POST-MAGMA OCEAN IMPACT AND IGNEOUS CONTRIBUTIONS TO THE LUNAR HIGHLANDS CRUST.

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Introduction: The lunar magma ocean hypothesis (e.g. [1]) provides the framework through which we understand the lunar highlands crust and basic lunar geology. In this scenario, plagioclase flotation on a dense magma ocean formed the Moon's primary anorthositic crust. That significant contributions of mafic material have been added to the anorthositic highlands crust is clear from gamma-ray spectroscopy measurements which show the typical lunar highlands contains 4-5 wt% FeO (about 15 vol% mafic minerals) [2], together with recent work that indicates the magma ocean likely concentrated plagioclase to an extreme degree (typically < several % mafic minerals) in the primary flotation crust [3][4].

We utilize improved, high resolution mineral maps [5] to revisit the three endmembers investigated by Crites et al. [6] as mafic contributors to the highlands crust: (1) inherently mafic lunar anorthosites [7]; (2) mafic post-magma ocean intrusive or extrustive igneous material [8]; and (3) mafic lower crust or mantle material excavated by large basins [9].

Methods: Lemelin et al. [5] used Kaguya Multiband Imager Data and radiative transfer modeling to produce quantitative mineral abundance maps of the lunar surface at 60-m resolution. The maps are produced from spectral mixtures of olivine, high-Ca pyroxene, low-Ca pyroxene, and plagioclase covering the full range of compositions defined for lunar highland rocks. These maps provide a starting point for our mixing model analysis.

Mineral map validation. Elemental abundances measured by gamma-ray spectroscopy are highly complementary to mineral abundances from near-infrared spectroscopy. We first use the Lunar Prospector gamma ray spectrometer oxides [2] as an independent evaluation and validation tool for the Kaguya Multiband Imager-based spectral mineral maps. Using simple stoichiometry along with assumptions about solid solution mineral chemistry, we convert the mineral abundances to oxides and downsample to 2 ppd for direct comparison with the gamma ray oxides. We confirm that, with a few excursions, the Lemelin et al. [5] mineral maps at global scale are in good agreement with Lunar Propector gamma ray measurements (selected oxide relationships shown in Fig. 1).

Modeling rock types. We follow the approach described in detail by Crites et al. [6] to model the abundances of various types of lunar rock types representing different sources: mantle ejecta (dunite, pyroxenite); post-magma ocean highlands igneous activity (troctolite, norite, gabbro); and mare basalt.

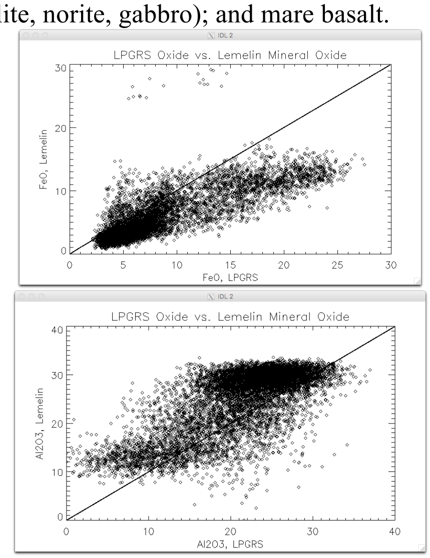

Fig. 1. Comparison of Al_2O_3 and FeO measured by LP GRS [2] with the same oxides calculated from Lemelin et al. [5] mineral maps. Both datasets are presented at 2 ppd and the line indicates a 1:1 correlation.

The compositions of each endmember rock type are based on average lunar sample compositions or simple assumptions (e.g. the dunite endmember is assumed to be 100% olivine). We test a variety of anorthosite endmembers, including pure plagioclase, "purest anorthosite" or PAN, with 2% mafic minerals, the lunar sample average of 7% mafic minerals, and a mafic endmember with 15% mafic minerals. In this study we focus on the composition and history of the lunar highlands crust and mask out the lunar nearside maria (in this work, defined as the nearside regions with FeO > 10 wt %).

Results & Summary: *Highland rock type distributions.* The result of each mixing model is a series of rock type abundance maps showing the distribution of primary magma ocean anorthosite, igneous rocks, and/or mantle material for a given set of assumptions (Fig. 2 shows one of 29 scenarios calculated in this work). The high spatial resolution of the base mineral maps mean that the distribution of modeled rock types can be investigated at a highly local scale.

