A CHEMICAL AND PETROLOGICAL MODEL OF THE LUNAR CRUST.

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It has long been recognized that the lunar crust is chemically and petrologically heterogeneous, although the exact details of its structure remain contentious. Various models of lunar crustal structure have been proposed that invoke lateral heterogeneity [e.g., 1], vertical variations [2,3], or both [4]. Recently, we presented the results of our attempts to make petrologic maps of the lunar highlands from orbital geochemical data [5]. These maps provide data on petrologic variations in the uppermost lunar crust. Moreover, recent studies have clarified the process involved in multi-ring basin formation [e.g., 6, 7], resulting in models that permit us to use basin as probes to understand the composition of the lower crust. Thus, it is now appropriate to reevaluate a variety of remote-sensing and lunar sample data to determine the probable chemical and petrologic structure of the lunar crust.

Composition and structure of the upper crust. The average composition of the highland crust under the Apollo 15 and 16 orbital groundtracks is that of "anorthositic gabbro" (Al_2O_3 26-28%) [5]. Within this area of coverage is considerable petrologic variation, ranging from deposits of "pure" anorthosite to KREEP basalt [5]. Our efforts to map highland rock types used the Fe - Th/Ti chemical plot; such a variation diagram readily separates the ferroan anorthosites (believed to be original crustal products of lunar primordial differentiation [8]) from the Mg-suite rocks and KREEP. Of the eleven petrologic units mapped in [5], five have "chondritic" Th/Ti ratios, indicating affinity with the ferroan anorthosite suite rather than with the Mg-suite or KREEP. These units make up over 80% of the toal highland region covered by the Apollo orbital data. Assuming that the Apollo groundtracks are representative of the whole Moon, we conclude that rocks of the Mg-suite represent a minor fraction of the upper lunar crust. The dominance of Mg-suite rocks in the sample collection is probably more apparent than real and may be mostly due to the emphasis placed on study of pristine clasts from highland breccias.

A consequence of the heavy bombardment of the lunar crust was the development of a thick, brecciated debris layer, the "megaregolith" [9]. The thickness of this layer has been estimated as 1-2 km [10-11] to as much as 40 km [12]. Because of the general paucity of pristine plutonic rocks and the lunar cratering history implied by the apparent 3.92 b.y. age of the Nectaris Basin [13,14], we favor values of tens of kilometers for megaregolith thickness. Mixing in such a debris layer would be dominantly vertical, analogous to mixing in the thinner regoliths developed on mare basalt flows. Such mixing would preserve "outcrops" of pure rock types such as those on the petrologic maps [5].

Composition of the lower lunar crust. Evidence for lower crustal composition comes from the composition of multi-ring basin ejecta. Of the eleven basins covered by Apollo orbital chemical data, nine display enrichments of norite in their continuous near-rim deposits, in contrast to the more anorthositic compositions of the interbasin terrain. Moreover, the relative fraction of norite in basin ejecta determined by mixing models increases with increasing basin diameter [4,5]. Assuming these relations to be non-coincidental, we suggest that the lower crust is composed dominantly of noritic rocks ($Al_2O_3 \sim 20\%$). Additional evidence for this noritic composition comes from the (probably) polymict "Very High Aluminum "(VHA) and "low-K Fra Mauro" (LKFM) basalt rocks, which appear to be basin impact melts [14]; these rocks are noritic in bulk chemistry. Given estimated formation energies of impact-basins [15,16] and projectile penetration depths [6], we consider most basin impact melts to have been generated at depths of about 30 to 60 km in the lunar crust. If VHA and LKFM basalt does represent basin impact melt, these rocks provide direct evidence for a noritic lower crust. To explain the lack of lunar mantle material in impact melts, Ryder and Wood [2] suggested that a noritic LKFM layer exists midway in the crust. Analysis of both the geologic settings of the Apollo landing sites [17,18] and particle movements during cratering flow [6,19] suggest such a crustal structure is not a requirement, as the basin impact melt sampled during Apollo missions should be contaminated with only shallow-level clasts. We believe that the available data are consistent with the hypothesis that the lower lunar crust is composed dominantly of norite.

A lunar crustal model. Our lunar crustal model is shown in Figure 1. It has essentially two-layers: anorthositic mixed rocks overlie a generally noritic crystalline basement. The contact between these layers is probably gradational on a scale of kilometers. The Mg-suite comprises a series of plutons, some of them layered, that are a subordinate fraction of the crustal volume. In this model, the crust is laterally and vertically heterogeneous on a scale of tens of kilometers.

