Crustal porosity reveals the bombardment history of the Moon

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Planetary bombardment histories provide critical information regarding the formation and evolution of the Solar System and of the planets within it. These records evidence transient instabilities in the Solar System's orbital evolution¹, giant impacts such as the Moon-forming impact², and material redistribution. Such records provide insight into planetary evolution, including the deposition of energy, delivery of materials, and crustal processing, specifically the modification of porosity. Bombardment histories are traditionally constrained from the surface expression of impacts — these records, however, are degraded by various geologic processes. Here we show that the Moon's porosity contains a more complete record of its bombardment history. We find that the terrestrial planets were subject to double the number of ≥ 20 -km-diameter-crater-forming impacts than are recorded on the lunar highlands, fewer than previously thought to have occurred. We show that crustal porosity doesn't slowly increase as planets evolve, but instead is generated early in a planet's evolution when most basins formed and decreases as planets evolve. We show that porosity constrains the relative ages of basins formed early in a planet's evolution, a timeframe for which little information exists. These findings demonstrate that the Solar System was less violent than previously thought. Fewer volatiles and other materials were delivered to the terrestrial planets, consistent with estimates of the delivery of siderophiles³ and water to the Moon⁴. High crustal porosity early in the terrestrial planets' evolution slowed their cooling and enhanced their habitability. Several lunar basins formed early than previously considered, casting doubt on the existence of a late heavy bombardment.

The Moon's lack of an atmosphere, lack of plate tectonics, and, excluding the maria, lack of large-scale volcanism make its cratering record one of the most complete in the Solar System⁵. The lunar highlands are among the oldest surfaces on the Moon, likely representing portions of the primordial anorthosite flotation crust thought to have differentiated from the Lunar Magma Ocean (LMO)⁶ 4.29–4.54 Ga^{7,8}. The cumulative bombardment of these surfaces resulted in the development of the lunar megaregolith⁹, erased the surface expression of massive basins¹⁰, and generated planetary-scale crustal porosity down to depths on the order of 10s of km¹¹. Deciphering the total number of impacts responsible for the evolution of a post-LMO era crust, however, has proven difficult¹². Particularly, the lunar highlands may have reached a state of crater equilibrium, such that the formation of every new crater, on average, is accompanied by the erasure of a similar sized, pre-existing crater¹³. If the lunar highlands are in a state of equilibrium, then an indeterminate amount of the Moon's visible cratering record has been lost, impeding efforts to use

it to understand the early Solar System history¹⁴. As such, it is unclear whether the observed crater populations of the most densely cratered lunar surfaces¹⁵, the southern nearside and the north-central farside highlands (Fig. 1), record the complete bombardment history¹⁶. Attempts to recover this information through a variety of approaches, including measuring regolith thickness¹⁷ and crater degradation¹⁸, have had only limited success.

Impacts, however, are also known to influence the porosity of the target material^{19–21}. The cratering process increases porosity^{20,21} through tensile stresses that extensively fracture the target bedrock²² and shear stresses that dilatantly bulk the collapsing material²³. This tensile damage can extend several radii past the rim of the impact structure and >10 km into the crust, making the largest basin-forming impacts particularly important for creating global-scale regions of high porosity²¹. The cratering process, however, can also reduce porosity, as shock wave propagation is influenced by the porosity of the target. If the target is sufficiently porous prior to impact, the impact energy will be concentrated near the impact site, causing local heating and thus pore collapse²³. This competition between the generation and destruction of porosity allows us to constrain the cratering history, and thus age, of planetary surfaces. The influences of the impact process on crustal porosity are evident in the gravity signatures of terrestrial²⁴ and lunar impact craters²⁵, including the effects of target porosity¹⁹.

The Gravity Recovery and Interior Laboratory (GRAIL) mission mapped the Moon's gravity field at unprecedented resolution²⁶. These data highly correlate with topography at spherical harmonic degrees >80, allowing researchers to map crustal density^{11,27,28}. Crustal porosities were derived from these data and grain densities mapped from Lunar Prospector Gamma Ray Spectrometer data²⁷. GRAIL-derived porosity reveals that the lunar highlands are more porous than previously thought, exhibiting an average 12% crustal porosity, varying locally between 4% and 21% and extending down 10s of km, perhaps to the mantle^{11,28}. This porosity exhibits a clear inverse correlation with crater number density (Fig. 1), reported as N(20) values (number of ≥ 20 -km-diameter craters per 10^6 km²), which we reproduced from Head *et al.*¹⁵ using refined positions for some basins¹⁰. Terrains exhibiting the highest porosity (most notably, regions surrounding the largest young basins Orientale and Moscoviense) exhibit the lowest N(20) values, while the lowest porosity regions (southern nearside and the north-central farside highlands¹⁵) display high N(20) values (Fig. 1).

We consider a model in which porosity is primarily generated by basin-forming impacts and subsequently removed by smaller impacts (see Methods). This would ideally result in a direct relationship between basin age and porosity. Overlapping basins of differing ages, however, introduce complexities²⁹ that obscure this relationship (Extended Data Fig. 1) thus requiring modeling to interpret. In our model, basins ≥ 200 km in diameter (based on observed basin porosity signatures, Extended Data Fig. 2) generate porosity, the magnitude of which depends on the basin size (up to 22% based on GRAIL observations^{11,29} and Apollo samples³⁰). Rather than explicitly modeling compaction by subsequent individual impacts, we assign basins' final porosities values based on their relative ages as determined by crater counting (Extended Data Fig. 3). Model porosities range from 18.5% for Orientale to 10% for South Pole-Aitken (SP-A) Basin³¹. Porosities are modeled as constant values interior to basin rims and tapered to pre-impact porosity values at 3.5 radii²⁹ (Extended Data Fig. 4).

