**THE MAFIC COMPONENT OF THE LUNAR CRUST.** Sarah T. Crites[1,]*, Paul G. Lucey[1], Jessica A. Norman[1], G. Jeffrey Taylor[1], B. Ray Hawke[1], Myriam Lemelin[1] [1]Hawai'i Institute of Geophys. & Planetology, 1680 East-West Rd., Honolulu, HI 96822, *scrites@higp.hawaii.edu.

**Introduction:** The lunar magma ocean hypothesis is well supported by both samples (e.g. [1][2][3]) and remote sensing (e.g. [4][5][6][7][8]). However, remote sensing observations by the Lunar Prospector gamma ray spectrometer [5] reveal that the typical lunar highlands surface contains 4-5 wt% FeO, equivalent to 15% or more mafic minerals, more mafic than strictly defined anorthosites. This raises the question of the origin of the mafic component in the lunar highlands crust.

We offer three hypotheses for the surface iron enrichment: 1) pure lunar anorthosites are contaminated by impact gardening of local mafic igneous intrusions and ancient volcanism [9]; 2) the highlands regolith is dominated globally by ejecta of very large basins, which includes mafic lower crust or upper mantle material [10] or 3) the lunar anorthosites themselves are inherently more mafic than the strict definition as suggested by Warren [2], with pure plagioclase detections the exception and not the rule.

We use new global mineral mineral maps based on Clementine spectra [11] and reconciled with Lunar Prospector neutron and gamma ray data as inputs to mixing models to examine the plausibility of the three sources of mafic material. We use a global spectral survey of of 4506 immature craters with diameters less than 1 km using near-IR data from the Kaguya Spectral Profiler as a constraint on mantle composition assuming the uppermost regolith sampled by these small craters is dominated by large basin ejecta [12].

**Methods:** We calculated 19 mixing models assuming different combinations of post-magma ocean igneous activity, mantle material excavated by large basins, and inherent mafic content of magma ocean anorthosites to account for the mafic minerals present in our Clementine and Lunar Prospector-based mineral maps. Table 1 summarizes the values for the variables used in our models: anorthosite mafic content; the maximum amount of mantle material excavated; and the presence of clinopyroxene in the mantle. For each combination of variables we used the mineral abundances to calculate the distribution of lunar rock types representative of each mafic source: anorthosite, the major crustal magma ocean product; norite, troctolite, and gabbro or mare basalt, used to represent post-magma ocean igneous intrusive or extrusive volcanism and mare basalt contamination; and dunite and pyroxenite, ultramafic rock types representing the lunar mantle.

We followed the method of Spudis [13] to calculate the total volume of ejecta and the proportion of this ejecta derived from the lunar mantle for each of the 42 largest lunar basins identified by [13] as well as the South Pole-Aitken Basin (SPA). In this method the excavation cavity is modeled as a sphere intersecting the sphere of the Moon, with the circle of intersection between the two spheres defined by the transient crater diameter. The depth excavated, or the depth to diameter ratio, can be changed by varying the radius of the excavating sphere and the distance of its center from the center of the Moon. Our initial calculations used a depth to diameter ratio of 1/10 [13] and using crustal thicknesses of 34 and 43 km [14] we obtained estimates of 30 to 40 vol% mantle that could be present in the uppermost regolith.

**Results and implications:** The results of our mixing models, along with the observations of Cheek et al. [8] that the Inner Rook Ring of the Orientale basin is almost entirely dominated by anorthosites with <1 vol% mafic minerals, with more mafic feldspathic material found elsewhere in the basin more susceptible to mixing, strongly suggest that, across vast regions of the lunar surface, the lunar magma ocean produced

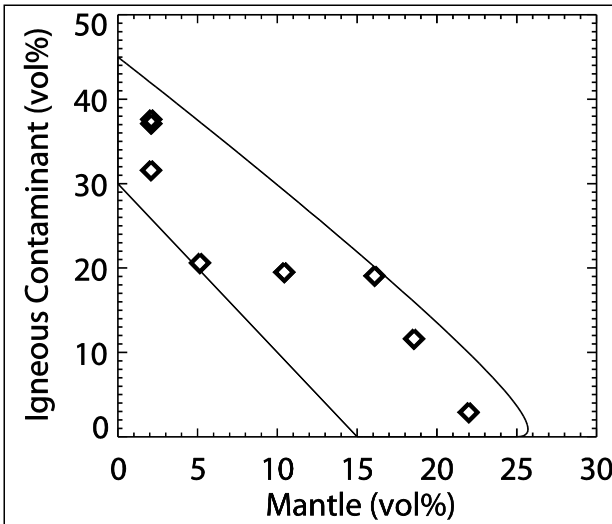

**Figure 1**. Summary of the range of abundances of sources of mafic contaminant consistent with our mineral maps. Open diamonds show scenarios calculated in this work. "Igneous contaminant" includes the highland rock types norite, troctolite, and gabbro as well as mare basalt.

