaumasia region and the Cimmeria-Sirenum block due to the possible specific origin of Thaumasia¹⁹. Maps are in Lambert azimuthal equal-area projection, centred on 0°E (left column) and 180°E (right column). Each map covers all of Mars except for a small region antipodal to the map centre. Maps are draped over present-day topography for reference. Grid lines are in increments of 30° of latitude and longitude.

Figure 2 | The radial crustal structure of Hellas Planitia. **a**, the azimuthally-average crustal thickness about Hellas (solid black line with hatching beneath). We calculate the mean crustal thickness in the transition zone, and then calculate the mass of crustal material above and below that datum within the “fitting zone.” The mass above the mass-conserving crustal thickness (the mass excess, red) integrated in an annulus around the feature is equal to the mass below it (the mass deficit, blue). The peak at 180° distance is Alba patera, which is approximately antipodal to Hellas. **b**, fitting and transition zone filters used in this reconstruction (Methods).

Figure 3 | Histograms of crustal thickness of three domains (Northern Lowlands, Southern Highlands, Cimmeria–Sirenum) of the Martian crust. **a**. Mars present crustal thickness. **b**. Mars’s crustal thickness without volcanoes and impact basins. Note that the contribution of Tharsis and Elysium is isolated to the northern lowlands to visualize the residual contribution

after removal. The black histograms show the global distribution of crustal thickness; when summed together, those coloured histograms equal the global histogram. Horizontal error-bars indicate the mean and standard deviation for each respective distribution.

Figure 4 | The geophysical and geochemical signature of the Cimmeria–Sirenum block. **a**, magnetic field intensity, evaluated at the surface of Mars²⁴. **b**, Potassium concentration (wt%)²⁶. **c**, Thorium concentration (ppm)²⁶. In both **b** and **c**, the northern hemisphere is hatched out to focus attention on the signatures south of the dichotomy. Maps are in Lambert azimuthal equal-area projection, centred on 0°E, and cover all of Mars except for a small region on the opposite hemisphere. Maps are draped over present-day topography for reference.

Methods: 2043 words, 7 figures and 7 references

Crustal thickness models. The combination of gravity and topography provide unique insight into the interior structure of planetary bodies—including their crustal thickness³³. Unfortunately, models of crustal thickness are inherently non-unique due to the degeneracy involved in inverting planetary gravity fields. Crustal thickness models require assumptions about the spectral characteristics of the crust-mantle interface, density of the crust and mantle (including lateral and vertical variations thereof), minimum crustal thickness, etc. To mitigate some of these degeneracies, we consider two different, published crustal thickness models: Model A (ref. 17) assumes a globally constant crustal density (2900 kg/m³) and Model B (ref. 18) assumes a higher crustal density in volcanic complexes (2900 kg/m³) and a lower crustal density elsewhere (2582 kg/m³). Goossens et al.¹⁸ also considered a model with laterally varying crustal density constrained by short-wavelength gravity data (Model C), although we did not use this model because these crustal densities are poorly constrained—particularly in the southern hemisphere

and Cimmeria–Sirenum in particular. For both models we find arrive at the same conclusion: the Cimmeria–Sirenum region is anomalously thick. Throughout this manuscript, we use Model B, unless otherwise stated.

Removing the contribution of impact basins with conservation of mass. We assume that impact basins reshaped the crustal structure of Mars in a way that approximately conserved crustal mass. Here we describe the method by which we reconstruct Mars’s early crustal structure using conservation of mass.

The first step in this process is translating crustal thickness maps into data products that more directly enable us to test mass-conservation. For Model A, the crustal density is the same everywhere, meaning that we can consider mass conservation by merely conserving crustal volume (i.e., crustal thickness $\times$ surface area). However, the same is not true for Model B, because this model has spatially varying crustal density. We accommodate this by rescaling the crustal thickness to the same crustal density (2582 kg/m³) everywhere. This scaling preserves crustal mass, and slightly increases the crustal thickness in regions with higher crustal density, i.e., volcanoes. Since we do not force mass conservation in volcanoes, this has a negligible effect on the crustal reconstruction. We only detail this here for completeness.

For each feature of interest, we calculate the azimuthally-averaged crustal thickness profile, $H(\gamma)$, as a function of radial distance from the centre of the feature, γ . This is achieved by interpolating the gridded crustal thickness models at a distance from the centre of the feature, γ , for all azimuths (0°–360°) and taking the mean (e.g. Extended Data Fig. 1–2).

