Letters

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ボレアレス盆地と火星の地殻の二分性の起源

The Borealis basin and the origin of the martian crustal dichotomy p1212

Jeffrey C. Andrews-Hanna, Maria T. Zuber & W. Bruce Banerdt

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日本語要約 | **Full Text** | PDF (641K) | Supplementary information

#2

火星の半球間での二分性を生じた超巨大衝突

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Margarita M. Marinova, Oded Aharonson & Erik Asphaug

doi:10.1038/nature07070

日本語要約 | **Full Text** | PDF (1,429K) | Supplementary information

#3

火星の半球二分性は衝突起源であると考えられる

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F. Nimmo, S. D. Hart, D. G. Korycansky & C. B. Agnor

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PLANETARY SCIENCE

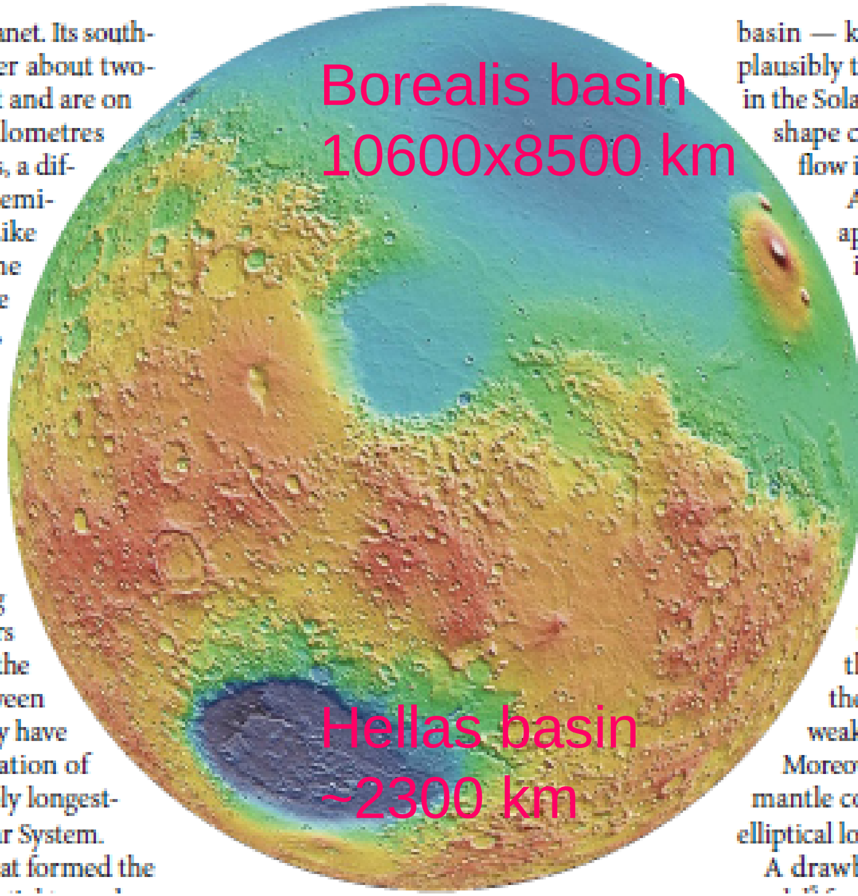
Forming the martian great divide

Walter S. Kiefer

Early in its history, Mars suffered a convulsion that left a lasting geological and topographical scar. The latest work adds to evidence that the cause was external — a massive impact.

Mars is a divided planet. Its southern highlands cover about two-thirds of the planet and are on average about 4 kilometres higher than the northern plains, a difference that is known as the hemispheric dichotomy[1] (Fig. 1). Like an ice cube floating in water, the high topography is held up by the buoyancy of thicker crust (Fig. 2, overleaf) — the crust is about 25 km thicker in the highlands than in the lowlands[2]. On the basis of the number of impact craters in both the highlands and lowlands, the dichotomy is thought to have formed more than 4 billion years ago, during the first few hundred million years of martian history[3]. Moreover, the location of the boundary between the highlands and lowlands may have controlled the subsequent location of Tharsis[4], the largest and possibly longest-lived volcanic region in the Solar System.

Unravelling the processes that formed the



NASA

basin — known as the Borealis basin — is plausibly the signature of the largest impact in the Solar System. They also argue that this shape cannot be produced by convective flow in the mantle.

A potential problem with the approach of Andrews-Hanna *et al.*[7] is its sensitivity to the thickness of elastic lithosphere. Although some independent evidence[10] supports the assumption of a thickness of 100 km or more, other observations[11] suggest that the lithosphere was less than 20 km thick during the Noachian period, about 3.8 billion years ago, when Tharsis began forming. If the lithosphere was less than 50 km thick during Tharsis formation, the elliptical shape calculated for the dichotomy lowlands is degraded[7], weakening the case for an impact model. Moreover, no calculations have shown that mantle convection is unable to produce an elliptical lowland basin.

A drawback of the original giant-impact

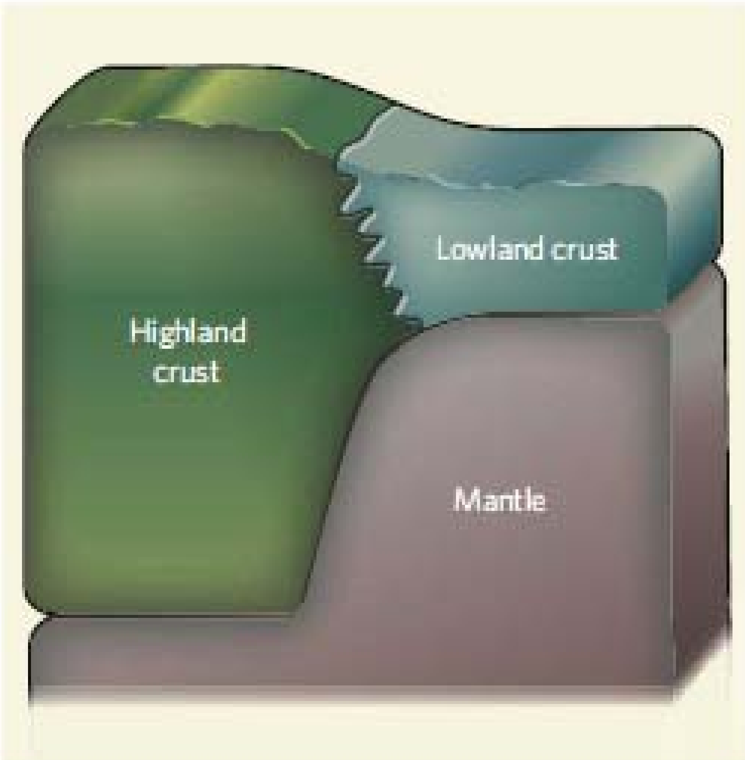


Figure 2 | Crust with a difference. The southern highlands (left) consist of relatively thick crust and high-standing topography. The northern lowlands (right) consist of thinner crust and lower topography. In the impact model for dichotomy formation, which is supported by the new work[7–9], the crust also differs in composition. According to this model, the highland crust formed early in martian history, and consists primarily of basalt rock. The lowland crust formed by shock melting of the mantle during the impact event, and so is both younger and different in composition compared with the highland crust.