We consider 77 basins, including the GRAIL-proposed basins¹⁰. Neukum chronology function model ages are reported for 30 basins, ranging between 3.81 and 4.31 Ga³¹, with the caveat that all absolute crater chronology ages older than 3.8 Ga are poorly calibrated with samples and are primarily derived from extrapolation³². We constrain the ages of the remaining, undated basins by optimizing the model fit in a two-step process. We start by constraining the average age of all un-dated basins, finding a best-fit average age of 4.28 Ga. We then adjust individual basin ages, keeping ages within observed relative age limits, and deriving best-fit ages and uncertainties from model residuals. Age uncertainties generally reflect the extent to which basins are overprinted by younger basins.

This model reproduces most of the large-scale porosity variations observed in the lunar crust (Fig. 2), simulating the lunar crustal porosity (excluding SP-A, Procellarum KREEP Terrane (PKT), and the mare) with a root mean square error in porosity of 1.3%. Deviations between modeled and observed porosity reflect inhomogeneities in target properties, complexities in the impact process not captured in our model, and post-impact geologic processes. In some locations, deviations may be attributed to slight errors in the grain densities used to derive porosity; in particular, impact mixing³³ likely produces a more diffuse surface boundary between PKT and the highlands than in the bulk crust (Extended Data Figs. 5 and 6). In other locations, such as Mare Smythii, volcanic intrusions may influence crustal density and porosity measurements³⁴. Oblique impacts exhibit increased porosity along the impact angle, with highest porosities in the up-range direction (Extended Data Fig. 7). The Moscoviense-region porosity, specifically the asymmetric distribution and lack of a bullseye pattern expected from a second smaller impact (Extended Data Fig. 8), indicates that Moscoviense is a single, Nectarian-aged, ~640-km diameter basin formed by an oblique from the east, consistent with topography³⁵.

Porosity-derived ages are in general agreement with reported stratigraphy and buffered nonsparseness crater counting (BNSC) ages (32, Table 1, Extended Data Figs. 9). The BNSC method adjusts the counting area of a region as a function of crater size in order to correct for the effect of resurfacing by large craters on the counts of small craters. Our results show that Pre-Nectarian basins, including Nubium, Fitzgerald-Jackson, and Dirichlet-Jackson, are similar in age to SP-A. While the age of Mendel-Rydberg derived from crater counting and relative stratigraphy is debated^{35,36}, the porosity-derived age ($4.27^{+0.04}_{-0.06}$ Ga) is well constrained, making it clearly Pre-Nectarian in age. The porosity-derived ages of Nectaris and Serenitatis (Extended Data Fig. 9) are considerably older than Imbrium and Orientale, casting doubt on the idea of a Late Heavy Bombardment (LHB)^{37,38}. The porosity-derived ages of Humboldtianum ($4.06^{+0.16}_{-0.08}$ Ga) and Crisium ($4.09^{+0.03}_{-0.1}$ Ga) do not resolve the debate regarding their relative ages^{35,36} (Extended Data Fig. 9). The ages of some basins with poorly preserved topography (TOPO-22, Fowler-Charlier, and Mutus-Vlacq¹⁰) are well preserved in porosity, ranging from 4.29 to 4.31 Ga (Extended Data Fig. 9). The ages of basins superposed by younger basins are not well constrained while those that formed in regions of poorly constrained porosity (because the grain density is less accurate, e.g., in/around PKA and SP-A) or anomalous porosity (because other processes, such as volcanic intrusion, have influenced the bulk density) are biased.

Porosity can also be used to identify the oldest portions of the lunar crust, providing insight into early KREEP magmatism³⁹ and the strength and timing of the early lunar dynamo⁴⁰. Two

regions on the Moon, the southern nearside and the north-central farside, exhibit the lowest observed and modeled porosities (10–13.5%), indicating that they are the oldest surfaces on the Moon, and have not been subject to any major geologic processes that would influence their bulk density (e.g., intrusive and extrusive volcanism and basin-forming impacts) after ~4.28 Ga. This is consistent with the cratering record, which reveals these regions to have the highest N(20) values¹⁵. While the N(20) values exhibit local variability that reflects the stochastic nature of impact cratering (Extended Data Figs. 10 and 11), averaging the N(20) values over length scales relevant to basin formation allows a more direct comparison of these records. The average N(20) values of the oldest terrains do not exceed ~250 indicating that these surfaces have reached equilibrium in crater surface number density. In contrast, their crustal porosities display a range of evolution states indicating that porosity has not reached an equivalent equilibrium (Fig. 3) and contains additional information regarding the relative ages of these oldest surfaces. The observed porosity requires these regions to have been subject to nearly double the number of ≥20-km-diameter-crater-forming impacts than are recorded on the surface (Fig. 3), consistent with BNSC results³¹ and estimates of the late-stage accretion of material onto the Moon that are based on the abundance of highly siderophile elements^{3,4} and water in the lunar mantle⁴. We find that the D>200 km basin record, however, is largely complete (see Methods). These result implies that an intense early period of bombardment implied by the “explosive megaregolith” model⁴¹ is not required to explain the porosity distribution of the lunar crust. Using the Neukum lunar chronology system, this corresponds to an absolute model age for the lunar crust of no more than 4.31 Ga, though this is likely a lower limit due to the lack of well-calibrated cratered surfaces prior to 3.8 Ga.

