Supplementary Materials for

A South Pole–Aitken impact origin of the lunar compositional asymmetry

Matt J. Jones*, Alexander J. Evans, Brandon C. Johnson, Matthew B. Weller, Jeffrey C. Andrews-Hanna, Sonia M. Tikoo, James T. Keane

*Corresponding author. Email: matthew_jones@brown.edu

Published 8 April 2022, Sci. Adv. 8, eabm8475 (2022)
DOI: 10.1126/sciadv.abm8475

The PDF file includes:

- Supplementary Text
- Tables S1 and S2
- Figs. S1 to S7
- Legends for movies S1 to S3
- References

Other Supplementary Material for this manuscript includes the following:

- Movies S1 to S3
Supplementary Text

Reference scenarios and supplemental models

Two Reference Scenarios (Fig. 2, 3) for the state of the lunar mantle at the time of the SPA impact are defined on the basis of expected relative ilmenite content of late-stage cumulates in Mantle Models 1 and 2. Reference Scenario 1 (RS1) includes the relatively cooler, hence more rigid, upper mantle of Model 1. Because Model 1 is initialized with an unmixed lunar mantle immediately following magma ocean solidification, we allow for the minimum late-stage cumulate viscosity ($A_{LSC} = 10^{-2}$) to represent a moderate to high, pristine ilmenite content which weakens the late-stage cumulate layer. In contrast, mixing of the underlying mantle as in Model 2 is suggested to be capable of diluting the ilmenite fraction of a subcrustal late-stage cumulate layer (15), so we consider an end-member Reference Scenario 2 (RS2) where late-stage cumulates have a low to moderate, rheologically negligible fraction of ilmenite ($A_{LSC} = 10^0$, i.e., no compositional viscosity contrast between late-stage cumulates and the mantle). Depending on the partitioning of strain between ilmenite and other mineral phases, RS1 could allow for ilmenite fractions as high as ~60% while RS2 could allow for ilmenite fractions up to ~10–15% (15). Because viscosity is highly temperature-dependent in our simulations, the relatively warmer upper mantle of RS2 leads to a lower effective late-stage cumulate viscosity than in RS1, even though RS2 has no late-stage cumulate viscosity reduction.

We additionally characterize the range of outcomes of SPA-induced convection with two supplemental suites of models that consider a slightly smaller thermal anomaly in Suite A and a larger thermal anomaly in Suite B. Variations in the thermal anomaly magnitude and extent can be interpreted as the result of variations in $C$, $S$, $v_{imp}$, and/or $R_{imp}$. The only parameters in Suites A and B that differ from the Reference Scenarios are $C$ and $S$ (Table S2). Rather than run additional simulations that vary $v_{imp}$ and/or $R_{imp}$, we simply determined the values of $R_{imp}$ that generate the Suite A and B thermal anomalies when using Reference Scenario values of $C$, $S$, and $v_{imp}$: for Suite A, $R_{imp} \approx 75$ km; for Suite B, $R_{imp} \approx 200$ km.

Supplemental simulations are named according to their Suite, Mantle Model, and late-stage cumulate viscosity prefactor $A_{LSC}$. Simulation B2-0, identical to RS2 except with the larger Suite B thermal anomaly, is referred to as Reference Scenario 2B (RS2B) in the Main Text. RS2B uses the same mantle structure as RS2 while representing an outcome from a larger SPA-induced thermal anomaly (e.g., larger impact).

Figures S3–S6 summarize results for Suites A and B at 600 Myr after the SPA impact. The general patterns that arise from the range of models are: relatively lower-viscosity upper mantle states promote more rapid development of the compositional asymmetry; and, a larger SPA-induced thermal anomaly promotes spherical harmonic degree 1 convection including formation of a hemispheric downwelling beneath the lunar nearside, in turn promoting localization of late-stage cumulates to directly beneath the SPA antipode.

In RS2 and simulation A2-0, the most significant late-stage cumulate thickening is not centered beneath the SPA antipode. Lateral upper mantle velocity in our simulations decreases with increasing angular distance from the SPA basin, which causes material to pile up at the edge of the late-stage cumulate “cap”. Furthermore, in all three Suite A2 simulations (Fig. S3), localization of late-stage cumulates to directly beneath the SPA antipode is hindered by the formation of nearside upwellings, which result from the thermally buoyant initial basal mantle layer and less extensive SPA thermal anomaly. For small to moderate SPA thermal anomalies, the precise timing, duration, and structure of nearside late-stage cumulate localization is evidently dependent in part on the deep thermal structure and late-stage cumulate viscosity.
contrast with the mantle. Downwelling of late-stage cumulates before they are localized beneath the SPA antipode, as observed in simulations A2-1 and A2-2, may not be observed if the deep mantle thermal structure is instead closer to adiabatic.