Determining if a crustal thickness profile conserves mass requires an assumption about (1) the size of the region over which we expect mass to be conserved, and (2) what the background (pre-impact) crustal thickness is. To avoid making arbitrary choices, we perform a parameter space search for each feature of interest to determine the best mass-conserving

structure. For each feature, we construct two related filters: one describing the “fitting zone” where we expect mass to be conserved, and one describing an annulus around the fitting zone which we expect to represent the background crustal thickness (the “transition zone”; Fig. 2). The fitting zone filter, $f(\gamma)$, is defined as 1 within the fitting zone ($\gamma \leq a$), tapering by a cosine-taper to 0 by the outer edge of the transition zone ($\gamma = b$). The transition zone filter, $g(\gamma)$, is defined as 0 within the fitting zone ($\gamma \leq a$), tapering by a cosine-taper to 1 by the outer edge of the transition zone ($\gamma = b$), and then defined as 0 beyond the transition zone ($\gamma > b$). In the transition zone, $g(\gamma) = 1 - f(\gamma)$. The use of a cosine-taper results in a smoother fit and prevents sharp discontinuities in the resulting corrected crustal thickness maps.

We calculate the background crustal thickness, H_0 , by taking the mean of the crustal thickness in the transition zone, weighted by the transition zone filter, $g(\gamma)$, and the surface area in that annulus, $S(\gamma)$:

$$H_0 = \frac{\sum H(\gamma) S(\gamma) g(\gamma)}{\sum S(\gamma) g(\gamma)}$$

where $S(\gamma)$ is defined as:

$$S(\gamma) = 2\pi R^2 [\cos(\gamma - \delta\gamma) - \cos(\gamma + \delta\gamma)]$$

and R is the radius of Mars (3396 km), and $\delta\gamma$ is one half of the step-size between successive radial distances, γ .

Next, we can apply the background crustal thickness, H_0 , to the fitting zone and determine if mass is conserved within that region. We calculate the mass anomaly, $M(\gamma)$:

$$M(\gamma) = S(\gamma)[H(\gamma) f(\gamma) - H_0 f(\gamma)]$$

where $M(\gamma)$ is positive if the crustal thickness in a given annulus is above H_0 , and $M(\gamma)$ is negative if crustal thickness in a given annulus is below H_0 . By summing all positive mass anomalies, we can calculate the total mass excess, $M^+ = \sum M(\text{if } M > 0)$, and we similarly calculate the total mass deficit by summing all negative mass anomalies, $M^- = \sum M(\text{if } M < 0)$. Mass is

conserved if $M^+ = |M^-|$. We define the mass balance as the ratio of mass excess to mass deficit, $B = |M^+ / M^-|$. If $B=1$, then mass is conserved.

We repeat the process above for a range of possible fitting zone and transition zone sizes, and calculate the mass balance for each case. Extended Data Fig. 3 shows an example output of this parameter space search. Mass-conserving solutions are identified by having mass balances equal to 1. For most features, there are multiple mass-conserving solutions—often highlighting correlations between the fitting parameters. In such cases, it is necessary to further constrain the mass-conserving solutions, and ultimately pick a single solution to implement. To do this, we select the mass-conserving solution with the smallest fitting zone size, between 1–5x the feature radius, and the smallest transition zone radius, greater than 1x the feature radius. The feature radius is the radius of the impact basin in question. This criterion is aimed at requiring the smallest structural change, and partly motivated by analytic models and empirical data that suggest that impact basins tend to deposit most of their ejecta within 1 crater diameter of the basin rim³⁴. In practice, the solutions are not strongly sensitive to these constraints, and the mass-conserving solutions tend to be indistinguishable (e.g., Extended Data Figure 3b–d). In some cases, no reasonable mass-conserving solutions can be found. In these instances, we follow the same bounding constraints listed above and select the solution that come the closest to conserving mass (i.e., the solution that minimize the quantity: $M^+ - |M^-|$). While it is not immediately obvious that this method would be appropriate for scenarios where mass may not be conserved, we find that this approach tends to result in crustal thickness corrections close to what we would pick if we had selected the fitting zone and background crustal thickness by hand (as we do with volcanoes).

While more complicated crustal-correction methods exist^{1,6,15,16}, our mass-conservation approach yields the same qualitative results as many past approaches. Additionally, while it was not noted as unusual, the Cimmeria–Sirenum crustal block stands out in previous crustal

correction studies^{6,19} (Extended Data Figure 5). Cimmeria–Sirenum is the thickest region of the Martian crust that is not directly overlapped by an impact basin, basin ejecta, or substantial volcanic deposits. This observation alone (coupled with the unique geochemical and magnetic anomalies of this region) could be viewed as evidence for an ancient origin of the Cimmeria–Sirenum region, without the need for reconstructing the crustal structure of early Mars in any detailed manner.