These results indicate that for the period of time during and immediately following the formation of most lunar basins (~4.31–4.28 Ga), the average crustal porosity was significantly higher than that of the present-day crust (Fig. 4). The highest porosity regions included most of the southern hemisphere crust (much of which was created by SP-A) and the farside highlands (the porosity of the PKT region is not recoverable). This has major implications regarding thermal conductivity of the lunar crust and suggests that the observed level of activity on the Moon might require less radiogenic heating than previously considered⁴². These results provide insight into the historic porosity of other terrestrial bodies including the Earth and Mars; this high initial porosity can create regions that are sheltered from radiation⁴³ and increase aqueous alteration depths that enhance serpentinization⁴⁴, both of which increase habitability⁴⁵.

Fig. 1 | Observed lunar crustal properties. **a**, GRAIL-derived lunar crustal porosity²⁸ and **b**, number density of ≥ 20 -km craters ($N(20)$, derived following *Head et al.*¹⁵, using 500-km moving window radius) exhibit an inverse relationship. The porosity inversion (**a**) uses spherical harmonic degree and order $l=150-310$ ²⁸ (Supplementary Dataset 2), which are most sensitive to mass anomalies within the lunar crust and less sensitive to mass anomalies in the mantle. This derivation uses a localized, multitaper spherical harmonic analysis that was performed on 400 grid nodes distributed in a quasi-equal area²⁸. White circles identify undated basins and black circles identify dated basins. Regions excluded from the analysis (PKT, SP-A and regions for which the density gradient (estimated by *Besserer et al.*²⁸) is $< 5 \text{ kg m}^{-3} \text{ km}^{-1}$) are shown in white. SP-A is assumed to be a circular basin 2028 km in diameter (the diameter of the main inner ring of Bouguer anomaly identified by *Neumann et al.*¹⁰), centered at 191°E , 53°S . The PKT region is located at the nearside and defined by surface thorium concentration greater than 3.5 PPM⁴². This leaves 267 of the 400 porosity grid points for our analysis. We calculated $N(20)$ values (**b**) within a 500-km-radius window centered at each node as the number of craters per 10^6 km^2 , using the catalog reported by *Head et al.*¹⁵, with the locations for craters $\geq 150 \text{ km}$ in diameter updated using GRAIL observations (Supplementary Dataset 3).

Fig. 2 | Modeled lunar crustal properties. **a**, modeled present-day lunar crustal porosity and **b**, modeled density of ≥ 20 -km craters $N(20)$. Crustal porosity is derived using our model (see Methods) and depends only on the sizes and ages of large (> 200 -km diameter) lunar basins. Modeled $N(20)$ values represent a complete record of impacts onto each region since the most recent basin impacted a that region. These values are derived by an extrapolating the exponential relationship between observed porosity and observed $N(20)$ (see Fig. 3 and Extended Data Fig. 10 for deriving this relationship). Regions shown in white and the white and black circles are the same as those defined in Fig. 1.

Fig. 3 | Observed relationship between porosity and crater number density for the lunar highlands. Data are area-weighted average samples. We observe an exponential decay relationship ($y = 3198e^{-0.197x}$) between porosity and N(20) for high-porosity surfaces (i.e., younger surface, for which both porosity and N(20) records most accurately reflect the number of impacts into the surface). Below ~15.6% porosity, the data deviate from this relationship, shown as a dashed line extrapolation to lower porosities. To reduce stochastic noise in N(20) values and relate to length scales relevant to larger basins that dominate crustal porosity, N(20) values are averaged using an 800-km radius moving window (Extended Data Fig. 10).

Fig. 4 | Modeled historic (~4.28 Ga) lunar porosity. These porosity values are derived by considering the only porosity generated basins ≥ 4.28 Ga (i.e., we exclude the subsequent compaction of porosity that occurred between 4.28 Ga and the present). For simplicity, we neglect any compaction that might have occurred between 4.31 and 4.28 Ga. Regions where large young basins have formed, and potentially erased evidence of older basins, should not be trusted in these models. Only basins ≥ 4.28 Ga are shown in black circles. Regions excluded from the analysis (PKT, SP-A and maria) are shown in white, however, basins from these regions ≥ 4.28 Ga are also shown (see all basins' modeled ages in Supplementary Dataset S1).

Table 1. Porosity-derived ages of basins in lunar highlands

Basin	Porosity age (Ga)	BNSC age ³¹ (Ga)	BCC age* (Ga)	Stratigraphic younger basins
Imbrium	$3.81^{+0.24}_{-0.16}$	$3.87^{+0.035}_{-0.046}$	$3.86^{+0.05}_{-0.06}$	
Moscoviense	$3.87^{+0.18}_{-0.16}$	$4.09^{+0.02}_{-0.024}$	$4.08^{+0.03}_{-0.03}$	
Freundlich-Sharonov	$4.03^{+0.13}_{-0.22}$	$4.14^{+0.019}_{-0.023}$	$4.1^{+0.02}_{-0.02}$	Moscoviense ^{35,36}
Humboldtianum	$4.06^{+0.16}_{-0.08}$	$4.08^{+0.026}_{-0.032}$	$4.06^{+0.02}_{-0.04}$	Imbrium ³⁵ , Crisium ³⁵
Crisium	$4.09^{+0.03}_{-0.1}$	$4.07^{+0.016}_{-0.018}$	$4.06^{+0.02}_{-0.02}$	Imbrium ³⁵ , Humboldtianum ³⁶
Mendeleev	$4.13^{+0.12}_{-0.32}$	$4.13^{+0.044}_{-0.064}$	$4.09^{+0.05}_{-0.07}$	
Korolev	$4.15^{+0.07}_{-0.25}$	$4.11^{+0.021}_{-0.025}$	$4.09^{+0.02}_{-0.03}$	Oriente ³⁵ , Hertzprung ^{35, 36(?)}
Schiller-Zucchi	$4.23^{+0.08}_{-0.29}$	$4.24^{+0.038}_{-0.052}$	$4.18^{+0.06}_{-0.09}$	Oriente ³⁵
Hertzprung	$4.24^{+0.04}_{-0.06}$	$4.09^{+0.03}_{-0.037}$	$4.08^{+0.03}_{-0.04}$	Oriente ³⁵

