# REVISED ESTIMATION OF THE BULK COMPOSITION OF THE MOON IN LIGHT OF GRAIL RESULTS, AND WHY HEAT FLOW SHOULD BE A TOP PRIORITY FOR FUTURE LUNAR MISSIONS.

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The elemental composition of the Moon shows aspects of similarity but also some important differences relative to Earth. The differences are key constraints for modeling the origin of the Moon and planetary origins in general. Most obviously, and regardless of the important FeO issue that is a major focus of this work, the Moon's total iron content is lower by a factor of 3-4 compared to Earth's total iron of ~34 wt%.

Recent analyses have revealed that "water" (OH) is vastly more abundant in lunar rocks than previously supposed [e.g., 1-2]. Still, as discussed in a companion abstract [3], hydrous phases and hydrothermal alterations are virtually nonexistent and the Moon is clearly volatile-depleted. Lunar rocks show depletion relative to their terrestrial counterparts by a factor of 5-10 in Na, and by factors of roughly 20 for volatiles such as In and Bi [4]. The well constrained ratio K/Th is lower in lunar rocks by a factor of ~5 [5].

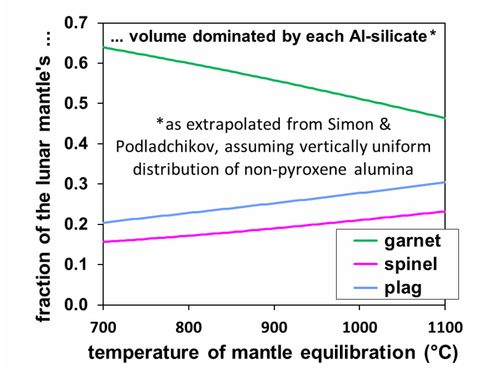
It has often been suggested that the Moon is enriched, versus the silicate Earth, in the whole class of refractory lithophile elements ($Al_2O_3$, CaO, $TiO_2$, and ~ 25 trace elements, including U, Th, REE) [*e.g.*, 5]. However, motivation for the refractory-enrichment hypothesis has recently nose-dived. Orbital measurements revealed that the nearside Apollo region is atypically Th-rich [6]. Reassessments of the lunar seismic data indicate the crust, which contains a major fraction of the Moon's total refractory lithophiles, is much thinner than previously supposed [7]. Gravity results from GRAIL confirmed the thin crust models, and also revealed that the crust is far more porous than previously supposed [8]. The mass of the crust now appears lower by a factor of 2.4 in comparison to the premise of, *e.g.*, [5]. By substituting the crustal mass from [8] for the one assumed by [9], and retaining the assumptions of [9] about mantle Th, we derive an estimate of 65 ng/g for the bulk-Moon Th content; and we model other refractory lithophile elements in chondritic proportion to Th (possibly Th is slightly depleted compared to less extremely incompatible elements, but see [10]). The net result for the refractory elements is no significant difference in comparison to the consensus-estimated composition of the silicate Earth [9].

The bulk-Moon $SiO_2$ content is not especially well constrained. It is customary to assume similarity to the silicate Earth, *i.e.*, a low-pressure *py* (≡ pyroxene/[pyroxene+olivine]) ratio of about 30 vol%, where *py* is basically a function of $MgO/SiO_2$. Compared to the noncarbonaceous types of chondrites that most closely match the Earth and Moon in stable-isotope space [11], by most estimations both bodies have elevated $MgO/SiO_2$. Earth's $MgO/SiO_2$ may have been fractionated by sequestration of Si as a high-pressure siderophile into the core [12].

The bulk-Moon FeO content is in many respects most easily gauged by constraining the ratio that petrologists call *mg*, i.e., MgO/[MgO+FeO]. Certainly the mare basalts, which typically have *mg* of about 40-60 mol% [4] derived from source regions with roughly 20 mol% lower *mg* than the Earth's mantle (89 mol%). Typical bulk-Moon *mg* estimates are in the range 81-84 mol%. However, the mare sources are believed to have formed mainly as cumulates from an evolved, late-stage remnant of the primordial magma ocean; and diminution of *mg* is one of the hallmarks of basaltic (and especially low-$fO_2$ basaltic) fractional crystallization. Also, melting of these sources was not aided by plate-tectonic vagaries, such as upwelling at mid-ocean ridges, so the most evolved parcels of the lunar mantle were probably favored sites for anatexis. Warren [13, 9] argued that the high *mg* of many Mg-suite highland rocks, and the moderate *mg* (up to 73 mol%) of highland regolith samples (blends of regional bulk upper crust), are indications that the lunar mantle as a whole is far less ferroan than the mare sources.

