

BULK COMPOSITION OF THE MOON: IMPORTANCE, UNCERTAINTIES, AND WHAT WE NEED TO KNOW.

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Introduction: The bulk composition of the Moon is important to test models for how the Moon formed and to understand how the terrestrial planets accreted. Models of the accretion of the terrestrial planets from a disk of lunar to Mars-sized embryos [1] indicate widespread mixing of the embryos and their fragments, so that each terrestrial planet formed from material originally located throughout the inner solar system (0.5 to 2.5 AU). Such a process would erase any initial radial chemical variations in the compositions of the planetesimals and in the final assembled planets. However, Robinson and Taylor [2] suggest that a distinct compositional gradient remains as shown by the FeO contents of the terrestrial planets: Mercury (3 wt%), Venus and Earth (8 wt%), and Mars (18 wt%). Drake and Righter [3] discuss the unique composition of the Earth and also conclude that planets accreted mostly from narrow feeding zones. Knowing the composition of the Moon will help us understand the full extent of the Earth's accretion zone. We examine what we know about the composition of the Moon, with emphasis on elements that can be determined by remote sensing techniques (FeO, Al₂O₃, and Th).

The Complex Structure and Composition of the Crust: The Clementine and Prospector missions have revolutionized our view of the lunar crust, but numerous uncertainties remain. For example, Jolliff et al. [4] identified several compositionally distinct terranes on the Moon. The compositions of the terranes are reasonably well established, but the volumes they occupy are not known very well. Using their nominal values for volumes and Th contents, and our measurements of FeO and Al₂O₃, we infer that the crust contributes 0.11 ppm Th, 0.6 wt% FeO, and 2.9 wt% Al₂O₃ to the lunar bulk composition. In contrast, we [5-7] have presented a somewhat different view of the crust. We suggest that it is layered with an upper mixed, somewhat mafic zone, underlain by an anorthosite zone, which overlies a more mafic lower crust. Using the volumes given by Taylor et al. [6], but with Jolliff's Procellarum KREEP terrain added as a separate unit, we calculate the following contributions to the lunar bulk composition: Th, 0.14 ppm; FeO, 0.7 wt%; Al₂O₃, 2.7 wt%. Both estimates indicate Th higher than in the nominal primitive terrestrial mantle (0.08 ppm [e.g., 8]). On the other hand, a reinterpretation of the lunar seismic data [9, 10] suggests that the crust might be only 40-50 km thick, much thinner than previous estimates. If correct, this will lower Th and Al₂O₃ in the calculated bulk Moon.

Mantle Composition: We know even less about the mantle. We can use the compositions of mare basalts to estimate the composition, but there are great uncertainties in Th, because magmas likely assimilated KREEP as they migrated

to the surface. One could assume that Th concentrated almost completely in the crust during initial lunar differentiation, leaving essentially none in the mantle, but we do not know if all lunar material participated in the primary differentiation. Experiments on mare basalts suggest derivation from olivine-pyroxene sources with FeO around 18 wt%, which would contribute 16.5 wt% FeO to the lunar bulk composition (if the mantle is 89.8 wt% of the Moon). The experiments also indicate that aluminous phases were exhausted, so Al₂O₃ might have been about 0.4 wt% in the mare basalt source regions. However, as Warren [11] has noted, mare basalts may come from an atypical region of the mantle. More magnesian and feldspathic rocks, such as the parent magmas of the Mg-suite rocks, would come from less FeO-rich (about 7 wt% if the parent was something like the HON composition [12]) and more aluminous (1-2 wt%). If 90% of the mantle was like this composition the lunar bulk FeO would be the same as the terrestrial bulk FeO (8 wt% [e.g., 8]; Al₂O₃ would be about 4 wt%, not too different from Earth (4.4 wt% [8]).

Data Needed: It is essential to determine the detailed structure of the crust and mantle. This requires emplacement of a global seismic network, preferably using a long-lived power source for extended operation over the course of at least 3-5 years. We also need to know the MgO and Al₂O₃ contents of the crust (the values for Al₂O₃ in the crust discussed above are inferred from the FeO content and the well established inverse relationship between FeO and Al₂O₃). This would give us a firmer handle on the abundance and nature of magnesian rocks in the crust. These elements can be measured from orbit with x-ray spectrometry.

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