A Chemical and Petrological Model of the Lunar Crust and Implications for Lunar Crustal Origin

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We utilize a variety of lunar sample and orbital geochemical data in conjunction with current knowledge of impact-cratering processes to develop a chemical and petrological model of the lunar crust. Orbital chemical data indicate that the upper highlands surface on the moon has the bulk composition of “anorthositic gabbro” (\(\text{Al}_2\text{O}_3\) 26-28 wt %); greater than 90% of the area covered is dominated by material having compositional affinities with the ferroan anorthosites, rather than with Apollo-type Mg-suite rocks. Considerations of the cumulative bombardment history of the moon indicate that the outer zone of impact brecciation extends tens of kilometers into the crust; given the resolution of the orbital gamma ray data, the ferroan-anorthositic composition derived for the highlands surface may represent the bulk composition of the upper half of the lunar crust. The observed enrichment in “noritic” components in basin ejecta with increasing basin size, together with considerations of impact melt petrogenesis in lunar basins, suggest that the bulk composition of the lower lunar crust is “noritic” (\(\text{Al}_2\text{O}_3\) ~ 20 wt %); samples of lower crustal material are probably present in the Apollo collections in the form of low-K Fra Mauro (LKF) and very high alumina (VHA) basaltic impact melts. Our estimated value of total crustal \(\text{Al}_2\text{O}_3\) content (24-25 wt %) suggests that the lunar crust contains too much aluminum to have originated by a purely “serial magmatism” mechanism. The large abundance of plagioclase within the lunar crust is probably a result of global-scale fractionation of plagioclase in early lunar history. The “magma ocean” hypothesis of crustal origin more readily explains the bulk composition of the lunar crust.

INTRODUCTION

The lunar crust is chemically and petrologically heterogeneous, although the exact details of its structure and origin remain contentious. After the first lunar sample return, study of feldspathic particles in highland soils provided the basis for postulating the dominantly plagioclase-rich nature of the lunar highlands [Smith et al., 1970; Wood et al., 1970]. Wood et al. [1970] suggested that the lunar crust formed by global melting (the magma ocean hypothesis), has an anorthositic bulk composition (based on study of Apollo 11 samples), and, if pure plagioclase, would be about 25 km thick (based on interpretation of Lunar Orbiter gravity data). Additional samples and surface geophysical data from subsequent Apollo missions provided more detailed information about the moon and produced a more complex perception of its crustal chemistry and petrology. As a result, various models of lunar crustal structure have been proposed that invoke lateral crustal heterogeneity [Warner et al., 1978; James, 1980], vertical variations in composition [Charette et al., 1977; Ryder and Wood, 1977], or both [Spudis et al., 1984a]. This perception of crustal heterogeneity prompted crustal genesis models that contend that the moon never underwent global melting, e.g., the "serial magmatism" models of Walker [1983] and Longhi and Ashwal [1985]. A consequence of the serial magmatism model is that the bulk chemical composition of the lunar crust is noritic or basaltic [Walker, 1983]. Longhi and Ashwal [1985] specifically state that "an implicit assumption of our model is that there is less than 10-20 km of ferroan anorthosite in the lunar crust." Knowledge of the bulk chemical composition and structure of the lunar crust would provide important constraints on the mechanism of crustal origin. Specifically, estimates of bulk crustal composition, the amount of plagioclase in the crust, and variations in crustal composition with depth are important tests of the magma-ocean versus serial-magmatism hypotheses.

We recently presented the results of our attempts to make petrologic maps of the lunar highlands from orbital geochemical data [Davis and Spudis, 1985]. These maps show the petrologic variations in that part of the uppermost lunar crust covered by the Apollo 15 and 16 orbital data. In this paper, we examine these data to determine the average composition and petrologic affinity of the upper lunar crust. These determinations are combined with information from cratering studies (specifically, the average depth of impact mixing) to estimate the average composition of the upper lunar crust.