Hemispheres Apart: The Crustal Dichotomy on Mars

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Key Words

geology, topography, gravity, crustal thickness, tectonics

Topographic Expression of the Dichotomy

MOLA: Mars Orbiter Laser Altimeter

MGS: Mars Global Surveyor

DEM: digital elevation model

The topography of Mars has been characterized with great accuracy by the Mars Orbiter Laser Altimeter (MOLA) on the Mars Global Surveyor (MGS) orbiter (**Figure 1, 2*a***) (Smith et al. 1998, 1999, 2001; Zuber et al. 2000). MOLA data have a maximum vertical range resolution of approximately 38 cm, a footprint of 168 m, and along-track shot spacing of 300 m (Smith et al. 1998, 2001). Although the cross-track resolution is variable, gridded and interpolated global digital elevation models (DEMs) with spatial resolutions of ~460 m/pixel and better can be generated (see Neumann et al. 2001).

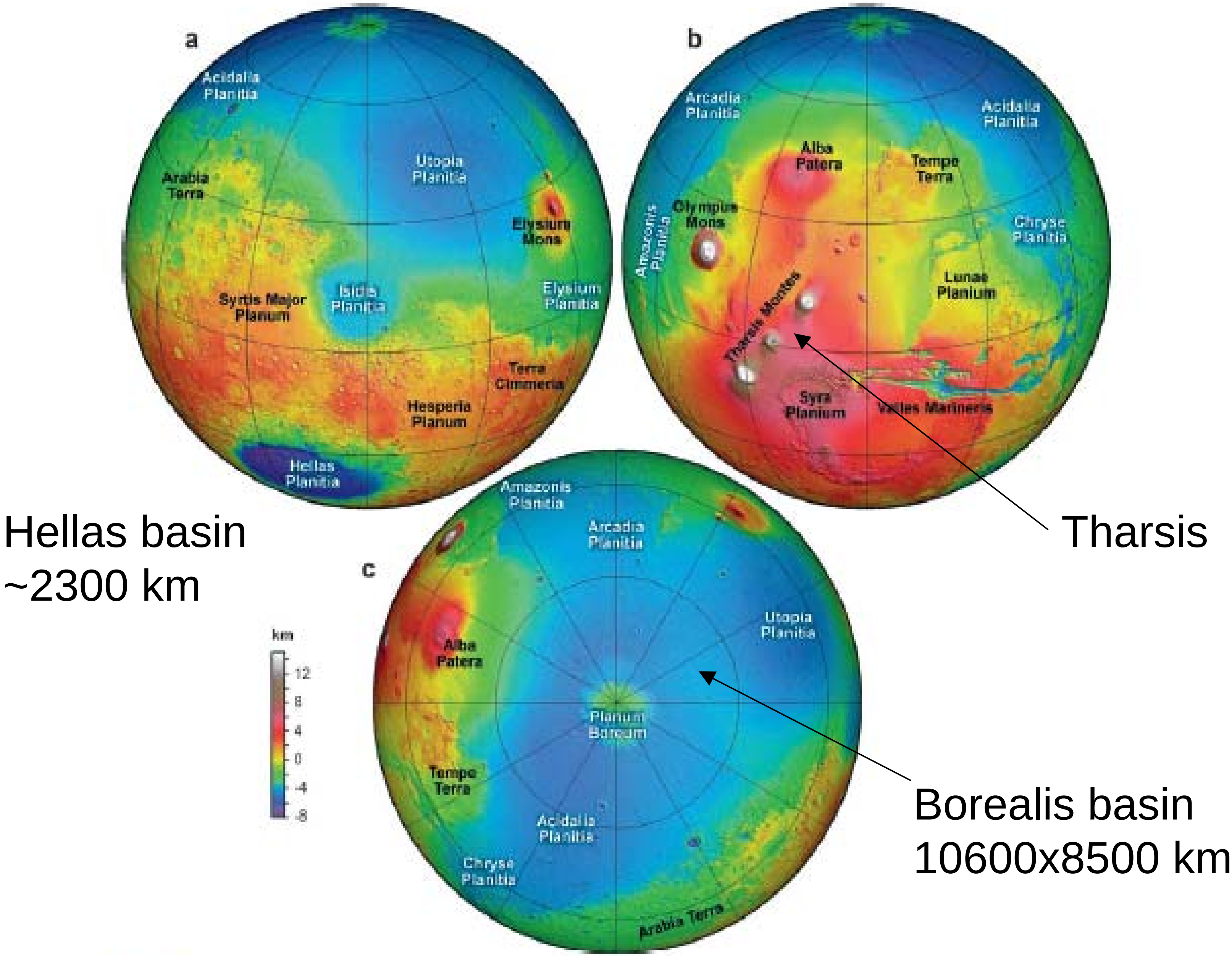

a
Acidalia Planitia
Arabia Terra
Utopia Planitia
Elysium Mons
Syrtis Major Planum
Isidis Planitia
Elysium Planitia
Terra Cimmeria
Hesperia Planum
Hellas Planitia
b
Arcadia Planitia
Acidalia Planitia
Alba Patera
Tempe Terra
Olympus Mons
Amazonis Planitia
Chryse Planitia
Lunae Planum
Tharsis Montes
Syria Planum
Valles Marineris
c
Amazonis Planitia
Arcadia Planitia
Utopia Planitia
Alba Patera
Planum Boreum
Tempe Terra
Acidalia Planitia
Chryse Planitia
Arabia Terra
km
12
8
4
0
-4
-8
Hellas basin
~2300 km
Tharsis
Borealis basin
10600x8500 km

