BASIN EXCAVATION, LOWER CRUST COMPOSITION, AND BULK MOON MASS BALANCE IN LIGHT OF A THIN CRUST. B. L. Jolliff[1], R. L. Korotev, and R. A.. Zeigler[2], [1]Dept. Earth & Planetary Sciences and The McDonnell Center for the Space Sciences, Washington University, One Brookings Drive, St. Louis, MO 63130, [2] NASA – JSC, KT, 2101 NASA Pkwy, Houston TX 77058. (blj@wustl.edu)

Introduction: New lunar gravity results from GRAIL [1,2] have been interpreted to reflect an overall thin and low-density lunar crust. Accordingly, crustal thickness has been modeled as ranging from 0 to 60 km, with thinnest crust at the locations of Crisium and Moscoviense basins and thickest crust in the central farside highlands [2]. The thin crust has cosmochemical significance, namely in terms of implications for the Moon's bulk composition, especially refractory lithophile elements that are strongly concentrated in the crust [3,4]. Wieczorek et al. [2] concluded that the bulk Moon need not be enriched compared to Earth in refractory lithophile elements such as Al. Less Al in the crust means less Al has been extracted from the mantle, permitting relatively low bulk lunar mantle Al contents and low pre- and post-crust-extraction values for the mantle (or the upper mantle if only the upper mantle underwent LMO melting). Simple mass-balance calculations using the method of [4] suggests that the same conclusion might hold for Th and the entire suite of refractory lithophile elements that are incompatible in olivine and pyroxene, including the KREEP elements, that are likewise concentrated in the crust.

Mass Balance: Of critical importance to mass-balance models is the lithologic makeup of this thin crust. Remote sensing results from Kaguya have been interpreted as revealing exposures of nearly pure anorthosite in central peaks and rings of craters and basins, and that these are indicative of a layer of pure anorthosite that dominates the (upper) crust of the Moon [5,6]. A model for the crust based on average thickness derived from GRAIL data (34–43 km) and assuming 34% Al_2O_3 beneath a 5 km megaregolith with 28% Al_2O_3 (Fig. 1) would contribute 1.7–2.1 wt.% Al_2O_3 to the bulk Moon content [2].

A crust thus enriched in Al_2O_3 throughout its entire depth is not indicated by the range of surface and sample compositions. Simply considering the megaregolith as a mixture of aluminous crust and a more mafic underlying material that has been sampled (exhumed) and mixed by large impacts requires either a more mafic lower crust (<34% Al_2O_3) or that upper-mantle material has been incorporated into the megaregolith via basin ejecta at numerous locations on the lunar surface. For example, if the average crustal thickness totals 40 km, comprising 5 km of megaregolith at the top, with 28% Al_2O_3, and some thickness of anorthositic crust beneath, with 34% Al_2O_3, then the anorthositic layer is *constrained by mass balance* to be <24 km thick if the

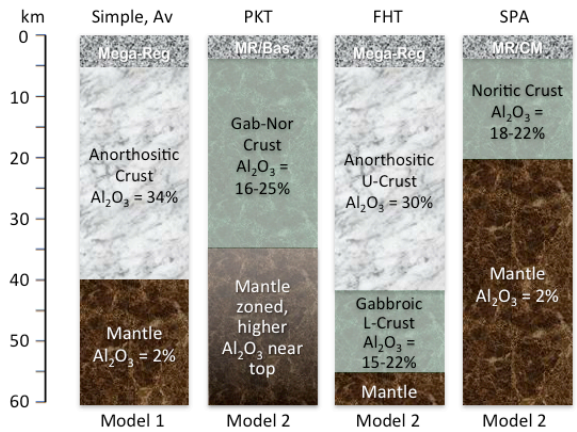

Figure 1. Conceptual models for crustal structure. (a) anorthositic single layer crust; (b) PKT; (c) FHT; (d) SPA.

mafic component of the megaregolith comes from lower crust that has an Al_2O_3 content of 12–22% Al_2O_3 and a corresponding lower crustal thickness of ~10–17 km. If the sub-anorthosite rock has <12% Al_2O_3, then it would likely represent uppermost mantle and the thickness of the anorthositic crustal layer could be >24 km. (The Al_2O_3 content of the magma ocean at plagioclase saturation is ~15 wt% [7], thus gabbro with >~15% alumina represents a plagioclase cumulate and <~12%, a pyroxene cumulate.) If the rock underlying the anorthositic layer has as little as 4% Al_2O_3, then the megaregolith developed by exhuming and mixing it must contain at least 20% of this (mantle) material, and this proportion of material should be recognizable in samples. Mafic impact-melt breccias produced by basin impacts are very important in this regard; none of the Apollo groups have <15% Al_2O_3. They are also important because they carry a large complement of the incompatible lithophile elements concentrated in KREEP. Strong enrichment of KREEP in mafic impact-melt breccias seems to have a crustal origin.

Crustal thickness or density distribution models must account for this mafic material, which in the Procellarum KREEP Terrane has a noritic to gabbronoritic composition and is rich in trace elements (e.g., >4 ppm Th). In the South Pole-Aitken (SPA) Terrane, crust exposed in crater central peaks and surrounding the interior of the basin has compositions ranging from noritic to gabbronoritic [8], and has Th ~2 ppm on average [4]. Does this material represent typical lower crust? Where does it fit in the gravity distribution reflected by GRAIL results? Can current crustal structure models based on gravity distinguish between a mafic

lower crust and an aluminous upper mantle, especially if the grain density is in the range of ~ 3100 to 3170 kg m^{-3}? Some alternatives are shown in Fig. 1.