anorthosite with inherently low mafic contents. In all mixing model scenarios that assumed anorthosites contain 15 vol% mafic minerals, 66% or more of highland pixels were inconsistent with the observed mineralogy of the highlands, whereas if anorthosites were assumed to contain 2 vol% mafics only 7% of pixels encountered no solution.

The total amount of mafic contaminant of the anorthositic primary crust ranged from about 15 vol% if all mafics originated in the mantle, to 45% if all mafics were in post-magma ocean igneous activity. This is in good agreement with the estimate of Warren [2] that 45-75% of the highlands crust is made up of direct products of the magma ocean (ferroan anorthosite suite rocks) (Figure 1). The occurrence of high-Ca pyroxene in the mantle exerts strong control over the maximum amount of mafic material that can be attributed to mantle ejecta. Mixing models that permitted high-Ca pyroxene in the mantle resulted in about 20 vol% mantle material in the lunar highlands, if all mafics not in anorthosites were assigned to the mantle**.**

To constrain the high-Ca pyroxene content of the mantle we obtained spectra from the SELENE (Kaguya) Spectral Profiler for ~2700 individual non-mare craters with diameters <1 km in order to sample the mega-regolith, assuming it is largely comprised of large-scale basin ejecta [12]. We estimated pyroxene chemistry based on the minimum position of the 1-um band, and find for the vast majority of the feldspathic highlands small crater population no high-Ca pyroxene is present. These results strongly support an orthopyroxene-dominated upper mantle. Mixing models based on this constraint and assuming a clinopyroxene-free mantle resulted in a maximum of 10 vol% mantle material in the highlands, which allows us to place an upper limit on the mantle contribution to the mafic component of the lunar highlands.

This upper limit of 10 vol% mantle material indicates that the simple basin ejecta model used to estimate a mantle component of 30-40 vol% significantly overestimates the amount of mantle material excavated. If the depth to diameter ratio in these simple calculations is adjusted to between 0.035 and 0.06 for the excavation cavities of the basins, mantle excavation estimates in agreement with the maximum permitted by the mineral maps can be obtained.

**Conclusions:** Our mixing models indicate that anorthosites are likely very low mafic, providing support for the observations by Cheek et al. [8] in the Orientale region and a basis for extending these observations to the rest of the lunar highlands. The small crater survey suggests that the lunar mantle is likely orthopyroxene rich, and as a result we conclude based on our mixing models that the mantle ejecta component of the highlands crust is less than 10 vol%, requiring 15-45% post-magma ocean igneous component (Figure 1). The mantle ejecta volume constraint also allows us to conclude based on simple basin ejecta models that the depth of excavation for the largest lunar basins was shallower than the 1/10 depth to diameter ratio observed for smaller basins, and is in agreement with the gravity observations of Wieczorek and Phillips [18] that SPA, Imbrium, and Serenitatis likely formed under anomalous conditions that led to shallow excavation cavities (near 0.05 for Serenitatis and Imbrium and near 0.01 for SPA).

**Table 1.** Compositional variable values used in models

| | | |
|---|---|---|
| Anorthosite mafic content (%) | 0 | Extreme case: pure anorthite |
| | 2 | [6] |
| | 7 | [15] |
| | 15 | [2] |
| Upper limit on mantle component in crust (%) | 0 | Extreme case: no mantle excavated |
| | 2 | [16] via [12] |
| | 20 | [17] via [12] |
| | 30 | [13], thick crust |
| | 40 | [13], thin crust |
| | No limit | Extreme case: all excess mafics attributed to mantle |
| Cpx limit in mantle | No limit | CPX permitted in mantle |
| | 0 | All CPX due to mare basalt |

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