Figure 1

Mars hemispheric dichotomy:
over 30 years question

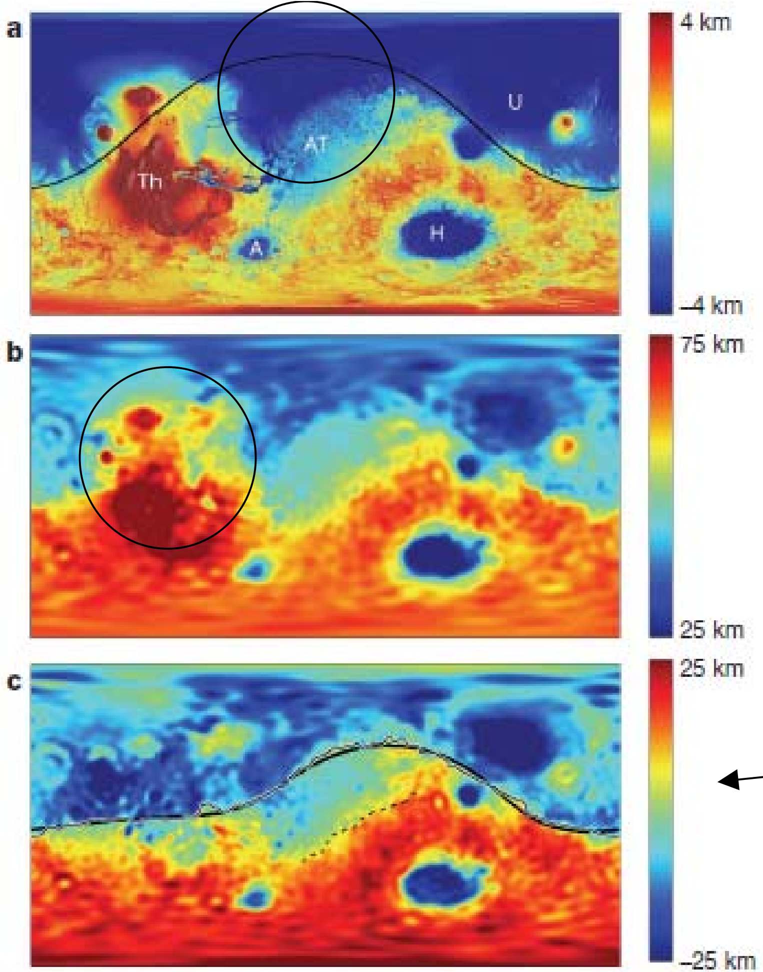
Two hypotheses:

Endogenic model by mantle convection

Vs.

Exogenic model by either one giant impact
or multiple impact.

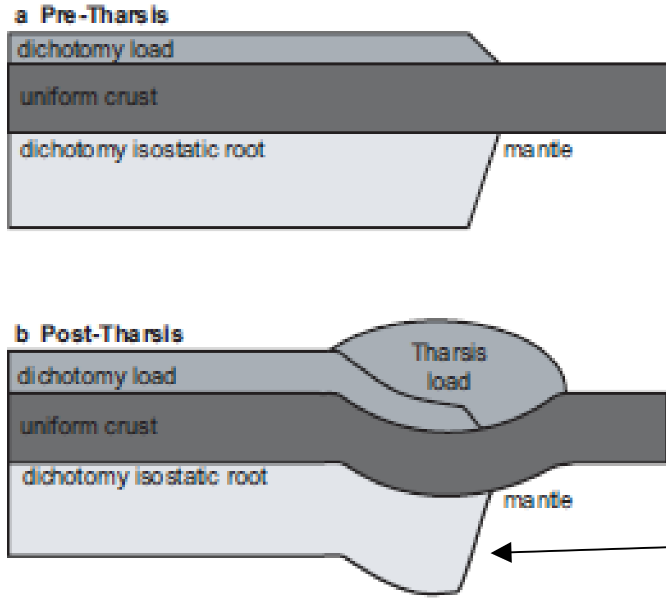
#1: MIT & Caltech,
Cite #2. Cited in #2.
reproduce dichotomy boundary under Tharsis.
Borealis basin is elliptical, suggesting giant impact origin.



Tharsis made after the impact

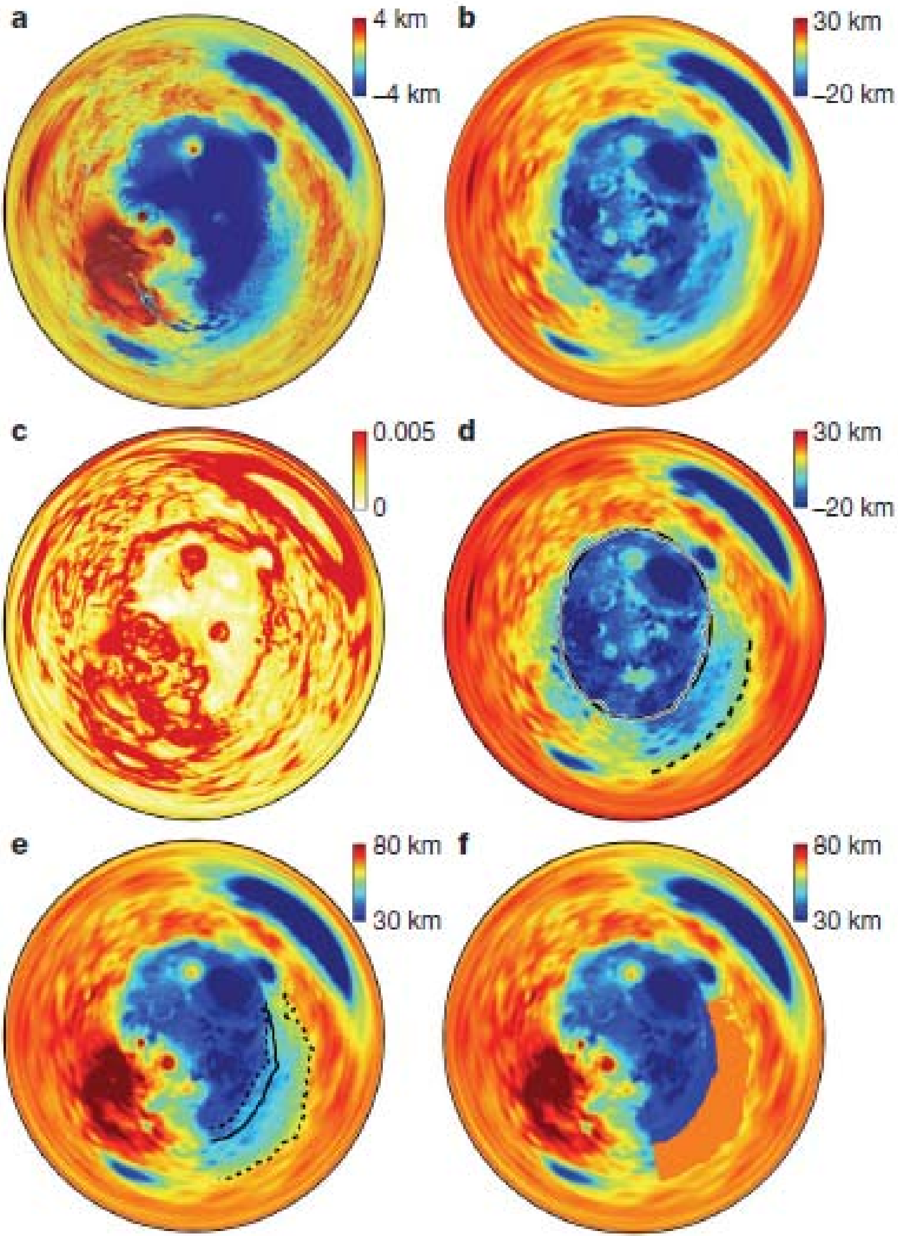
Isostatic root: They believe this.