In addition, several recent studies have addressed the processes of multiring basin formation [e.g., Croft, 1981; Grieve et al., 1981; Spudis et al., 1984a], resulting in cratering models that permit better interpretation of basin ejecta as probes of the lower crust. Basin-forming processes must have excavated the lunar crust to a depth of many kilometers. Basins are widely distributed over the moon [Wilhelms, 1984] and at least 11 basins were overflown by Apollo spacecraft with orbital geochemical sensors. We examine these data to determine the composition of basin ejecta and to attempt to identify chemical components that are not derived from the upper levels of the lunar crust, as represented by the average composition of the surrounding interbasin terrain. These tasks are accomplished primarily by using the results of geochemical mixing model studies [Hawke and Spudis, 1979; Spudis and Hawke, 1981; Spudis et al., 1984a; Spudis, 1986]. Where candidate samples can be related to a basin-forming impact [Ryder and Wood, 1977; Spudis, 1984], additional evidence for the lower crustal composition is available. We then use all this new information to infer the probable chemical and petrologic structure of the lunar crust.

COMPOSITION AND STRUCTURE OF THE UPPER LUNAR CRUST

As described in Davis and Spudis [1985], the chemical plot of Th/Ti ratio against Fe distinguishes samples of lunar ferroan...
anorthosite, mare basalt, and the Mg-suite rocks, because they fall into three widely separated fields (Figure 1). This separation was the basis for similar plotting of geochemical data from the Apollo gamma ray spectrometer to define petrologic units in the lunar highlands. An important property of the Th/Ti-Fe diagram is its ability to distinguish regional provinces that have affinities with the ferroan anorthosites (which have roughly chondritic Th/Ti; Figure 1) from provinces that have affinities with the Mg-suite and KREEP (which have Th/Ti values at least an order of magnitude greater). If sampled Mg-suite rocks are global rock types, the frequency distribution of orbital data points on this plot can be used to determine the relative contribution from the ferroan and Mg-suites for the lunar regions overflown by Apollos 15 and 16.

Using orbital gamma ray Th/Ti and Fe data from the Apollo 15 and 16 spacecraft groundtracks, Davis and Spudis [1985] concluded that the chemically mixed lunar rock type “anorthositic gabbro” (Al$_2$O$_3$ 26–28 wt %) best matched the composition of the average highland surface. Two problems that were not addressed in that study were the following: (1) the relative contributions of the ferroan anorthosite (FAN) suite and the Mg-suite to lunar highlands composition (now generally agreed to represent different magmatic events [Warren, 1985]), and (2) the depth to which the surface composition extends into the lunar crust. In this section, we consider these two problems in order to estimate the composition and structure of the upper lunar crust.

By examining the distribution of orbital highland Th/Ti data points, we can estimate the relative abundance of FAN and Mg-suite rocks at the lunar surface (Figures 1 and 2). For the purpose of this study, we assume that Apollo-type Mg-suite rocks (Th/Ti > 10 × chondrites) are global rock types and do not represent anomalous lithologies confined only to the lunar nearside. In support of this assumption, we note that in our previous results [Davis and Spudis, 1985, Plate 2] several petrologic units (e.g., units 2, 3, and 10) appear on the lunar limb and farside regions; all of these units have mean Th/Ti values in excess of 10 × chondrites. Examination of the Apollo orbital Th data alone [Metzger et al., 1977] indicates that these regions are not pure KREEP. The most straightforward interpretation of this relation is that these regions are composed of Mg-suite rocks (norites and troctolites) that have chemical characteristics similar to Mg-suite rocks collected by the Apollo missions.

An improvement over our previous work has been incorporated into this study and is discussed in detail in a companion paper [Davis and Spudis, 1987]. In that study, we generated error databases associated with orbital gamma ray Th, Ti, and Fe values and used the triangular separation of anorthosite, mare basalt, and the Mg-suite (Figure 1) to produce a ternary diagram that determines the compositional affinities of the orbital data points with lunar rock types. The results indicate that more than 90% of the highland surface covered by Apollo data has chondritic Th/Ti values, indicating affinities with the ferroan suite rather than the Mg-suite (Figure 2). These results agree with our previous determination [Davis and Spudis, 1985, Table 2] that, in general, the Mg-suite is a minor component of the upper lunar surface.