Mendel-Rydberg	$4.27^{+0.04}_{-0.05}$	$4.13^{+0.022}_{-0.026}$	$4.09^{+0.02}_{-0.03}$	Oriente ³⁵
Dirichlet-Jackson	$4.30^{+0.01}_{-0.08}$	$4.23^{+0.022}_{-0.026}$	$4.19^{+0.02}_{-0.02}$	Korolev ³⁶
Fitzgerald-Jackson	$4.31^{+0.04}_{-0.06}$	$4.26^{+0.044}_{-0.063}$	$4.14^{+0.04}_{-0.04}$	Freundlich-Sharonov ³⁶

*BCC age is determined by minimizing the difference between the observed crater SFD³⁶ and Neukum crater SFD⁴⁶. Upper and lower bounds for the BCC ages are set as the Poisson error of the number of craters in each crater diameter bin.

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Methods

Modeling the basin porosity in the lunar crust

We model porosity in the lunar crust by assuming that basin-sized impacts generate porosity in their interiors and surrounding terrain, which is subsequently reduced over time via compaction by smaller impacts. Thus, the amount of compaction of basin-generated porosity depends on the

age of a basin and the impact rate. In our model, we consider basins to be those ≥ 200 km in diameter, the size for which mantle uplift is detected^{10,19}. Extended Data Fig. 2 shows N(200)-N(400) maps (derived using the same moving radius of 500 km as Fig. 1), are similar to each other. Additionally, N(30)-N(90) maps are distinct from N(200)-N(400) maps, but similar to the N(20) map (Fig. 1). The regions surrounding the two youngest large basins, Moscoviense and Orientale, and the PKT mostly depict a lower crater density for N(30), N(50), N(90) and N(150). This demonstrates that the majority of the higher porosity regions on the Moon is set by more recent, large basins, and the formation of >200 -300-km-diameter craters generates most of the observed crustal porosity.

We estimate the impact rate for each of the 77 basins in our study using a standard lunar chronology model (Neukum chronology)¹², which assumes the accretion tail scenario. A recent dynamical study suggests the intense bombardment of the Moon beginning at ~ 3.9 Ga is compatible with the accretion tail scenario if the highly siderophile elements were segregated from the mantle after the core formed³. The Neukum chronology provides a means to estimate the cumulative cratering history of >1 -km diameter craters, N(1), from crater counting ages. We consider the crater counting age derived by Orgel et al.³¹ that their buffered non-sparseness correction (BNSC) minimizes errors introduced from overlapping craters. This N(1) can then be converted to N(20) by applying an empirical measure of the lunar N(1):N(20) ($\sim 1400^{45}$).

Extended Data Fig. 3 shows the historic impact rate, normalized to present-day; the impact rate was ~ 600 times higher than the present-day impactor rate at the time SP-A formed (4.31 Ga) and 20 times higher when Orientale formed (3.81 Ga). Using these impact rates, we model the present-day porosity of each basin based on its age, using the porosities of the oldest basin (SP-A) and youngest basin (Orientale), as boundary conditions and linearly interpolating between them based on relative impact rates. Thus, our model simulates the generation of porosity by a basin, and the subsequent reduction in porosity via impact bombardment, as a single step. For the oldest basin, SP-A, the porosities have been reduced to be equal to the pre-existing surrounding porosities, which is set to be 10% of porosity in our model. Thus, the porosity distribution for SP-A as a function of radial distance is constant (10%). We note that, while there are a few regions with lower porosities than this, using 9% does not yield a better fit with the observation.

Based on the results of Wahl et al.²⁹, we include a size dependence on the peak porosity of a basin in our model:

$$\begin{cases} p_0 = \frac{18.5 - 15}{900 - 200}(D - 200) + 15, & 200 \text{ km} \leq D < 900 \text{ km} \\ p_0 = 18.5, & D \geq 900 \text{ km} \end{cases},$$

, where p_0 is initial peak porosity of a basin, and D is its diameter. This yields a lower peak porosity for smaller basins (e.g., a 200-km-diameter basin has a peak porosity that is reduced to 15% relative to a 900-km-diameter basin). Including this dependence improves the model fit, supporting the observation that some size-dependent processes including either porosity generation or porosity degradation may have affected the present-day observed porosities.

The observed porosity distribution from Orientale Basin suggests that the porosity peaks at the basin rim (peak porosity) and gradually decreases to the surrounding terrain's pre-existing porosity as a function of radial distance from the basin rim (Extended Data Fig. 4), out to a distance of ~ 3.5 –4 radii²⁹. Orientale Basin's present-day porosity distribution represents an ideal example, in which its initial porosity distribution formed ~ 3.8 Ga ago and the length of ~ 3.8 billion years

long bombardment reduced some of this initial porosity to what it is currently observed. Therefore, we use this porosity radial profile in our model, scaled to the peak porosities derived from basin ages and diameters, as described above. Supplementary Dataset S1 summarizes the diameter, relative crater count ages from Orgel et al.³¹, and model peak porosity of the 77 basins used in our study.

