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The Crust of the Moon as Seen by GRAIL

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Abstract

High resolution gravity data obtained from the dual GRAIL spacecraft are providing an unprecedented view of the Moon's crust. The bulk density of the highlands crust is found to be 2550 kg m^{-3} , significantly lower than generally assumed, and when combined with remote sensing and sample data, an average crustal porosity of 12% to depths of at least a few km is required. Lateral variations in crustal porosity correlate with the largest impact basins, whereas lateral variations in crustal density correlate with crustal composition. The low bulk crustal density allows construction of a global crustal thickness model that satisfies the Apollo seismic constraints, and with an average crustal thickness between 34 and 43 km, the bulk refractory element composition of the Moon is not required to be enriched with respect to Earth.

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The crust of the Moon plays an integral role in deciphering its origin and subsequent evolution. Being composed largely of anorthositic materials [1], its average thickness is key to determining the bulk silicate composition [2], and by consequence, whether the Moon is derived from Earth materials or from the giant impactor that is believed to have formed the Earth-Moon system [3]. Following formation, the crust of the Moon suffered the consequences of 4.5 billion years of impact cratering. The Moon is the nearest and most accessible planetary body to study the largest of these catastrophic events that were common during early solar system evolution [4,5]. In addition, it is an ideal laboratory for investigating the cumulative effects of the more numerous smaller events. Spatial variations in the Moon's gravity field are reflective of subsurface density variations, and GRAIL's high resolution measurements are particularly useful for investigating the crust.

Previous investigations of the Moon have made use of gravity data derived from radio tracking of orbiting spacecraft, but these studies were frustrated by the low and uneven spatial resolution of the available gravity models [6,7]. NASA's Gravity Recovery and Interior Laboratory (GRAIL) mission [8] consists of two co-orbiting spacecraft that are obtaining high-resolution gravity measurements by intersatellite ranging over both the near and far side hemispheres of Earth's natural satellite. Gravity models at the end of the primary mission resolve wavelengths as fine as 26 km, which is more than 4 times smaller than any previous global model. The mass anomalies associated with the Moon's surface topography are one of the most prominent signals seen by GRAIL [9], and as the measured gravity signal at short wavelengths is not affected by the compensating effects of lithospheric flexure, these data offer the first opportunity to determine unambiguously the bulk density of the lunar crust. The density of the crust is a fundamental property required for geophysical studies of the Moon, but also provides important information on crustal composition over depth scales that are greater than those of most other remote sensing techniques.

The deflection of the crust-mantle interface to surface loads makes only a negligible contribution to the observed gravity field beyond spherical harmonic degree 150 (supporting online materials). At these wavelengths, if the gravitational contribution of the surface relief were removed with the correct reduction density, the remaining signal (the Bouguer anomaly) would be zero if there were no other density anomalies present in the crust. An estimate of the crustal density can be obtained by minimizing the correlation coefficient of the surface topography and Bouguer anomaly. To neglect complicating flexural signals, and to interpret only that portion of the gravity field that is well resolved, the gravity and topography were first filtered to include spherical harmonic degrees between 150 and 310. Gravity and topography over the high density mare basalts are excluded from analysis, as their presence would bias the bulk density determination given their preference to pool in low-lying regions.

For our analyses, the correlation coefficient of the Bouguer gravity and surface topography was minimized using data within circles that span 12° of latitude. Analyses were excluded when more than 5% of the region was covered by mare basalts, and when the minimum correlation coefficient exceeded the 95% confidence limit as estimated from Monte Carlo simulations and the gravity coefficient uncertainties (supporting online materials). The

average density of the entire highlands crust is found to be 2550 kg m^{-3} , and individual density uncertainties are on average 18 kg m^{-3} . As shown in Fig. 1, significant lateral variations in crustal density exist with amplitudes of $\pm 250 \text{ kg m}^{-3}$. The largest positive excursions are associated with the 2000-km diameter South Pole-Aitken basin on the Moon's farside hemisphere, which is a region that has been shown by remote sensing data to be composed of rocks that are considerably more mafic, and thus denser, than the surrounding anorthositic highlands [10]. Extensive regions with densities lower than average are found surrounding the impact basins Orientale and Moscoviense, which are the two largest young impact basins on the Moon's farside hemisphere. The bulk density determinations are robust to changes in size of the analysis region by a factor of two, and are robust to changes in the filter limits by more than ± 50 degrees. Nearly identical bulk densities are obtained using a localized spectral admittance approach (Fig. S6).

The bulk crustal densities obtained from GRAIL are considerably lower than the values of 2800 to 2900 kg m^{-3} that are used typically for anorthositic crustal materials [11]. We attribute the low densities to impact-induced fractures, and quantify the total porosity by use of independent estimates of crustal grain density. Using an empirical relation between the grain density of lunar rocks and their concentration of FeO and TiO_2 [12], along with surface elemental abundances derived from gamma-ray spectroscopy [13], grain densities of lunar surface materials are estimated globally with a precision and spatial resolution that is comparable to the GRAIL bulk density measurements (Fig. S3). Assuming that the surface composition of the Moon is representative of the underlying crust, the porosity of the upper levels of the highlands crust is on average 12% and varies regionally from about 4 to 21% (Fig. 2). These values are consistent with, though somewhat larger than, Kaguya-based estimates made using longer wavelengths and a lithospheric flexure model [12]. The crustal porosities in the interiors of many impact basins are lower than their surroundings, consistent with a reduction in pore space by high post-impact temperatures that can exceed the solidus. In contrast, the porosities just exterior to many basins are higher than their surroundings, which is consistent with the generation of fractures by the ballistic deposition of impact ejecta and the passage of impact-generated shock waves.