Do impacts conserve crustal mass?

Impacts can both add material to Mars (from the impactor) and remove material from Mars (in high-speed ejecta). However, for typical impacts, the mass of material excavated and displaced is several orders-of-magnitude larger than the mass of the impactor, which in turn is generally larger than the mass ejected^{35,36}. Impacts also change the density structure of the crust; impacts often generate higher density, lower porosity impact melt sheets in the impact basin, while also depositing lower density, higher porosity ejecta blankets around the impact basin³⁷. Crustal thickness models A and B do not account for density variations in/around impact basins. These density variations likely exist, but are unresolvable in the current geophysical datasets. These variations may slightly alter the crustal reconstruction in/around impact basins.

It is plausible that impact basins do conserve mass, but not in a symmetric fashion. Our method assumes impacts are axisymmetric, yet all of the features we remove have some axisymmetric structure that is not captured in our reconstruction. For example, Hellas and Borealis are notably elliptical. There is no simple way to relate the ellipticity of the central depression to the asymmetry in the surrounding ejecta blanket and deformation—as these processes do not necessarily share the same symmetry. For example, the South Pole–Aitken basin on the Moon is notably elliptical, yet the associated ejecta deposit is not simply a larger ellipsoid surrounding it⁷. Nonetheless, we considered more complicated fitting schemes that

incorporated elliptically symmetric structures, but ultimately opted for the simpler, axisymmetric solution as it reduces the number of fitting parameters and yields qualitatively similar results.

Extended Data Fig. 4 shows the mass-balance for each of the features removed in our nominal crustal reconstruction (Fig. 1e–f). Extended Data Fig. 4c shows that our method is able to find mass-conserving solutions for most impact structures, with one specific exception: Utopia Planitia. Utopia Planitia is a large mass deficit (mass deficit > 100-times the mass excess). This mass-imbalance is far larger than we anticipate for most impact basins, and is discussed in the next section.

Utopia. Our mass-conservation methodology identified mass-conserving crustal thickness profiles for every impact basin—except Utopia Planitia. Utopia is unique amongst the Martian impact basins in that it is a prominent topographic basin and region of thinned crust, but lacks a significant annulus of excess crustal material around it (Extended Data Fig. 2). There is a small topographic and crustal ring around the basin ($\sim 30^\circ$ away from the centre, most visible the NW–NE), but the mass excess in this ring is >100-times smaller than the mass deficit within the basin. It is not clear why Utopia shows such a significant mass imbalance. One possible explanation is that the crustal density in this region is significantly different than expected in the standard crustal thickness models (Models A and B). If the crustal density in the basin or the surrounding annulus were different, it might result in a mass-conserving solution. In fact, our method produces a mass-conserving solution for Utopia when using spatially-varying crustal thickness model of ref. 18 (Model C; although for reasons described above, we are not inclined to use this model for the global crustal structure of Mars). Alternatively, Utopia may be significantly modified by the substantial sedimentary layer that overlays it. It is conceivable that the deposition and erosion of this material affected the crustal structure in some non-axisymmetric way. Regardless, detailed study of the Utopia basin is left for future study.

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448 **Borealis and the hemispheric dichotomy.** In this work, we focused on removing the crustal
449 signature of the four largest, unequivocal impact basins (Hellas, Argyre, Utopia, and Isidis).
450 However, some researchers have suggested that the geometry and geophysical structure of the
451 northern lowlands may be the diagnostic signature of one or more giant impact basins ^{2,3,6,38,39}.
452 The existence of a “Borealis” impact basin is still debated, so we did not include it in our
453 primary analysis. Nonetheless, we did experiment with adding Borealis into our reconstruction,
454 and we discuss those results here.

455 Extended Data Fig. 5 shows what happens when we take our nominal model (Fig. 1e–f),
456 and use our mass-conservation technique to remove Borealis. Since Borealis is truly global, we
457 had to augment our mass-conservation approach. Rather than exploring a parameter space of
458 fitting/transition zones (as discussed above), we simply calculated the crustal thickness at which
459 the crustal mass excess above that datum equalled the crustal mass deficit beneath it (using the
460 Fig. 1e–f as the initial condition; Extended Data Fig. 5). Phrased a different way, we found the
461 solution where the crustal mass deficit in the northern lowlands is roughly equal to the crustal
462 mass excess in the southern highlands. Removing the contribution of impact basins, volcanoes,
463 and Borealis reveals an extremely subdued crustal structure for Mars, with no hemispheric
464 dichotomy (Extended Data Fig. 5). Nonetheless, the Cimmeria–Sirenum region remains an
465 anomalous region of enhanced crustal thickness. Thus, regardless of the veracity of the Borealis
466 impact hypothesis, the Cimmeria–Sirenum crustal block is geophysically distinct.