In our models, the initial lunar upper mantle viscosity structure is influenced by the compositional viscosity reduction on late-stage cumulates as well as the upper mantle thermal state. Our results indicate that the mantle thermal structure is a more significant controlling factor on SPA-induced convection than late-stage cumulate viscosity, as highlighted by the grouping of surface-equivalent late-stage cumulate thicknesses shown in Figures S4 and S6. The relatively warm upper mantle states favored by SPA basin-formation simulations (13) (as in Mantle Model 2) lead to a strong asymmetry where the vast majority of late-stage cumulates are removed from the lunar farside hemisphere by 600 Myr post-impact.

The size of the SPA-induced thermal anomaly also has an important influence on the development of the asymmetry (Fig. S7). Compared with RS1 and RS2, corresponding Suite A simulations A1-2 and A2-0 show similar outcomes whereas Suite B simulations B1-2 and B2-0 result in a much more exaggerated asymmetry as a result of the larger Suite B thermal anomaly. The minor differences in results between RS1 and RS2 and simulations A1-2 and A2-0 indicate that our choice of shock EOS parameters (within a reasonable range of materials possibly relevant to the lunar mantle) do not have significant bearing on our conclusions. However, larger SPA impacts as allowed for by some constraints from SPA basin-formation simulations (22) could potentially be energetic enough to lead to degree-1 SPA-induced convection which entrains late-stage cumulates in a nearside downwelling, as discussed in the Main Text.

Correspondence of surface and subsurface asymmetry

In our simulations, the center of late-stage cumulate convergence is the antipode of the SPA-induced thermal anomaly, which corresponds to the antipode of the SPA basin. The SPA antipode lies in the northeastern PKT (Fig. 1) and is misaligned from the lunar surface compositional asymmetry (i.e., the center of the PKT) by roughly 35° of arc (~1000 km). A number of factors may influence the spatial relationship between the surface asymmetry and the expected subsurface asymmetry of our results.

Oblique impacts, like that which formed the SPA basin (17), may generate elongated thermal anomalies centered downrange from impact (44). Assuming a projectile trajectory from south to north, this would push the center of late-stage cumulate convergence closer to the center of the lunar nearside hemisphere, hence closer to the center of the PKT and the surface asymmetry.

Another potential factor is the lunar crustal thickness asymmetry and thinner crust in the nearside and the PKT (45) which may influence the distribution of subsurface late-stage cumulates that impart their compositional signature to the surface. Shallower late-stage cumulates would more easily be excavated by basin-forming impacts (e.g., (24)), a primordial asymmetric crust may concentrate late-stage cumulates beneath the PKT even before the SPA impact (46), and areas of thinner crust may facilitate the ascension of late-stage cumulate-infused magmas (1).

Furthermore, the observed surface distribution of KREEP-rich material likely does not correspond exactly with the subsurface distribution based on other features. The surface distribution is strongly influenced by ejecta from the Imbrium basin (24) and by KREEP-rich mare basalts which preferentially flood impact basins (e.g., (42)). There is also evidence for a
low crustal magnetization province in the northeastern PKT that has been putatively interpreted as a signature of subsurface KREEP (47).

Combined with the above considerations, unconstrained structural, compositional, or thermal heterogeneities or other complications to our simulations could result in misalignment of the lunar compositional asymmetry at and below the surface relative to the predicted center of late-stage cumulate convergence in our simulations. We observe significant overlap in the region of subcrustal late-stage cumulate thickening in our simulations with the present-day lunar surface asymmetry, particularly the PKT, thus a SPA-catalyzed subsurface compositional asymmetry remains consistent with surface observations.
Table S1.
Model parameters for Reference Scenario 1 (RS1) and Reference Scenario 2 (RS2).

