STRUCTURE AND COMPOSITION OF THE LUNAR CRUST Paul D. Spudis[1], D. Ben J. Bussey[2], B. Ray Hawke[3] 1. Lunar and Planetary Institute, Houston TX 77058 (spudis@lpi.jsc.nasa.gov) 2. ESTEC, ESA, Noordwijk NL 3. PGD, Univ. Hawaii, Honolulu HI 96822

Since the first return of lunar samples indicated that global differentiation of the Moon had occurred , numerous models of crustal structure have been proposed (summarized in [1]). With the completion of the first global reconnaissance mapping by Clementine [2] and Lunar Prospector [3], we are now in position to re-evaluate crustal structure and composition at a global scale. Although this is a difficult and complex task, and one requiring significant study, some first order results are apparent now and are quite telling. We here summarize our current view of crustal structure and identify some required knowledge to better understand the origin and evolution of the lunar crust.

Models of Crustal structure. Wood *et al.* [4] attempted to estimate the amount of plagioclase in the crust, based on the average elevation difference between mare and highlands and some simple assumptions about anorthosite and basalt as responsible for the principal lunar rock types. Later, more complex models emerged, involving layered crusts of feldspathic material over more basaltic material [5, 6] or a laterally variable crust, with Mg-suite plutons intruding a grossly anorthositic crust [7]. Later models attempted to reconcile these contrasting styles by incorporating both features [e.g., 8]. In part, crustal structure was inferred by the envisioned mode of crustal formation. A decade-long debate on the reality of the lunar "magma ocean", stimulated by the provocative notion of Walker [9] that the Moon never had a magma ocean, and the recognition that the anorthosites and Mg-suite probably recorded different and unrelated magmatic events [10]. Such a scenario leaves much about crustal structure an open question, but allows for both lateral and vertical heterogeneity, thus accommodating both principal crustal models.

New data from Clementine and LP Global maps of iron [11], titanium [11, 12], and thorium [13] both confirm old ideas and create new problems. It is clear that vast areas of the lunar highlands are extremely low in iron [11], consistent with a significant amount of anorthosite. Such a distribution supports the magma ocean. However, the average lunar highlands composition is, as long suspected, that of "anorthositic norite" [11, 14], a mixed rock type, somewhat similar to many of the lunar meteorites (e.g., ALHA 81005; [15]) and more mafic than pure ferroan anorthosite. Anorthosite proper does occur on the Moon; it is found almost exclusively within the inner rings of multi-ring basins [16]. These basins span a range of ages and distributions [17]. Mafic provinces occur in the central Procellarum region of the front side and on the floor of the South Pole-Aitken basin. In these areas, the lunar surface is "highland basaltic" composition (FeO ~9-10 wt.%). Additional highland basaltic areas occur in the vicinity of near side basins, such as Serenitatis. The major lunar "hot spot" of high Th concentration (~10 ppm) occurs within a broad, oval depression approximately coincident with Oceanus Procellarum. Slightly less elevated amounts (~ 4 ppm) are associated with the basaltic floor of SPA basin on the far side. Aside from this, Th highs are isolated and minor.

A "new" crustal model On the basis of the new global data, as well as from our continuing study of the composition of basin ejecta to probe the deep crust [17], we have slightly modified our existing crustal model [8] to accommodate the new findings (Figure 1). We propose a three-layer model of crustal configuration. The uppermost zone, down to depths of ~15-20 km, consists of megabreccia of mostly anorthositic norite composition (FeO ~ 4-6 wt.%; Al_2O_3 ~26 wt.%). This zone is neither laterally or vertically uniform [14], displaying anomalous compositional zones at scales of tens to hundreds of km, but is remarkably homogeneous at planetwide scales. In bulk composition, it resembles the "ferroan anorthositic norite" suite of mixed rocks described by Lindstorm *et al.* [18] and many of the highlands regolith breccias found as lunar meteorites [15]. It is also similar to the average crustal composition inferred by Taylor [19], on the basis of Apollo granulitic breccias and limited orbital chemical data. Although some areas on the northern far side appear very anorthositic [11], most areas of the upper highlands different from this composition are more mafic, not more feldspathic, showing affinities to highland basalt, with or without KREEP.