Although we do not know to what degree the Apollo groundtracks represent the entire lunar surface, two additional data sets suggest that the lunar nonequatorial regions probably are not compositionally bizarre. Radioactivity data obtained by the high-inclination orbiter Luna 10 [Sukov, 1981] suggest that the lunar highlands as far north and south as about latitude ± 70° display U and Th concentrations typical of the highland crust. Analysis of near-infrared spectral reflectance data for fresh surfaces (isolated spots a few kilometers in size) in the lunar nearside highlands [Pieters, 1986] indicates the presence of a diversity of rock types, but nothing inexplicable within the context of our current knowledge of lunar rocks. For our purposes, we will assume that the Apollo orbital geochemical data are representative of the entire surface of the moon, noting that this assumption cannot be tested further until global data are available from future lunar missions.
TABLE 1. Composition of Basin Ejecta and Equivalent Thickness of Plagioclase at Basin Target Sites

<table>
<thead>
<tr>
<th>Basin</th>
<th>Diam (km)</th>
<th>Tc* (km)</th>
<th>D/T</th>
<th>Anorth</th>
<th>Angab</th>
<th>Nor</th>
<th>KREEP</th>
<th>Mare</th>
<th>Ref. (wt%)</th>
<th>(vol %)</th>
<th>Dcîl (km)</th>
<th>Equiv. T-plg. 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orientale (Or)</td>
<td>940</td>
<td>90</td>
<td>10.3 ± 1.3</td>
<td>25</td>
<td>59</td>
<td>5</td>
<td>11</td>
<td>1.0</td>
<td>5</td>
<td>77</td>
<td>582 ± 77</td>
<td>30 ± 5</td>
</tr>
<tr>
<td>Hertzsprung (Hz)</td>
<td>570</td>
<td>90</td>
<td>6.3 ± 0.8</td>
<td>52</td>
<td>25</td>
<td>5</td>
<td>18</td>
<td>2.0</td>
<td>5</td>
<td>75</td>
<td>408 ± 59</td>
<td>20 ± 4</td>
</tr>
<tr>
<td>Korolev (Ko)</td>
<td>440</td>
<td>100</td>
<td>4.4 ± 0.4</td>
<td>95</td>
<td>9</td>
<td>5</td>
<td>2</td>
<td>2.0</td>
<td>5</td>
<td>81</td>
<td>347 ± 52</td>
<td>19 ± 3</td>
</tr>
<tr>
<td>Freundlich-Shareov (FS)</td>
<td>600</td>
<td>70</td>
<td>8.6 ± 2.4</td>
<td>63</td>
<td>21</td>
<td>15</td>
<td>1</td>
<td>2.0</td>
<td>22</td>
<td>66</td>
<td>422 ± 60</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>Mendeleev (Me)</td>
<td>330</td>
<td>90</td>
<td>3.6 ± 0.5</td>
<td>73</td>
<td>15</td>
<td>12</td>
<td>2</td>
<td>15</td>
<td>70</td>
<td>207</td>
<td>207 ± 45</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>Milne (Mi)</td>
<td>270</td>
<td>90</td>
<td>3.9 ± 0.5</td>
<td>93</td>
<td>7</td>
<td>7</td>
<td>2</td>
<td>7</td>
<td>77</td>
<td>175</td>
<td>175 ± 35</td>
<td>9 ± 1</td>
</tr>
<tr>
<td>Smythi (Sm)</td>
<td>740</td>
<td>60</td>
<td>12.3 ± 7</td>
<td>70</td>
<td>20</td>
<td>10</td>
<td>2</td>
<td>20</td>
<td>72</td>
<td>488</td>
<td>488 ± 67</td>
<td>23 ± 3</td>
</tr>
<tr>
<td>Crisium (Cr)</td>
<td>540</td>
<td>60</td>
<td>9.0 ± 1.8</td>
<td>76</td>
<td>23</td>
<td>1</td>
<td>3</td>
<td>23</td>
<td>77</td>
<td>394</td>
<td>394 ± 57</td>
<td>21 ± 4</td>
</tr>
<tr>
<td>Nectaris (N)</td>
<td>860</td>
<td>70</td>
<td>12.3 ± 7</td>
<td>75</td>
<td>25</td>
<td>3</td>
<td>2</td>
<td>25</td>
<td>75</td>
<td>544</td>
<td>544 ± 73</td>
<td>27 ± 4</td>
</tr>
<tr>
<td>Serenitatis (Se)</td>
<td>920</td>
<td>60</td>
<td>15.3 ± 3.1</td>
<td>70</td>
<td>3</td>
<td>26</td>
<td>4.0</td>
<td>73</td>
<td>45</td>
<td>572</td>
<td>572 ± 76</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>Imbrium (I)</td>
<td>1160</td>
<td>60</td>
<td>19.3 ± 3.9</td>
<td>42</td>
<td>8</td>
<td>29</td>
<td>5.0</td>
<td>50</td>
<td>52</td>
<td>685</td>
<td>685 ± 86</td>
<td>21 ± 2</td>
</tr>
</tbody>
</table>