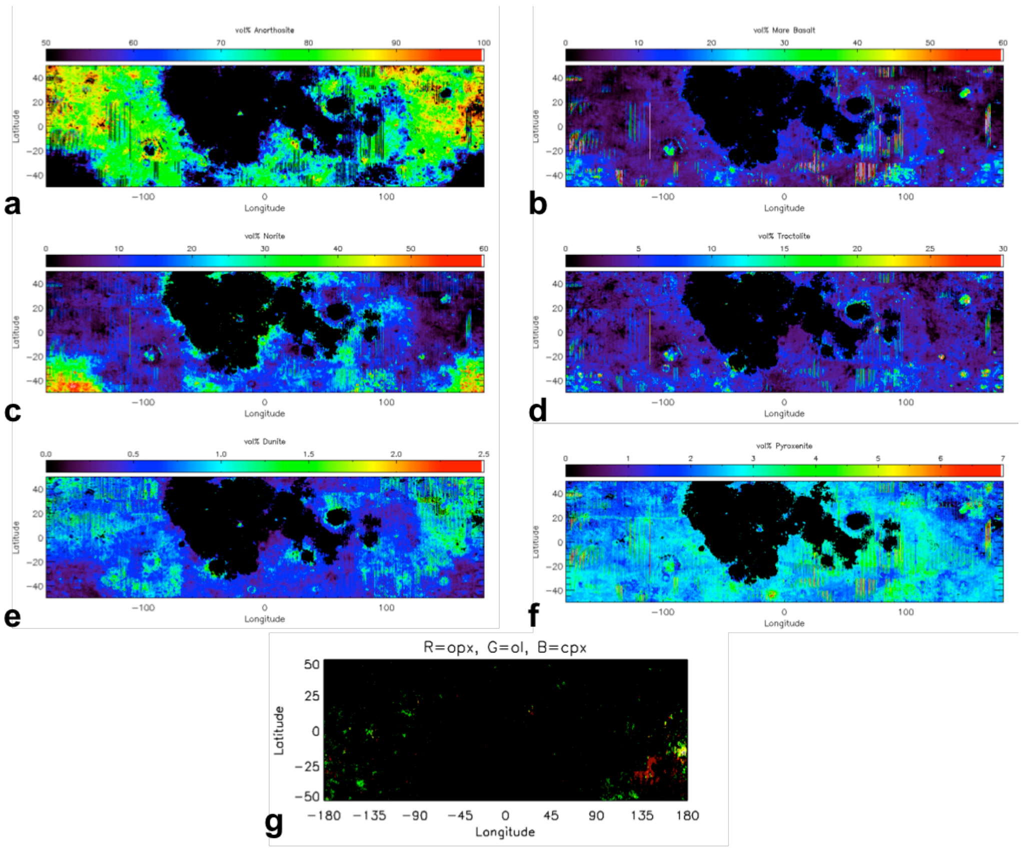

Fig. 2. Calculated abundances of (a) anorthosite, (b) mare basalt, (c) norite, (d) troctolite, (e) dunite, (f) pyroxenite, and (g) the limiting mafic mineral for all pixels returning no solution following the approach of [6]. This scenario was calculated with purest anorthosites (2 vol% mafic minerals), 2 vol% mantle material permitted, and all excess clinopyroxene not assigned to the mantle assigned to mare basalt.

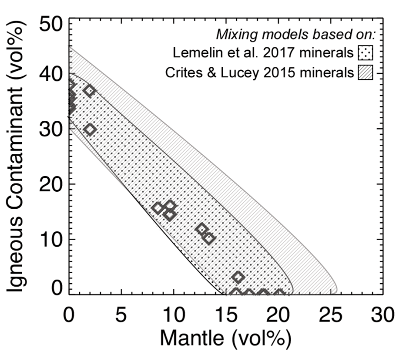

Fig. 3. Summary of mixing models showing the range of mafic contaminant to the highlands crust from different sources. Dots show range covered by the 29 models calculated in this work; diamonds show selected models; lined region shows range covered [6].

The new, higher-resolution mineral maps of [5] reveal more plagioclase-rich regions and mixing models based on these maps strongly support a relatively pure anorthositic endmember, with all scenarios incorporating "mafic anorthosites" (15% mafics) encountering no solution over 90% or more of highland pixels. The average abundance of anorthosite in the highlands is relatively constant, in the range of 60-80%. The remainder of the highlands crust is made up of either ejected mantle (15-20%) or igneous material (30-40%). These results are in overall agreement with the conclusions of [6], indicating that between 15-40% of the highland crust is made up of non-primary magma ocean products, and also places strong constraints on the excavation depths of lunar basins, with a maximum of 20 vol% mantle material permitted.

References: [1]Wood, J.A., et al. (1970), *Proc. Apollo 11 LSC*, p. 965–988. [2]Prettyman et al. (2006), *JGR*, *111*, E12007. [3] Ohtake, M. et al. (2009), *Nature, 461,* 236-240. [4] Cheek, L.C. et al. (2013), *JGR, 118,* 1805-1820. [5] Lemelin, M., et al. (2016), *47th LPSC*, #2994. [6] Crites, S.T. et al., (2015), *American Mineralogist, 100*, 1708-1716. [7] Warren, P.H., (1990), *American Mineralogist, 75*, 46-58. [8] Ryder, G. and Spudis, P., (1980), Proc. Conf. Lunar Highlands Crust, 353-375. [9] Ryder, G., and Wood, J.A., (1977), *Proc. 8th LSC*, 655-668.