| Parameter                                      | RS1 Value | RS2 Value (if different) | Citation |
|------------------------------------------------|-----------|---------------------------|----------|
| Mantle radius $R_0$                            | 1700 km   |                           | (45)a    |
| Core-mantle boundary (CMB) radius $R_c$         | 330 km    |                           | (26)     |
| Reference density $\rho_0$                      | 3300 kg/m³|                           | (7)a     |
| Surface gravity $g$                             | 1.62 m/s² |                           | (48)     |
| Heat capacity $c_p$                             | 1200 J/kg·K|                          | (49)b    |
| Internal heating $H$                            | 4.27×10⁻¹²|                           | (49)a,b  |
| Thermal diffusivity $\kappa$                     | 10⁻⁶ m²/s |                           | (9)      |
| Thermal expansivity $\alpha$                     | 2×10⁻⁵ K⁻¹|                           | (50)     |
| Reference viscosity $\eta_0$                     | 3×10²⁰    |                           | (49)a,b  |
| Late-stage cumulate viscosity prefactor $A$      | 10⁻²      | 10⁰                        | (15)a    |
| Minimum viscosity limit $\eta_{min}$ (normalized to $\eta_0$) | 10⁻³      | 10⁻¹                       | -        |
| Maximum viscosity limit $\eta_{max}$ (normalized to $\eta_0$) | 10²       | 10³                        | -        |
| SPA impactor radius $R_{imp}$                    | 85 km     |                           | (13, 16) |
| SPA impactor velocity $v_{imp}$                  | 10 km/s   |                           | (13, 16) |
| Shock EOS slope $S$                              | 1.5       |                           | (38)     |
| Shock EOS intercept $C$                          | 5.2 km/s  |                           | (38)     |
| Temperature at top of mantle $T_{surf}$          | 1100 K    | 1600 K                     | (7)a     |
| CMB temperature $T_{CMB}$                        | 1850 K    |                           | (7)      |
| Shock-heating temperature limit $T_{s,max}$      | 1850 K    |                           | -        |
| Initial late-stage cumulate layer thickness      | 60 km     |                           | (7)a     |
| Activation energy $E_a$                          | 3×10⁵ J/mol|                          | (50)     |
| Activation volume $V_a$                          | 6×10⁻⁶ m³/mol|                        | (9)      |

*aValue(s) adapted from results of cited study

*bCited study adapts values from additional references therein
Table S2.

Summary of supplemental model varied parameters. All other parameters are as in Table S1.

| Model ID | Mantle Model | $T_{surf}$ (K) | $\Delta T$ (K) | $A_{LSC}$ | $\eta_{min}/\eta_0$ | $C$ (km/s) | $S$ |
|----------|--------------|----------------|----------------|-----------|---------------------|------------|-----|
| A1-0<sup>a</sup> | 1 | 1100 | 750 | $10^0$ | $10^1$ | 6.0 | 1.46 |
| A1-1<sup>a</sup> | 1 | 1100 | 750 | $10^{-1}$ | $10^{-2}$ | 6.0 | 1.46 |
| A1-2<sup>a</sup> | 1 | 1100 | 750 | $10^{-2}$ | $10^{-3}$ | 6.0 | 1.46 |
| A2-0<sup>a</sup> | 2 | 1600 | 250 | $10^0$ | $10^1$ | 1.82 | 1.77 |
| A2-1<sup>a</sup> | 2 | 1600 | 250 | $10^{-1}$ | $10^{-2}$ | 1.82 | 1.77 |
| A2-2<sup>a</sup> | 2 | 1600 | 250 | $10^{-2}$ | $10^{-3}$ | 1.82 | 1.77 |
| B1-0<sup>b</sup> | 1 | 1100 | 750 | $10^0$ | $10^1$ | 6.0 | 1.46 |
| B1-1<sup>b</sup> | 1 | 1100 | 750 | $10^{-1}$ | $10^{-2}$ | 6.0 | 1.46 |
| B1-2<sup>b</sup> | 1 | 1100 | 750 | $10^{-2}$ | $10^{-3}$ | 6.0 | 1.46 |
| B2-0<sup>b</sup> | 2 | 1600 | 250 | $10^0$ | $10^1$ | 1.82 | 1.77 |
| B2-1<sup>b</sup> | 2 | 1600 | 250 | $10^{-1}$ | $10^{-2}$ | 1.82 | 1.77 |
| B2-2 | Not included due to computation non-convergence |

<sup>a</sup> $C$ and $S$ values for diabase (51), a relevant shock EOS for the lunar mantle.

<sup>b</sup>$C$ and $S$ values for anorthite (52), a relevant shock EOS for the lunar crust.

