BULK COMPOSITION OF THE MOON: A POST-CLEMENTINE, PRE-PROSPECTOR APPRAISAL

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The bulk composition of the Moon is one of the key constraints on its origin, and thus also on the origin of its primary, Earth. As an immediate reaction to the Apollo 11 discovery that many mare basalts are remarkably high in Ti and extremely volatile-poor, plus the simultaneous inference that the nonmare crust is highly anorthositic, the notion became popular that the Moon must be enriched in refractory lithophile elements in comparison to chondritic materials, or to the bulk Earth. The refractory lithophile elements (RLE) include the major elements Al and Ca, plus nearly all of the highly incompatible (or KREEPy) elements such as REE, Th and U. These elements are a geochemically coherent set during main-stage nebular processing, and even during some forms of low-pressure igneous processing (but plagioclase fractionation causes Al and Ca to fractionate apart from the incompatible RLE). The undoubted depletion of the Moon in a few tens of percent of metallic (core) matter, and in <1% of minor and trace volatile elements (most notably NaO and K2O), obviously implies at least a few tens of percent of counterbalancing enrichment in the RLE. However, the persistent widespread enthusiasm for greater enrichments, significantly above the RLE levels of the Earth’s "primitive mantle" (mantle+crust) [e.g., 1], rests on some questionable assumptions and extrapolations that will hopefully soon be tested by global geochemical data from the Lunar Prospector mission, and by seismic and heat-flow data from planned Japanese penetrator missions.

Actually, some of the assumptions that have formed the basis for the RLE enrichment hypothesis can already be questioned. A recurring theme among advocates of RLE enrichment has been application of mass balance, i.e., extrapolation from the average nonmare surface composition, assumed representative of the entire crust, to constrain the Moon's bulk composition. Symptomatic of the case that has been made for the RLE enrichment, these models typically [e.g., 2-3] assume that 12 wt% of the Moon is represented by the surface composition, based on the volume percentage that corresponds to the pre-Clementine estimation (73 km) of the average crustal thickness. Actually, since these models assume bulk-crust compositions with \( \approx 25 \text{ wt}\% \mathrm{Al}_2\mathrm{O}_3 \), they imply crustal densities of \( \approx 2.92 \text{ g/cm}^3 \) (or even lower assuming slight porosity). The bulk-Moon density being 3.34 g/cm\(^3\), the wt% of the Moon contributed by its crust, assumed 73 km thick and 2.92 g/cm\(^3\), is only 0.87\% as great as the vol%. In addition, the post-Clementine estimation of average crustal thickness is 64 km [4], bringing the implied wt% contribution of the crust down to \( \approx 0.77x \) the percentage assumed by [2] and [3].

The Moon's crust is probably not quite an anorthositic at depth as the surface composition. But even assuming it is, mass balance for a bulk Moon with the same \( \mathrm{Al}_2\mathrm{O}_3 \) content as Earth's primitive mantle (EPM, \( = 3.6 \text{ wt}\% \)) would still imply that fully 1/3 of the total \( \mathrm{Al}_2\mathrm{O}_3 \) remains in the mantle — despite the expectation that during magma ocean crystallization plagioclase would efficiently float toward the surface. Invoking a significant bulk-Moon enrichment of say 1.5x EPM implies that over 50% of the Moon's total \( \mathrm{Al}_2\mathrm{O}_3 \) has mysteriously remained in its mantle.

More elaborate arguments for RLE enrichment have involved mass balance for K, Th and U [2-3], again predicated on the questionable assumption that the average surface composition, using the canonical estimate of [5], is representative of the entire thickness of crust. Th and U are strongly KREEP-correlated elements. They both emit natural radioactivity, and thus can be mapped by orbital spectrometry, as applied to about 20% of the Moon's surface by the Apollo program, and hopefully soon to the entire surface by Prospector. Actually, we do not have to wait for Prospector for a global map of Th-U distribution. A long-neglected resource for lunar science is a nearly global map of combined Th+U activity, published by Surkov [6-7] using data from the 1966 Luna 10 and 20 missions. Surkov's map is problematical. Besides being based on ancient and thus mildly questionable data, the map only vaguely indicates its spatial resolution, appears slightly misaligned for the central far side (Van de Graaff is shown at 159°E; the true position is 172°E), and only indicates Th+U levels in terms of five categories (from "very low" to "high"), the meanings of which, in terms of µg/g concentrations of these two tightly correlated elements, is never defined, except indirectly. Fig. 1 shows this map translated onto an azimuthal equal-area projection, where darkness of symbol correlates with the Th+U abundance category. I have deduced the quantitative meanings of the categories such as "very low" and "low" by comparing Surkov’s assignments for the nine Apollo+Luna sampling sites, vs. the well-determined average regolith compositions at these locations. The "very low" to "low" cut-off is the most difficult to deduce, but must correspond to Th being <<1 µg/g. The "low" to "medium/low" cut-off corresponds to Th = roughly 1.5 µg/g. The "high" category signifies Th > about 8 µg/g.
The Clementine mission provided the first detailed observations on the giant South Pole Aitken (SPA) basin. Based on the limited Apollo orbital spectrometry data, Th+U (i.e., KREEP) appears strongly concentrated along the margins of the two great near side basins, Procellarum and Imbrium. But Apollo orbital coverage only extended to the northern edge of SPA, near van de Graaff, where a mild Th+U hot spot (Th =2.5 µg/g) was detected within the otherwise consistently KREEP-poor far side highlands [5]. However, the Luna 10-12 data (Fig. 1) include five “points” almost precisely on the E and W margins of SPA, plus one “point” only a few hundred km from its center. These positions are all “very low” in Th. Prospector will soon provide the true test, but the Luna 10-12 data already available strongly suggest that the SPA region is not appreciably more Th-rich than the rest of the far side. Thus, any inventory of the total Th+U in the Moon’s crust [5] must be extremely sensitive to assumptions about how far the Imbrium-Procellarum hot zone extends to the N and S (its E-W extent is already well constrained by Apollo data). The one “point” on Surkov’s [7] map that constrains this problem (for the highland just S of central Frigoris) indicates the northern margin of Imbrium is far less Th-rich than its central and southern margins. In short, the Luna 10-12 orbital spectrometry data suggest that the Apollo orbital database [5] is probably unrepresentative, implying higher mean surface Th+U than actually occurs.

As noted previously [8], Th vs. K/Th systematics for lunar meteorites (3/4 of which are regolith breccias, mostly with remarkably low Th+U) clearly indicate that many of the K data in the Apollo orbital database of [5] were spuriously high.

The magnitude of RLE in the bulk-Moon composition remains an open question. But for purposes of constraining the origin of the Moon [2-3], I would rather adopt the simpler assumption that bulk-Moon RLE concentrations are not greatly different from those of Earth’s primitive mantle — a material that resides in the same small region of the Solar System, and features a virtually identical set of oxygen isotopic ratios [9].