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Extended Data Figures:

Extended Data Figure 1 | Topography and crustal structure around Hellas Planitia. **a**, MOLA topography of Mars (ref. 9). **b**, crustal thickness of Mars based on crustal model B (ref. 17, Methods). In **a–b**, the maps are in Lambert azimuthal equal-area projection, centred on Hellas Planitia. Each map covers all of Mars except for a small region antipodal to the map centre. Maps are draped over present-day topography for reference. **c**, radial profiles of surface and mantle topography measured from the centre of Hellas. **d**, radial profiles of crustal thickness. In **c–d**, each coloured line represented a different radial profile, coloured by the azimuth of that profile. The white lines are the mean of the surface and mantle topography profiles.

Extended Data Figure 2 | Topography and crustal structure around Utopia Planitia. **a**, MOLA topography of Mars (ref. 9). **b**, crustal thickness of Mars (ref. 17). In **a–b**, the maps are in Lambert azimuthal equal-area projection, centred on Utopia Planitia. Each map covers all of Mars except for a small region antipodal to the map centre. Maps are draped over present-day topography for reference. **c**, radial profiles of surface and mantle topography measured from the centre of Utopia. **d**, radial profiles of crustal thickness. In **c–d**, each coloured line represented a different radial profile, coloured by the azimuth of that profile. The white lines are the mean of the surface and mantle topography profiles.

Extended Data Figure 3 | The parameter space for finding the mass-conserving crustal structure for Hellas Planitia. **a**, the fitting parameter space. Colour and contours show how well each tested model conserves mass: reds are models dominated by mass excesses, blues are models dominated by mass deficits, and green are models where mass is approximately conserved. Contour levels are indicated by tick marks in the colour bar. The yellow dash-dot region indicates the confining region where we look for the best mass-conserving solutions that

are plausibly the result of Hellas. **b–h**, example solutions from the parameter space (marked with an “x” in panel a). Symbols and lines are the same as in Fig. 2, and are labelled in panel c. In this example model run, panel c is the best-fitting model.

Extended Data Figure 4 | Mass balance for each feature of interest removed in our crustal reconstruction. **a**, mass excess (red) and mass deficit (blue) for each feature of interest. **b**, the total mass excess (mass excess + mass deficit) for each feature of interest. Mass-conserving structures have a total mass excess of zero. **c**, the ratio between mass excess and mass deficit. Mass-conserving structures have a ratio of one.

Extended Data Figure 5 | Crustal thickness map and simplified radial profile after the removal of each feature. **a**, Mars today. **b**, removing Elysium Mons. **c**, removing Olympus Mons. **d**, removing Pavonis Mons. **e**, removing Arsia Mons. **f**, removing Ascraeus Mons. **g**, removing Alba Patera. **h**, removing central Tharsis. **i**, removing Tharsis rise. **j**, removing Argyre. **k**, removing Isidis. **l**, removing Hellas. **m**, removing Utopia. **n**, removing Borealis. On simplified radial profiles, the mass excess is in red and the mass deficit in blue.

Extended Data Figure 6 | Boundary of the Cimmeria-Sirenum block with >50 km thick crustal regions indicated in green (c–d). The question mark to the east of the block indicates the unclear boundary between the Thaumasia region and the Cimmeria-Sirenum block due to the possible different origin of Thaumasia¹⁹.

Extended Data Figure 7 | Topography before Tharsis. **a–b**, MOLA topography of Mars (ref. 9), with the Cimmeria–Sirenum region outlined. **c–d**, topographic model of Tharsis, and the rotational deformation arising from TPW due to the formation of Tharsis (ref. 20). **e–f**,

536 topography of Mars without the effects of Tharsis. Panel e is equal to panel a minus panel c;
537 panel f is equal to panel b minus panel d. The Cimmeria–Sirenum region has anomalously high
538 topography in this corrected map. This early work hinted at the unusual nature of this terrain.
539 Maps are in Lambert azimuthal equal-area projection, centred on 0°E (left column) and 180°E
540 (right column). Each map covers all of Mars except for a small region antipodal to the map
541 centre. Maps are draped over present-day topography for reference. Grid lines are in increments
542 of 30° of latitude and longitude.
543