*Simulation B2-0 is also Reference Scenario 2B.
Fig. S1.

Cross-sectional profiles of SPA-induced temperature increase in the lunar mantle given different shock equations of state (EOS). Selected EOSs are in the range of materials potentially relevant to the lunar mantle. Diabase EOS is from (38). Terrestrial upper mantle EOS is from (57). Dunite and bronzitite EOSs are from (53). Reference Scenarios 1 and 2 use the diabase EOS and Suite A simulations use the terrestrial upper mantle EOS.
Fig. S2.

Model initial conditions for the thermal and compositional structures of the lunar interior. Temperature profile of Mantle Model 1 (solid line) represents an early end member for the state of the lunar mantle at the time of the SPA impact and is adapted from model results for the state of the cumulate lunar mantle immediately following solidification of the primordial lunar magma ocean (7). Temperature profile of Mantle Model 2 (dashed line) represents a later end member with a cumulate lunar mantle that is thermally mixed after solidification of the lunar magma ocean, in line with some considerations of the thermal state of the lunar interior at the time of the SPA impact (e.g., (13)). Both models consider a compositional structure with a 60 km-thick late-stage cumulate layer extending from the base of the lunar crust (taken to be a radius of 1700 km) overlying the rest of the mantle which extends to the core-mantle boundary at 330 km.
Fig. S3.
Cross-sections from Suite A (smaller SPA-induced thermal anomaly) simulations of the lunar mantle state at 600 Myr after the SPA impact. Top row shows simulations for Mantle Model 1, bottom row for Mantle Model 2. Each pair of composition (left) and temperature (right) cross sections show simulation results for a different pair of Mantle Model and late-stage cumulate viscosity reduction factor $A_{LSC}$. Dark grey in composition cross-sections represents lunar mantle with 0% of the initially subcrustal late-stage cumulate layer. Lunar core (inner white circle) is shown to scale.
Lunar compositional asymmetry from Suite A (smaller SPA-induced thermal anomaly) simulations at 600 Myr after the SPA impact. Surface-equivalent thickness of late-stage cumulates above 500 km depth (left axis) is shown for all six Suite A simulations (red and blue lines). Thicknesses are normalized to the initial late-stage cumulate layer thickness. Present-day lunar surface Th mean concentration (black line) and 1σ variation (grey shaded region) are also shown (right axis). Simulated thicknesses and observed Th concentrations are each azimuthally averaged with respect to latitudinal distance from the center of the present-day SPA basin. Left and right vertical axes are scaled independently.
Fig. S5.
Cross-sections from Suite B (larger SPA-induced thermal anomaly) simulations of the lunar mantle state at 600 Myr after the SPA impact. Top row shows simulations for Mantle Model 1, bottom row for Mantle Model 2. Each pair of composition (left) and temperature (right) cross sections show simulation results for a different pair of Mantle Model and late-stage cumulate viscosity reduction factor $A_{LSC}$. Dark grey in composition cross-sections represents lunar mantle with 0% of the initially subcrustal late-stage cumulate layer. Lunar core (inner white circle) is shown to scale. Simulation B2-2 is excluded because of computation non-convergence before 600 Myr.
Fig. S6.
Lunar compositional asymmetry from Suite B (smaller SPA-induced thermal anomaly) simulations at 600 Myr after the SPA impact. Surface-equivalent thickness of late-stage cumulates above 500 km depth (left axis) is shown for all six Suite A simulations (red and blue lines). Thicknesses are normalized to the initial late-stage cumulate layer thickness. Present-day lunar surface Th mean concentration (black line) and 1σ variation (grey shaded region) are also shown (right axis). Simulated thicknesses and observed Th concentrations are each azimuthally averaged with respect to latitudinal distance from the center of the present-day SPA basin. Left and right vertical axes are scaled independently. Simulation B2-2 is excluded because of computation non-convergence before 600 Myr.
Fig. S7.
Comparison of results for Reference Scenarios 1 and 2 with corresponding simulations from supplemental Suites A and B. Differences in the resulting asymmetry between corresponding simulations from the Reference Scenarios, Suite A, and Suite B are the result of differing thermal anomaly sizes. The thermal anomaly of Suite B is larger than that of the Reference Scenarios, which in turn is larger than that of Suite A.
Movie S1.
Animation of Reference Scenario 1 simulation output. Composition is on the left and temperature is on the right. Time is shown in millions of years (Myr) from the start of the simulation. SPA impact-induced heating is calculated at \( t = 5 \) Myr.