If the crustal density was constant at all lunar radii beneath the deepest topographic excursion, our bulk density estimates would represent an average over the depths sampled by the topographic relief, which is on average about 4 km. Since the deeper crust would not generate lateral gravity variations in this model, this depth should be considered a minimum estimate for the depth scale of the GRAIL density determinations. If crustal porosity were solely a function of depth below the surface, the depth scale could be constrained using the relationship between gravity and topography in the spectral domain, since deep short-wavelength mass anomalies are attenuated faster than shallower and longer wavelength anomalies. Two models were investigated: one where the porosity decreased exponentially with depth below the surface, and another where a constant thickness porous layer overlies a non-porous basement (supplemental online materials). The $1-\sigma$ upper bound of both depth scales is largely unconstrained, with values greater than 30 km being able to fit the observations in most regions. $1-\sigma$ lower bounds for the two depth scales are constrained to be less than 31 km, which implies that at least some regions of the highlands have significant

porosity extending 10s of kilometers deep into the crust, and perhaps into the uppermost mantle.

Our density and porosity estimates are broadly consistent with laboratory measurements of lunar feldspathic meteorites and feldspathic rocks collected during the Apollo missions. The average density of the most reliable of these measurements is $2580 \pm 170 \text{ kg m}^{-3}$ [14] (supplemental online materials), and the porosities of these samples vary from about 2 to 22% with an average of $8.6 \pm 5.3\%$. The ordinary chondrite meteorites have a similar range of porosities as the lunar samples, and this has been shown to be the result of impact-induced micro fractures [15]. A 1.5 km drill core in the Chicxulub impact crater shows that impact deposits have porosities between 5 and 24%, whereas the basement rocks contain porosities up to 21% [16]. Gravity data over the Ries, Tvären and Granby terrestrial impact craters (with diameters of 23, 3 and 2 km) imply the existence of 10-15% excess porosity 1 km below the surface [17, 18], and for the Ries, about 7% porosity at 2-km depths. Whereas the impact induced porosities associated with these three craters are a result of single events, on the Moon, each region of the crust has been affected by numerous impacts.

Compression data of lunar igneous rocks show that the lithostatic pressures encountered in the crust and upper mantle are insufficient to close all fractures. About 2-3% porosity can be removed at the 4 kbar pressures encountered 100 km below the surface [19, 20], and the complete closure of pore space is instead likely to occur by viscous deformation at elevated temperatures. Given the exponential dependence of viscosity on temperature, and the increase in temperature with depth below the surface, porosity will be removed over a narrow depth interval [21]. Using representative temperature gradients over 4 billion years, this transition depth is predicted to lie between 50 and 110 km below the surface (supplemental online materials). Where the crust is thinner than these values, porosity could exist in the underlying mantle, as has been suggested by S-wave velocity profiles derived from the Apollo seismic data [22].

With our new constraints on crustal density and porosity, we construct a global crustal thickness model using GRAIL gravity and Lunar Reconnaissance Orbiter topography [23] data. Our model accounts for the gravitational signatures of the surface relief, relief along the crust-mantle interface, and the signal that arises from lateral variations in crustal grain density as predicted by remote sensing data (supplemental online materials). Crustal densities beneath the mare are extrapolated from the surrounding highland values, and by neglecting the thin veneer of dense basalts [11], the total crustal thicknesses could be biased locally by no more than a few km. As constraints to our model, we use end-member seismically determined thicknesses of 30 and 38 [22, 24] km near the Apollo 12 and 14 landing sites, and assume a minimum crustal thickness near zero given that at least one impact event is likely to have excavated through the entire crust [11, 25]. After choosing a porosity model of the crust, a unique model that fits the observations is obtained by varying the average crustal thickness and mantle density. Since some of the short wavelength gravity signal is a result of unmodeled crustal signals, our inversions make use of a spectral low-pass filter [26] near degree 80, yielding a spatial resolution that is 60% better than previous models [27]. Remote sensing data of impact crater central peaks imply some subsurface

compositional variability, but do not require broad compositional layering [28], justifying our use of a model that is uniform in composition with depth.