Another problem with a single-layer anorthositic crust is that this endmember model represents a nearly 100% efficient plagioclase separation from the LMO. Separation of plagioclase was more likely imperfect, resulting in some rocks of intermediate plagioclase content such as troctolite, norite, and gabbro in the lower crust. Lunar samples in fact indicate that such crustal rocks exist, and although they are plagioclase-rich, they are not pure plagioclase. It is also likely that the uppermost mantle is not as depleted in plagioclase as is implied by a 2% Al_2O_3 content, suggested by some for depleted mantle [2,9]. Once plagioclase saturation in the LMO occurs, Al_2O_3 remains between 10–15% for the remainder of LMO solidification [7]. Aluminous basalts provide evidence that the upper mantle has Al_2O_3 contents > 2%, at least locally. Thus a relatively aluminous uppermost mantle and/or a relatively mafic lower crust should be factored into crustal structure models based on gravity.

A simple one-layer, constant anorthositic composition model [2], however, may provide an endmember on the maximum Al_2O_3 content of the crust. For a mass-balance model using anorthositic upper crust and more mafic lower crust, with variations according to crustal terranes [4] and crustal thicknesses consistent with the GRAIL model [2], we obtain a crustal contribution of some 1.3% Al_2O_3, and a bulk lunar Al_2O_3 content that varies from 4.4% for upper mantle melting to 3.4% Al_2O_3 for whole-Moon melting, assuming a differentiated mantle average alumina content of 2.2 wt.%. Interestingly, for this Al_2O_3 mass balance, values for upper mantle-only vs. whole-Moon melting begin to converge. Using the same distribution of crustal materials and mantle layering, estimates of bulk Moon Th concentration range from 0.07 ppm to 0.12 ppm, depending on whether the lower mantle is differentiated. The composition of the lower mantle remains a key unknown; new seismic data are needed.

Basin Impact Ejecta. The place on the Moon to look for evidence of excavated lower crust or mantle components is in the ejecta deposits of impact basins, especially those that are very large (e.g., Imbrium, SPA) or where gravity models indicate very thin crust, e.g., Crisium, Humboldtianum, Moscoviense, Poincaré, and Apollo [2]. Using spectral Profiler data, Yamamoto et al [6] identified numerous points around Crisium, Moscoviense, and several other basins that have olivine-rich spectra. Assuming that early LMO cumulates overturned and came to the uppermost mantle, these exposures could signal mantle excavation. Magnesian components of impact breccias, including several lunar meteorites, suggest that magnesian olivine was a likely mixing component, *e.g.,* Shişr 161 [10,11]. Magnesian olivine is also present as a component (chemical and petrographic) in mafic impact-melt breccias, presumably formed in the Imbrium event [12], and olivine exposures have also been identified in a few places along the rim of Imbrium [6].

The largest preserved basin on the Moon, SPA, produced an extensive mafic deposit that is reflected by LP-GRS data, *e.g.,* [8]. Although these deposits have been reworked by numerous large impacts, the compositional signature remains, and although variable, the data suggest a trend to ferroan compositions [13]. Strongly magnesian compositions are not indicated and rocks exposed from depth by impact processes are noritic [14], not anorthositic, and apparently not peridotite, as one might expect if mantle material was excavated. Mantle components could be well mixed with crustal material and therefore obscured from our detection by remote sensing; however, average Th concentrations of ~ 2 ppm are consistent with a lower crust, not mantle, origin. Of the few lunar meteorites thought to possibly have originated in the SPA Terrane, Dhofar 961 [15] has an impact-melt component that contains olivine and ~15% Al_2O_3. This impact-melt component contains two lithologies, one with olivine phenocrysts and one with incompatible-element enrichment. If this impact melt component comes from somewhere in SPA, it could represent, in microcosm, a component from the lower crust (incompatible-element-enriched), and a mantle component (olivine-bearing). Both lithologies are relatively mafic and ferroan. SPA may hold the key to the lower crust and the crust-mantle transition on the Moon.

We need to return to the Moon to collect new samples with known provenance, especially from locations such as South Pole-Aitken basin and areas with potential magnesian exposures such as circum-Crisium.

References: [1] Zuber et al. (2012) *Science*, 10.1126/science.1231507; [2] Wieczorek et al. (2012) *Science*, 10.1126/science.1231530; [3] Taylor[3] (2006) *GCA* 70, 5904; [4] Jolliff et al. (2000) *JGR* 105, 4197; [5] Ohtake et al. (2009) *Nature* 461, 236; [6] Yamamoto et al. (2012) *GRL* 39, L13201; [7] Snyder et al. (1992) GCA 56, 3809; [8] Prettyman et al., (2006) JGR 111, E12007; [9] Mueller et al. (1988) JGR 93, 6338. [10] Wittmann et al. (2012) 2nd Conf. on Lunar Highlands Crust; [11] Wittmann et al. (2013) This Conf.; [12] Korotev (2000) *JGR* 105, 4317; [13] Jolliff (2006) LPSC 37, #2346; [14] Pieters et al. (2001) *J. Geophys. Res.* 106, 28,001; [15] Zeigler et al. (2013) This Conf.

Acknowledgements: We thank NASA for support through NASA grant NNG04GG10G (RLK) and LROC/ASU contract NNG07EK00C (BLJ), and for supporting the LRO and GRAIL missions that are leading to new understanding of our old Moon.