Figure 1 | Topography and crustal structure of Mars. a, Topography[11] and **b,** crustal thickness[2] of Mars (cylindrical projection). Main features labelled in **a** include Tharsis (Th), Arabia Terra (AT), Hellas (H), Argyre (A), and Utopia (U), as well as the Borealis basin outline proposed by Wilhelms and Squyres[5] (solid line). **c,** Modelled bottom crustal thickness perturbation (isostatic root), showing continuation of the dichotomy boundary beneath Tharsis. The observed dichotomy boundary (thin line) is compared with the best-fit ellipse (bold line) in **c.** The break in slope separating Arabia Terra from the highlands is shown as a dashed line.



Reproduce this

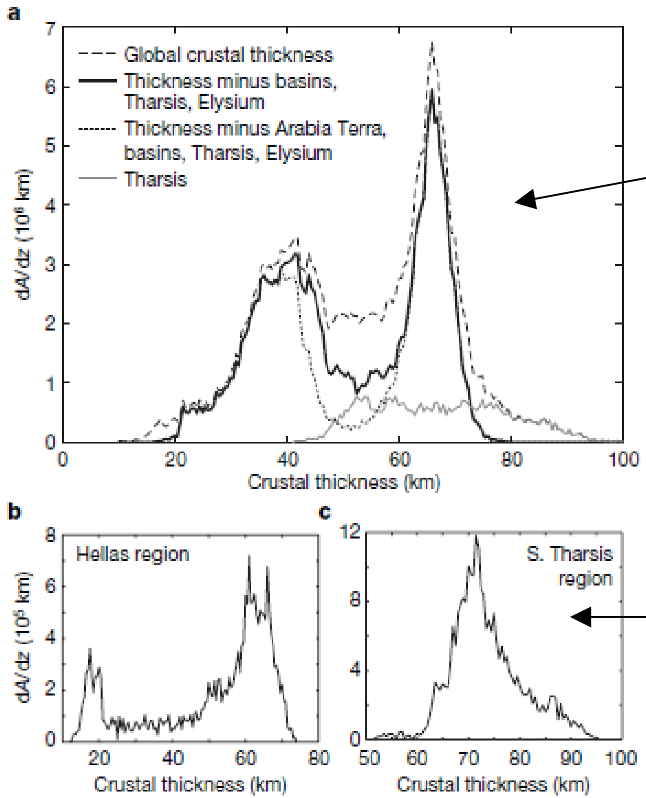
Supplementary Figure 1. Schematic representation of the crustal structure before (a) and after (b) Tharsis loading. The isostatic dichotomy is dominated by the crustal root, while Tharsis is predominantly a top load that results in a downward displacement of the crust and lithosphere. The model divides the crust into loads and isostatic roots, thereby allowing us to isolate the sub-Tharsis dichotomy boundary. The lithosphere is not explicitly labeled, but may include part or all of the crust, as well as portions of the upper mantle. The crust and lithosphere deform together during Tharsis loading.



Spherical harmonic
thin-shell model.

Elastic deformation
is accounted.

Giant impact with low-angle
Can make elliptic basin.



Bimodal suggest giant impact.

Volcanic process did not make bimordal pattern

Figure 3 | Crustal thickness histograms. **a**, Global crustal thickness histogram (dashed), after removal of the major impact basins and volcanic rises (solid), and after removal of the anomalous Arabia Terra region as well (dotted). The histogram of the Tharsis region (excluding surrounding terrains) is shown in grey. For comparison, histograms are also shown of the Hellas impact basin and surrounding highlands (**b**), and the southern portion of Tharsis and the surrounding highlands (in order to avoid the competing effects of the superimposed dichotomy boundary beneath Tharsis; **c**). Histograms are presented as total area A per unit crustal thickness z, calculated in thickness increments of 0.5 km.