For our first set of models, we assumed either that a constant thickness porous layer exists above bedrock or that the porosity decreases exponentially with depth. With a mantle grain density of 3360 kg m^{-3} [29], both models are incapable of fitting simultaneously the seismic and minimum thickness constraints as a result of the relatively small density contrast at the crust-mantle interface. For our second set of models, we assumed that the porosity of the entire crust was constant. With 12% porosity and the 30-km seismic constraint, an acceptable solution is found with an average crustal thickness of 34 km and a mantle density of 3220 kg m^{-3} (Fig. 3). For the 38-km constraint, values of 43 km and 3150 kg m^{-3} are found, respectively. By reducing the porosity to 7%, the mantle density increases by about 150 kg m^{-3} , but the average crustal thickness remains unchanged. Identical average crustal thicknesses are obtained using a crustal density map extrapolated from Fig. 1. The mantle densities should be considered representative to the greatest depths of the crust (~80 km below the surface), and if the grain density of mantle materials is 3360 kg m^{-3} , then a maximum of 6% porosity could exist in the uppermost mantle.

Before GRAIL, the average thickness of the Moon's crust was thought to be close to 50 km [11, 27] (supplemental online materials). Our revised estimates that are up to 16 km thinner have important implications for the abundance of refractory elements in the Moon, which is an important parameter for assessing processes that operated during lunar formation. Published estimates [2] for the bulk silicate abundance of the refractory element aluminum fall into two categories: One group indicates that the Moon contains the same abundance as Earth, whereas the other suggests at least a 50% enrichment. Assuming that the lunar crust consists of an upper mixed layer 5-km thick containing 28 wt.% Al_2O_3 [2] with the remainder being nearly pure anorthosite (34 wt.% Al_2O_3), we calculate that a 34-km thick crust contributes 1.6 and 1.7 wt.% to the total bulk silicate abundance of Al_2O_3 for crustal porosities of 12 and 7%, respectively. A 43-km thick crust contributes 2.0 and 2.1 wt.%, respectively. The inclusion of more mafic materials in the lowermost crust has little effect on the average crustal abundance of aluminum [1]. In order for bulk lunar silicate aluminum abundances to match those for Earth (4 wt.% Al_2O_3), the lunar mantle would need to contain 1.9-2.4 wt.% Al_2O_3 , whereas a 50% enrichment in refractory elements would require mantle abundances of 4.1-4.5 wt.% Al_2O_3 . Petrologic assessments indicate mantle Al_2O_3 abundances close to 1-2 wt.% [30], supporting a lunar refractory element composition similar to Earth. Estimates derived from modeling the Apollo seismic data have a broad range, from 2.3-3.1 wt.% for the entire mantle [31], to 2.0 to 6.7 wt.% for the upper and lower mantle [32], respectively. Although further constraints on the composition of the deep lunar mantle are needed, the modest contribution to the bulk lunar Al_2O_3 from the crust does not require the Moon to be enriched in refractory elements.

Crustal thickness variations on the Moon are dominated by impact basins with diameters from 200 to 2000 km. With a thinner crust, it becomes increasingly probable that some of the largest impact events excavated through the entire crustal column and into the mantle [11]. Two impact basins have interior thicknesses near zero (Moscoviense and Crisium), and three others have thicknesses that are less than 5 km (Humboldtianum, Apollo, and

Poincaré). Remote sensing data show atypical exposures of olivine-rich materials surrounding some lunar impact basins that could represent excavated mantle materials [25], and the most prominent of these are associated with the Crisium, Moscoviense, and Humboldtianum basins. Our crustal thickness model strengthens the hypothesis that these impact events excavated into the mantle, and given the importance of the mantle in deciphering the origin and initial differentiation of the Moon, these exposures represent prime targets for future sample return missions.

Since the crust of the Moon has experienced only limited volcanic modification, and in addition lacks aqueous and atmospheric erosional processes, the Moon is an ideal recorder of processes that must have affected the crusts of all terrestrial planets at some point in their evolution. Large impact events were common in the first billion years of solar system history, and the crusts of the terrestrial planets would have been fractured to great depths, just as was the Moon. For Earth and Mars, this porosity could have hosted significant quantities of ground water over geologic time [33]. For planets lacking groundwater, such as Mercury, crustal porosity would significantly reduce the effective thermal conductivity, hindering the escape of heat to the surface, and affecting the planet's thermal and magmatic evolution [34].

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Fig. 1.

Bulk density of the lunar crust from gravity and topography data. At each point on a 60-km equally spaced grid, the bulk density was calculated within 360 km diameter circles (spanning 12° of latitude). Thin lines outline the mare basalts, and solid circles correspond to prominent impact basins, whose diameters are taken as the region of crustal thinning in Fig. 3. The largest farside basin is the South Pole-Aitken basin. Data are presented in two Lambert azimuthal equal-area projections centered over the near (left) and far (right) side hemispheres, with each image covering 75% of the lunar surface, and with gridlines being spaced every 30°. Names of prominent impact basins are annotated in Fig. 3.

Fig. 2.
Porosity of the lunar crust, with bulk density from GRAIL and grain density from sample and remote-sensing analyses. Image format the same as in Fig. 1.

Fig. 3. Crustal thickness of the Moon from GRAIL gravity and Lunar Reconnaissance Orbiter topography. With a crustal porosity of 12% and a mantle density of 3220 kg m^{-3} , the minimum crustal thickness is less than 1 km in the interior of the farside basin Moscoviense, and the thickness at the Apollo 12 and 14 landing sites is 30 km. Image format the same as in Fig. 1, and each image is overlain by a shaded relief map derived from the surface topography.