Our model uses the same 400 grid nodes (Supplementary Dataset S2) that Besserer et al.²⁸ used to derive the GRAL-derived porosity map. We simulate porosity from basins in chronological order, allowing younger basins to superpose porosity generated by older basins. For each basin, we consider each nodes' radial distance from the basin center and pre-existing porosity value. For each of the nodes within 3.5 radii of the basin, we determine the slope (parameter a) and interception (parameter b) of a natural logarithm function from the pre-existing porosities and the derived present-day peak porosity of the basin (as reported in Supplementary Dataset S1), and estimate the porosity from the radial distance between the node and basin center. Porosity values of nodes >3.5 radii from the basin are unaltered. We modeled the porosity distribution of all 77 basins, but only maintain record of the 267 grid nodes within our research of interest (the lunar highlands). For example, we include Imbrium (a PKT basin) in the model considering some of the affected area of a basin-generated porosity for Imbrium is outside PKT. Because we expect the entire lunar crust was subject to at least some degree of cratering leading up to the formation of SP-A, the lunar crust would have some non-zero "initial" porosity in our model. We considered a range of initial porosity values and find that an initial porosity of 10% (the lowest average porosity observed today) provides the best model fits.

We model the 47 undated basins in a two-step process. We begin by assuming a common age for each of these basins in the model, finding a best fit model age of 4.28 Ga (though the RMS error for an average model age of 4.29 Ga is only 0.02% higher). Next, we optimize the model fit by adjusting the ages of individual basin, considering ages between 3.81 Ga (Orientale) and 4.31 Ga (SP-A); this older bound is on the fact that the porosity of even the most degraded undated basins is still higher than that of SP-A and thus unlikely to be older than SP-A. Each undated basin is considered individually, keeping the ages of the remaining basins fixed.

Model errors and bias

Errors in our analyses could arise from both errors in the GRAIL-derived porosities from either inaccuracy in the reduction of the GRAIL gravity data to derived bulk density and/or in the grain densities used to convert bulk density to porosity, or in our modeled porosity from erroneous basin ages or un-modeled secondary effects such as oblique impacts. Extended Data Fig. 5 shows our best-fit porosity map alongside the GRAIL-derived porosity and a "residual" map that highlights differences between the two. Regions that exhibit the residuals greater than $2 \times$ the RMS error ($\sim 2.6\%$) include the area around PKT boundary (Coulomb-Sarton and Lorentz, and Medii), east to Smythii Basin, SP-A basin's eastern rim, and central farside. Our model underpredicts the porosity along the northwestern boundary of PKT, which we believe it results from differences between the grain densities measured at the surface and those of the bulk crust. The grain densities used to derive porosity are estimated from LP-GRS abundance maps, which is only sensitive to the top meter thick crust. Impact gardening will mix materials between compositional units³³, for example highlands and PKT. This mixing will be most efficient at the surface, thus resulting in a difference in the composition (and thus grain density) of material near the surface and at depth. This slight overestimate in grain density in highland side across the PKT boundary can result in higher porosity if assuming derived bulk density is constant,

$$\phi = 1 - \rho_{bulk}/\rho_{grain},$$

where ϕ is porosity, ρ_{bulk} is bulk density, and ρ_{grain} is grain density. Extended Data Fig. 6 shows a trend in grain density used in deriving observed porosity across northwestern PKT boundary and Orientale Basin, consistent with the previous report using Lunar Orbiter IV images in the western PKT region⁴⁷. The bulk crust likely exhibits a much sharper boundary in grain density.

Extended Data Fig. 7 indicates the 1 and 2 radii distances from the centers of the oblique impact basins identified by Wilhelms et al.³⁵: Orientale, Schrödinger, Hertzprung, Korolev, Humboldtium, Moscoviense, and Freundlich-Sharonov. The impact azimuth interpreted from basin asymmetries in Wilhelms et al.³⁵ and porosity distribution are summarized in Extended Data Table 1. Although these basins are small, and thus near the resolution of our model, we can conclude from Orientale, Schrödinger, and Moscoviense that porosity is highest up-range of the impact. Using the reported impact azimuth (90°, measured clockwise from north) for Hertzprung does not give us an asymmetric distribution of porosity; however, we can obtain a porosity asymmetry by adjusting this impact azimuth to be slightly larger (e.g., 100-180°). Unfortunately, the formation of Orientale, southeastern of Hertzprung (in the up-range direction of Hertzprung) has affected the porosity distribution in this region, and thus limits our ability to use porosity to a tight constraint on impact azimuth.

Error estimate of basin porosity-derived ages

A chi-square minimization method is employed to derive ages of each basin based on its present-day porosity and to test the sensitivity of our model to the prescribed crater count ages of individual basins. Chi-squared is the squared sum of the residuals weighted by their uncertainties:

$$X^2 = \frac{\sum_{i=1}^n [O_i - M_i]^2}{\sigma_i^2},$$

where we assume the same observed error and take a squared root to convert to porosity in unit for convenience of the discussion. Thus, the equation becomes: $X^2 = \frac{\sum_{i=1}^n [O_i - M_i]^2}{n}$, where n is the number of observed data point ($n = 267$ for only lunar farside), O_i is the GRAIL-derived porosity value, and M_i is the modeled porosity value. For each basin of 77 basins, we consider a range of ages, from 3.81 Ga to 4.31 Ga, uniformly divided into 51 ages with the resolution of 0.01 Ga. Orientale and SP-A serve as the boundaries of our model and thus are not considered in this exercise. At the beginning of each simulation a new chronology is determined. A single chi-squared value of the model fit is recorded for each simulated basin age. We used 0.01% porosity as a measure of uncertainty for the best solution of porosity-derived age. Extended Data Fig. 9 shows the chi-squared plot as function of age for basins. Minimum chi-squared values represent the best-fit basin ages based on the observed porosity and our model. We tested the sensitivity of our model to the relative ages of Crisium and Humboltianum as their stratigraphy relationship is debated. Because the chi-squared plot for Humboltianum shows two local minima at around 4.06 Ga and 4.16 Ga, we tested how fixing Humboltianum's age affects the global porosity distribution. Our model yields slightly better results if Crisium is older than Humboltianum, but the difference between the porosity-derived age of Humboltianum, and the crater counting age for Crisium is only 0.01 Ga. However, the older age for Humboltianum (4.16 Ga) does not yield a better overall model fit. Considering a larger variation of porosity-derived ages for Humboltianum (4.06 – 4.16