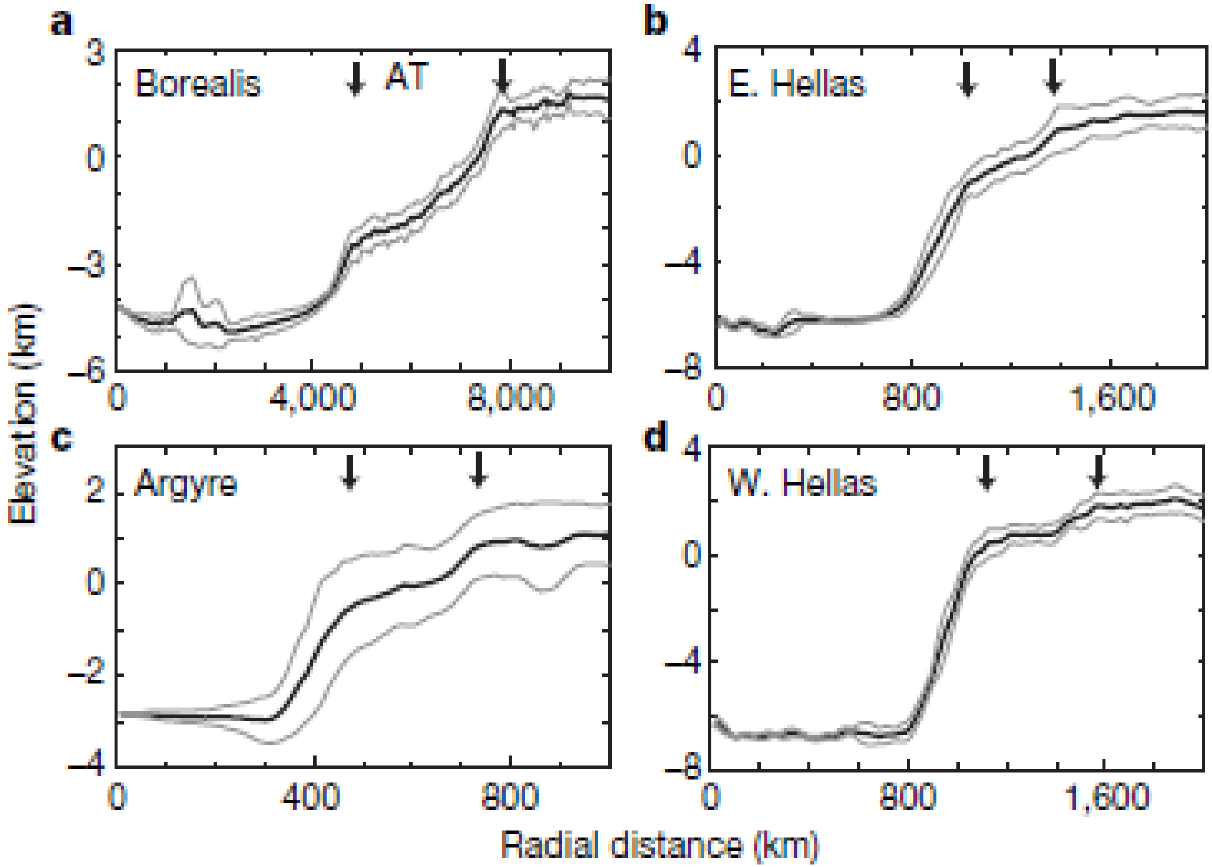


Figure 4 | Radial profiles of the Borealis (through Arabia Terra), Hellas and Argyre basins. Average profiles (black) and the 1σ variation (grey) were calculated from radial profiles at 1° increments. Borealis and Hellas were stretched in a basin-centred polar coordinate system to circularize the basins before averaging. Profiles of Hellas and Argyre avoided regions with obvious evidence of fluvial, volcanic, or subsequent impact modification (see Supplementary Fig. 6 for locations of profiles). The arrows indicate the approximate locations of the basin rim and outer ring.

#2: Caltech & UC Santa Cruz,
Cite #1. Cited in #1.

Assume single mega impact, and conduct 3D hydrodynamic simulation to constrain the nature of the impact (~3×10^{29}J, ~6km/s, ~45°).

SPH: a lagrangian method.

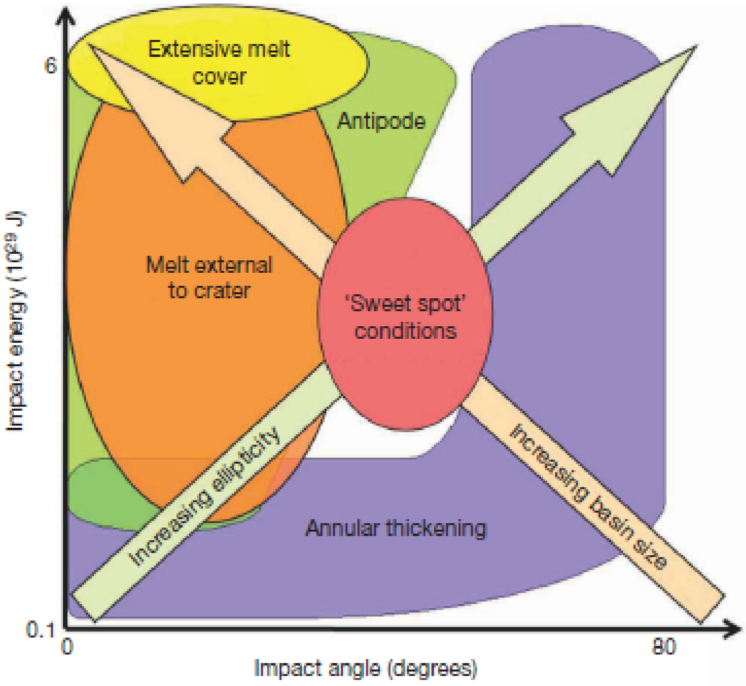


Figure 1 | Summary of simulation results. Shown are the impact characteristics resulting in extensive surface melt cover (>25% of the surface), significant melt outside the crustal excavation boundary, presence of antipodal crustal disruption, presence of a thickened annulus of crust around the crustal excavation boundary, and the directions of increase in ellipticity and basin size. The results at a given energy are averaged over impact velocity. A 'sweet spot' of impact conditions emerges for which the resulting simulation characteristics closely match the observed Mars dichotomy features[2]. A compatible hypothesis is found at an impact energy of $\sim 3 \times 10^{29}$ J, velocity $\sim 6\,\mathrm{km\,s^{-1}}$ and, importantly, an impact angle of $\sim 45°$. These parameters represent probable impact conditions in the early Solar System[3,11].