*Model values of crustal thickness from Bills and Ferrari [1976, 1977]; all values ± 10 km.

1 Mixing-model studies: 1, Spudis et al. [1984a]; 2, Spudis et al. [1984b]; 3, Hawke and Spudis [1979]; 4, Spudis and Hawke [1981]; 5, Spudis [1986].

Total fraction of “norite” (norite, LKFM, KREEP) in basin ejecta.

Total fraction of plagioclase in basin ejecta, extracted from all components and expressed as volume percent.


Total fraction of plagioclase in basin ejecta, converted to an equivalent thickness of pure plagioclase at basin target sites (see text).

A consequence of the heavy bombardment of the lunar crust was the development of a thick brecciated debris layer, the “megaregolith” [Hartmann, 1973, 1980]. The thickness of this layer has been estimated to be from 1–2 km [Short and Forman, 1972; Hörz et al., 1976] to as much as 40 km [Cashore and Woronow, 1985]. In this discussion, we term “megaregolith” to refer to that part of the outer portion of the lunar crust that has been brecciated and somewhat mixed by the cumulative lunar bombardment. We do not mean to imply that this mixing has produced complete chemical homogenization, nor do we imply that this zone consists of unconsolidated, comminuted (regolith-like) debris. As discussed by Hartmann [1980], the combination of an early high impact flux, global magnetism, and high heat flow within the early moon would produce a thick, extensive zone of broken debris that would weld together as consolidated breccia as the early lunar lithosphere grew in thickness.

Unbrecciated, igneous plutonic rocks make up a small proportion of surface deposits, despite their collection from at least three basin ejecta blankets; this observation may indicate that many of the returned lunar samples were already polycrystalline breccias before examination by basin impact [Hörz et al., 1983], The apparent 3.92 b.y. age of the Nectaris Basin [James, 1981; Spudis, 1984] implies that the most heavily cratered surfaces on the moon are no older than about 4 b.y.; this result suggests that an earlier, intense cratering epoch would have brecciated and mixed the upper lunar crust to depths of tens of kilometers [Spudis, 1984]. We suggest that the observed brecciation of lunar basin deposits reflects this large cumulative bombardment of the moon and, consequently, favors values of tens of kilometers for megaregolith thickness. Mixing in such a debris layer would be analogous to mixing in the thinner regoliths developed on mare basalt flows [Hörz, 1977]. Such mixing would preserve zones (“outcrops”) of relatively pure rock types, such as those shown on the petrologic maps [Davis and Spudis, 1985, 1987].