The next zone of the crust is found at depths between 15 and ~35 km. It appears to consist largely of nearly pure, ferroan anorthosite (FeO < 2 wt.%; Al_2O_3 > 33 wt.%). Outcrops of pure anorthosite principally occur on the Moon in the inner rings of multi-ring basins (Figure 1), which are structurally uplifted blocks from mid-crustal levels [20], or rarely, as central peaks in some selected craters (Alphonsus, Aristarchus; [16]). The anorthosite is apparently confined to middle levels in the crust; moreover, it appears to be at least partly of global extent, as basin rings of anorthosite are found in basins spanning the globe, from Orientale [16, 17] to Humboldtianum [21]. Because anorthosite is most likely to represent the primordial crust [10], we interpret this global "layer" of anorthosite as the remnant of the original crust of the Moon.

The petrological nature of the roughly half of the crust below the anorthosite zone (depths of 35 to 65 km) remains obscure, but several observations may be made about the likely nature of rocks to be found there. First, where most of the upper crust has been removed by large, basin-forming impact (such as the floors of SPA [22] and Imbrium basins [23]), the crustal composition appears to be that of highland basalt (FeO ~ 9-12 wt.%; Al_2O_3 ~ 18-20 wt.%). Second, a plot of the total iron content of basin ejecta (determined from orbital measurements; [11]) against basin size shows that larger basins excavate more mafic (iron-rich) material [24]. This relation suggests that the lower levels of the crust are more "basaltic" than middle or upper levels. Finally, basin impact melts, typified by the Apollo 15 and 17 impact melt breccias [1, 8], are of highland basaltic composition, and were probably formed by massive melting of middle-to-lower crustal levels [5, 6, 8]. These observations in total suggest that the lower crust is broadly "highland basalt" in composition. The petrological nature of the lower crust remains obscure, but the high Mg# and KREEP trace-element signature of basaltic impact melts from the Moon indicate that the Mg-suite must represent a major contributor to the bulk composition (Figure 1).

Origin of the highlands "megaregolith" The upper zone of the Moon's crust has been heavily processed by repeated impact cratering. In our model, it is analogous to the regolith found at any Apollo site in a shallow maria, such as Apollo 11 [1]. In that case, a thin lava flow overlies a feldspathic, highlands substrate. Regolith formation by post-mare craters mixes minor amounts of highlands debris into a ground-up layer of mostly basaltic composition. The resulting regolith is thus slightly contaminated with feldspathic material, although dominantly basaltic.

In the highlands crust, the inverse case holds. The original feldspathic, anorthosite crust of the Moon overlies a more mafic, "basaltic" lower crust. The massive impact bombardment of this target produces a megaregolith of dominantly feldspathic, anorthositic composition. However, small amounts of the underlying, mafic lower crust is admixed into the megaregolith, making it slightly more mafic than the anorthosite layer it rests on. As in the case at the Apollo 11 site, the dominant character of the "regolith" is that of the zone it immediately rests on, but is "contaminated" by the contrasting composition of the deep layer below it.

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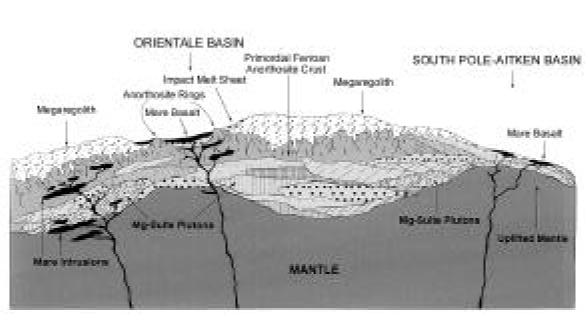

Figure 1. Proposed model of the lunar crust.