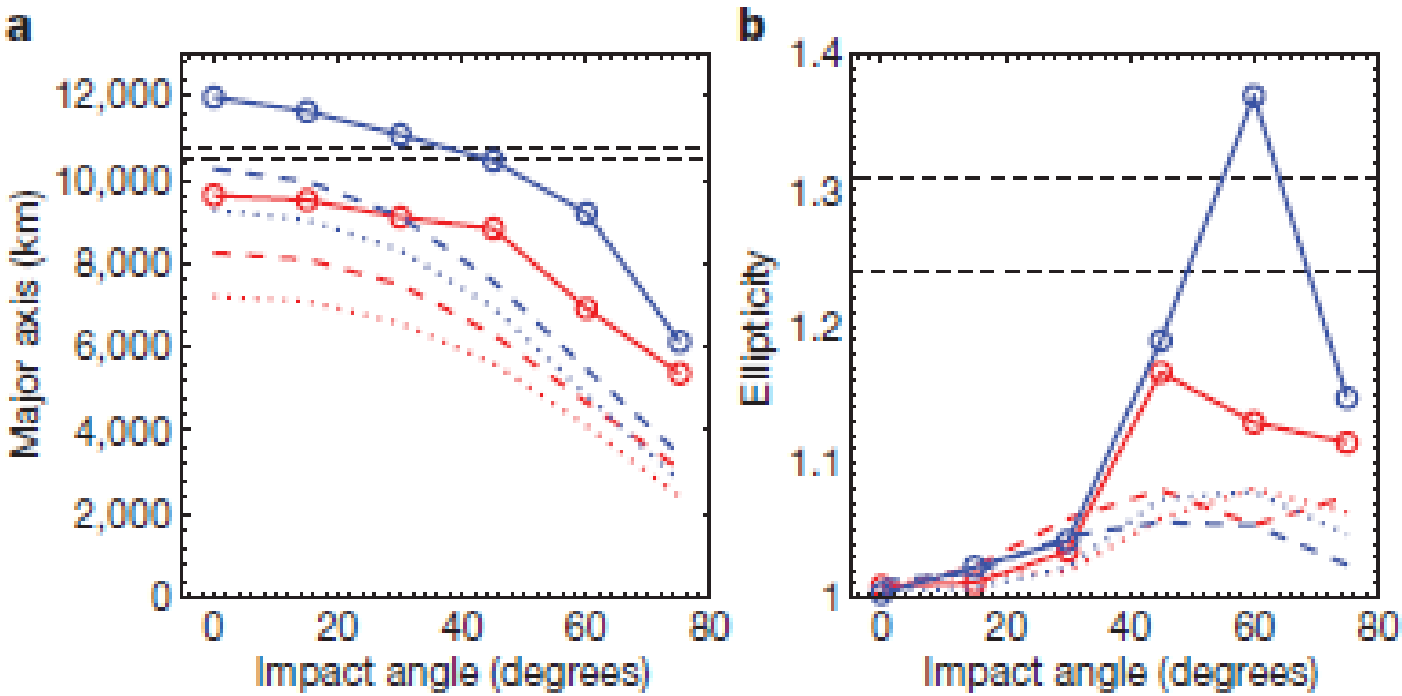


Figure 3 | Major axis and ellipticity for impact energies of 3. 1 × 10^{29} J and 5.9 × 10^{29} J (red and blue, respectively). a, Excavated cavity major axis; **b,** ellipticity. Shown are impact velocities of 6 km s^{-1} (solid line), 10 km s^{-1} (dashed line) and 50 km s^{-1} (dotted line). Major axes and ellipticities of mapped dichotomy boundary ellipse fits[2] are shown (black dashed lines), representing the range of possible boundary locations (reported uncertainty of ± 100 km). A 'sweet spot' emerges for these impact energies and at impact velocities of 6–10 km s^{-1} and impact angles of 30–60°.

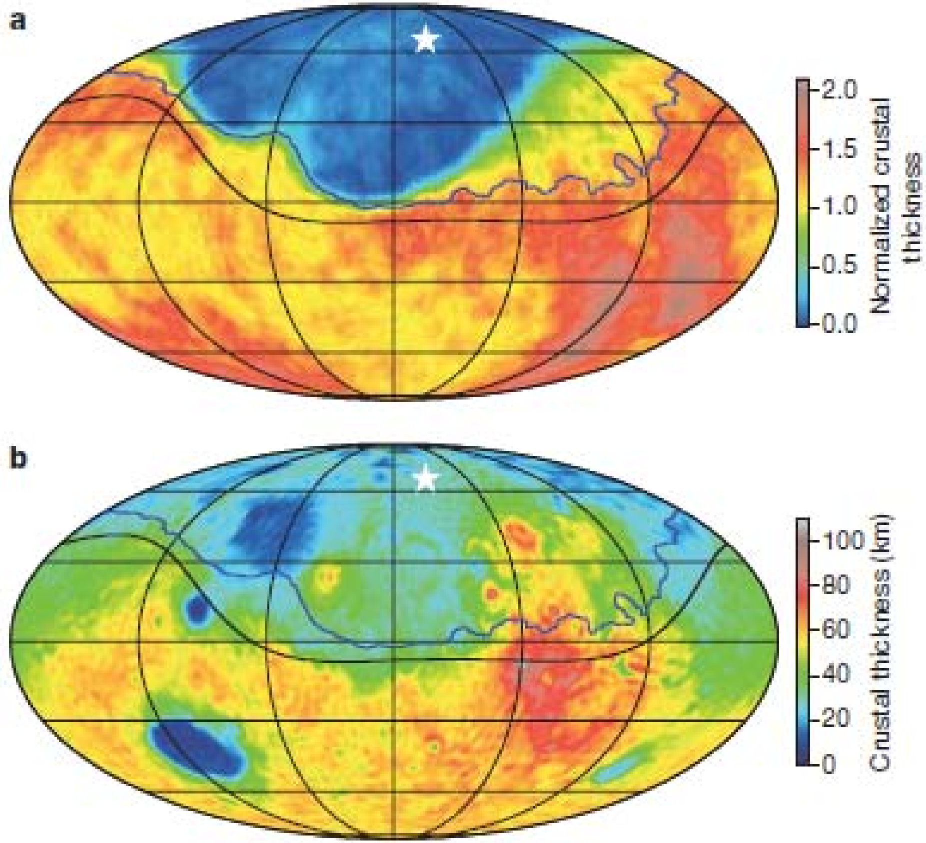
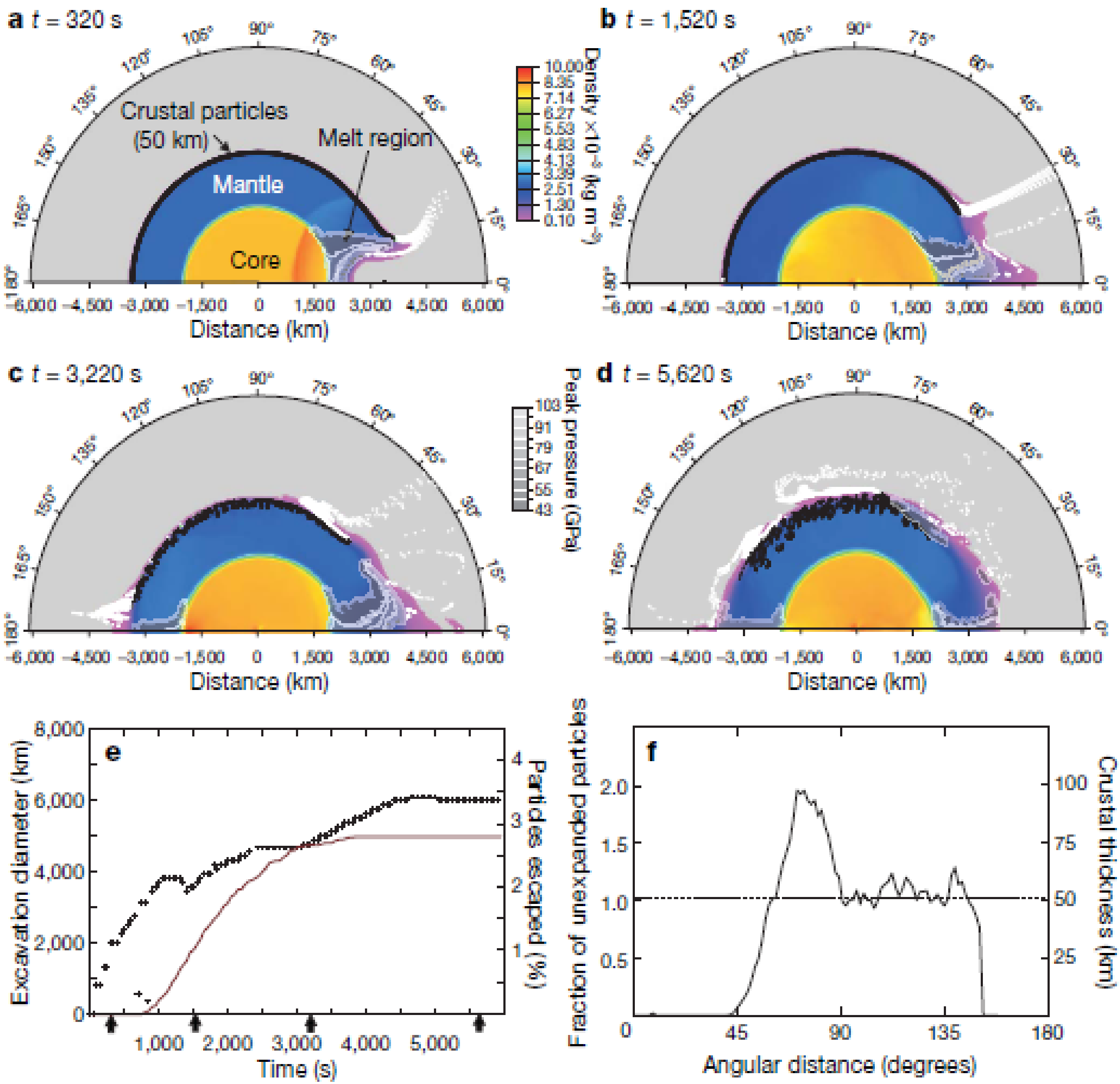