Movie S2.
The same as Movie S1 for Reference Scenario 2.

Movie S3.
The same as Movie S1 for Reference Scenario 2B (simulation B2-0).
REFERENCES AND NOTES

1. C. K. Shearer, P. C. Hess, M. A. Wieczorek, M. E. Pritchard, E. M. Parmentier, L. E. Borg, J. Longhi, L. T. Elkins-Tanton, C. R. Neal, I. Antonenko, R. M. Canup, A. N. Halliday, T. L. Grove, B. H. Hager, D.-C. Lee, U. Wiechert, Thermal and magmatic evolution of the Moon. Rev. Mineral. Geochem. 60, 365–518 (2006).

2. B. L. Jolliff, J. J. Gillis, L. A. Haskin, R. L. Korotev, M. A. Wieczorek, Major lunar crustal terranes: Surface expressions and crust-mantle origins. J. Geophys. Res. Planets 105, 4197–4216 (2000).

3. E. J. Dasch, C.-Y. Shih, B. M. Bansal, H. Wiesmann, L. E. Nyquist, Isotopic analysis of basaltic fragments from lunar breccia 14321: Chronology and petrogenesis of pre-Imbrium mare volcanism. Geochim. Cosmochim. Acta 51, 3241–3254 (1987).

4. L. A. Taylor, J. W. Shervais, R. H. Hunter, C.-Y. Shih, B. M. Bansal, J. Wooden, L. E. Nyquist, L. C. Laul, Pre-4.2 AE mare-basalt volcanism in the lunar highlands. Earth Planet. Sci. Lett. 66, 33–47 (1983).

5. P. H. Warren, J. T. Wasson, The origin of KREEP. Rev. Geophys. 17, 73–88 (1979).

6. P. H. Warren, The magma ocean concept and lunar evolution. Annu. Rev. Earth Planet. Sci. 13, 201–240 (1985).

7. L. T. Elkins-Tanton, S. Burgess, Q.-Z. Yin, The lunar magma ocean: Reconciling the solidification process with lunar petrology and geochronology. Earth Planet. Sci. Lett. 304, 326–336 (2011).

8. E. M. Parmentier, S. Zhong, M. T. Zuber, Gravitational differentiation due to initial chemical stratification: Origin of lunar asymmetry by the creep of dense KREEP? Earth Planet. Sci. Lett. 201, 473–480 (2002).

9. S. Zhong, E. M. Parmentier, M. T. Zuber, A dynamic origin for the global asymmetry of lunar mare basalts. Earth Planet. Sci. Lett. 177, 131–140 (2000).

10. J. Arkani-Hamed, A. Pentecost, On the source region of the lunar mare basalt. J. Geophys. Res. Planets 106, 14691–14700 (2001).

11. N. Zhang, M. Ding, M.-H. Zhu, H. Li, H. Li, Z. Yue, Lunar compositional asymmetry explained by mantle overturn following the South Pole–Aitken impact. Nat. Geosci. 15, 37–41 (2022).

12. A. J. Evans, J. C. Andrews-Hanna, J. W. Head, J. M. Soderblom, S. C. Solomon, M. T. Zuber, Reexamination of early lunar chronology with GRAIL data: Terranes, basins, and impact fluxes. J. Geophys. Res. Planets 123, 1596–1617 (2018).

13. R. W. K. Potter, G. S. Collins, W. S. Kiefer, P. J. McGovern, D. A. Kring, Constraining the size of the South Pole–Aitken basin impact. Icarus 220, 730–743 (2012).
14. D. P. Moriarty, R. N. Watkins, S. N. Valencia, J. D. Kendall, A. J. Evans, N. Dygert, N. E. Petro, Evidence for a stratified upper mantle preserved within the South Pole–Aitken basin. *J. Geophys. Res. Planets* **121**, e2020JE006589 (2020).

15. N. Dygert, G. Hirth, Y. Liang, A flow law for ilmenite in dislocation creep: Implications for lunar cumulate mantle overturn. *Geophys. Res. Lett.* **43**, 532–540 (2016).

16. A. J. Trowbridge, B. C. Johnson, A. M. Freed, H. J. Melosh, Why the lunar South Pole–Aitken Basin is not a mascon. *Icarus* **352**, 113995 (2020).