An average megaregolith thickness of about 20 to 40 km implies that the chemical composition of the lunar highlands surface obtained from the gamma ray data may be representative of the composition of the upper half of the lunar crust. This suggestion, however, does not imply complete chemical homogenization of the upper lunar crust for two reasons. First, the average “anorthositic gabbrro” composition is the result of integrating all highland data; even within the gamma ray groundtracks, we can distinguish petrologic provinces several hundred kilometers in extent [Davis and Spudis, 1985, 1987]. Second, the inherent resolution of the gamma ray detector (100 km) cannot resolve petrologic heterogeneities smaller than this dimension. Near-infrared spectral data for the lunar highlands indicate a diverse, heterogeneous upper crust [Pieters, 1986], which is not inconsistent with our results because the spatial resolution of these spectral data (2–3 km) is much greater than the integrated orbital data.

On the basis of orbital geochemical data and the characteristics of the megaregolith, we conclude that the upper lunar crust consists of an impact-brecciated zone, compositionally diverse on a scale of tens of kilometers, that is anorthositic in bulk composition (i.e., related to the ferroan suite). Any former shallow-level, Mg-suite plutons in the upper crust would have been comminuted and incorporated into the megaregolith; these hypothetical plutons probably did not make up more than 10% (Figure 2) of the upper lunar crustal volume.

**COMPOSITION OF THE LOWER LUNAR CRUST**

Although the lower lunar crust is inaccessible for direct investigation (e.g., by drilling), large multiring basins provide a series of natural “drill holes” into the lower crust. Quantitative estimates of excavation-cavity dimensions of basins [Croft, 1981; Grieve et al., 1981; Spudis et al., 1984a; Spudis, 1986] enable us to reconstruct the probable composition and structure of the prebasin impact target. Additionally, if specific, basin-related samples from deep within the crust can be identified in the Apollo collections (discussed below), we will have direct sample evidence for the composition of the lower crust.

One indication of lower crustal composition comes from the composition of multiring basin ejecta. Of the 11 basins covered by Apollo orbital chemical data, 9 display enrichments of “norite” [as used here, any mafic component whose (Th/Ti)k...
Fig. 3. Plot showing the relative fraction of "norite" components (the sum of norite, KREEP, and low-K Fra Mauro fractions) in basin ejecta as a function of observed basin diameter (D), normalized to local crustal thickness (Tc; Table 1). (See Table 1 for symbols for basin names.) Error bars represent uncertainties in crustal thickness and mixing model results. The tendency for points to fall near a straight line of positive slope suggests that basins of increasing size, which excavate deeper levels of the lunar crust, display enrichments of "norite" in their ejecta. This enrichment suggests that the lower lunar crust has a bulk composition of "norite." See Spudis et al. [1984b].

> 10 (Figure 1), including KREEP and the polymict, "low-K Fra Mauro basalt" in their continuous near-rim deposits, in contrast to the more anorthositic compositions of interbasin terrain [Spudis et al., 1984b; Davis and Spudis, 1985]. Moreover, the relative fraction of "norite" in basin ejecta as determined by mixing models generally increases with increasing basin diameter (Table 1, Figure 3; Spudis et al. [1984b]). If we assume these relations to be noncoincident, they suggest that the lower crust is composed dominantly of "noritic" rocks, with increasing amounts of lower crustal material being excavated from basins of increasing size.

The petrographic nature of the lower lunar crust remains unresolved by this technique. Ryder and Wood [1977] envisioned a layered sequence of norites and KREEP-norites underlain by mafic, Mg-suite rock types. Their crustal model was based on the chemical characteristics and geologic occurrence of noritic melt rocks ("low-K Fra Mauro," LKFM) that were collected from the rims of the Imbrium and Serenitatis basins. A variety of lunar highland impact melts rocks of broadly noritic composition [LKFM and VHA ("very high-alumina") melt rocks] was proposed by Spudis [1984] to represent basin impact melts from a number of events.

The energy required to form a lunar basin has been estimated by various workers [e.g., Baldwin, 1963; Gautel et al., 1975; Croft, 1977; Grieve and Dence, 1979]. For a basin impact that had an energy equivalent to that which formed the Imbrium Basin (E ~ 10^{22} to 10^{23} ergs) and that formed by a spherical, chondritic projectile hitting the moon at near r.m.s. impact velocity (about 20 km/s; Shoemaker [1977]), a projectile diameter of about 30 to 50 km is indicated. Models of the penetration depths of basin-forming projectiles [Croft, 1980, 1981] suggest that the effective origin of the cratering flow field is established about one projectile diameter below the planetary surface; this point is also the locus of the greatest peak shock pressures during excavation cratering flow, hence the zone around which impact melt will be produced [Grieve et al., 1977, 1981; Stöffler, 1981].