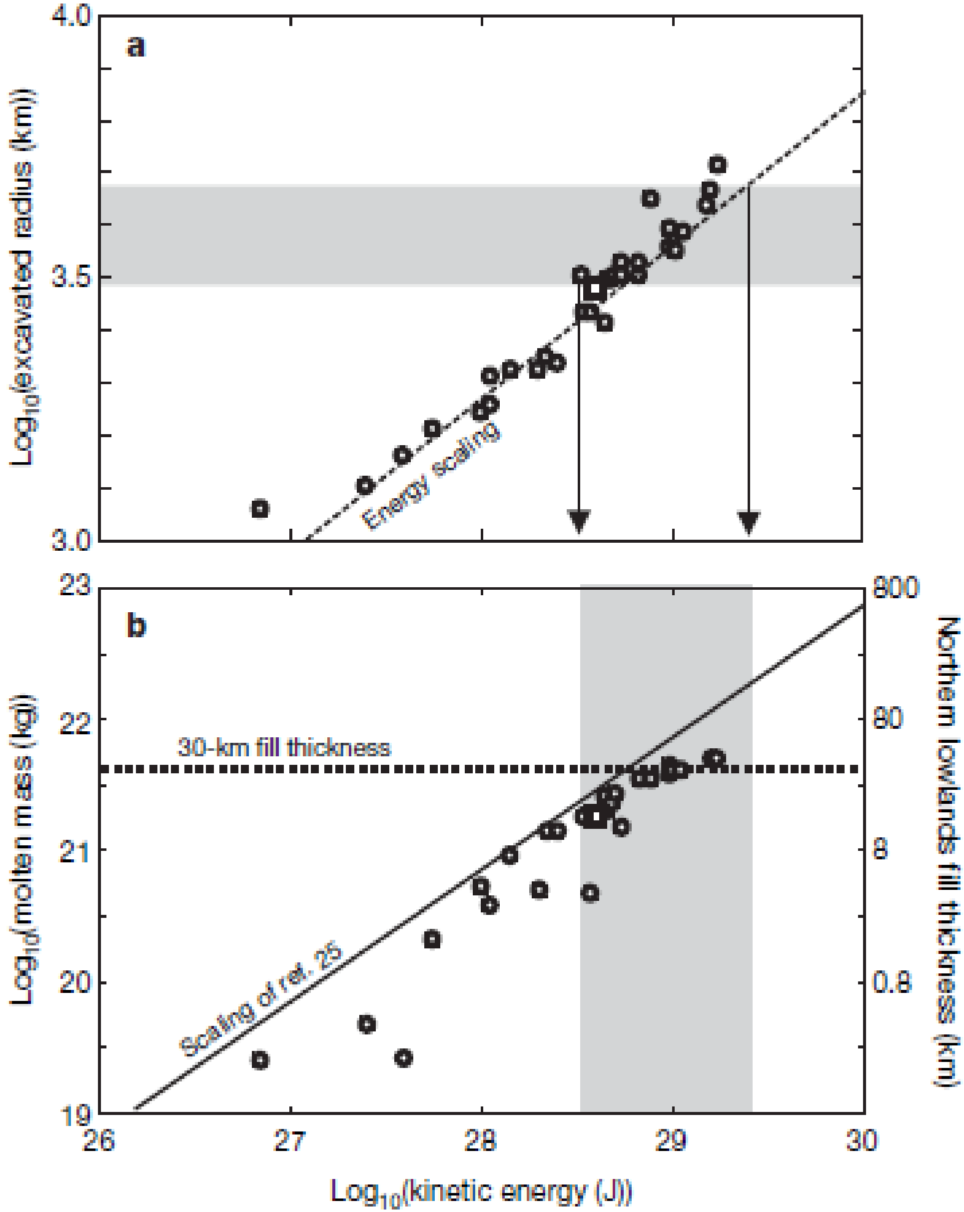
Figure 4 | A favoured impact hypothesis compared with Mars's crustal thickness. Post- to pre-impact simulation crustal thickness ratio (**a**), and model thicknesses (based on gravity and topography[10], revised by Neumann *et al.*, manuscript in preparation) (**b**). Superimposed are the Andrews-Hanna *et al.* dichotomy boundary[2] (black line) and the crustal excavation boundary from the simulation results (blue line). Impact simulation characteristics: 3.1×10^{29} J (nominal 10,000-km crater), 6 km s^{-1}, 45°, impactor diameter 2,230 km. Crustal excavation boundary centre[2] (star) shown at 66° N, 206° E. In **a**, the crustal thickness is computed at a 2° resolution and smoothed over a 10°-diameter cap area.

#3: UC Santa Cruz & U. of London, Cite #2.
High resolution 2D axially symmetric hydrocode (Zeus) to model vertical impact (not mention on ellipticity).