17. I. Garrick-Bethell, M. T. Zuber, Elliptical structure of the lunar South Pole–Aitken basin. *Icarus* **204**, 399–408 (2009).

18. P. H. Schultz, D. A. Crawford, Origin of nearside structural and geochemical anomalies on the Moon. *GSA Special Papers*, **477**, 141–159 (2011).

19. H. J. Melosh, *Impact Cratering: A Geologic Process* (Oxford University Press, 1989).

20. E. Pierazzo, A. M. Vickery, H. J. Melosh, A reevaluation of impact melt production. *Icarus* **127**, 408–423 (1997).

21. W. A. Watters, M. T. Zuber, B. H. Hager, Thermal perturbations caused by large impacts and consequences for mantle convection. *J. Geophys. Res.* **114**, E02001 (2009).

22. H. J. Melosh, J. Kendall, B. Horgan, B. C. Johnson, T. Bowling, P. G. Lucey, G. J. Taylor, South Pole–Aitken basin ejecta reveal the Moon’s upper mantle. *Geology* **45**, 1063–1066 (2017).

23. H. Hiesinger, J. W. Head, U. Wolf, R. Jaumann, G. Neukum, Ages and stratigraphy of lunar mare basalts: A synthesis. *GSA Special Papers* **477**, 1–51 (2011).

24. L. A. Haskin, The Imbrium impact event and the thorium distribution at the lunar highlands surface. *J. Geophys. Res. Planets* **103**, 1679–1689 (1998).

25. L. T. Elkins, V. A. Fernandes, J. W. Delano, T. L. Grove, Origin of lunar ultramafic green glasses: Constraints from phase equilibrium studies. *Geochim. Cosmochim. Acta* **64**, 2339–2350 (2000).

26. R. C. Weber, P.-Y. Lin, E. J. Garnero, Q. Williams, P. Lognonné, Seismic detection of the lunar core. *Science* **331**, 309–312 (2011).

27. N. Zhang, N. Dygert, Y. Liang, E. M. Parmentier, The effect of ilmenite viscosity on the dynamics and evolution of an overturned lunar cumulate mantle. *Geophys. Res. Lett.* **44**, 6543–6552 (2017).

28. Y. Zhao, J. de Vries, A. P. van den Berg, M. H. G. Jacobs, W. van Westrenen, The participation of ilmenite-bearing cumulates in lunar mantle overturn. *Earth Planet. Sci. Lett.* **511**, 1–11 (2019).
29. J. H. Roberts, J. Arkani-Hamed, Effects of basin-forming impacts on the thermal evolution and magnetic field of Mars. *Earth Planet. Sci. Lett.* **478**, 192–202 (2017).

30. R. I. Citron, M. Manga, E. Tan, A hybrid origin of the martian crustal dichotomy: Degree-1 convection antipodal to a giant impact. *Earth Planet. Sci. Lett.* **491**, 58–66 (2018).

31. J. C. Andrews-Hanna, M. T. Zuber, W. B. Banerdt, The Borealis basin and the origin of the martian crustal dichotomy. *Nature* **453**, 1212–1215 (2008).

32. M. M. Marinova, O. Aharonson, E. Asphaug, Mega-impact formation of the Mars hemispheric dichotomy. *Nature* **453**, 1216–1219 (2008).

33. S. Zhong, M. T. Zuber, L. Moresi, M. Gurnis, Role of temperature-dependent viscosity and surface plates in spherical shell models of mantle convection. *J. Geophys. Res.* **105**, 11063–11082 (2000).

34. A. K. McNamara, S. Zhong, Thermochemical structures within a spherical mantle: Superplumes or piles? *J. Geophys. Res.* **109**, B07402 (2004).

35. E. Tan, E. Choi, P. Thoutireddy, M. Gurnis, M. Aivazis, GeoFramework: Coupling multiple models of mantle convection within a computational framework. *Geochem. Geophys.* **7**, Q06001 (2006).

36. J. H. Roberts, J. Arkani-Hamed, Impact-induced mantle dynamics on Mars. *Icarus* **218**, 278–289 (2012).

37. C. C. Reese, V. S. Solomatov, Fluid dynamics of local martian magma oceans. *Icarus* **184**, 102–120 (2006).

38. R. G. McQueen, S. P. Marsh, J. N. Fritz, Hugoniot equation of state of twelve rocks. *J. Geophys. Res.* **72**, 4999–5036 (1967).

