# REVISED THICKNESS OF THE LUNAR CRUST FROM GRAIL DATA: IMPLICATIONS FOR LUNAR BULK COMPOSITION.

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**Introduction:** High-resolution gravity data from GRAIL have yielded new estimates of the bulk density and thickness of the lunar crust. The bulk density of the highlands crust is 2550 kg $m^{-3}$ [1]. From a comparison with crustal composition measured remotely, this density implies a mean porosity of ~12%. With this bulk density and constraints from the Apollo seismic experiment, the average global crustal thickness is found to lie between 34 and 43 km [1], a value 10 to 20 km less than several previous estimates.

Crustal thickness is a central parameter in estimating bulk lunar composition. Estimates of the concentrations of refractory elements in the Moon from heat flow [e.g., 2], remote sensing and sample data [e.g., 3-5], and geophysical data [e.g., 6-7] fall into two categories: those with refractory element abundances enriched by 50% or more relative to Earth, and those with abundances the same as Earth. Settling this issue has implications for processes operating during lunar formation. The crustal thickness resulting from analysis of GRAIL data is less than several previous estimates. We show here that a refractory-enriched Moon is not required.

**$Al_2O_3$ in the crust:** From the average crustal thickness (34–43 km) and estimates of $Al_2O_3$ in the crust, we tested the limits of $Al_2O_3$ enrichment in the Moon. We first considered a one-layer model in which the crust consists entirely of ferroan anorthosite (FAN) with a porosity of 12% and containing 34 wt% $Al_2O_3$. This scenario is clearly unrealistic but provides an upper limit on the amount of $Al_2O_3$ in the crust. The contribution of the crust to the bulk lunar $Al_2O_3$ content (Fig. 1) ranges from 1.75 (34-km-thick crust) to 2.2 wt% (43-km-thick crust). We also examined a two-layer model. The upper layer corresponds to the megaregolith, for which we assume a thickness of 5 km and an $Al_2O_3$ content of 28 wt% (from lunar highland meteorites). We assumed that the lower crust is pure anorthosite [8] and contains 34 wt% $Al_2O_3$. The contribution to bulk lunar $Al_2O_3$ is not markedly different from the pure anorthosite case, ranging from 1.6 wt% (34-km-thick crust) to 2 wt% (43-km-thick crust). Note that in both models, a thick crust (>50 km), as previously thought, contributes substantially more to the bulk lunar $Al_2O_3$ abundance.

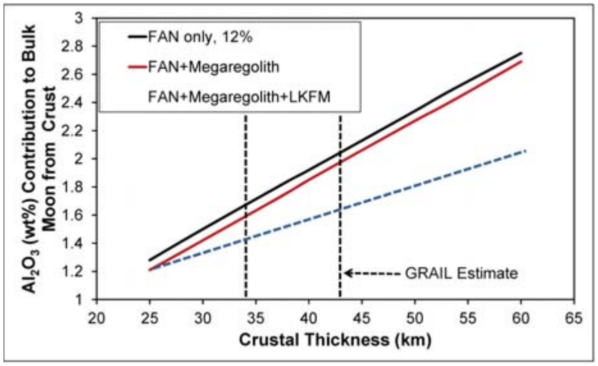

**Fig. 1.** Crustal contribution to bulk lunar Al2O3 as a function of crustal thickness [1].

The third case takes into account the supposition that there must be mafic (noritic) rock in the crust, as demonstrated by the occurrence of Low-K Fra Mauro (LKFM) "basalt," an impact melt common in the Procellarum KREEP Terrane and might be representative of the major-element composition of the interior of the South Pole-Aitken basin [3]. We adopted a three-layer model consisting of 5 km of megaregolith, 20 km of FAN, and the remainder consisting of rock with the composition of LKFM (18 wt% $Al_2O_3$). The thickness of LKFM varies from 9 km to 18 km for our estimated crustal thickness, almost certainly too high, but another useful limit. The presence of abundant mafic material such as LKFM results in a much lower contribution of the crust to bulk lunar $Al_2O_3$ (Fig. 1).

**$Al_2O_3$ in Lunar Mantle:** From the crustal abundance and the assumption that the bulk Moon has the same abundance as the Earth, we can determine the mantle $Al_2O_3$ as a function of the thickness of the crust (Fig. 2). For our estimated crustal thickness, the mantle would contain between 2.2 and 2.5 wt% $Al_2O_3$ if the Moon has the same abundances of refractory elements as does the Earth. For a 50% enrichment compared with Earth, the lunar mantle would have 4.3–4.7 wt% $Al_2O_3$ (Fig. 2).