Three observations suggest that lunar LKFM impact melts are direct samples of the lower lunar crust. First, it appears that for large basin-forming impacts, the melt zone will encompass large volumes of lower crustal material; only basin-forming impacts are of sufficient magnitude to reach these crustal levels. Second, the impact-melting process tends to chemically homogenize lithologically diverse target rocks [Grieve et al., 1977]. Thus potential samples of basin impact melts should form a more or less chemically restricted suite of rocks. Moreover, if the lunar crust is vertically heterogeneous, such a suite should be chemically different from typical, upper crustal compositions. Third, examination of the petrologic maps derived from orbital geochemical data [Davis and Spudis, 1985] indicates that the typical highlands terrain is both too aluminous and KREEP-poor to serve as the lithologic precursor for the genesis of LKFM by the formation of small (10-100-km-diameter) impact craters. The observed enrichment in "noritic" components in basin ejecta with increasing basin size (Figure 3) suggests that such compositions are present within the lower levels of the crust.

We consider most basin impact melts to have been generated at depths of about 30 to 60 km in the lunar crust and that VHA and LKFM basalts represent basin impact melt. These rocks provide direct evidence for a noritic lower crust. We therefore believe that the observed enrichment of "noritic" in basin ejecta and the composition of lunar basin impact melt rocks are consistent with the hypothesis that the lower lunar crust is of dominantly "noritic" composition.

A LUNAR CRUSTAL MODEL AND IMPLICATIONS FOR LUNAR CRUSTAL ORIGIN

On the basis of analysis of the orbital petrologic maps, the cumulative bombardment history of the lunar highlands, and the use of basins to probe the lower crust, we now present a revised model of the chemical and petrologic characteristics of the lunar crust that is consistent with the most recent available data (Figure 4). The lunar crust has two zones: a mixture of mostly anorthositic rocks overlying a generally noritic crystalline basement. The contact between these two layers is probably gradational on a scale of kilometers. The Mg-suite comprises a series of plutons [James, 1980; Warren, 1985], some layered, that are a subordinate fraction of the crustal volume and are probably confined mostly to the lower half of the crust [Warren and Wasson, 1980]. The crust is laterally and vertically heterogeneous on a scale of tens of kilometers.

This crustal model has implications for the bulk compositions of the lunar crust and impact melt rocks in the Apollo collection. A two-layer crust in which the upper half consists of "anorthositic gabbro" (Al_{2}O_{3} 26-28 wt %) and the lower half of "norite" (Al_{2}O_{3} ~ 20 wt %) implies that the bulk lunar crustal composition corresponds to that of "anorthositic norite" (Al_{2}O_{3} 24-25 wt %; Figure 4). This estimate is identical to that of Taylor [1982], although for different reasons. In his modeling, Taylor calculated

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the bulk crustal composition by estimating the average highland Al/Si ratio from the orbital X ray data (Al/Si = 0.62 ± 0.10) and by assuming a nonlayered, homogeneous crust. Keeping SiO₂ constant at 45 wt %, he derived a bulk crustal Al₂O₃ content of 24.6 wt % [Taylor, 1982, p. 230]. However, the Apollo X ray data are confined to the equatorial, sunlit hemisphere centered on the lunar eastern limb (about 10°W to 160°E longitude); our previous analysis of orbital gamma ray data [Davis and Spudis, 1985] suggested that these highland terrains are anomalously Fe-rich (hence Al-poor) compared to the western limb highlands. The mafic nature of these highlands may result from extensive ancient mare volcanism in the eastern region that predated the end of heavy bombardment [Schultz and Spudis, 1983; Davis and Spudis, 1985]. The global (equatorial) gamma ray data indicate that the upper crust is richer in Al, but we also find evidence in basin ejecta for vertical nonuniformity in the crust (i.e., it is more mafic with depth; Figure 3). Thus the correspondence in bulk crustal Al₂O₃ between our estimate (24–25 wt %) and that of Taylor [1982] (24.6 wt %) is coincidental.