Impact energy: 3×10^{28}-1×10^{29} J
to make the size of dichotomy.
Similar period with the moon forming impact



a t = 320 s
b t = 1,520 s
c t = 3,220 s
d t = 5,620 s
Crustal particles (50 km)
Melt region
Mantle
Core
Distance (km)
Density ×10⁻³ (kg m⁻³)
Peak pressure (GPa)
e
Excavation diameter (km)
Particles escaped (%)
Time (s)
f
Fraction of unexpanded particles
Crustal thickness (km)
Angular distance (degrees)



a
b
4.0
3.5
3.0
Log10(excavated radius (km))
Energy scaling
23
22
21
20
19
Log10(molten mass (kg))
30-km fill thickness
Scaling of ref. 25
800
80
8
0.8
Northern lowlands fill thickness (km)
26
27
28
29
30
Log10(kinetic energy (J))

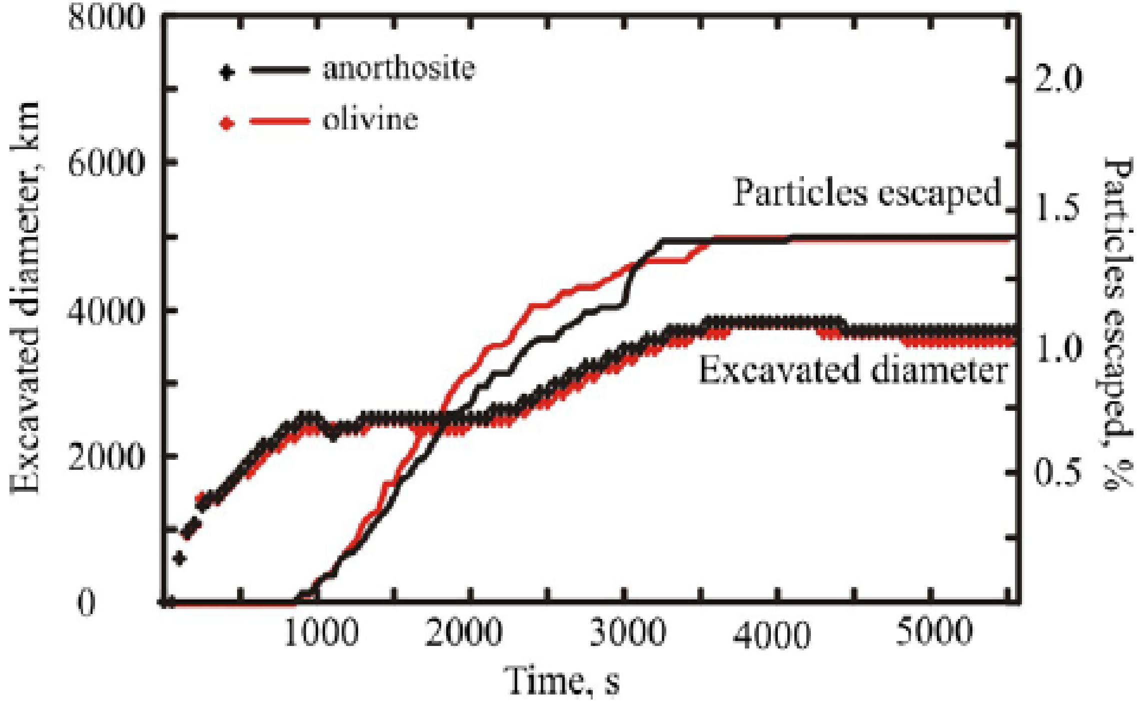


Figure S1. Comparison between Zeus results for cases using anorthosite and olivine equations of state for both impactor and mantle. Olivine equation of state from [16]. Impact velocity and radius 15 km/s and 200 km, respectively, in both cases.

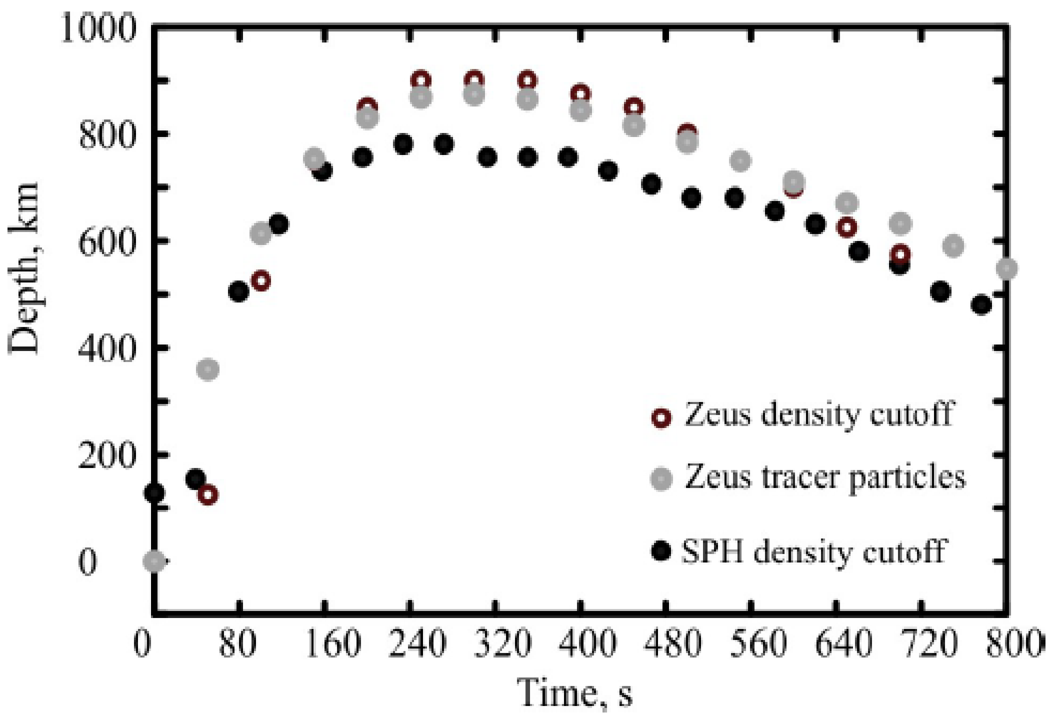


Figure S3. Comparison between transient crater depth evolution from Zeus and SPH codes. Zeus crater depth is calculated by following tracer particle immediately beneath impact point, or by tracking where the density field drops below 2 g/cc directly beneath the impact point. SPH code (*N*=30,000) uses gridded density data in x-z plane and the same density cutoff as Zeus model. Impactor has velocity 15 km/s and radius 200 km, vertical incidence angle.