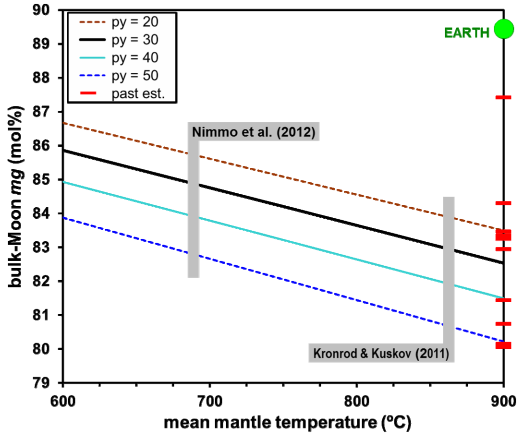
One way to constrain the bulk-Moon *mg* is by application of the improved array of geophysical constraints on the lunar interior. The usual interpretation of the sparse seismic data favors a low *mg* [e.g., 7, 14]. A more Earthlike *mg* is possible, if the mantle's *py* ratio is higher than Earth's [9]. The seismic data have been used to tease out constraints on the size and density of the lunar core. Weber et al. [15] estimate the core's radius at 330 ± 20 km, and its mean density at 6.22 g/cm$^3$. GRAIL mission has provided dramatically improved global gravity data [8], and the crust's average thickness is now inferred to be only ~34.5 km. Considering that [8] derived 2.55 g/cm$^3$ for the density of the "highland crust", we take 2.60 g/cm$^3$ for the density of the total crust. Together, these constraints, along with the Moon's radius of 1737.4 km and total lunar mass of $7.346\times10^{22}$ kg, imply a precisely constrained density of 3.369 g/cm$^3$ for the bulk mantle.

Since the lunar mantle consists preponderantly of just two similar-density mafic silicate minerals, olivine and pyroxene, this density constraint can be used to constrain the bulk-mantle *mg*. A few percent of Al-silicate phase is also present, but *in its current thermal condition* most of the lunar interior has garnet as the preponderant Al-silicate (Fig. 1; extrapolated from



[16]). In shallower parts, the mantle Al-silicate is spinel or plagioclase. The exact proportions depend on the *T* to which the mantle mineralogy has equilibrated (after 4 Gyr of cooling) and the vertical distribution of Al within the mantle, but probably the overall mantle Al-silicate density is in the range 3.3-3.5 $g/cm^3$; i.e., so close to 3.369 $g/cm^3$ that the exact proportion of Al-silicate is, for bulk *mg* estimation, inconsequential.

We also assume, by implication from the bulk-Moon refractory-lithophile inventory (see above) 0.25 vol% of mantle ilmenite. Temperature is the key unknown. Thermal expansion and pressure compression are modeled by the methods of [17], but the mean temperature $T_{\rm m}$ of the lunar mantle is not well known. Models discussed by [18] and [19] indicate 690-870°C. Older models reviewed in these papers extend to both lower and (more commonly) higher extremes. Our density-keyed modeling for 750°C suggests a bulk-Moon *mg* of 84.2 mol%. Results are shown as a function of $T_{\rm m}$ and *py* (and assuming 4 wt% of Al-silicate of mean density 3.4 $g/cm^3$) in Fig. 2.



Taking all of the above constraints (including the highland rock and regolith *mg* data) into consideration, our best estimate for the bulk-Moon *mg* is 85 mol% (see Fig. 2 for a comparison with previous estimates). This carries an implication that FeO is enriched by a factor of ~1.36 relative to the silicate Earth (Table 1). However, the uncertainty (one-sigma) in this estimate, realistically, is probably close to 0.2 (*i.e.*, 2 mol% in *mg*); leaving a slight chance that the Moon's *mg* is fully as high as that of the bulk-silicate Earth. Our estimate for the bulk composition of the bulk silicate Moon (Table 1) is modified from the estimate of Warren [9] by the aforementioned increase in FeO (reducing *mg* from 87.4 to 85 mol%); by reduction of Th from 71 to 66 ng/g; with 27 other refractory lithophile elements, including Al and Ca, reduced by the same factor; and by moderation of the $MgO/SiO_2$ ratio from 1.1× CI-chondritic to 1.0×. This $MgO/SiO_2$ modification keeps the implied *py* ratio relatively unchanged.

***Discussion:*** The nominal uncertainty in core radius cited by [15], 20 km, corresponds to 1.0 mol% of implied bulk-Moon *mg*. It is far from certain that the lunar mantle is devoid of the high-density phases that are assumed perfectly concentrated into the core. If the same 1 wt% concentration of $Fe^0$ that some [19] have proposed is stable (fails to sink into the core) in the Earth's deep mantle, were present in the lunar mantle (as an unsunken, never-oxidized "late veneer"), our *mg* results would need to be increased by 5 mol%. Otherwise, *the biggest uncertainty in this approach is temperature*. The Nimmo et al. [18] selenotherm (assuming *py* = 30 mol%) implies a bulk-Moon *mg* of 84.9 mol%; that of [14] implies 82.9 mol%. More lunar heat flow data, to augment the pathetically few (2) Apollo HF measurement sites, would not only definitively test the inference of Earthlike concentrations of refractory lithophile elements, they would also, by constraining the interior *T*, go a long way toward determining the bulk-Moon's precise *mg* and thus its [FeO].

Table 1. Estimated bulk composition of the bulk silicate Moon (wt%, excerpt Th, ng/g, V and Ga, µg/g).

| | Th | $Na_2O$ | MgO | $Al_2O_3$ | $SiO_2$ | CaO | $TiO_2$ | $Cr_2O_3$ | MnO | FeO | V | Ga | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| New estimate | 66 | 0.05 | 33.7 | 3.59 | 48.2 | 2.84 | 0.17 | 0.44 | 0.152 | 10.6 | 101 | 0.51 | 99.8 |
| Bulk silicate Earth* | 75 | 0.34 | 36.4 | 3.97 | 47.2 | 3.19 | 0.19 | 0.40 | 0.132 | 7.67 | 92 | 3.7 | 99.5 |

* Average of 7 estimates for bulk silicate Earth, from review by Warren (2005).

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