Our model has several implications for lunar crustal origin and evolution. Concurring with previous suggestions (see review in [8]), we believe that a global magma system produced an original ferroan anorthosite crust by plagioclase flotation and olivine/pyroxene sinking. As the crust grew downward and the mantle upward, the residual liquid had a noritic composition [2,20]; this layer formed the noritic lower crust and eventually, a layer of material (KREEP substratum; Fig. 1) greatly enriched in incompatible trace elements [20,21]. Partitioning of incompatible elements into this KREEP layer was not totally efficient, resulting in the production of KREEP-rich norites in the lower crust [2]. Concurrent with this episode was intrusion of Mg-suite rocks to form plutons within the original anorthositic crust. This activity was virtually complete by 4.36 b.y. ago [22]. Massive extrusions of mare basalts [5] and continued heavy bombardment of the crust followed until about 3.85 b.y. ago. During this interval, the hot, low-density KREEP material migrated upward [23] and was disseminated through most of the lower crust. Thus, basins forming around 3.9 b.y. ago incorporated a KREEP trace-element pattern into their noritic impact melts ("Melt rocks"; Fig. 1). In the Imbrium region, KREEP basalts were erupted on the surface both before [24] and after [25] the Imbrium impact. After the heavy bombardment ended, mare basalts continued to be extruded, forming the visible maria. Continued study of lunar samples and new remote-sensing data from the proposed Lunar Geoscience Observer Mission will be required to assess the validity of this lunar crustal model.

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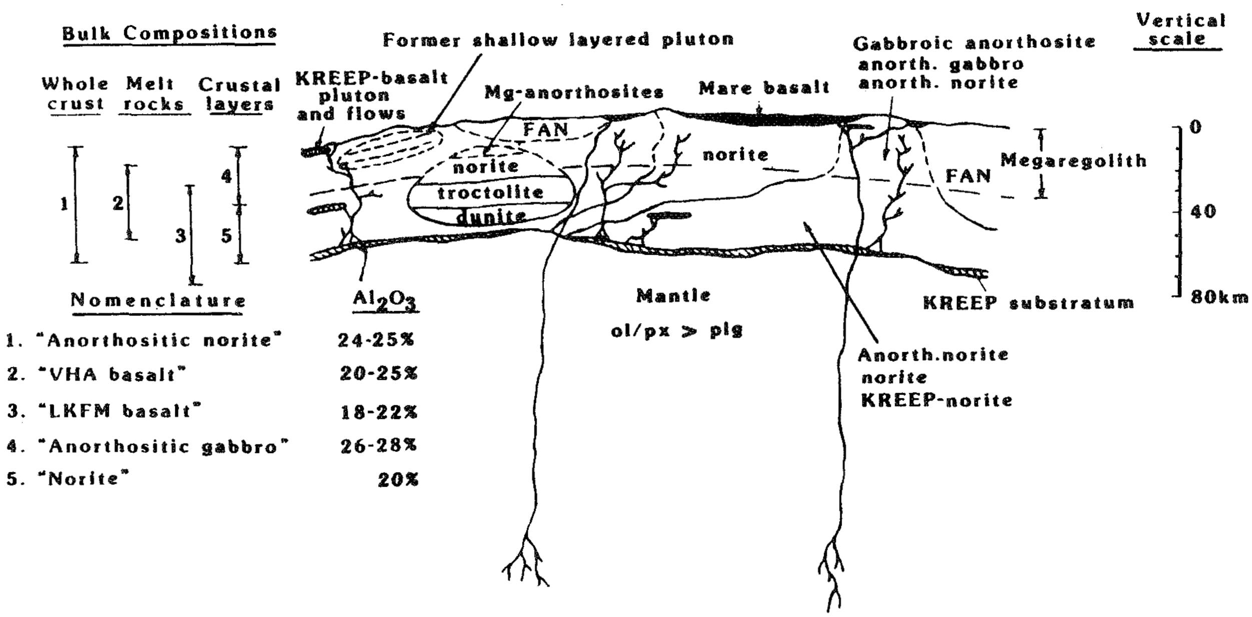

Figure 1. Proposed model of the lunar crust. FAN refers to ferroan anorthosite. Provenance of bulk compositions indicated at left by arrows. See text for discussion.