Ga) and the small difference between the best result of Humboltianum's age and Crisium's reported age, it suggests that Crisium and Humboltianum are likely similar in age, around 4.06 Ga. Note that we do not report the porosity-derived ages for basins located in regions with less reliable observed porosity. Basins that are completely overprinted by younger basins, such as Crüger-Sirsalis, Grimaldi, Crisium-East, Medii, and Orientale-Southwest, exhibit chi-squared plots that are almost flat, indicating that their ages are unconstrained by porosity. Basins partially overprinted by younger basins, such as Serenitatis, Fecunditatis and Deslandres, exhibit chi-squared plots that are only provide a younger-limit to the porosity-derived age (older than the basin overprinting them). Our model provides well-constrained porosity-derived ages for six undated basins: Keeler-West, Gagarin, Fowler-Charlier, Mutus-Vlacq, TOPO-22, and Australe-North. While Nectaris is located in a region where porosity is poorly constrained, given its importance to lunar chronology, we still report its porosity-derived age. In our model, Nectaris is only constrained by the southern region of its ejecta and is $4.25^{+0.02}_{-0.04}$ Ga, much older than $4.17^{+0.012}_{-0.014}$ Ga of crater counting age. The lower bound of porosity-derived age, ≥ 4.21 Ga, however, is closer to the oldest impact melt age, 4.22 Ga U-Pb-dating age from Apollo 16 sample 67955⁴⁸ than the 3.94 Ga crater-counting age⁴⁹.

Statistical analysis in relationship between observed porosity and cratering record

To statistically determine if the observed $N(20)$ values in lower porosity (i.e., older) regions deviate from the observed relationship between $N(20)$ values and porosity in higher porosity (i.e., younger) regions, we applied the Bayesian Information Criterion (BIC)⁵⁰ under the assumption of an independently, normally distributed error variance⁵¹. BIC provides a criterion for selecting a finite set of parameterized models by penalizing additional parameters that are introduced in more complex models. BIC uses the maximum log likelihood function (L) and a penalty term ($\sim p \ln(n)$) to evaluate models of differing complexity:

$$BIC = L + p \ln n,$$

where p is the number of unknown parameters in a model, n is the sample size, and L is the maximum log likelihood. Under the assumption of a normally distributed model error variance, L , is written as,

$$L = n \ln(S_R^2),$$

where S_R^2 is the sum of the squared residuals, $\sum_{i=1}^n [y_i - \gamma(x_i)]^2$ in which y_i is the observed $N(20)$ value and $\gamma(x_i)$ is the estimated $N(20)$ value with the observed porosity of x_i for a specific model.

We considered three models to analyze the relationship between the observed porosity and the observed $N(20)$ values. Our null model is single slope model, depicting no statistical break in slope that would indicate a change in the relationship between these variables. In this model, the BIC value is a fixed value that is obtained from fitting a linear least square method and penalizing the three free parameters in the linear least square method (intercept, slope, and the model error variance).

Our second model is two linear slope model that includes five free parameters (the slopes of the two linear lines that describe the relationship between porosity and $N(20)$ for lower porosity regions and higher porosity regions, the intercept, the porosity value at which the relationship changes (i.e., the break point), and the model error variance). This is the simplest form to determine

whether the cratering record in lower porosity regions differs from the record in higher porosity regions.

The third model is a modified version of the second model with an exponential decay function for the high-porosity data. The third model (the exponential decay function at second slope) provides a physical interpretation and is consistent with the assumption that when porosity is higher, it is more readily reduced, but as impacts reduce porosity, the net reduction in porosity from each new impact becomes increasingly smaller. A first order differential equation can be written as $\frac{d\phi}{dN} + \frac{c}{N} = 0$. By separating the same variable (ϕ and N) into the same side, an analytical solution is obtained: $N(\phi) = N_0 e^{-\phi/c}$, where $N_0 = N(\phi_0) e^{\phi_0/c}$ in which $N(\phi_0)$ is defined as 1 (at least one impact occurs in order to reach a convergent solution). This model includes five free parameters (proportional coefficient and decay coefficient of an exponential function, intercept, the position of break point, and the model error variance). The first slope is implicit, controlled by the intercept and the exponential function.

For the purpose of comparing these models, the BIC values are calculated, where the single slope model has the BIC value of ~1812 (Extended Data Fig. 10) and the BIC values for the other two models depend on the position of break points. To quantitatively determine the measure of likelihood of one model over another, we used the Bayes factor. Given equal weight on the prior probabilities of the two models, the Bayes factor can be simplified to only consider the BIC values of the two models, H_0 and H_1 , as $B_{01} = e^{BIC_0 - BIC_1(50)}$. According to a standard by Jeffreys⁵², $1 < B_{01} < 10^{1/2}$ is evidence for the alternative model, “but not worth more than a bare mention,” $10^{1/2} < B_{01} < 10$ is “substantial” evidence for the alternative model, $10 < B_{01} < 10^{3/2}$ is “strong” evidence for the alternative model, $10^{3/2} < B_{01} < 10^2$ is “very strong” evidence for the alternative model, and $10^2 < B_{01}$ is “decisive” evidence for the alternative model.