Another consequence of this crustal model is that the specific composition of lunar basin impact melts is determined by the magnitude of the basin-forming event. Large basins, such as Imbrium, were formed by very energetic impacts; projectile penetration well into the lower crust and part of the upper mantle would produce very mafic, Mg-rich melt rocks, as is observed [Ryder and Wood, 1977]. Smaller basin-forming projectiles, such as that which formed the Nectaris Basin, would not penetrate as deeply, producing slightly more aluminous, although still noritic, melts [Spudis, 1984]. The provenance of two broad groups of basin melt rocks (VHA and LKFM) is shown in Figure 4. Our crustal model further predicts that the melt sheets of typical complex craters (50 to 200 km in diameter) in the highlands probably have the composition of "anorthositic gabbro" (layer 4; Figure 4), except in regions dominated by lateral crustal heterogeneities (see petrologic maps of Davis and Spudis [1985, 1987]).

In addition to estimating the bulk Al₂O₃ content of the lunar crust, we have used the basin ejecta compositional data in Table 1 to estimate the total amount of plagioclase in basin targets. This technique is described in detail in Spudis and Davis [1985] and is briefly outlined here. Given the average end-member rock composition of basin ejecta determined by mixing models (Table 1) and the average fraction of plagioclase within each end-member [Taylor, 1975], we can extract the total fraction of plagioclase in the basin ejecta and express this quantity as a volume percent (anorthite assumed; density = 2.75 g/cm³). The volume fraction of plagioclase in the ejecta of 11 lunar basins is given in Table 1.

The dimensions of lunar basin excavation cavities may be quantified according to the proportional-growth model [e.g., Grieve et al., 1981; Croft, 1981, 1985]. The total basin ejecta volumes are calculated according to the transient cavity diameters predicted by the proportional-growth model (Table 1) and assuming a spherical-cap excavation geometry [Spudis et al., 1984b]. In this model, we approximate the shape of a "Z-model" excavation cavity [Croft, 1980, 1981; Hötz et al., 1983] by constructing a spherical cap with diameter equal to the transient cavity diameter and a thickness at the basin center equal to one-tenth its diameter [Croft, 1980]. Applied to a spherical moon, this geometry produces a convex lens-shaped body of excavation that closely approximates a true Z-model excavation cavity. For this spherical cap excavation body, the total ejecta volume is calculated.

Taking the estimates of the volume of plagioclase in the basin ejecta and restricting this volume to the uppermost part of the crustal target, we can calculate the thickness of an equivalent layer of pure plagioclase in the crust at each basin target (Table 1). This equivalent thickness of plagioclase does not represent the petrologic structure of the crust, but does allow the comparison of variable amounts of plagioclase between the basin targets. Moreover, the estimates presented in Table 1 do not represent the total crustal inventory of plagioclase at the basin sites, as only the Imbrium basin was apparently large enough to excavate the complete crustal column [Spudis, 1986]. Thus the values of equivalent thickness of plagioclase in Table 1 are minimum estimates.

The mean equivalent thickness of plagioclase at these basin
sites is 19.3 ± 3 km. The average thickness of plagioclase in the crust was also calculated by Wood [1986] based on the difference in elevation of mare and highlands on the moon and observed gravity anomalies within mascon basins; his value for the plagioclase equivalent thickness is 20.4 km. We consider these two values, obtained by different techniques, to be in good agreement. We again emphasize that our estimate of plagioclase is a minimum one, noting that the equivalent thickness at the one basin excavating the complete crustal column (Imbrium) is 21 ± 3 km.