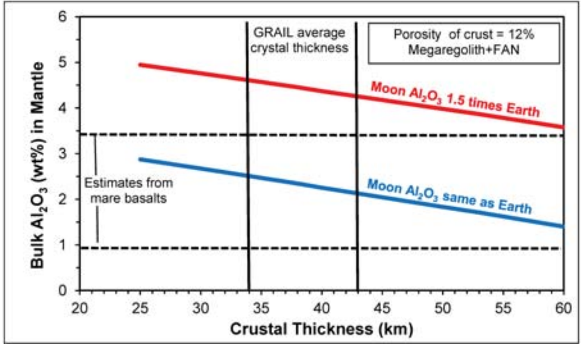

**Fig. 2.** $Al_2O_3$ in mantle as a function of crustal thickness, compared with estimates of $Al_2O_3$ in mare basalt source regions.

We can test these estimates against other data. Modeling of seismic data yields $Al_2O_3$ estimates that range from 2.2–3.1 wt% for the bulk mantle [9] to 2.0 wt% for the upper mantle and 6.7 wt% for the lower mantle [6]. The mantle source regions of mare basalt primary magmas (e.g., see list in [10]) provide complementary information. Multiple saturation experiments on these compositions show that pyroxenes in equilibrium with the magmas contain 1.4 to 6 wt% $Al_2O_3$, with most values in the range 2–3 wt%. If olivine (which is Al-free) constitutes less than half of the residue, then the source regions are left with 1–1.5 wt% $Al_2O_3$ after mare basalt magmas were removed. The magmas contained ~8 wt% $Al_2O_3$, indicating that the initial $Al_2O_3$ concentration was about 1.8–2.3 wt%, for 10% partial melting. A more elegant way to calculate the source region $Al_2O_3$ is to use the experimentally determined partitioning coefficient for orthopyroxene (the most abundant pyroxene), taking pressure into account [11]. Equilibrium partial melting of primary mare basalt magmas containing 8–13 wt% $Al_2O_3$ (including aluminous mare basalts) and 20–50% olivine gives an initial mantle source $Al_2O_3$ content of 0.8 to 3.5 wt%, as indicated in Fig. 2. Thus, essentially all mantle $Al_2O_3$ contents are in the expected range for an Earth-like abundance for crustal compositions in the range we estimate from GRAIL data.

**Th in the mantle:** If lunar refractory element abundances are the same as in Earth, we can estimate Th in the mantle from its abundance in the crust. We used the approach taken earlier [5] to assess the crustal abundance of Th. Besides the thickness of the crust, the most important parameter is the proportion of the crust that is composed of LKFM and the Th content of LKFM. With judicious assumptions for these parameters, we estimate that bulk crustal Th ranges from 0.61 to 0.91 µg/g (Fig. 3). The average Th in the mantle required for the Moon to have the terrestrial Th abundance (0.0795 µg/g [12]) ranges from 0.03 to 0.05 µg/g. These values are somewhat higher than an earlier estimate [4]. We use Th concentrations in mare basalts to estimate Th contents of their source regions (Fig. 3) under 5 or 10% partial melting. The inferred range is very large, indicating that Th is heterogeneously distributed in the mantle. However, it is important to keep in mind that mare basalt source regions may not be representative of the entire mantle [4].

**Implications:** The crustal thickness derived from GRAIL data leads to the conclusion that the bulk Moon has abundances of refractory elements similar to Earth. Processes operating during lunar formation did not fractionate these elements. Geochemical uncertainties arise from the heterogeneous distribution of Al, and particularly Th in the crust and mantle, and a lack of knowledge of the composition of the lower mantle.

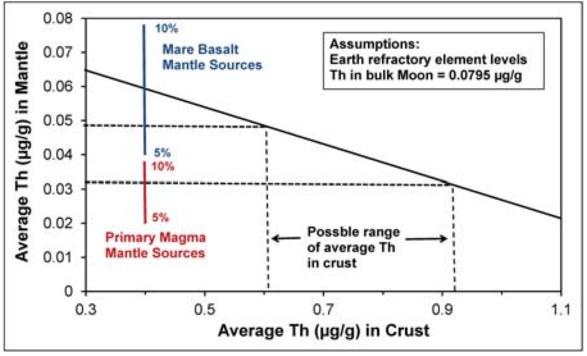

**Fig. 3**. Mantle Th content for a terrestrial abundance of refractory elements.

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