The question of whether or not the lunar surface records cratering dates back to the Apollo days. Answering this question is not simple. As terrains evolve and become more heavily cratered, craters become obscured by newer impacts. As this process is random, the significance of this random noise in $N(20)$ increases for older terrains; leading to greater variability in $N(20)$ values for the oldest / most cratered surfaces. To understand how $N(20)$ variability changes with observed porosity, we derived $N(20)$ maps using different moving window radii, ranging from 90 to 800 km, each normalized to an area of 10^6 km^2 (Extended Data Fig. 11). $N(20)$ values are highly variable when using the smallest moving window radii, showing variations in $N(20)$ of up to ~600 over short distances. This variability is reduced as the moving window radius increases. This maximum average $N(20)$ values remain relatively unchanged in lower porosity regions.

Extended Data Fig. 10 shows the relationship between $N(20)$ and porosity for three different $N(20)$ moving-window radii. For the smaller two moving windows, the data are too noisy to be used to identify any statistically significant change in $N(20)$ –porosity relationship between higher and lower porosity values. When the data are sufficiently smoothed using a larger moving window, however, we see that the two linear slope model is preferred “substantially” over the single-slope model and that there is “strong” evidence to prefer the linear–exponential function over the single-slope model (Extended Data Fig. 11c). This indicates that the $N(20)$ record of the oldest lunar surfaces is in fact incomplete.

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549 in the main text or the supplementary materials. The codes for generation modeled data are stored
550 in Harvard Dataverse. Correspondence and requests for materials should be addressed to Y.H.H.
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Extended Data Figure 1 | Statistical analysis for relationships between observed porosity and crater counting ages. (Left) Linear least square fitted relationship between the crater-counting age and observed porosity of lunar highlands basins for (a) all 29 dated basins, (b) dated basins excluding inside-SP-A basins, and (c) the youngest basins >4.11 Ga. (Right) Normalized probability of the slope of the data shown on the left from 50,000 bootstrapping samples with 95% BCa (bias-corrected and accelerated), confidence intervals. BCa approach accounts for the non-Gaussian distribution of the slopes. We assume a linear relationship between porosity and basin age, and use bootstrapping to estimate confidence intervals for fitted parameters. If we consider all dated basins and all non-SP-A dated basins, we find no statistically significant relationship between basin age and porosity (a slope of zero is within the 95% confidence intervals in Extended Data Figs. 1a and S1b), though the non-SPA dated basin slope distribution is skewed and the mean

564 is far from a slope of zero. When we only consider the youngest basins (>4.11 Ga), however, we
565 find a statistically significant relationship between basin age and porosity (Extended Data Fig.1c).

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567 **Extended Data Figure 2 | Number density maps of lunar craters.** Those maps are similar to
568 Fig. 1b, but with different cutoff sizes of crater diameter larger than 30 (a), 50 (b), 90 (c), 150 (d),
569 200 (e), 300 (f) and 400 (g) km against the observed porosity as same in Fig. 1a (h, bottom right).

570 When the number of craters per averaging window is small (i.e., density maps of ≥ 200 km diameter
571 craters), the density map are dominated by few circles (approximately the size of the basin).

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Extended Data Figure 3 | The lunar impact rate based on the accretion tail scenario hypothesis¹². The present-day is toward the right side of the x-axis. Crater count ages for the SP-A and Orientale Basins are 4.31 and 3.81 Ga³¹, respectively, and their relative impact rates are indicated in a dashed line.

Extended Data Figure 4 | The porosity radial profiles of Orientale Basin. Those profiles are porosity distributions plotted as a function of radial distance from the rim of Orientale basin's center. The top panel (a) represents the observed porosity distribution of Orientale Basin, and the bottom panel (b) shows an example of an idealized porosity distribution for Orientale Basin. Because the interception (the parameter b) in the observed porosity for Orientale Basin is not exactly 18.5 (we round it to 18.5% porosity in our model), this affects the value of the parameter a in the natural log function. We note that in our simulation, the parameter a is adjusted according to the preexisting porosity of surroundings of a basin that we model. The x-axis represents the radial distance from the center of Orientale Basin scaled by the radius of Orientale Basin, and the y-axis is porosity value in percentage unit. We sampled porosities from the surroundings of Orientale Basin up to 4 radii and binned those porosities into 0.5 radii. The solid point from each bin represents a mean value from the porosity distribution in the bin, and the vertical solid lines at the points represent one standard deviation of the sampled porosity values. The dashed line is a fitting function by using natural logarithm function in the top-right of the figure, where R^2 is for how much fraction of data points fall into a fit function.

Extended Data Figure 5 | Model residual map. (a) Observed porosity, (b) modeled porosity, (c) grain density (d) $\geq 2|\sigma|$ model porosity residual (a minus b). Red and blue dots indicate grid points for which model residuals are $\geq 2|\sigma|$ ($\sim 2.6\%$ porosity).

Extended Data Figure 6 | Grain density variation across Northwestern boundary of PKT and Orientale Basin. The top panel shows the relative distance of Hertzprung Basin from Imbrium Basin is approximately 3200 km. The dashed lines represent the center of the basins.

Extended Data Figure 7 | Map of oblique lunar-highlands basins. GRAIL-derived porosity is shown on a cylindrical projection. Black circles indicate the 1 and 2 radii extents of each basin.

Extended Data Figure 8 | Modeled lunar crust porosity for a double impact in Moscoviense region. Bull-eyed pattern (lower porosity) in the northwestern part of 640 km diameter Moscoviense results from the smaller impact, ~401 km diameter. This 640 km diameter Moscoviense is modeled slightly older than the smaller impact ~401 km diameter. The smaller basin impacts into pre-existing highly porous region generated from ~640 km diameter Moscoviense, reducing some of pre-existing porosity.