A corollary of the serial magmatism hypothesis for crustal origin is that the bulk crustal composition is basaltic or noritic [Walker, 1983]. This model implies that bulk crustal Al₂O₃ must equal 15–20 wt % and that the total equivalent thickness of plagioclase in the crust is less than 10–20 km [Longhi and Ashwal, 1985]. Our results indicate that the bulk crust is more feldspathic than the serial magmatism model would imply. Our derived bulk composition supports the concept that large-scale magmatic processes are responsible for lunar crustal origin. Using the analogy developed by Longhi [1983] to the terrestrial Stillwater complex, a global mean minimum plagioclase layer 20 km in thickness on the moon implies a parental magma body at least 140 km thick. The need for such a thick magma body indicates that the magma-ocean hypothesis for crustal origin [Wood et al., 1970] best explains the bulk composition of the lunar crust.

We believe that a global magma system produced an original ferroan anorthositic crust by plagioclase fractionation and olivine/pyroxene sinking. As the crust grew downward and the mantle upward, the residual liquid developed a noritic composition [Wood, 1972; Ryder and Wood, 1977]; this liquid formed the noritic lower crust and, eventually, a layer of material (KREEP substratum; Figure 4) greatly enriched in incompatible trace elements [Wood, 1972; Warren and Wasson, 1979]. Partitioning of incompatible elements into this KREEP layer was not completely efficient, resulting in the production of some KREEP-rich norites in the lower crust [Ryder and Wood, 1977]. Concurrent with this episode was the intrusion of Mg-suite magmas to form plutons within the original anorthositic crust [e.g., James, 1980]; because we find little evidence for extensive bodies of Mg-suite material actually intruded into the upper crust, most of this intrusive activity probably occurred at middle to lower crustal levels [Warren and Wasson, 1980]. This magmatic activity was virtually complete by 4.36 b.y. ago [Carlson and Lugmair, 1979]. Massive extrusions of mafic basalts [Davis and Spudis, 1985] and continued heavy bombardment of the crust [Hartmann, 1980; Wilhelms, 1984] followed about 3.85 b.y. ago. During this period, the relatively hot, low-density KREEP material migrated upward [Shirley and Wasson, 1981] and was disseminated throughout most of the lower crust. Thus basins that formed about 3.9 b.y. ago incorporated a KREEP trace-element pattern into their noritic impact melts (*melt rocks*; Figure 4). In at least the Imbrium-Procellarum region, KREEP basalts were erupted on the surface both before and after the Imbrium impact [Hawke and Head, 1978; Spudis, 1978]. After the heavy bombardment, extrusion of mafic basalts continued, although in gradually declining volumes, to form the visible maria.

**SUMMARY AND CONCLUSIONS**

The Apollo orbital geochemical data have been combined with information from cratering processes to determine the probable chemical and petrologic structure of the lunar crust. From this, we conclude the following:

1. The highland surfaces under the Apollo 15 and 16 groundtracks have a composition approximating "anorthositic gabbro" (Al₂O₃, 26–28%). Given the cumulative bombardment history of the moon, which has mixed the upper half of the lunar crust on a scale of hundreds of kilometers, we suggest this anorthositic gabbro composition represents the bulk composition of the upper half of the lunar crust.

2. The composition of multiring basin ejecta displays increasing fractions of noritic components (norite, low-K Fra Mauro basalt, and KREEP) with increasing basin size. This relation suggests that the bulk composition of the lower lunar crust is "noritic" (Al₂O₃ ~ 20%). Direct evidence for a noritic lower crust is present in the sample collection by numerous LKFM and VHA melt rocks that were collected from impact melt deposits ejected from lunar basins.

3. The bulk composition of the lunar crust corresponds to "anorthositic norite" (Al₂O₃, 24–25%). The minimum thickness of a hypothetical pure layer of plagioclase in the lunar crust at basin target sites is 19.3 ± 3 km. This composition is not consistent with crustal origin by a purely serial-magmatism mechanism, but it is consistent with the global magmatic event postulated by the lunar magma-ocean hypothesis.

These conclusions are based on the ~19% of the lunar surface for which we have orbital geochemical data. The global remote-sensing data to be provided by the future Lunar Geoscience Observer mission will enable this crustal model to be refined, and quite probably modified, in order to explain the complex evolution of the lunar crust.

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**References**


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