39. E. J. Speyerer, M. S. Robinson, B. W. Denevi; LROC Science Team, Lunar reconnaissance orbiter camera global morphological map of the Moon, *42nd Lunar and Planetary Science Conference*, Houston, TX, 7 to 11 March 2011, 2387 (Lunar and Planetary Institute, 2011).

40. D. J. Lawrence, R. C. Elphic, W. C. Feldman, T. H. Prettyman, O. Gasnault, S. Maurice, Small-area thorium features on the lunar surface. *J. Geophys. Res. Planets* **108**, 5102 (2003).

41. T. H. Prettyman, W. C. Feldman, D. J. Lawrence, G. W. McKinney, A. B. Binder, R. C. Elphic, O. M. Gasnault, S. Maurice, K. R. Moore, Library least squares analysis of lunar prospector gamma-ray spectra, *LPSC, 33rd Lunar and Planetary Science Conference*, Houston, TX, 11 to 15 March 2002, 2012 (Lunar and Planetary Institute, 2002).

42. L. T. Elkins-Tanton, B. H. Hager, T. L. Grove, Magmatic effects of the lunar late heavy bombardment. *Earth Planet. Sci. Lett.* **222**, 17–27 (2004).

43. G. A. Neumann, M. T. Zuber, M. A. Wieczorek, J. W. Head, D. M. H. Baker, S. C. Solomon, D. E. Smith, F. G. Lemoine, E. Mazarico, T. J. Sabaka, S. J. Goossens, H. J. Melosh, R. J. Phillips, S. W. Asmar, A. S. Konopliv, J. G. Williams, M. M. Sori, J. M. Soderblom, K.
Miljković, J. C. Andrew-Hanna, F. Nimmo, W. S. Kiefer, Lunar impact basins revealed by gravity recovery and interior laboratory measurements. Sci. Adv. 1, e1500852 (2015).

44. S. Wakita, H. Genda, K. Kurosawa, T. M. Davison, Enhancement of impact heating in pressure-strengthened rocks in oblique impacts. Geophys. Res. Lett. 46, 13678–13686 (2019).

45. M. A. Wieczorek, G. A. Neumann, F. Nimmo, W. S. Kiefer, G. J. Taylor, H. J. Melosh, R. J. Phillips, S. C. Solomon, J. C. Andrews-Hanna, S. W. Asmar, A. S. Konopliv, F. G. Lemoine, D. E. Smith, M. M. Watkins, J. G. Williams, M. T. Zuber, The crust of the moon as seen by GRAIL. Science 339, 671–675 (2013).

46. I. Garrick-Bethel, F. Nimmo, M. A. Wieczorek, Structure and formation of the lunar farside highlands. Science 330, 949–951 (2010).

47. M. A. Wieczorek, Strength, depth, and geometry of magnetic sources in the crust of the Moon from localized power spectrum analysis. J. Geophys. Res. Planets 123, 291–316 (2018).

48. F. G. Lemoine, S. Goossens, T. J. Sabaka, J. B. Nicholas, E. Mazarico, D. D. Rowlands, B. D. Loomis, D. S. Chinn, D. S. Caprette, G. A. Neumann, D. E. Smith, M. T. Zuber, High-degree gravity models from GRAIL primary mission data. J. Geophys. Res. Planets 118, 1676–1698 (2013).

49. A. J. Evans, M. T. Zuber, B. P. Weiss, S. M. Tikoo, A wet, heterogeneous lunar interior: Lower mantle and core dynamo evolution. J. Geophys. Res. Planets 119, 1061–1077 (2014).

50. M. Laneuville, J. Taylor, M. A. Wieczorek, Distribution of radioactive heat sources and thermal history of the Moon. J. Geophys. Res. Planets 123, 3144–3166 (2018).

51. R. G. McQueen, in Shock waves in condensed media: Their properties and the equations of state of materials derived from them (Lecture notes for the Enrico Fermi School of Physics, Varenna, Italy, 1989).

52. M. B. Boslough, S. M. Rigden, T. J. Ahrens, Hugoniot equation of state of anorthite glass and lunar anorthosite. Geophys. J. Int. 84, 455–473 (1986).

53. S. W. Kieffer, Impact conditions required for formation of melt by jetting in silicates. in Proceedings of the Symposium on Planetary Cratering Mechanics, Flagstaff, AZ, 13 to 17 September 1976 (Pergamon Press, Flagstaff, AZ, 1977).