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Extended Data Figure 9 | Chi-squared plots for lunar highland basins. Blue lines indicate the minima in the chi-square plots, which correspond to the most likely age of a basin based on our model and the GRAIL-derived porosity. Red lines indicate the reported crater-counting age of the basin (when available). Green horizontal lines indicate a chi-squared value of the minimum plus 0.01 (% porosity in unit); where the chi-squared plot (black line) crosses this green line provides a measure of the model's sensitivity to the age of the basin. Abrupt changes in chi-squared values indicate ages in which the chronology of overlapping basins changes.

725 **Extended Data Table 1 | Porosity distribution in up-range and down-range from an oblique**
726 **impact**

Basin name	Impact azimuth θ (clockwise from North)	Porosity in up- range direction (0 – 1 R)	Porosity in down-range direction (0 – 1 R)	Porosity in up- range direction (1 – 2 R)	Porosity in down-range direction (1 – 2 R)
Orientale	60	19.41±0.50	17.01±1.47	18.53±1.16	15.52±1.31
Schrödinger	60 or 240	12.19±0.00 12.42±1.17	NaN NaN	NaN NaN	12.42±1.17 12.19±0.00
Hertzprung	90 < θ < 180 (this study) 90	14.95±0.00 13.97±1.38	12.99±0.00 NaN	14.0–15.4 NaN	13.9–14.1 14.13±1.39
Humboltianum	260	16.46±0.00	15.82±0.61	15.24±0.76	13.89±0.93
Korolev	100	NaN	14.27±0.00	13.58±0.18	13.96±0.90
Moscoviense	100	17.10±0.24	16.72±0.54	15.78±0.96	15.41±0.56
Freundlich- Sharonov	105 or 285	NaN 15.40±0.00	15.40±0.00 NaN	14.51±1.16 15.85±0.88	15.85±0.88 14.51±1.16

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Extended Data Figure 10 | Bayesian Information Criterion (BIC) test on the relationship between the observed porosity and N(20) crater density. Those relationships are estimated from using moving window radius of 290 km (a), 500 km (b), and 800 km (c). Green and blue solid lines represent BIC values of two slope model and exponential function at second slope model over a series of testing break point, respectively. Black horizontal solid lines represent BIC value of single slope model. Lower BIC values are better.

Extended Data Figure 11 | N(20) maps calculated using different moving window radii. Panels represent moving window radii of (a) 90 km, (b) 150 km, (c) 200 km, (d) 290 km, (e) 400 km, and (f) 800 km. Note that the colors stretch varies between panels.

Figures

Figure 1

Observed lunar crustal properties. a, GRAIL-derived lunar crustal porosity and b, number density of ≥ 20 -km craters ($N(20)$, derived following Head et al. 15, using 500-km moving window radius) exhibit an inverse relationship. The porosity inversion (a) uses spherical harmonic degree and order $l=150-31028$ (Supplementary Dataset 2), which are most sensitive to mass anomalies within the lunar crust and less sensitive to mass anomalies in the mantle. This derivation uses a localized, multitaper spherical harmonic analysis that was performed on 400 grid nodes distributed in a quasi-equal area. White circles identify undated basins and black circles identify dated basins. Regions excluded from the analysis (PKT, SP-A and regions for which the density gradient (estimated by Besserer et al. 28) is $< 5 \text{ kg m}^{-3} \text{ km}^{-1}$) are shown in white. SP-A is assumed to be a circular basin 2028 km in diameter (the diameter of the main inner ring of Bouguer anomaly identified by Neumann et al. 10), centered at 191°E , 53°S . The PKT region is located at the nearside and defined by surface thorium concentration greater than 3.5 PPM⁴². This leaves 267 of the 400 porosity grid points for our analysis. We calculated $N(20)$ values (b) within a 500-km-radius window centered at each node as the number of craters per 10^6 km^2 , using the catalog reported by Head et al. 15, with the locations for craters $\geq 150 \text{ km}$ in diameter updated using GRAIL observations (Supplementary Dataset 3).

Figure 2

Modeled lunar crustal properties. a, modeled present-day lunar crustal porosity and b, modeled density of ≥ 20 -km craters $N(20)$. Crustal porosity is derived using our model (see Methods) and depends only on the sizes and ages of large (>200 -km diameter) lunar basins. Modeled $N(20)$ values represent a complete record of impacts onto each region since the most recent basin impacted a that region. These values are derived by an extrapolating the exponential relationship between observed porosity and observed $N(20)$ (see Fig. 3 and Extended Data Fig. 10 for deriving this relationship). Regions shown in white and the white and black circles are the same as those defined in Fig. 1.

Figure 3

Observed relationship between porosity and crater number density for the lunar highlands. Data are area-weighted average samples. We observe an exponential decay relationship ($y=3198e^{(-0.197x)}$) between porosity and $N(20)$ for high-porosity surfaces (i.e., younger surface, for which both porosity and $N(20)$ records most accurately reflect the number of impacts into the surface). Below $\sim 15.6\%$ porosity, the data deviate from this relationship, shown as a dashed line extrapolation to lower porosities. To reduce stochastic noise in $N(20)$ values and relate to length scales relevant to larger basins that dominate crustal porosity, $N(20)$ values are averaged using an 800-km radius moving window (Extended Data Fig. 10).

Figure 4

Modeled historic (~ 4.28 Ga) lunar porosity. These porosity values are derived by considering the only porosity generated basins ≥ 4.28 Ga (i.e., we exclude the subsequent compaction of porosity that occurred between 4.28 Ga and the present). For simplicity, we neglect any compaction that might have occurred between 4.31 and 4.28 Ga. Regions where large young basins have formed, and potentially erased evidence of older basins, should not be trusted in these models. Only basins ≥ 4.28 Ga are shown in black circles. Regions excluded from the analysis (PKT, SP-A and maria) are shown in white, however, basins from these regions ≥ 4.28 Ga are also shown (see all basins' modeled ages in Supplementary Dataset S1).

Supplementary Files

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